CHAPTER 1
THE PHYSICS CASE

1.1 Nuclear Physics

The atomic nucleus is the paradigm of finite, many-body systems, where quantal size effects play a central role. So far, our knowledge on nuclear structure has been mostly gained by studying nuclei near the valley of beta stability or on the neutron-deficient side, with respect to the variables of excitation energy and spin. New combinations of proton and neutron numbers, i.e. the isospin degree of freedom, are expected to provide new information on the nuclear forces. New effects will be discussed in the following as a motivation for the design and construction of a facility devoted to acceleration and experiments with neutron-rich radioactive nuclei.

The main goal of the proposed facility is to provide an accelerator system to perform forefront research in nuclear physics by studying nuclei far from stability. In its first configuration, the SPES project is concentrating on the production of neutron-rich radioactive nuclei with mass in the range 80-160. However, this accelerator system will allow to produce also lighter ions or proton rich nuclei by adding, in a second phase of the project, few elements to the accelerator complex. The emphasis to neutron-rich isotopes is justified by the fact that this vast territory has been little explored, if one excepts some decay and in-beam spectroscopy following fission. Therefore, reactions in inverse kinematics will allow a new class of data to be obtained.

The final energy of the radioactive beams on target will range from few MeV/u to approximately 20 MeV/u. This energy allows to overcome the Coulomb repulsion between the radioactive beam and the target nuclei in most systems and opens up new possibilities for experimental studies of neutron-rich nuclei employing different reaction mechanisms such as Coulomb excitation, inelastic scattering, single-and multiple-nucleon transfer, fusion reactions, etc. Such reactions not only provide invaluable nuclear structure information but they also allow to reach nuclei even further away from the stability line. Beams of neutron-rich nuclei offer better chances to synthesize heavy elements because the fused system will be less neutron deficient, therefore closer to the valley of stability and with better chances to survive. It must be mentioned too that the very high intensity of the driver accelerator will produce unprecedented amounts of radioactive isotopes far from stability available for investigations without being post accelerated.

In addition to pure nuclear structure aspects, radioactive beams will have a number of applications e.g., at very low energy (traps for fundamental tests of symmetries in decay spectroscopy), at low energy (reactions of astrophysical interest performed in inverse kinematics). As for interdisciplinary applications the availability of intense neutron fluxes will allow specific programs in the field of cancer therapy, and material sciences.

Overview

The outstanding constrain on our ability to further advance our understanding of nuclear physics has been the fact that, in any nuclear reaction chosen for the study, both the beam and target species must be stable. This imposes a severe restriction on both the type of information, which can be obtained, and the regions of the nuclear chart, which can be accessed. The most
critical ingredients in determining the predicted properties of a nucleus from a given effective interaction, are the overall number of nucleons and the ratio N/Z of neutrons to protons. It is the extremes in these quantities, which define the limits of existence for nuclear matter that will be opened up for study with radioactive beam accelerators.

As neutrons are successively added to a nucleus on the stability line, the binding energy of the last neutron decreases steadily until it vanishes and the nucleus decays by neutron emission. The loci of the nuclei where this happens defines the neutron drip line. It lies much further away from the valley of stability than the corresponding drip line associated with protons. This is due to the absence of electrical repulsion among neutrons. The location of the neutron drip line is only known for nuclei with mass up to around 30.

The interest in the study of nuclei with large neutron excess is not only focused on the location of the drip line but also on the investigation of the density dependence of the effective interaction between the nucleons for exotic N/Z ratios. In fact, changes of the nuclear density and size in nuclei with increasing N/Z ratios are expected to lead to different nuclear symmetries and excitation modes. While in the case of some very light nuclei a halo structure has been identified, for heavier nuclei the development of a skin of neutrons on the outside of the nucleus has been predicted. New modes of collective motion are expected in connection with this phenomenon, namely oscillations of the neutron skin against the core, similar to the soft dipole mode already identified in the case of very light halo nuclei. Presently, neither the thickness, nor the detailed properties of the neutron skin of exotic nuclei are known. This information is, on the other hand, needed to enable a quantitative description of compact systems like neutron stars, where exotic nuclei forming a Coulomb lattice are immersed in a sea of free neutrons, a system which is expected to display the properties of both finite and infinite (nuclear matter) objects.

A key aspect related to changes in size and diffusivity encountered in neutron rich nuclei is the modification of the average field experienced by a single nucleon. This is a basic ingredient in the many-body theories used to describe nuclear properties. Therefore it is very important to study experimentally how the single-particle levels shift or re-order with neutron excess, inducing changes in shell gaps and, possibly, even the breakdown of the standard magic numbers.

Another important frontier of nuclear physics, which could be probed by SPES, concerns that of the maximum values of charge and mass, which a nucleus can accommodate. The number of elements, which can be created in nuclear reactions, is limited by the increase with nuclear charge of the fission, and proton emission probabilities. Indeed, within the charged liquid drop description of the nucleus, a nucleus with Z > 104 would fission spontaneously. However, the description of the nucleus as a quantal system results in a overall energy which is a combination of the macroscopic liquid drop energy and the microscopic single-particle energy. The latter term gives rise to a stabilizing effect when the neutron and proton configurations coincide with closed shell-like structures, as a result from the underlying mean field. This additional stability enhances the probability for super heavy nuclei to survive sufficiently long so that their properties can be measured. The present predictions concerning the new expected shell closures are in contrast with one another, proposing either Z = 114 or Z = 126 as the next magic number.

The physics of the proton drip line and that of the nuclei with N=Z can also be addressed by the proposed facility because the driver will also be able to accelerate heavy ions. Fusion evaporation reactions induced by heavy ions produce heavy neutron-deficient nuclei that can be post-accelerated by the linac system but also be directly available for spectroscopy after some kind of separation or of identification. The study of the proton decay is an important tool to provide information on the structure of nuclei even beyond the proton drip line owing to the Coulomb barrier. Other issues at N ~ Z are isospin symmetry and the observation of proton-
neutron Cooper pair formation as a very important element in a realistic description of the proton-neutron effective pairing interaction.

The potential key role of radioactive beams in the field of nuclear astrophysics is mainly related to the problem of nucleosynthesis. It deals with the reactions at astrophysical energies in inverse kinematics for light nuclei and in measurements of beta-decay, gamma, and n-capture rates in medium mass very n-rich nuclei along the so called r-process path.

Following the issues mentioned above the SPES project proposes an ISOL facility to be built at LNL, planned for acceleration of radioactive beams up to approximately 20 MeV/nucleon. The high-intensity beams open new possibilities in nuclear structure physics, nuclear astrophysics, as well as in reaction dynamics studies. The planned experimental studies of nuclei produced at SPES are not merely driven by the attempt to reach farther out of the known region of the nuclear chart towards the most exotic nuclear species. At new combinations of nucleon numbers, especially large neutron excess, new aspects of nuclear properties have been predicted and are expected to be observed at the proposed facility that should allow a more complete approach of the description of the nucleus. A few of these nuclear physics related subjects will be described here. These subjects represent only a few selected topics of interest in nuclear physics that can be addressed with the proposed facility.

1.1.1 Nuclear Structure

The understanding of the evolution of nuclear properties towards the neutron drip line depends on how the shell structure changes as a function of neutron excess, an evolution which has consequences, among other things, on the ground state properties (spin, parity and electromagnetic moments) and on the single-particle and collective excitations. Many phenomena may affect the shell structure such as the isospin dependence of the effective interaction, in particular the spin-orbit term.

While shells and magic numbers are important to determine the properties of the atomic nucleus, polarization effects can be as important to determine its structure. Specifically, there are collective effects involving several to all nucleons in the nucleus and leading to a variety of phenomena such as vibrations, rotations and giant resonances. They are driven by correlations among nucleons. Collectivity leads to deformation and a weakening of the (spherical) shell structure. Much of the richness of nuclear structure derives from the interplay between these competing tendencies, namely the interweaving of single-particle and collective motion, and their subtle dependence on nucleon number.

To investigate the nuclear structure properties it is very important to determine how the nucleus reacts to rather gentle external perturbations such as those induced by Coulomb excitation and inelastic scattering between two reacting nuclei. These reactions are known to probe well the characteristic collective motions such as vibrations and rotations of the nucleus as a whole.

In the case of radioactive beams few measurements of proton inelastic scattering have been made in inverse kinematics and results concerning the excitations of low lying vibrational states of quadrupole and octupole characters were obtained with beam intensities as low as \(10^3\) -\(10^4\) pps (experimental data concerning the study of \(^{20}\text{O}\) are shown in Fig. 1.1).

A combination of Coulomb excitation (sensitive to the electromagnetic part of the nuclear interaction) and proton and deuteron inelastic scattering (sensitive to both electromagnetic and strong interactions) will provide information on the proton and neutron contribution to the matrix elements connecting the ground state with excited states. In nuclei along the line of stability, the ratio of the proton to neutron matrix element, \(M_p/M_n\), is known to be investigated with a
combination of \((p,p')\), \((d,d')\) \((e,e')\) and \((\pi,\pi')\) reactions, qualitatively given by \(Z_\nu / N_\nu\) where \(Z_\nu\) and \(N_\nu\) are the numbers of valence protons and neutrons. Along the stability line, protons and neutrons occupy the same or neighboring shells and thus the dependence on the spatial extent drops out. In neutron rich nuclei the situation is rather different and the ratio \(M_p/M_n\) might be modified to \(Z_\nu <r^2>_p / N_\nu <r^2>_n\), that is including a dependence on the root mean square radius of protons and neutrons. The latter may be considerably larger than the former. Therefore, measuring the \(M_p/M_n\) ratio can test whether our standard picture of the wave function of low-lying collective states in nuclei, remains true far away from stability. Theoretically, an increasing isovector character is expected for these states in \(n\)-rich isotopes.

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**Fig. 1.1 - Left panel:** Scatter plot of recoiling proton energy versus scattering angle in the laboratory frame for \(^{20}\)O beam at 43 MeV/A. The very intense line (g.s.) corresponds to elastic scattering. The curves correspond to the expected loci of the 2\(^+\) and 3\(^-\) excited states of \(^{20}\)O, respectively. **Right panel:** Elastic and inelastic angular distributions. The lines are calculations including ground states and transitions densities obtained with HF+BCS and QRPA models [1].

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**Energies of the lowest collective states**

The location of already a few lowest-lying excited states provides crucial information on the structure of the nucleus. This will tell us whether nuclear structure is strongly modified as we approach the dripline. In particular, the studies of even-even isotope chains carried out along the valley of stability have provided a wealth of information on the interplay between pairing correlations and quadrupole surface distortion in nuclei. We refer here to the location of the first excited 2\(^+\) state and of the 4\(^+\), 2\(^+\) and 0\(^+\) states and of transition rates. Near closed shells the properties of these states are dominated by the coupling between particle-hole and two particle-two hole excitations while far away polarization effects lead to symmetry breaking (deformation) and to development of rotational bands. The understanding of these phenomena at large neutron excess making use of collective models, of nuclear field theory, and of algebraic approaches are expected to provide much insight on the mechanisms which are at the basis of atomic nuclei.

In general, dynamical symmetries provide elegant and analytic paradigms for the behavior of a wide variety of physical systems, ranging from molecules to elementary particles, while nuclear field theory and shell model calculations allow for a detailed microscopic description of these states in terms of the motion of particles and of their coupling with external and internal fields.
Below we illustrate the evolution of nuclear structure in terms of the number of valence nucleons and the corresponding algebraic descriptions related to symmetry groups like U(5) (spherical vibrational nuclei), SU(3) (axially deformed nuclei) and O(6) (unstable nuclei).

The basic idea is sketched in Fig. 1.2, where the ratio of the energies of the first 4+ and 2+ states is shown for nuclei, which span a vibrational to axial-rotor region. Included in the figure are sketches of the potential at different stages along the structural evolution. There are two competing minima, spherical and deformed, in the potential. At the critical point, these two minima cross and the nuclear shape changes from spherical to axially deformed (as discontinuously with nucleon number as the finite nature of nuclei permits). This behavior is reflected in the sharp rise of the ratio of the energies of the first 4+ and 2+ states. Nuclei at the critical point of a vibrator to axial rotor phase transition are well described with a new analytical description which has been introduced with the development of a new class of symmetries based on the solutions of differential equations (dynamical symmetry denoted with X(5)) (Fig. 1.2).

**Fig. 1.2 - Left:** Schematic representation of the phase transition from spherical to deformed shapes taking place in Sm isotopes as a function of neutron number (the experimental points are shown with open circles). **Right:** The ratio of the experimental energy of the yrast states to the energy of the lowest quadrupole excitation for Nd and Sm isotopes in comparison with the predictions of different coupling schemes (adapted from Ref. [2]).

The extent to which these features are modified in very neutron rich nuclei is not clear. The large neutron excess might tend to stabilize spherical shapes, as in the case of Sn isotopes. It is also not clear whether triaxial shapes, which do not appear to be predominant in the ground state configurations of nuclei measured up to now, are present in neutron rich nuclei, where the neutrons occupy shells with a much larger spatial extent than in the case of stable nuclei.

In completely unexplored regions as for example the medium heavy mass region (see Fig. 1.3) which is accessible with the proposed facility, the simplest-to-obtain data concerning the first 2+ and 4+ states can provide, as shown above, clues of structural changes. An analysis of experimental trends in terms of structurally significant quantities can reveal new properties of the nuclear interaction. One such quantity, which reflects the importance of the proton-neutron interaction among valence nucleons, is, within the framework of algebraic models, the simple product of the number of valence protons and of the valence neutrons. In exotic neutron-rich nuclei the major shell gaps possibly change. This phenomenon is a consequence of the predicted more diffuse surface that weakens the spin-orbit splitting. This could modify the standard gaps and, consequently, the number of nucleons contributing to the valence space. This may cause
the breakdown of the smooth empirical relations established near stability, providing in that way a clear signature. In addition, close to drip lines, should pairing drastically change due to the scattering of pairs into continuum states, these empirical relationships may be expected to break down as well.

