Strategy of Nuclear Physics Research in Romania

1. Introduction

2. Nuclear Physics at Low Energy

3. Nuclear Astrophysics

4. Astroparticle Physics

5. Hadron Physics

6. Applications of Nuclear Physics

General Recommendations

Annex: Published Papers (2001-2010)

1. Introduction

Nuclear Physics (NP) is going to be 100 years old in 2011. By all accounts it is now a mature and accomplished branch of science, but also a vigorous field of current and future research. It has already a well established place among basic sciences, with an important contribution in the understanding of the Universe that we are part of, as a whole, and of many details of its composing parts. At the time lord Rutherford made his crucial scattering experiments in 1911, radioactivity and the transmutation of elements, also nuclear phenomena, were already known, but the physicists and the world had no idea that they originate in a part of the atoms (a 2500 years old concept experimentally proven only in the 19th century) that is 4-5 orders of magnitudes smaller in size, but contains most of their mass. The atoms could, therefore, be cut into smaller parts and it did not take long until physicists accepted (first with the discovery of neutron, later of new 'elementary particles', latest with quarks and gluons), more readily this time, that the division can go further, and that we should at all times admit that we may not have reached the 'ultimate elementary building blocks of matter'.

In these 100 years NP has not only generated new knowledge, it has also brought into our society:

- new ideas, concepts and set precedents with models for the modern scientific research and its management – large government funded institutions, the national laboratories which are today the norm in basic research and beyond;
- has generated weapons and security tools that were the basis of the (insane, but working) balance during the cold war era;
- has generated the nuclear power industry and a large number of direct industrial and medical techniques;
- has generated and set precedents for large scale international cooperation, including (trans-national) international institutions (earlier CERN Geneva, JINR Dubna; more recently FAIR Darmstadt, ITER, etc.)
- embraced early on the computers and demanded better and better performances from them; lead to the invention of the Internet in SUA and of the World Wide Web at CERN.
- Gave birth to particle physics, today considered a separate science branch, and to a large number of research tools for other sciences (material sciences, medical research, etc.), either directly or incidentally.

"The effort to understand the Universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy." These words are from a Nobel Prize winner (S. Weinberg, in *"The first three minutes"*). They express well the need for basic science, in general. Our part in that struggle for grace, here, is our work in nuclear physics.

In a simple, but comprehensive definition, NP is the science of the atomic nuclei, and of the nuclear matter. Nuclei are the **core of the mater**; overall they carry most of the mass of the objects in the visible Universe, from humans all the way to the stars. The nuclear physics of the 20th century lead us to understand that nuclei were and are the **fuel of the stars** and that the creation of chemical elements was (and is) the result of nuclear processes. The atomic nucleus is a **quantum many-body system**, made of **fermions**, the nucleons: protons and neutrons. These nucleons interact through 3 of the 4 fundamental interactions known: the strong nuclear interaction, the weak and the electromagnetic interaction. The research of the 20th century has proven that the nucleons are made of **quarks**, and are therefore not elementary. Quarks are bound into hadrons by the strong force described by Quantum Chromodynamics.

Among the most important challenges and fundamental questions for today's scientific research one find that many of them directly concern Nuclear Physics. Just few examples, and obviously this does not represent a complete list, are enumerated in the following as indication about the complexity and importance of the field.

- The structure of nuclei is complex and may vary drastically along the nuclide chart. Most of the current concepts were extracted from the study of a restricted area of nuclei, on or around the stability valley. They represent only a small fraction of the about 7000 bound isotopes, and new techniques permit to extend the studies to regions far from stability. New facilities producing radioactive ion beams by fragmentation in-flight or by isotope online separation will allow the extension of structure studies far from stability.

- Nuclei allow studying key aspects of fundamental interactions and symmetries. Precision measurements of weak interaction, including very low probability decays can be made due to advances in detection techniques and in the production of rare probes or rare phenomena. What is the nature of the neutrinos, their masses and their contribution to the evolution of the Universe?

- Recently, the possibility to detect very high-energy particles from the universe has opened up a new challenging field, Astroparticle Physics (AP), with an exciting potential for fundamental discoveries. These "cosmic messengers" are gamma rays, charged particles, nuclei and their isotopes, neutrinos or yet-unknown particles. Their energies extend to 10^{20} eV to energies, many orders of magnitude higher than those produced by man-made accelerators. These cosmic messengers propagate through the Universe and the analysis of their propagation can yield information on the properties of inter-galactic magnetic field. There are some intriguing questions to know: How and where thee particles are accelerated to such extreme energies? Their origin could be in the decay of exotic massive particles produced in the Early Universe or in the decay of new heavy particles?

- What is the origin of the chemical elements and what are the reactions driving the stars and their evolution? In many cases we do not have yet enough precise knowledge to distinguish between various stellar evolution scenarios. Among the unknowns are the nuclear data for nucleosynthesis. Nuclear astrophysics has become an important motivation for today's nuclear physics developments; in particular, the use of radioactive nuclear beams (RNB).

- The study of the fundamental strong interaction by looking at the subnucleonic degrees of freedom.
- The development of theory methods to answer the questions of QCD, of the interpretation of the experimental results and the link to the understanding of nuclear structure.
- New applications of nuclear techniques with impact for society and the quality of life.

From the beginning of its institutional existence, with the creation of IFA – Institutul de Fizica Atomica - Bucharest in 1949, the Romanian nuclear physics was anchored in the international research efforts. It did evolve slowly or in big steps – like the ones that brought the nuclear reactor, the cyclotron or the tandem accelerator – but it can be told in earnest that it was or aimed always to be internationally competitive. In time, a solid basis of qualified research personnel and instrumentation was built, a true Romanian school of nuclear physics. This statement is proved to be true by the successful participation of Romanian scientists in the international nuclear physics research of the last two decades. Even at times of strong financial distress for the whole society, nuclear physics community could survive because its members were well qualified and competitive, capable to engage directly in top world research abroad. An improvement of the financial conditions in the second part of the first decade of this century lead to an equal-peer participation and to the formal recognition through membership in many international institutions or endeavors (particularly European). Currently Romania is member of CERN, Facility for Antiproton and Ion Research (FAIR) - Darmstadt, as well as of the Joint Institute for Nuclear Research (JINR - Dubna).

In this context, it is not a surprise that the contribution to the Romanian society of the national research in nuclear physics has been benefic and driving toward progress, closely mirroring the effects of civil nuclear physics research at global level. For instance the first studies in nuclear power research started in IFA and the current specialized institute, Institute for Nuclear Research, former Institute for Nuclear Reactors (IRNE) was separated from it in 1977. Most of their specialists were educated in IFA. The main successor of IFA, the "Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), has today a crucial role in the development and implementation of nuclear techniques and methods in Romania. Another sound example is the fact that the first Romanian computer was born in IFA in 1955 and the first mainframe computer (IBM 370) was installed here. Later, as CERN did at global level, Romanian nuclear physics community was topping the demand and use of computers in Romania, imported or locally produced, and was spearheading the introduction of Bitnet and Internet in the country in 1990, and the construction of GRID computing in recent years.

Along the years, the Romanian nuclear physics community had identifiable successes in experimental studies of statistical reactions, of resonant reactions, in beta and in-beam gamma-ray spectroscopy, in the measurement of static properties of nuclear states, in reaction dynamics and in the theoretical description of alpha and cluster decays, of collective nuclear models, reaction theories. After 1990, the contributions, and the publications accompanying them, increased drastically with the opening of new possibilities to participate to international collaborations. Most of these were in large European facilities, but also in USA and in Japan. A large number of nuclear scientists worked for short or long periods in prestigious laboratories and contributed to many recent achievements in nuclear physics in the world.

The goal of this document is:

- To review the achievements of NP research in Romania, within the broad framework of the international efforts
- To identify open problems in which Romanian nuclear physics can contribute, in particular the niches in which it can put a mark
- Outline strategies and make recommendations for future studies in the field
- Identify the most effective ways to integrate and remain competitive in the international initiatives, European in particular.

We can state that NP is a scientific field in which our community had and can continue to have a clearly identifiable and visible contribution of the Romanian science, due to its traditions, existing human potential and educational possibilities.

Nuclear Physics research in Romania is conducted in "Horia Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), Nuclear Research Institute Pitesti, Institute for Space Science (ISS), University of Bucharest, University Politehnica Bucharest, "Babes-Bolyai" University Cluj-Napoca, "Valahia" University Targoviste and other institutes and universities.

The document is divided in chapters covering the major areas of research in Nuclear Physics conducted by Romanian groups. In the end of each chapter there is an Annex with all relevant journal publications in 2001-2010 with at least one author affiliated with one Romanian institution.

2. Nuclear Physics at Low Energies

2.1. Introduction
2.2. Present status of experimental research, theoretical understanding, and future challenges
    2.2.1. Weakly bound nuclei
    2.2.2. Nuclear shell structure
    2.2.3. Isospin degree of freedom
    2.2.4. Symmetries and phase transitions in nuclei
    2.2.5. Collective properties; evolution with spin and excitation energy
    2.2.6. Ground state properties
    2.2.7. Dynamics of nuclear reactions
    2.2.8. Emission processes
2.3. Physics at Large Scale Facilities
    2.3.1. Radioactive ion beam facilities
    2.3.2. Experimental infrastructure
2.4. Physics at Local research infrastructure
    2.4.1. Role of "small scale research"
    2.4.2. Accelerator and instrumentation
    2.4.3. "Niche" researches at the Tandem van de Graaff accelerator
2.5. ELI – Nuclear Physics
2.6. Recommendations

2.1. Introduction

The main goal of nuclear physics at low-energy is to understand the structure of atomic nuclei and its dependence of the number of its constituents, protons and neutrons. The structure of nuclei is very complex and may vary drastically along the nuclide chart that is schematically shown in Fig. 2.1. Most of the current concepts (like magic numbers, regions of shapes/deformation, collective and single-particle degrees of freedom, etc.) are based on the study of a restricted area of nuclei, on or around the stability valley. This represents, however, only a small fraction of the about 7000 isotopes predicted to be bound. As observed in Fig. 1, more than half of the nuclei predicted to exist were not observed yet. Also, for many of the observed nuclei the experimental information existing at present is very limited. The same figure also shows that the nuclei far from stability play an important role in the nucleosynthesis processes that led to the formation of the stable nuclei as observed today in the Universe. New techniques are necessary in order to reach and study the unstable, exotic nuclei from the regions far from stability. These include new accelerator facilities that will produce radioactive ion beams by fragmentation in-flight or by isotope online separation, as well as new detectors and instrumentation that will allow detection and identification, with unprecedented efficiency and sensitivity, of nuclei produced in nuclear reactions and of their decaying radiations.

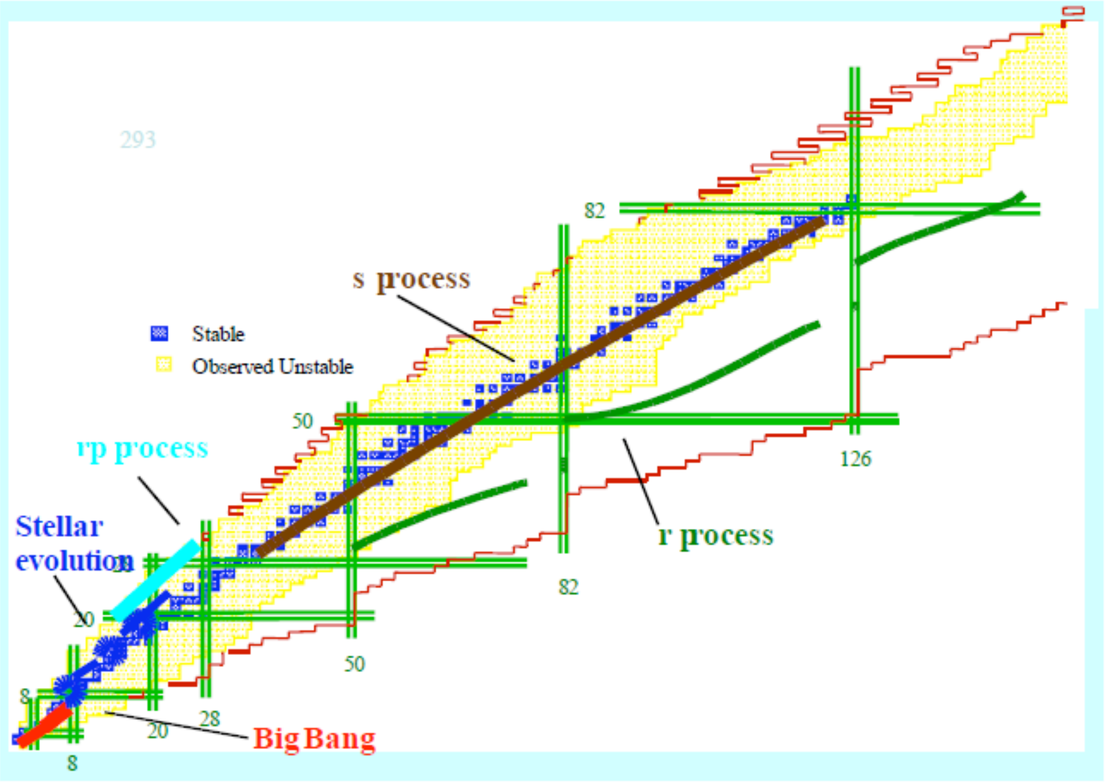


Figure 2.1. *The chart of nuclides. The narrow valley of stability is in blue and the drip lines in red. The classical magic numbers are in green (number of neutrons on the x-axis, number of protons on the y-axis). The paths for the s-, r-, and rp-process (presumed) and the contributions of different nucleosynthesis processes are also shown.*

Among the key questions of the nuclear structure physics to be answered are:

- What are the limits of stability of the nuclear system?
- What is the complete description of the nucleon-nucleon force?
- What is the relation between the phenomenological models for nuclear physics and QCD?

Progress in understanding nuclear structure and its evolution relies on advances in both experimental and theoretical approaches, which are strongly interdependent.

2.2. Present status of experimental research, theoretical understanding, and future challenges

2.2.1. Weakly bound nuclei

Dealing with ligh mass nuclei that have a very different proton-to-neutron ratio as compared to stable nuclei, finally answers a very important question: how does binding energy and extreme proton-to-neutron asymmetries affect nuclear properties?

For such exotic systems, that reach the limits of the nucleon binding, a large part of their wave function occupies regions that are classically forbidden, dominated by weak binding of the valence nucleons and occupancy of low angular momentum orbits for which the centrifugal barrier is suppressed. The properties of such systems are therefore influenced by both the continuum and many-body correlations, and thus one must study and consistently understand the interplay between scattering states, resonances, and bound states. In order to characterize such nuclei, all spectroscopy techniques are needed, but pushed to extreme selectivity and sensitivity. For example, the measurement of the momentum distribution of particles emitted in transfer or knock-out reactions is a powerful technique to obtain information on the wave functions of nuclei far away from stability, but, so far, in the cases when the number of excited states in the residual nucleus is high, it is strongly limited by the usual energy resolution of the actual detectors.

The availability of radioactive beams and new detection techniques will enable more detailed studies of the continuum properties of both unbound and weakly bound nuclei, and one of the most interesting points of the future studies is the mapping of the shell model changes beyond the drip lines. Until now, only several light nuclei beyond the drip lines were observed, such as the neutron-rich isotopes of H up to ^{7}H, He up to ^{10}He, and Li up to ^{13}Li, and ^{10,11}N and ^{12}O on the proton-rich side, but new detection systems with higher selectivity and resolution are needed to obtain unambiguous properties and advance in the neutron drip-line direction to heavier nuclei, because the production cross-sections of such nuclei are extremely small and therefore they come with a very high background.

Close to the drip lines the nucleons are very weakly bound, and the nuclear properties can be described in terms of different structures such as *halos, skins, alpha clusters,* and *nuclear molecules*. It is a huge task to find the right degrees of freedom that describe such structures. Even though halo structure nuclei were discovered during the 80's, the most studied neutron halo nuclei are still being investigated to evidence their excited states and the correlations between their neutrons. For example, in the case of 2-neutron halo nuclei, strong correlations between the two neutrons were found in the ground state (the case of ^{11}Li). There is evidence of nuclei that can be understood as "nuclear molecules": two cores (clusters) that share (or exchange) valence neutrons. The structure of such nuclei is characterized by excited states having characteristic electromagnetic decay towards the low-lying normal states; for example, such states in ^{10}Be may be understood as due to two alpha clusters bound together by two common neutrons. Also, in nuclei with large neutron excess, the volume occupied by neutrons is no longer equal to that occupied by protons, as in 'normal' nuclei: they are characterized by a large spatial extension with the last nucleons having a weaker binding energy, compared to the much higher density in the interior. Thus, for example, in Sn nuclei the strongly neutron-enriched outer zone (the neutron skin) would have a thickness of up to 1 fm, therefore the outer zone has almost half of the total volume. This fact is very interesting because the composition in that region approaches that of the neutron matter with an average density below that of nuclei. Studying these neutron-rich nuclei is significant for nuclear astrophysics, because these nuclei belong to the r-process path, a route by which about half of the heavy elements were synthesized.

As emphasized already, the study of the light exotic nuclei means experiments of the highest degree of sophistication concerning both their production and detection. At FAIR and SPIRAL-2 such experiments will integrate in the same experimental setup both the accelerator and the separation facilities. Detectors of high efficiency and high granularity are being developed for neutrons, charged particles, and gamma rays.

From theoretical point of view, traditional methods, like shell model, Bardeen-Cooper- Schrieffer (BCS), Hartree-Fock-Bogolyubov, and quasiparticle random phase approximation have been extended to unstable nuclear systems such as to take into account the coupling of the bound states to the states in continuum. Such approaches will continue to be developed and applied to exotic unstable nuclei. Also, the breakup and removal reactions as means to investigate neutron-rich nuclei will be pursued.

2.2.2. Nuclear shell structure

The nuclear shell model constitutes one of the most important paradigms of nuclear structure, until recently based on the belief that the known magic numbers (neutron and proton numbers of 8, 20, 28, 50, 82, …, where the nuclei are most stable) are valid throughout the whole nuclear chart. However, going away from the valley of stability, it turned out that with changing the number of protons and/or neutrons, the so-called shell structure (clustering of the single-particle orbitals around the magic numbers) changes. This fact raises important theoretical questions as for the reasons of this shell evolution, and it is not clear yet which factors cause it. Some of them may be different components (like pairing, tensor interaction, etc.) in the residual interaction, or even different nuclear potentials (due to a different mean field).

The search for changes in the shell structure of nuclei far from stability constitutes a broad field of activity. Such changes appear even in the very light nuclei. For example, in ^{11}Be the well known inversion of parity in the ground state is due to the disappearance of the shell gap between the *p* and *sd* shells: the *s* orbital from the *sd* shell competes with the *p* orbit and becomes an intruder ground state (vanishing the magicity of N=8).

Many other evidences for the disappearance of the known magic numbers were found. For example, the magic character of the neutron number N=20 vanished in ^{32}Mg (a phenomenon called 'island of inversion'). Similar changes were found for nuclei around N=28 - which is no longer magic in the Si isotopes (Fig. 2.2.1). These changes were attributed to the strong p-n interaction between spin-orbit partners, due to the monopole part (tensor interaction) of the effective nucleon-nucleon interaction that induces strong changes in the single-particle energy diagram.

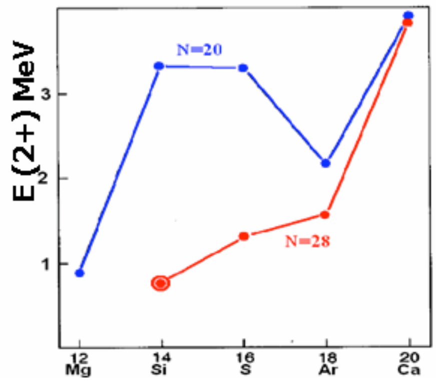


Figure 2.2.1. *Illustration of an island of inversion: N=28 is no longer magic number in Si.*

If the mean-field potential modifies with increasing proton/neutron excess, this will be reflected in changes of the single-particle levels. As an example, gradual changes in the nuclear potential may cause a gradual change of the single-particle levels, which may even cross within one major shell. Such an effect was observed in the region of the magic nucleus ^{68}Ni, where an inversion of the $1f_{5/2}$ and $2p_{3/2}$ orbitals is predicted to occur in the Cu isotopes between ^{75}Cu and ^{79}Cu (Fig. 2.2). It is not clear what causes these changes: changes in the mean-field itself or in the residual neutron-proton interaction.

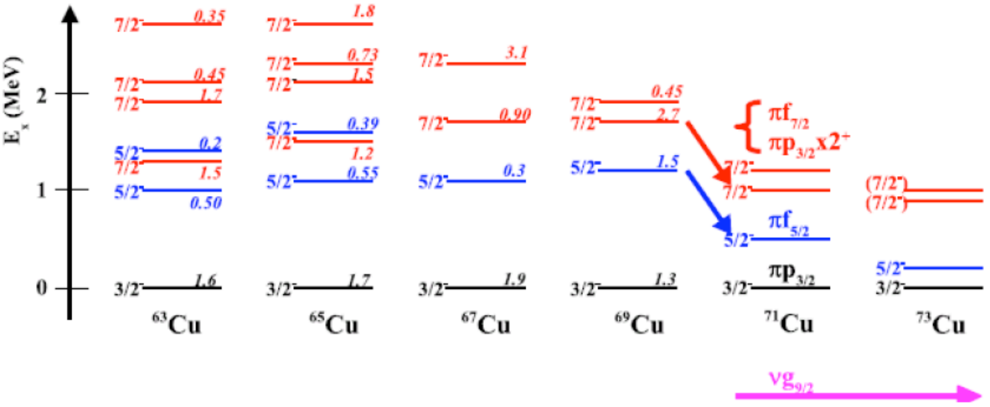


Fig. 2.2.2. Evolution of the experimental excited states in Cu isotopes.

One believes that away from stability changes in the spin-orbit strength may occur due to a change in the surface diffuseness. This will tend to cluster together the orbits of the same parity, considerably changing the shell-structure of nuclei close to the neutron-drip line. The suggested (and partially observed) new magic numbers are N=16 and N=34, while those with N=8 and N=20 disappear. New magic numbers N=40 and N=70 could also appear. This migration of the single-particle levels will undoubtedly be a subject of active research with the expected availability of intense and pure RIBs. An especially useful method to map the single particle states and their occupancy across broad nuclear regions away from stability will be the direct transfer reactions in inverse kinematics, using radioactive (tritium) and polarized targets, in conjunction with gamma-ray arrays.

The evolution of the shell structure in neutron-rich nuclei reflects the spin and isospin dependence of the nucleon-nucleon interaction. In nuclei close to stability the strong neutron-proton interaction induces deformation of the nucleus. In nuclei far from stability, a decoupling between the valence neutrons and the core may occur (polarization effect). Another intriguing question related to the properties of the neutron-rich nuclei is whether the extended neutron distribution could produce new collective modes, in which neutrons and protons exhibit different motions (for example, the neutron skin rotates but the core does not). Such phenomena can be seen by measuring the electric quadrupole strength B(E2) in the even-even nuclei along long isotopic or isotonic chains, because it is sensitive to the proton contribution to the excitation. Together with the evolution of the excitation energy of the first 2^+state, they give an image of the evolution of the collectivity (for example, of the low-lying vibrational mode) of nuclei. For example, B(E2) measurements in the light Sn isotopes show an asymmetry with respect to the middle of the neutron shell (N=66) which is not understood theoretically. Systematics of such data as B(E2) (measured, for example, by Coulomb excitation of radioactive beams) as function of proton and neutron numbers will certainly be pursued in the future.

2.2.3. Isospin degree of freedom

The *isospin symmetry*, a property of the strong interaction, leads to the concepts of isobaric multiplets and mirror nuclei, whose structure differs only because of the Coulomb interaction that lacks this property. Thus, nuclei that mirror across the N=Z line, are expected to show excited states that differ only by the contributions due to the Coulomb energy. Precise measurements of mirror energies became possible and are being used as crucial probes of the isospin symmetry and its validity with increasing mass and Z number. Studies of the mirror energy differences give information on the nucleon alignments, the evolution of nuclear radii along bands, and, finally, on the interplay between the Coulomb potential and possible isospin-breaking nuclear interaction terms (Fig. 2.2.3). Such studies have been performed for medium mass nuclei, but extension to higher masses are important, and being planned, because in this way one may determine the limits of validity of the isospin symmetry, identify the origins of possible symmetry breaking, and eventually find new Coulomb effects. Thus, measuring more isospin multiplets, which means exploring nuclei on both sides of the N=Z line at higher masses, is a difficult but very attractive experimental task. Measuring mirror pairs with large isospin quantum numbers, which maximizes the Coulomb differences, will become possible only with the next generation of RIBs and gamma-ray arrays

Another possible way to study the *isospin breaking* is to observe deviations from two rules: E1 ($\Delta T=0$) transitions in N=Z nuclei are forbidden; and E1 transitions in mirror nuclei must have equal strengths. Failing to obey these rules may be due to different factors such as: isospin breaking of nuclear interactions; isospin mixing due to coupling with the continuum; isospin mixing of quasi-degenerate levels with different isospin; isospin mixing with the isovector giant magnetic resonance. Forbidden E1 transitions were observed until now only in the even-even ^{48}Cr and ^{64}Ge nuclei, and irregular transitions were also measured in light mirror pairs, such as ^{35}Ar-^{35}Cl. Therefore, such investigations are only at their beginning.

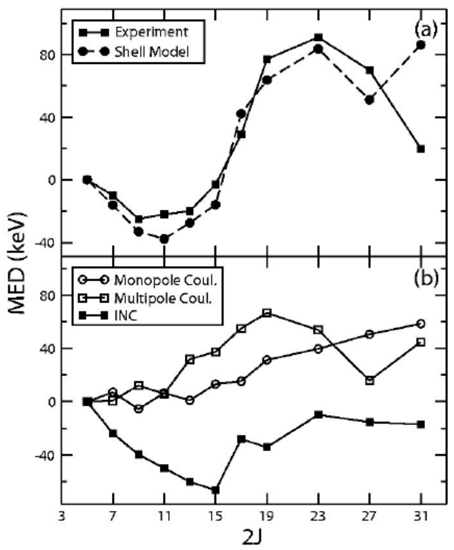


Figure 2.2.3*. Mirror energy differences for ground state rotational band in ^{49}Mn-^{49}Cr, and their comparison with shell model; contribution from different terms in the lower panel.*

Pairing, which is an important ingredient of the effective nuclear interaction, is relatively well understood from studies near the stability, but it is interesting to learn its properties as a function of isospin, therefore investigate the properties of exotic nuclei. An outstanding point of interest are the N=Z nuclei, which exhibit an additional symmetry related to the similarity of the proton and neutron wave functions at the Fermi surface. In ‘usual’ nuclei, the like-nucleon pairs (*p-p* and *n-n*), or Cooper pairs, dominate. This type of pairing is active only in the channel of isospin T=1 (due to the Fermi principle). In contrast, the *n-p pairing* can exist both with T=1 and T=0, the isoscalar type of pairing (with T=0) being practically unknown. In the N=Z nuclei, it is expected that this type of pairing brings a sizable contribution, therefore there is a chance to study its properties (in effect, this is a *new type of superfluidity*, different from that based on the Cooper pairs). Theoretical progress was made in describing self-consistently the *n-p* pairing correlations. Different types of experiments will continue to play a major role in studying this phenomenon: (i) study of collective behaviour of the nuclei with N≈Z nuclei, because the crossing frequencies and the moments of inertia at higher spins may be influenced by the different components of the *n-p* pairing (the isoscalar *n-p* pairs are not destroyed by the Coriolis forces due to the rotation); (ii) investigation of the ground state regime properties of odd-odd N=Z nuclei and of their beta decay; (iii) study of the two-nucleon transfer reactions, which are expected to have enhanced cross-sections in the presence of strong pairing in inverse kinematics, such as the (p,^{3}He) and (d,α) reactions, with the latter probing only the T=0 pairing.

The advance on the N=Z line has led until now only to the experimental observation of ^{100}Sn. Spectroscopic studies could be made only for odd-odd nuclei up to ^{92}Nb and ^{96}Tc (by isomeric decays) and for even-even nuclei up to, very recently, ^{92}Pd. The observed lack of backbending in the ground state band in the nuclei up to ^{88}Ru was a first indication that the T=0 *n-p* pairing may be important. The recent observation of an ‘oscillator-like’ (almost equidistant levels up to the 6^{+} state) yrast band in ^{92}Pd gave a more definite proof for the importance of the n-p pairing (Fig. 2.2.4).

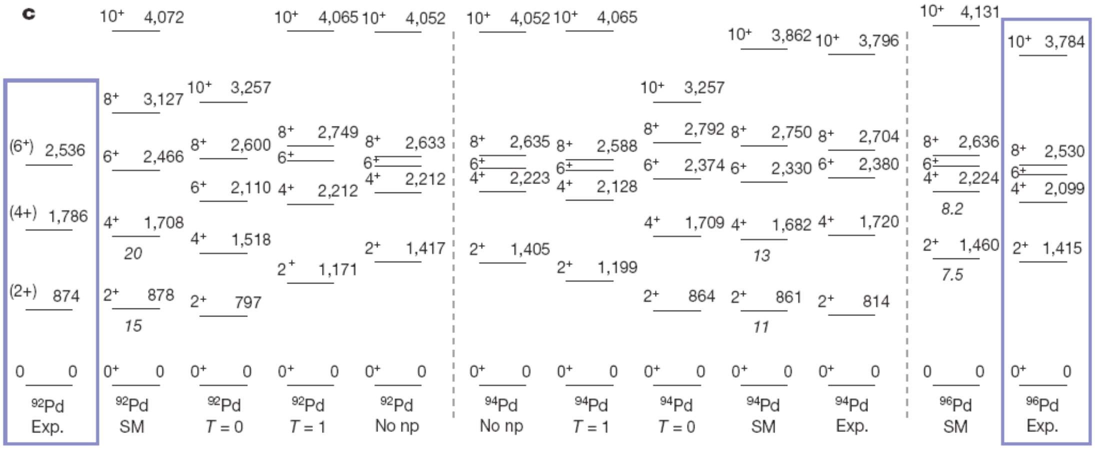


***Figure 2.2.4**. Experimental level scheme of ^{92}Pd, compared with shell-model calculations, including different n-p interactions, SM denotes the full interaction.*

The future studies of ^{96}Cd and ^{100}Sn would be extremely valuable because it was suggested that the *n-p* pairing effect in these heavier nuclei would enhance their collectivity. The N=Z=50 nucleus ^{100}Sn is especially important, to see to what extent shell gaps and collectivity are preserved under such conditions of ‘double magicity’. In addition, the variation of the pairing field with isospin will be experimentally approached through the study of the two-neutron transfer (p,t) and (t,p) reactions with a large variety of neutron-rich RIBs. Finding appropriate fingerprints of the *n-p* pairing correlations in neutron-rich nuclei remains an interesting item.

Advancing in the proton-rich region towards the limits of stability, in order to map the proton drip line becomes possible with the new generation of RIBs for the whole nuclide chart. Near the proton drip line one meets the one- and two-proton radioactivities, which give the unique opportunity to study the coupling between bound nuclear states and the continuum. The one-proton drip line is known up to mass ~180, whereas the tw-proton drip-line is known only up to mass 54. Heavier two-proton decay candidates are ^{59}Ge, ^{63}Se, and ^{67}Kr, therefore both their study and more detailed studies of known nuclei (such as ^{45}Fe, ^{48}Ni, and ^{54}Zn) will be valuable for a better understanding of the physics involved.

Study of the prompt particle decay will be extended to heavier nuclei, where new detector developments are needed in order to avoid the influence of the time of flight of the recoils through the separator.

2.2.4. Symmetries and phase/shape transitions in nuclei.

Nuclear collectivity is changing rapidly when the number of valence protons and neutrons are varying. Mapping the evolution of the nuclear collectivity with varying Z and N is very challenging. The geometric models comprise three idealized regimes for the collective nuclear motion: the anharmonic vibrator (realized near closed shells), the symmetrically deformed rotor (prolate or oblate, realized mainly in the middle of the major shells), and the soft triaxial rotor. The algebraic Interacting Boson Approximation model, defines these regimes as *dynamical symmetries* (U(5), SU(3), and O(6), respectively). The way the nuclear structure changes from one dynamical symmetry to another, when the number of valence nucleons is varied, is one of the most interesting questions. Indeed, in spite of the limited number of constituents of the nucleus (‘mesoscopic’ system), it was discovered that the transitions between the dynamical symmetry points pass through critical phase (shape) transition points. These critical points are analitically described as new symmetries, like E(5) (the critical point between U(5) and O(6)) and X(5) (between U(5) and SU(3)). Candidates of real nuclei for these critical points were found in the N=90 isotones between Nd and Er [for X(5)] and in ^{134}Ba [for E(5)]. Mapping of the shape/phase transitions was limited so far to the neutron-deficient nuclei relatively close to stability, but other regions far from stability are of interest, as shown as an example in Fig. 2.2.5.

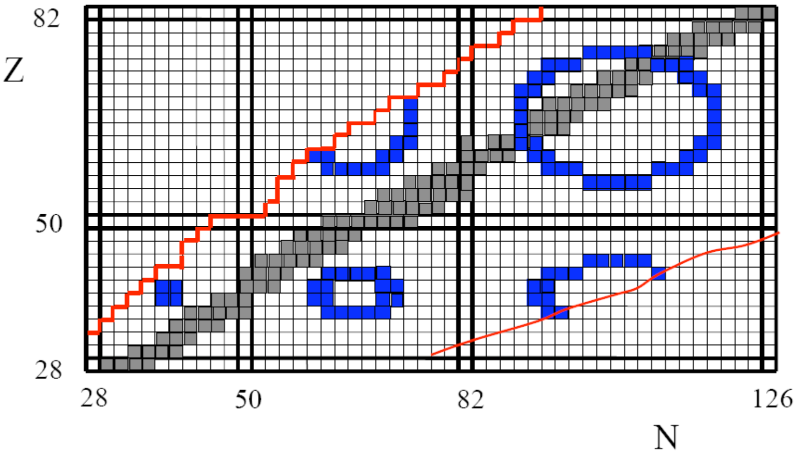


Figure 2.2.5. *Nuclear regions with possible X(5) candidate nuclei (the blue rectangles, showing nuclei with $P \approx 5.0$, as expected for that symmetry, where $P = N_p N_n/(N_p + N_n)$, with N_p, N_n the number of valence protons and neutrons, respectively).*

At the critical phase/shape transition point, the respective shapes coexist. Microscopically, this is due to the particle-hole excitation across a sub-shell gap. The mechanism is similar to that producing the shape coexistence exhibited by intruder states in nuclei near closed shells, clearly demonstrated some time ago in Z~50 and Z~82 nuclei even at low excitation energies (where spherical and deformed shape compete for the ground state) but in that case the excitations are cross-major-shells.

Shape transitions, shape coexistence, and shape mixing, identified in different mass regions, will undoubtedly play an important role in the exotic nuclei. A self-consistent treatment of such shape coexistence phenomena represents a challenge for the nuclear many-body models and its realistic description is still an open problem.

Another feature of the nuclear excitations stems from the two-fluid character of the nuclei, which manifests itself in the so-called mixed-symmetry states: low-lying quadrupole collective isovector modes in near-spherical nuclei, and scissors-mode excitations in rotational nuclei. To disentangle the microscopic mechanisms of thsese excitations, systematic information about these states is needed in many unstable nuclei.

2.2.5. Collective properties; evolution with spin and excitation energy.

Besides extending the nuclear structure studies in the isospin direction (broad variations of Z and N), another dimension of interest for study is the angular momentum. How the nucleus responds to increasing rotation is a real laboratory to study the nuclear forces, and it is manifested by a range of phenomena involving shape changes and various types of rotational damping at higher excitation energy. The study of such phenomena will benefit from the use of new RIBs and detection techniques (such as the new tracking gamma-ray array).

One of the most strinking shape changes with rotation is the *superdeformation* (SD). The occurrence of the SD bands, characteristic of very elongated shapes at high angular momenta allowed extending the mean field description to extreme deformations. In spite of knowing a large number of SD bands nowadays (more than 200), many of them are still poorly described in terms of spin values and modes of decay. It is especially interesting to find such structures in light nuclei (as for example found in the *sd* shell nucleus ^{36}Ar) for which large scale shell model calculations are possible and thus can offer a microscopic understanding of the phenomenon and a comparison to the mean field calculations. Observation of the SD band up to their termination (single particle configuration with all spins of valence nucleons aligned) and even beyond is also challenging because it can give important information on the nucleon orbitals involved. *Hyperdeformed* shapes (with ratio between the long and short deformation axes of about 3:1) were also predicted theoretically for a long time, but the experimental search for discrete HD rotational bands is still continuing. Such studies will benefit from fusion reactions induced by neutron-rich projectiles that populate larger angular momenta than those of stable beams due to the increase of the fission barrier with increasing N.

At even higher angular momenta, other shape changes are expected, such as the Jacobi shape transition (change of the equillibrium shape of a liquid drop from an oblate spheroid, through a sequence of triaxial shapes, to a triaxial ellipsoid rotating about its shortest axis, analogous to the rotating stars). Unlike the SD shapes, the elongation occurs due to the large centrifugal forces, at very high spins, and is expected over a wide range of nuclei. Experimental evidence of a Jacobi shape transitions has been obtained only for nuclei around mass 46.

Other nuclear shapes, stabilized by rotation, present a large interest as well. Theory has predicted stable triaxial shapes for a long time, but their experimental proof was, until recently, very elusive. The recently discovered ‘wobbling bands’ in odd-A Lu isotopes are a unique fingerprint of stable triaxiality; such bands have an underlying intrinsic structure, but part of their collective angular momentum is transferred from the axis of largest moment of inertia to the two other axes, and this gives them a unique, characteristic decay pattern. The limited observation (only in odd-A Lu isotopes) of these bands raises numerous questions. Another type of bands related to triaxiality are the *chiral bands*. A detailed experimental characterization of such bands (such as measurements of their absolute electromagnetic transition probabilities) is still necessary, as none of the known cases presents all the expected theoretical features. Theory predicts the existence of other exotic shapes as well, among which the nuclei having *tetrahedral symmetry* even in their ground state, at certain own magic numbers (Z.N = 32, 40, 56, 64,etc). The search for ‘islands’ of nuclei with tetrahedral symmetry, characterized by bands with missing or very small E2 transitions, is a real challenge. Another ‘exotic’ type of excitation are the so-called *magnetic rotation* bands, which are rotational-like sequences of strong magnetic dipole transitions that occur in near-spherical nuclei (such as light-mass Pb isotopes). It is not understood, however, why they were not seen in neighbor nuclei (like Bi or Po) which have similar deformation and the same particle and hole configurations, therefore their detailed investigation as well as search for them in other nuclei presents a considerable interest in the future studies.

Overall, the high-spin studies that led to such a broad range of phenomena have been restricted to a rather narrow region of nuclei, situated on the neutron-deficient side. The extensions of such studies allowed by the new RIBs will greatly revigorate this domain.

At higher excitation and temperature, where the density of levels becomes very high, other phenomena occur that characterize the nuclear system from a statistical point of view, as well as its collective response as a whole. Thus, close to the ground state, the nuclear states have good intrinsic quantum numbers and their decays are governed by selection rules. At higher energies, the level density and level mixing increase, and this breaks the concept of quantum numbers and their associated symmetries, this being a signature of quantum chaos. The transition between the regular ground state regime and the chaotic one at higher energies (the *order to chaos transition*) is an actual study direction, the experimental efforts being concentrated on understanding the damping of the rotational motion as a function of mass, deformation, and intrinsic configuration.

