CHAPTER I

PHYSICS CASE

1.1 Introduction

A very large knowledge on the world of the nuclei has been acquired in the last 30 years thanks to many researches both experimental and theoretical. The nuclide chart has been widely explored by means of a variety of reactions from fusion-evaporation to direct reactions, from deep-inelastic collisions to central explosive interactions at high energies. All of this has given us access to a rather detailed description of the properties of atomic nuclei.

At rather low bombarding energies, fusion reactions opened the study of nuclei at high excitation, of both thermal and collective type, up to the maximum values of angular momentum that the system can sustain. At such high excitations it has been possible to discover and study very particular nuclear shapes with special attention to their decay and the coupling with the low-energy modes and with the Giant Dipole Resonance. By means of fusion processes, moreover, it has been possible to push the study of proton-rich nuclei towards the p-rich side of the stability valley. A part from nuclear physics, also astrophysics benefited of this investigation because many stellar processes and nucleosynthesis are based on nuclear reactions involving systems far from normal ‘beta-stability line’. Coming to higher bombarding energies, many experiments have been performed to look at the behaviour of nuclei when produced at temperatures close to the nucleon binding energies: strange decays of nuclei in many pieces (multifragmentation decays) have been observed and studied, thus one could explore the Nuclear Equation of State (NEOS) far from equilibrium conditions; exciting scenarios well known on a macroscopic scale and with aspects important for general physics, such as phase transitions and liquid-gas phase coexistence, have been suggested and perhaps discovered.

Notwithstanding the enormous quantity of studies, till now it is impossible to predict, for example, the limits of nuclear stability or the behaviour of the NEOS at low and high barion densities. The asymmetry term in the NEOS is largely unknown but in the region close to saturation; however it is just this energy which plays an important role in setting the stability limits. For this reason many studies started worldwide to better investigate the behaviour of nuclear matter far from stability. There are of course many activities which can and must be pursued by means of conventional stable beams; however this is not sufficient to push the knowledge in the very far regions of the nuclide chart especially towards the n-drip line. Therefore many laboratories started a game to equip themselves with modern accelerator complexes to produce energetic high quality exotic (i.e. unstable) ion beams and to develop new generation detector devices.

Since years LNL represents a cornerstone for this type of physics at an European level as demonstrated by many recent activities, collaborations and initiatives which are in progress therein. Therefore, LNL endeavoured to upgrade the design of the SPES machine to match the request of the community of nuclear physics, both Italian and European. In this respect, it is important to note that the completion of the facility can be achieved in a reasonable time, quite competitive with the other European efforts in the direction of exotic ion beams.

In the following paragraphs we present some key experiments chosen among the wide research field addressable with SPES and extensively discussed in previous reports.
1.2 Spectroscopy of neutron rich nuclei

One of the most critical ingredients in determining the properties of a nucleus from a given effective interaction, is the overall number of nucleons and the ratio N/Z of neutrons to protons. One aspect which is presently strongly discussed concerns the modification of the average field experienced by a single nucleon due to the changes in size and diffusivity for nuclei with strong neutron excess. For large neutron excess the softening of the Woods-Saxon shape of the neutron potential is expected to cause a reduction of the spin-orbit interaction and therefore a migration of the high-l orbitals with a large impact on the shell structure of nuclei far from stability [1-5].

A different scenario has been recently suggested where the evolution of the shell structure in going from stable to exotic nuclei can be related to the effect of the tensor part of the nucleon-nucleon interaction. The tensor-force, one of the most direct manifestation of the meson exchange origin of the nucleon-nucleon interaction, is responsible of the strong attraction between a proton and a neutron in the spin-flip partner orbits. A recent generalization of such mechanism foresees a similar behaviour also for orbitals with non identical orbital angular momenta. It is expected an attraction for orbitals with antiparallel spin configuration and a repulsion for orbitals with parallel spin configuration. In most of the cases one is dealing with a combined effect of the attraction among orbitals with antiparallel spins and repulsion between orbitals with parallel spins [6-8].

Those effects become particularly visible when moving away from the line of stability. In such cases the proton-neutron interaction is changed by emptying of the partner orbit causing a modification into the effective single particle energies (evolution of the shell structure).

The change of the shell structure based on such mechanism has been recently discussed in different mass regions of the nuclear chart. In such contest neutron-rich nuclei close to shell gaps are particularly interesting since, when compared with the shell model prediction, they allow to search for anomalies into the shell structure. It is predicted, for example, that the Z=28 gap for protons in the pf-shell becomes smaller moving from $^{68}$Ni to $^{78}$Ni as consequence of the attraction between the proton f$_{5/2}$ and neutron g$_{9/2}$ orbits and the repulsion between the proton f$_{7/2}$ and the neutron g$_{9/2}$ configurations. The same argument also predicts a weakening of the N=50 shell gap when approaching the $^{78}$Ni nucleus due to the attraction between the neutron g$_{9/2}$ and d$_{5/2}$ configurations with the proton f$_{5/2}$ state and the repulsion between the neutron g$_{7/2}$ with the proton f$_{5/2}$ state.