Another important measurement, which could be carried out with the new facility, is that of mapping out the location and properties of the low-lying negative parity states in even-even nuclei. The low-lying negative parity states are dominated by octupole correlations. The surface modes are important sources of renormalization of single-particle motion and of their interaction. In fact, most of the nucleon effective mass and about half of the pairing correlations among like and among n-p pairs of nucleons arise from the exchange of these modes. When a large neutron excess is present the system becomes highly polarizable and the renormalization effects are expected to become very important, in particular because also of the possible presence of low-lying "soft" dipole modes.

![Chart of Nuclides](image)

**Fig. 1.3** - Part of the chart of nuclides where the properties of the low-lying nuclear excitations of neutron rich nuclei could be mapped out by SPES (lowest right corner) similarly as was done in the case of proton rich nuclei with existing facilities (upper left corner). The numbers reported in the figure are (from the topmost to the bottommost line) the energy of the first $2^+$ state (in keV) the ratio of the energy of the first $4^+$ to $2^+$ state and the reduced transition probability $B(E2)$ in unit of electron-barns squared.[3].

**Shell structure**

The structure of the atomic nucleus is well described by the shell-model, which is based on a picture where nucleons generate a potential following their own distribution and where a single nucleon experiences a mean field generated by all the others. The nucleons are arranged in shells, each one able to contain up to a certain number of nucleons determined by quantum numbers. The magic numbers correspond to fully occupied shells. A sizeable energy gap appears between the last occupied and first unoccupied shell and provides extra stability to this particular combination of nucleons. Magic numbers are well established for nuclei along the stability line and for most radioactive nuclei known presently. There are a few exceptions of unexpected magicity but of local character, e.g. $^{68}\text{Ni}$, $^{96}\text{Zr}$, $^{146}\text{Gd}$ due to large subshell gaps at $N=40$, $Z=40$ and 64.
For neutron-rich nuclei far from stability the vanishing of the classical shell gaps and the presence of new magic numbers might however occur. A very diffuse surface and a weakening of the spin-orbit splitting have been proposed as possible causes of the so-called "shell quenching", particularly in the vicinity of the drip line. The spin-orbit splitting plays an important role in the binding and structure of nuclei. In fact, the introduction of spin-orbit splitting of the nucleon orbitals in the nuclear mean-field potential has been a landmark in the development of the nuclear shell model. Depending upon the relative orientation of the intrinsic spin and the orbital angular momentum, the energy of the level is either pushed up (if antiparallel) or down (if parallel). This effect generates the magic numbers as we know them for nuclei close to stability. New magic numbers could be similar to those produced by a harmonic oscillator when switching off the spin-orbit coupling. In this case, the neutron and proton numbers 40 and 70 may become magic. These predictions can be tested by measuring energies and occupation probabilities of single particle states and measuring the collectivity of low-lying vibrational states in nuclei with neutron and proton number around N, Z = 40, 50, 70.

Presently efforts are also being made to infer the single-particle properties of unstable nuclei along the r-process path by studying the r-process component of the solar system abundances of heavy elements. In Fig.1.4 the results of r-process calculations are illustrated for various assumptions of “shell strengths”. A quenching of the shell effects at N=82 and N=126 can lead to clear improvements between the calculated and experimentally determined abundances of nuclei around A = 118, 176, and above 200.

![Fig. 1.4 - r-process abundance (shown with dots) determined experimentally in comparison with two calculations, which differ in the strength of the spin-orbit interaction. A spin-orbit splitting weaker at the drip line than for stable nuclei gives a better agreement with the data. Adapted from Ref. [3].](image)

In Fig. 1.5 the shell gaps predicted for the neutron magic numbers N=50, 82 and 126 are shown as a function of the atomic number Z. It is interesting to note the sizeable reduction of the shell gap for the N=50 isotones $^{82}$Ge and $^{80}$Zn. These nuclei are expected to be easily accessible with SPES.

Considerable experimental effort has been devoted recently to the study of shell closures at N=40, 50 and 82 in the isotopes around $^{68}$Ni, $^{100}$Sn and $^{132}$Sn. These works have been made possible by the first generation of radioactive beam facilities at GANIL and GSI based on projectile fragmentation. In particular, for a number of isotopes of Ni with 28≤N≤40 and for Sn isotopes with 70≤N≤84 the energy systematics of the lowest-lying $2^+$ states could be established. Let us concentrate, on the N=82 shell closure in unstable nuclei that has only been partially investigated. The SPES facility will eventually offer the opportunity to probe not only $^{132}$Sn in...
detail but also the neighbouring nuclei including those with the valence neutrons above the gap. The very high value of the $2^+$ state of $^{132}\text{Sn}$ fits well with the expected doubly magic character. A definitive proof would be the measurement of reduced transition probabilities, which still is missing. Studies of the more neutron-rich isotopes, are especially interesting for the single-particle structure above $N=82$ and to see how the residual interaction between valence particles behaves far from stability. For this last purpose, spectroscopic data for $^{134}\text{Sn}$ would be highly instrumental. Moreover, while different effective forces predict rather similar excitation energies of low-lying collective surface vibrations for instance in $^{132}\text{Sn}$ and $^{134}\text{Sn}$, they predict reduced transition probabilities differing by factors of two. This is a serious limitation in the understanding of the effective nuclear forces, which could only be overcome with new and detailed data on these unstable nuclei. Data in this region have been obtained so far by decay spectroscopy. New opportunities with SPES will be transfer reactions performed in inverse kinematics.

One-particle transfer reactions will allow not only to determine the position of the single-particle states (providing information on the effective mass), position which in some cases have been measured in decay spectroscopy (see Fig. 1.6), but also their occupation probabilities via the spectroscopic factors.

These latter indeed provide detailed information on the mixing of single particle states with more complicated configurations. The mixing is expected to be mainly with configurations containing a low-lying surface vibrational mode. Estimates of absolute one-particle transfer cross sections for (p,d) reactions indicate cross sections of the order of few mb/sr at bombarding energies in the interval of 5-10 MeV/u. With SPES the evolution of single-particle levels, of which only few are known, can be studied with transfer reactions involving medium-energy beams of nuclei around the $Z=50$ closed proton shell or the $N=82$ neutron shell.

**Fig. 1.5 - Values of the neutron shell gap predicted with a macroscopic model [4] for different isotones with neutron closed shells.**

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Fig. 1.6 - **Left panel:** Single-particle and single-hole levels of the $^{132}$Sn core. The experimental values (in the rightmost part from Ref. [5]) are compared with two predictions [6]. The one on the left is based on Hartree-Fock (HF) calculations with the SGII effective interaction while the one shown in the middle includes also the self-energy contributions from the coupling to collective phonons. **Right panel:** Spectroscopic factors associated with the different single particle (and hole) levels obtained in HF plus phonon coupling.

While the single-particle gap and $2^+$ excitation energy ($\approx 5$ MeV and $\approx 4$ MeV, respectively) could recall the situation similar to that of $^{208}$Pb ($\approx 4$ MeV for both quantities), the pairing correlation energies associated with the systems with two neutrons outside closed shell (i.e $^{134}$Sn and $^{210}$Pb) are approximately 0.7 and 1.4 MeV respectively. Two-particle transfer reactions are the specific tools to probe these correlations and to shed light on the apparent fact that $^{132}$Sn seems to be the best available closed shell candidate to date. Absolute cross sections of the order of 0.5-1 mb/sr are expected for these reactions. A related topic is the study of the spin-orbit splitting in $^{132}$Sn nucleus, namely those of the $g$ and $h$ levels governing the magnitude of the Z=50 and N=82 shell gaps.

According to certain model predictions, the energy splitting of these spin-orbit partners should decrease or even vanish far from stability for very neutron-rich isotopes. These conclusions were drawn independently from calculations of abundances of elements created in the r-process (see nuclear astrophysics). To extend our knowledge on the spin-orbit splitting far beyond the doubly-magic nucleus $^{132}$Sn is a prime subject for SPES.

Another manifestation of the shell structure is the presence of isomeric states. The spin-orbit interaction brings a high spin single-particle state among states of lower spin and opposite parity. Therefore isomers can occur if the energies are close enough. This situation occurs
preferently below major shell closures. Other isomers can occur if configurations are pure and isolated, which occurs in systems with few valence nucleons. Such a case is displayed by the nucleus $^{98}\text{Cd}$, being a two proton hole system with respect to the $^{100}\text{Sn}$ closed shell nucleus. Fusion evaporation reactions studied by the Euroball and Gammasphere collaborations indeed brought evidence for an isomeric $8^+$ state. Persistence of the shell closure for $Z = 50$ at $N=82$ implies the presence of such an isomeric state in the neutron-rich nucleus $^{130}\text{Cd}$.

**Static nuclear moments and nuclear masses far from stability**

Measurements of the electric and magnetic moments provide more detailed information on nuclear structure such as nuclear shape and composition of wave functions.

Electric quadrupole moments are closely related to the reduced transitions $B(E2)$ discussed in connection with collective properties. They therefore follow the same trends versus the number of valence nucleons. The quadrupole moment measures the deformation of the state. The technique used for neutron-rich nuclei has been mainly based on the lifetime of excited levels populated by beta-decay or in beam using fission. It will be possible with SPES to extract the $B(E2)$ value from the cross section for Coulomb excitation of the radioactive beam nuclei. In case of ground states the nuclei could be put to interact with laser light in order to exploit the hyperfine interaction (coupling the nuclear moments with the electromagnetic field created at the nucleus by the atomic electrons). For the measurement of even-even nuclei where there is no hyperfine splitting, the monopole shift of the resonance line is a sensitive tool to extract the nuclear deformation via the mean squared radius (see Fig. 1.7).

Magnetic moments of odd-even nuclei are particularly important since they provide information on the single particle configurations via the $g$-factor of the state.

This aspect is of interest since single particle orbitals might be strongly influenced by weak bindings. An example is given in Fig. 1.8 for the case of Xe isotopes. With radioactive beams, these studies can be performed either by using directly the high-energy radioactive beam, polarizing it by means of the tilted-foil method, or by introducing the polarization or orientation needed for the measurements using reactions such as fusion-evaporation.

Figure 1.9 shows a $g$-factor measurement recently performed at GANIL using the Time Differential Perturbed Angular Distribution (TDPAD) method to determine the properties of an $I^\pi = 9/2^+$ isomer in $^{67}\text{Ni}$. The experiment allowed comparison with shell model calculations, constraining in this way the theoretical possibilities to describe this nucleus. So far the TDPAD method is the only way to study $g$-factors of isomers in neutron-rich nuclei having lifetimes between 100 ns and 50 $\mu$s. Similar studies can be performed on other magic or semi-magic nuclei accessible with SPES, where as mentioned previously, there should be numerous isomers.

An experimental approach particularly suited to radioactive beams is the transient field technique, which allows to measure low-lying excited states populated by Coulomb excitation. Moments of states populated by this method can be deduced for levels with lifetimes ranging from less than a pico-second up to nanoseconds.
Fig. 1.7 Comparison between experimental changes in mean square charge radii (solid circles) and droplet model predictions corrected for quadrupole deformation calculated from B(E2) values (open circles). The droplet model isodeformation curves are shown as solid lines. A value of $< \beta^2 >^{1/2} = 0.125$ for $^{88}\text{Sr}$ was used as reference. The dashed lines indicate the systematic errors for the $\delta<r^2>$ values from the calibration procedure. (Adapted from [7]).

Fig. 1.8 - Magnetic moments of the ground states of odd mass Xe nuclei. The sudden change at neutron number $N=66$ is due to a change in single-particle configurations [8].
Fig. 1.9 - g-factor determination of a $I^+ = 9/2^+$ isomer in $^{67}$Ni. The ion arrives at $t=0$. The oscillation pattern $R(t)$ of the isomeric $\gamma$-decay is obtained by filtering out the exponential decay of the state. Its oscillation frequency is proportional to the isomeric g-factor [9].

Nuclear masses are one of the most fundamental nuclear properties. Masses of radioactive isotopes obtained as very low energy beams can be very accurately measured in ion traps or using time-of-flight methods. These methods are direct measurements. Progresses in trapping with respect to the accuracy and lower lifetime limit of the trapped radioactive ions are continuous. In decay studies the conventional method of measuring the end-point energy of the beta spectrum is probably still well adapted to the very short-lived and most exotic isotopes. It measures the differences between masses of mother and daughter nuclei and is therefore a relative measurement. With the advent of intensive neutron-rich beams SPES will allow to use reactions for mass measurements via the energy balance. This method is accurate but will require excellent beam quality or beam tracking devices to reconstruct the kinematics event by event.

Another domain where nuclear masses are a key parameter are calculations of abundances of elements created by the r-process. The gross decay properties, the half life and the probability for beta-delayed neutron emission $P_n$, are very sensitive to the decay energy, the Q-value. The former depends approximately on the 5th power of Q and the second on Q and the neutron separation energy in the daughter. At the equilibrium under the high neutron flux the waiting-point nuclei accumulate in proportion of their lifetimes. This implies a strong dependence of the abundances on Q, while the $P_n$-value controls the mass of the final nucleus after successive beta decays.