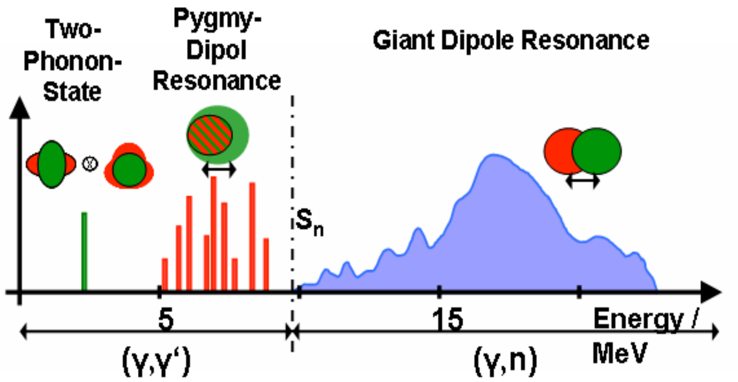


Figure 2.2.6. *Pictorial representation of the pigmy and giant dipole resonances.*

The bulk properties of the nuclei are revealed by the *giant resonances*, which are collective states at high excitation energies that represent coherent contributions of many nucleons. Their strength is concentrated above the particle threshold, and their properties are determined by macroscopic nuclear properties, such as size (radius), shape, (neutron) skin, viscosity, etc. Many such modes are known, as studied with different probes of various selectivity, and are classified according to quantum numbers such as multipolarity, spin, and isospin. An outstanding interest is presented by the additional dipole strength observed at lower excitation energy (close to the separation threshold in neutron-rich nuclei): the so-called *pigmy dipole resonances,* which were associated to a vibration of the neutron skin against the core. Detailed studies of the fine structure of these pigmy resonances can be made in stable nuclei with both electromagnetic and hadronic probes (Fig. 2.2.6). The study of the properties of the giant resonances gives information about the nature of both low- and high-energy components of the dipole strength. This is important for the unstable nuclei, because of their implication in astrophysical processes, but also, the evolution of the strength with N, Z, deformation and temperature is important to determine intricate details of the equation of state for asymmetric nuclear matter. Experimental investigation of giant resonances of other multipolarities is also a challenge, and will benefit of the new generation of RIBs and techniques based on inverse kinematics reactions.

2.2.6. Ground state properties

Quantities such as charge and matter radii, nuclear moments and spins, and masses of nuclei, contain important information related to structural changes that have already been discussed: onsets of deformation, pairing, proton-neutron interaction, symmetry effects.

Specific techniques to measure such quantities for unstable nuclei with the future RIB facilities have been developed. Thus, at future ISOL facilities, different laser spectroscopy methods with increased sensitivity and applicable to wide ranges of elements have been developed that will allow to measure charge radius, spin, magnetic dipole moment, and electric quadrupole moment: collinear resonance ionization spectroscopy (at ISOLDE and SPIRAL2), in-source laser spectroscopy. Charge radii along isotopic chains reveal how varying the number of neutrons modifies the proton distribution; also, compared to matter radii provides information on the onsets of halos and skins. For the study of ground state moments, spin-oriented radioactive beams will be developed at the in-flight facilities.

Nuclear masses, though accounting for the total binding energy of the nuclei, embed a vast quantity of information on the nuclear forces, a reason that made them always one of the key quantities for both experiment and theory. They play a major role in deriving the effective nuclear interactions and in the nuclear astrophysics nucleosynthesis calculations. The techniques of determining precise masses has advanced in a spectacular way, based on ion traps, storage rings, and time-of-flight spectrometry. Such methods will be adapted to different systems existing at RIB facilities, aiming at measuring precise masses even for very neutron-rich nuclei.

2.2.7. Dynamics of nuclear reactions.

Understanding the nuclear reaction dynamics has a twofold aspect. First, the nuclear reactions are used to create the unstable nuclear species of interest, therefore, especially in the multinucleon transfer reactions for a long time performed with stable beams but now being increasingly used with unstable nuclei, one must investigate how valid are different approximations or choices made for form factors, matrix elements, and degrees of freedom (single particle or collective modes). Also, in order to choose the most effective reaction for producing an exotic nucleus, one must understand in detail the reaction mechanism; this is essential, for example, in the study of, and search for superheavy elements, which are produced in very small quantities by different reactions. Second, the nuclear reactions are themselves ways by which the nuclear phase space is investigated in temperature, angular momentum and isospin, therefore their dynamics must be understood in detail. There are many types of reactions involved in nuclear investigations, ranging from the better understood processes of rearrangements of a few individual nucleons, up to less understood processes of massive rearrangement of nucleons (deep inelastic, fission, multifragmentation). Thus, investigating the evolution of the cross-section of fusion, and direct and deep-inelastic processes with the energy and type of the colliding nuclei, will constitute a direction of investigation with RIBs. Finally, the power of one-nucleon knockout reactions with RIBS of large energies (above 50 MeV/u), and of proton-induced knockout reactions as a quantitative spectroscopic tool to determine quantum numbers and occupancies for valence nucleons was recently demonstrated (as an example, Fig. 2.2.7).

This will enable to map the single-particle strength over broad nuclear regions, in order to study the isospin dependence of the short- and long-range correlations of nucleons in nuclei. Information on cluster structures will also be derived from appropriate reactions (as, for example, an alpha-knockout reaction). The absolute cross sections of nucleon removal reactions also determines the asymptotic normalization constant in the ground state, which in turn determines the direct component of the astrophysical S factor for the corresponding radiative capture reactions. Therefore, the study of different breakup and removal reactions to investigate exotic nuclei and various processes of astrophysical interest will continue to be of interest, both experimentally, and theoretically (developing of microscopic approaches for the calculation of the cross sections).

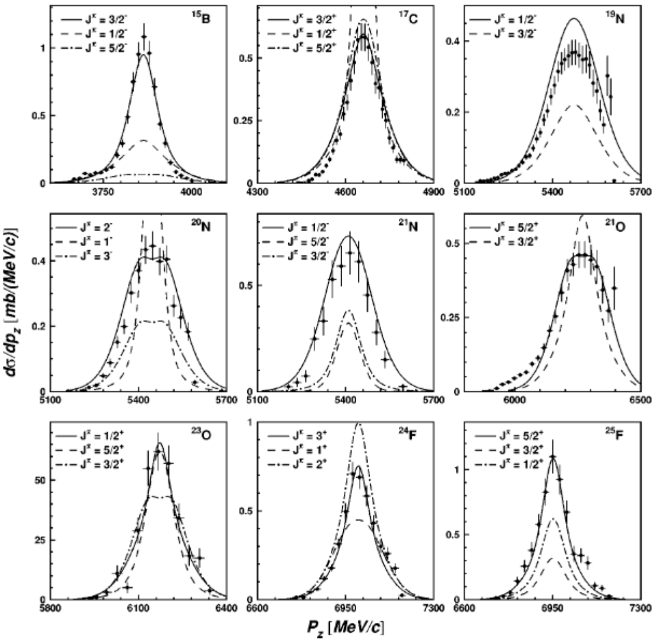


Figure 2.2.7. Examples of core fragment longitudinal momentum distributions from reaction on carbon target, measured at GANIL, compared to calculations. Solid lines give the assigned spin/parity for the projectile ground state.

Heavy ion collisions remain the main tool for probing nuclear matter properties at intermediate energies. The nuclear multifragmentation has been intensively studied in connection with various phase transitions in nuclear matter. New models are needed for the investigation of the dynamics and transport phenomena in heavy ion reactions. Extensions of such models to unitarily describe the nuclear statistical equilibrium over the whole density, temperature and isospin asymmetry domains relevant up to the physics of supernovae and neutron stars constitute a future challenge.

New experimental setups, including different particle detectors, being developed both at FAIR and at the next generation ISOL facilities will allow a much better characterization of the reaction dynamics at different energies.

2.2.8. Emission processes

The exotic unstable nuclei are characterized by various emission processes (or decays), some of them absent near the valley of stability. Studying these processes brings specific new information that should be accounted for by the available nuclear models.

Alpha and cluster emission. The theoretical prediction of the heavy cluster radioactivity (in 1980) is a Romanian achievement. The α-spectroscopy is an important tool for investigating the structure of medium and heavy nuclei, and it is complementary to the γ-ray spectroscopy. It remains the main possibility to investigate the superheavy nuclei. For this reason, developing systematics of this phenomenon and their theoretical understanding within different theoretical approaches, both phenomenological and self-consistent, remains an important issue.

Proton and two-proton emmision. This types of radioactivity become the main tools to investigate the most exotic proton-rich nuclei (see also end of sec. 2.3). Reliable procedures to assign experimental quantum numbers of proton emitters, as well as new systematic of spectroscopic properties of proton rich nuclei (such as their half-lives) and their microscopic understanding, are needed. Theoretical developments concerning the coupling of bound states to the continuum, and the probing of the pairing interaction by using the angular distribution of the two-proton emission are also expected.

Fission. The use of the fission processes for producing exotic (neutron-rich) nuclei remains important, and still open in what concerns many aspects of its dynamics. Microscopic extensions of the fission process based on the two-center shell model, with realistic pairing and dissipation, will be pursued.

Double beta decay. Double beta decay is one of the most exciting topics of nuclear physics since the rate of the process is obtained by combining formalisms of the electroweak interaction with those yielding nuclear matrix elements. The $2\nu\beta\beta$ process is interesting by its own, but is also very attractive because it constitutes a test for the nuclear matrix elements that are used for the $0\nu\beta\beta$ process. Discovery of this process may provide an answer for the fundamental question whether neutrino is a Mayorana or a Dirac particle. Important theoretical improvements for the description of these processes are expected, based on RPA and shell model.

2.3. Physics at Large Scale Facilities

2.3.1. Radioactive ion beam accelerator facilities

After decades of experiments using stable ion beams, the nuclear physics is now being revolutionized by the appearance of new radioactive ion beam (RIB) accelerator facilities, which are extremely complex and incorporate state-of-art scientific and technological developments both on the beam production and the infrastructure for experiments. Several RIB facilities are already available in the world, like ISOLDE at CERN, and will be further extended in the near future through important investments. At European level, two of the major projects aiming to build new infrastructures for nuclear physics are dedicated to the construction of radioactive beam facilities: FAIR in Germany or SPIRAL2 in France. This dynamic development will provide the experimental basis for a broad program of research in fundamental nuclear physics and astrophysics.

ISOLDE experimental facility dedicated to obtain radioactive ion beams, situated at CERN, is chronologically the first installation of this kind in the world, and has proved, along the years, to be one of the most prolific regarding the scientific output. The present research programs cover a wide scientific spectrum, including nuclear physics (gamma spectroscopy, radioactive decay, precise nuclear mass measurements, etc), astrophysics, solid state, radioisotopes bio-medical researches for diagnostics and treatment. ISOLDE offers at present a wide range of radioactive isotopes, beside this, the installation of a post-accelerator (REX-ISOLDE), has opened new RIB research fields especially in high-energy area. From this point of view, ISOLDE is complementary to other RIB European facilities like SPIRAL (Ganil, France), or GSI (Darmstadt, Germany), and offers a wider range of intense RIBs than HRIBF (Oak Ridge, USA) or ISCA (Vancouver, Canada). Till present were produced, with intensities up to 10^{11} atoms/μC proton beams, more than 600 isotopes with life times up to few milliseconds for almost 70 chemical elements, from helium to radium. Facility developing plans include increased radioactive ions beams intensities, improvement of their quality and higher beam energies, from 3.1 MeV/u in the present, to 5.5 MeV/u in the first stage and than to 10 MeV/u in the second stage as foreseen in the HIE-ISOLDE project. The increase of the radioactive beam energy will be achieved by replacing the current REX LINAC by superconducting cavities. In the same time, the new CERN injector LINAC 4 will provide a major boost of the proton intensity onto the ISOLDE target and will lead to the increase of the radioactive ion beams with one order of magnitude. These major upgrades will broaden the research possibilities, especially with the reference to the exotic nuclei.

The biggest European radioactive beam facility, the FAIR (Facility for Antiproton and Ion Research) complex is now being built in Darmstadt, Germany at the site of the present GSI. FAIR will provide unique opportunities in the fields of hadron, nuclear, atomic, and laser physics, and applications and is recognized by ESFRI (European Strategy Forum on Research Infrastructures) as the major RIB in-flight facility for Europe. It will provide capabilities unmatched worldwide. An international consortium in which Romania is full member builds this facility, which will be able to produce intense, high brilliance beams of all stable chemical elements up to uranium with energies in the range E~1-30 GeV per nucleon and also antiprotons. Beams of short-lived radioactive species will be generated in fragmentation/spallation and fission reactions. Such an in-flight facility has the advantage of being able to provide any isotope independent of the chemical properties of the element and, since the production process is fast, it can produce beams of the shortest-lived, and hence most exotic, nuclei. FAIR will be unique among the planned fragmentation facilities in several ways: (i) experiments can be carried out at high energies up to 2 GeV per nucleon; (ii) it will provide the cleanest radioactive beams for heavy nuclei; and (iii) it will be the only one to have storage rings.

Studies with radioactive ion beams form one of the major research programmes at FAIR. The radioactive-beam facility at FAIR offers unique experimental opportunities for this area of research. The secondary beams of unstable nuclei are produced by fragmentation of a primary heavy-ion beam of any nucleus or by fission of a ^{238}U beam at energies up to 1-2 GeV per nucleon, followed by in-flight separation in a partially superconducting magnetic separator (Super-FRS). The facility at FAIR surpasses in many respects the capabilities of existing RIB facilities and competes with corresponding projects in Japan and USA in particular by innovative experimental concepts through instrumentation not available elsewhere.

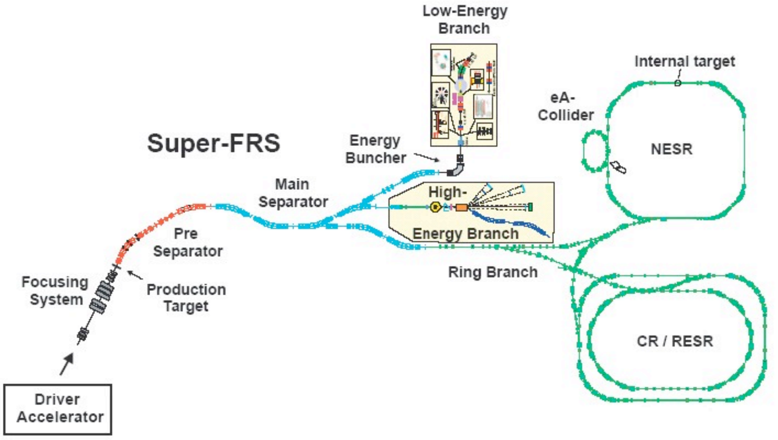


__Figure 2.3.1__: Schematic view of the rare-isotope-beam facility at FAIR with the superconducting in-flight separator (Super-FRS) and its three experimental branches: the high-energy reaction area, the low-energy area, and the storage ring complex (CR-RESR-NESR) with the intersecting electron collider (eA).

The FAIR synchrotrons, operated in a high-intensity mode (primary beam intensities of several 10^{11} ions per second) together with the excellent phase-space acceptance of the in-flight fragment separator (Super-FRS) yield secondary beam intensities with several orders of magnitude higher than those presently available. Since the production process is chemically not selective and since the transport time is negligible, isotopes even of shortest lifetimes can be provided and studied. Secondary beams are delivered with high purity with a wide range of beam energies and with variable (pulsed or quasi-DC) time structure and are eventually delivered to the target stations or are injected into storage rings. FAIR will be the unique facility in the world to deliver RIBs with the highest energy of 1-2 GeV per nucleon (the maximum energy of RIBs at RIKEN is about 350 MeV per nucleon).

The Super-FRS will separate efficiently in-flight rare isotopes produced via projectile fragmentation of all primary beams up to ^{238}U and via fission of ^{238}U beams. The latter reaction is a prolific source of very neutron-rich nuclei of medium mass. However, due to the relatively large kinetic energy released in the fission reaction, the products populate a large phase space and thus demand an extraordinary acceptance. Compared with the in-flight fragment separator (FRS) presently existing at GSI, more than one order of magnitude is gained in transmission of fission products due the increased momentum and angular acceptance. If all technical challenges will be overcome, FAIR will provide intense secondary beams of unstable isotopes across the entire nuclear chart. Beam intensities will exceed those available at existing rare-isotope-beam facilities by several orders of magnitude and beam energies are variable up to 1-2 GeV per nucleon, providing the highest-energy radioactive ion beam facility in the world.

Another major facility for the production of radioactive ion beams, SPIRAL2, is now under construction at GANIL, in Caen, France. The key element of this facility will be a high power, superconducting driver LINAC, which will deliver a high intensity, 40 MeV deuteron beam as well as a variety of heavy-ion beams with mass over charge ratio equal to 3 and energy up to 14.5 MeV/nucleon. The intense flux of fast neutrons resulted from the breakup of the 5 mA of deuterons in a Carbon converter will irradiate a Uranium carbide target and will induce a rate of up to 10^{14} fissions/s. The expected RIB intensities in the mass range from A=60 to A=140 are of the order of 10^{6} to 10^{11} particles/second. The beams of neutron-rich fission products will be complemented by beams of nuclei near the proton drip line created in fusion-evaporation or transfer reactions. Similarly, the intense, heavy- and light-ion beams from LINAG on different production targets might be used to produce high-intensity beams of light radioactive species with the ISOL technique. The extracted RIB will subsequently be accelerated to energies of up to 20 MeV/nucleon (typically 6-7 MeV/nucleon for fission fragments) by the existing CIME cyclotron. For this energy range SIPRAL2 will be one of the best radioactive beam facilities in the world, and will give the possibility of performing a rich scientific program in nuclear physics and other research fields.

2.3.2. Experimental instrumentation

Together with the construction of radioactive beam facilities, it is of paramount importance to build highly efficient and versatile instrumentation needed to perform physics experiments. Very efficient spectrometers for various types of radiations are needed in all the stages of the experiments, and new devices are developed using the knowledge acquired by doing experiments at the existing stable and radioactive ion beam facilities. The coupling of 4π Germanium arrays like EUROBALL or GASP with high efficiency charged particle detectors like EUCLIDES and large arrays of neutron detectors proved to be an excellent approach for studying nuclei produced in fusion evaporation reactions. On the same time, exotic nuclei produced in reactions like fragmentation, fission or deep inelastic collisions were successfully studied with efficient Germanium arrays like EXOGAM, MINIBALL, RISING or CLARA coupled with large heavy ion spectrometers like VAMOS (GANIL), PRISMA (LNL) or the FRS (GSI).

The instrumentation refers to a wide class of devices of various degree of sophistication built to fulfill objectives like separation of rare species and measurement of their most important characteristics (energy, A, Z, mass, lifetime, type of decays, etc.). Some of them are site specific (especially those performing the separation of rare species), other will to be used at several radioactive beam facilities. SPIRAL2 has a vast program for instrumentation which includes a number of projects with large international support: S3 (Super Separator Spectrometer), NFS (Neutrons for Science), ACTAR (Active-target detection system), AGATA (Advanced Gamma Tracking Array), DESIR (Decay, excitation and storage of radioactive ions), EXOGAM2 (a second generation of the previous well known EXOGAM array of Ge detectors), FAZIA (a 4π A and Z identification array), GASPARD (GAmma Spectroscopy and PARticle Detection), NEDA (Neutron detector array, ancillary detector planed to be coupled with AGATA), PARIS (Photon Array for studies with Radioactive Ion and Stable beams). Romania is interested and will actively participate to the realization of some of these collaborative projects: AGATA (see below), NFS, DESIR, FAZIA, EXOGAM2.

NFS plans to use the high flux neutron source of SPIRAL2 for a wide range of measurements: data of interest for reactors, data about the details of the fission induced by neutrons, activation measurements, measurements of interest for astrophysics, biology, and others.

DESIR, an installation of the ISOL type, will have a radiofrequency cooler, a rebuncher and a high-resolution separator. IFIN-HH will provide data on production mechanisms by fusion-evaporation reactions.

FAZIA, a complex multidetector that will include high granularity SI-CsI telescopes, prospects the possibility of large scale use of diamond crystal detectors, known for their excellent timing performances. A team with leading Romanian scientists pursues these prospects. For gamma detection, EXOGAM2 is a new, improved version of EXOGAM array that in the past served in many experiments done at GANIL with relevant Romanian contribution. It is therefore natural to pursue this line of research at GANIL, in the frame of the long established collaborations.

A major step forward in gamma detection is the construction of the Advanced Gamma Tracking Array (AGATA) by a large European collaboration in which Romania is full member. The basic concept of this high-resolution gamma spectrometer is to track the energy release of photons in segmented Germanium crystals, and to deduce from this the positions of the interactions and the original photon energy. In this way are achieved very fine granularity, good peak efficiency and high counting rate capability, characteristics that make AGATA an ideal gamma detector for any radioactive beam facility. A small-scale "demonstrator" version of AGATA, with 15 crystals from the total of 180 of the final 4π configuration, is already in use at Laboratori Nazionali di Legnaro, where is coupled with the heavy ion PRISMA spectrometer. The number of available segmented Germanium crystals will increase in the following years, and during the different growing stages the AGATA detector will be used in large-scale laboratories as GSI and GANIL.

Experiments at the FAIR RIB facility are organized in a broad umbrella collaboration called NuSTAR (Nuclear Structure, Astrophysics, and Reactions), which has more than 800 members. With specific of low-energy nuclear physics are the HISPEC and

DESPEC collaborations, in which the Romanian nuclear physics community is actively involved. HISPEC devices will be dedicated to in-beam studies of very exotic isotopes with relativistic Coulomb excitation or fragmentation reactions with radioactive beams. It is based on AGATA as gamma detector with high efficiency and excellent granularity coupled with state-of-art particle and heavy ion detectors like LYCCA. The overall good position resolution obtained with the HISPEC detectors will allow to have precise Doppler correction even for recoil velocities of ~50% of the speed of light, which will be a major breakthrough in the spectroscopy of very rare isotopes. DESPEC collaboration develops state-of-art detectors for decay spectroscopy, like the position sensitive and large dynamic range implantation detector AIDA, the efficient gamma tracking array DESPEC-Ge and a $LaBr_3$:Ce fast timing array. Romanian groups are highly interested and actively participating in the above mentioned developments, with particular emphasis on building a new type of high-surface, particle-tracking plunger device, the construction of the high-efficiency granular fast-timing array and the DESPEC Germanium array. Moreover, these last items are foreseen to be part of the Romanian in-kind contribution at FAIR.

2.4. Physics at Local Research Infrastructure

2.4.1. Role of "small scale research"

Sections 2.2 and 2.3 presented some the top experimental research directions in Nuclear Structure. They are mainly related to the study of unstable, exotic nuclei, which are situated far away from the valley of stability. The approach of such nuclei, as a rule, requires the use of highly sophisticated facilities: accelerators that provide intense stable beams, or radioactive beam facilities, and sophisticated instrumentation for the analysis and identification of reaction products and different decaying radiations (gamma rays or particles). The high degree of sophistication can be attained only by big laboratories, backed by large collaborations, such as FAIR at Darmstadt, SPIRAL2 at Caen, and ISOLDE at Geneva. One may say that with these large-scale facilities (LSF), one makes "large scale research".

In parallel with these LSFs, smaller laboratories continue to exist in many European countries, having technical facilities of comparatively lower power, where one may still address certain Nuclear Physics research directions, although of smaller complexity than those pursued at LSFs. It is worth examining the question whether keeping active research programs at such laboratories is still a rewarding option. For the sake of discussion, and by contrast with the 'large scale research' as conventionally defined above, we refer to this type of research as 'small scale research'. An examination of the advantages and disadvantages of both these two types of research shows that they are almost complementary.

Thus, the main *advantage of the large-scale research* consists in the possibility to address top physics problems (such as study of the most exotic nuclei).

On the other hand, the *large-scale research can be seen as having the following disadvantages*:

- The proposals of experiments must pass through and international PAC (Physics Advisory Committee), often in strong competition with a large number of other proposals. Sometimes it may be difficult to pass certain ideas simply because they do not entirely belong to 'en vogue' directions. And, even when a proposal of experiment has been approved, there may be a long time to wait for the beam time, when it will be actually performed.

- Most of the participants in the experiments at LSFs, and especially young people, coming from outer laboratories, have reduced chances to know in detail the experimental setup, or even interfere with changing experimental conditions. Most students may have a perception of the experimental setup that is close to an image of a 'black box' that provides some 'data'.

By contrast, working in *small-scale research has the following advantages*:

- The beam time may be more easily accessible, even when proposals pass by a PAC;
- The experiments performed may be characterized as 'niche' experiments in the domain, that concern special cases and directions where detailed and systematic studies are required, and may lead to significant results. Such experiments, or directions of research, are usually based on a good expertise of the local research team. And indeed, in such smaller laboratories, one often finds a very good expertise in certain areas, which can be successfully used in researches at LSFs as well.
- The 'small scale research' activity, when performed at good standards, has a high educational value. Students are involved in practically all stages of an experiment, like preparation of the proposal, preparation of the target, building up of the setup, electronics tuning, data acquisition, data processing, etc. up to the final preparation of the results for the publication. Nicely running 'live' experiments, with clear physics points, have an extraordinary power to attract students towards Nuclear Physics research, and to shape more advanced students into good researchers, with a broad know-how and skills, that can bring significant contributions to the 'large scale research' experiments too. Last, but not least, such small laboratories are appropriate places for testing/developing (parts of) instruments and methods for the LSF programs.

Thus, in our view, a well organized Nuclear Physics laboratory, even of a small size, with a reasonable infrastructure and having a good expertise in certain areas, may be very important in (i) producing good physics results, complementary to those of the 'large scale research' and (ii) significantly contributing to the international pool of researchers in Nuclear Physics. Therefore, our option is to keep a good balance between participating in development programs and experiments at LSFs, and developing an 'in-house' research programme.

2.4.2. Accelerator and instrumentation

The main infrastructure in experimental Nuclear Physics research in Romania is related to the Tandem van de Graaff accelerator at IFIN-HH. It was built by HVEC in 1973, but it was recently completely refurbished. The terminal voltage was upgraded from the original 7.5 MV to 9 MV, and the present charge transport system is a Pelletron. With a NEC sputtering ion source, and a duoplasmatron ion source, the accelerator currently delivers a large variety of ion beams, from protons to medium mass (~60) nuclei (including He). There are also two pulsing systems for the beam: an electrostatic chopper working in the region from millisecond to hundreds of seconds, and a nanosecond chopping/bunching system using a 5 MHz generator, delivering 2 ns beam bunches separated by multiples of

200 ns. This accelerator is unique in Central and Eastern Europe. Details about it can be found at http://tandem.nipne.ro.

The most important setup for nuclear spectroscopy is a mixed array of hyper-pure Germanium (HPGE) and $LaBr_3$:Ce scintillator detectors. The mechanical arrangement accommodates at present only up to 8 HPGe detectors and 8 $LaBr_3$:Ce detectors, but a new arrangement will be available to accommodate up to 25 detectors. The HPGe detectors have relative efficiencies around 55%, and in the new arrangement they will all have BGO anticompton shields. For good efficiency at low gamma-ray energies, 3 planar Ge detectors are available. Two clover Ge detectors, each having a total efficiency of about 100% and anticompton shield are also available. In addition, the setup can be completed with Silicon telescopes for charged particles, and one NE213 liquid scintillator neutron detector. The good energy resolution HPGe detectors, and the fast LaBr3:Ce detectors make a unique combination for measuring lifetimes in the range from several tens of ps to several ns by using the fast timing method in heavy-ion or light-particle induced fusion-evaporation and transfer reactions. The photo below (Fig. 2.4.1) shows the mixed detector array, here featuring 7 HPGe detectors and 8 $LaBr_3$:Ce detectors. The total efficiency of the system in this configuration reaches about 0.8% for HPGe and about 1% for $LaBr_3$:Ce, respectively, at at energy of 1.33 MeV.

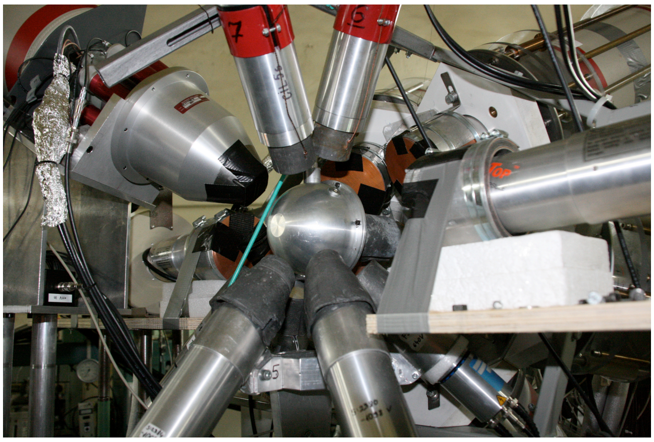


Figure 2.4.1. *The mixed HPGe and LaBr3:Ce detectors array.*

The gamm-ray spectroscopy group has also built a modern recoil-distance (plunger) device, with piezoelectric computer-controlled movement. Modular electronics and a computer multiparametric data acquisition system allow coincidence data between all mentioned detectors to be recorded and then off-line processed by specialized programs.

2.4.3. "Niche" researches at the Tandem van de Graaff Accelerator

The previous chapters briefly presented the big international effort in the nuclear structure field, in building important experimental facilities and techniques, aiming at mapping the whole nuclear map up to its stability borders. However, this represents just one (although the most important) facet of the present investigations. Of much importance is the study of different other aspects of nuclear structure, such as its evolution with the angular momentum and the excitation energy (temperature) of the nucleus. One should emphasize one important aspect of the experimental studies of nuclear structure. Due to the fact that nuclei farther away from stability are reached by nuclear reactions that have small cross-sections, the future studies of exotic nuclei, even with the most sophisticated facilities, will provide little information compared with what has usually been achieved for nuclei close to stability: observation of a few excited states, or of one or two electromagnetic transition probabilities or moments, for example, will be the norm, in contrast to the much more detailed such information obtained for tens or even hundreds of excited states in nuclei closer to stability. Such limited information will hopefully be useful in revealing basic trends in the evolution of nuclear structure (such as collectivity, individual particle shells, etc.). On the other hand, many important structure phenomena have become visible only after painstaking measurements of many details, and the subsequent observation of regularities in their behaviour with mass, angular momentum, etc. (for example, the observation of nuclear bands of the superdeformed, chiral, magnetic rotational, wobbling, etc. type, isomeric states, measurements of lifetimes and electromagnetic moments of excited nuclear states, etc. each underlying very important nuclear properties). Thus, detailed nuclear spectroscopy measurements, with existing instrumentation, remain still of high importance for the advance of the field.

The research directions that will be pursued belong to this direction, and aim at the enrichment of the database of properties of the nuclear structure. As they imply experiments proposed to expand our knowledge on the structure of nuclei, even if they are stable or close to stability, but, for different reasons, were less studied or not studied until now. Actually, the experimental conditions attract today research teams from Europe and other countries, which propose experiments to be performed here. The proposals of experiments are being presented to an international PAC (Physics Advisory Committee), similar to the procedures used at other facilities that are nominated as of European interest. The research directions where experiments in Bucharest can contribute with new results and insights for the nuclear structure are listed below.

2.4.3.1. Determinations of nuclear level schemes characteristics

This concerns determinations of new excited states (with their characteristics: energy, spin, parity, electromagnetic decay mode) or of details for a better characterization of existing data, by gamma-ray spectroscopy either in-beam, with different reactions (such as proton- or α-particle induced reactions, that are not selective in spin, for low-spin states; or heavy-ion induced reactions for higher spin states), or beta-decay of nuclei populated in such reactions. The cases for study are chosen according to criteria like proving nuclear symmetries, looking at special states (for example, excited 0^+ states), etc.

2.4.3.2. Determinations of lifetimes of nuclear excited states

Measuring the lifetime of a nuclear excited state is valuable because it is the main ingredient that leads to the determination of the absolute electromagnetic decay rates of that level. These decay rates, in turn, are related to the matrix elements of known operators between the initial and final states involved, therefore they constitute rather sensitive tests for the validation of the different theoretical nuclear structure models that have been proposed. In this domain, the existing expertise covers a broad range of lifetimes using various methods.

Doppler Shift Attenuation Method.

This method has been used for a long time to determine lifetimes in the range from tens of fs (10^{-15} sec.) to ~1 ps (10^{-12} sec.). It uses the stopping of the recoiling ions (in the target or in a stopping medium) as measuring clock, by looking at the γ-radiations emitted from the nuclear states of the recoils during the stopping process. We have developed a very good expertise in using the DSA method in non-selective reactions, such as (α,nγ) reactions. Such a reaction populates non-selectively low- and medium-spin states, therefore is an almost ‘complete spectroscopy’ tool for such states, which may offer important structure information. Application of this method (the analysis of the Doppler-broadened transition lines) is relatively straightforward in the case of the heavy-ion induced reactions, where the recoil velocities are large. In the (α,n) reactions the recoil velocities are relatively low, leading to small Doppler effects, therefore the lineshape analysis must be done extremely accurately. Figure 2.4.2 shows an example of the application of this type of analysis.

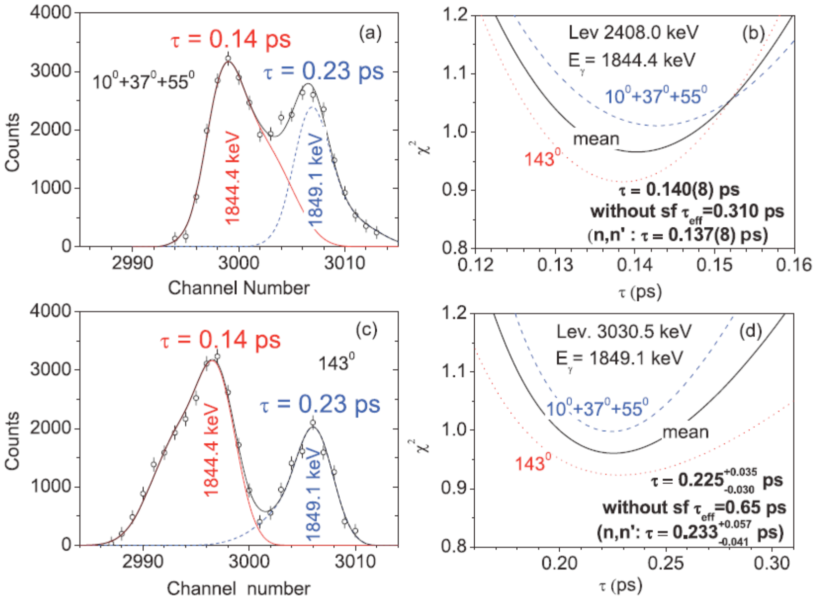


***Figure 2.4.2**. Example of Monte-Carlo lineshape analysis of two γ-ray transitions in the reaction ^{119}Sn(α,nγ)^{122}Te.*

The accuracy and reliability of these lifetime determinations is ensured by a Monte-Carlo simulation of both the production and slowing-down of the recoils and the production and detection of the γ-rays, as well as a reliable estimation of the level side-feeding times, a precise knowledge of the instrumental response of the detectors, and adequately accounting for the cascade feedings of the levels. The abundance of data (many low- and medium-spin states) obtained in a single nucleus recommends the use of this method for detailed tests of nuclear models.

Recoil-Distance Method (Plunger).

With this method lifetimes are measured in the range from ~1 ps to tens of ps. We use the new plunger device, which has a good stability in distance, and analyze γ-γ coincidence data with the so-called differential decay curve method, by which examination of the intensities of the shifted and unshifted components of a transition, obtained in coincidence with the shifted component of a transition directly feeding the level of interest results in a value of the lifetime for each target-to-stopper measured distance. This method eliminates errors due to unobserved feedings and de-orientation effects. An example of such measurement is shown in Fig. 2.4.3, for the lifetime of the 3^- level at 3176 keV of the ^{44}Ti nucleus, determined from the shifted and unshifted components of its decaying 2093 keV transition, gated by the 885 keV transition above. The measurement of the E1 transitions from this state (that are strictly forbidden between T=0 states) will allow to estimate isospin-mixing effects in this N=Z nucleus.

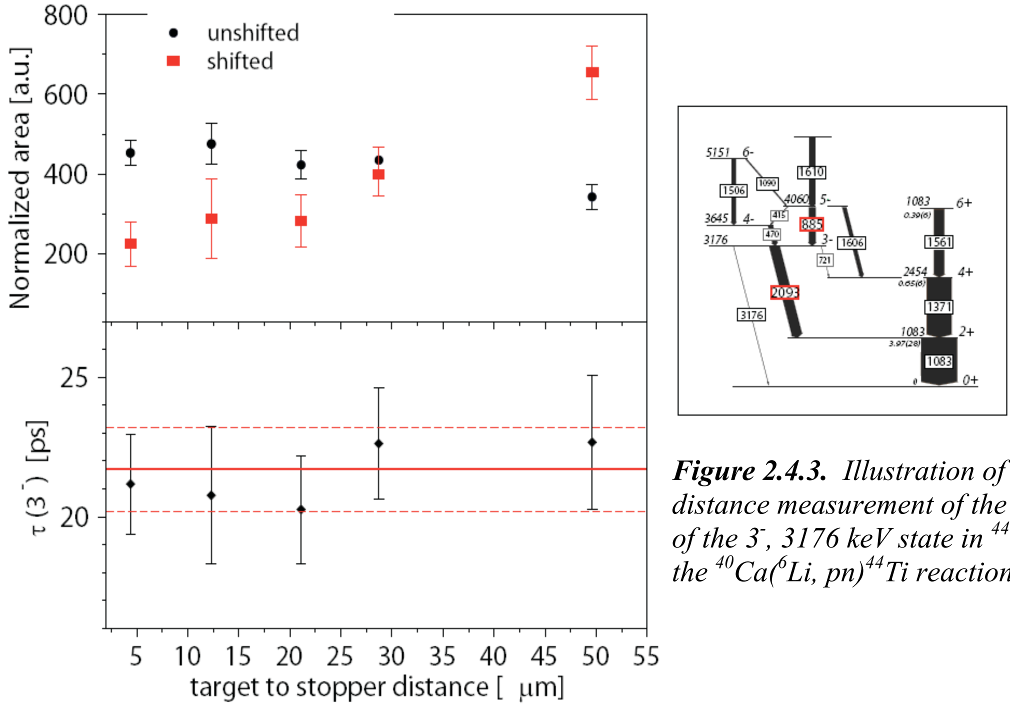


Figure 2.4.3. *Illustration of recoil-distance measurement of the lifetime of the 3⁻, 3176 keV state in ^{44}Ti, with the ^{40}Ca(^{6}Li, pn)^{44}Ti reaction.*

The Fast Timing Method

Using fast γ-ray detectors to measure lifetimes with the electronic method, which directly measures the time decay spectrum of a decaying state covers the lifetime range from several picosecond to several nanoseconds. Until recently, the preferred fast detectors were the BaF_2 scintillator crystals, but their use was limited mostly to beta decay studies, due to their weak energy resolution. The appearance of the new $LaBr_3$:Ce fast scintillators, which have a much better energy resolution, made it possible to apply the electronic method to reactions induced by heavy ions, such as fusion-evaporation or fragmentation, where the number of nuclear states populated and, consequently, of gamma-rays in the spectrum, are much larger. The mixed HPGe and $LaBr_3$:Ce detector array represents a unique setup that was developed having in mind the extension of this method to in-beam γ-ray measurements. Triple γ-γ-γ coincidences are recorded in such measurements. The good energy resolution HPGe detectors are used to select the two interesting gamma-transitions (feeding and decaying the level of interest) by gating on (cascades of) gamma rays that feed these transitions, and time spectra are determined from the time differences between the two transitions as detected by the fast detectors. In order to make full use of the efficiency of the fast detector array, that is, add up coincidences between any pair of fast detectors, an original method was developed by which the time walk (with energy) of these detectors is corrected for, and thus all pairs of detectors are aligned in time.

As an example of application of this method, Fig. 2.4.4 illustrates measurements of sub-nanosecond lifetimes, both with the usual method of unfolding the delayed time decay spectrum (left), or with the centroid shift version of this method (when the lifetime of the state is comparable to the time resolution of the system).