Properties inconsistent with shell closure have been found in several neutron-rich systems around shell-model magic numbers [9, 10].

In the last few years, the use of binary reactions, quasi-elastic, multinucleon transfer or deep inelastic scattering, combined with modern γ-ray arrays (GASP, Gammasphere, Euroball, etc.) with or without efficient ancillary detectors, has increased substantially the amount of information available on the structure of previously inaccessible nuclei far from stability. An example is the neutron-rich nucleus $^{68}$Ni, where investigation of the structure have revealed the doubly-magic character of N=40 Z=28 subshell closure.

The neighbouring $^{71}$Cu nucleus has also been investigated that way. The knowledge of the determined residual interactions has opened the way for shell model calculations for nuclei in the region around N=40 Z=28 [11].

Deep-inelastic collisions have also been used to access different neutron rich nuclear regions at medium and high spin [12-14]. The Sn isotopes with N=72, 74 and 76 have been reached, allowing the identification of the 10$^+$ isomeric states with $\nu h_{11/2}^n$ configuration. In the region of doubly-magic $^{208}$Pb, the two body, neutron-neutron residual interaction and the neutron single particle energies have been determined from the structure of the $^{210}$Pb and $^{209}$Pb nuclei, also populated in the afore-mentioned collisions. The information extracted on this nuclei is very
important for the understanding of the states in nuclei with valence neutrons above the shell closure at N=126.

In nuclear systems with quadrupole deformation, the coherent addition of the excitations induced by multinucleon transfer or deep-inelastic processes (and by Coulomb excitation) populates high angular momentum states. Some examples of this phenomenon are revealed in studies of the rotational bands and the alignment of $v_{11/2}$ pairs in the $^{100}$Mo region, or the investigation of rotational structures in the neutron-rich Dy, Yb and Sm isotopes.

The use of high resolution large acceptance spectrometer coupled to anti-Compton γ-ray detector array has marked a step forward with respect to the previous spectroscopy studies with deep inelastic or multinucleon transfer reactions. Examples are the PRISMA spectrometer of the LNL coupled to the CLARA detector array and the VAMOS spectrometer of GANIL coupled to the Exogam detector. They provide, for most of the reaction products, the full identification of mass and Z. This makes available information from reaction products of very low cross section and thus allows measurements on nuclei further away from stability.

**Fig. 2.1:** Coupled channel calculations performed with the program GRAZING. The production of neutron rich channels is strongly increased by the use of neutron rich beams.

Beams of neutron rich radioactive nuclear beams of sufficient intensity offer the interesting possibility to further extend our knowledge of neutron rich nuclei.

Since, as already mentioned, the multinucleon flux moves from proton-stripping and neutron-pick up to vice-versa when going from proton-rich to neutron-rich beams, heavy neutron-rich projectiles can be used to populate the most exotic final products.

Figure 2.1 shows the production of neutron rich nuclei calculated using the program GRAZING [14a]. One should notice that the relative intensity of the neutron rich channels strongly increase when using an heavy neutron rich beam or a neutron rich radioactive nucleus.
Radioactive beams like $^{92}$Kr, $^{94}$Kr, $^{132}$Sn and $^{134}$Sn, when used with heavy targets like $^{208}$Pb or $^{238}$U, allow access to a range of neutron-rich nuclei of interest to address the following questions:

1. Study of the evolution or breakdown of shell gaps, resulting from the combined effects of the spin-isospin tensor interaction and of the density dependent terms of the nuclear force on single particle states. Of particular interest are the mass regions close to magic numbers far from stability like $Z=28$, $N=50$ or $Z=50$, $N=82$.
2. New region of deformation.
3. New nuclear symmetries (critical point symmetries, chirality). New critical point symmetries have been recently proposed and experimentally found. The new symmetries describe nuclei at the critical point respect to a shape/phase transition. Particularly interesting is here the $N=90$ mass region around Gd and Ce ($X_5$ symmetry, spherical to prolate axial) as well as the $^{170}$Er nucleus ($Y_5$ symmetry, spherical to $\gamma$-soft). Chiral symmetry has also been suggested to be present in nuclear systems based on the energy degeneracy of the levels. A recent test of such symmetry based on the measurement of absolute transition matrix elements has shown that chirality does not appear in mass $A=130$. Of high interest is to check for existence of chirality in the $A=106$ mass region where almost complete energy degeneracy has been found.

1.3 Multiple particle transfer and sub-barrier fusion

Transfer reactions between heavy ions at Coulomb energies provide invaluable information for both nuclear structure and reaction dynamics studies. While from the stripping and pick-up of one neutron or proton one can deduce information about the shell structure of the two colliding nuclei, from the exchange of many nucleons one can study nuclear correlations, pairing in particular, in the nuclear medium. An important and highly debated item in the field of nuclear reactions, which is receiving new impulse in view of the future availability of intense radioactive beams like those produced by SPES, is the interplay between single particle and pair (or even cluster) transfer modes.