**Decay Spectroscopy**

The techniques to study excited states of nuclei are the in-beam and decay spectroscopy. The former is performed at the target with large detector arrays for light charged particles, gammas and neutron detectors. Extensions to very high spins are discussed in a following section. Decay spectroscopy assumes the nuclei to be implanted and be at rest when radiations are emitted. For decays of neutron-rich nuclei produced by fission beta, gamma, conversion electrons and beta-delayed neutrons must be detected. On-line mass separators have been the working horse for studies of neutron-rich nuclei, while the recent advent in the last decade of large arrays has allowed levels with higher spin and extended band structure to be observed. The two methods are complementary. The power of decay spectroscopy resides in its ability to populate low-spin non-yrast states. An excellent example is the identification of beta and intruder bands in even-even nuclei. The decay can proceed from ground states or isomers, sometimes offering a wide access to daughter states. A very good example is the beta decay of
Beta decay is not only the tool to populate excited states in the daughter nucleus but it carries very useful information. The end-point energy is the Q-value i.e. the mass difference between mother and daughter nuclei. The partial half-lives for the different branches to excited states give an indication of the character of the transition, therefore on the spins and parities of daughter levels. This method could well be the only practicable one for nuclei very far from stability. In neutron-rich nuclei Fermi transitions are impossible since nucleons occupy very different shells. Thus the fastest transitions are the Gamow-Teller ones where the intrinsic spin changes its orientation with respect to the orbital moment (spin flip). There is still a non understood quenching, meaning that experimental transition strengths are lower than the calculated ones. In general, the understanding of beta decay in heavy nuclei requires two renormalizations, one due to the quenching of the Gamow-Teller coupling constant ($G_A$) and the second due to the mixing of small components in the wave functions of the low-lying states coming from high-lying multiparticle-multihole excitations. Measurements of beta decay in these neutron-rich nuclei will help to understand to which extent these renormalization effects depend on the value of the isospin. In case of the most neutron-rich nuclei that can be produced with SPES the measurement of only gross properties will be possible. They nevertheless are of considerable interest for r-process calculations, by providing the required nuclear input from an experimental basis rather than from nuclear models. Thus, the fraction of beta feeding going to states above the neutron separation energy $S_n$ in the daughter gives the probability of beta-delayed neutron emission $P_n$. In nuclei at midshell, often deformed, the configurations are well mixed and the dependence of structural effects should be rather weak. However, in a spherical nucleus close to a magic number the configurations are rather pure. Consequently, the decay is likely to have a very strong single branch. If the final level is high and above $S_n$ there will be a large $P_n$ -value and a 'long' lifetime (less decay energy for this particular branch). This will increase the abundance of nuclei of the current mass. The reverse is of course true if the final level is low-lying. Thus, changes of decay characteristics may occur very far from stability where shells are possibly weakening, configurations become more mixed and changes in decay and neutron separation energies will show up.

Some isomeric states as mentioned previously could be good testing cases of shell closure effects. Another case of isomerism is the other extreme situation of very deformed nuclei where the spins of the initial and potential final states do not differ very much but the intrinsic structure is very different (the so called K-hindrance). The electromagnetic decay can be hindered and the intrinsically slower beta transitions can compete with them. The features of beta decay have been explicated above. Isomers living less than about 1 µs can be studied by in beam spectroscopy. If the half life is larger they can be separated at recoil separators and their decay is observed, the identification being performed by the direct methods based on the separator properties and/or by the detection of subsequent decays to known nuclei. Isomers reveal details of shell structure, existence of intruder states due to particle-hole excitations or different nuclear shapes. They are thus a privileged signature to get insight into nuclear structure in the new regions accessible with SPES. Let us mention that, as illustrated above with the time differential perturbed angular correlation or collinear laser spectroscopy, dedicated techniques could enable to measure g-factors, quadrupole moments, thus providing detailed structural data.

**Low-lying dipole strength**

The giant dipole resonance (GDR) is quite sensitive to a non-uniform charge and mass distribution in nuclei. For example, halo and skin structure neutron rich nuclei are known to display in many cases an electromagnetic response function, which differs markedly from that of
stable nuclei. A vibration of the neutron halo or skin with respect to the core would appear as a giant dipole states but displaying a much lower energy than that associated with the systematic of the GDR associated with nuclei along the valley of stability ($\approx 80/A^{1/3}$ MeV). As a rule, the GDR strength is expected to be more fragmented as due to the modification of the mean field as a function of the N/Z ratio. The measure of the dipole response in neutron rich nuclei could be of use for extrapolating the properties of the collective motion to describe the behavior of neutron matter.

It has been discussed that the existence and strength of low energy component of the giant dipole resonance in neutron rich nuclei can have influence on the path of the r-process. During part of the r-process, photo absorption in the continuum followed by neutron emission ($\gamma,n$) and radioactive capture ($n,\gamma$) are in equilibrium. However, as the temperature and neutron densities decrease these reactions fall out of equilibrium. In this situation, nucleosynthesis depends on the absolute rates of the ($n,\gamma$) and ($\gamma,n$) processes which in turn depend on the giant dipole resonance response function. This point is illustrated in Fig. 1.10 where the relative abundances of elements are compared with two calculations, one with a normal GDR response function and the other one with a response function with some dipole strength at low energy (pygmy resonance).

Among many new and unique structure phenomena exhibited by nuclei with large neutron excess, the possible occurrence of collective isovector modes in the energy region below the giant resonances has recently attracted considerable interest. This is because the isovector pygmy modes could provide important information on isospin and density dependence of the effective nuclear interaction. For example the pygmy dipole resonance can be directly related to the neutron excess, and therefore the splitting between the giant dipole resonance centroid energy and that of the pygmy resonance represents a measure of the neutron skin. In Fig. 1.11 calculations of the centroid energies of the GDR in neutron rich Ni and Sn isotopes are shown.

![Fig. 1.10 - The experimental data on the relative abundances (red squares) are displayed in comparison with two theoretical predictions of the r-process one making use of the standard parametrization of the GDR (blue curve) and the other including also the pygmy resonance(green curve) [10].](image)
Fig. 1.11 - Centroid energies of the isovector dipole strength distribution in the region of giant resonance (upper panels) and in the low-energy region below 10 MeV (lower panels) as a function of mass number for Ni and Sn isotopes (adapted from Ref. [11]). The calculations shown with the filled circles were performed using relativistic random phase approximation. The calculations shown with the filled triangles correspond to the hydrodynamical model.

An experimental tool to measure the pygmy resonance is that of measuring high energy gamma rays following the stripping reaction \((d,p\gamma)\) at low bombarding energy (5-10 MeV/u) in inverse kinematics. In fact, with neutron capture reactions or with neutron stripping or pick-up reactions such as \((d,p\gamma)\) and \((^3\text{He}, ^4\text{He})\) on stable nuclei it was already possible to identify in the gamma-ray continuum of a number of stable nuclei some structures (resonances) of much lower strength than that expected for neutron-rich nuclei.

High-spin states produced with fission fragments

The study of rapidly rotating, highly excited nuclei has been one of the main topics in nuclear structure research in the last decade. The response of the nucleus to the rotational stress gives rise to a wide variety of nuclear structure phenomena like shape changes, pairing effects, magnetic rotation, rotational damping. The most striking shape change is superdeformation. The study of superdeformation helps to bridge the gap in our knowledge between the spherical and normally deformed nuclei on one hand and on the fission process of cold nuclei on the other. It has enabled to extend mean field description in the case of extreme deformation putting its predictions under severe tests. It also enabled us to make a study of the unique feeding mechanisms and on the way the shape of a cold nucleus can change from an extreme shape to a normal shape.

One of the present limitations in the study of very deformed states at high spin is the maximum value of the angular momentum that the nucleus can sustain before fissioning. This is particularly severe in the search of even larger nuclear deformation as the hyper-deformation or in the search of a new shape phase transitions which are expected to occur at around spin $70\ h$.

The fusion reaction induced by neutron-rich projectile nuclei has the great advantage to populate angular momentum values, which are larger than those populate with stable beams because of the increasing value of the fission barrier with increasing neutron number. This is illustrated in Fig.1.12 for two nuclei in different mass regions.
Fig. 1.12 - Fission barrier as a function of the mass number \( A \) and for two values of \( Z, Z=56 \) and \( Z=70 \) [12]. Few reactions with stable and neutron-rich beams are indicated to show the influence of the neutron excess on the fission barrier.

As far as hyperdeformation is concerned it is important to recall that it is predicted by theory to exist around the neutron number \( N=108 \). The isotopes of interest \( (^{176}\text{Er}, ^{178}\text{Yb}, ^{180}\text{Hf}) \) can be produced by \(^{130}\text{Cd}, ^{132}\text{Sn}, \) and \(^{134}\text{Te} \) induced reaction, respectively, on a \(^{48}\text{Ca} \) target and studied with devices like EUROBALL or AGATA.

In addition to hyper-deformation there is another shape change expected to occur at very high spins, which is related to “Jacobi’s shape transitions”. This shape phase transition of nuclei is similar to that taking place in rotating stars. It has been found that at a certain critical angular momentum the stable equilibrium shape of the gravitating mass rotating synchronously changes abruptly from a slightly oblate spheroid to a triaxial ellipsoid rotating about its shortest axis. This shape transition is expected also in the case of atomic nuclei idealized as charged incompressible liquid drops endowed with a surface tension. This oblate-to-triaxial transition was demonstrated also in the more realistic self-consistent, semi-classical nuclear Thomas-Fermi model under the same assumption of synchronous rotation. The Thomas-Fermi model provides a good description of shell-averaged static nuclear properties, but the assumption of synchronous rotation is known to be strongly violated at low angular momenta, where measured moment of inertia are considerably smaller than the “rigid-body” values implied by synchronous rotation. Experimental indications of the Jacobi phase transitions were obtained so far only through the study of the giant dipole resonance for the light nuclei \(^{45}\text{Sc} \) and \(^{48}\text{Ti} \) (having the critical angular momentum for the Jacobi transition at spin somewhat lower than that of the fission limit). In that case a change in the line shape of the giant dipole resonance with increasing angular momentum was found which is consistent with the oblate to triaxial (approximately prolate) shape transition. It should be noted that in those experiments the GDR gamma decay was probing the high temperature interval of 2-3 MeV, and therefore it provides no evidence of such transitions in cold nuclei.

The experimental feature expected for the Jacobi transition in cold nuclei is a sharp giant backbend in the plot of the gamma ray energy of the quadrupole transition from the rotational state with angular momentum \( L \) to the state with \( L-2 \), as a function of angular momentum. This is illustrated in Fig. 1.13 in the case of the nuclei \(^{142}\text{Ba} \) and \(^{106}\text{Mo} \). It is important to note that Jacobi shapes are expected to exist only in a rather limited interval of angular momentum and this interval extends further out if the fission barrier is larger.
Another topic of interest is the thermal nuclear response, which is investigated by studying how the elementary modes of excitations are modified by the thermal environment. In this connection the transition from order to chaos, which is expected to occur at rather low temperatures, is of special interest. In fact, low lying nuclear states are characterized by quantum numbers and their decay modes are governed by selection rules. A very different situation is encountered at the rather modest excitation energy corresponding to the neutron separation energy of 6-8 MeV. In this region the properties of neutron resonances are instead well described by random matrix theory which now constitutes the basis for the general concept of quantum chaos. Nuclei at an excitation energy lying between the regular ground-state region and the chaotic neutron resonance region can be characterized as \textit{warm}. The transition between order and chaos occurs in \textit{warm} nuclei. The warm excitation energy region has been studied in deformed nuclei through the analysis of the features of quasi-continuum spectra with gamma transition energies in the interval 0.8 –2 MeV.

The measured quasi-continuum spectra were found to originate from gamma transitions de-exciting strongly mixed rotational bands. The band mixing mechanism is due the residual interaction and to the increase in level density and is also denoted as \textit{rotational damped motion}. Because of the configuration mixing, the rotational E2 gamma decay from an off-yrast compound state at spin I is fragmented over many final state at spin l-2. The width of the associated B(E2) strength function is defined as $\Gamma_{\text{rot}}$, that is the rotational damping width.

Several experimental efforts have been made to study the mass, deformation, configuration dependence of the rotational damping. The configuration dependence of rotational damping at a fixed deformation is particularly interesting as it shows the importance of nuclear structure effects in the order-chaos transition region. Mixed band calculations based on cranked shell model plus residual interaction predict a variation of $\Gamma_{\text{rot}}$ with neutron number which is due to the shell structure. This is because $\Gamma_{\text{rot}}$ is dominated by the dispersion of rotational frequencies arising from particle alignment (depending on particle orbits) along the rotational axis. The shell
structure effect of the rotational damping is illustrated in Fig. 1.14. Experiments with neutron rich nuclei such as \(^{176}\)Yb are therefore very important to probe in detail the rotational damping picture and to obtain a better understanding of the order-chaos transitions.

New phenomena at high spin to be searched with beams of neutron rich nuclei are those related to the rotation of neutron-skin nuclei. The nucleus \(^{144}\)Xe represents a good case since it is predicted to have a sizeable neutron skin. High-spin states and thus rotation of such a neutron-skin nucleus has never been observed and might give new insight into its structure and in particular into the influence of the neutron skin on the rotational behavior of such nuclei, thus providing a severe test to the mean field theories.