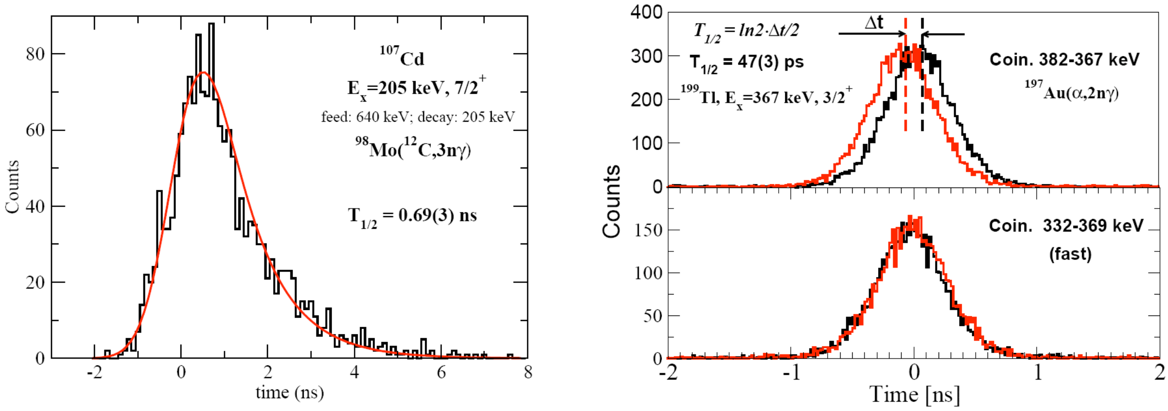


Figure 2.4.4. Examples of determination of lifetimes with the fast timing method, for excited states in ^{107}Cd (left), and ^{199}Tl (right), populated with different reactions.

Due to the reasonable efficiency of the mixed γ-ray array, which allows triple coincidences measured with enough statistics even for relatively weak reaction channels, numerous lifetimes have been measured to date, and there is a big interest in using this method in the future. This is because lifetimes accessible by this method are met in many situations of interest, for example, for nuclear states marking a change in the structure of the nucleus (e.g., backbendings, band terminations). An attractive feature is also the overlap in the time range of this method and that of the plunger method.

2.4.3.3. Measurement of reaction cross-sections

Gamma-ray measurements can be used to determine reaction cross sections. A setup and a method were developed, by which small reaction cross-sections can be measured, especially at energies close to the Coulomb barrier, where, for many nuclei, such data are of astrophysical interest. The method is that of the target stack activation: a stack of targets is irradiated to produce the radioactive species whose activities are measured after the irradiation has stopped.

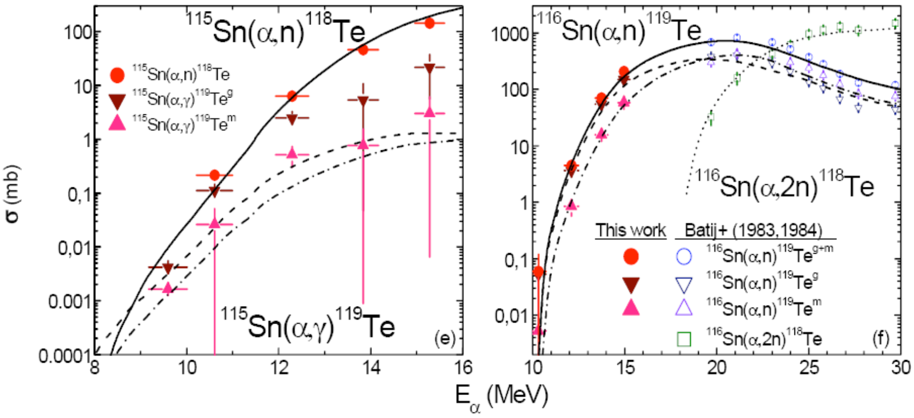


Figure 2.4.5. Cross-sections for (α,n) and (α,γ) reactions measured with the stack foil activation technique and compared to statistical plus preequilibrium model calculations (curves).

Accurate and reliable measurements are achieved by precise determinations of the target foil thicknesses, real time recording of the beam intensity during the irradiation, and detection of the γ-rays with a close geometry setup with accurately determined efficiency (with summing effects taken into account). An example of such measurements is shown in Fig. 2.4.5, where cross-sections for several reactions (α,n) and (α,γ) were determined by activating stacks of ^{116}Sn and (^{116}Sn + ^{115}Sn) targets. Both experimental determinations and consistent theoretical descriptions (direct, preeqilibrium, and statistical model contributions taken into account) of cross sections of reactions induced by light projectiles will be performed. For example, deuteron induced processes will be carefully investigated in order to determine appropriate deuteron global optical model parameters (missing at present) and take into account both the deuteron breakup contributions and the deuteron stripping and pickup processes.

2.5. Extreme Light Infrastructure - Nuclear Physics (ELI-NP) facility

ELI-NP facility (http://www.eli-np.ro) is one of the pillars of ELI, the proposed European Research Infrastructure devoted to high-level research on ultra-short pulse high-power lasers, laser-matter interaction and secondary radiation sources with unparalleled possibilities. ELI-NP will be devoted to nuclear physics studies and is to be built in Magurele, near Bucharest (Romania). Two other pillars, ELI - Attoseconds and ELI – Beamlines, will be located in Szeged (Hungary) and respectively in Prague (Czech Republic). The unified operations of the pillars will be assured by ELI-ERIC (European Research Infrastructure Consortium), which has to be established before 2015 when the construction phase of the first three pillars will be completed.

ELI-NP will be based on two major instruments:

- A very high intensity laser system, where two 10 PW lasers are coherently added to the high intensity of 10^{23}-10^{24} W/cm^2 or electrical fields of 10^{15}V/m;
- A very intense (10^{13} γ/s), brilliant γ beam, 0.1 % bandwidth, with E_γ = 19 MeV, which is obtained by incoherent Compton back scattering of a laser light off a very brilliant, intense, classical electron beam (E_e = 600 MeV).

Compared to former γ facilities, the much-improved bandwidth is decisive for this new γ beam facility. The γ beam will have unique properties in worldwide comparison and opens new possibilities for high-resolution spectroscopy at higher nuclear excitation energies. Several experiments, like the parity violation experiment, only become possible due to this much better bandwidth. They will lead to a better understanding of nuclear structure at higher excitation energies with many doorway states, their damping widths, and chaotic behavior, but also new fluctuating properties in the time and energy domain. The detailed investigation of the pygmy dipole resonance above and below the particle threshold is essential for nucleosynthesis in astrophysics.

Light nuclei with known highly excited parity doublets in ^{14}C,^{14}N,^{15}O,^{16}O,^{18}F and ^{20}Ne were theoretically investigated for the enhancement of parity mixing amplitudes of E1/M1 or E2/M2 transitions. According to first order perturbation theory calculations, the mixing is strongly enhanced because the parity violating matrix element is divided by the small energy difference of the two levels of opposite parity. The doublet levels are at excitation energies between 5 MeV and 12 MeV and can be nicely reached with the high-resolution γ beam facility of ELI-NP. Until now many nuclei with a possible E1/M1 mixing have been investigated, but for now experimental accuracies were insufficient. With the brilliant, tunable, polarized and monochromatic γ beams the effect of parity non-conservation will be studied at higher excitation energies. For circularly polarized γ beams a forward-backward asymmetry, which is linear in the parity mixing amplitude, can be used to measure mixed parity transitions, where a high sensitivity is reached by switching the sign of the circular polarization. The experiments will allow understanding the fundamental role of the exchange processes of weakly interacting bosons in the nucleon-nucleon interaction.

Figure 2.5.1 *Architect's view of the ELI Nuclear Physics facility (http://www.eli-np.ro)*

The powerful laser system will be able to achieve intensities at which the Radiation Pressure Acceleration (RPA) becomes relevant when thin targets are employed. In RPA a localized longitudinal field enhancement is present that co-propagates with the ions as the accompanying laser pulse pushes the electrons forward. By changing the laser polarization to circular, electron heating and expansion are efficiently suppressed, resulting in a phase-stable acceleration that is dominated by the laser radiation pressure and is maintained for an extended time. Thus, the whole target is accelerated ballistically as a quasineutral, dense plasma bunch. At intensities around 10^{23}W/cm^2 simulations show that protons become relativistic within one half-cycle of the laser pulse and acceleration by the laser radiation pressure is dominant even for linear polarization in what is referred to as the laser-piston regime. Here, the target can be viewed as a relativistic plasma mirror with Lorentz factor γ being propelled by the reflected laser and the laser-to-ion conversion efficiency $\eta = 1 - 1/(4\gamma^2)$ approaches unity in the ultrarelativistic limit. For even higher laser intensities of 5×10^{24}W/cm^2 at a wavelength of 1 μm, protons can be driven to relativistic velocities directly by the laser field. This regime of direct ion acceleration has not been studied in simulations so far since the new phenomenon of radiation damping strongly changes the laser-plasma interaction, hence preventing the straightforward application of existing PIC (Particle-in-cell) codes. Only by comparison with experiment the proper theory can be established. Employing the laser system at ELI-NP, unprecedented intensities of the order of 10^{24} W/cm^2 become available for experiments, allowing for improved RPA and for the first time study of the laser-piston regime as well as direct proton acceleration.

The use of the very high intensity laser and the very brilliant, intense γ beam will achieve major progress in nuclear physics and its associated fields like the element synthesis in astrophysics. In ion acceleration the high power laser allows to produce 10^{15} time denser ion beams than achievable with classical acceleration. The cascaded fission-fusion reaction mechanism can then be used to produce very neutron-rich heavy nuclei for the first time. At ELI-NP, the high power laser pulses will be used to accelerate Thorium nuclei at several MeV/nucleon. The dense Th bunch will impinge a thorium secondary target inducing the fission of both in flight and at rest nuclei. The high density of fission products, part of them forward focused with the mean energy of the bunch, could lead to their fusion. These nuclei allow to approach and investigate the $N = 126$ waiting point of the r-process in nucleosynthesis.

A new experimental window into the largely unexplored domain of nonperturbative quantum electrodynamics (QED) will be opened by ELI-NP. The long-standing spectacular prediction of spontaneous decay of the vacuum in terms of Schwinger pair production, i.e., production of electron-positron pairs in strong electric fields exists already since the early days of quantum field theory. The most recent nonperturbative QED calculations predict that one can observe already at 10^{24} W/cm^2 the catalytic pair creation from the vacuum. The Schwinger mechanism can be dynamically assisted by superimposing a strong electric field with a weak but rapidly varying field, leading to an enhancement of pair creation rate. A realistic experimental scenario is given by a setup where a strongly focused high-power optical laser pulse in a purely electric standing wave mode is superimposed by a plane-wave γ-ray probe beam. This superposition leads to a dramatic enhancement of the expected yield of e^+e^- pairs.

In ultra-high laser fields the vacuum shows a changed index of refraction, where the real part results in a birefringence for light traversing the laser focus. The polarized vacuum acts as a medium with preferred directions dictated by the external fields that we assume to be generated by the high-power lasers of ELI-NP. The birefringence of the vacuum can be measured for the first time by the small turn of the linear polarization of the γ beam, which can be measured with high accuracy using nuclear resonance fluorescence (NRF).

The combined availability in the same infrastructure of the very high-intensity laser system and the brilliant γ beam allows for advanced research in nuclear physics, which will push significantly the boundaries of present knowledge in the field.

2.6 Recommendations

Nuclear physics at low energies is a research field with tradition in Romania, internationally competitive and internationally recognized. This high scientific potential should be conserved and developed. For this, we strongly recommend:

- *The main local experimental facility is based on the recently refurbished Tandem accelerator, which is unique within the European low-energy Nuclear Physics landscape. Additional developments in the detection and acquisition systems are necessary in order to increase the experimental capabilities in nuclear spectroscopy. The present research program, including a more extended network of international collaborations, should be developed to the level that recommends the existing Romanian Nuclear Physics laboratory for the status of European facility.*

- *ELI – Nuclear Physics will represent a large step forward in the Romanian Nuclear Physics research. As soon as this facility is firmly approved, a final shaping of the experimental setups must be made, by using the expertise of both local group and of collaborating outside groups. The experimental research program using the gamma source should be the first to be strongly pursued.*

- *The high level attained by the local theoretical research in Nuclear Structure must be continued in strong connection with the achievements and goals of the experimental efforts, especially in developing new microscopic approaches both in the nuclear structure and nuclear reaction studies.*

- *The participation of the Romanian scientists in the projects developed at the European large-scale facilities FAIR-Darmstadt, ISOLDE (CERN) – Geneva, SPIRAL2 – Caen must be maintained and kept at a high level. Involvement in the construction and testing of new detector systems for these projects should be supported by developing an appropriate local infrastructure.*

- *The capabilities of the unique Nuclear Physics facilities located in Romania should be disseminated among the scientists of all Romanian Institutes and Universities such as to attract in the related research programs the most suitable and competitive groups.*

- *Increase the efforts of presenting the key issues and the achievements of the domain, as well as the opportunities presented by the existing national research facilities, in order to (i) ensure a better funding of the domain, and (ii) attract more students and young researchers.*

3. Nuclear Astrophysics

3.1. Introduction

3.2 Status of the field

3.3 Direct nuclear astrophysics measurements

3.4 Indirect methods

3.5 Romanian contributions to nuclear astrophysics

3.6 Future activities

3.7 Nuclear astrophysics at ELI-NP

3.8 Recommendations

3.1 Introduction

As essentially a fundamental science, Nuclear Physics was from its beginnings taking a front place in the human endeavor of understanding of the Universe. Our Universe! It was and continues to be part in understanding its composition, its dynamics, its origins and history, and possibly, its future. We study our universe through observations, but also through experiments in the laboratory. It is actually considered that cosmology went from the realm of philosophy and speculation into that of science when physicists started to use nuclear physics data to model the genesis of chemical elements (Bethe and Critchfield, 1938; Alpher, Bethe and Gamow, 1948) and compare their quantitative predictions with the observations. Since then, many and fundamental advances were made, a large and rich spectrum of new astrophysical observations was added to our knowledge and for their interpretation more detailed nuclear and particle data were necessary. Isotopic abundances, available from astronomical observations, are unique fingerprints of the evolution of stars. In the 1930s the hypothesis was advanced that nuclear reactions are the source of the solar energy, the very source that made and makes possible life on Earth. But nuclear reactions could not happen at the measured temperature of the solar spectrum and one can say that only in the late 60s the existence of the nuclear reactions was proved by the detection of solar neutrinos originating from the much hotter interior of the Sun. This was a joint achievement of what we call today nuclear astrophysics and astroparticle physics. They are becoming more and more important parts of modern physics research.

Advances were made in the last decades in understanding the needs, the instrumentation and the theory behind the models used. It has also become clear in the latest decades that the field requires large international cooperations and the synergy of specialists from many different subfields of physics. Below we will address a few of the problems and achievements of the field, with emphasis on parts that involve Romanian participation.

3.2 Status of the field

Nuclei are the fuel of the stars! It was only possible to explain the origin of the solar energy when nuclear processes were understood in the 1930s. The detailed mechanisms of this energy production could only be understood and described, in part yet, much later with the advance of *nuclear physics for astrophysics*, or *nuclear astrophysics* (NA).

All chemical elements in the Universe as we know it were produced in processes that we call generically nucleosynthesis. Nucleosynthesis occurred in various stages of the evolution of the Universe, in various places and in different types of events: Big Bang Nucleosynthesis (BBN) or later stellar evolution, far away or around us, explosive or steady burning. And we have firm evidence collected in the latest decades that nucleosynthesis happens today, even in our own galaxy, close to where we live. We also know today that the nuclear processes occurring in stars are not only the source of energy for cosmic processes, but also that nucleosynthesis gives us unique and indelible fingerprints of these processes. Many nucleosynthesis scenarios exist today. Some were formulated for some time, beginning with the seminal works by Burbidge, Burbidge, Fowler & Hoyle, 1957 and independently by Cameron, 1957: Big Bang Nucleosynthesis (BBN), Inhomogeneous Big Bang Nucleosynthesis (IBBN), the s-process, the r-process, the rp-process, etc., and some are newer proposals. The possibilities to check the detailed predictions of specific models occurred only recently, with the availability of more and better astrophysical observations, of more nuclear data, of advances in understanding the dynamics of non-equilibrium processes, and of increased computing power. It turns out that an important component of all these nucleosynthesis model calculations is represented by the data for the nuclear processes involved. Only good nuclear physics data permit to make definite, quantitative predictions that can be checked against the ever increasing observational data sought and obtained by astrophysicists.

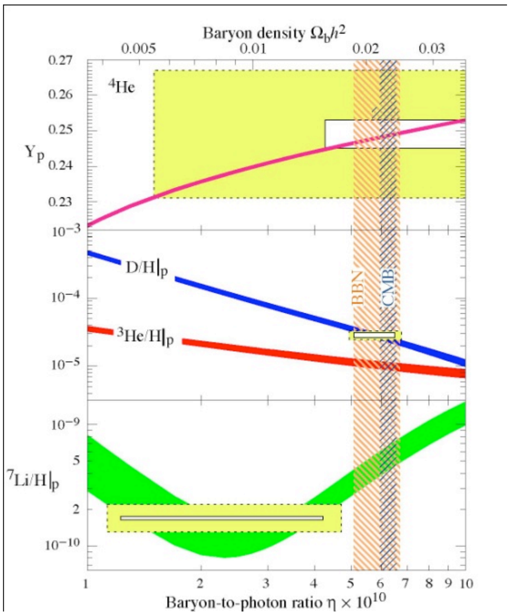


Figure 3.2.1 *The abundances of ^{4}He, D, ^{3}He, and ^{7}Li as predicted by the standard Big Bang Nucleosynthesis, as function of the baryon-to-photon ratio η. The vertical bands show the η values given by the CMB and by the BBN. Boxes indicate the observed light isotopes abundances ($\pm 1\sigma$, and $\pm 2\ \sigma$ errors). From the Particle Data Group (http://pdg.lbl.gov/2010/).*

This is the object of the nuclear physics for astrophysics, a subject that is most often called *nuclear astrophysics*. It does not deal with the specificities of the dynamics of different stellar processes, but only with the nuclear reactions involved, in particular with how we obtain these data from direct or indirect measurements. However, more recently the modeling of stellar processes and the dynamics of stars came closer and closer to the realm of interest of nuclear physicists and there is increased synergy of the two fields.

There are thousands of nuclear reactions and nuclear processes that occur in stars. Some are very important, some are less important and some are irrelevant in one type of process, while becoming important in another, depending on the conditions of the particular process: composition, densities and temperatures involved. There are also many nucleosynthesis processes, and our knowledge about them differs.

It is an important success of physics in general that we can describe now the **primordial abundances** (in BBN) over ten orders of magnitude. This description is parameter free after the baryon-to-photon ratio was determined independently and quite exactly η_{WMAP}=6.19(15)*10^{-10} from the measurement of the Cosmic Microwave Background using 7-year WMAP data. Only the abundance of ^{7}Li is not exactly matching the observations and remains “the Li puzzle of BBN” (see Fig. 3.2.1).

Closer to home, we have a good understanding of how our **Sun** works. Nuclear astrophysics measurements provide currently data for most of the reactions important in Sun: those in the pp-I and pp-II chains responsible for most of the energy production and those in the CNO cycle. And for the ^{3}He(^{4}He,γ)^{7}Be and ^{7}Be(p,γ)^{8}B reactions at the end of the pp-III chain (Figure 3.2.2, right), reactions crucial for the evaluation of the solar neutrino production. However, the cross sections accuracies of around 5% called for by the current Standard Solar Model are not met in all cases.

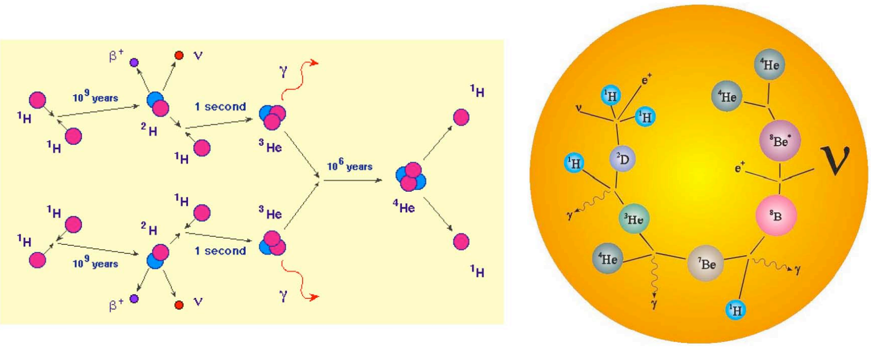


__Figure 3.2.2__ The reactions in the pp-chains taking place in Sun and producing most of the energy (pp-I left) and most of the observed neutrinos (pp-III, right).

Jointly nuclear astrophysics and observational astrophysics have also proven that **nucleosynthesis is an on-going process** in the Universe: it happened at various evolution stages in the past, but is still happening now. This very important concept has been proven by the gamma-ray space-based telescopes like COMPTEL and INTEGRAL, through the identification of characteristic gamma-rays emitted following the β-decay of long-lived isotopes like ^{26}Al ($T_{1/2}$=0.7 My) or ^{60}Fe ($T_{1/2}$=1.5 My), or not so long-lived ones, like ^{44}Ti ($T_{1/2}$=60 y) or ^{22}Na ($T_{1/2}$=2.6 y). The detection of gamma-rays originating from ^{26}Al, with a lifetime considerably shorter than that of the Universe, or of that of our Galaxy, was the first proof that nucleosynthesis is an on-going process. Figure 3.2.3 presents schematically the nuclear process involved and a sky map of the measured distribution of ^{26}Al sources.

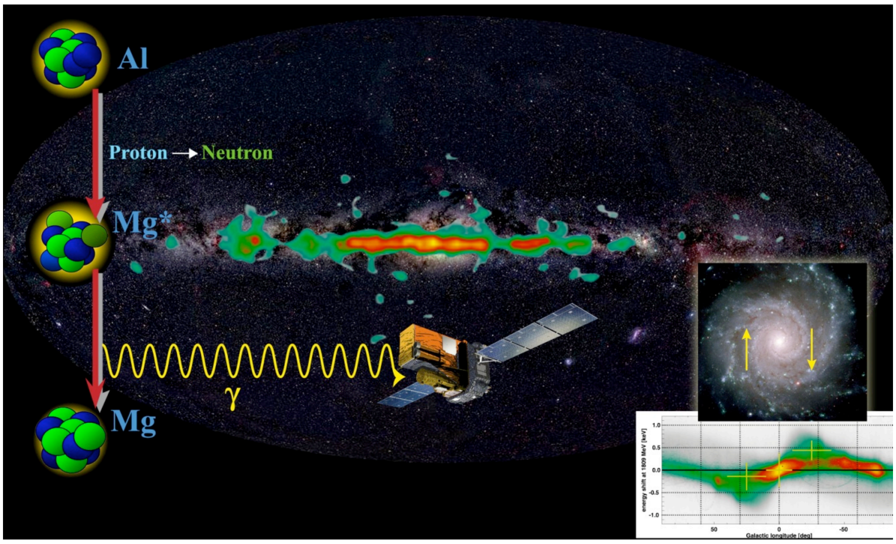


__Figure 3.2.3__ Scheme of the decay of ^{26}Al leading to the detection of characteristic 1.8 MeV gamma-rays by a space-based telescope and the sky map of ^{26}Al sources. The inserts at the bottom right prove the gallactic origin of the sources. From. R. Diehl et al., Nature 439, 45 (2006). doi:10.1038/nature04364.

The distributions of sources can give information not only about the location of the nucleosynthesis sites, but also of the dynamics of mixing of the matter in the galaxy by measuring distributions for sources of various lifetimes. However, we do not have yet a precise and quantitative understanding of the nuclear processes leading to the production of these isotopes. Nor of the transport dynamics of the matter ejected from the underlying cosmic processes and more nuclear physics data are needed.

We can presently describe relatively well **H- and He-burning** in some environments like novae and X-Ray Bursters (XRB) and we have models for various types of **supernovae** (SN), more or less successful, but we do not know major things, for example the cosmic environments of the **s- and r-processes**. We should say here that these processes account, each, for the production of about 50% of the chemical elements heavier than Fe, essential for life and our own existence. The origin of these heavy elements is considered one of the greatest unanswered questions of contemporary physics. The least we know today about the formation of heavier elements through the repeated absorption of neutrons at high neutron densities and high temperatures, the so called r-process. It is not clear what the exact path of these reactions is because we do not know key elements like the lifetimes of very neutron-rich nuclei or their neutron absorption cross sections. And for sure we do not know the exact location of the neutron dripline for medium and heavy elements. As this is dominantly a fast chain of reactions, followed by decays, it may not be needed to know all reactions precisely, but currently we have very limited knowledge even about the crucial ones at the waiting points at N=82 and N=126 shell closures. For many of the reactions involved the uncertainties are a few orders of magnitude! Therefore, much more work is needed before we fully understand and describe stellar nucleosynthesis and it is to be expected that the new facilities will bear answers to some of the above questions and to new ones that will appear.

3.3 Direct nuclear astrophysics measurements

Nuclear astrophysics data are obtained from direct and from indirect measurements. Direct nuclear astrophysics measurements are those that study exactly the reactions at the energies at which they occur in stars or stellar environments. The energies for the reactions in stars are small (tens or hundreds of keV/nucleon) compared with those used in our nuclear physics laboratories (let us say 1-100 MeV/nucleon). The stars are cold! Consequently the cross sections are extremely small in reactions involving charged particles, due to the Coulomb repulsion. This presents experimental challenges, related to beam intensities, target making and background. As the reactions between charged particles (radiative proton capture, radiative alpha capture, (α,p), (α,n) reactions...) have cross sections of the order of nanobarns, picobarns, and even smaller at stellar energies, typically one could only make nuclear astrophysics measurements at somewhat larger energies (MeV/nucleon, some few hundred keV/nucleon) and then extrapolate them down to the relevant energy window (called the Gamow peak). These extrapolations of the cross sections or, equivalently, of the corresponding astrophysical S-factors (the astrophysical S-factors are defined to factor out the Coulomb barrier penetration effects that are leading to drastic, exponential energy dependencies), may induce important uncertainties themselves. It is only in the last few years, after the opening of the underground facility LUNA at Laboratorio Nazionale del Gran Sasso, Italy, that the first reactions could be measured down to the stellar energies. Only a few could be measured so far. That facility is situated deep underground, under about 1.5 km of rock, which significantly diminishes the cosmic background by screening. Following this successful example, many other underground laboratories are planned in the world, and most include accelerators and detectors for nuclear astrophysics.

3.4 Indirect methods

Two important challenges for the direct measurements occur. We have said already that one stems from the very low cross sections in reactions between charged particles at stellar energies due to the Coulomb repulsion: *direct measurements are difficult* at such low energies and involve extrapolations. The other is that in many cases the reactions that occur in stars involve unstable nuclei not existing in nature: *direct measurements are difficult or impossible* in these cases. These two reasons combined lead to the use of indirect methods and of radioactive nuclear beams (RNB).

Several, but not many, indirect methods are used today in nuclear astrophysics:

- Coulomb dissociation
- One-nucleon transfer reactions (the ANC method)
- Breakup reactions at intermediate energies
- Spectroscopy of resonances (many types of studies here!)
- Trojan Horse Method (THM)
- Tests of reaction models and parameters
-

All these experiments are done at "typical" laboratory energies (1-10-100 MeV/nucleon) to extract nuclear structure information, test models and/or extract their parameters. This information is then used for nuclear astrophysics, that is, to evaluate reaction cross sections at low energies (10s-100s keV) and the resulting reaction rates at stellar temperatures. There are two steps here where theoretical calculations occur: from experiments at laboratory energies to nuclear structure information, and from it to cross sections at energies relevant in astrophysics. An important practice is to check the results of indirect methods with those from direct method, wherever possible!

These indirect methods are becoming more and more important with the increased of the availability of beams of unstable nuclei, or RNB. RNBs extend the nuclear astrophysics studies in regions of the nuclide chart where one cannot reach with stable beams and targets.

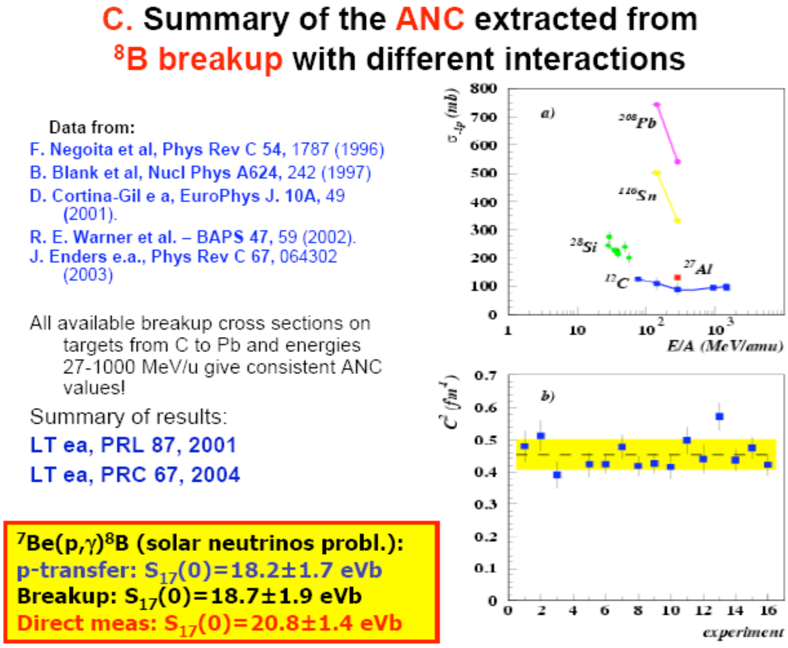
3.5 Romanian contributions to nuclear astrophysics

Studies motivated by nuclear astrophysics are only at the beginning in Romanian laboratories. However, Romanian scientists already have important contributions in international collaborations.

Direct measurements in nuclear astrophysics require dedicated facilities: proton or alpha particle accelerators of very high intensities at low energies and, if possible, low background and special detection systems. Such a facility does not exist in Romania and therefore, direct measurements were not made in Romania. In the last 5 years or so, a group attempted the installation of such a facility in a salt mine. While the action failed to bear fruit, it has revealed an important aspect: salt mines can present very good conditions for such a laboratory. While salt mines are not so deep, they reduce in sufficient measure the background of cosmic provenience, and have the advantage of presenting a reduced background from the radon emission that accompanies more readily the rock formations. Other groups from the world have noticed this finding.

Romanian physicists have more visible contributions in indirect measurements. One group from IFIN DFN started experimental studies at the Bucharest tandem accelerator engaging in the wider efforts of European groups in precise measurements of charged particle reaction cross sections (like (α,γ)) on medium mass and heavy nuclei to be compared with reaction code calculations. The goal is to determine directly some astrophysical S-factors and, at the same time, to better constrain the statistical codes and their parameters used in the evaluation of reaction cross sections and reaction rates on hard-to-reach unstable target nuclei. This effort is continuing.

Another remarkable contribution is that made in the last 15 years in the use of proton transfer reactions (the ANC method) and of breakup reactions at intermediate energies for nuclear astrophysics, both in collaboration with a group at Texas A&M University, USA, which comprises several Romanian scientists. The methods are original and involve the use of RNBs around 10 MeV/nucleon (for transfer) and 50-100 MeV/nucleon (for breakup). To connect the experimental results at these energies to nuclear structure information, good and credible reaction calculations were necessary. A successful double folding procedure was developed to determine the nucleus-nucleus optical model potentials (OMP) needed to describe the one-nucleon transfer reactions used to extract the asymptotic normalization constants (ANC). The procedure, originating in IFIN-HH, was proved to describe and even predict very well elastic scattering of *p*-shell and *sd*-shell RNBs and is crucial in the success of the ANC method developed by the Texas A&M group and currently used worldwide.



C. Summary of the ANC extracted from ^{8}B breakup with different interactions

Data from:
F. Negoita et al, Phys Rev C 54, 1787 (1996)
B. Blank et al, Nucl Phys A624, 242 (1997)
D. Cortina-Gil e a, EuroPhys J. 10A, 49 (2001).
R. E. Warner et al. – BAPS 47, 59 (2002).
J. Enders e.a., Phys Rev C 67, 064302 (2003)

All available breakup cross sections on targets from C to Pb and energies 27-1000 MeV/u give consistent ANC values!

Summary of results:
LT ea, PRL 87, 2001
LT ea, PRC 67, 2004

^{7}Be(p,γ)^{8}B (solar neutrinos probl.):
p-transfer: $S_{17}(0)=18.2\pm1.7$ eVb
Breakup: $S_{17}(0)=18.7\pm1.9$ eVb
Direct meas: $S_{17}(0)=20.8\pm1.4$ eVb

***Figure 3.5.1** The summary of the ANC extracted from ^{8}B breakup data.*

Similarly, a method was developed to extract ANCs from breakup reactions at intermediate energies and connect them to astrophysical S-factors and reaction rates for NA. An elaborated Glauber-type reaction model based on the eikonal approach developed at IFIN-HH was used. One remarkable contribution of this method was in the determination, in 2001-2004, using all available data from the breakup of ^{8}B at intermediate energies, of the astrophysical factor S_{17} for the ^{7}Be(p,γ)^{8}B reaction at the end of the ppIII chain (Fig. 3.2.2, right), reaction crucial for the solar neutrino problem. This is considered one of the most important astrophysical reactions; the value obtained was independent and in agreement (within uncertainties) with best determinations of S_{17}, at a time when the solar neutrino puzzle was not yet solved through the confirmation of neutrino oscillations by the SNO and SuperKamiokande measurements. The method consisted in the determination of the ANC of the $^{8}B \rightarrow {}^{7}Be+p$ system using the breakup of ^{8}B at energies from 27 to 1400 MeV/u and on targets from C to Pb (Fig. 3.5.1). Then, the ANC extracted was used to evaluate S_{17}. Some of the ^{8}B breakup data were from the thesis of a Romanian scientist.

Many H-burning reactions occurring in cold or hot stellar cycles, proton capture reactions on sd-shell nuclei or heavier, are dominated by resonances. Some of these are affected by *threshold phenomena*. The problem of relationship between threshold phenomena and spectroscopic factors is a priority result of our researchers and is now a topical problem in the Gamow Shell Model. The nuclear astrophysics studies have to consider such "threshold effects" as renormalizations of the reduced widths and Thomas-Ehrman shift. The theoretical study of high excited proton threshold states implies a parallel analysis of mirror nuclei (^{27}Al, ^{27}Si) and (^{23}Na, ^{23}Mg).

The 2005, 2007 and 2010 editions of the traditional Carpathian Summer Schools of Physics, which were organized under the title “Exotic Nuclei and Nuclear/Particle Astrophysics”, constitute a particular form of activities in nuclear astrophysics in Romania. Each of the 3 editions have attracted about 120 participants from all continents, from students to best known professors and specialists in NA and AP and are already among the most prestigious in the field. That led to the invitation to be in the future part of a network of 4 European schools under the egis of the EUROGENESIS program.

3.6 Future activities

As noted above, no direct nuclear astrophysics measurements are currently possible in Romania. One notable avenue could be evaluated, though: it was shown recently in Dresden, Germany, that considerable background reduction can be obtained in laboratories placed in shallow-underground sites, at modest depths, like ~ 50 m, if the detectors are equipped with active screening. There are several unused, shallow underground constructions in Romania, many around Bucharest (built initially for military or industrial purposes and not used now), which could be inspected and retrofitted for such a purpose. The active screening of the gamma-ray detectors usable in such measurements is not more complicated than the usual anti-Compton devices, for example. Groups in IFIN are actively involved in developing such large efficiency detectors, based on hyper-pure Ge or on newer materials like $LaBr_3$:Ce, and the costs for them and the active shielding are not prohibitive. In many reactions relevant for nuclear astrophysics measurements one needs to detect gamma rays. It would become advantageous to use the new type of LaBr3:Ce detectors because they have sufficient resolution, while their efficiency is larger than for Ge detectors. High intensity low energy proton and alpha accelerators are commercially available and not very expensive. These would make one such project affordable in Romania.

More experiments at the newly refurbished tandem accelerator will be motivated in the future by nuclear astrophysics problems. Already groups from abroad (USA, UK, Italy) have proposed and executed experiments using activation, in-beam gamma-ray spectroscopy, “complete spectroscopy” measurements or the Trojan Horse Method. They will use the existing detection equipment (the gamma-ray detectors array, neutron detectors), will bring their own detectors or will use detectors that will be jointly developed. The cooperation with Romanian group will add and improve the needed local expertise in the field.

Another particular avenue will be the participation to large international cooperations, European ones in particular. IFIN-HH will contribute with detector development and with beamtime at the tandem accelerator for testing methods and newly built equipment. Romania participates in SPIRAL2 and FAIR, to the program EUROGENESIS.

Theory developments will continue on subjects with direct application to NA. A goal is the improve the description of nuclear reactions involving nuclei close to the driplines and to increase the reliability and accuracy of the absolute values of the calculated cross sections. That involves both advances in theoretical methods and in computational methods. CDCC methods are already tested in collaboration with scientists from Italy, USA and Japan.

The spectroscopic factors of high-excited proton threshold states, involved in cold stellar cycles will be calculated using the Shell Model, while the reaction rates for hot stellar cycles are calculated within the Statistical Model. The problem of proton subthreshold resonances (negative energy resonant states) and of their spectroscopic properties, the renormalized reduced width or asymptotic normalization constant, will be approached in R-matrix terms.

3.7 Nuclear astrophysics at ELI-NP

With the construction and commissioning of the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP) in Magurele, near Bucharest, nuclear astrophysics research in Romania could enter into a radically new phase. The facility will not only create new and unique possibilities to study individual nuclear reactions, but will create conditions close to those existing in very hot and dense stellar environments. It will also enlarge considerably the nuclear astrophysics research done in Romania by international groups. However, the techniques and the instrumentation implied need also to be radically new. The White Book of ELI-NP describes in more detail the types of information that can be extracted using the facility, the experiments or types of experiments possible.

The new opportunities will be offered by the laser acceleration, by the large energy brilliant gamma ray source and the very high electric field and short pulses produced. Below we only point to three proposed subjects.

Neutron-Rich Nuclei around the N = 126 Waiting Point of the r-Process produced via the Fission-Fusion Reaction Mechanism using laser accelerated Th beams

A laser driven acceleration mechanism recently observed was proposed to produce neutron rich nuclei around the N~126 waiting point, a key region of nuclear chart for understanding the heavy elements formation in fast neutron capture nucleosynthesis. The density of accelerated ions is predicted to be 15 orders of magnitude higher than in any classical acceleration, such that secondary reactions involving two unstable nuclei become possible. At ELI-NP, the high power laser pulses will be used to accelerate Thorium nuclei at several MeV/nucleon. The dense Th bunch will impinge a thorium secondary target inducing the fission of both in flight and at rest nuclei. The high density of fission products, part of them forward focused with the mean energy of the bunch, could lead to their fusion. The mass distribution of fission fragments has a maximum for the neutron rich nuclei with A=80-100 (light fragments) and a second maximum at A=130-150. The fusion of light fragments is the process of interest for production of neutron rich nuclei with A<200 and N~126. The nuclei of interest are expected to exit the target in forward direction allowing separation in magnet spectrometers followed by spectroscopic studies of their decay, or accurate mass measurements using a Penning trap.

The proposed method for production of radioactive nuclei could give access to N=126 waiting point nuclei with much higher yields than the existing or next generation of radioactive beams facilities such as FAIR, SPIRAL2 or FRIB, especially if one takes into account that high-power laser system are expected to evolve rapidly, in terms of energy per pulse and repetition rate, during the coming years.

Neutron Capture Cross Section of s-Process Branching Nuclei with Inverse Reactions

The heavy elements above the iron peak are mainly produced in neutron capture processes: the *r*-process (*r*: rapid neutron capture) and the *s*-process nucleosynthesis (*s*: slow neutron capture). We said already that nuclear information about the nuclei and nuclear processes along the *r*-process path is scarce. However, even for the *s*-process there is not, currently, sufficient information to control effectively the quantities that are driving it: beta-decay lifetimes and neutron capture cross sections. All current nucleosynthesis calculations have to rely on theoretically driven extrapolations and on parameters that we know that in many cases are not yet tested by experiment or are failing to give reliable predictions. It was proposed to determine neutron capture cross sections (n,γ) from the inverse (γ,n) reactions using the intense gamma-ray beam from ELI-NP. The predictions of the Hauser-Feshbach calculations will be tested against experiments with the goal to select the best underlying parameter sets. Such efforts started or are planned at other facilities world-wide, but the energies and intensities possible at ELI-NP are far better suited for such research.