![Gammas](image)

**Fig. 1.14** - Expected values of the rotational damping width as a function of neutron number for the Yb isotopes (adapted from Ref. [14]). On the right hand side the width of the B(E2) distribution (denoted \(\Gamma_{\text{rot}}\)) for the transition from spin I to spin I-2 is illustrated

**Nuclear structure of very heavy and search for super-heavy nuclei**

The study of the quantal behavior of nuclei having extremes in masses (heavy and superheavy nuclei) provides an important test to nuclear structure theory. At present, the results obtained with different state of the art models, are very different concerning the position of the next proton (spherical) shell closure beyond \(Z=82\) of very heavy systems. In fact, while the Skyrme-Hartree-Fock theory predicts \(Z=114\) for this quantity, the relativistic mean field predicts \(Z=124-126\).

The difference of the two approaches lies in the different treatment of the spin-orbit force, difference which is magnified for heavy systems due to the fact that as the single-particle spectrum becomes compressed, spin-orbit splitting is attenuated and Coulomb effects are enhanced. It is expected that a proper inclusion of the coupling of single-particle motion to quantal size fluctuations provides a strong screening of the Coulomb field (exchange of high lying modes) as well as important renormalization of the effective mass (\(\hbar\)-mass) smoothing out the mean field differences and leading to more uniform predictions.

In particular, states with spin up to 20 \(\hbar\) have been observed in \(^{252,254}\)No isotopes. The lowest transitions are strongly converted and remained unobserved. However, B(E\(2^+,2^+\rightarrow0^+\)) values can be estimated from empirical relationships connecting halflives and energies. Fig. 1.15 shows these values and the product of valence protons \(N_p\) and neutrons \(N_n\) in case of shell
closure at $Z=114$ and $Z=126$, respectively, and at $N=184$. The straight line is the relationship of $B(E2)$ versus $N_pN_n$ extrapolated from systematics of nuclei lighter than $^{208}\text{Pb}$. The present experimental situation does not allow to distinguish between them. Precise measurements of nuclei in this region are necessary.

More neutron-rich very heavy ions may be produced by fusion reactions with radioactive fission fragments. For example, heavy nobelium or seaborgium isotopes can be produced by $^{132}\text{Sn}$ induced reactions on $^{130}\text{Te}$ and $^{138}\text{Ba}$ targets. The resulting $^{260}\text{No}$ and $^{268}\text{Sg}$ can be e.g. detected with the PRISMA spectrometer using the recoil-decay-tagging method and the gamma-rays can be observed with arrays of germanium detectors. Other nuclei may be produced with different beam/target combinations. The more neutron-rich heavy elements are not at all accessible with stable beams.

Definitive experimental information on the positions of the shell gaps can only come from direct measurements of superheavy nuclei lying close to the expected positions of the closed shells.

With stable beams, it is believed to be difficult to reach these closed shells. In particular, it seems to be difficult to produce super-heavy elements near closed shells with sufficiently low excitation energy by means of stable beams. It is generally agreed that the so called 'cold fusion' of strongly bound isotopes will give less excitation in the compound system and therefore a better chance of survival of the residual heavy nucleus. SPES will allow a wide choice of radioactive projectiles with strong binding and some other advantages due to the neutron-rich character (the fused system is less neutron deficient and closer to stability, there is less Coulomb repulsion at contact since larger nuclear size for the same charge). For example with the use of neutron-rich krypton isotopes, one expects to produce new isotopes and eventually even new elements in the vicinity of the predicted closed shells. The identification of new super-heavy elements is usually based on the observation of their decay in a sequence of $\gamma$-decays. These $\gamma$-decay chains allow to link the new isotope to known lighter super-heavy isotopes and thus to clearly identify the super-heavy nuclide produced. However, for the more neutron-rich super-

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**Fig. 1.15.** Experimental $B(E2)$ values of the first $2^+ \rightarrow 0^+$ transition in $^{252,254}\text{No}$ versus the product of valence protons and neutrons assuming shell closure at $Z=126$ (open points) and at $Z=114$ (filled points). The solid line is extrapolated from systematics of lower-Z nuclei (adapted from Ref. [15]).
heavy isotopes, these links to known isotopes do no longer exist, because the properties of the lighter decay products are not known. Therefore, it is of crucial importance to study the reaction mechanism at energies around the Coulomb barrier, to produce neutron-rich nuclei of elements between Z=100 and Z=110 as well as to study their decay properties. These isotopes can be produced with reasonable counting rates with neutron-rich fission fragments from SPES.

**Multi-nucleon transfer reactions**

Transfer reactions between heavy-ions constitute an important field of research in low-energy nuclear physics with stable nuclei and are likely to become even more important when radioactive beams of high intensity will be available. This is true, both, for nuclear structure and reaction mechanism studies, topics that are intimately interconnected, especially at energies close to the Coulomb barrier. The best example of this interconnection is provided by the large enhancements, at sub-barrier energies, of the fusion cross sections.

Fig. 1.16 Isotopic distributions of the fragments measured in the collision of $^{40}$Ca on $^{208}$Pb at 234.8 MeV. The histograms are calculation with the semi-classical mode GRAZING, the top row corresponds to calculations when only single-particle transfers are considered, the bottom row corresponds to calculations when a proton pair-transfer mode is added.

The transfer reactions are the ideal tool to check the quenching of the energy gap predicted in the single particle energy spectra of neutron drip-line near the magic number N=82. Multi-nucleon transfer reactions are excellent to investigate the residual interaction acting among the nucleons in the nuclear medium in particular to investigate the component that is responsible for the tendency of identical nucleons to couple in pair with total angular momentum zero. These special types of correlations are attributed to the existence of short-range residual forces that are responsible for important properties of nuclei and for the enhancement of the rates for multiple pair-transfer modes.

In Fig. 1.16 we show inclusive cross-sections for multi-nucleon transfer channels in the collision of $^{40}$Ca on $^{208}$Pb at a bombarding energy of 234.8 MeV measured at the Laboratori Nazionali di Legnaro with the PISOLO spectrometer. The histograms correspond to calculations done with a semi-classical model (GRAZING) that solves, in an approximate way the system, of coupled equations that govern the exchange of, mass, charge, energy and angular momentum...
between projectile and target taking into account the excitation of surface modes and the successive transfer of independent single or pair of nucleons. To show the importance of a pair-transfer mode in the description of these cross sections we show in the top of Fig 1.17 the results of the model when only single-particle transfer modes are included in the calculation. It is clear the model describes quite well pure neutron and the one-proton stripping channels but underestimates the cross section when more than one proton is transferred. The inclusion of a pair-proton mode seems to suffice for the description of all the measured transfer channels, at least up to the six-protons stripping. Clearly the availability of a high resolution mass-spectrometer like PRISMA will allow us to go much more in detail in the reaction mechanism since information on the individual levels populated by the reaction should be obtainable.

The transfer reactions should also enable us to test specific properties of the pair-correlations. For instance, an important question awaiting an answer is how the pairing force is renormalized due to the exchange of collective surface modes and eventually of pygmy resonances associated with the skin phenomena or halo, typical of neutron rich-nuclei.

![Fig. 1.17](image-url) - Calculated cross sections for multiple particle transfer reactions with the two neutron rich beams $^{95,98}$Kr on Ge and Sn targets (adapted from Ref. [16]).

A very important aspect of nuclear transfer reactions, with neutron rich-beams, is the production of other neutron-rich systems. The optimal Q-value conditions that govern the transfer of nucleons in heavy ion collisions have so far prevented the possibility of moving towards the neutron drip line via multi-particle transfer reactions. In fact, reactions involving stable nuclei between a lighter projectile and a heavier target virtually rule out proton pick-up and neutron stripping processes. These are the transfer modes that are precisely needed to populate neutron-rich isotopes of target-like elements. In contrast, as projectiles become progressively richer in neutron number the trend is reversed. First, the population gradients in the NZ-plane evolve to be comparable and eventually, it is the neutron stripping and proton pick-up processes that end up being predominant. Multi-nucleon transfer processes induced by neutron-rich beams would thus become an optimal mechanism for the production of medium heavy systems closer to the neutron drip line. In addition the densities of states available to the nucleon
flow are large enough so that, even after the nucleon evaporation following primary formation, the size of production cross sections remain detectable.

In Figs. 1.17 and 1.18 predicted cross sections are given for some reactions induced by neutron rich Kr and Sm isotopes. One can note that many of the production cross sections are detectable and in some cases will allow nuclear structure studies by using the magnetic spectrometer PRISMA combined with an efficient germanium array for gamma spectroscopy.

Heavy-ion subbarrier fusion

The dynamics of heavy-ion fusion near and below the Coulomb barrier has been the object of many experimental and theoretical studies in many laboratories since the 80’s, using stable beams and, more recently, radioactive beams as well.

The fusion barrier distribution arising from couplings to reaction channels, obtained from the second energy derivative of the excitation function, allows a deep insight on the fusion dynamics and on its interplay with nuclear structure. Interesting results were reached at LNL in this field, and the availability of the new beams from SPES will open up much wider possibilities, especially linked to the study of fusion between heavy and neutron-rich nuclei. A more complete understanding of such processes on the basis of simple nuclear structure and few-nucleon transfer modes, will also allow to put the research for superheavy nuclei on a firm ground, with cleaner perspectives for the future.

Fusion experiments with medium-mass exotic nuclei will be performed at LNL with the PRISMA spectrometer, with a few developments and upgradings for the set-up, mainly necessary for the measurements at $0^\circ$ and at angles near $0^\circ$ where evaporation residues are produced. Indeed, PRISMA was not designed for such uses, and no provision for beam rejection exists presently.

The operation in gas-filled mode is already under study and scheduled to begin in 2004 (this will be very interesting also for other type of experiments using the SPES beams, mainly
connected with nuclear structure studies). Consequently, at least part of the detectors at the focal plane of PRISMA will have to be replaced by more suitable ones.

A further upgrading will be adding to the spectrometer a beam-rejecting device (e.g. a Wien filter like in the Vamos set-up). This makes it possible to study fusion reactions in inverse kinematics, too.

A complementary, and highly-efficient, detector for fission fragments would be also very useful, since both evaporation residues and fission fragments will have to be measured in many cases.

The study of fusion of heavy systems led in early days to the development of the concept of extra-push, so to explain the experimental evidences for small and slowly increasing fusion cross sections around the nominal Coulomb barrier, for systems where the product $Z_1Z_2$ exceeds about 1600.

There is a recent renewed interest for such investigations, stimulated by the observations linking specifically the fusion probability in that energy range to the structure of the colliding nuclei, i.e. shell closures and/or static deformations. For instance, the system $^{82}\text{Se} + ^{138}\text{Ba}$, where the Ba target has $N=82$, shows a much higher fusion probability than $^{82}\text{Se} + ^{134}\text{Ba}$ (four neutrons away), and than $^{124}\text{Sn} + ^{96}\text{Zr}$ leading to the same compound nucleus $^{220}\text{Th}$. The fusion enhancement is nearly two orders of magnitude.

Now, it is predicted, and in some cases has been observed, that shell structure changes when one goes from the stability line towards neutron-rich exotic nuclei. New shell closures might be discovered in that region in the next few years, hence exotic beams from SPES having those magic numbers could be ideal to produce very neutron-rich compound nuclei.

There are other experiments showing that, when fusing a spherical with a deformed nucleus, tip collisions need an extra-energy over the Coulomb barrier to fuse (the extra-push), whereas side collisions can evolve into complete fusion without such extra-energy. The more compact configuration of the dinucleus in side collisions at the touching point, seems to be the decisive factor for the dynamics.

Modern coupled-channels models of heavy-ion fusion may be able to reproduce such observations in terms of elementary modes of excitation like surface modes or one- and two-nucleon transfer couplings. This will positively address the choice of systems when using radioactive beams.

In general, fusion of heavy systems will take great advantage from the availability of the medium-mass and neutron-rich SPES beams. In particular, interesting beams are the heavy Tin isotopes (e.g. $^{128,132,136}\text{Sn}$), and other ions nearby, like $^{126,130}\text{Cd}$, $^{134,136}\text{Te}$, $^{140,144}\text{Xe}$. In the region of lighter nuclei, one can envisage the use of $^{82}\text{Ge}$, $^{84,88}\text{Se}$, $^{90,94}\text{Kr}$, $^{100,104}\ldots\text{Zr}$.

Typically needed energies will be those currently in use with the Tandem-PIAVE-ALPI accelerator complex, where complementary measurements with stable beams will be necessary in any case.

As far as exotic beam intensities are concerned, selected experiments will already be possible with around $10^5$ ions/sec. The higher intensities which seem to be reachable, at least in some cases, for the SPES beams, will be ideal to perform a large art of the measurements described here above.

A few examples: the systems $^{84,88}\text{Se} + ^{138}\text{Ba}$ and $^{96}\text{Zr} + ^{132,136}\text{Sn}$, all leading to Thorium isotopes, might reveal strong dynamical and/or shell effects in the fusion probability. Fusion of heavier systems, like e.g. $^{132}\text{Sn} + ^{160}\text{Gd}$ (provided the Sn beam intensity will be high enough), may open the possibility of synthetizing real superheavy nuclei in collisions of a spherical rigid
nucleus (the $^{132}$Sn beam) with a neutron-rich deformed target ($^{160}$Gd in this case), leading to the compound nucleus $Z=114, N=178$.

1.1.2 Nuclear Astrophysics

The knowledge of the properties of nuclei far from stability both on the neutron and the proton rich sides is essential for the understanding of several open astrophysical problems. Let us mention the evolution of stars and the abundances of the elements found in the solar system.

To understand stellar evolution and the production of the elements in the universe, extensive model calculations are used to describe and simulate the different processes occurring in the stars. Especially for violent processes like supernovae explosions or X-ray bursts, mainly the properties of unstable nuclei are the crucial inputs to the models.

On the neutron rich side the rapid neutron capture ($r$-process) takes place in conditions of high temperature and high neutron flux density thought to exist in supernovae explosions and on decompression of neutron star matter. Starting from iron, the nucleus with the largest binding energy, acting as a seed, a succession of neutron captures and beta decays creates very neutron-rich nuclei. After an element has captured enough neutrons there is an equilibrium of n-captures and photodisintegrations giving chance to the slower beta decay process to occur. This forms the next element and the sequence is resumed. Of particular importance are nuclei with closed neutron shells because the neutron capture rate is reduced. The $r$-process path comes closer to the valley of stability and the process is slowed down by the longer halflives. These 'waiting point nuclei' are thus those of particular interest in nuclear physics. For some of them, e.g. $N=82$ $^{130}$Cd experiments could be performed. After freeze out of the neutron flux the nuclei decay. This creates abundance peaks of the nuclei descending from the waiting point nuclei that have accumulated during the neutron burst. The experimental abundances, however, suggest that the standard shells are weakening very far from stability as illustrated in Fig. 1.4. This is an unusual case of a conclusion drawn about nuclear structure from astrophysical data and calculations. It was later supported by nuclear models invoking the diffuse nuclear surface at large neutron excess. Nevertheless, it is obviously necessary to rely on experimental data rather than extrapolations of model predictions in order to provide a reliable input to these $r$-process calculations. The inputs needed are nuclear masses, beta-decay halflives, probabilities of beta-delayed neutron emission and neutron-capture cross sections. Therefore, decay measurements and transfer reactions in inverse kinematics with neutron-rich fission fragments (see Fig. 1.19) are overdue.

Neutron-capture cross sections are, as a rule, calculated with the Hauser-Feshbach model. These calculations assume that a statistical picture is applicable. However, close to magic numbers, and especially far from stability, the level density becomes so low that this picture is no longer valid. Therefore, measurements are needed to determine these capture cross sections. A possibility is to measure cross-sections for neutron transfer via a $(d,p)$ reaction with neutron-rich radioactive beams. Here too, the possible vanishing or weakening of the shell closure at $N=82$ and $N=126$ mentioned in connection with the $r$-process, will be of special importance.

In addition to nuclear reactions that play a role in astrophysical processes at the equilibrium, other individual reaction cross sections are important in explosive environments. This implies the need to determine quantities like the level density, the gamma width, and the proton and neutron optical potentials (see discussions in the following sections).
The topic of nuclear structure at finite temperature and at high spin using fusion and fission reactions has been central in the physics program of laboratories delivering low energy heavy ion beams. Nuclear fusion and fission are also best suited to be used to determine the dynamical properties of moderately excited nuclei. In particular exclusive measurements of the reaction products have shown the possibility to study the properties of the nuclei produced in the fusion reaction among heavy nuclei such as their temperature, the effective emission barrier for charged particles and neutrons decay, the angular momentum, fission competition and fission barrier. In addition, the role of these effects in the population of particular nuclear structures such as superdeformed bands has been particularly useful for gamma spectroscopy studies at high spin.

Based on a purely static point of view, the presence of a sizable neutron skin systematically lowers the fusion barrier and thus facilitates the formation of compound nuclei at lower excitation energies. This brings up the possibility of a large dynamic polarization in the projectiles that could still add orders of magnitude to the fusion cross sections. Some of these features have particular relevance for the population of high spin states and in the search for nuclear shape transitions and in the synthesis of super-heavy elements.

The properties of hot rotating nuclei formed in fusion reactions are deduced from the measured spectra and multiplicities of light particles such as protons, neutron and alpha particles and gamma-rays. In particular, measurements of light charged particles have provided information on the statistical equilibration of the nucleus, on the nuclear temperature and on the density of levels in the continuum region. The high energy gamma-rays have been measured to study the giant dipole resonance in hot rotating nuclei and the shapes of these systems.
In connection to the fission process, which probes the nuclear large amplitude collective motion, the comparison of the fission width with the particle evaporation width have provided information on the nuclear viscosity which is found to be temperature dependent.

The isospin dependence of these mechanisms is also an unexplored field of research of great interest in itself and which will have some impact also in nuclear astrophysics problems such for example for the understanding of the r-process and supernova explosion requiring the knowledge of the level density and binding energy of medium-mass neutron-rich nuclei.

Level density

The description of thermally excited nuclei needs as a basic ingredient the density of nuclear states. The evolution of the level density with excitation energy, nuclear mass and angular momentum allows to localize the opening of decay channels for an excited nucleus, and to observe possible phase transitions. The level density is an important input for cross section calculations, which are in turn essential in predicting astrophysical processes. At present, the level density has only been studied in nuclei close to the valley of stability and mainly on the neutron-deficient side. The SPES facility will allow to extend such a study to the level density of neutron-rich nuclei, which is expected to be significantly different from that of nuclei close to the valley of stability. Particularly interesting is the study of the effects on the level density, due to the isospin distribution as well as to the symmetry energy.

a) Isospin distribution

In the framework of the Fermi-gas model the isospin effects on the level density can be taken into account by an isospin distribution related to the isospin component $T_3=(N-Z)/2$ as well as to the density of single-particle states at the Fermi energy and the excitation energy of the system. According to this, the level density is expected to decrease with increasing $|T_3|$. It has been recently shown that, compared to this prescription, a reduction factor of the level density based on the distance from the valley of stability $Z-Z_0$, where $Z_0$ is the $Z$ of the beta stable isotope with the same mass, provides a better description of the available data. These recent predictions concerning the level density up to excitation energy of 5 MeV are shown in Fig. 1.20. The test of these model predictions requires measurements of nuclei far off the stability line not presently available but which can be produced with the SPES facility.

b) Symmetry energy

The effective nucleon mass $m^*$ is expected to decrease with increasing temperature for $T \leq 2$ MeV. This implies, apart from the decrease of the level density parameter $a \propto m^*$, an increase with the temperature, of the symmetry (kinetic) energy contribution to the nuclear binding energy through the dependence on the isospin component: $E_{\text{sym}}(T)=b_{\text{sym}}(T)\cdot 4T_3^2/A$. 
Variations of the nuclear symmetry energy change the rate of electron capture in a collapsing star, and this in turn changes the energy of the final supernova explosion. For the case of SN1987 and from direct observations of the supernova, it has been shown that the typical kinetic energy of the material ejected was of the order of \( E_{\text{kin}} \approx 1.5 \times 10^{51} \text{ erg} \). This kinetic energy is a measure of the strength of the explosion. In Fig. 1.21 it is shown the gain in kinetic energy \( \Delta E_{\text{kin}} \) that is obtained when the temperature dependence of \( m^* \) is taken into account (as compared to the case with no temperature dependence). The level curves for \( \Delta E_{\text{kin}} \) (in units of \( 10^{51} \text{ erg} \)) are reported in the \( \omega-T_0 \) plane, where \( \omega \) is related to \( m^* \) and \( T_0 \) to the nuclear temperature. The shaded area corresponds to region of values of the parameters found for some of the most abundant nuclei present in the collapsing star. It shows a gain in the explosion energy of the order of \( \Delta E_{\text{kin}} \approx 0.5-0.7 \times 10^{51} \text{ erg} \), value comparable to the explosion energy itself. This finding clearly shows that the temperature dependence (via the effective nucleon mass) of the symmetry energy is of important relevance in the astrophysical context.

Experimentally, these effects related to the isospin distribution as well as to the symmetry energy would appear as a change in the particle multiplicity as well as in the relative yields of the compound nucleus decay channels. In particular, level densities can be deduced from the spectral shapes and multiplicities of light particles.
**Fig. 1.21** - The contour plots of the gain in kinetic energy of the material ejected by the supernova explosion is shown as a function of the two parameters $\omega$ and $T_0$. The first parameter is related to the effective $\omega$-mass of the nucleon and the second is related to the nuclear temperature. The shaded area is the region of interest [18].

**Fig. 1.22** -  

- **a)** Ratio between $1n$ and $2n$ channel cross sections for the composite system $^{109}\text{Mo}$ as a function of the excitation energy;  
- **b)** neutron energy spectra in the c.m. system for the $1n$ channel for the same compound nucleus at $E_x=16$ MeV. Calculation have been carried out by Lilita_N97 code: i) including in the level density the symmetry energy ($E_{\text{sym}}$) and the $(Z-Z_0)$ dependence (square); ii) using standard parameters (rhombs). Lines are drawn to guide the eye.

In the case of neutron-rich nuclei the charged particle emission is expected to be significantly lower than that of stable or proton rich nuclei. Therefore, neutron emission will play a more relevant role in the de-excitation process than charged particle emission. In addition,
measurements of nuclei at moderate excitation energies giving rise only to few particle emission are very interesting as they provide a stringent test of the statistical model, the decay not being integrated over many particle steps. In particular, the analysis involving only one neutron emission allows a direct measurement of the level density. As an example of possible experiments, the channels 1n and 2n could be studied bombarding a $^4$He target with medium-mass neutron-rich projectiles provided by SPES. These reactions meet the conditions of providing a high fusion cross section with a low excitation energy (15-20 MeV) of the composite systems. Furthermore, the relatively low angular momenta and excitation energies involved in these reactions are expected to enhance the effects of the isospin on the level density.

In order to evaluate these effects we have carried out statistical model calculations using the code Lilita_N97, for neutron-rich Mo isotopes, whose study is relevant, as they represent an important part of the chemical crust composition of these stars. We show in Fig. 1.22 a) the calculated ratio between 1n and 2n channel cross sections as a function of the excitation energy of the $^{109}$Mo, taking into account in the level density for the symmetry energy $E_{sym}$ as well as for the Z-Zo dependence. The standard calculation is also reported for comparison. The corresponding neutron spectra at Ex=16 MeV are reported in Fig. 1.22 b). Significant effects are observed, indicating that the evaporative neutrons are a powerful tool for such a study. This composite system could be formed in the reaction $^{105}$Zr + $^4$He at $E_{lab}$=192–330 MeV. Studies of Mo nuclei at higher excitation energy (50-100 MeV) could be carried out with reactions on heavier targets as for example the $^{98}$Kr + $^{12}$C $\rightarrow$ $^{110}$Mo. As a general behaviour, also for this reaction the statistical model predicts significant isospin effects on the evaporation process.

**Limiting temperature**

The limiting temperature at which a nucleus can be formed is linked to a decrease of the level density at high excitation energies. The measurement of this temperature is a necessary information as it helps to constrain the nuclear equation of state at finite temperatures in the vicinity of the saturation density. To measure the limiting temperature one needs to control the energy deposited, the degree of equilibration, and the reaction mechanism. For stable nuclei, the limiting temperatures were found to be rather high.

In the vicinity of the proton drip line, Coulomb instabilities are predicted to decrease drastically the limiting temperature (see Fig. 1.23). Within this context it will be illuminating to study an isotopic chain of compound nuclei produced via fusion-evaporation reactions from the proton-rich side to the neutron-rich side (with SPES) by precisely measuring the de-excitation pattern of particle emission in coincidence with evaporation residues in an excitation energy range between 1 and 3 MeV/nucleon. Additionally, these studies allow to investigate the influence of the Coulomb interaction on the expansion of a nuclear system initially strongly compressed.

These studies require projectiles of e.g. $^{114}$Xe to $^{145}$Xe at energies of 5 MeV/nucleon to 30 MeV/nucleon with intensities of about $10^{6}$ particles per second impinging on calcium targets. Other systems to be studied are based on beams of $^{74,96}$Kr impinging on iron targets. Another way of performing these studies is to investigate the opening of the multifragmentation regime, identifying the region of entrance into the plateau of the caloric curve. Recent studies have pointed out that, even at low energies depending on the mass of the system, the exploration of the $T_{lim}$ – A correlation is feasible.
Extension of measurements to nuclei with the same mass and with very different N/Z ratios would therefore be very interesting. This will also allow to determine the critical parameters for nuclei very far from the beta-stability, thus testing the isospin dependence of the equation of state.

**The Dynamical Dipole Oscillation in fusion heavy ion reactions**

One of the open questions in the study nuclei at high excitation energy is that of the temperature dependence of the equilibration times of the different collective degrees of freedom. Several experimental and theoretical efforts have been made in connection to the study of the fusion and fission mechanisms probing the nuclear large-amplitude slow motion, particularly in the energy range 5-20 MeV/u.

In dissipative collisions energy and angular momentum are known to be fastly distributed among all single particle degrees of freedom while charge equilibration takes place on larger time scales. Therefore, if the value of the N/Z of the projectile and of the target is very different during the formation time of the compound nucleus one expects a collective dipole oscillation of the nucleons along the beam axis characterized by a frequency typical of a very elongated system (in the interval 8-12 MeV). To investigate this effect one needs to compare the yield of gamma rays from a very asymmetric reaction with that produced by a more symmetric reaction both leading to the same compound nucleus.

Experiments performed with stable beams searching for this dynamical dipole emission have shown some evidence of these mechanisms but only at the order of 10-15%.

Recent model predictions (shown in the triangles in Fig. 1.24) were obtained considering the evolution of the collective dipole acceleration from the time when it suddenly rises until it is completely damped to a pure thermal component. In particular, in the figure, the expected ratio of the gamma production in the region around 10 MeV for the two reactions $^{40}$Ca + $^{100}$Mo and $^{36}$S + $^{104}$Pd is shown as a function of the compound nucleus excitation energy (the corresponding bombarding energy being in the interval 4-12 MeV/u).
The use of radioactive beams will enhance the possibility of such observation. A simple estimate based on a rescaling of the available calculation based on the N/Z of projectile and target (presented in the figure with the filled circle) is given as a guideline of a possible measurement with radioactive beams. For example the excess gamma yield from the reaction $^{108}\text{Mo} + ^{40}\text{Ca}$ as compared with that from the reaction $^{48}\text{Ca} + ^{100}\text{Mo}$ is expected to be of the order of 40% and therefore almost a factor of 3 larger that that obtainable with stable beams.