Measurements of (γ, p) and (γ,α) Reaction Cross Sections for p-Process Nucleosynthesis

Another class of photodisintegration rates that could be measured at ELI-NP – (*γ, n*), (*γ, p*), and (*γ,α*) – play an important role in the nucleosynthesis of the so-called *p* nuclei. These are medium mass, proton-rich, in general very low-abundancy isotopes on the left side of the beta-stability valley and cannot be produced by neutron capture reactions. Complete network calculations on *p*-process nucleosynthesis include several hundred isotopes and reaction rates. Theoretical predictions of the rates, normally in the framework of the Hauser-Feshbach theory, are necessary for modeling. The reliability of these calculations needs to be tested experimentally for selected isotopes. Many efforts using continuous bremsstrahlung spectra have been made at the S–DALINAC at Darmstadt and at the ELBE setup at Forschungszentrum Dresden, both in Germany, to determine energy-integrated photodisintegration reaction rates without any assumptions on the shape of the cross section's energy dependence in the astrophysically relevant energy region close above the reaction threshold. Measurements of the energy dependence of these reaction rates are possible using monoenergetic photon beams produced by Laser Compton Backscattering. Very few places in the world can compete on this subject and none has the intensities of ELI-NP. It will only become possible to develop a broad database of photodisintegration rates if the times needed for experiments are short as it will be the case with the highly intense *γ* beam of ELI-NP.

3.8 *Recommendations*

From a handful of laboratories in the whole world and small groups working on the subject in the past, nuclear astrophysics has emerged in the last decades as a strong motivation for nuclear physics studies in most if not all laboratories, large and small, and will continue to be increasingly so, as we aim at understanding better the underlying phenomena that are driving the energy production in stars and the synthesis of chemical elements.

We recommend therefore:

- *To develop a more robust nuclear astrophysics in IFIN-HH and create the conditions for it to be actively and efficiently pursued.*
- *To finance and realize the ELI-NP facility and to include in its research a strong program motivated by nuclear astrophysics. To finance the design and construction of the instrumentation needed for the program.*
- *To strengthen the international cooperation in the field through the participation in European programs on this subject.*
- *To support the formation of personnel to work in nuclear astrophysics research, in particular with the new possibilities to be offered by ELI-NP.*

4. Astroparticles Physics

4.1 General considerations

Astroparticle Physics (AP) is a new multidisciplinary field of research studying the particles coming from the Universe, where nuclear and particle physics, astronomy, astrophysics and cosmology converge. In 2002, Ray Davis and Masatoshi Koshiba were awarded the Nobel Prize in Physics for opening the neutrino window to the Universe, specifically for the detection of neutrinos from the Sun and Supernova SN1987A in the Large Magellian Cloud. In the last one or two decades, most of fields of Astroparticle physics have moved from infancy to technological maturity, when instruments and methods have been born for doing science with high discovery potential.

Astroparticle Physics seeks to answer to fundamental questions: where do cosmic rays come from, what is the view of the sky at extreme energies, what is the role of neutrinos in cosmic evolution, what neutrino tell us about the interior of stars and other astrophysical active objects, what are dark matter and dark energy, what is the nature of the gravity, do protons have a finite life-time.

As the cosmic messengers (gamma rays, charged particles, neutrinos) are rare and difficult to detect, the technique employed requires deployment of large area detectors and use of large volume natural detector media (atmosphere, see water, ice, salt mines). Astroparticle Physics apply methods and instruments originally developed in nuclear and particle physics to study the formation of the universe from its smallest to the largest component. Large infrastructures are: Pierre Auger Observatory (PAO), large telescope array to detect charged cosmic rays, KM3NeT, a neutrino telescope under the Mediterranean Sea, LAGUNA, a megaton scale detector to investigate properties of neutrino, CTA, Cherenkov telescope array to detect cosmic high energy gamma rays and underground gravitational antenna. Astroparticle Physics infrastructures, technology and methods have potential applications for environmental and climate studies.

With ERA-NET scheme under FP6, a project ASPERA started in July 2006 for 3 years and is extended under FP7 as ASPERA-2 for another 3 years. ASPERA is a network of governmental agencies responsible for coordinating and funding national research in AP. In 2007 a network ROASTROPART (ROmanian ASTROPARTicles) for collaborative experimental and theoretical studies in the field of Astroparticle Physics in Romania was established between IFIN-HH Bucharest-Magurele, (Institute of Physics and Nuclear Engineering), ISS Bucharest-Magurele (Institute of space Science), UB (University of Bucharest) and UPB (University Polytechnica Bucharest) Based on the experience accumulated by the above partners in the field of astroparticle physics, and the complementarity between the directions already addressed by each one individually, Romania was accepted as partner in ASPERA and as observer in ApPEC (Astroparticle Physics European Coordination).

4.2 Astroparticle Physics research in Romania

4.2.1 Study of High Energy Cosmic Rays, (HECR)

Investigation of HECR with participation in the large international experiments

The high interest worldwide on the particles in the cosmic radiation is due to the yet unsolved questions of their origin and the fact that these particles carry the highest energies per particle known to man, orders of magnitude up to (and even above) 10^{20} eV, impossible to achieve in any present or foreseen man made accelerator devices.

One of the prime objectives of the vast majority of cosmic ray studies is to measure their energy and to establish the mass distribution of the primary particles in the cosmic radiation. This kind of information can probe numerous theories on the origin of high energy particles and production mechanisms, acceleration and propagation mechanisms and high energy hadronic interaction models.

The energy spectrum of the cosmic rays has monotonous $E^{-\gamma}$ dependence, interrupted by several discontinuities, which have to be clarified. The first one, called "knee", (due to the resemblance in shape with a bent human leg), has been found at around 10^{15} eV due to the CR light component decrease. Around 10^{17} eV, another discontinuity appears and around (10^{19} -10^{20}) eV, the spectrum flattens in the region called "ankle. The direct observation of the cosmic particles is efficient only up to energies of 10^{14} eV, where the flux becomes too low to allow efficient direct observation. Fortunately, the very high energetic primary cosmic ray is interacting with the nuclei of Earth's atmosphere and secondary particles are produced developing EAS, (Extensive Air Shower), which arrive at the ground distributed over a large area, and can be signaled by complex detectors spread on large surface. Thus, the effects of the cosmic radiation in the Earth's atmosphere, are obtained by investigating EAS (avalanches of particles), using the atmosphere as the detector medium.

The reconstruction of the primary cosmic rays spectrum via the observation of extensive air showers, is based on the simulations of the development of the particle cascades in the atmosphere, where the most known program is **CORSIKA** code, setup in KIT, Karlsruhe, Germany. This code is under continuous improvement, detailing the hadronic interactions (governing the charged particles and neutron production) and the propagation mechanisms of the particles in the atmosphere.

Some experiments exist worldwide that are designed to measure the energy and mass composition of the cosmic radiation. Such an experiment is the KASCADE-Grande, hosted by the Karlsruhe Institute of Technology, (KIT), Germany at 110 m a.s.l and operated by an international collaboration between Germany, Italy, Poland and Romania (IFIN-HH and UB). The shape of the array is rectangular with a length of ~700 m and it is composed of many detector stations that are distributed over a wide area (Fig. 1). Grande is an extension of a smaller array, the KASCADE array, operated since 1996, (Fig. 4.1), set-up to record air showers initiated by primaries with energies in the 10^{14} -10^{16} eV range for investigating the first "knee" range.

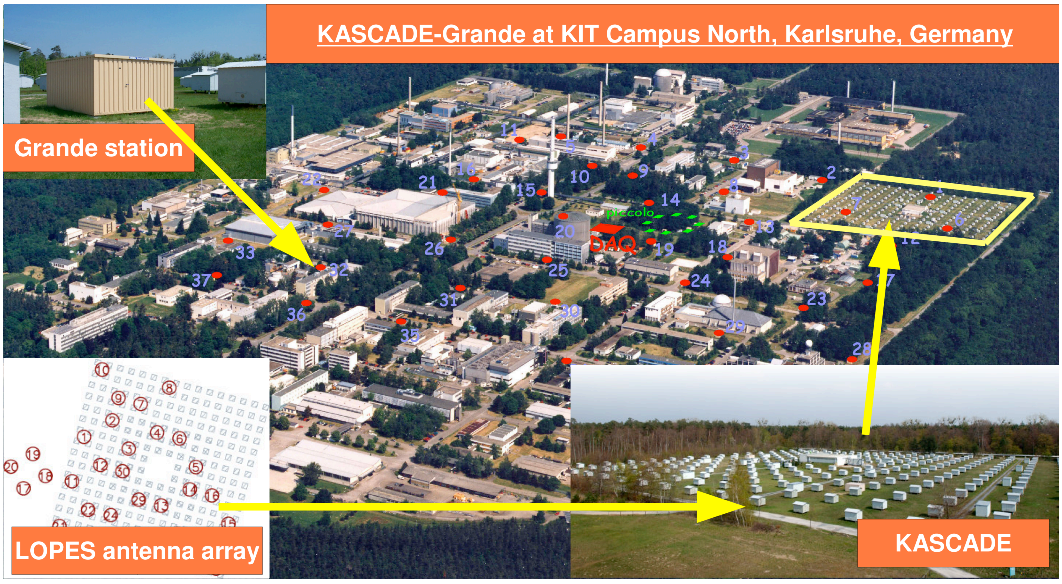


Figure 4.1 *The location and layout of the KASCADE-Grande (Nucl.Instr. and Meth. A620 (2010) 202-215) and LOPES experiments at the Karlsruhe Institute for Technology (KIT), Karlsruhe, Germany (in the upper left photo there is an image of a Grande station among the KASCADE stations; the lower left image shows the placement of LOPES antennas among the KASCADE stations).*

The extension to the KASCADE-Grande array was guided by the aim to extend the energy range for efficient EAS detection to 10^{16} -10^{18} eV (Fig. 4.2). This extended energy range provides various interesting aspects: the expected transition from galactic to extragalactic cosmic rays and, in particular the question whether there exists a further "knee" in the energy spectrum at energies of about 4×10^{17} eV. Though suggested by the measurements of some experiments (i.e. Yakutsk, Haverah Park, Fly's Eye, HiRes-MIA), the existence of this feature is still not proved. Further structures of energy spectrum are visible at even higher energies, the case of the "ankle" at around 5×10^{18} eV. The ankle is observed in experiments like the Pierre Auger Observatory. The two spectral features, “knee” and “ankle”, are strongly correlated however in the models describing them. Some models predict that the surviving heavy (mostly Fe) galactic component brakes down at energies few times 10^{17} eV and the transition to the extragalactic component occurs, leading to another knee-like feature, the second knee. In this model the ankle is regarded as purely a feature of the extragalactic radiation "cooling" in a reaction producing electrons and positrons. A second model describes how an additional source of radiation extends the galactic spectrum up to energies close to the ankle. In that energy range ~10^{19} eV the extragalactic proton component is mixed with the extended galactic spectrum and the ankle is a feature of the superposition of the two (a transition effect). Thus the second knee and the ankle are two spectral features that are intimately related.

At the KASCADE-Grande experiment, the Romanian partner has brought fundamental contributions by developing a new and independent reconstruction technique. Thus, experimental and simulated data are analyzed with reconstruction tools that function independently form the standard ones. The contributions have been in the direction of reconstructing the primary energy and mass of primaries from the information of charged particles density in air showers (Fig. 4.2). The observables of interest are the the charged particle densities at fixed distances 200 m, S(200), and 500 m, S(500), to shower axis (due to their special properties - mass sensitivity of S(200) and mass insensitivity of S(500)).

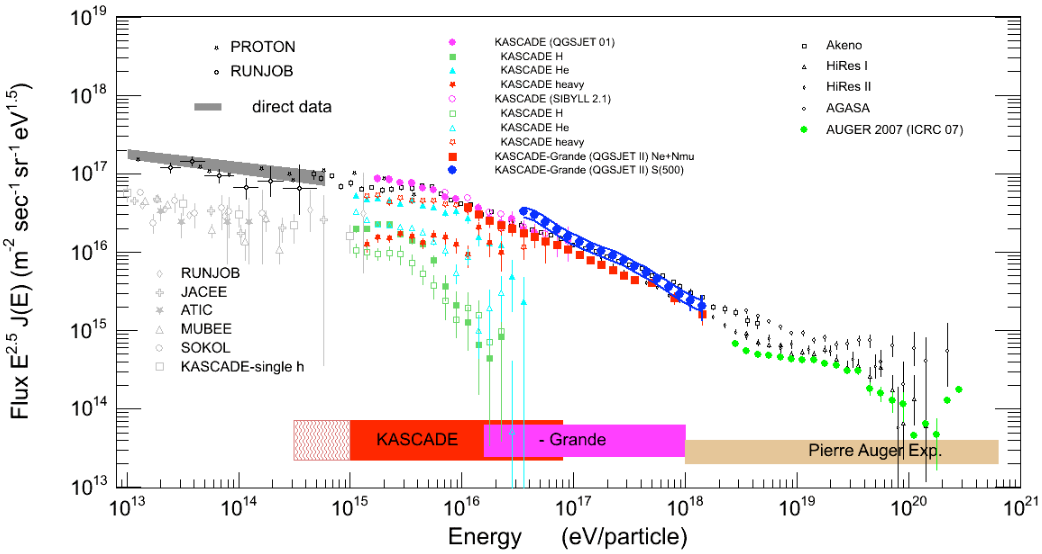


Figure 4.2 *Reconstructed experimental energy spectrum by various experiments including KASCADE-Grande (from the particular case of charged particle density at 500 m distance to EAS shower axis, S(500), multiplied by $E^{2.5}$) (not yet published).*

For the future, the activity will be focused on the reconstruction of the energy and the mass composition of cosmic rays from the experimentally recorded data (as mentioned above, most cosmic rays investigations are related to the reconstruction of these observables). The main aim is to obtain the energy spectrum of primary cosmic rays in the (10^{16} – 10^{18}) eV energy range and to relate the results to previous measurements at lower energies. This objective is directly linked to the hottest topics in modern astrophysics and cosmic ray physics for the proposed energy range: interpreting spectral features (i.e. the second knee or the ankle) and identifying transition effects in order to understand the origin of cosmic rays (galactic/extragalactic), the production and acceleration mechanisms.

Based on a successful Romanian-German co-operation in the experiments KASCADE-Grande si LOPES, since March 2011 Romania is accepted as Associate Country with Germany in Pierre Auger Observatory with the participation of IFIN-HH, UPB and UB. It is the largest air showers hybrid detector in the world, placed in the Mendoza province, Argentina, with over 1600 detector stations spread over an area of 3000 km^2, (Fig.4.3). The experiment is being operated by an international collaboration whose members come from universities and institutes in 19 countries. The Romanian partner will use its expertise in the cosmic ray studies and will contribute to the investigation of cosmic rays by analyzing the experimentally recorded EAS data, in order to reconstruct relevant observables of the cosmic radiation (primary energy and mass are two observables of utmost relevance). Additional contributions will be in the direction of improving the various aspects of the reconstruction technique, a field in which the Romanian partner also has considerable expertise. The novelty of our investigation lays in the use of data from the two above experiments whose optimal energy detection ranges overlap and cover together the two spectral features of interest.

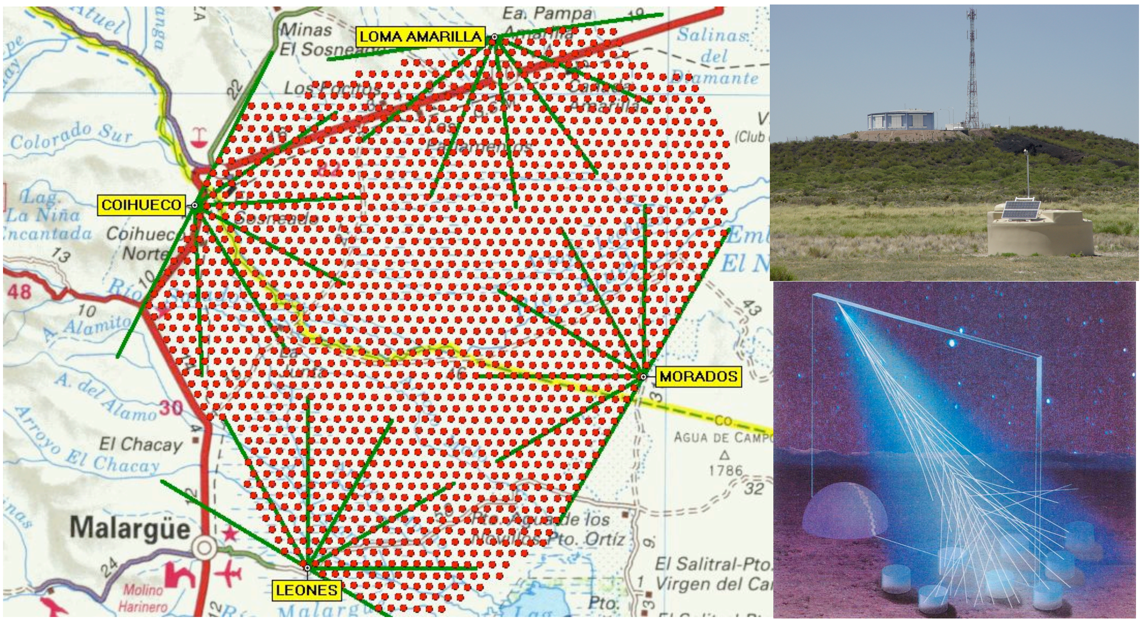


__Figure 4.3__ The layout of the Pierre Auger Observatory; in the upper right there are two detector stations, a water Cherenkov tank and a fluorescence detector station and in the lower right an artist view on the hybrid detection of an air shower (Pierre Auger Observatory Design Report (March 1997), www.auger.org/admin).

Investigation of high-energy cosmic rays with local infrastructure

Studies of the flux and of the charge ratio of the atmospheric muons

The muons are the most important EAS component, as they are deep penetrating long living particles, which can inform about the primary cosmic particle. In IFIN-HH Bucharest a detector WILLI has been set up in collaboration with KIT, Germany, to measure and to study the flux and the charge ratio (the ratio of the positive to negative muons) of the atmospheric muons. We use a new improved method to determine the muon charge ratio by measuring the lifetime of the muons stopped in the matter, overcoming the uncertainties appearing in the measurements based on magnetic spectrometers, which are affected by systematic effects at muon energy less than 1 GeV due to the problem in the particle and trajectory identification (under the influence of the Earth's magnetic field). The measurements of East-West effect in muon charge ratio permit to verify the hadronic interaction models in simulating neutrino and muon fluxes, the geometry of detection in a complex sphere and the the influence of geomagnetic cut-off and the local magnetic field on muon propagation in atmosphere. The measurements with rotatable WILLI, inclined on 45° direction show a pronounced East-West effect (see Fig. 4.4), in good agreement with simulations data (DPMJET model) and with the East-West effect found in neutrino measurements. The muon charge ratio is a quantity to probe the influence of the magnetic field.

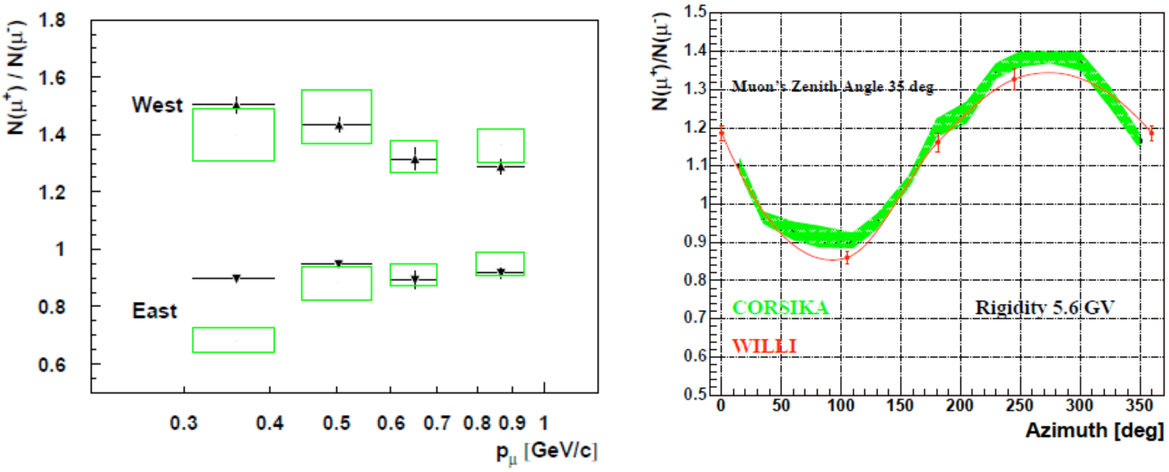


Figure 4.4 *The Energy dependence of the muon charge ratio, measured separately for East and West directions, with comparing experimental data and simulations [Nucl.Phys.Proc.Suppl. 151 (2006) 295-298] – left; the azimuthal variation of the muon charge ratio measured with WILLI compared with CORSIKA (DPMJET model) simulation [AIP Conf.Proc. 972 (2008) 500].*

The detector is extended to WILLI-EAS by a mini - array of scintillation detectors (see Fig. 4.5) for studies of the muon charge ratio in EAS, (Extensive Air Showers). Recently the features of the charge ratio of the density of the EAS muon component have been extensively studied on basis of Monte Carlo simulations revealing that the radial and azimuthal muon density distributions of EAS observed by surface detector are strongly influenced by the magnetic field of the Earth, (see Fig. 4.6) The features depend on the direction of EAS incidence (zenith and azimuth angles) relative to the geomagnetic field, on the energy of the registered muons and on the mass of the primary cosmic particle.

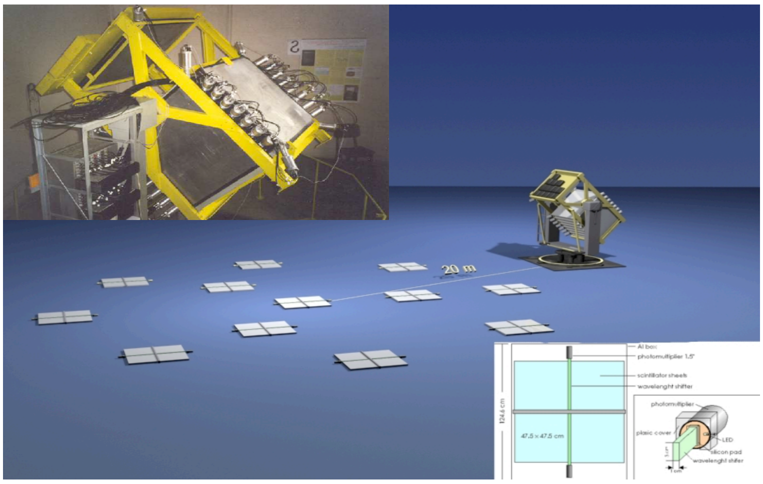


Figure 4.5 *The WILLI-EAS detectors system for the measurement of atmospheric muons set up in IFIN-HH in collaboration with KIT, Karlsruhe, Gemany; WILLI-EAS is composed by the WILLI detector (in the upper left corner) and a mini array of 12 stations with plastic scintillators (detail of one detection station in the lower right corner) Nucl.Phys.B (Proc.Suppl.)196 (2009) 227.*

The system WILLI-EAS is in operation since 2011, being the unique system in the world to provide data on the muon charge ratio in EAS, measurements which could bring information to test hadronic interaction models. Taking into account the acceptance of WILLI detector for muon energy less than 1 GeV, the simulations of showers produced by H and Fe cosmic primaries, show a different variation of the muon charge ratio on the azimuth position of WILLI, such effect could show features about the mass composition of the cosmic rays. To get reliable statistics the measurements will run for minimum 5 years. Such measurements are expected to provide information about the influence of the geomagnetic field on the atmospheric muons, about hadronic interactions governing the air shower development and about primary mass composition for showers with energies between $(10^{13} - 10^{15})$eV.

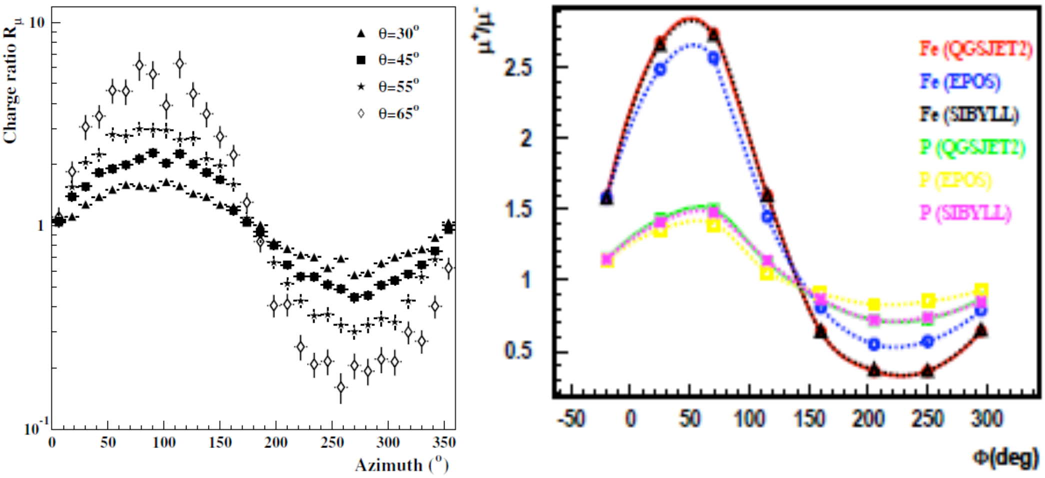


Figure 4.6 *Azimuthal variation of the charge ratio of the muon density of proton-induced EAS incident with different zenith angles from the North with the primary energy of* 10^{15} *eV, observed at a radial distance of 45–50 m and for a muon energy threshold of 0.1 GeV [J. Phys. G: Nucl. Part. Phys. 35 (2008) 085203] – left; the dependence of the charge ratio on the azimuth position of WILLI for proton and iron induced showers,at 15-20 m [Nucl.Phys.B Proc.Suppl. 196 (2009) 462-465] - right*

Correlation of the cosmic muons with solar events

The primary cosmic flux can be influenced by the solar activity and this modulation is reflected in the muon flux observed at ground level. Important solar events, like coronal mass ejections, can cause magnetic storms. By observing secondary muons with ground based telescopes we can investigate the correlation of solar events with features in the muon flux and could help predict magnetic storms.

The influence of the solar activity on the muon flux will be investigated by measuring the diurnal variation of the muon flux (see Fig. 4.7). The influence of season variation and of the meteorological condition on the muon flux will be study using WILLI detector and the mobile muon detector correlated with a portable whether station.

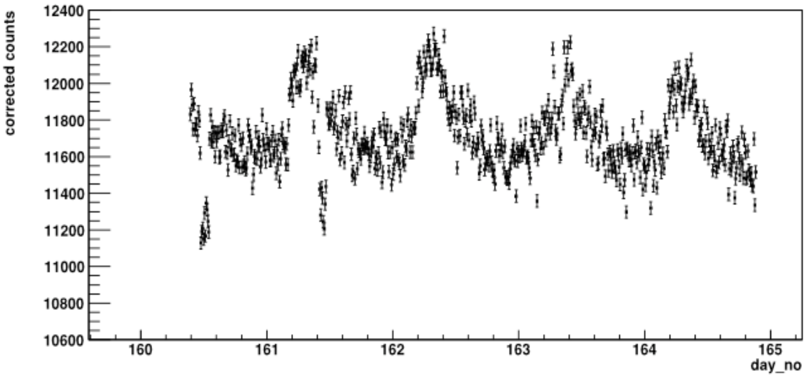


Figure 4.7 *Diurnal modulation of ground level atmospheric muon count observed with the WILLI detector in Bucharest as a function of day number of the year, for a period of 4.5 days.*

Studying the cosmic radiation in the underground

IFIN-HH has a small underground laboratory in the Slanic Salt mine, which is included in LAGUNA (Design of a pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics), a research project, supported by the European Union to setup the infrastructure for a large underground laboratory. The aim is to explore adequate locations for looking for extremely rare events like proton decay or for the experimental research of Dark Matter. This project is prolonged as LAGUNA-LBNO (Long Baseline Neutrino Oscillation), for studying liquid argon as active detection media for the GLACIER experiment.

The Romanian partner will be mainly involved in the fields of theoretical and experimental physics, particle and astroparticle physics, cryogenic technologies, numerical simulation and optimization of electromagnetic structures, consultancy and expertise in geology, salt extractive industry, salt processing and environmental protection.

4.2.2 Neutrino astronomy, neutrino properties and diverse physics with neutrino telescopes

ISS is a member of the **ANTARES** (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) since 2006, fully deployed south of Toulon, France, at a depth of 2500 m in the Mediterranean Sea, and tacking data. The detector is optimized for the search of upward going charged relativistic particles (muons produced by cosmic neutrinos crossing the Earth), but have very good sensitivity for downgoing particles too. ANTARES is completed with instruments dedicated to sea sciences, geophysics and marine biology (Fig. 4.8). Results concerning the search for the high energy diffuse neutrino flux, or on the atmospheric neutrino flux measurement are among the first published.

ANTARES is the main precursor to the future KM3NeT neutrino telescope, to be deployed in the Mediterranean Sea starting 2013 or 2014.

The Romanian partner contributes to the general tasks of the experiment, and in particular is involved in the "diverse physics" group where it coordinates the search for nuclearites in the penetrating cosmic radiation. The group intends to expand its research activity in ANTARES by implementing dedicated strategies for the search of slow GUT magnetic monopoles and for Q-balls.

ANTARES commitment is to continue its operation till at least one block of the future KM3NeT telescope will became operational in the Mediterranean Sea.

Figure 4.8 *A complete ANTARES line prepared for deployment. The 25 storeys, each equipped with 3 optical modules (the shiny spheres) and an electronics container are visible. The large yellow object in the right is the buoy ensuring the line stability under water.*

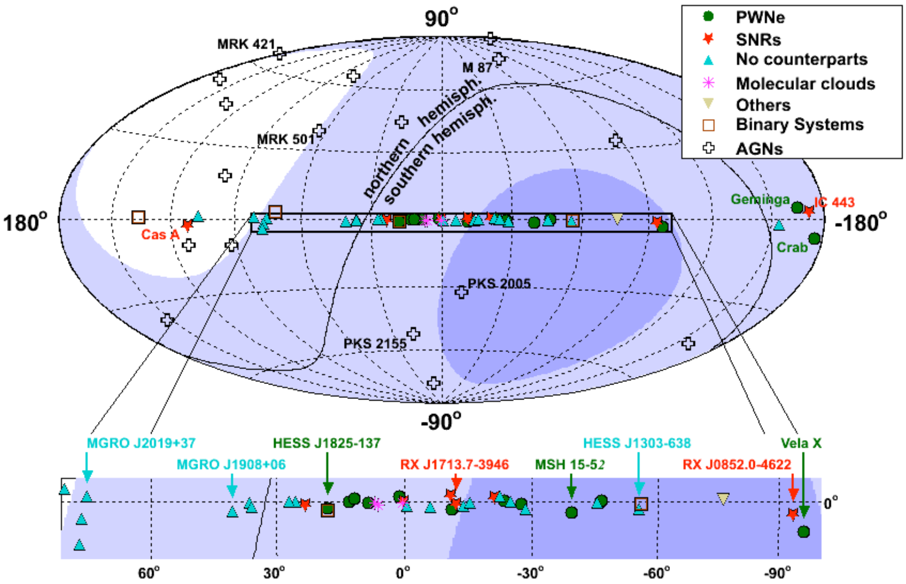


Figure 4.9 *Sky coverage of KM3NeT (and also ANTARES). Darker areas correspond to larger duty cycles. Some known target sources are indicated.*

ISS is also a member of the **KM3NeT** (Fig. 4.9) Collaboration. KM3NeT, included in the ESFRI priority list, will be a very large undersea neutrino telescope to be deployed also in the Mediterranean Sea. In his full configuration (about 6 km^3 of instrumented deep sea volume) KM3NeT will reach the sensitivity requested for the discovery of neutrino point sources in our Galaxy. The scientific program of KM3NeT will be very broad, including the search for slowly moving exotic particles in the cosmic radiation.

The Romanian partner coordinates an experiment aiming to deploy and test a KM3NeT (Fig. 4.10) – like optical module on the instrumentation line of ANTARES, and contributes (both with hardware and software) to the Pre-production model, to be deployed in 2012.

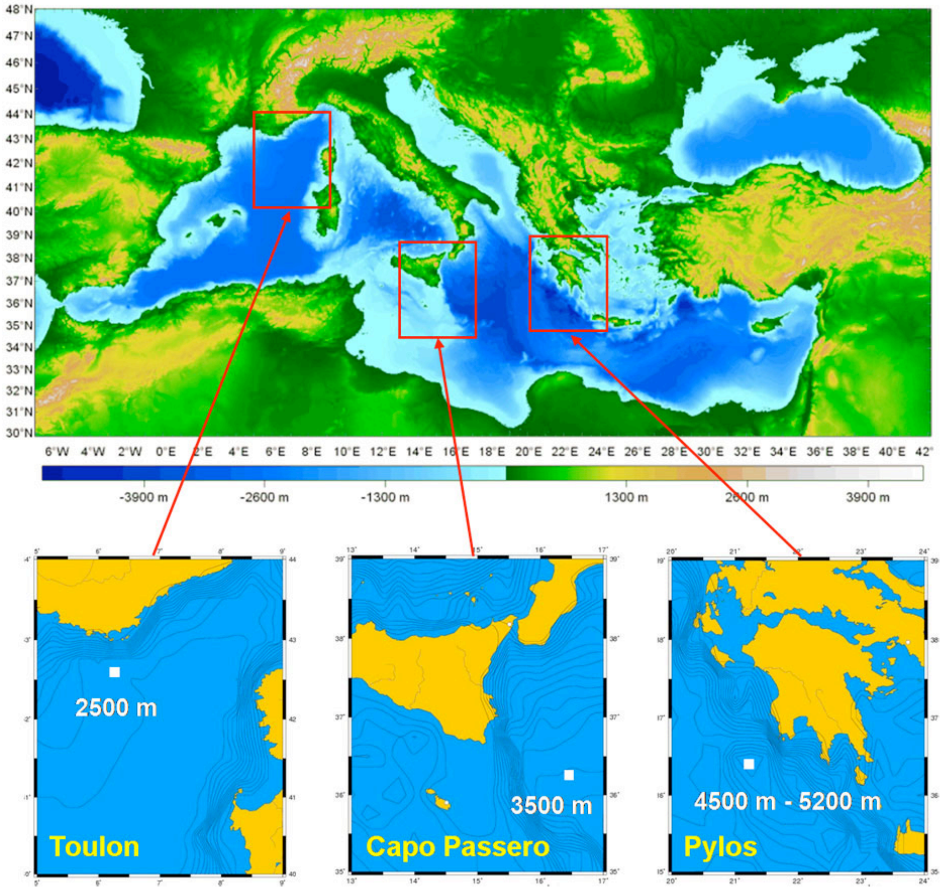


Figure 4.10 *Possible locations of the KM3NeT neutrino telescope. A multi-site option is possible.*

4.2.3 Observational cosmology

ISS participates to the ESA PLANCK mission, launched in 2009 in the Lagrange L2 point, and is investigating the properties of the Cosmic Background Radiation (CMB). The research directions of the Romanian partner include the interplay between cosmology and particle physics.

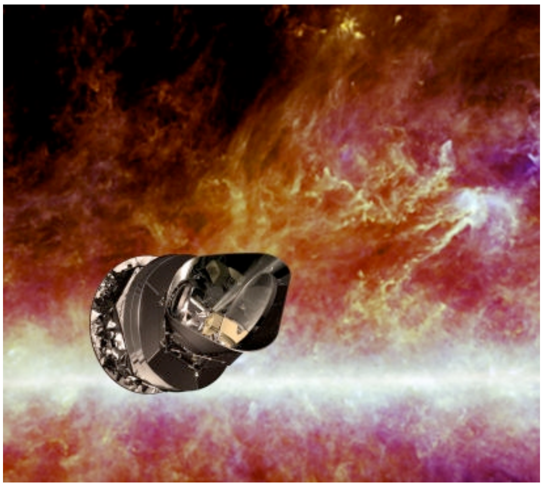


***Figure 4.11** An artist view of the PLANCK observer.*

Recently ESA decided to expand the PLANCK (Fig. 4.11) mission after the shutdown of its high frequency instrument (due to cooling limitations), focusing on the low energy instrument, where ISS is mostly involved.

After Romania became an ESA member, ISS was accepted as a full member in the Euclid (The European Dark Energy Mission) consortium, being already represented in the science team since the initial proposal, in order to contribute also in the hardware (ground segment) development. Euclid main scientific goal is to study the Dark Energy, the properties of the Dark Matter, and testing the principles of General Relativity. Euclid is a medium class mission candidate for launch in 2017 in the Cosmic Vision 2015-2025 program.

4.2.4 Instrumentation

Radio detection techniques

Investigation of EAS with radio antennas

For the investigation of CR a new experimental technique is developed, the radiodetection of EAS, based on the direct measurement of the electromagnetic pulse created during the passage of the shower through the detector media. The advantages of the radiotechnique lie in the fact that the radio waves are easy and cheep to detect and that they propagate in a number of media with very little attenuation. Therefore, radio signals can be transported over large distances (in the atmosphere many tens of kilometers)

A LOPES experiment (Fig. 4.12), with international participation, (Germany, Holland, Italy, Poland, Romania), is built as an array of radio antennas, in co-location to the KASCADE-Grande setup. It is meant to observe the radio emission from atmospheric showers by an array of antennas operated in coincidence with the scintillation detectors. The radio antennas are sensitive in the 40-80 MHz frequency range and are detecting radio waves coming from air showers in nanoseconds pulses of small amplitudes, micro-volts.

The radio system has been taking data since 2005 in several configurations, only East-West polarization, both East-West and North-South polarizations, and, starting with 2010, also vertical polarizations.

The radio signal has been proved to be correlated with the geomagnetic angle and the production mechanism of the signal is believed to be a synchrotron emission in the Earth's magnetic field. The geomagnetic angle is the angle between the local magnetic field line and the shower axis. This angle is higher for larger inclinations of the shower, and thus, studying inclined showers can yield information on the geomagnetic dependence. The exact dependence of the radio signal on the geomagnetic angle is yet to be established.

The production mechanism is investigated by looking at correlations between the radio signal and several shower parameters, inferred from the Grande particle detectors that gather data in coincidence with the radioantennas. Production mechanism in EAS is still under investigation.

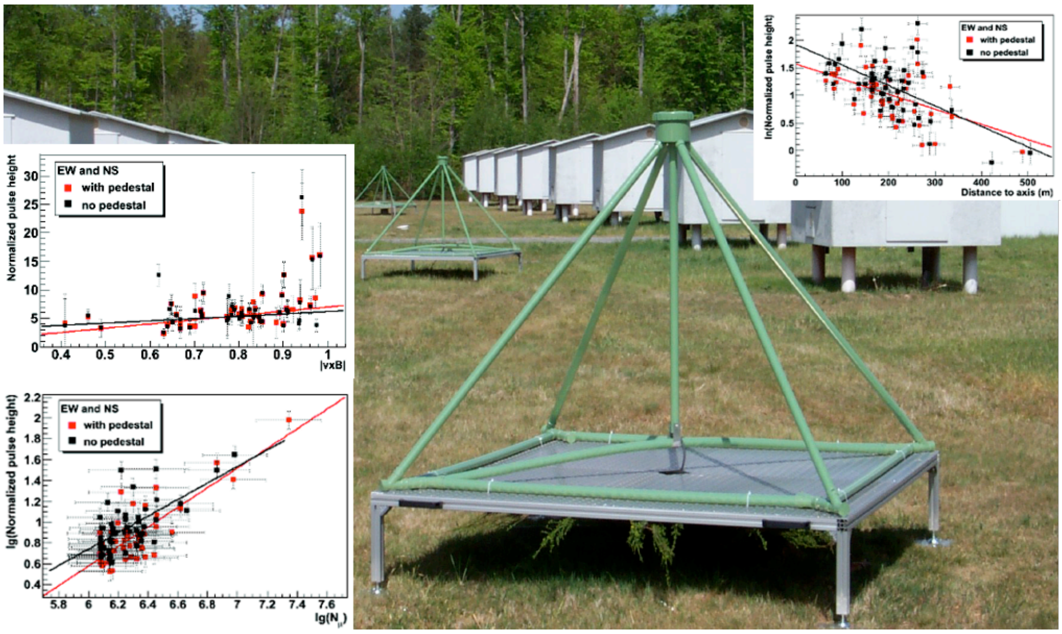


Figure 4.12. *LOPES antennas in the dual polarization configuration and example of results obtained with this configuration: geomagnetic dependence of radio pulse amplitude (upper left panel), on muon number, estimator for primary energy (lower left) and on distance from shower axis to the antennas (right).*

For vertical showers the vertical component of the electric field is close to zero and thus not important in analysis, but as the inclination of a shower increases the vertical component of the electric field increases too. By observing all the polarization components we have access to the complete information on the signal.