Measurements of this type are of importance to assess the role collective dipole mode plays in the reaction dynamics and on the different equilibration times.

**Fig. 1.24** - The photon multiplicity exceeding that from an equilibrated system is shown as a function of excitation energy (adapted from [19]). This is obtained using a pair of reactions (as those indicated inside the boxes) leading to the same compound nucleus and excitation energy but with different values of the N/Z of the projectile and target. The point shown with filled circle is the expected value for a pair of reactions one being induced by the neutron rich $^{108}\text{Mo}$ nucleus.

### 1.1.4 Nuclear physics experiments with trapped radioactive beams

Trapping of radioactive nuclei is presently considered as a very promising tool for precision measurements in nuclear and atomic physics. Peculiar characteristics of nuclei stored in a trap are in fact their very small phase space and the possibility to work in a clean environment with a negligible source thickness. Once ion/atoms have been properly produced, purified and transported, experiments of different kinds can be performed.

Particular relevant are studies on fundamental interactions, like parity conservation (PNC) in atoms and nuclear beta decay, since one might get indications on physics beyond the standard model of electroweak and strong interactions. While in nuclear weak processes the vector-axial form of the weak current is quite well defined, the constraints on scalar S and tensor T couplings are very poor. Scalar interactions give rise to a $\beta$-decay process which is forbidden in the SM, but which would occur if a scalar boson or a leptoquark were exchanged instead of the charged W. Signatures of a scalar or a leptoquark exchange can be inferred in the lepton eelicitie or in the neutrino-lepton angular correlation coefficients of Fermi and/or Gamow-teller transitions. Such experiments can be performed in a trap by detecting the electrons in coincidence with recoil nuclei and first steps in this direction are being pursued in various laboratories with radioactive alkalines, namely Na (Berkeley), K (Triumf), Rb (Los Alamos).
By making use of laser spectroscopic techniques borrowed from experience with atomic beams, one can also look at tiny atomic level shifts and/or transition strength generated by PNC, which is a manifestation of electron-quark interactions through $Z^0$ gauge boson exchange at extremely small momentum transfer.

These PNC effects arise from mixing of electronic states with opposite parity, giving rise for instance to forbidden electric dipole transitions between states of the same parity. Experiments in this field played a very important role in the past in the building-up of the Standard Model as they allow to determine four of the 13 coupling parameters of the neutral-current interactions. PNC still today represents a valuable tool to test the radiative electroweak corrections and may be very sensitive to signatures of non-SM physics through precision measurements of lepton-quark coupling constants.

After the recent important results obtained with stable Cs atomic beams in determining PNC effects, where even the spin dependent part of the PNC interaction was evidenced, to pin down uncertainties on atomic physics calculations and to cross-check different systems, it is highly desirable to perform measurements on chains of isotopes. Especially important is the possibility to test high Z atoms, like Francium, since the PNC effect goes roughly as $Z^3$. Atomic spectroscopy on radioactive Fr isotopes is being performed at Stony Brook and, recently, a new set-up to produce, transport and trap Fr is being mounted at Legnaro.

Trap technology is also a suitable one for making studies on ground state properties of nuclei far from stability. One can in fact perform measurements on nuclear masses, radii, magnetic and quadrupole moments with high precision and efficiencies. The mass resolution obtained in ion traps is presently of the order of $10^{-7}$ for $A=100$ nuclei, i.e. comparable to that obtained in storage rings although limited to lifetimes longer than ≈100 ms. Nuclear radii and moments can be measured by atomic level shifts and hyperfine splitting determination, using laser spectroscopy methods. Proper techniques for these experiments have been already exploited at laboratories like Isolde using collinear atom laser beams. In these cases, as well as with traps, applications are particularly relevant for radioactive beams with low intensities, i.e. when less than $10^3$-$10^4$/$s$ are available.

Another application of traps for nuclear physics can be foreseen in measuring the shape change in nuclei by detecting the asymmetry in alpha-decay on a polarized sample. This can be done in principle with much higher precision than obtained in the past since alpha particles from trapped nuclei do not suffer from distortions due to source thickness. Charged particles can be also detected in coincidence with beta and gamma detectors to be placed extremely closed to the radioactive sample. Nuclei of interest, for instance to investigate the octupole deformation in the ground state, are those in the actinide and transactinide region. Such nuclei can be produced even via fusion-evaporation reactions in the proton-rich area or via deep-inelastic or multinucleon transfer reactions in the neutron-rich area. Gas-filled separators or magnetic spectrometers used in a gas-filled mode, can be coupled to a gas cell for deceleration of nuclei from the MeV to keV-$\mu$eV energy range. Finally, nuclei can be stored and manipulated in an ion or atom trap. Such a scheme has been already followed for instance at GSI with the Shiptrap project and at Argonne with the CPT spectrometer coupled to a split-pole. A complete set-up of a magnetic separator coupled to both an ion and an atom trap for precision measurements of nuclear decays and fundamental interactions is being designed at KVI. A similar development may be envisaged with the Prisma spectrometer at LNL.
1.2 Instrumentation and techniques

1.2.1 General requirements

The broad range of experimental conditions with respect to energy, mass, and intensity of the radioactive beams and with respect to the different types of reactions to be used requires the availability of different detector types arranged in efficient powerful arrays. At LNL a variety of powerful and up to date set-ups for both nuclear structure and reaction studies is already available and/or under construction. In addition, in connection with the future instrumentation the needs of experiments with neutron-rich exotic beams, like those produced with the proposed facility will be taken into account in the designing criteria.

A key requirement in next generation of experiments is to select, identify and measure rare events through the use of powerful detection systems like sophisticated $\gamma$-ray detector arrays and/or modern magnetic spectrometers with high acceptances. Because many of the experiments of interest will be made with low intensity beams, it is very important that the detector systems cover a large fraction of the total solid angle. In addition, a rather common situation will be that of dealing with impure beams and therefore the selection of the reactions of interest requires the detection of the outgoing coincident particles with good mass and charge identification. For all these reasons, the requirements for experimental equipments differ from those of the current generation. At LNL an effort is being made to develop techniques and a variety of new detectors.

One common feature of several experiments based on reactions with radioactive beams is that of being in inverse kinematics. This implies that the reaction products are all focused at small angles and therefore their measurement requires detectors with higher granularity than that of detectors used with stable beams. This is true not only for the measurements of charged particles but also for $\gamma$-rays. In fact, in the latter case the velocities of the emitting sources are much larger than those typical of the spectroscopy measurements with stable beams and therefore the Doppler broadening can prevent, if the detector is not properly segmented, the identification of discrete gamma-transitions. In addition, the decay of scattered radioactive beam particles will produce a high rate of background in particle and gamma-ray detectors, and again an high segmentation will be essential to identify and eventually reject the background events.

LNL has acquired a long experience in constructing and hosting large $\gamma$-ray detector arrays like GASP and EUROBALL used in combination with ancillary detectors (Fig.1.25) to achieve the necessary reaction channel selection for nuclear spectroscopy studies. Moreover LNL is presently involved, with other Italian groups, in the framework of the program for training and mobility of research in Europe, in developing new devices aiming at tracking $\gamma$-ray with high spatial resolution (MARS).

The most powerful method of selecting nuclei far from stability, produced by fusion evaporation or transfer reactions, relies on direct identification by a Recoil Mass Spectrometer or a large acceptance ray-tracing spectrometer like respectively CAMEL [20] or PRISMA [21] at LNL. Coincidence measurements of gamma-rays, detected in a large Ge array, with the mass of the emitting source, selected by magnetic spectrometers, have indeed made possible to approach the proton drip line.
In addition to the nuclear structure program concentrating in the low excitation energy region, several experiments performed at LNL concern the region of hot nuclei. In that case the investigation of the thermal nuclear properties requires the ability to measure the de-excitation of compound nucleus (formed in heavy ion reactions) involving the detection of evaporation residues, fission fragments, light charged particle, neutrons and high energy gamma-rays. Hodoscopes covering 4\(\pi\) are of primary importance in this connection. The 8\(\pi\)LP array, GARFIELD, RIPEN, HECTOR, are example of the complementary set-ups presently in operation at LNL (Figs.1.26-1.28).

**Fig. 1.25** - (left) The GASP gamma-array with the ISIS ancillary detector for charged particle coincidence; (right) coupling of GASP with the recoil mass spectrometer CAMEL.

**Fig. 1.26** - The GARFIELD apparatus is devoted to multifragmentation research and is based on Micro Strip Drift Gas Chamber – CsI(Tl) telescopes around the target and ionization chamber-Si strip-CsI(Tl) telescopes in the forward direction.
**Fig. 1.27** - HECTOR is a set-up for detection of high energy gamma rays with BaF2 detectors. A multiplicity filter with 90% coverage of $4\pi$ is coupled to 8 large volume detectors.

**Fig. 1.28** - $8\pi$ LP is a $4\pi$ detector for light charged particles. Trigger detectors for fusion and/or fission products operated in coincidence with the hodoscopes allow the selection of the reaction channel. It involves almost 250 Si-CsI(Tl) telescopes with pulse shape discrimination to detect light charged particles and gas counters for heavy-ion detection.

As far as “out of beam measurements” are concerned, it is important to mention that there is at LNL a new program based on the use of ion traps. In fact, a Magnetic Optical Trap (MOT) is presently under development and experiments are planned employing also some of the presently available beams. The use of such a trap allows to investigate very short-lived $\beta$-decay
processes, whose study is expected to provide a stringent test to fundamental theories. In this context, the possible existence of new phases of nucleonic matter such as proton-neutron pairing is just an example.

In the next sections more details are given in connection with the measurement techniques and the instrumentation needed for experiments with the SPES beams keeping in mind, as a starting point, the present situation and the expertise of the experimental groups using the LNL facilities.

1.2.2 Gamma-ray detectors

Gamma-rays detection will be important in many experiments. Arrays of clustered germanium detectors can be configured in a compact geometry and can be used in decay studies for gamma detection around the target, or at the focal plane of a mass separator for isomer studies, or for beta-gamma-gamma coincidence experiments. High efficiency, granularity and resolution are of primary importance in determining the resolving power of the gamma-spectrometers. The need for high efficiency is clearly due to the low intensity of the beams, expected always for the most exotic ions, while high granularity is essential both to reduce the Doppler effect in nuclear reactions and to track $\gamma$-rays in order to distinguish total energy absorption from Compton scattering events. The present generation of highly efficient and high resolution $\gamma$-arrays, like Gasp, Euroball and Gammasphere, have opened new possibilities in nuclear structure studies [22].

While the present state-of-the-art detector arrays, which consist of large volume germanium crystals surrounded by a suppression shield of BGO, have pushed this particular detector technology to its limit, it has become apparent that significant further gains in sensitivity will be possible as a consequence of an innovative concept based on $\gamma$-ray energy tracking in electrically segmented Ge crystals. This new technology leads to improvements of orders of magnitude in resolving power for high multiplicity events. Such highly segmented detectors, which follow each $\gamma$-ray through its interaction path in the detector material, are currently under study both in USA (Greta) and in Europe (AGATA) and Italian researchers are deeply involved in these developments [23].

Since most gamma-rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to "track" the path of a given gamma-ray. The full gamma-ray energy is obtained by summing only the interactions belonging to that particular gamma-ray. In this way there are no lost scatters into suppression shields and so a much higher overall efficiency can be achieved. Other key design benefits of a highly segmented Ge array include high energy resolution, high counting rate capability, good position resolution (critical for Doppler shift corrections of the many experiments involving high recoil velocities), the ability to handle high multiplicities without a high double-hit probability, and the ability to pick out low-multiplicity events hidden in a high background environment. Such device would have sensitivity 100-1000 times better than that of the current gamma spectrometers (EUROBALL and GAMMASPHERE). Such tracking detector systems will enable new classes of high resolution gamma ray experiments in nuclear structure, nuclear astrophysics, and weak interactions. This revolutionary technology will have enormous benefits for the broader low energy physics community, while holding the promise of important spin off applications in other fields, such as, medical, environmental, security, and space exploration.

In many cases a good selection of the reaction channel requires the use of ancillary detectors for light charged particles and neutrons to be coupled to germanium spectrometers. Arrays of Si telescopes giving the total energy (E) and the energy loss ($\Delta E$) information used for particle discrimination have been developed at LNL-Padova and extensively used both with
GASP and EUROBALL. In order to achieve, at least partially, the discrimination between low-energy light particles and heavy fragments that stop into the first stage $\Delta E$ detectors, the pulse shape technique has been applied [24]. The highly efficient $4\pi$ Si-ball EUCLIDE [25], using this pulse shape technique and designed as a trigger device for the EUROBALL $\gamma$-ray spectrometer, was developed at LNL.

1.2.3 Charged Particles, Heavy-Ions and Neutron Detectors

Large charged particle detection systems with good energy and angular resolutions are necessary for the studies of reaction mechanisms as well.

For unstable nuclei these reactions can be performed by using radioactive beams in inverse kinematics where the unstable nucleus of interest impinges on a light target nucleus. The most powerful method for determining the scattering angle and excitation energy is the accurate measurement of the angle and energy of the recoiling light target nucleus. This can be achieved by using a large solid angle position sensitive light particle array. First generation arrays dedicated to such measurements, and based on Silicon strip technology, have been implemented in several laboratories delivering radioactive beam experiments (GANIL, MSU and RIKEN) and have already produced impressive results [26]. A major goal in the future would be a significant increase of the solid angle coverage and of the performances of such arrays; these objectives could most efficiently be achieved through international co-operations. Such detectors can also be used together with spectrometers in order to tag different exit channels.

Interesting fields of investigation are also the competition between break-up and fusion reactions or the inelastic excitation of light projectiles impinging on medium mass target nuclei, in which the presence of a neutron skin/halo can influence rather strongly the reaction mechanisms and rates, with severe implications on astrophysical problems.

An open problem is the study of the nuclear matter Equation of State by means of heavy-ion collision at intermediate energies as a function of the charge asymmetry and its influence on the fragmentation processes. Collisions of systems with equal charge but different N/Z ratios are useful to study the isospin distillation and the charge dependent part of the nuclear interaction far from normal conditions as well as the formation of exotic shapes and the survival to fission in the super heavy mass region. These kinds of experiments require arrays for the detections of medium and heavy ion with large coverage of solid angle and good position and energy resolution together with low-energy identification threshold.

Neutrons should also be measured in many reactions, their emission being the most important de-excitation channel of highly excited neutron-rich nuclei. In particular, they should be detected in coincidence with charged particles and/or $\gamma$ rays. As the requirements for neutron detection are incompatible with the presence of massive detectors, a compromise is often accepted for measurements focusing on the properties of neutron spectra and multiplicity.

At LNL are operative two arrays of medium size for charged particles and intermediate mass fragments; 8$\pi$LP [27] and GARFIELD [28] are respectively used for studying reaction mechanism in fusion-fission/evaporation and multi-fragmentation experiments. Some hundreds of analog and timing channels are handled with remote control systems and powerful data acquisition.

The R&D for particle detectors requires a better position identification and large dynamic range in energy, Z and mass. Thousands of channels are expected and an improvement is needed to integrate read-out electronics and detectors with up-to-date microelectronics and detectors technology.
For neutron experiments the RIPEN array is available at LNL. It is a multi-detector with up to 30 cells of liquid scintillators BC501, operated in coincidence with fission fragments and evaporation residue detectors. Neutron angular distribution, mean multiplicity and energy measurements (by Time of Flight) with selected reaction channel, are possible.

### 1.2.4 Magnetic Spectrometers

Two classes of applications for magnetic spectrometers are envisaged in a Radioactive Beam Facility: separation of reaction products for secondary beam production or separation of reaction products for reaction studies. The expertise in this kind of device is in any case crucial. Form the point of view of reaction studies new generation of magnetic spectrometers are needed, with efficiencies one order of magnitude larger than the existing ones. A highly efficient heavy-ion spectrograph (PRISMA) [20] is presently under commissioning at LNL. Its optical design is very simple (one quadrupole singlet and one dipole magnet), but PRISMA will exploit fully the possibilities offered by tracking techniques along the ion paths. It combines good mass (1/300) and energy (up to 1/1000) resolutions with a large momentum acceptance (±10%) and a very large solid angle coverage (up to 80 msr). PRISMA will be extremely useful in the studies of reaction dynamics (transfer and deep inelastic processes, fusion-fission,...) with RIB. A pictorial view of the spectrometer is shown in Fig. 1.29. Further classes of experiments will be possible with PRISMA in conjunction with large γ arrays, where the spectrometer will allow to identify and tag exotic neutron rich nuclei populated via multi-nucleon transfer and deep-inelastic reactions. These spectroscopic studies can be complemented by using fission reactions induced by medium or heavy projectiles. An analogous spectrograph of the next generation (VAMOS) has been constructed at GANIL, where RIB is already available. VAMOS will also offer the possibility of beam rejection for the use at 0°, while at LNL the recoil mass spectrometer CAMEL [19] can be used for this purpose.

### 1.2.5 β decay spectrometer

Advanced facilities for exotic beams open new possibilities also for β decay studies. A recent collaboration among LNL, University of Surrey, IRES at Strasbourg and the University of Valencia intends to develop a spectrometer well suited to the study of β decay of exotic nuclei [29], to be employed first with beams of radioactive nuclei of 60 keV energy available now at CERN-ISOLDE, in view of its eventual use at the LNL radioactive beam facility.

Studies of β decay are an essential part of our attempts to obtain a better understanding of the structure of atomic nuclei. They are important in themselves for the information they carry about nuclear structure, and they are also important for our understanding of other physical processes. For example, β decay plays an important role in nucleosynthesis in stars, particularly in the determination of the reaction pathways followed in explosive nucleosynthesis. β decay also plays a particularly important role in studies of nuclei far from stability. First, the Q-values of β decay increase rapidly as we move away from the line of stability so that we have access to a wider range of states. Second, at the extremes of production, β decay will often provide the first information on new nuclei and may be crucial for identifying them.
Fig.1.29 - The PRISMA spectrometer, recently installed at LNL, is devoted to transfer reaction studies. It has a large acceptance of 80 msr and coupled to a germanium array at the target position, will allow to study nuclei far from stability populated by transfer reactions.

However, experimental determinations of the Gamow-Teller (GT) strength distribution are not easy. Usually the strength to a particular daughter state is measured by detecting the gamma-rays emitted subsequently from this state. In general the state is fed directly in $\beta$ decay and indirectly by electromagnetic transitions from higher-lying levels. The $\beta$ decay strength is deduced from the balance of feeding and de-excitation by electromagnetic transitions.

It is common to use semiconductor detectors in such measurements. Their efficiency for high-energy $\gamma$-rays is low; often it is as low as a few percent. As a result the experimenters rely on estimates of how much of the feeding of the levels flows indirectly from the higher-lying states, resulting in unreliable GT strengths.

A major experimental step in the direction of improving the knowledge of the GT strengths will be connected to the use of the Total Absorption Gamma Ray Spectrometer (TAGS) technique. This technique allows to measure directly the total population of the states fed in beta-decay. A TAGS [30] consists of a large scintillation detector (photo peak efficiency 70% at 5 MeV), of NaI type or with liquid Xe, with a hole through the centre to allow the low energy beam of radioactive nuclei to enter either directly, or through a tape system. This hole also allows the insertion of ancillary detectors for positrons, electrons, X-rays or $\beta$-delayed protons/alphas.

1.2.6 RIB with Ion and Atomic Traps

Ground state properties of radioactive ion beams (RIB) can be efficiently studied with a wealth of experimental methods making use of laser spectroscopic techniques [31] coupled to ionic [32] or atomic traps [33, 34]. The combined use of such techniques to RIB is very recent and full of potential applications for a large variety of experiments and technological developments. These studies can be performed with very low energy beams, typically $\lesssim 50$ keV,
as they come out from a conventional ISOL source. However, the applications are much wider and involve even cases in which the beam intensity is too low to make nuclear reaction studies, i.e. when less than $10^3 - 10^4$ p/s are available. Since for nuclei very far from stability the intensities are expected to be anyway of that order, it is straightforward that a substantial part of the research program in any new designed RIB facility should consider the development of such techniques. Besides for measurements of ground state properties of nuclei, the trap technology has been demonstrated to be a suitable one for precision measurements of fundamental interactions [35, 36], making the subject very attractive for a wider community of physicists. QED tests [36], CPT invariance [37], parity non conservation (PNC) and $\beta$ decays are some of the main topics in experiments performed with traps.

Other fields of application for ion/atom traps are the experimental determination of the mass of short lived nuclides and the measure of nuclear moments by laser spectroscopy. Very accurate mass measurements have been recently performed at ISOLDE (CERN) with accuracies on the order of $10^{-7} - 10^{-8}$ (10-1 keV) [38, 39]. These very accurate measurements serve for testing nuclear models, help to increase their predictive power for nuclides far from stability and can reveal nuclear structure. Additionally, some mass values represent important input parameters for Standard Model tests and astrophysical calculations.

Atoms/ions stored into a trap may have holding time of several hours and a very efficient laser spectroscopy can be performed on a very small number of atoms/ions. Laser spectroscopic techniques to short lived radioisotopes is a powerful tool to determine the energy of the atomic levels due to the very large photon absorption cross section at resonance. The nucleus affects the electronic levels via the hyperfine interactions, and it is from the precision measurements of the energy levels of the atom that one can deduce nuclear properties. One important observable is the mean square radius $r^2$ of the nucleus, which depends on its size (volume effect), deformation, and vibrational nature. $r^2$ is derived from the measurement of the isotope shifts (IS), which are typically less than $10^{-5}$ of the central frequency, but which can be determined to 1% or better by laser spectroscopy. If the nucleus has a spin, the atomic levels depend on the orientation of the nuclear magnetic dipole moment $\mathbf{R}$ and of the electric quadrupole moment $\mathbf{Q}$ with respect to the atomic fields, producing a multiplet of levels for each state. It is then usually possible to determine $g$ and $Q$ from the position and intensities of the hyperfine components (HFS). Sensitivity reached nowadays is impressive, being possible to deal with nuclear production rates as low as ten atoms per second [31].

In general, besides RIB, trap devices already found important applications in several other areas, micro gravity, metallic clusters [40], antimatter [41], atomic physics (high Z ions) [42], condensed matter physics (Bose-Einstein condensation) [43], and chemistry [44]. The instrumentation for RIB in general requires various technological developments, ranging from radio frequency (RF) devices, cryogenic systems and lasers, but the feedback in other important parts of RIB equipments has been demonstrated to be very fruitful, in particular in accelerator related areas [45]. This is the case, for instance, of the bunching system for the REX-ISOLDE project [46] or in a SPIG device [47]. Activity with traps for RIB is very recent [48, 49, 50, 51, 52] and some experiments are still in their infancy, with promising applications in a wide range of physics programs. A large effort in trap measurements and developments is going on at worldwide laboratories as CERN, GSI, TRIUMF, Stony Brook, and Los Alamos.

At LNL a laser cooling facility is under developments [53]. The first goal is to realize a Magneto Optical Trap for Francium trapping. Francium is the heaviest of the alkali atoms and it has many of the properties of the other alkalis. In fact, despite its radioactive complications, francium is still the heaviest simple atom. This is an important issue as a good crossed check among experiments and theory is possible. Francium does not have any stable isotopes and its abundance is so small that there is at most one ounce of francium in the whole Earth at any given
time as a result of the decay of other radioactive elements. It is the most unstable of the first 103 elements in the periodic table. In fact, its longest lived isotope has a half life of 22 minutes. The half-life of the $^{210}$Fr isotope is about 3.2 min, it has an estimated $\alpha$ decay branching fraction of 60 ± 30 % with the remaining decays being $\beta^+$ or electron capture. Francium trapping has been already achieved in Stony Brook where its energy level structure is under study [54] in view of future experiments on PNC. At LNL an experimental apparatus is under development to demonstrate the efficient trapping of Fr (and possibly other alkaline) produced with the XTU Tandem accelerator. Such an improvement in trapping efficiency should be achieved by special coating of the MOT and the implementation of the ‘broad band laser’ technique [55].

The set up has three main parts: a hot room with the production target, a transfer beam-line with a neutralizer and the MOT. $^{210}$Fr is produced by the nuclear reaction $^{18}$O + $^{197}$Au $\rightarrow ^{210}$Fr + 5n, the target is heated to a temperature near to the gold melting point to maximize both francium diffusion toward the gold surface and the escape rate of francium ions. After a pathway of few meters, francium ions hit the neutralizer, kept at relatively high temperature, from which are extracted as neutral atoms and collected in a vapour cell where are cooled and trapped by the lasers in the MOT. Neutralizer materials such as Yttrium and Zirconium are presently under test. A test has been already made in which the francium production rate as a function of the target temperature and of the electrode voltage was studied. The francium ions were collected onto an aluminium catcher and its production rate was measured looking at the $\alpha$ particles generated in the decay; production of the order of 5x10^4 $^{210}$Fr ions per second was obtained with a beam current of 50 nA.

The installation of the secondary beam line and the MOT is under completion (Fig.1.30), the laser system is already operative.

![Fig.1.30 - The optical table with laser set-up for the MOT installation and the spectra of francium produced recently at LNL.](image-url)
1.3 Experimental facility for skin melanoma treatment with BNCT

Boron Neutron Capture Therapy (BNCT) is one of the most promising and less patient shocking approach for the treatment of some kind of brain tumors, e.g. Glioblastoma Multiforme, which has been setting up in the last years. Nevertheless this therapy revealed able to be successfully implemented for other kind of body tumors such as Melanoma, due to its selectivity in cell killing.

It’s based on the use of a proper (thermal or epithermal) neutron flux impinging on previously, boron compound loaded, tumor tissues. Due to high thermal neutron capture cross section (3837 barn) \(^{10}\text{B}\) nuclides gives rise to a fission reaction originating two particles: \(^{4}\text{He}\) of 1.47 MeV and \(^{7}\text{Li}\) of 0.84 MeV. The densely ionizing fission fragments have ranges in soft tissues (~8 µm for the \(\alpha\) particle, 5 µm for the lithium ion) as short as the diameter of a cell (~10 µm). Depending on the fission fragments geometry, all the energy can be released within the cell volume and partly in the cell nucleus, avoiding this way the cell replication by causing the DNA double strands break. The extremely local \(^{10}\text{B}\) fission reaction rate is high enough to cause a lethal damage to one or more cells in the tumor tissue, while only a limited one can be imparted to surrounding healthy tissue cells.