The latest configuration LOPES-3D, is designed especially for this purpose; so the antennas are sensitive to all of the three components of the polarization. We will focus on the study of these 3D events for a better understanding of the characteristics of the radio emission. Our studies continuously provide a starting point for studies and experimental test for other configuration in Pierre Auger Observatory.

Investigation of high-energy neutrinos using radio antennas in salt

The underground site from Slanic Prahova, with a ultra-low radiation background is a suitable site for high energy neutrino investigations based on radiodetection. The ROASTROPART consortium will investigate the possibility to detect high energy neutrinos using radio-antenna in the salt mine, an unique experiment in Europe. Neutrinos cannot be directly detected, but they can be indirectly observed through their interactions with ordinary matter. We consider a detection strategy based on coherent radio Cherenkov emission from neutrino-induced electromagnetic showers (see Fig. 13). This is due to the Askaryan effect that states that a high-energy particle which travels faster than the light in dense dielectric will produce a 20% excess of fast moving negative charges at the shower maximum. As a result nanosecond pulses of coherent Cherenkov radio emission could be observed in directions corresponding to a ''spread'' conical surface with the opening equal to Cherenkov angle. For photons with wavelengths longer than the transverse dimensions of the cascade, like radio frequency (RF) photons, the radiation is coherent and the electric field is proportional to the negative charge excess in the cascade. The radio power coherently emitted scales inversely with the square of the radiation length of the medium and goes like the square of the primary shower energy. Based on this principle, several new neutrino detectors were developed and built recently around the world in different dielectric media.

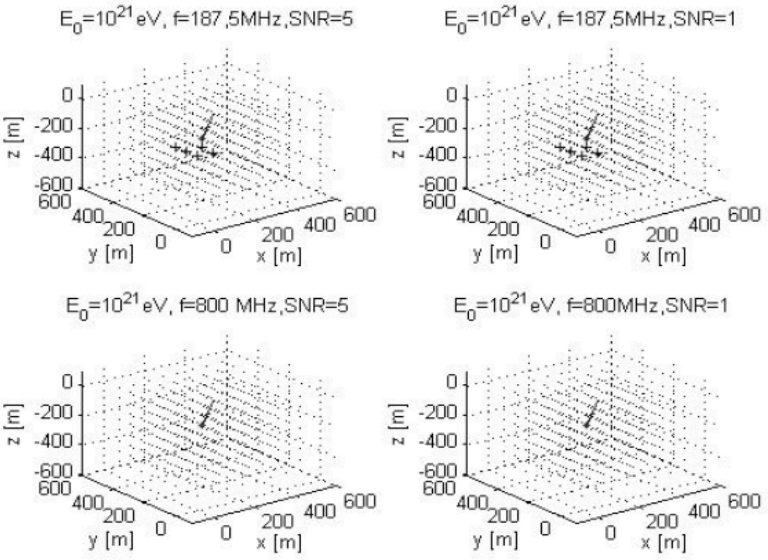


__Figure 4.13__ Simulation of detection in a grid of radio antennas placed in salt for two different signal to noise ratios, 5 (left) and 1 (right), for 187 MHz (upper figures) and 800 MHz (lower figures). Crosses represent antennas that have a signal above detection threshold.

In the underground site at Slanic Prahova the experiment would be carried on in salt. The detector should be able to reconstruct the energy and direction of the primary particle based on the measured properties of the electrical field generated by the initial neutrino.

Muon detection with a mobile detector

A mobile detector has been set up in IFIN-HH Bucharest for measuring the muon flux at different sites, (see fig. 4.14). The mobility of the detector implies a considerable practical flexibility of using the procedure of measuring muon flux differences for various aspects.

The results will be analyzed by comparing the experimental results with detailed Monte-Carlo simulation codes CORSICA, MUSIC and GEANT. CORSIKA (**CO**smic **R**ay **SI**mulation for **KA**scade), is a sophisticated Monte-Carlo code for simulations of the development of extensive air showers (EAS) in the atmosphere, will be use to estimate the muon flux at surface. As input for the simulations the primary cosmic ray spectrum (for different primary masses) in addition to a model for the hadronic interaction of the primaries with the Earth's atmosphere is necessary. Some measurements of the high energy muon flux has been performed with the mobile detector in the underground of the Slanic salt mine, where IFIN-HH has a small laboratory.

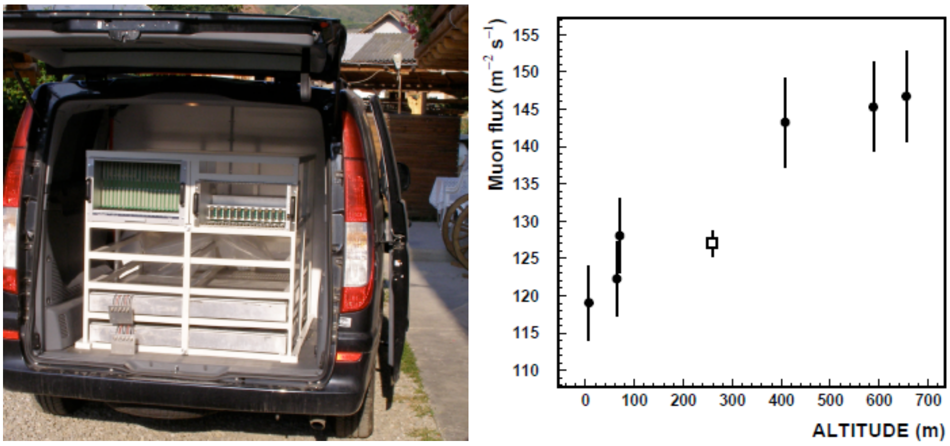


Figure 4.14 *The photo of the mobile detector mounted in a van – left; measured results of the muon flux variation with altitude in m a.s.l. - right. The rectangle point represents the results from [Phys.Rev. 61 (1942) 212].*

Further measurements at different locations in Unirea mine will be performed, in order to get an improved overview on the variation of the Unirea mine's water equivalent depth. We expect that the muon flux varies for different locations of the mine due to the variation of the overburden at the Unirea mine.

Muon detection with Multi Pixel Photon Counter

IFIN-HH astroparticle physics group will investigate high energy cosmic muons at the ground level and in the underground using a **Multi Pixel Photon Counter, (MPPC) Muon Detector** representing the next generation of detectors for the cosmic radiation.

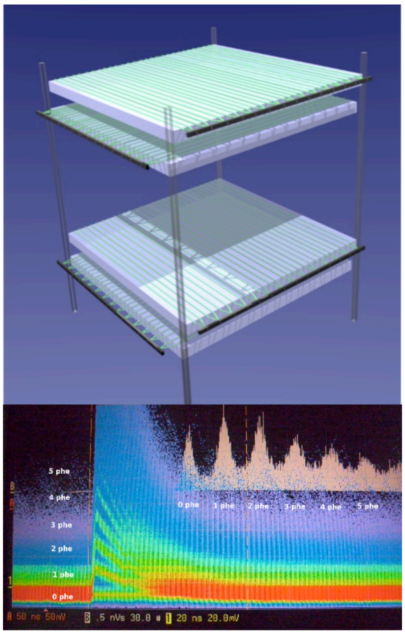


Figure 4.15 *New muon detector composed of scintillator plates read with optical fiber by MPPCs. Two plates are placed with the fibers perpendicular in a group at a given distance from the other two plates to provide a good reconstruction of the muon trajectory (in the low part, graphical output showing a good signal discrimination for different numbers of simultaneously detected photons).*

Such detector, based on a new technology using photodiode SiPM and fast readout electronic allows a better identification of the cosmic particle. It has a compact form, permits to measure the muon flux and the angle of incidence of the muons and it is suitable for cosmic rays observation at ground, in the underground and in the space, see Fig. 4.15.

4.2.5 Cosmic Rays Array for Education

Astroparticle physics could have as main spin-off the education; it has a significant impact potential on the young generation. Offering on hand experience to high school students trough simple cosmic rays experiments could influence their future evolution (not necessarily pointing to a career in the field, but focusing their attention on a more wide spectrum of technical, mathematical and natural sciences). Different countries (in Europe and Northern America) have already implemented networks made of CR detectors in high schools, with good results in the medium term.

ISS have already developed two prototype cosmic ray stations (each made of 3 individual detectors operated in coincidence), meant to be used in an educational network that will involve Romanian high schools. A potential network of high schools and Universities was identified, in close collaboration with UB and UPB. The future network is intended to be a part of a European educational network, the application to the next FP7 call on the “Science and Society” program. One of the cosmic ray stations is already operated in a small-scale demonstrative network, together with similar stations in the Czech Republic, Slovakia and United Kingdom (Fig. 16). A local station cannot yield significant scientific results, but a broad network of such low cost stations could also produce results, mostly in the case of transients.

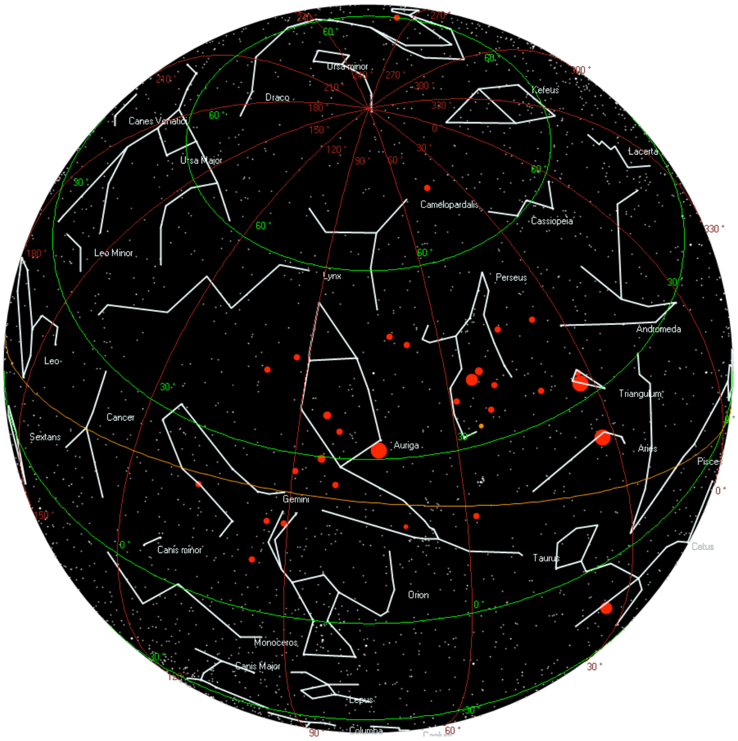


Figure 4.16 *A map of the pointing directions of cosmic ray showers, obtained with the ISS demonstrative station, in less than one hour of run.*

4.3 Recommendations

High-energy cosmic rays

The study of the high-energy cosmic rays addresses important physics problems and need a sustained long-term program. The interplay of the energy spectrum and the propagation through the background radiation, magnetic fields and atmosphere requires both careful experimental studies and theoretical modeling.

We recommend the study of the energy spectrum and primary mass for the range (10^{16} -10^{18}) eV to clarify the gap between the "knee" and "the ankle" , the KASCADE-Grande range, and to intensify the effort for studies in the "ankle"region, corresponding to Auger observatory.

We also recommend using the local infrastructure, WILLI-EAS detector, to clarify aspects regarding the hadronic interactions, the mass of the primary cosmic rays and the influence of the Geomagnetic fields on the cosmic muons.

High-energy neutrinos

Resources for a Mediterranean detector should be pulled in a single optimized large research infrastructure, KM3NeT. Start of its construction is preceded by the successful operation of small scale or prototype detectors in the Mediterranean, e.g. ANTARES.

Dark energy

We recommend taking part in the activities of the Astroparticle physics, Astrophysics and Cosmology community dedicated to the investigation of the nature of Dark Energy.

Instrumentation

The rapid development of Astroparticle Physics has led to new types of experiments at the ground level, in the see or in the underground, with specially designed instruments and new technology.

We recommend the technique of the radiodetection of air showers used in LOPES and in Pierre Auger Observatory and of the radiodetection of high-energy neutrinos in the underground of the salt mine.

We recommend the use of the new technology based on photodyodes with MPPC muon detector for a better identification of the particle and more compact system of detection of the cosmic rays.

We also recommend the use of a mobile detector for rapid measurements of the cosmic muons in different sites, as a facility also for applications in environment and geophysics.

5. Hadron Physics

5.1. Introduction

Nuclear matter, of which atomic nuclei are composed, is a system of strongly interacting particles called nucleons. One can create strongly interacting matter (as opposed to assemblies of independent particles) in accelerator based collision experiments and study its properties.

In the last decades, detailed experimental results based on versatile experimental devices at various colliding energies, from pp (ppbar) to heavy ion collisions, led to a tremendous progress in the understanding of the main mechanisms of collision processes and the properties of the new form of matter based on strongly interacting constituents starting from nuclear state at zero temperature all the way to a deconfined matter of quarks and gluons, the state through which our universe evolved shortly after the Big Bang. Based on a joint effort of theory and experiment, the phenomenology of the different regions of the phase diagram of strongly interacting matter started to be coherently interpreted and reveals first signatures of a phase transition from a quantum liquid to a hadron gas at intermediate energies and of a phase transition from hadronic matter to a deconfined matter of quarks and gluons at ultra-relativistic energies. As far as the new states of matter are obtained in laboratory using heavy ion collisions, it is mandatory to have under control the influence of the finite size and dynamical aspects on the measured observables i. e. the dynamical evolution of the transient piece of matter produced in heavy ion collisions characterized by collective pattern.

Collective behaviour frequently reveals qualitatively novel features of the complex system under study. Thermodynamics provides a general framework for the understanding of how properties of macroscopic matter and collective phenomena emerge from the laws governing the microscopic dynamics. The most dramatic example of collective behaviour is the occurrence of phase transitions, accompanied by qualitative changes in matter properties. Experimentally accessible strongly interacting systems are expected to exhibit transitions between characteristic phases: a liquid-gas phase transition, a confinement-deconfinement transition and a chiral transition between massive hadrons and almost massless quarks or even richer structure, specific for such interactions.

In most many-body systems the macroscopic conditions influence the microscopic properties. For strongly interacting systems such medium modifications are significant, and they appear on a much more fundamental level.

In practice, strongly interacting many-body physics has to be studied in systems, where the characteristic length and coherence scales are very small. The study of collective phenomena at such scale requires innovative approaches. The strong coupling allows for effective multiple interactions of particles even in small systems and on very short time scales, which makes collective behaviour an important characteristic of medium- and high-energy nuclear reactions. On the “macroscopic” level the properties of an interaction are reflected by the equation of state of the produced matter.

Understanding baryonic matter at low energy density constitutes a formidable challenge for strong interaction theory. A microscopic approach to the effective interaction acting among nucleons in the nuclear medium from Lattice QCD is still in its infancy. Therefore, considerable uncertainties still exist in the equation of state of nuclear matter (EoS), particularly concerning its behaviour as a function of the isospin asymmetry. Studies of dissipative collisions from light to heavy nuclei, on a energy range between the Coulomb repulsion up to the Fermi energy, revealed detailed information on the interplay between the collective phenomena and single nucleon-nucleon interactions and have shown the possibility to transfer the relative collision energy in the excitation energy of the colliding nuclei up to the limit of stability of the final system. Transition from a sequential emission to spontaneous break-up of the excited final nuclei was evidenced with increasing the collision energy. At low density and excitation energy of the order of the binding energy of a nucleus, a first order liquid-gas phase transition terminating in a second order critical point is predicted for neutral nuclear matter, believed to connect a homogeneous dense liquid phase with a phase of homogeneous diluted gas of neutrons and protons. It is by now understood that in the diluted disordered phase many-body correlations and clustering play an important role, thus opening perspectives for the understanding of systems where this phase transition occurs in nature, namely in the cores of type II supernovae and in the crust of neutron stars, whose properties can be closely linked to experiments investigating the liquid-gas phase transition in accelerator based heavy-ion collisions. At such low temperatures, quarks and gluons are confined inside color neutral hadrons whose mass is much larger than the sum of the bare masses of its constituents, due to the spontaneous breaking of a fundamental symmetry, the chiral symmetry. Such effects completely dominate the low-energy phenomenology of the strong interaction, and make the theoretical treatment extremely difficult. At high temperature, or at high net baryon density, the strong coupling decreases and the confining part of the interaction potential is expected to vanish, chiral symmetry should be re-established, which in turn should manifest itself as an observable modification of constituent masses. At very high temperatures, a transition to a system of free and massless quarks and gluons, coined as quark-gluon plasma (QGP), is expected. This state of matter should have existed in the very early universe, a few μs after the Big Bang, when temperatures were extremely high. The QGP phase transition is probably the only phase transition of the early universe that can be studied experimentally. The QGP should also exist in the core of dense neutron stars, where the net baryon density is very high. Detailed information on the corresponding equation of state would help understanding the behaviour of these astrophysical objects.

High-energy collisions also constitute a powerful tool to study the distribution of quarks and gluons (under one term partons) inside nucleons and nuclei. When viewed, through the ‘microscope lens’ afforded by nuclear collisions at the highest energy, nuclear matter is expected to reveal entirely new features reminiscent of those of glasses. The density of gluons inside nucleons is governed by a balance between two effects: 1) the splitting of gluons into two lower momentum gluons and 2) the recombination of low momentum gluons into a single high momentum gluon. The gluon density therefore is expected to saturate at a characteristic value and thus can be regarded as a state representing the classical field limit of the strong interactions.

In summary, the investigation of the phases of strongly interacting matter addresses some of the most important open questions of fundamental physics today. These include:

- What are the fundamental properties of matter interacting via the strong interaction as a function of temperature and density?
- What are the microscopic mechanisms responsible for the properties of high density strongly interacting matter?
- How do hadrons acquire mass?
- How is mass modified by the medium it moves in?
- What is the structure of nuclei when observed at the smallest scales, i.e. with the highest resolution?

We are now on the verge of a significant new revolution in the field, owing to the recent and future availability of very high energy nuclear beams at the LHC (at CERN) and very high intensity beams at FAIR (at GSI). These two central facilities, which are at the forefront of the European research arena, will pave the way to the exploration of completely unexplored regimes of the strong interaction. The new generation of powerful state of the art experiments will provide unprecedented resolving power. The LHC will provide an energy increase as compared to RHIC by a factor of almost 30. We note that in the past, each major boost in energy scale has invariably been accompanied by significant discoveries.

In the following sections the fundamental questions, which will be addressed in the coming years by theory and experiment will be discussed, based on a short review of some of the most salient accomplishments of the past years, obviously underlying those were the Romanian community in the field were or will be actively involved. The strategies necessary to ensure that the Romanian Nuclear Physics community will be able to play a role in this field at the international level will be underlined. In the final section we will summarize the prospects at reach and indicate the efforts that the community considers as priority.

5.2. The QCD Phase Diagram

The properties of nuclear matter at finite temperature T and net-baryon density (or chemical potential μ_B) are describable from the theory of strong interactions, QCD. The thermal properties and the equation of state (EoS) of nuclear matter are best quantified within Lattice QCD (LQCD), a numerical formulation of the theory on a space-time grid, through analytical methods can provide complementary insights. As it was shown in the previous paragraph, hot and dense nuclear matter could be explored experimentally through the study of collisions of heavy ions at ultra-relativistic energies.

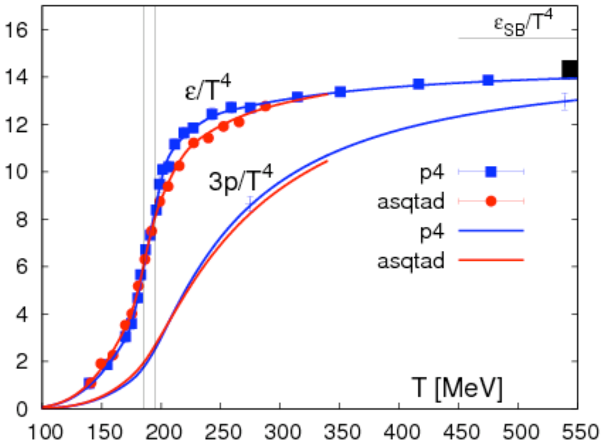


Figure 5.1 *Recent LQCD calculation showing the energy density and pressure of nuclear matter as a function of temperature. The calculations were performed in (2+1)-flavor QCD, i.e. they include effects of two light (u, d) quarks and one strange. The predicted QCD transition temperature is in the range 170-190 MeV. (Courtesy F. Karsch et al.)*

As could be seen in Fig. 5.1, the energy density increases rapidly in a narrow temperature interval, behaviour that generally is interpreted as being due to deconfinement, i.e. the liberation of quark and gluon degrees of freedom. The pressure also exhibits an increase at the deconfinement temperature, although a more gradual one, related to residual interactions between the constituents. Confinement is not the only phenomenon responsible for rapid changes in the thermodynamic state variables. The transition related to the breaking of chiral symmetry resulting in the dynamical generation of hadron masses and the appearance of pions as Goldstone bosons plays an essential role. The chiral transition is characterized by a rapid decrease of the quark-antiquark condensate with T and μ_B, which in fact plays the role of an order parameter of strongly interacting matter. Chiral partners must be degenerate implying significant modifications of hadronic spectral functions by the medium as the transition is approached. Schematic models and numerical studies with LQCD have been developed to quantify in-medium modification of physical observables due to the restoration of chiral symmetry. The chiral condensate has been shown in LQCD to drop rapidly over the same temperature interval where the energy density drops. This suggests that deconfinement and the restoration of approximate chiral symmetry in QCD may be coincidental. However, the exact relation between the deconfinement and chiral phase transition is quantitatively far from established in LQCD.

The origin of the masses of particles is one of the most fundamental questions that we may ask about Nature. The visible matter in our universe mainly consists of protons and neutrons, which have a mass of about 1 GeV/c^2 each. However, within the *Standard Model*, the elementary building blocks of protons and neutrons, the quarks and gluons, are massless. Gluons mediate the interaction between the quarks and have like the photons, no restmass. The quarks, on the other hand, should be massless due to a fundamental property of the strong force, chiral symmetry. In laboratory experiments on Earth, however, we observe non-zero (and very different) quark masses, See Fig. 5.2. In the *Standard Model*, quarks acquire mass through their interaction with an elementary field filling all space, the so-called Higgs field. The Higgs field breaks chiral symmetry explicitly, generating quark masses. The search for the Higgs particle is one of the main goals of the LHC experiments.

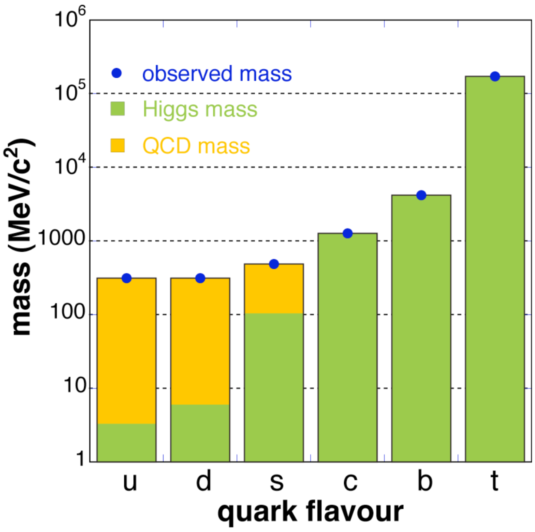


Figure 5.2

green bars – the masses of quarks explained by Higgs mechanism

yellow bars – the mass resulting from the interaction of light quarks with the condensate of quark-antiquark - chiral symmetry breaking

The Higgs mechanism is able to explain the masses of the heavy quarks (green bars in Fig.2). For the light quarks, which account for the mass of the matter surrounding us, the explicit symmetry breaking is very small, and the resulting small quark masses (5 – 10 MeV/c^2) are by far insufficient to explain the observed mass of hadrons (for example the proton mass of ≈ 1 GeV/c^2). In order to explain the mass of a hadron, the vacuum surrounding a quark or gluon inside the hadron must be filled with a strong field of quark-antiquark pairs, called the chiral condensate.

The interaction of the light quarks with this condensate breaks chiral symmetry spontaneously, and generates the large quark masses. Increasing of the temperature or baryon density of a system, for example through a high-energy nuclear collision, modifies the vacuum. The chiral condensate is diluted and chiral symmetry is partly restored, causing a modification (reduction) of the masses of hadrons. At very high density or temperature the spontaneous breaking of the symmetry should completely disappear and the condensate should vanish. This transition may in fact coincide with the deconfinement transition. The search for signatures of chiral symmetry restoration is of fundamental importance in physics and one central objective of high-energy heavy-ion collision experiments.

Experimentally, different regions of the QCD phase diagram can be probed in heavy ion collisions by varying the beam energy of the colliding nuclei. At very high energies, such as those that are reachable at RHIC and at the LHC, the region of small μ_B and large T is explored, for which reliable LQCD predictions are available. At lower energies, one probes the regime of high μ_B at moderate T, which can only be described with phenomenological models. The first principle LQCD studies and effective models, as well as heavy ion experiments, are essential to characterize the phase structure and the EoS of hot and dense nuclear matter.

A qualitative presentation of the QCD phase diagram can be followed in Fig.3. The experimental exploration of the phase diagram relies heavily on the applicability of thermodynamics to the system created in heavy-ion collisions. Once this is established, phenomenological studies of the bulk properties yield important information on thermal parameters relevant for this exploration. Three important observables to study global properties using hadron distributions in the final state have been established: particle correlations, particle yields, and particle spectra.

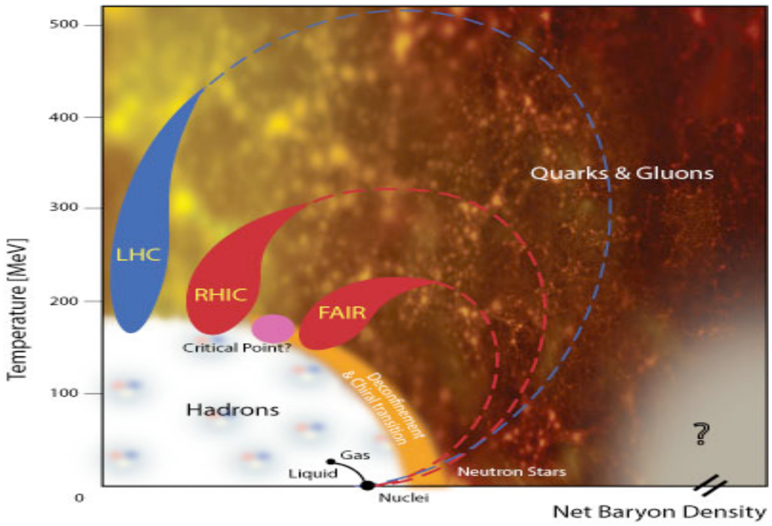


Figure 5.3. *Qualitative representation of the phases of strongly interaction matter*

5.3. Strongly interacting matter in the nucleonic regime

Dissipative Collisions

About four decades ago, with the advent of modern accelerators, capable to deliver heavy mass projectiles at larger energies, emerged a new branch of nuclear physics called “Heavy Ion Physics”. Studies of dissipative collisions from light to heavy nuclei, on an energy range between the Coulomb repulsion up to the Fermi energy, revealed detailed information on the interplay between the collective phenomena and single nucleon-nucleon interactions and have shown the possibility to transfer the relative collision energy into the excitation energy of the colliding nuclei up to the limit of stability of the final system. The impressive amount of experimental information collected by many research groups using accelerators and new generation of experimental devices all over the world and their theoretical interpretation consolidated our understanding on the energy transfer from the relative motion of the colliding ions to their internal excitation and on the details of the dynamics of formation and evolution of the transient system. It was shown that these process are very similar for different masses of colliding nuclei, from light ions up to the heaviest ones, the of energy transferred from the relative motion to the internal excitation of the transient system.

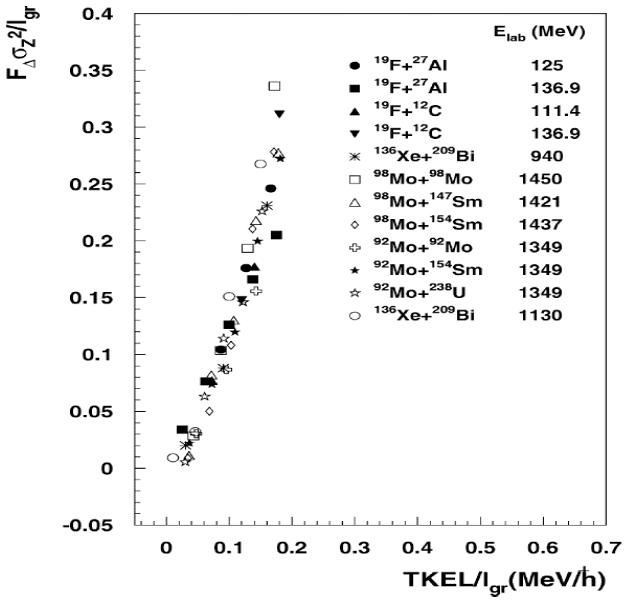


Figure 5.4

The variance of charge distribution of dissipative collision final fragments as a function of total energy transferred to the colliding system divided by the largest value of the angular momentum participating to the collision

Fig. 5.4 shows such a systematic in terms of variance of the charge distribution of the final products of two-body channel as a function of total kinetic energy loss divided by the grazing angular momentum.

This was the period when a coherent activity of developing versatile experimental devices based on advanced detection and identification systems, associated front end electronics, data acquisition architectures and dedicated computing resources was started by various research groups also in Romania. Fig. 5.5 shows such an experimental device designed and built by researchers from NIPNE and operated for many years at LNS-Catania in collaboration with Italian researchers of different branches of INFN.

Complete relaxation was reached in such collisions, corresponding to temperatures in the fragments of up to 5 MeV when the primary mass distributions tend to spread over the full range of mass asymmetries, indicating a loss of the initial target and projectile identity and hence the disappearance of an essential feature of the deep-inelastic process.

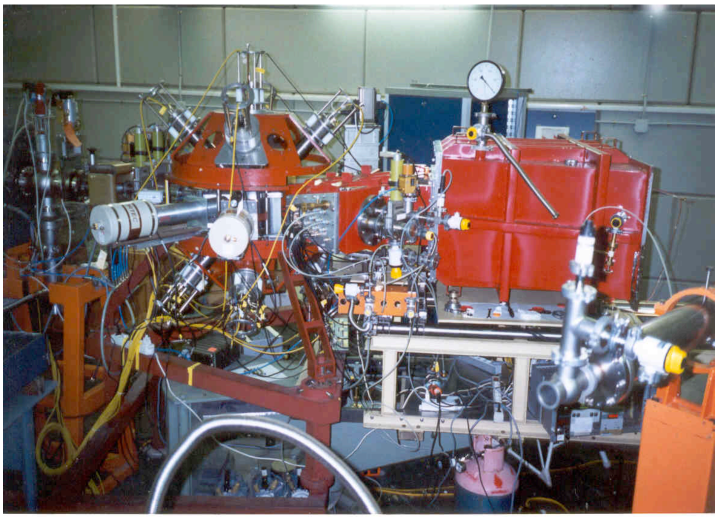


Figure 5.5

DRACULA device based on large area position sensitive ionization chambers, time of flight and hybrid detectors coupled to an array of NaI and Ge gamma detectors

Liquid-gas phase transition

Increasing the collision energy, a transition from a sequential emission to spontaneous break-up of the excited final nuclei was evidenced. This is the regime where, like boiling water, a nuclear liquid-gas phase transition is expected to take place. If this is the case, then the characteristic properties of the matter are expected to exhibit a sudden variation at the transition energy.

Theoretical calculations show that the size of the heaviest cluster A_{big} produced in such fragmentation process plays the role of an order parameter of which distribution shows a bimodal behaviour (doubly peaked) at the transition, the two peaks being interpreted as the two coexisting phases (see Fig. 5.6). The energy is represented in units of the coupling parameter ε. The jump in the excitation energy between the two phases corresponds to the latent heat of the transition.

Experimental results from different beam energies and experimental setups and data analysis techniques confirmed these expectations. Approximate values for the temperature, energy, and density of this phase change have been established. Studying the transition with finite nuclei has the extra advantage of revealing the thermodynamic anomalies, which should be associated with first order phase transitions of any finite system (negative heat capacity, bimodal distributions). A negative heat capacity from anomalously large kinetic energy fluctuations was observed in the past, but the signal has turned out to be inconclusive. This is mainly attributed to uncertainties connected to the evaluation of the effect of secondary decays. Very recently bimodal distributions of the order parameter have been measured for the Au+Au system using different experimental setups.

In the next-generation experiments, the onset of fragmentation will be established using the techniques that have been developed for stable beams. The change of the fragmentation threshold with the source charge and asymmetry will provide access to the charge and asymmetry dependence of level densities and limiting temperatures. Experiments exploring the asymmetry in a yet inaccessible region through the study of scaling violations of fragment observables may reveal new physics. The study of multi-fragmentation with exotic beams has important astrophysical consequences. Indeed, multi-fragmentation is a unique laboratory for the formation of inhomogeneous structures due to the interplay between nuclear and Coulomb effects. Such structures have to be correctly modelled for the supernova explosion process

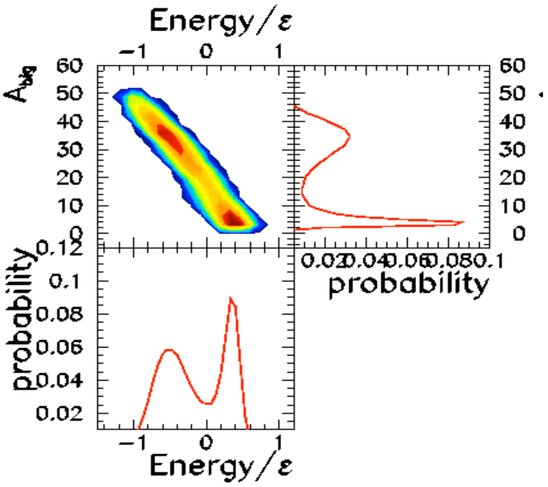


Figure 5.6

Probability distribution of A_{big} as a function of energy scaled to the coupling parameter ε

and the cooling dynamics of proto-neutron stars. Moreover, the electron capture rate on nuclei and/or free protons in pre-supernova explosions is especially sensitive to the symmetry energy at finite temperatures. This information can be extracted from isotopic ratios of light particles and fragments from carefully selected space-time emission regions. These regions will be separated using collective observables and imaging techniques, which are already currently developed in the field.

The comparison of data with different asymmetries and similar centrality will also allow to quantify the different isotopic composition of coexisting phases for isospin asymmetric systems, a phenomenon known as isospin fractionation. Up to now this has only been studied for stable systems. Fractionation is a generic feature of phase separation in multi-component systems. In particular, since an increased fractionation is expected, if fragmentation occurs out of equilibrium, a quantitative study of fractionation will elucidate the role of spinodal instabilities in the as yet unclear mechanism of fragment production.

At the theoretical level, extraordinary progress has been achieved in the past years connected to microscopic calculations for nuclear matter at sub-saturation densities, where correlations and clustering of nucleons into fragments dominate. The extension of these calculations to neutron rich systems will be available in the next few years and will need to be confronted with experimental data. New progress in the studies of dynamical non-relativistic transport theories will be essential for the interpretation of transport observables. Such calculations are required to quantitatively extract the EoS from experimental data. Microscopic transport model of Boltzmann-Nordheim-Vlasov (BNV) type will shed light on mechanisms like pre-equilibrium dipole mode, the competition between fusion and deep-inelastic, binary mechanism at low beam-energies and the effects of density dependence of symmetry energy around saturation using reactions with exotic nuclei**.**

Equation of State

A quantitative understanding of the properties of nuclear matter in the nucleonic regime requires a precise description of the effective interaction in nuclear matter. This is uniquely linked to the Equation of State (EoS). In particular, the determination of the incompressibility of symmetric nuclear matter close to saturation density (the density at which nucleons begin to touch) has been a longstanding challenge in the field.

The functional form of the EoS cannot be directly deduced from experiment. However, the different energy functionals can be implemented in transport equations and converted to transport model predictions that can be measured in nucleus-nucleus collisions. The combined measurements of collective flow of K^+ mesons, protons and light fragments in the energy range of about 0.05 – 1.5 A GeV, have now constrained the incompressibility modulus at saturation, $\rho_0 \approx 0.17$ fm^{-3}, to values of K = 170 - 250 MeV. The transport calculations used to interpret the data need to involve momentum-dependent interactions as well as in-medium potentials to properly describe the data. The incompressibility at higher density is still very poorly known and needs to be addressed in future experiments at relativistic energies, where degrees of freedom different from protons and neutrons become important.

Most of the investigations have been concentrated initially on the incompressibility of the symmetric nuclear matter EoS, neglecting the isovector dependence, i.e. the dependence on the difference between neutron and proton densities. This symmetry energy plays a critical role in neutron stars where it is responsible for most of the pressure supporting the star at densities less than twice the saturation density. It has implications for the density profile of neutron stars, the mass boundary between neutron stars and black holes, and neutron star cooling. Predictions for the total energy released during a type II supernova collapse and its time dependence are also strongly influenced by the symmetry term. Last but not least, the symmetry energy plays a key role in the dynamics of heavy ion collisions, the process used to produce new forms of matter in the laboratory. Thus, the determination of symmetry energy from low to high densities is a strong motivation for significant experimental and theoretical efforts. Due to the dominance of many body correlations and clustering at low density, the behaviour of the symmetry energy below nuclear matter saturation cannot be extrapolated from the theory or experimental data for normal nuclear matter. It is therefore essential to extract information on this quantity from experiments where clusters are actually formed, namely in multi-fragmentation reactions which, according to transport calculations, typically explore a density domain between one third of saturation and saturation. Almost no experimental information is available for the symmetry energy at super-saturation densities. Several observables in collisions between isospin asymmetric nuclei sensitive to the symmetry energy have been identified by dedicated transport calculations, including neutron and proton collective flow, ratios of neutron/proton, π^+/π^-, K^+/K^- and Σ^-/Σ^+. Information on the density dependence of the symmetry energy in this regime is one of the challenging tasks for future experiments at relativistic energies.

The difference in the effective mass of protons and neutrons is intimately connected to the momentum dependence of the EoS. Predictions for this quantity differ widely in different theoretical approaches, even at normal density. Experimental constraints on the mass splitting provide important input for nuclear structure, and for the structure of neutron star crusts. The difference between the effective masses determines the kinetic observables established in the entrance channel, i.e. the transverse momentum distributions of pre-equilibrium particles and collective flow.

5.4. Hadronic Matter

Hadron Correlations

Strong evidence for collective expansion in heavy ion collisions is derived from the observation of the anisotropy in particle momentum distributions correlated with the reaction plane. One of the most striking manifestations of anisotropic flow and strong collective expansion is the so-called elliptic flow, evidenced in mid-central heavy ion collisions. The strength of this elliptic flow is characterized by the second Fourier coefficient (v_2) of the azimuthal momentum-space anisotropy.

Detailed analysis of the collective expansion azimuthal distributions at mid-rapidity, different impact parameters and incident energies was done at SIS energies by FOPI Collaboration using a versatile experimental device presented in Fig.5.7.