The Legnaro BNCT facility will use the intense proton beam provided in the framework of SPES project to deliver thermal neutrons for melanoma experimental treatments. The facility will be used to validate the optimal therapeutic beam features in preliminary therapeutic trials. The radiation fields will be fully characterized with spectroscopic, dosimetric, microdosimetric and radiobiological study steps. In the following the medical problem and the facility is briefly introduced, as well as a brief summary on the BNCT projects in the world.

1.3.1 The skin melanoma

Once a rarity in oncological management, there has been an exponential increase in incidence of malignant melanoma (MM) during the past 20 years giving it a new clinical pertinence. In 1975 there were an estimated 9000 new cases in the United States with approximately 5000 expected deaths. By contrast, in 1995 there were an estimated 34100 new cases with an expected 7200 cancer deaths [56]. In the Veneto region (Northeast of Italy) we have 10 new MM per 100,000 inhabitants a year and this rate is increasing [57].

Whereas surgery provides optimal management for localized disease, treatment options for more advanced disease has been less successful. Advanced MM remains a very fatal disease requiring all of the oncology resources available. In a multidisciplinary approach to the treatment of MM the role of radiation therapy is often relegated to one of minor importance. There is a supporting body of scientific literature that shows a relative radioresistance of MM when compared with other malignancies. Therefore BNCT could be the best treatment for those skin tumors, which are nowadays resistant to ordinary therapy. In fact the high-LET radiation resulting from the \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\) capture reaction are equally as lethal to hypoxic and to oxygenated cells, and non dividing cells in G0 phase.

In 1987 the first patient with MM was treated by BNCT on a subcutaneous metastatic lesion of the occipital region. The irradiation was delivered in a single fraction after perilesional administration of BPA, at the Kyoto University [58]. The complete objective response and tolerability reported were followed by further treatments of patients with primary or metastatic MM when surgical excision was not feasible. At least other 20 patients with MM underwent BNCT in Japan. Up to date available case reports and retrospective studies show that the method is not standardized [59,60]. The preliminary clinical results are promising, but the reports in
some cases are not exhaustive. In more recent clinical trials epithermal neutrons were delivered on the tumors instead of thermal neutrons, due to their greater deep of penetration in the tissues [61,62].

The 5% of MM tumors develop surface metastases which can be treated with BNCT. The 40% of patients with MM develop metastases in other parts of the body. Some of these metastases could be successfully treated with BNCT. However, considering that MM cannot always be controlled locally without mutilating surgery, there may be a role for this high LET radiotherapy in association with conservative surgery as a primary treatment such as in limb sparing and in head and neck tumors.

In short, the Veneto Tumor Observatory points out that 50 patients a year could take great advantage from a BNCT therapy. Although the estimation for Italy is more uncertain, a reasonable assessment is 500 new patients every year. Moreover BNCT could even be used in mixed therapeutic plans wherever high LET booster could be useful.

1.3.2 The LNL BNCT facility

An accelerator-based thermal neutron source, aimed at the BNCT treatment of skin melanoma (shallow tumor), is foreseen to be installed at the INFN-LNL in the framework of SPES project. The BNCT device will exploit the intense proton beam provided by a 5 MeV, 30 mA (Radio Frequency Quadrupole) RFQ that will be the first accelerating step of the designed 100 MeV Legnaro exotic nuclei production beam facility. The SPES-BNCT facility design will exploit the experience gained, in the last years at the INFN-LNL, with the experimental thermal neutron source set-up driven by the 7 MV (3 µA max. current), CN Van de Graaff accelerator on beryllium target [63, 64, 65, 66]. A feasibility study, both to select the best neutron yielding nuclear reaction and the related ion beam target engineering issues, as well as the optimal neutron moderator design, is simultaneously being carried out on the BNCT-LNL experimental mock-up. Different ways of generating neutrons with 5 MeV proton beam which exploit $^7$Li(p,n)$^7$Be, $^9$Be(p,n)$^9$B and $^{13}$C(p,n)$^{13}$N nuclear reactions are being taken into account. The $^9$Be(p,n)$^9$B reaction at 5 MeV is indeed characterized by the highest neutron yield [67]. Anyway other proton energies will be investigated as well as deuteron beams, in a research aiming to optimize the moderator dimensions versus the projectile energy and current. A cross sectional view of the current accelerator based facility, which shows the geometrical and material configuration, is reported in Fig. 1.31.
The design of the target cooling system is a quite critical engineering issue, because of the heat flux of about 5 kW cm\(^{-2}\) (referred to 5 MeV, 3 mA and beam radius 1 cm), which has to be removed from a site of not easy access (the target is contained in a pipe inserted in the D\(_2\)O moderator). However, a first technical study [68] suggests that a safe target cooling is feasible both with water and air coolants. The use of water seems to be more suitable for sake of disk temperature level and cooling loop simplicity. The thermal neutron fluence required for the treatment is 10\(^9\) cm\(^{-2}\) and the maximum irradiation time is 1-2 hours, basing on the melanoma BNCT performed in Japan [69]. The cumulative dose due to prompt gamma rays and fast neutrons should be kept below 2 Gy for the whole treatment, versus about 20 Gy delivered to the tumour by the \(^{10}\text{B}(n,\alpha)^7\text{Li}\) reaction products. The maximum depth of the lesion, which will be considered for treatment, is 3 cm while the size of irradiation field will be 10x10 cm\(^2\).

### 1.3.3 Brief Summary on the BNCT projects in the world

Only nuclear reactors are being used in the first patient trials all over the world so far. They, in fact, are able to provide a relatively high yield neutron source, other than the ability to achieve the neutron flux parameters suitable for therapeutic application. Nevertheless, the high facility cost, the continuous operating power and, overall, safety and public acceptance issues, relative to a hospital-based reactor facility, are the most important items, which make this solution suitable only for early experimental investigations of BNCT. Since few years ago only few facilities (in USA and Japan) were provided with a beam shaping assembly aimed at BNCT patient treatment. The BMRR [70,71], Brookhaven (out of order because of the recently reactor shut down), and the M-67 MITR-II [72,73] at Harvard-MIT, operating in the USA, started the Phase I trials in the '90. In order to meet the needs to provide a high quality beam a new, fission converter-based [74], high performance epithermal neutron beam has been designed at MITR-II, which is foreseen to begin the first irradiation treatment in the 2003. On the other hand two units, the JRR-4 [75] and the KUR [76] reactors, where Prof. Hatanaka’s first experimental patient treatment began since the late ’60 [77] with a particular surgery technique based on thermal beam, are the only two facilities in Japan which have undergone in recent years to heavy layout modification, in order to be upgraded for epithermal treatment too. Finally the JRC-HFR [78]-Petten (The Netherlands) is instead the facility where the first experimental clinical treatment protocol in EU started in the late ’90 [79], followed by the FiR1 [80,81] at Espoo (Finland) and, more recently, by R2-0, near Studsvik [82] (Sweden). All facilities reported have in progress (or already concluded) a series of patient trials mainly restricted on terminal patients. Their main goal is in fact to acquire as detailed data as possible, related both to the toxicity level of boron compounds which are frequently being used (Borophenylalanine-BPA, as well as the Sodiumdodecaborate-BSH) and the maximum tolerable dose by health tissue. In Table 1.1 some BNCT operative beam parameters are reported.
Table 1.1 - BNCT operative beam parameters

<table>
<thead>
<tr>
<th>Facility</th>
<th>Reactor Power (MW)</th>
<th>Thermal flux ($x10^8$ n/cm^2s)</th>
<th>Epithermal flux ($x10^9$ n/cm^2s)</th>
<th>$D_{ef}$/Φ_{epi} $x10^{-13}$ (Gycm^2/n)</th>
<th>$D_{γ}$/Φ_{epi} $x10^{-13}$ (Gycm^2/n)</th>
<th>$D_{γ}$/Φ_{th} $x10^{-13}$ (Gycm^2/n)</th>
<th>J/Φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMRR</td>
<td>3</td>
<td>-</td>
<td>0.84</td>
<td>4.8</td>
<td>2.0</td>
<td>-</td>
<td>0.80</td>
</tr>
<tr>
<td>M-67 (MITR-II)</td>
<td>5</td>
<td>-</td>
<td>0.20</td>
<td>13.0</td>
<td>13.0</td>
<td>-</td>
<td>0.55</td>
</tr>
<tr>
<td>HB-11 (HFR)</td>
<td>45</td>
<td>-</td>
<td>0.33</td>
<td>10.3</td>
<td>8.6</td>
<td>-</td>
<td>0.80</td>
</tr>
<tr>
<td>FiR1</td>
<td>0.25</td>
<td>1.00</td>
<td>2.0</td>
<td>0.5</td>
<td>-</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>R2-0</td>
<td>1</td>
<td>1.8</td>
<td>0.76</td>
<td>5.2</td>
<td>-</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>KUR</td>
<td>5</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>-</td>
</tr>
<tr>
<td>JRR-4</td>
<td>10</td>
<td>1.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.2</td>
<td>-</td>
</tr>
</tbody>
</table>

1.4 Physics of Neutrons

Thermal neutron scattering is one of the most important tools to study condensed matter and it is now a technique which is routinely used in a very broad area of scientific research ranging from the most basic properties of solid and fluids to the industrial applications, like advanced non destructive tests of equipment components.

Thermal neutron scattering, like its companion techniques, namely x-ray scattering using synchrotron radiation, is generally a technique based on a rather large facility. These two techniques allow to do small science and representing the most important effort performed by the advanced countries in order to study condensed matter.

At present, there exist several facilities where it is possible to perform neutron scattering experiments and Europe has a definite worldwide leadership in this field, due to the large neutron scattering community (in excess of 4000 scientists from the most developed countries) and to the availability of high class sources together with the most advanced neutron instrumentation.

During the next years the most important activity in the neutron scattering will be the construction of two new sources of great dimension: the Spallation Neutron Source Source (Oak Ridge, USA) and the source of the joint project, JAERI/KEK for High Intensity Proton Accelerators (Tokai campus of JAERI, Japan). These two sources have similar characteristics: they are spallation sources which produce neutrons by means of protons accelerated up to a few GeV. The American source has been financed in the year 1999 and the construction started in the year 2000. The operation of the source will start in the year 2005. The Japanese source has been financed in the year 2001 and the construction will finish in the year 2006. The cost of both sources is of the order of 1300 M$ at present costs.

In Europe a very important project is being developed. This is the European Spallation Source (ESS) which is the project of a very high power source which will compete with the other two sources being built. The European source is based on a 5 MW accelerator, however such a project is still being prepared and several technical problems have to be solved.

The accelerator based neutron sources represent the only real development of the neutron sources. Indeed, apart from political considerations on the use of fission nuclear reactors, it is clear that their performance as neutron sources has reached the technical limit with the high flux reactors built at the end of the '60 (HFIR at Oak Ridge and HFR at Brookhaven in USA and HFI
at Grenoble in Europe). As previously observed the development of the ESS project is extremely important for the European research, but the absence of a national source makes the Italian participation very difficult.

The lack of a national source, even of small size, is a real limit for the organic growth of the scientific Italian community. The present project has the role of starting the constitution of a structure able to minimize the effect of the present fragmentation of the technical knowledge over the country. This fragmentation of the project capability of the Italian community has a negative impact of the weight of the Italian community at the international level for what concerns the development of new instrumentation and sources. Therefore the project has as main purpose the constitution of an operative group having high level technical knowledge to be the national reference point. To this purpose the project must allow the creation of an adequate number research and technical personnel with high capability level to properly participate to the project of the European neutron source of the next generation ESS (2001-2003) and to its possible construction (2004-2010).

Although a source of this size is not competitive with those available at the main international institutions, it has the advantage of a low radiation release and a smaller activation level as compared to the spallation sources, whose cost is more than two orders of magnitude higher. The low radiation level allows for a small size biological shielding, thus allowing for a smaller reduction of the neutron flux as a consequence of the distance between the source and the area where the beam is employed.

It is possible to make a first estimate of the performance of the above source by scaling the results of the previous tests performed employing the beryllium target (deuterons 6 MeV and 100 nA), which gave a flux of 50 n/s at a distance of 1.5 m from the source. One obtains a flux of the order of $5 \times 10^5$ n/s at a distance of the order of 3 m (protons 100 MeV and 1 mA, duty cycle 0.01). Such a flux can be increased by optimizing the moderator and improving the transport characteristics of the neutrons from the source to the use point, using neutron guides. The main characteristic of this source is its considerable simplicity and its efficacy due to the pulsed nature of the beam which allows for the use of time of flight techniques, very useful in the test of neutron instrumentation components.

The Italian neutron scattering community is composed of about 200 scientists from almost all the fields covered by neutron scattering and is strongly involved in international collaborations at the most important sources in Europe. The construction of the new source will allow for the uses, which will be described in the following to be developed in Italy, where no other source is currently easily available to the purpose of neutron scattering and related activities. The most important possibility offered by the new source will be the test of instrument components. This point is very important because in order to have an efficient collaboration with the various existing and future international facilities the Italian community has to collaborate to the design and construction of new neutron scattering instruments. In order to do this it is very important to have an easily available source where the various components can be tested. The source will be used to test also new solutions for the neutron optics as well as neutron detectors. The Italian community is well prepared in these fields as various Italian groups are already collaborating with the most important international facilities in building new sophisticated instruments.

The second activity could be based on a basic instrument which could be installed at the new source. Such a basic instrument could be very important for the training of young people approaching neutron scattering. The availability of an instrument where the access is not subjected to the strong constraints of large scale facilities will allow performing test experiments which are very important to teach the basic technique of neutron scattering in small scale but real experiments. Also experimental schools could be possible where the students will perform all the
steps of a real experiment. These activities will be extremely important for the development of a group of young scientists to be involved in the future continental plans.

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