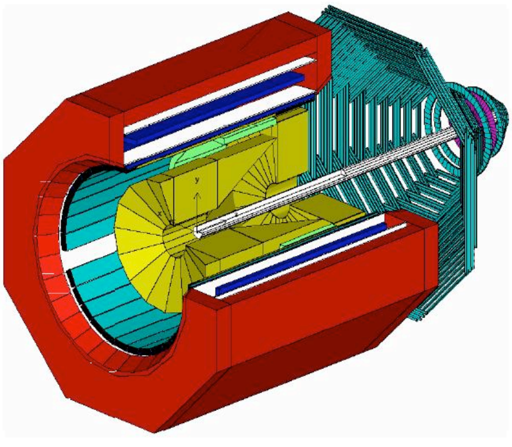


Figure 5.7

FOPI experiment at SIS - GSI

The experimental azimuthal distribution of collective expansion is characterized by

$$E_{coll} = E^0_{coll} - \Delta E_{coll} \cdot \cos 2\varphi.$$

The extracted E^0_{coll} and ΔE_{coll} for different collision geometries expressed by the number of participating nucleons to the collision – A_{part} can be followed in Fig.8. Transport model calculations based on BUU code, using momentum dependent mean fields (m□/m=0.79), in-medium elastic cross-sections and soft (K=210 MeV, gray zone) or stiff (K=380 MeV, dashed zone) EoS are compared in Fig. 5.8 with the experimental results.

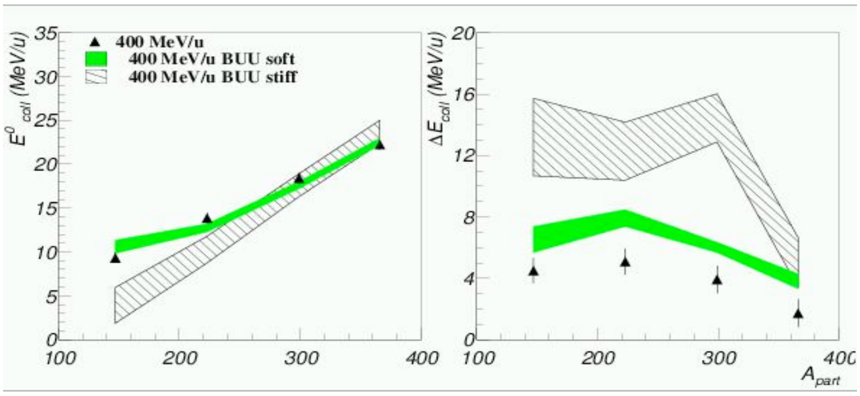


Figure 5.8 *E^0_{kin} and ΔE_{kin} as a function of Apart, for Z=1 (A=1,2,3) fragments, Au+Au at 400 A·MeV. The experimental results are represented by triangles, while the BUU results are represented by gray zones for soft EoS and by dashed zones for stiff EoS, respectively.*

One should mention that the light fragments (up to A=3) are produced in a few-nucleon processes inverse to composite break-up, relative to the general coalescence recipe used by microscopic transport codes. The calculations with the soft EoS reproduce the overall trends of the experiment while the calculations with the stiff EoS overestimate significantly the ΔEcoll values at lower centralities, respectively. These results support the conclusion that the equation of state of baryonic matter at densities of about two times normal density ($2\rho_0$) and temperatures of about 50-70MeV is soft. This conclusion seems to be also supported by kaon production in heavy ion collisions as it was shown by KAOS Collaboration.

Figure 5.9 shows the measured dependence of v_2 extracted from azimuthal distribution of the corresponding particles on the center-of-mass energy. At low energies (E_{CM} < 1.5 GeV) v_2 is positive reflecting the angular momentum conservation of di-nuclear systems, which leads to a preferential in-plane emission.

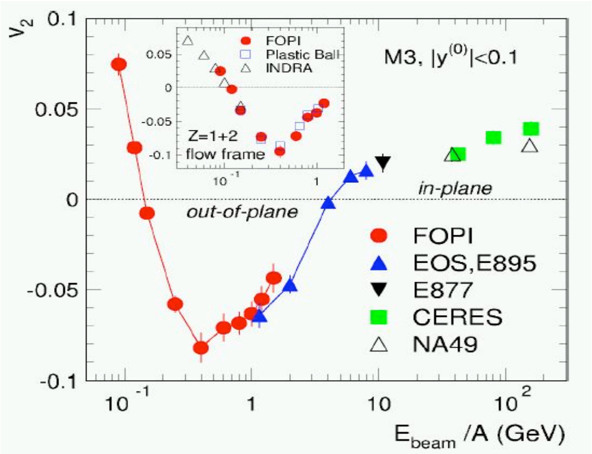


Figure 5.9

Elliptic flow v_2 at mid-rapidity and integrated over transverse momentum.

With increasing energy the sign changes to negative and v_2 reaches its lowest value at energy of about 2 GeV reflecting particle emission from the strongly compressed matter in the center of the collision that is shadowed by the passing spectator nucleons. This causes the produced particles to emerge perpendicularly to the reaction plane leading to a negative value of v_2 (squeeze-out). At these energies the elliptic flow is very sensitive to the nuclear compressibility, i.e. the EoS.

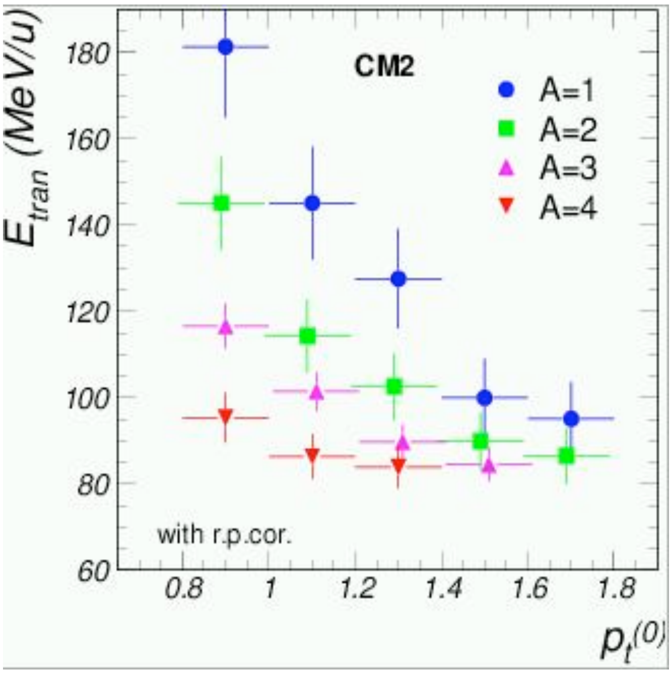


Figure 5.10

The collision energies – E_{tran} at which the azimuthal distributions in mid-central heavy ion collisions changes from in-plane, rotational like to out-of-plane, squeeze-out type as a function of of transverse momenta of the corresponding emitted particles

The collision energies – E_{tran} at which the azimuthal distributions in mid-central heavy ion collisions changes from in-plane, rotational like to out-of-plane, squeeze-out type as a function of transverse momenta of the corresponding emitted particles can be followed in Fig.5.10.

Above 2 GeV collision energy v_2 rises and becomes positive again. At AGS, SPS, and RHIC energies the timescale for spectator nucleons to pass the created hot and dense system becomes much shorter than the characteristic time for the build-up of the transverse flow. At these energies the elliptic flow becomes in plane again (positive v_2). The magnitude of v_2, above (E_{CM} = 10 GeV) is directly proportional to the initial spatial anisotropy and the interactions among the constituents. The large elliptic flow observed indicates a high level of equilibration at a relatively early stage of the collision. Comparison of RHIC data to hydrodynamical models suggests that equilibration occurs early in the collision history.

Hadron Yields

Integrated yields of different hadrons provide information on the medium properties. A detailed analysis of heavy ion data from SIS(GSI) to RHIC(BNL) energies has shown that relative yields of most hadrons can be described with statistical hadronization models using only two global parameters: the chemical freeze-out temperature and the baryon-chemical potential. While this observation is striking, it is only necessary but not sufficient evidence for the thermal origin of particle production. However, the indication of early equilibration from elliptic flow measurements makes a thermal description the most plausible one, in particular at high energies beyond SPS. However, measured yields at lower energies are also consistent with a thermal picture. Recently, it was conjectured that the above features of hadron production observed in nuclear collisions can be explained by the existence of three forms of matter: Hadronic Matter, Quarkyonic Matter, and a Quark-Gluon Plasma which meet at a "triple point" in the QCD phase diagram located at the center of mass energy near 10 GeV.

Hadron Spectra

Hadron spectra provide complementary information on the medium evolution. The shape of the spectra of most hadrons at low transverse momentum is consistent with thermal emission of a collectively expanding source. While the shape alone does not demand a thermal description, the evidence from elliptic flow and the consistency with the hadron abundances make an interpretation of spectra in terms of models inspired by hydrodynamics meaningful. The particle yield as a function of transverse momentum reveals the properties of the system at the kinetic freeze-out, where interactions of hadrons cease. In the simplified version of such models hadron spectra can be effectively characterized by two parameters: the kinetic freeze-out temperature T_k and the average transverse flow velocity v_t.

A detailed analysis of particle spectra in heavy ion collisions has shown that at a given collision energy there is a common set of parameters (T_k, v_t), which describes measured low-momentum spectra of most hadrons simultaneously. The parameters indicate collective radial expansion, which increases with the collision energy. Deviations from this behaviour, which are observed for particular hadron species at some collision energies, can be explained by e.g. smaller hadronic cross sections or in-medium modifications.

A detailed analysis of azimuthally isotropic expansion in highly central collisions for three symmetric systems (Au+Au, Xe + CsI, Ni + Ni), different incident energies and two regions of polar angles in the centre of mass system was performed by FOPI Collaboration. The results are presented in Fig.5.11. While in the forward polar region, $25^\circ \leq \vartheta_{cm} \leq 45^\circ$, all three systems show the same flow at all measured energies, along the transverse direction and mid-rapidity, i.e. $80^\circ \leq \vartheta_{cm} \leq 100^\circ$, the collective expansion is lower, its dependence on the incident energy is not that steep and at the same incident energy the collective expansion increases with the mass of the colliding system. Calculations based on IQMD model at 250 A·MeV showed that the nucleons emitted at 90° suffer in the average 3.5 collisions relative to 1.7 of those emitted at smaller polar angles. This tells that at 90° the observed effect is most probably coming from an equilibrated fireball, while at forward angles the Corona effects, transparency and uncertainty in impact parameter selection play an important role. The experimental results support the microscopic transport model predictions, IQMD and BNV, based on soft equation of state.

While these trends were qualitatively reproduced by the QMD microscopic transport model, the absolute value of mean kinetic energy per nucleon is systematically underestimated for all fragments. The experimental values were reproduced rather well by a hybrid model based on hydrodynamical expansion coupled with a statistical fragmentation at the break-up moment.

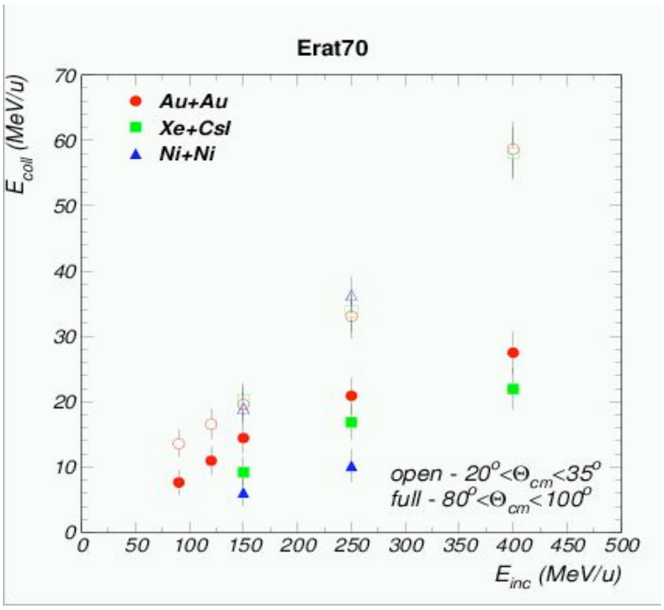


Figure 5.11

Collective energy, E_{coll}, as a function of incident energies in highly central Au+Au, Xe+CsI and Ni+Ni collisions. Open symbols $25^{\circ} \leq \vartheta cm \leq 45^{\circ}$, full symbols $80^{\circ} \leq \vartheta cm \leq 100^{\circ}$.

This supports the model prediction that different species originate with different probabilities as a function of position within the fireball and time, heavier fragments being emitted later, at lower temperature and lower expansion. This was confirmed in the meantime by small angle correlations studies for pairs of nonidentical reaction species.

The three observables together sketch a consistent picture of the dynamics of the matter created in heavy ion collisions describing the low-momentum properties of hadron distributions. In heavy ion collisions at very high energies the created system exhibits equilibrium features, which are already established in the very early stage. It attains a collective expansion velocity driven by pressure with anisotropies of the initial state being reflected in the measured particle momentum distributions. The system undergoes first chemical and then kinetic freeze-out, which appears at a lower temperature due to a larger elastic cross section of hadrons. At the SPS and higher energies the chemical freeze-out happens near the QCD phase boundary suggesting, that particles originate from a hadronizing QGP.

5.5 Exploring the QCD phase diagram at large baryon-chemical potentials

One of the goals of future heavy-ion collision experiments at relativistic beam energies is the precise scanning of the QCD phase diagram in the region of high net-baryon densities.
Such experiments address fundamental physics questions: What are the properties of very dense nuclear matter? Is there a first order phase transition between hadronic and partonic matter? Is there a critical or a triple point, and, if yes, where are these points located? Is there a chiral phase transition, and, if yes, does it coincide with the deconfinement phase transition? Are there new QCD phases such as "quarkyonic" matter?
As mentioned in the previous chapter, the observation of a limiting chemical freeze-out temperature of about 160MeV indicates a change in the degrees-of-freedom of the fireball. Such temperatures may be reached using heavy ion collisions at about 30 AGeV on fixed targets. At the same energy, maxima in the excitation functions of the ratio of strange-to-nonstrange particles have been found. This observation has been interpreted as a signature

for a transition from baryon to meson dominated matter, but is still controversial. In particular, the strangeness-to-entropy ratio measured by NA49 at SPS energies exhibits a sharp structure, which cannot be described by hadronic models. This disagreement between theoretical estimates and data has triggered speculations about the possible onset of deconfinement already at low SPS energies.

A careful beam energy scan will be required to discover structures possibly caused by the deconfinement phase transition and/or the critical endpoint in the QCD phase diagram. In order to obtain a consistent picture one has to investigate a comprehensive set of observables, and search for a non-monotonous behavior in their excitation functions. The challenge is to identify signatures of the partonic phase, which survive hadronization. It is obvious that those observables which are generated in the early phase of the collision, and which are not distorted by final-state interactions during the evolution of the fireball, are the most promising candidates in this respect. These observables will be discussed in the following.

Collective Flow

One of the observables, which is sensitive to the initial (anisotropic) fireball shape in coordinate space, as it was mentioned already in the previous chapter, is elliptic flow. A central question is, whether the hadron elliptic flow, although expected to be significantly smaller in magnitude than at RHIC energies, will show features similar to those found at high energy. In particular, whether, the flow scales with the number of constituents quarks, thereby suggesting that the effect originates already in the partonic phase. Will this scaling feature disappear below certain beam energy? The answer to this question requires beam energy scan of the elliptic flow of pions, kaons, phi-mesons, D-mesons, charmonium, as well as of nucleons, and (multi-) strange hyperons (including the antiparticles). The experimental challenge will be to measure all these particles up to high transverse momenta.

Particles with low hadronic cross sections like Φ mesons, Ω hyperons, and J/Ψ mesons are expected to be particularly sensitive probes of the partonic phase. Indeed, in Pb+Pb collisions at 158 A GeV the inverse slope parameter (or effective temperature) of Φ, Ω, and J/Ψ and Ψ' is found to be

T_{eff} =200–250 MeV which is significantly lower than T_{eff} for protons or Lambdas. This observation indicates that Φ, Ω, and J/Ψ and Ψ' pick up less radial flow, and their T_{eff} values are dominated by the temperature of an earlier phase of the system evolution. A similar observation was made for lepton pairs. The inverse slope parameters T_{eff} of the dimuon transverse momentum spectra measured in In+In collisions at 158 A GeV increases with invariant mass of the muon pair up to 1 GeV/c^2, and then drop and stay constant for heavier masses. A possible interpretation of this effect is the following: the low mass muon pairs are created via π-π collisions and, hence, are blue-shifted by the collective radial motion of hadrons, whereas the heavy muon pairs are created via q-q fusion in the partonic phase.

Charm production and absorption

Heavy charm quarks are very promising diagnostic probes of hot and dense nuclear matter. The (c,c-bar) pairs are created in hard parton collisions in the initial stage of the nucleus-nucleus reaction, and subsequently propagate through the dense medium. If this medium is deconfined, Debye screening hinders the formation of the charmonium hadronic state, and the charm quarks mostly combine with light quarks into hadrons with open charm. A suppression of the J/Ψ yield relative to muon pairs from Drell-Yan processes was observed by the NA50 collaboration for central Pb+Pb collisions at 158 A GeV. However, absorption of J/Ψ in cold nuclear matter also leads to significant charmonium suppression, which is able to explain most of the experimentally observed effect. Beyond this cold nuclear matter effect, an 'anomalous' suppression of J/Ψ mesons by about 25% is still visible in very central Pb+Pb collisions. In establishing this result, knowledge about the J/Ψ absorption cross section obtained from measurements in p+A collisions has been essential. In order to disentangle charmonium absorption in cold nuclear matter and shadowing effects from charmonium dissociation due to Debye screening in partonic matter, high-precision multi-differential data on charmonium and open charm production in nucleus-nucleus and proton-nucleus collisions are needed. The suppression of charmonium can be ideally studied by normalising the yield of J/Ψ and Ψ' mesons to that for charmed mesons. However, no measurement of D mesons has been performed in heavy ion collisions at SPS energies up to date. Future experiments will have to perform comprehensive and systematic measurements of open and hidden charm in order to fully exploit the potential of charm as a diagnostic probe of dense baryonic matter.

Critical fluctuations

The presence of a phase transition is associated with a rapid change (with temperature and chemical potentials) of the thermodynamic susceptibilities, which reflect the fluctuations of the active degree of freedom of the system. The well-known phenomenon of critical opalescence is a result of fluctuations at all length scales due to a second order phase transition. First order transitions, on the other hand, give rise to bubble formation, i.e., large density fluctuations. Therefore, an experimental search for a possible critical point and for a first order phase coexistence region in the QCD phase diagram has to include the measurement of particle number or momentum fluctuations event by event and correlations in heavy ion collisions as function of beam energy. Fluctuations of higher-order moments of particle distributions are expected to be particularly sensitive to the correlation length, which should fluctuate at the critical point. Experiments at top SPS and RHIC energies so far did not find indications for non-statistical fluctuations, except for the measured kaon-to-pion ratio at low SPS energies. Future progress in the search for the critical point and a first order phase transition requires a careful beam energy scan in the region of low SPS/FAIR energies together with a systematic measurement of fluctuations of various observables event by event.

Hadron properties in dense matter

One of the most important goals of heavy ion collision experiments is to search for signatures of chiral symmetry restoration, which is expected to happen at very high baryon densities and/or temperatures. An observable consequence of chiral symmetry restoration would be a modification of hadron properties, as nuclear matter approaches the phase boundary. Indications for in-medium hadron modifications have been found for kaons and for vector mesons. The yields and anisotropic flow of charged kaons show strong effects of in-medium modifications in heavy ion collisions at threshold beam energies as measured by KaoS, FOPI and recently by HADES. The measured results can be described under the assumption of a repulsive potential between K^+ mesons and nucleons, and an attractive potential between K^- mesons and nucleons. This is in qualitative agreement with calculations based on the Chiral Lagrangian. The necessary detailed transport calculations, which need to include, e.g., off-shell dynamics, are only in a preliminary state and are not yet able to achieve satisfactory agreement with the experimental data. From the current investigations it is apparent that these modifications do not allow a direct conclusion on chiral symmetry restoration. Nevertheless, it is a theoretical challenge to systematically explore chiral symmetry in nuclear many-body systems with kaons. Dilepton decays provide direct access to the properties of light vector mesons in dense and/or hot nuclear matter. In heavy ion collisions at the SPS, CERES and NA60 found a significantly enhanced yield of lepton pairs in the invariant mass range between 200 and 700 MeV/c2. The excess yield is defined relative to dimuon yields from known hadronic decays, including the ω and the φ meson. According to microscopic calculations, the excess dilepton yield is dominated by π-π annihilation, which proceeds through the ρ vector meson due to vector dominance. The shape and the magnitude of the excess can be explained assuming that the ρ-meson mass distribution is substantially broadened. The calculations indicate that the coupling to baryonic resonances plays a crucial role. A central objective of dilepton measurements is to find signatures of chiral symmetry restoration in the quark-hadron transition. To this end a connection between observables and chiral order parameters must be established.

According to the calculations, the vector spectral function, which is dominated by the ρ-meson at invariant masses below 1 GeV, broadens to such an extent that it smoothly goes over to the quark rate in the plasma phase. Since chiral symmetry is restored in this phase the broadening of the ρ-meson could be viewed as a consequence of chiral symmetry restoration. A more direct measure of chiral symmetry restoration is the degeneracy of the vector and axial vector spectral functions. An important step forward would be the systematic derivation of both in-medium vector and axial vector spectral functions based on the Chiral Lagrangian, together with accurate dilepton measurements to constrain the vector channel.

The SIS-100 accelerator at FAIR (see Fig. 5.12) will deliver heavy ion beams with energies up to 14 A GeV to CBM experimental setups (Fig. 5.13).

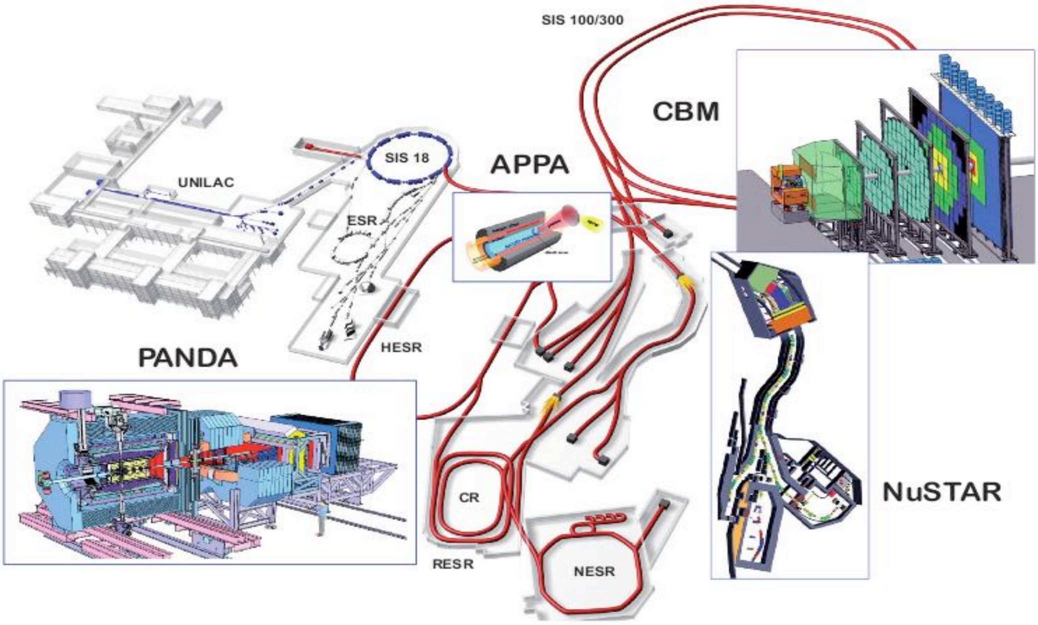


Figure 5.12

This energy range is ideally suited to produce and to investigate net baryon densities as they exist in the cores of neutron stars. For the first time, penetrating probes like dileptons and multi-strange particles such as Ω-hyperons will be used to study systematically the properties of baryonic matter in this beam energy range. The 30 GeV proton beams from SIS-100 will allow pioneering measurements to be performed on (open) charm production at threshold energies, as well as the detailed study of charm propagation in cold nuclear matter.

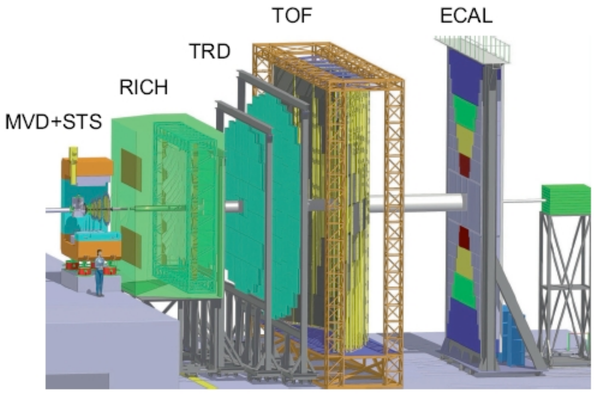


Figure 5.13

The SIS-300 accelerator will deliver high-intensity heavy ion beams with energies up to 45 A GeV to the high-rate CBM experiment providing excellent conditions for the investigation of the QCD phase diagram at large baryon-chemical potentials.

5.6. The High-Energy Frontier

The higher centre-of-mass energies becoming recently available at LHC at CERN, provide new opportunities for studying ultra-dense region of the QCD phase diagram well above the QGP transition temperature. New results are expected in the following subjects:

Collective phenomena above the QGP transition

Based on the experimental and theoretical results at lower incident energies, at higher centre-of-mass energy in proton-proton and nucleus-nucleus collisions, the initial phase of the the matter produced is expected to be denser, to equilibrate faster and at a higher initial temperature, characterized by a larger volume of space-time. All these are premises for development of collective phenomena and therefore a tool to study macroscopic properties of hot and dense QCD matter.

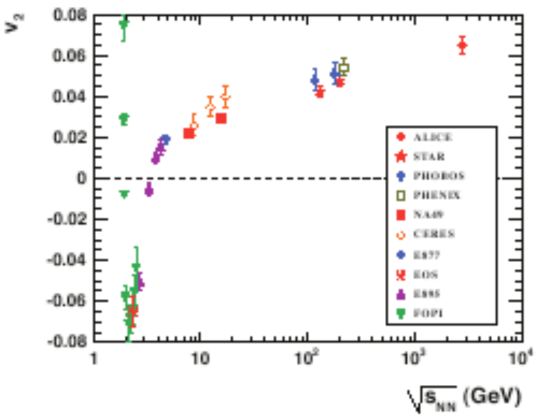


Figure 5.14
Integrated elliptic fow at 2.76 TeV in Pb-Pb 20%-30% centrality class compared with results from lower energies taken at similar centralities.

Access to hard probes of dense matter

At such energy the high momentum transfers, called "hard probes", lead to the production of jets quarkonia and high transverse momentum hadrons with much larger cross-section. Such probes could be used as tomographic tools for a detailed diagnosis of dense QCD matter.

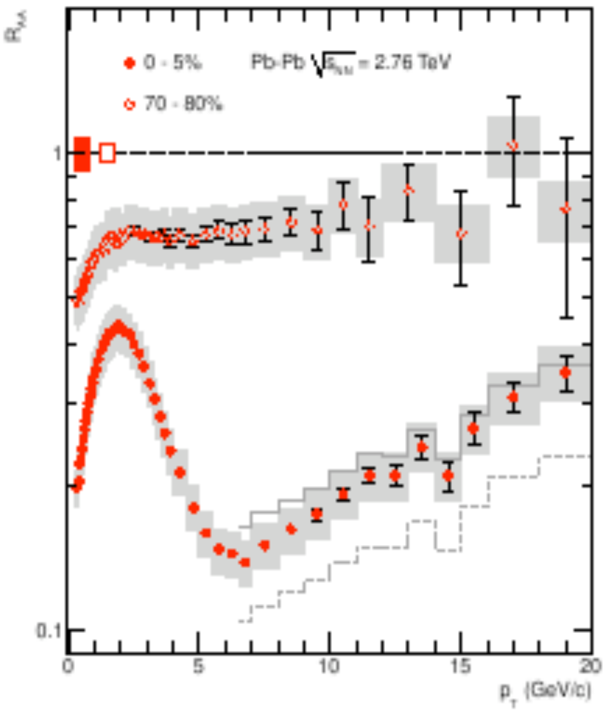


Figure 5.15
R_{AA} in central (0–5%) and peripheral (70–80%) Pb–Pb collisions at $\sqrt{s}$ = 2.76 TeV. Error bars indicate the statistical uncertainties. The boxes contain the systematic errors in the data and the p_T dependent systematic errors on the pp reference, added in quadrature. The histograms indicate, for central collisions only, the result for R_{AA} at $p_T > 6.5$ GeV/c using alternative pp references obtained by the use of the ppbar measurement at $\sqrt{s}$ = 1.96 TeV in the interpolation procedure (solid) and by applying NLO scaling to the pp data at 0.9TeV (dashed) The vertical bars around R_{AA} = 1 show the p_T independent uncertainty on Ncoll.

Saturated initial conditions

The structure of the colliding nuclei is essential for understanding the initial conditions from which hot QCD matter is produced in heavy ion collisions. At ultra-relativistic energies, bulk hadron production is dominated by nuclear parton distributions at very small momentum fractions x. These distributions can be studied in proton-nucleus collisions at high energies. They are expected to be sensitive to a qualitatively new state of cold QCD, maximally saturated.

Detailed studies of p + p and heavy ion collisions at the LHC will determine detailed characterises of QCD matter at high-temperature phase. Calculations of lattice-regularised QCD provide indications that characteristic properties of the QCD high-temperature phase, such as its interaction or its bulk viscosity, undergo qualitative changes if the temperature is raised well above the QGP transition. These changes are regarded as signalling the onset of a transition of the quark gluon plasma to more and more gas-like properties at higher temperatures.
LHC experiments (see ALICE experiment in Fig. 5.16) are well set to constrain our understanding of QCD thermodynamics and transport theory in the QCD high temperature

phase. Within the LHC baseline programme of p+p and Pb+Pb collisions, this includes the measurement of abundances, spectra and collective flow in terms of their dependence on particle species, transverse momentum, rapidity, collision centrality, etc. It is necessary to better constrain the initial conditions of the collective phenomena, since they are currently a major source of uncertainty in determining properties of hot matter. Experimentally this will be achieved studying proton-nucleus collisions, which provide an opportunity for identifying separated from that of a complex collective expansion. The dependence of collective flow on the centre-of-mass energy of the collision allows scanning the dependence of properties of matter on the initial temperature and density attained in the collision.

Figure 5.16

In the same time one should emphasise the important role of nuclear theory in analysing the vast amount of data on soft and hard probes at hadron colliders. In these studies, nuclear theory faces the challenge to interface a highly sophisticated and experimentally tested understanding of hard QCD processes in the vacuum with an a priori unknown interaction of these processes with the QCD plasma, into which they will be embedded for the first time. The role of theory is not limited to providing firm first-principle calculations of the sensitivity of hard probes to QCD thermodynamic and transport properties. It also includes the development and further improvement of complex phenomenological modelling tools, which are indispensable for relating measured medium modifications of hard processes to characteristic the properties of new forms of QCD matter. It starts to include essential theoretical contributions to data analysis techniques. Definitely an improved interplay between experiment and theory is mandatory.

Saturated gluon matter

The knowledge of the density of quarks and gluons (partons in general) in a proton or a nucleus is crucial information for the understanding of high-energy scattering. While the parton distribution functions (PDFs) are relatively well known for the proton, nuclei cannot be treated as simple superpositions of protons and neutrons. Their PDFs are subject to large uncertainties in kinematic regions of interest to current experiments. Even more interestingly, the parton density seen in a proton or nucleus is known to increase at large momentum transfer Q2 (i.e., high spatial resolution) when the momentum fraction x they carry decreases. At low parton density, this density increase is linear and can successfully be described within perturbative QCD. This increase cannot, however, continue indefinitely. At some point the large number density of gluons would violate fundamental unitarity bounds and, in fact, for large densities non-linear effects, become important and compensate the increase with a corresponding decrease due to gluon fusion processes. This balance of creation and annihilation leads to the so-called gluon saturation. Gluon saturation is a small x phenomenon that sets in below a certain characteristic scale in Q, the saturation scale Qs. This scale, and with it the momentum range where this matter is visible, increases with decreasing parton momentum fraction x. Saturation effects are generic phenomena of all hadrons, including protons and nuclei; however, due to the higher gluon numbers in nuclei they are enhanced by a factor $A^{1/3}$, and so is the saturation scale. The experimentally accessible saturatio region increases substantially with centre-of-mass energy. Investigations of this state will enter a completely new, as yet unexplored regime of quantum field theory. It also plays an important role in defining the initial conditions for any high-energy hadronic interaction. Its investigation will have far-reaching consequences in high-energy physics. Saturated gluon matter reveals itself through a modification of the momentum distributions of gluons and a change from a collection of incoherent gluons to a coherent state. It is expected that the first important information about the saturation region can be obtained from proton-nucleus collisions at the LHC. These studies will significantly reduce uncertainties in the nuclear PDFs. In addition, p-A collisions are unique for the study of strong interaction effects of the initial state, e.g., multiple scattering. It is therefore vital to establish a proton-nucleus collisions programme at the LHC. Traditionally, in high-energy physics, hadron accelerators pave the way to discoveries while the electromagnetic probes provide precision tools. Therefore, in the long-term perspective, electron-proton and electron-ion collision data will be indispensable for a precise and unambiguous characterisation of the small-x structure of nuclear matter and the saturation regime. The currently available data from e+p scattering at HERA have been shown to be consistent with the gluon saturation picture, but can also be explained by linear evolution. Stronger signals of gluon saturation from DIS will require e+p or e+A collisions at still higher energy compared to HERA. A future high-energy hadron-electron-collider (LHeC), as currently being discussed as a future project at CERN, would be designed to penetrate deeply into the saturated region, thus providing a unique opportunity for determining the saturation scale and characterizing the properties of the saturation region.

5.7. R&D - new generation of detectors, front-end electronics, DAQ

Forefront experiments in nuclear physics in general require innovative instrumentation.
Therefore, better performing accelerators, detectors, data acquisition and the associated highly sophisticated electronics are of continuous demand.
Next generation particle detectors have to be operated at extremely high counting rates and track densities. At the same time, these detectors have to provide excellent time and position resolution, as well as a low material budget to reduce multiple scattering and background. Evolving detector technologies with a rich R&D program include advanced diamond detectors, frontier photon detectors based on nanotechnology, inorganic scintillation fibers, or on silicon photo multipliers, large-area low-mass gas counters, fast compact Cherenkov counters for particle identification, ultra-light and large-area tracking systems based on GEM or Micromegas technology, ultra-light tracking and high-resolution vertex detection systems based on silicon sensors. The future CBM experiment at FAIR will be confronted with the selection of rare probes in high multiplicity environment at collision rates of up to 10^7 events/sec. Therefore fast, large granularity and radiation hard

detectors for electron as well as hadron identification, high resolution secondary vertex determination and a high speed event-selection and data acquisition system have to be developed. The ongoing R&D activities along these lines have to be continued in order to exploit the high intensity beams envisaged at the future FAIR facility by the CBM experiment.

At the same time, the ALICE upgrade program will enhance the present discovery potential and make use of the high luminosity of LHC. Recent developments in integrated circuits technology and advances in computing and networking power significantly improved the performance of all experiments in nuclear physics. Field-programmable gate arrays, including more than one million logic gates, are used in fast trigger-, pattern recognition-, real-time tracking and position-determination circuits and event builders. Upgrades of present experimental devices and design of future ones will take advantage of these developments and advances in fast digitizers. Optical fibere and transceiver performance, with transfer rates of 5–10 Gbits/s/link is now available off-the-shelf. Therefore, event building and recording rates of up to 1 Gbytes/s is at reach. The resulting datasets of petabyte scale, their storage and analysis are challenges addressed by developments in distributed computing and GRID technology.

5.8. Computing requirements

The complexity of the experimental devices and physics programs of high-energy nuclear physics has already reached the level typical for particle physics experiments. The new generation nuclear physics experiments will exceed HEP experiments in terms of computing requirements, both CPU power and data volume. The need for a solid computing framework and an efficient grid infrastructure is no longer a nicety. Initiated more than a decade ago in Romania by our community, the present Romanian GRID computing infrastructures play an important role in the Worldwide LHC Computing Grid – CERN and show to be an essential need to access the huge experimental information delivered by the large experiments at CERN in which Romania is involved and the necessary computing power and massive data storage needed for calibration and analysis for achieving physics results.

The GRID has demonstrated its potential to distribute computing resources in a coherent fashion, and the ALICE Grid implementation is one of the most efficient such structure within the Worldwide LHC Computing Grid. In view of this, a joint venture between nuclear and particle physics communities will be beneficial to both programs, LHC experiments offer a very good starting point in this direction.

For thermodynamics calculations, with moderate demand on computer memory and communication, high-end graphic cards (GPUs) promise to be a powerful alternative to massively parallel architectures. Similar strategies are followed for next generation of high level trigger architectures foreseen to be used for FAIR or high luminosity LHC experiments, where rare events of interest have to be selected on line in a collision rate environment up to 10^9 times higher. Interpretation of the experimental results in terms of fundamental properties of matter requires sophisticated modeling of the collision dynamics based in principle on three –dimensional viscous relativistic dynamics followed by hadronic Boltzmann transport processes. Such large-scale calculations can be efficiently performed on computing infrastructures of GRID type.

5.9. Network of Excellence

When the nuclear physics community embarked on relativistic and ultra-relativistic heavy ion collisions, R&D activities were started at the European level. Over the years, the community has coherently built up a real network of excellence of infrastructures and expertise across Europe. This network had a major impact on the development of high performance detection and identification methods, associated front-end electronics, building important parts of large scale experiments, structuring distributed computing centers as part of large scale GRID infrastructures and physics programs of the associated international collaborations. This unique achievement has to be consolidated at the national level such to secure our contribution for running the experiments, for fully exploiting their physics potential as well as for the preparation and construction future experimental facilities., all these within the large international infrastructures to which Romania is member, i.e. CERN - Geneva and FAIR – Darmstadt. In this respect it is highly desired to initiate and develop an efficient network of excellence at the national level based on visible and competitive research groups of different national institutes and universities, allover the country structured along scientific targets of common interest. Based on well-defined criteria, on-line monitoring and regular evaluation of its components, such a network could serve as an expert panel for governmental organizations to secure their financial support and promote the nuclear physics field on an national and international level.

5.10. Local research infrastructures

Over the years, in IFIN-HH was set-up a detector laboratory at international standards (see Fig. 5.17) where have been developed prototypes of different detection and identification systems for low up to ultra-relativistic heavy ion experiments.

Figure 5.17

Based on this was realized the largest contribution which Romania ever had within a large international collaboration, i.e. 24% of the TRD chambers of ALICE experiment (see Fig. 5.18).

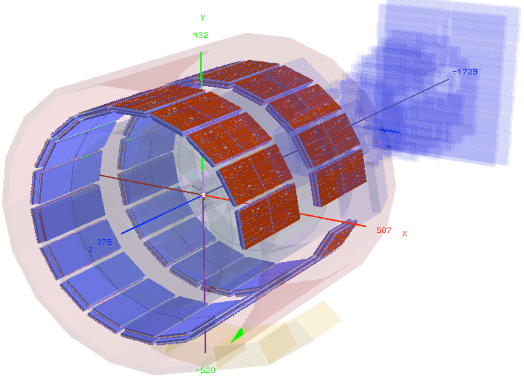


Figure 5.18

Equally important is the infrastructure for the associated front-end electronics based on CADENCE design, bonding device, design software and devices for SMD technology.

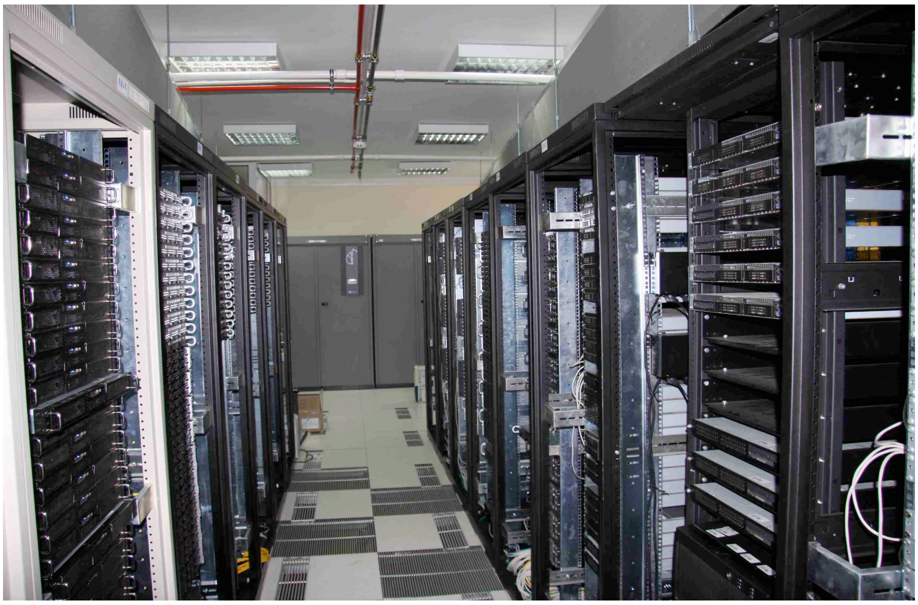


Figure 5.19

As it was shown above, initiated more than a decade ago in Romania by our community, the present Romanian GRID computing infrastructures play an important role in the Worldwide LHC Computing Grid – CERN and show to be an essential need to access the huge experimental information delivered by the large experiments at CERN in which Romania is involved and the necessary computing power and massive data storage needed for calibration and analysis for achieving physics results. Fig.5.19 is a view of IFIN-NIHAM Data Centre, component of the Romanian branch of of WLHC.

5.11. Recommendations

Based on the past activities, results and experience, the Romanian research community could have a real contribution to the European efforts concerning:

- *The understanding of the properties of the Quark Gluon Plasma in the context of the full exploitation of the unique new energy regime opened up by the LHC at CERN. Support for participation to a comprehensive physics programme with proton-proton, proton-nucleus and nucleus-nucleus collisions at several energies using the ALICE detector must be assured.*

- *The construction of the FAIR accelerators and the CBM experiment must be strongly supported in order to enable the study of matter at extremely high baryonic densities. Such studies will shed light on the nature of the phase transition to Quark Gluon Plasma and on the existence of a critical point in the phase diagram of matter that interacts via the strong interaction. The future high-intensity beams from SIS-300 coupled with a detector capable of operating at very high rates will provide access to rare probes. Experiments using beams of rare (n-rich and n-poor) isotopes are essential for understanding the isospin properties of nuclear matter and the nuclear liquid gas phase transition. This implies exploiting the existing facilities and detectors and requires the contribution to the construction and use of FAIR and SPIRAL2 (with the energy upgrading) and of the dedicated detector systems. Specific R&D activities have to be supported and dedicated infrastructure is required.*

- *Nuclear theory is essential to exploit fully the new opportunities arising from existing and future facilities and to link by theoretical modelling the upcoming experimental data to fundamental theory. Funding and human resources for the maintenance and further development of sustainable large-scale high-performance computing resources, such as the GRID, must be secured as computing facilities have become a key factor in the modelling and analysis of experimental data in this field.*

- *The Romanian expertise in developing highly versatile detection and identification systems, the associated front-end electronics, construction of significant sub detectors of large experimental devices within large scale international collaborations, distributed computing architectures has to be conserved and developed by involvements in mid-term international projects like FAIR or LHC experiments upgrades or long-term ones as high-energy hadron-electron-collider (LHeC), as currently being discussed as a future project at CERN.*

- *Initiating and developing an efficient network of excellence at the national level based on visible and competitive research groups of different national institutes and universities, all over the country, structured along scientific targets of common interest.*

- *Suitable career programmes for young researchers, in theory and experiment, need to be fostered in order to exploit fully the long-term perspectives.*

6. Applications of Nuclear Physics

Introduction

According to the ESF's Forward Look "*Perspectives of Nuclear Physics in Europe*" – NuPECC Long Range Plan 2010, Nuclear Physics since its beginning has been intimately tied with applications in daily life. Nuclear physics finds increased applications in trans-disciplinary areas as Nuclear Energy cycles, Life Sciences, Environment and Space, Security and Monitoring, Materials Science, Cultural Heritage, Arts and Archeology. More than other domains of Physics in its development Nuclear Physics were strongly related with development of advanced radiation sources (accelerators and reactors) and new detection techniques. By taking into account the Romanian experience in this field and also the priorities of the national development the forthcoming subjects have a high potential for socio-economic benefits and international visibility.

6.1 Nuclear Energy

With increasing awareness of the global changes to the environment, nuclear power is re-gaining its position as an appropriate option for energy supply with negligible emission of greenhouse gases. This position is subject to the condition that new concepts of nuclear technology for power production (Generation IV, ADS) meet the criteria of sustainable development: increased inherent safety, reduction of the risk of fissile material proliferation and a viable solution to the problems of long-term radioactive waste disposal.

The actual technological societies as well as the emerging economies require ever more energy resources. The nuclear energy is able to provide a long lived viable source and does not produce carbon dioxide. However, recent incidents at nuclear power plants reopened the debate. Among the most important objections against this kind of energy are the security failures and the production of nuclear waste with all consequent associated problems. Fully aware of the importance of creating new nuclear power plants, with a high degree of security and with the problem of radioactive waste either solved or drastically diminished, a number of states decided to make a common effort for elaborating a new concept in the field, the so called Generation IV reactors. Meant to become operational at the horizon of the years 30 this ambitious program has two basic working tools: sophisticated simulation programs able to cope with all imaginable scenarios for the plants of the future and the input for these programs, the Nuclear Data Base (NDB). The role of nuclear physicists is to provide high accuracy measurements of various cross sections for the processes of interest in the simulation of the functioning of a nuclear reactor which will become entries into NDB. Often the target accuracy for these data is below 5% i.e. a difficult task that requires state of the art methods and experimental devices, specific to Nuclear Physics.

Nuclear Data

The modern development of nuclear physics and technology is closely related to the creation, the maintenance and the update of the nuclear data. Together with the most important discoveries of the theoretical physics, the development of databases storing experimental information represents the most important achievement of the scientific effort worldwide. The nuclear structure data stored in ENSDF (Evaluated Nuclear Structure Data) and the nuclear reaction data stored in ENDF-6 libraries (e.g. JEFF-3, ENDF-VII) represent the link between fundamental and applied nuclear physics.

The nuclear data evaluation is a complex process which implies experimental measurements, theoretical predictions, statistical analysis and processing and validation through benchmarking against integral data. At IFIN-HH and at the Faculty of Physics, University of Bucharest (UB) there are research teams with high visibility in the international nuclear data community with expertise and significant contributions on all levels of the evaluation process.

Nuclear Structure Data

The most important nuclear structure database is the Evaluated Nuclear Structure File (ENSDF) which is stored at the National Nuclear Data Centre (NNDC) at Brookhaven National Laboratory (BNL), U.S. and is freely available on the Internet. ENSDF is developed and maintained by an international Nuclear Structure and Decay Data (NSDD) network of evaluators. They continuously compile all the information produced in the field of nuclear structure and, based on a very critical evaluation of the experimental results, decide on the best available experimental information for each nucleus. At present ENSDF contains the experimental information about practically all nuclei that were discovered up to now (3120 nuclides). The information regarding the energy levels and gamma transitions and their proprieties are stored in a formatted file together with the decay proprieties. This represents a huge quantity of knowledge, the best results of the experimental effort made in the field of nuclear structure up to now by the entire scientific community worldwide. The importance of the ENSDF data base cannot be overstressed. Practically all theoretical developments in the field of nuclear structure are based on this data base. The information available here is highly reliable due to the great expertise accumulated at the level of the evaluators. Therefore the theoreticians base their assumptions and test their models trying to explain the basic features on the nuclear structure most of the time on the experimental information from ENSDF. Further, ENSDF is used on practically all applications of the nuclear physics requiring structure information. We emphasize here the particular importance of the decay data. Basic properties of radionuclide, such as half-lives, decay modes and branching ratios, radiation energies and emission probabilities, are used in various applications. Reliable, accurate and updated evaluated nuclear decay data are needed in nuclear power applications, fuel manufacture, reprocessing and waste storage, safeguards and proliferation issues, but also for the new developments in nuclear medicine and radiological protection. Therefore, since 1995, a dedicated international collaboration, Decay Data Evaluation Project (DDEP), produces and disseminates high quality evaluated nuclear decay data sets, characterizing the radionuclide of interest for the worldwide users. DDEP collaborates with the International Atomic Energy Agency (IAEA), Bureau International des Poids et Mesures (BIPM), International Committee for Radionuclide Metrology (ICRM) and, of course, with the Nuclear Structure and Decay Data evaluators network (NSDD).

Both ENSDF and DDEP include Romanian participation. An ENSDF workshop was organized by IFIN-HH in collaboration with IAEA in 2009 with the purpose of training and integrating new evaluators in NSDD. The workshop was big success and was finalized with the complete evaluation of the nuclei with mass number A=84. Since then the scientists from IFIN-HH were involved also in the evaluation of nuclei with A=75, 94 and 106. Since 2006, also DDEP includes a Romanian participation, within the NDS-IAEA CRP on Updated Decay Data Library for Actinides having as goals the evaluation and/or measurement of radionuclide half-lives, α-particle and γ-ray emission probabilities, the evaluation of actinide decay data, and assembly of database and the production of improved/recommended decay data files for actinides of direct application in nuclear facilities, and waste management.

Nuclear Reaction Data

Experimental data

During the last eight years, in close collaboration with teams from IRMM-Geel-Belgium, institute belonging to JRC of EC and other research institutes (e.g. IRES Strasbourg France) a considerable amount of high quality nuclear data of interest for energy applications has been produced. Among them, should be mentioned the accurate, high resolution neutron inelastic scattering cross section measurements on various materials of interest for the development of Generation IV fission reactors. The Romanian physicists had an important contribution both in the development of experimental devices (e.g. GAINS, an array of Ge detectors) and in the data analysis and publication of results and their inclusion in nuclear data bases. They take an active part in a number of European research programs like EUFRAT, ANDES and ERINDA. Further, the so-called surrogate method that tries to infer neutron induced cross sections based on the investigation of particle induced reactions is currently under investigation. These premises are a firm guarantee for further quality work provided in the future.

Model based evaluations

The evaluated data stored in ENDF-6 libraries must be complete, meaning that they have to contain the cross sections for all the open channels, angular distributions, double-differential spectra etc. and the associated covariance on the entire energy range required by applications. Such complete and self-consistent sets of data are obtained using state-of-the-art reaction models implemented in evaluation codes with appropriate input parameters deduced from the overall fit of the experimental data. The Romanian physicists have important contributions on the nuclear models' refinement, on testing and establishing systematics for the input parameters and in developing nuclear reaction codes. In this context should be mentioned the advanced fission formalism based on the optical model for fission. It uses a recursive method to calculate transmission through multi-humped barriers with absorption in minima, and provides an accurate description of the fission cross section, including the resonant structure at sub-barrier energies of the fertile nuclei. Another important contribution is represented by a generalization of the Madland-Nix model for the calculation of the prompt fission neutron spectra, the average number of neutrons/fission and other post-scission data that replaces some of the average quantities with more realistic calculations. Key ingredients for the reaction data calculations are the optical potential parameters, the level densities, and the fission barrier parameters. Different types of regional and global parameters, phenomenological and microscopic have been extensively tested, compared and analyzed before being included and recommended in the Reference Input Parameter Library (RIPL) created and maintained by NDS-IAEA. There are several well-known codes used in evaluation the most used being GNASH, TALYS and EMPIRE. They include a complete set of up-dated nuclear models and direct access to data bases such as RIPL or EXFOR and produce ENDF-6 formatted output files. All of them have been used in different evaluations. It is worth saying that EMPIRE's developers team has a Romanian member.

The emerging applications of nuclear technology require reliable estimates of uncertainties associated with evaluated nuclear data in order to predict construction margins involved in the new designs. This type of information is very incomplete and often obsolete even in the most recent nuclear data libraries. The Romanian experts were invited to join the large international effort to meet the needs of the advanced nuclear designs and based on their expertise, to improve the deterministic (Bayesian) and Monte-Carlo evaluation of reaction nuclear data covariance in the fast neutron region.

Improved Nuclear data requested by fission reactors technologies

Among the new concepts of nuclear technology for power production investigated to satisfy the needs of increased safety, reduction of the risk of fissile material proliferation and a viable solution to the problems of long-term radioactive waste disposal is the Thorium-based nuclear fuel cycle. Neutron capture in ^{232}Th yields ^{233}U, which is a highly efficient nuclear fuel, therefore a thermal breeder (or near-breeder) reactor concept based on thorium fuel is feasible. The build-up of long-lived higher actinides, which are the main source of long-term residual radioactivity in the waste, is much smaller in thorium fuel. This fact can be used with advantage in the design of critical as well as subcritical accelerator-driven systems. Thorium fuel is more proliferation-resistant due to highly radioactive constituents, which cannot be separated out by chemical means. Handling of such material in improvised clandestine laboratories is practically impossible. World reserves of thorium are much larger than reserves of uranium. NDS-IAEA organized a CRP on evaluated nuclear data for thorium-uranium fuel cycle to improve the database of relevant nuclear data for neutronics calculations in view of anticipated needs by reactor designers. The nuclear data evaluations for ^{232}Th, ^{231}Pa and ^{233}Pa in the fast region (0.001 – 60 MeV) have been performed by a Romanian tem with EMPIRE code. These new evaluated data files provide narrower uncertainly estimates that will at least reduce the gap between observed and target uncertainties in the nuclear data and therefore have been adopted by the major library ENDF-VII.0 and the specialized library INDL/Th-U.

Presently, when one of the major challenges for a social acceptability of the nuclear energy in the forthcoming decades is to prove the feasibility of systems able to reduce or to transmute long-lived radioactive nuclear wastes, beside the major actinides, the long-lived minor actinides (produced in nuclear reactors by successive neutron capture on the fuel nuclei followed by beta minus decay) become of great interest. Minor actinides constitute about 0.1% of the weight of discharged fuel. They consist of about 50 % neptunium, 47 % americium and 3 % curium, all of them being very radiotoxic and presenting also potential terrorist risk. These actinides can be transmuted in a fast neutron flux, since the ratio of their fission to capture cross-section is quite large for fast neutrons. Therefore, nuclear data of the actinides in radioactive waste are crucial for deciding on the scenario regarding (a) fuel cycles, (b) long term storage of the highly radioactive waste (c) proliferation resistance and consequently, on the emerging nuclear energy technologies (Gen IV, ADS). For these reasons the study of neutron data for minor actinides is addressed by many groups among which the Romanian physicists play an important role.

While major actinides are challenging because their data have to be known with 1-5% uncertainty, the minor actinides are difficult to be evaluated because the experimental information is very scarce. The main reason for this is their high radioactivity. On the other hand their data are requested to be evaluated up to 150 MeV which implies theoretical evaluations based on nuclear reaction models with reasonably good predictive power and input parameters retrieved from regional or global statistics. Such evaluations have been performed within the NDS-IAEA CRP on Minor Actinide Neutron Reaction Data (MANREAD) having as objectives the critical evaluation, uncertainty assessment and production of neutron cross section data for an agreed set of minor actinides. Crucially important for the criticality of the fission reactors are the prompt fission neutron spectra, fission neutron multiplicity and all the post-scission fission data. Using the refined Madland-Nix model implemented in the original SPECTRUM code and physical grounded methods of parameterization, these data have been calculated for many major and minor actinides. The results obtained in collaboration with EC-JRC-IRMM, CEA-DAM-Bruyères-le-Chàtel, CEA-Cadarache in the frame of FP5,6,7 projects have been adopted by

JEFF3.0, JEFF3.1 libraries. Presently this activity develops also within NDS-IAEA CRP on Prompt Fission Neutron Spectra of Actinides. One of the important aspects of nuclear data and of cross sections in particular is that the various data tend to be correlated to an important degree through the measurement processes and the different corrections made to the observable quantities to obtain the microscopic cross sections. In many applications when one is interested in estimating the uncertainties in calculated results due to the cross sections, the correlations among the data play a crucial role. The format of the reaction evaluated data libraries was changed to accommodate this type of information in the covariance files. Need for new covariance has been advocated by the members of the reactor community on many occasions. It was stressed, that even relatively rough approximation would be of enormous help for the development of new concepts - the essential factor being availability of the covariance data for all materials of significant importance. This interest was formalized in the establishment of five subgroups within OECD Nuclear Energy Agency WPEC (Working Party on International Nuclear Data Evaluation Cooperation) meant to find a strategy and to coordinate the international activities dedicated to nuclear data covariance evaluation and processing. Recently, the need of a similar committee within CSWEG (Cross Section Evaluation Working Group) was claimed too. At present, there are two methods that are being used for evaluation of covariance data in the fast neutron region: Monte-Carlo method and KALMAN-filter. EMPIRE code embraced both methods to generate covariance. In the deterministic case the sensitivity calculations are performed by EMPIRE and transferred to KALMAN code. In the second case, the cross section covariance matrix is calculated in EMPIRE using Monte Carlo method to propagate the parameter uncertainties and transferred to a dedicate code known which treats the theoretical cross section covariance as prior information, updates it by considering the experimental data and produces the *a posteriori* covariance which contains all the information about the uncertainties and the correlations of the studied cross-sections.

Despite the remarkable progress registered during the last years, finding an appropriate methodology to produce massively nuclear data variances and covariance is still in an initial stage. Most of the previous actions focused mainly on the formal part of creating tools, code assemblies, formatting and much less on the refinement of the models and methods absolutely necessary to meet the requirements of the new nuclear designs. Therefore, more efforts should be dedicated to (i) the direct and fast transfer of the latest progress and information from the fundamental nuclear physics to the applied nuclear physics assuring the improvement of the reaction models used in evaluation and of their prediction power, the estimation of the parameter uncertainties and their correlations, (ii) the development of the statistic procedures to generate covariance by considering the parameter uncertainties' correlations, the trans-reaction channel correlations and the trans-material correlations (extremely important for criticality calculations), (iii) extending these procedures to fission data, the covariance for major and minor actinides being considered priority zero, (iv) building efficient algorithms able to generate massively nuclear data covariance matrices. Collaborations on this topics with NNDC, Los Alamos National Laboratory, IAEA-NDS and within the FP7 ANDES project are ongoing. A preliminary set of evaluations for 18 major and minor actinides accompanied by sensitivity studies and estimations of parameter uncertainties have been already delivered to NNDC to be used for covariance calculations. These data have been also used for the " assimilation project" developed in collaboration with NNDC and Argonne National Laboratory meant to adjust model parameters to the integral experiments. Calculating covariances for reaction data is an ambitious and complex process. It involves different fields: from basic nuclear physics (structure models, reaction models, fission) and modern techniques of statistic analysis

(Bayesian inference, decision theory, information theory, Monte Carlo sampling) to the physics of new generation nuclear reactors, advanced fuel cycles, and nuclear waste management. On the other hand it allows to: identify those uncertainties with impact on the pre-conceptual, design and optimization stages of the future nuclear technologies, identify and quantize the improvement of the nuclear data (per nuclide, reaction channel and energy range), and establish the priorities needed to meet the target accuracies. Last, but not least the results of the proposed statistic analysis would contribute to a better understanding of reaction mechanisms and to the refinements of the evaluation techniques.

Improved Nuclear Data Requested by Actual Fusion Technology

Basic problems are still present within neutron data evaluations even in the case of the most advanced nuclear reaction models, involved presently within European projects as the Joint Evaluated Fission and Fusion File (JEFF) evaluated nuclear data project at OECD/NEA Data Bank, and Fusion Evaluated Nuclear Data Library (FENDL 3) project of the Nuclear Data Section/IAEA-Vienna. The nuclear data topic is considered a critical task for selecting and validating the best materials for constructing fusion power reactors, so that it is a priority of the European Commission (EC) Research Programme and the corresponding EC domestic agency Fusion for Energy (F4E) related to the International Thermonuclear Experimental Reactor (ITER) and International Fusion Material Irradiation Facility (IFMIF) fusion programmes. Moreover, there are on-going advanced experimental programs at the CERN-Geneva Neutron Time-of-Flight (n_TOF) facility, or planned within the Neutron For Science (NFS) project at SPIRAL-2 / GANIL, in order to provide additional measured data to be used in validation of theoretical models. The need of high accuracy nuclear data triggered also the EC/EURATOM/EFDA *Technology Workprogramme Task TTMN-001 (Nuclear Data: EFF/EAF data file upgrade, processing & benchmark analyses*), developing the European Activation File (EAF) library as part of the JEFF project. This activity was continued through the F4E call F4E-2008-GRT-014 (ES-AC) with the action title *"Improvement of nuclear data, development of tools and experimentals/validation in support of ITER activities"* as part of the F4E Work Programme „ITER > Engineering Support > Nuclear Data". Since the Contract of Association establishment for the *Fusion Association EURATOM-MEdC* in 2000, the present IFIN-HH group joined successfully the EAF workprogramme within both EFDA and F4E organizations.

This current research interest concerns an improved nuclear-model evaluation of fast-neutron induced reactions, by using consistent model-parameters as well as parameter sensitivity analysis. Its main contribution should be the answers to some still existing question marks on the model predictions which combine the direct interaction (DI) and pre-equilibrium emission (PE) mechanisms with the statistical model (SM) decay of the equilibrated compound nucleus. Our primary aim of the targeted works carried on under, e.g., EUTATOM/F4E calls, has been to comply with the needs of a reliable neutron cross section data library to address safety and environmental issues of fusion program. On the other hand, the same results should enable a consistent assessment of the above-mentioned nuclear models. A particular consideration should be given to PE assumptions of the Geometry-Dependent Hybrid (GDH) model - most important at the medium energies where the global predictions have shown a larger variance with respect to the measured data. The final aim is the understanding of the model constraints which are responsible for the calculated reaction cross section variations. The general objective of this studies is to contribute to EU activities in the measurement and evaluation of basic neutron nuclear data needed for the safety assessment of nuclear installations and for the feasibility study of systems for waste transmutation concepts. Overall, the theoretical description of the neutron interactions with nuclei needs significant improvements that could be validated by suitable description of experimental data. At the same, following the Romanian researchers achievements as well as in order to additionally check them, connection of computational studies and further measurements is planned. There are thus concerned further experiments at n_TOF/CERN and NFS/SPIRAL-2 facilities, as well as at the IFIN-HH Tandem accelerator, through international collaborations.

Future objectives

The strategic objectives related to this subject include:

- forming young scientists to work in the field, here including both experimental abilities and the ability to work with complex, state of the art simulation codes;
- investments in the field of experimental equipment;
- development of new, complementary methods of obtaining information concerning the cross sections (using, for example the so called surrogate reactions that can be studied at the Tandem accelerator).
- continuing the existing fruitful collaborations and enlarge our relations with colleagues from other research institutes working in the field, possibly in the frame of European Programs

Decommissioning of nuclear installations

IFIN-HH, as operator of VVR-S nuclear reactor for research and radioisotope production (thermal power 2 MW, using light water as coolant, reflector and moderator), during a 40 years period (1957-1997), without any nuclear or radiological incident, is responsible for the decommissioning of this reactor. The decommissioning activity began in 2010 and will run over the next 10 years. This is the first complex nuclear installation that will be decommissioned in Romania and in order to complete these activities through the release from the license requirements, important financial, human and technological resources will be used in accordance with the documentation approved for the deployment under radiological and nuclear safety conditions of the decommissioning. In the last years, within some international technical cooperation projects with the International Atomic Energy Agency (IAEA), the USA Department of Energy – National Nuclear Security Administration, Argonne and Sandia National Laboratories and European Union's PHARE, has been obtained a strong support for the implementation of the reactor decommissioning activities. From 2011, within the international project managed by IAEA - Research Reactor Decommissioning Demonstration Project (R^2D^2P), IFIN-HH changes from the international expertise beneficiary into technical expertise donor for the decommissioning of research reactors, VVR-S reactor decommissioning project being accepted as a demonstration model within a Romanian school for the decommissioning of complex nuclear installations. It is expected that over the next 10-20 years, there will be a peak in the decommissioning requests for nuclear and radiological installations worldwide, most research reactors and nuclear power plants from the 50's -60's being at the end of their operation under safety conditions, permanently shut down and ready to be decommissioned. The decommissioning technologies in the field of decontamination, dismantling, cutting, structures demolishing, management of materials resulted, developed and implemented will be used within the decommissioning of radiological and nuclear installations, therefore, amortizing the initial investment in human resources and materials. The lessons learned from the application of technologies and scientific research of physical and mechanical properties of materials dismantled from the decommissioned nuclear installations, will contribute both to the judicious and documented selection of new building materials and the planning of future nuclear installations, by designing structures and systems which are difficult to be activated, easy to be decontaminated, dismantled, cut, demolished, reducing thus the decommissioning cost, improving the radiological protection, the environment and property protection when carrying out nuclear activities. The computer codes have been used to estimate, from the design phase, the quantity of radioactive waste resulted during the operation and from the decommissioning of nuclear installations, the radiation dose rates and the quantities of liquid and gaseous effluents. These computer codes will be another field of practical interest of the nuclear physics applications in ensuring nuclear and radiological safety.

Radioactive wastes management

The objective of radioactive waste management is to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations. Management systems play an important role in realizing this objective, and should be implemented for all stages of waste management, from waste generation to disposal. The management system should support the development, implementation and continued enhancement of a pragmatic and positive safety culture, and promote the adoption of best practices, regardless of the type, scale, complexity, duration, and evolution of the waste management activities. The management system for radioactive waste activities should support the safety and environmental protection culture throughout all levels of the organizations involved. ***Storage*** of waste packages is a very specific stage of waste management, which could be very long and challenge management systems. Extensive technical research is required in the preparatory phase in order to minimize surface contamination and surface dose rates meet requirements; the intended movements of waste packages within the storage facility can be performed safely, preclude inadvertent criticality, and minimize occupational exposures; and, obvious, procedures are in place for monitoring the integrity of waste packages, controlling, maintaining surveillance of the operational status of accident detection and mitigation equipment and ensuring that waste packages can be easily identified, located and accessed. ***Disposal*** is the best solution but that involves a variety of technical and management issues, and can extend over a very long time (e.g., potentially hundreds of years). For this reason, the disposal decision is based on several consideration involved in assessing and demonstrating safety and environmental protection (e.g., site evaluation, facility design, environmental impact assessment, authorization processes, establishment of waste acceptance criteria, planned and systematic methods for waste inspection and emplacement, operational data collection, facility monitoring and surveillance systems). All these issues are subjects for future extensive, multidisciplinary research.

6.2 Life Sciences

Nuclear Medicine

Ongoing researches in Nuclear Physics to be applied in Medical Sciences are mainly to develop new tracers for diagnosis and radiotherapy using so called “medical radioisotopes” and to test the pharmacologic-active ingredients of new medicines using radiolabelled compounds.

Applications of nuclear techniques are highlighted in Romania, having a history of over 30 years in the research and small-scale production of radiopharmaceuticals and radiolabelled compounds.

- Nuclear medicine uses radiation to provide *diagnostic* information about the functioning of a specific organ. Radionuclide *imaging* modalities (positron emission tomography, PET; single photon emission computed tomography, SPECT) are diagnostic cross-sectional imaging techniques that map the location and concentration of radionuclide-labeled radiotracers. *Molecular imaging* is an essential tool in oncological research in cell apoptosis, gene and nucleic acid-based approach, angiogenesis, tumor hypoxia and metabolic imaging and its potential to redirect optimal cancer diagnosis and therapeutics was demonstrated.
- Radiotherapy, based on high linear energy transfer radionuclide, can be used to *treat* some medical conditions, especially cancer, using radiation to weaken or destroy particular targeted cells.

Tens of millions of nuclear medicine procedures (imaging and radiotherapy) are performed each year worldwide, and demand for radioisotopes is increasing rapidly. Researchers are investigating both the *agents* that seek out specific tumor cells for treatment and the *radioisotope* payload that delivers the radiation. Improvement of both scintigraphic imaging and targeted radiotherapy is extensively determined by the development of more specific radiopharmaceuticals. Thus, new functional pharmaceuticals have to be developed and evaluated in animals and humans. Many medical radioisotopes or parents are made in nuclear reactors, some in cyclotrons. Generally neutron-rich ones and those resulting from nuclear fission need to be made in reactors; neutron-depleted ones are made in cyclotrons.
There are about 40 activation product radioisotopes and five fission product ones made in reactors. At IFIN-HH new tracers are under investigations based on some of these radionuclide: Iodine-125 (60 d): cancer brachytherapy, deep vein thrombosis and radioimmuno-assays; Iodine-131 (8 d): treatment of thyroid cancer and imaging; Lutetium-177 (6.7 d), Rhenium-186 (3.8 d), Rhenium-188 (17 h): Samarium-153 (47 h): therapy/ imaging/follow-up and pain relief; Molybdenum-99 (66 h): used as the 'parent' in a generator to produce technetium-99m; Technetium-99m (6 h): imaging (skeleton, heart muscle, brain, thyroid, lungs, liver, spleen, kidney, gall bladder, bone marrow, salivary and lachrymal glands, heart blood pool, infection and numerous specialized medical studies);Yttrium-90 (64 h): brachytherapy and palliation; Bismuth-213 (46 min): targeted alpha therapy; Holmium-166 (26 h): diagnosis and treatment of liver tumors. Studies involving cyclotron produced medical radioisotopes will benefit both from an existing infrastructure, to be augmented in the near future by the commissioning of the Research Center for Radiopharmaceuticals (CCR) including a cyclotron (14-19 MeV protons and 8-9 MeV deuterons; working in “dual beam” system), dedicated target chambers and hot cells, clean room for aseptic preparation, tomography scanner for small animals. The studies proposed to be performed are based on positron emitters Fluorine-18 (110 min), Copper-64 (12.7 h), Iodine-124 (4.2 d), Gallium-68 (68 min), Carbon-11 (20.3 min), Nitrogen-13 (9.9 min), Oxygen-15 (2 min), and include: (a) developing of new F-18 PET tracers (beyond FDG, fluorodeoxyglucose) aimed for more specific tumor imaging, such as FLT (fluorothymidine), F-miso (fluoromisonidazole), 18F-choline; (b) developing of Cu-64/67 tracers to study genetic diseases affecting copper metabolism and for tumor imaging and therapy; (c) unconventional PET/SPECT tracers based on I-123/124 and Ga-68; (d) ultra short-lived radionuclides for brain physiology and pathology studies. Additionally, studies regarding cyclotron production of 99mTc to address Mo-99 shortage and fusion of imaging modalities (SPECT/MRI and PET/CT) are envisaged.

Pharmacology

New drugs developed in pharmaceutical industry must be investigated in respect to their pharmacokinetics. Labeling of the drugs with radionuclide at certain positions of the molecule structure is the most appropriate method for detailed examination of the metabolism (ADME studies) due to high sensitivity. Depending of envisaged study and synthesis time, short-lived radioisotopes such as C-11 and O-15 or long-lived T or C-14 can be used for labeling, while the measurements is by direct/liquid scintillation counting or by autoradiography. PET imaging is a unique scientific tool in pharmacology research due to its ability to detect both pharmacokinetic and pharmacodynamic events. This is particularly important in toxicity and therapeutic efficacy testing as well as drug abuse. This kind of studies will add valuable information for better understanding of the molecular mechanisms as well as practical questions such determining therapeutical doses for clinical testing of new drugs, interactions and side effects, resistivity and sensitivity to treatment.

Effects of ionizing radiation on biological systems

Basic research at molecular, cellular or whole body level is performed to study the effects of ionizing radiation on biological systems. The ongoing research activities cover the following domains:

- Evaluation of cellular radio sensitivity in pathologies associated with oxidative stress and DNA repair impairment - multiple sclerosis, cancer. Chromosomal radio sensitivity and apoptosis induced by external gamma irradiation were studied in peripheral blood lymphocytes cultures obtained from patients with genital cancer and patients with secondary progressive multiple sclerosis. The results are discussed also in correlation with the level of oxidative stress biomarkers (carbonil contents in plasma proteins, antioxidant activity of plasma) associated with these pathologies.
- Study of epigenetic, no targeted effects induced by low dose and low dose rate irradiation: adaptive, bystander and hormetic responses. Adaptive and bystander effects are studied in fibroblasts cell cultures (L929 and V79) after low dose gamma irradiation and bleomycine treatment..
- In vitro and in vivo toxicology type studies of radio-pharmaceuticals ^{188}Re radiolabelled DOTA-TATE and ^{188}Re-anti-VEGF-Mab cytotoxicity were tested at cellular or whole body level, on cell cultures and on rats.

One of the application of the research activity aimed the development of specialized technologies for detection of low concentrations of substances in biological or environmental samples (Radio Immuno Analysis / ELISA) . RIA kits have been obtained for steroid hormones and pesticides.

For the perspective:

- The research activity in the domain of low dose/low dose rate irradiation will be oriented towards the field of low dose radiation risk assessment, addressing health issues specific for nuclear activities developed in Romania. The aim is to initiate a biomarker study for identifying disturbances that might underlie and/or predict the harmful effects of low dose radiation exposures. The ex vivo experiments will assess also the cellular radiosensitivity using cells from *in vivo* exposed individuals, subsequently subjected to experimental in vitro irradiation, in the attempt to observe possible adaptive responses.

- Will be continued the research activity concerning the epigenetic, nontargeted effects produced by low dose/low rate irradiation also in view of possible applications in pathologies with wide impact as diabetes.
- The radiobiological studies will be oriented also towards the development of complex cellular systems (co-cultures of lymphocytes and endothelial cells or oligodendrocytes with neuronal cells) in order to be used as cell-cell interaction biological models, appropriate for the understanding of the low dose irradiation effects on circulatory and nervous systems.
- An important research direction will remain that of toxicological studies (performed in vitro and in vivo) on radio-pharmaceuticals products developed in IFIN-HH and intended to be used in radio immunotherapy.

Imaging PET and CT

Positron Emission Tomography (PET) is a diagnostic method which permits the determination, in vivo, of a tracer distribution; the tracer is marked with a positron emitting radio-isotope and the radioisotope is attached to a chemical substance tolerated by the human body, like FDG, and injected or inhaled; the emitted positron slow down in the tissues and after a 1 to 6 mm range it annihilates emitting two collinear 511 keV gamma rays with a random direction. The tomography key is the detection of the coincident gamma rays and the preservation and storing the direction, named as coincidence line; the collection of all lines of coincidence indexed after the angle is stored in projections. Positron Emission Tomographs are today available with a dual operation mode: PET (positron emission tomography which perform the reconstruction by means of recording the coincidence lines) and SPECT (computer tomography based on the amplitude analysis of gamma rays passing through the human body). In the “only coincidence gamma ray” mode, these tomographs perform axial sections through the human body and with limitations, by axial translation, a quasi 3D image with a small axial extend (aprox. 10 cm). Gamma rays coincidence detection and recording is performed within rings of detectors only in the same transversal plan; the coincidence of gamma rays belonging to a different plan (tilted from the transversal) is excluded.

For the perspective:

- The next step is a real 3D tomography based on a new concept for gamma detectors (large scale planar detectors) and a simplified acquisitions electronics; the tomograph’s large Field view will allow the simultaneous 3D scan and image of whole body of the patient.
- To develop new planar detectors, like Resistive Plate Chamber (RPC) or Large photodiodes arrays.
- To develop new column like scintillators of large dimensions
- To design new acquisition systems, more simplified; large part o the acquisition will be situated on the backplane of the planar detector.

New methods for producing radioisotopes for medicine

The Research Center for Radiopharmaceuticals (CCR) is a new investment that is now growing in IFIN-HH.

New TR19 Cyclotron

Short Term Objectives

- Commissioning for R/D activities of a system which comprises: cyclotron and radiochemistry modules, including a quality control laboratory, for the achievement of researches related to the radioisotopes for PET, in agreement with GMP of the EU.
- Interdisciplinary research regarding medical applications of the ionizing radiations, which converge towards the use of short-life radioisotopes, of those emitting/transmitters β or α, having as target the diminution or the limitation of the noxious action on healthy tissues.
- Foundation for the first time in Romania of a laboratory for testing in vivo small animals, positron transmitters radiopharmaceutical products used in diagnosis and cure, laboratory developed around an equipment for high-resolution computed tomography images specialized for small animals, known as microPET.

Long Term Objectives

- Research capacity increase by developing R-D infrastructure having as purpose the increment of the scientific competitiveness level on international scale. This investment will allow the approach in condition of an Excellence Research Center of some prioritary research directions:
- Neutron activation of nanoparticles using a cyclotron;

- The goal of this research is to design a cyclotron-driven neutron activator for the production of beta- emitting radioisotopes for brachytherapy. Brachytherapy is an advanced cancer treatment, a radiation therapy given at a short distance: localized, precise, and high-tech. Radioactive seeds or sources are placed in or near the tumor itself, giving a high radiation dose to the tumor while reducing the radiation exposure in the surrounding healthy tissues. The radioisotopes used in this technique are generated through high-flux neutron irradiation and at present can be efficiently produced only in nuclear reactors. This is a major limitation due to several factors, lack of availability of nuclear reactors for medical applications, heating typical of nuclear reactors the difficulty conditions of injectable preparations of nanoparticles suspensions to be irradiated. Starting from the Adiabatic Resonance Crossing concept proposed by C. Rubbia in 1998 (ARC patent), a few researcher groups have developed a compact cyclotron-driven neutron activator capable of efficiently activating injectable suspensions of nanoparticles. It was demonstrated that the ARC method is feasible when coupled with small sized cyclotrons currently used for PET isotopes production (16-19 MeV, 100 mA), and can be efficiently used to produce therapeutic doses of radiopharmaceuticals for brachytherapy;
- Feasibility study on production of ^{123}I (13.2h) from the reaction ^{123}Te(p,n);
- Development technologies for intense irradiation of solid, liquid and gaseous targets;
- Development technologies for the production of non-standard PET radionuclides and equipment for radiosinthesis of biomolecules with these radionuclides.

6.3 Environmental Applications

The development and maintaining of expert systems to support the decision makers for the assessment of a nuclear accident or radiological emergency. A special direction was devoted to original methods, models and computing codes in quantitative risk analysis and complex system vulnerability focused on critical infrastructure.

The most important expert system RODOS (Real time on-line decision support) has been developed as a result of collaborative actions in the European Community Framework programmes which can be applied within Europe. It can be used in national or regional nuclear emergency centers, providing coherent support at all stages of an accident (i. e., before, during and after a release), including the long term management and restoration of contaminated areas. The main activities in Romania consisted in customization and adaptation of RODOS to Romanian conditions (e.g. CANDU NPP) and its installation in the Emergency Centre of General Inspectorate of Emergency Situations (IGSU).

Another expert system is MOIRA, adapted to hydrological radioactive release developed and applied to Danube's river. The systems were applied to support decision makers during the emergency exercises for CANDU-NPP (Romania) or Kozloduj – NPP (Bulgaria).

In the same time the domestic programmes (Notepad, SAT, RAT,EDAT,QVA) are developed and they are generic in model assumptions/constitutive equations, provide for specificity by offering exemplary case-input libraries; flexible option-oriented interfaces for model choice and data and comprehensive and convenient in use GIS facilities as I/O (input/output) platforms.

The overall objective of the research was to enhance the operational versions of expert systems for supporting and increasing its broader acceptance through an improved applicability with respect to: data network conditions, different categories of users and for a broad spectrum of release types and environmental conditions.

The most important future objective is to develop a unique emergency system for all European countries, customized and adapted to Romanian conditions and fully installed in Emergency Centre for Nuclear Accident and Radiological Emergency belonged to IGSU. Another objective is to develop the operational procedures for the NERIS Platform on nuclear and radiological emergency response and recovery preparedness. The NERIS platform is supported by EC in the 7th framework programme.

The development of a complex dynamic model for tritium and ^{14}C transfer in farm and laboratory animals, wild biota, birds and aquatic food chain. The research had valuable contributions to the IAEA technical documents and TECDOCS concerning the assessment of ^{3}H and ^{14}C emissions for routine and accidental situations and in developing dynamic models for ^{3}H and ^{14}C transfer in crops based on plant physiology and crop growth processes. The tritium human dosimetric model was developed and tested with human data and important contributions to wet deposition of tritium were reported. The coordination of the “Tritium Accident” Working Group in the frame of IAEA’s EMRAS (Environmental Modeling for Radiation Safety) programme was an international recognition of the scientific results. The expertise concerning tritium and ^{14}C modeling is directly connected to the needs of Romanian nuclear energetic, contributing to the revision of the derived release limits (DRL) for ^{3}H and ^{14}C emissions from CANDU reactors.

Another accomplishment of the research is the development meteorological and radiological survey system in IFIN-HH, which works non-attended in real time (http://meteo.nipne.ro).

The next following steps of the research activity are the development of a robust dynamic model of tritium transfer in plants, the model tests with the experimental data; the development of the integrated model for tritium accidental risks emissions in Romania; and the following development of the meteorological and radiological system for a complete characterization of local atmosphere and inputs information for the advanced atmospheric transfer models as are needed for the advanced nuclear sites. The final goal is to integrate the tritium model into the atmospheric dispersion models in order to be applied to Cernavoda NPP. The development of activities on environmental radioactivity monitoring, individual supervision, maintenance of recognition of these activities by the authorized institutions and research activities in laboratory of experimental physics in underground.

The main future objectives are:

- to create a database for monitoring of all activities in order to obtain useful statistical information requested at national and international level;
- participation in intercomparison exercises with other European research institutes;
- measurement of very low specific activities of different samples and materials in ultra-low radiation background;
- measurement of very low radiation doses using thermoluminiscent detectors;
- measurement of atmospheric muons in underground and on surface.

At University Babes-Bolyai, Cluj_Napoca and IFIN-HH are performed systematic measurements on radioactivity of environmental samples as follows.

Radon measurements

- Indoor radon and thoron concentrations monitoring (passive and active methods)
- Radon tests
- Radon mapping
- Population exposure to radon and health impacts
- Radon exhalation studies (soil and building materials)
- Measurements of soil radon and permeability
- Risk communication strategies
- Mitigation techniques of indoor radon

Gamma and alpha spectrometry on environmental samples

- Measurement of radium in soil and building materials
- Water and soil quality (NORM measurements)
- NORM and TENORM measurements in coal in uranium mining areas
- Natural occurring radioactive nuclides in soils and other geological materials
- Uranium disequilibrium dating methods
- Pb-210 and Cs-137 dating methods
- Monitoring soil erosion processes
- Estimating lake sedimentation rates
- Input data on atmospheric pollution monitoring

Nuclear dating

Set up of the laboratories and implementation of state-of-the art techniques in thermoluminescence, optically stimulated luminescence dating and young sediment dating by Pb-210 method.

Future research

- U-234/Th-230 Dating based on alpha and IPS-MS measurements. Speleothemes and travertine aplications.
- Improving luminiscence measurements for different systems (loess, send, delta sediments) with palaeclimatological applications
- Erosion soil studies and sedimentation in hydrological basins using Cs-137 and Pb-210.
- Implementation of remedial measures for radon mitigation in old and new buildings.
- Developing of new techniques to improving limit of detection in natural radioactivity measurement (U, Th, Ra, Rn, Cs, Be),
  - Studies on atmospheric radioactivity by alpha and gamma spectrometry
- Thoron studies and its contribution to the natural exposure.

6.4 Nuclear Methods in Materials Science

Ion Beam Analysis (IBA) techniques

In Romania there is an important research activity by using Ion Beam Analysis (IBA) techniques: Rutherford Backscattering Spectrometry (RBS), Elastic Recoil Detection Analysis (ERDA), Non-Rutherford Backscattering Spectrometry (NRBS) and Proton Induced X-ray Emission (PIXE). There is international access to: a 9 MV Van de Graaff Tandem accelerator, dedicated reaction chambers for measurements using IBA techniques, detectors for charged particle spectroscopy, a ΔE-E detector telescope (ionization chamber-silicon detector), programs for data analysis. Among the various micro analytical techniques used today to investigate the physical properties of solid surfaces, microanalysis using a MeV charged particle beam is a tool, particularly well suited to study physical and chemical phenomena taking place in the near-surface region of solids, and which implies quantitative determination and depth profiling of very small amounts of elements. Rutherford backscattering of charged particles (RBS), mainly $^4He^+$ ions, permits the determination and depth profiling, with a depth resolution of l00 - 300 Å in regions of a solid up to 1 μm. As this method is essentially non-destructive, it has been frequently used to determine the stoicheometry and thickness of thin films (e.g. SBN thin films growth by RF plasma beam assisted pulsed laser deposition, sol-gel PZT films and $YBa_2Cu_3O_{7-x}$ films obtained by pulsed laser deposition. A severe disadvantage of conventional RBS is low sensitivity for light elements. The Rutherford scattering cross section is proportional to the square of the nuclear charge of the target nucleus. Therefore, the scattering peaks from light elements such as C, N and O are superimposed on a relatively high background due to backscattering from heavy elements in the sample. In recent years, backscattering using 4He+ ions with energies higher than 2 MeV has been extensively used in materials analysis to enhance the sensitivity for light elements. Advantages associated with the use of higher energy 4He+ beams are: improved mass resolution, increased probing depth and improved accuracy in measured stoicheometric ratios. For example, the Non-Rutherford Backscattering Spectrometry (NRBS) technique has been used to determine the stoicheometry and thickness of SiC layers on silicon. When high energy 4He+ ion backscattering is used for quantitative analysis of light elements the elastic cross sections for these elements should be known. There exists a complement to RBS which allows unambiguous particle identification and which is also quantitative: elastic recoil detection analysis (ERDA). ERDA is based on the detection of low–mass target elements, which are ejected by a heavier projectile; the depth distribution is derived from the energy spectrum of the recoils. Since the detected particle is the recoil, it is possible to discriminate between different elements by their nuclear charge or mass. Different detection techniques have been used to achieve this separation. Based on the method mentioned above a collaboration with CSNSM-Orsay (France) has been established. The main object of this collaboration is the study of the modifications, induced by He and Ar ions implantation and thermal treatments, of zirconia, spinel and SiC, using IBA methods and other advanced techniques. Future prospects are related with the installation of a new 3 MV Van de Graaff Tandem accelerator, dedicated reaction chambers for measurements using IBA technique, equipped with a two-axis goniometer, detectors for charged particle spectroscopy, a ΔE-E detector telescope (ionization chamber-silicon detector), and programs for data analysis. It will have an implantation line with excellent homogeneity over large surfaces and an IBA line with channeling. Furthermore, under channeling conditions, the technique may be exploited to give information about the sample structure and lattice locations of impurities. Channeling is a powerful technique which is widely used for ordered samples characterization. This new facility will thus fill the gap existing in Ion Beam Analysis (IBA) techniques presently used in IFIN-HH. Its performances and equipments, along with the low-duration, cost-effective and non-activating characters of ion irradiation, will allow experimentation in tight association with the specialists of modelling and numerical simulation from CSNSM-Orsay (France), for a *mutual fertilisation* of experiment and modelling.

Elemental and structural RBS analysis using microbeams

Ion microbeam facilities are analytical tools with high spatial resolution exploiting MeV ion beams. The interactions of beam particles with atoms and nuclei of the target induce the emission of characteristic radiation, the energy of which provides signatures of the compositional and/or structural properties of the target; Ion-Beam Analysis (IBA) techniques, based on the detection of such radiation, enable characterisation of samples of interest, e.g. in material and earth sciences, cultural heritage, biology, medicine, and environmental studies. External beams, obtained by extracting the particles into the atmosphere through a thin window, have many attractive features, e.g. non-destructive/non-invasive analysis and ease of working.. External microprobes have made it possible to obtain probes in the micron range by adopting strong focusing lenses, ultra-thin windows for beam extraction, and short/ultra-short external path of beam particles in light gases; they have also made possible the use of new external IBA techniques, e.g. RBS, ERDA, STIM, and IBIC. By adopting systems to raster scan the beam over the sample, imaging capabilities have also become available for ex-vacuo analysis. External scanning microprobes combined with IBA techniques have enabled the characterisation of samples with high spatial resolution, comparable with that achievable in-vacuum for thick

Radiology and irradiation using X-ray and ion microbeams

A goal of research in radiobiology is to identify the radiation-sensitive target(s) in cells and characterize the mechanisms of damage and repair. To this end, a micro beam of ionizing radiation (ions or x-rays) able to deliver a defined dose to individual cells or sub-units of cells is a useful tool. Low energy, microfocus X-ray-generators are now commercially available, but only few of them are used in radiation biology experiments.

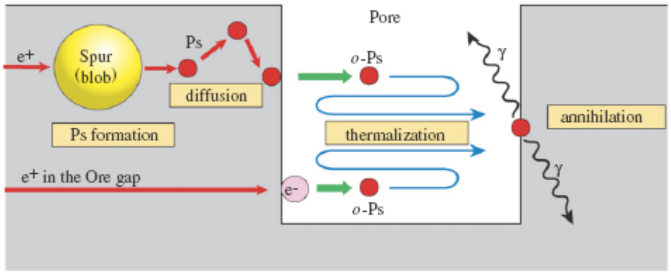
X-ray and Ion microbeams are commonly used to study local irradiation effects in living cells, as it has been established that ion beam irradiations can lead to deleterious changes in cells that are not struck directly by the microbeam. Such changes, which take place over distances long compared to the size of the irradiation spot and for times long compared to the time of irradiation, are collectively termed radiation-induced bystander effect (RIBE). Free-radical chemistry is frequently invoked to explain the RIBE but no unified model is available at present. Ion microbeams when coupled with advanced methods for observing free radicals are the tools of choice for investigating the chemistry and biological processes governing RIBE.

Fast neutron irradiation and dosimetry

The neutron beam of the Cyclotron U-120 is generated by deuterons of 13 MeV bombarding a thick beryllium target. The facility can be used for microdosimetric measurements inside and outside the useful beam. The dose fraction due to gamma rays is known. Another type of application consists in the irradiation of different material with the scope to determine the hardness of these materials to the fast neutron.

Positron Annihilation Spectroscopy

The most powerful approach is to monitor the physical and chemical changes at molecular level by means of atomic probes, such as Atomic Force Microscopy (AFM), Scanning Electron Microscopy (SEM), and by molecular spectroscopic methods, such as Fourier Transform Infrared (FTIR) and Raman spectroscopy, Nuclear Magnetic Resonance (NMR) and Electron Spin Resonance (ESR). Along with the above-mentioned techniques, Positron Annihilation Spectroscopy (PAS) can reveal useful information about the electronic and defect properties of materials. Positron Annihilation Lifetime Spectroscopy: when a positron is injected into a polymeric medium it thermalises and forms a quasi bound state with electron, namely, positronium (Ps) atom. There are two type of Ps, *para*-Ps (*p*-Ps) and *ortho*-Ps (*o*-Ps) with life-time of 125 ps and 142 ns, respectively. Both, *p*-Ps and *o*-Ps undergo pick-off annihilation with surrounding electrons. This renders the life-time of *o*-Ps to a few nanoseconds while the *p*-Ps life-time remains practically unaffected due to its high intrinsic decay rate. The fate of *o*-Ps is monitored to obtain specific information about the free-volume structure of the polymer because Ps has extreme sensitivity to holes or region of low electron density in the material where it is localized. The life-time measurement of Ps species provides information about the size of the free-volume hole. Doppler broadened annihilation radiation measurement, on the other hand, provides information about the momentum distribution of electrons which is often represented by a shape parameter, namely, *S*-parameter defined as the ratio of central low momentum region to total peak area of the 511 keV photo peak. It is a sensitive index of the pore fraction in the polymeric material. Coincidence Doppler Broadening Spectroscopy (CDBS) has the advantage - over single detector spectroscopy - that a lower background is present in the region of high longitudinal momentum of the annihilation pair electron-positron. These annihilations correspond to fast electrons, making CDBS method suitable for probing the chemical sensitivity in open (free) volumes trapping sites. Many researches proved that Ps is a powerful porosimetric and chemical probe for exploring the adsorption, pore filling, porosity and surface properties of various systems. To further enhance the capability of the Ps probe, of absolute necessity is to deepen our understanding of its formation, diffusion, thermalization and annihilation to make quantitative predictions possible. Since the first application of positron annihilation to porous materials, new materials have been synthesized and a number of novel applications have emerged. It is our hope that positron annihilation will find wider applications in this rapidly and continuously developing field of science and technology.



***Ps in a porous system*.**

Experiments with a High-Density Positronium Gas

A high-density gas of interacting positronium (Ps) atoms can be created by irradiating a thin film of nanoporous silica with intense positron bursts and measured the Ps lifetime using new single-shot technique.

Positronium physics (interaction with internal or external electromagnetic fields)

The annihilation of ortho-Positronium (o-Ps) and para-Positronium (p-Ps) atoms annihilation is influenced by a magnetic field.

The effect can be used for developing new experimental techniques for measuring of internal magnetic field and o-Ps interaction in internal and external magnetic fields.

Porous polymer films have attracted much attention due to their usefulness as supporting media in tissue engineering, membranes in separation process, templates for inorganic growth, dielectric materials for electronic devices and optical materials. Porous structures seen in the entire thickness direction in addition to the two-dimensional top surface of the film become very important to control the desirable properties of porous films, such as cell grow rate, selectivity of membrane and effective refractive index of an optical film. Pore structure in polymer films has influence on the mechanical, electrical and transport properties of the film. The growth in the interest of polymer thin films has also been catalyzed by the increase in the number of techniques available to characterize thin polymer films. From the engineering side, there are challenges that are faced in producing perfectly uniform thin films. Yet, this in turn has sparked the interest from the physics community in studies on instabilities in thin films and on the confinement of highly ordered structures. Controlling interfacial interactions has presented numerous challenges to surface chemists, both small molecule chemists and polymer chemists. The influence of confinement on phase transitions like crystallization, phase separation and micro phase separation, has piqued the interest of physicists and physical chemists.

Future research:

- To develop of a slow positron device able to accelerate positrons at energies in range of tens keV. This kind of device will be able to deliver thermalized positrons at various depths in thin films (from tens of nanometers to few micrometers).
- To extend the materials under studies like porous materials and thin polymer films used in solar cell research or special applications.
- To enlarge the use of positrons in more fields like *Positron-excited Auger Electron Spectroscopy (PAES)*
- To exploit the brilliant positron source at ELI-NP.

Nuclear Activation Analysis (NAA) and Nanomaterials

In the new field of „Nanomaterials and Nanotechnologies” there are great efforts to develop new materials, including in Romania, as well as new technologies capable to extend our present performance and knowledge, with a great impact in industry, biology, genetics, medicine.

Nanotechnologies led to a growing market, characterized by ‚Engineered nanoparticles” (ENPs), and found widespread applications. These applications include such ENPs in a wide variety of consumer products – from cosmetics to medical applications, and to food packaging materials, processing technologies and novel or functional foods.

However, it is already known that most part of ENPs presents a certain (variable) degree of toxicity – through the relationship between the metal properties and the toxic effects), becoming thus a „hot"topic around the world. Studies developed for such effects are hampered by the lack of tools to localize and quantify ENPs in water, sediments, soils, organisms. NAA studies of waters and soils may be of the great usefulness for identification of the spontaneous dispersal of the radioactive ENPs into water and soil, passing successfully through filters. The applicability of the NAA technique has been demonstrated in this type of applications in several published studies. On the other hand, the NAA technique, coupled with Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) may be of great usefulness to study the new materials (including nanomaterials, or nanostructures) produced for future applications in nuclear power plants. In the field of medicine, nano-particles from medicine treatment can be absorbed into the bloodstream, and their tracks and localization must be known and controlled. The NAA technique is the best analytical technique for these aims. Other possible topics to be applied using NAA coupled with the Gamma-ray spectroscopy studies may be applied to study and give answers to other problems:

- Radioprotection: Studies of the „Non-targeted-effects" under radiation (bystander effects, abscopal effects, systemic reactions and hormesis), using IFIN-HH facilities (Cyclotron) and a powerful TEM System .
- Study of the materials modifications under heavy ions and laser beams impact.

***Future research**:*

- To develop new studies on new materials, comprising nanostructures, designed for the field of energy.
- To develop applications for identification of nanoparticles in soil, water and blood by using "injected" radioactive particles
- To initiate new studies concerning modification of the micro and nano-structure of materials by SEM and TEM analytical techniques
- To initiate new studies, useful/ necessary in the Radioprotection field, concerning the NON-targeted effects, using the TEM technique.

Radiation processing of materials

By its features, Radiation processing illustrates in an exemplary manner the final and most honorable role of science - to assist human society in its progress, also the pragmatic, concrete way from basic science to useful services and products. This is happened because radiation processing is a domain placed at a triple border:

- the border between nuclear physics and nuclear engineering;
- the border between basic science and applied science;
- the border between a linear development of any single science and a synergic development – typically in the frame of a multidisciplinary approach;

The state of the art of this domain, also the development perspectives and directions are based on the phenomenon of interaction between the ionizing radiation and the substance in that range of radiation energy that do not give birth to nuclear reactions. The target of any radiation processing is to obtain useful modification in the substance inner structure. If the target substance is a living organism or tissue, DNA damage is obtained associating death (of the cancer tissue, microorganism) and/or severe physiological modification giving birth to different organisms (genetic modification). Major applications are multidisciplinary and developed for:

- medicine: sterilization of medical devices
- nutrition: food decontamination
- genetics: genetic modification of plants
- biology: sterile male technique
- chemistry: modification of material properties
- environment related sciences: treatment of chemical pollutants from gases, water and sewage sludge
- culture: preservation of cultural heritage artifacts

Briefly one may say the radiation processing is a domain of applied nuclear physics involved in most important human areas of interest: health, food and environment. As a consequence in its most probable future picture the mentioned applications will be consolidated and extended. Useful radiation is considered:

a) gamma radiation produced by radioisotopes (Co60, Cs137)
b) electron-beams produced by accelerators
c) X-ray produced by the "bremsstrahlung" of the accelerated electrons

Gamma radiation has the advantage of good penetration but has the disadvantage of associating radioactive wastes. Also gamma irradiators have a good reliability. E-beams having a reduced penetration are mostly limited at producing surface or gaseous reactions. Accelerators are expensive equipments with expensive spare parts but produce "push-button" radiation associating no radioactive wastes. Also, there is an important development reserve in the direction of manufacturing more convenient equipment for producing ionizing radiation. This reserve extends on all equipment types: electron accelerators, accelerators used to produce X-rays and gamma irradiators. There are good scientific, technical, economical reasons to hope in the next decade will be available on the market cheaper and more reliable e-beam accelerators which will support the large implementation of technologies for suppression of chemical pollutants. X-ray conversion of accelerated electrons is performed now with a yield less than 10%. Increasing this yield is an attractive development direction. Gamma irradiators - more convenient from the exploitation point of view have the inconvenient of using isotopic sources that associate nuclear wastes. Especially the R&D hope in a successful transmutation (ELI project) would solve the big problem of nuclear waste and would transform the isotopic sources used now in radiation processing (Co60 and Cs137) in environmental friendly and more attractive equipment for producing ionizing radiation.

6.5 Archaeometry and Cultural Heritage

Tomography in Archaeometry

X-ray Computed Tomography (CT) is a widely spread non-destructive examination technique used in various applications, such as medicine, industry, material science, cultural heritage. The most often encountered kind of tomography measurements are the ones in transmission mode, in which the attenuated X-ray photons are measured. They provide maps of the absorption coefficient of transversal slices of the examined object, which, in turn, can be related to variations in density of the analyzed sample.

- The structure of a tomography device depends on the application in which the apparatus is to be used. The spatial resolution and maximum size of the object that is to be scanned are crucial when deciding to develop such equipment.

- The performance of a tomography device in terms of spatial and contrast resolution (the last parameter corresponding to differences of contiguous materials in terms of absorption coefficient) essentially depends on the characteristic of the X-ray beam and of the X-ray detector.

The technique of Computed Tomography (CT) combined with the pertinent interpretation of the obtained images is a powerful diagnostic tool which can provide details on the internal structure of a large class of objects, being nowadays largely employed in medical, industrial, material science and art work investigations.

. By using a dedicated apparatus and software, the inside of bigger, closed artifacts could be determined without breaking them. The tomography scans led to relatively good quality reconstructed images of the investigated objects, images obtained in a short time and with a spatial resolution that is more than satisfactory for the purposes of such studies. Thus, by using this tomography device, hidden structural details that otherwise would have had remained completely unknown to the archaeologists were revealed inside the investigated objects.

Ion Beam analysis and X-Ray Fluorescence

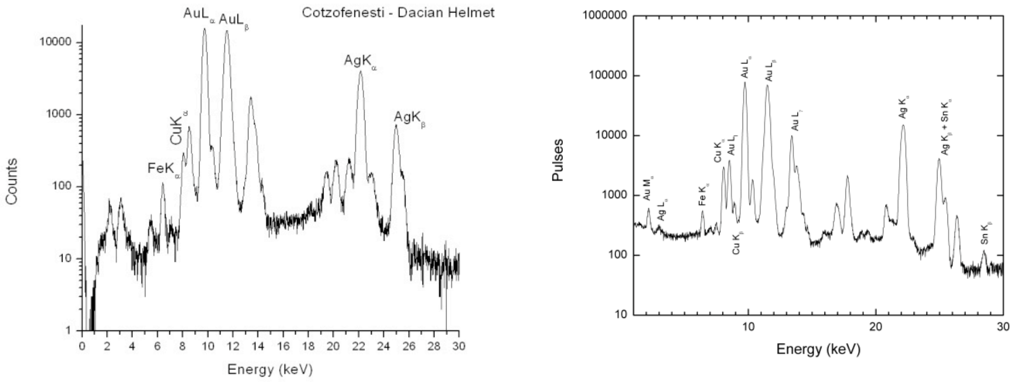
In the frame of archaeometrical research using nuclear and atomic analytical methods as Ion Beam Analysis (IBA) and X-Ray Fluorescence (XRF) two directions will be developed: archaeometallurgy and archaeological geology.

In archaeometallurgy, the composition of ancient artifacts – mainly gold, silver and copper-bronze – is studied, from elemental analysis to layers structure techniques as gilding and silvering. These aspects are essential for authentication – provenance studies on valuable Cultural Heritage items – jewelry, coins, adornments, toreutics, weapons, and other museum objects. For archaeological geology the goal is to characterize minerals sources (mines, placers, geological deposits) for metals, gemstones, obsidian, inorganic pigments and to compare them with the similar materials used in artifacts – gold, silver, copper, lead, obsidian, garnets, rubies, ceramics pigments in order to obtain provenance information – ancient workshops, technologies, long-range trade routes, historical commercial and military aspects. Studies on painted art objects – pictures, icons, wood sculptures, manuscripts, etc – will be also started for authentication/provenance conclusions. For all the Cultural Heritage artifacts the problem of forgery detection (authetication) is essential. The totally non-destructive analytical methods used will be XRF – especially portable and micro-spot equipment, Particle Induced X-ray Emission (PIXE) – especially the micro-PIXE investigation (micrometric beam of protons for micro-structural investigations), Synchrotron Radiation X-Ray Fluorescence (SR-XRF) – especially the micro-SR-XRF procedure.

X-ray tube Portable XRF Spectrometer

Am-241 XRF Spectrometer

A new non-invasive (only micrograms of sampling needed) method – LA-ICPMS will be also used for trace elements detection down to the ppb level. This type of research demands multidisciplinary teams – physicists, chemists, archaeologists, geologists, conservators, art experts, both in the frame of the Institute and in institutional networks (physical research units, museums, universities, art&archaeology institutes).



Spectra analysis of Dacian gold helmet and gold bracelet

Applications of irradiation techniques with photons for preservation of cultural heritage objects will be pursued in the future.

6.6 Particle accelerators and AMS studies

Electrostatic accelerators

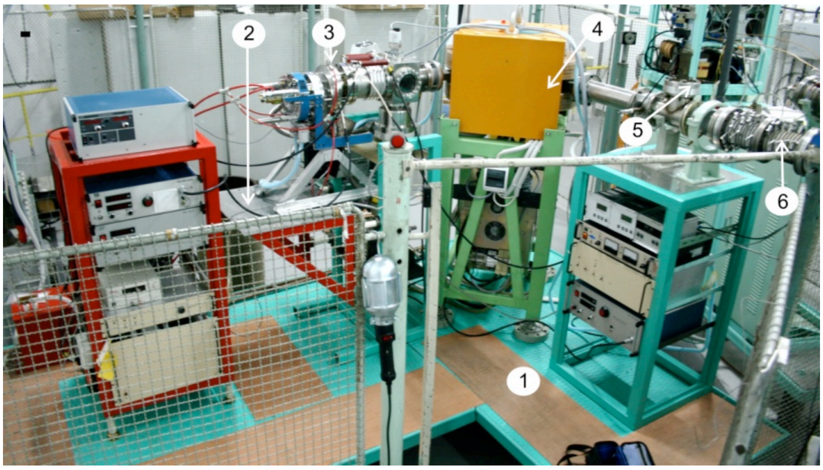
At present the FN Tandem Accelerator in IFIN-HH is the biggest machine of its kind in this region of Europe. The main research infrastructure around the machine consists of the following major experimental setups: the setups dedicated to nuclear structure (mixed multi-detection array consisting of HPGe detectors and fast LaBr3:Ce scintillation detectors), the setups dedicated to RBS, PIXE, ERDA type of experiments, a spectrometer for separating the fusion evaporation reaction products, a neutron array and the AMS system consisting of a very clean sputtering ion source with multiple cathode holder and a dedicated beam line. In the next years another two electrostatic accelerators will be installed on IFIN-HH site. The radiocarbon AMS system based on a 1 MV Tandem (TANDIMED) accelerator and a 3 MV Tandem accelerator (EMMAS) part of a big infrastructure project. The radiocarbon accelerator will be dedicated to environment and biosciences. The AMS system will be dedicated for measuring carbon, aluminum and beryllium, but also measuring other elements will be a goal of the research. The EMMAS center will consist of a 3 MV accelerator system including sputtering and alpha ion sources, Tandetron accelerator, ion beam analysis chamber with micro-beam implantation chamber. These are machines for to scientific research works, with a high degree of versatility. Therefore a constant technical research activity should be dedicated to the field of electrostatic accelerators and ion optics.

Accelerator Mass Spectrometry (AMS)

The Accelerator Mass Spectrometry (AMS) is a modern analyzing method that has the highest analyzing sensitivity known today, which is 10^{-16} (ratio: isotope/element). This sensitivity is equivalent to the real possibility to select and register one single type of atom from one million of billions atoms of other types. Such facilities are working all over the world in developed countries bringing important benefits to our life and knowledge on our planet. The AMS laboratory of IFIN HH has a ten years experience in performing sensitive analysis for *Nuclear physics* measuring of nuclear cross sections of transmutation reactions, for Environmental *physics* detection of the attendant effects of routine nuclear releases from nuclear facilities, for the *Atmospheric physics* the characterisation of stratosphere-troposphere exchange processes and determination of the fall out of cosmogenic produced isotopes, for *Nuclear fusion experiments and Tokamak reactors* measurements for diagnose of the plasma confinement, plasma heating, Neutral Beam supplementary heating and its interactions with the plasma, for the divertor ensemble the inventories of particle accumulation and spatial distribution on the protection tiles, rapid inter-comparison of detritiation techniques based on Laser beam, for the investigation of hydrogen retention in special materials devoted to nuclear facilities. Other AMS analysis were performed to establish the content of ^{11}B and ^{10}Be in special carbon materials.

The Romanian AMS facility was constructed at the 9 MV-HVEC-FN15 TANDEM accelerator in Bucharest. It consists of an ion injector deck, the accelerator, a Wien velocity filter and the ion detection system. The injector deck was recently upgraded and a new ion source form NEC (40 sample MC-SNICS) was introduced. For ions of different mass range the AMS facility has three detection systems: a detector array of three sequential PIN diodes, a gas filled Bragg-ionization chamber and an E-DE gas field Bragg detector with TOF.

In accordance with the Key Issues for Environmental applications of NuPECC LRP 2010, in the near future a new and more compact AMS system, based on a 1.0 MEV tandetron, will be installed in Bucharest. It will open the possibility of measurement of heavier log-lived isotopes (up to ^{240}Pu) and to extend the applications performed until now. It is envisagement to expand the present applications and to start new and important AMS researches as will be listed below.



The new upgraded ion injector deck of the AMS facility in Bucharest:
1) Injector deck polarized -100 kV, 2) second platform, polarized -30 kV with respect to the injector deck,
3) the 40 NC-SNICS,
4) the analyzing magnet,
5) Slits and retractable Faraday Cup,
6) pre-acceleration NEC tubes.

For pharmaceutical products. AMS with ^{26}Al and ^{14}C will be used for fast validation of new products. The high sensitivity of AMS for ^{26}Al and ^{14}C detection permits a new approach in the research of new products concerning their metabolism and kinetics. The extremely small quantities (micro dosing) of substances labelled with ^{26}Al or ^{14}C will shorten the duration of the testing procedures by about 50%. In the USA this is already a common employed procedure.

Medicine. AMS with ^{26}Al will be used to study the bio-kinetics of Al and Al compounds and adjutants. Such investigations will be carried out in co-operation with medical clinics.

Earth, Climate and Environment. AMS with ^{36}Cl, ^{26}Al and ^{10}Be will be used to measure the erosion rates of rocks and of the Earth's crust, lake sediments etc. The use of the cosmogenic produced radionuclides (^{36}Cl, ^{10}Be, ^{26}Al), measured by AMS in different compartments of the environment makes possible to obtain data about climatic changes and atmospheric exchange processes. Similar studies were performed by our laboratory in the past and there exists a data base of interpretation models and the associated computer codes.

Nuclear pollution. It is our future aim to establish an international scientific network with the task to monitor and prevent nuclear activities having negative impact on the environment and human health. The nuclear monitoring activity will extend over a large geographical area (Europe, Asia, Africa, South America and Antarctica). Therefore, the general level of nuclear pollution in water, soil and air, will be monitored. A reconstruction of the modern history of nuclear contamination will be also established.. The following isotopes will be measured by AMS in the environment; ^{3}H, ^{129}I, ^{239}Pu, ^{240}Pu.

*Fusion Energy production***.** Envisioning the future International Experimental Fusion Reactor (ITER), special interest is paid to the AMS depth profiling measurement of Tritium and Deuterium. Introduced as gas or produced by the DD fusion reaction, Tritium is partially deposited in the protection tiles of the vessel walls of the Tokamak. Since in a Tokamak, the energetic Tritium is released from the DD reaction with 1.1 MeV depth measurements of T concentration provide interesting information about the kinematics of the plasma particle inside the fusion reactor. AMS is able to characterize the plasma confinement and stability, the quality of neutral beam injector and its perturbing interaction produced on the plasma confinement. It localizes the plasma disruption phenomenon and provides the dosimetry of the energetic tritium in the Tokamak. For the divertor assembly it determines the efficiency of the magnetic field by eliminating the low energetic particles that contribute to the heat dissipation. Furthermore, AMS is able to perform a rapid and sensitive comparison of the remnant T content in various PFC materials after the application of laser detritiation techniques. All these applications will be continued in the future and are requested by the JET EFDA association. The new AMS facility will be able to perform measurements of actinides and participate in the international network of detecting undeclared nuclear facilities or illicit traffic of nuclear materials. The ratio ^{240}Pu/^{239}Pu is a good fingerprint to detect weapon nuclear reactors.

6.7 Metrology of ionizing radiations and radionuclide metrology

As a result of working with radioactive isotopes and ionizing radiations, inside the Romanian nuclear physics community has been accumulated a very high level of competence regarding the metrology of these two items.

Concerning the metrology of ionizing radiations, there are now in Romania accredited and internationally recognized the competences on **(a)** the calibration of the dosimetric instruments dedicated to the dosimetry for the radiological protection and for the environment and **(b)** the characterization of the medical X-ray radiological equipment. This recognized competence is used now and will continue to be used for researches regarding

- the development of standards

- the development of calibration methods
- for the dosimetric equipment used in the new techniques for radiodiagnostic and radiotherapy (hadrontherapy)
- the development of the calibration methods for the dosimetric instruments dedicated to the measurement of dose rates at the natural radiation background (and lower).

For radionuclide metrology, Romanian primary activity standard is equivalent at international level CIPM (Comité International des Poids et Mesures), being included in all annexes A-D, of the (CIPM-MRA) and EURAMET (European Association of the National Metrology Institutes. At national level, the entire metrological traceability chain is assured for many domains, as: health, food and environment survey, etc. The present and future objectives of the radionuclide metrology in Romania are:

- Development of new methods and equipment for primary standardization of radionuclides of interest for: energy, industry, environment and health; enlargement of the international equivalence of the primary Romanian activity standards
- Development of new types of radioactive standards (reference materials) and calibration services for assurance of national metrological traceability
- Determination and evaluation of the decay data for radionuclides.

6.8 Radiation Transport Research

Numerical simulations of the ionizing radiations behavior in matter are key ingredient for most of the Nuclear Physics applications. In particular for the research pursued in Romania the developments of advanced radiation detectors, nuclear energy, environmental studies radioprotection and nuclear medicine are the most relevant applications to benefit from the Radiation Transport Research.

Nowadays, there are developed internationally recognized computer codes for radiation transport studies. These are MCNPX (Los Alamos), GEANT, FLUKA (CERN), PHITS (Japan) and GESPECOR. There are few research groups in Romania, using at professional level these codes for different applications. It is important to underline the fact that these codes use as input nuclear data libraries and an open problem is the precise evaluation of sensitivities of these codes to the cross section.

Future research in this field is based on the existing Romanian competences and refers to the following subjects:

- Precise modeling of radiation detectors with GESPECOR and GEANT codes;
- Detailed modeling of the interactions of heavy charged particles with biomaterials required by the hadrontherapy and other radiotherapy techniques, with FLUKA, PHITS and MCNPX codes;
- Advanced radioprotection and dosimetry calculations required by the ELI-NP Project and the new accelerators, by using FLUKA and MCNP codes;
- Studies of sensitivity of the radiation transport codes at the nuclear data required as input;
- Simulation of radiation transport in the environmental systems as required by the nuclear waste storage activity;
- Specialized educational programmes in this field established at Romanian universities in closed collaboration with the research institutes. Strong competences in the physics of radiation interaction with matter and advanced software

development are highly required by this research subject. A well developed national school for radiation transport and radioprotection calculations, with competences proved at international standards is a matter of national interest;

- A coherent endeavor is highly recommended for the Romanian research teams to enter the "code developer teams" also for the CERN and Los Alamos based radiation transport codes.

6.9 Recommendations

Specific recommendations for each subject are given in the previous sections. Further on are synthesized the ones with more general impact on the future development of the future Applied Nuclear Physics projects in Romania.

Nuclear Energy

The following subjects has to be pursued by the future Romanian research in Applied Nuclear Physics, in close collaboration with international teams and programmes:

- *Physics of the Generation IV nuclear reactors and advanced fuel cycles;*
- *Research related with nuclear waste management and decommissioning of the nuclear installations;*
- *Nuclear data evaluation including co-variances and novel measurements;*
- *Nuclear physics input for fusion research in collaboration with ITER Project;*
- *Forming young scientists to work in the field, here including both experimental abilities and the ability to work with complex, state of the art simulation codes.*

Life Sciences

- *Research on new radioisotopes for diagnostic and treatment, especially based on the new experimental facilities;*
- *The radiobiological studies will be oriented towards the understanding of the low dose irradiation effects on circulatory and nervous systems;*
- *Neutron activation of nanoparticles using a cyclotron;*
- *Toxicological studies (performed in vitro and in vivo) on radio-pharmaceuticals;*
- *Developing detectors, experimental configurations and data acquisition systems for the new 3D tomografic systems, including PET.*

Environmental Applications

- *Create a database for monitoring of all environmental radioactivities in order to obtain useful statistical information requested at national and international level;*
- *Participation in intercomparison exercises with other European research institutes;*
- *Measurement of very low specific activities of different samples and materials in ultra-low radiation background. Developing of new techniques to improving limit of detection in natural radioactivity measurement (U, Th, Ra, Rn, Cs, Be);*
- *Measurement of atmospheric muons in underground and on surface.*
- *Improving luminiscence measurements for different systems (loess, send, delta sediments) with palaeclimatological applications;*
- *Erosion soil studies and sedimentation in hydrological basins using Cs-137 and Pb-210.*
- *Implementation of remedial measures for radon mitigation in old and new buildings.*
- *Studies on atmospheric radioactivity by alpha and gamma spectrometry. Thoron studies and its contribution to the natural exposure.*

Nuclear Methods in Material Science

The goals of applied nuclear research in this subject are:

- *To extend at the new facilities the Ion Beam Analysis (IBA) techniques: Rutherford Backscattering Spectrometry (RBS), Elastic Recoil Detection Analysis (ERDA), Non-*

Rutherford Backscattering Spectrometry (NRBS), Proton Induced X-ray Emission (PIXE);

- *To develop neutron, charged particle and (at ELI-NP) photon activation techniques;*
- *To develop micro-beam applications in material science;*
- *To develop of a slow positron device able to accelerate positrons at energies in range of tens keV. This kind of device will be able to deliver thermalized positrons at various depths in thin films (from tens of nanometers to few micrometers);*
- *To enlarge the use of positrons in more fields like Positron-excited Auger Electron Spectroscopy (PAES);*
- *To exploit the brilliant positron source at ELI-NP;*
- *To find new applications for material processing and sterilization in high radiation fields.*

Cultural Heritage, Arts and Archeology

- *To develop the tomography techniques in Archaeometry;*
- *Extending Ion Beam analysis and X-Ray Fluorescence methods in this subject;*
- *To enlarge collaborations with other institutions (non-physics) involved in the scientific research on this subject.*

Particle accelerators and AMS studies

- *A constant technical research activity should be dedicated to the field of electrostatic accelerators and ion optics;*
- *AMS studies should be pursuit at the two national facilities. A close collaboration with the European network on the field must be followed.*

Metrology of ionizing radiations and radionuclide metrology

- *Development of new methods, equipment and standards required at national and international level*
- *Ensure constant contacts with national industry to facilitate the technological transfer in the field*

Radiation Transport Research

- *Advanced radioprotection and dosimetry calculations required by the ELI-NP Project and the new accelerators, by using FLUKA, GEANT and MCNP codes;*
- *Entering European projects dedicated to radiation transport simulations for the new radiotherapeutic techniques, e.g. hadronic therapy;*
- *Establishing specialized educational programmes in the field of radiation transport. Creating strong competences in the physics of radiation interaction with matter and advanced software development, highly required by this research subject. A well developed national school for radiation transport and radioprotection calculations, with competences proved at international standards is a matter of national interest;*
- *A coherent endeavor is highly recommended for the Romanian research teams to enter the "code developer teams" also for the CERN and Los Alamos based radiation transport codes.*

General Recommendations

- *Support for the existing and future Romanian infrastructure in Nuclear Physics: Tandem Van de Graaff 9 MV, 3 MV, 1MV accelerators and TR19 Cyclotron, to become recognized European Research Infrastructures.*

- *Strongly recommend approval and funding of the new project ELI-Nuclear Physics*

- *Recommend full and steady financing of the research related to the European large-scale facility especially at those where Romania is a member: FAIR, CERN and IUCN.*

- *Strongly recommend continuous and predictable funding of the Nuclear Physics research, to avoid any short and long-term negative effects generated by large fluctuations of the funding level from one fiscal year to another.*

- *To strengthen the participation in pan-European collaborations in low-energy nuclear physics, nuclear astrophysics, astroparticle physics and hadron physics.*

- *Full support of the theory development needed to address the challenging basic issues that exist or may arise from new experimental observation*

- *Further develop the applications of nuclear physics in energy generation, medicine, material, cultural heritage, environment and security*

- *To support broad educational programmes in Science and Technologies as basis to attract younger generations in physics research and in Nuclear Physics in particular.*

Annex:

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2. *Nuclear Physics at Low Energies*

2.2.1. Weakly bound nuclei

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