Extensive work, done in the past, with $(p,t)$ and $(t,p)$ reactions [15] stressed the ability of nucleons to correlate in pairs thus leading to the construction of the pairing vibrational and pairing rotational models correlating the spectra of neighboring nuclei. Later on, studies of inclusive cross sections for the transfer of one and two nucleon pairs in heavy ion collisions [16] suggested the presence of large enhancement and possibly the onset of a nuclear Josephson effect due to the coherence of the superconducting states involved in the transition [17].

More recently, several systems have been studied at LNL [18] and detailed experimental mass and nuclear charge yields were obtained together with angular and total kinetic energy loss distributions that allowed a good comparison with state-of-art theoretical models. In particular, interesting results were obtained for the $^{40}$Ca+$^{208}$Pb system [19], where data have been compared with semi-classical models [20,21] where the surface modes of target and projectile, and the transfer channels are treated on the same footing. The transfer channels include the one- and pair-transfer modes (stripping and pick-up), and the multi-nucleon transfer that is treated in the sequential approximation of the fundamental modes.

Interesting hints for the possibility to observe multi pair-phonon excitations are coming from recent investigations on the $^{40}$Ca+$^{208}$Pb [22], $^{40}$Ca+$^{96}$Zr and $^{90}$Zr+$^{208}$Pb [23-25] reactions where $\gamma$-particle coincidences have been performed with PRISMA+CLARA, which allowed the observation of weak $\gamma$ decays from high-lying $0^+$ states in $^{42}$Ca in the excitation energy region expected for pairing vibrations.
It is very important to investigate the correlation properties far away from the stability, especially on the neutron rich side, since in this region the correlations, in particular the one due to the pairing interaction, should play a dominant role in defining the properties of these nuclei. A key point, yet unexplored, is whether transfer processes involving neutron-rich nuclei can lead to the onset of super-currents with very large number of neutrons transferred among the colliding nuclei. These super-currents, driven by the exchange of pairs, should allow an easy identification of the pair-modes, and they should alter in a very significant way the imaginary part of the optical potential with a polarization component that should be repulsive. The use of nuclei with an extended neutron distribution should allow to study in detail the density dependence of the pairing force, as well as to disentangle the role of the coupling to the continuum in the dissipation of energy and angular momentum, and in the formation of the compound nucleus (fusion). These effects are likely to be seen in the behavior of the yield distributions of the different multi-nucleon transfer channels as well as in the enhanced population of selected states with specific structure that reflect the transfer of correlated pairs. At variance with what happens with stable beams where the main transfer flux is along the pick-up of neutrons and stripping of protons, with radioactive beams one can populate nuclei along both the pick-up and stripping of protons and neutrons. In this way not only the \( (nn) \) and \( (pp) \) correlations but also the \( (np) \) correlations can be studied at the same time looking at the population pattern of specific final states reached via addition and removal of pair-phonons. In Fig. 3.1 we show predicted cross sections in the reaction \( ^{44}\text{Ar} + ^{208}\text{Pb} \), from which one observes the “symmetric” population of transfer products.

Using the heavy neutron-rich beams, which will be provided by SPES, the reactions of \(^{132}\text{Sn}\) beam on the \(^{40,48}\text{Ca},^{58}\text{Ni},^{90}\text{Zr}, \) and \(^{112}\text{Sn}\) targets at energies close to the Coulomb barrier can be studied. In these reactions one aims at measuring the cross sections of different transfer channels, as well as the final state strength distribution. Studies should also be performed at sub-barrier energies [27,28], where only the tail of the wave functions enter into play and thus they should be of simpler analysis. To give a hint of why it is so, we recall that the nuclear part of the inelastic form factor is well described by the derivative of the optical potential and thus has a decay length of about half (~ 0.65 fm) of that of the transfer form factors (~ 1.3 fm). In this way, at sub-barrier energies the two ions probe their densities only at large distances. Here the nuclear couplings are dominated by transfer processes and the multi-nucleon transfer proceeds via a sequential mechanism.

![Fig. 3.1: Total cross sections for the indicated reaction calculated with the code GRAZING. \( \Delta N \) and \( \Delta Z \) represent the number of transferred neutrons and protons, respectively.](image-url)
The investigation of the transfer channels with very neutron rich beams may be also very useful to elucidate the role played by these different degrees of freedom in the fusion process. It has been shown that with stable beams fusion is generally dominated by strong couplings to nuclear shape vibrations and deformations [29] but the role of the nucleon transfer degrees of freedom has not been clarified yet. Fig. 3.2 shows the measured fusion cross sections [30] and the corresponding barrier distributions for the three cases $^{40}$Ca + $^{90,94,96}$Zr, in a reduced energy scale. One notices the much faster decrease of the $^{40}$Ca + $^{90}$Zr cross sections below the barrier with respect to the other two systems, and the progressively wider and structureless barrier distribution when going from $^{90}$Zr to $^{96}$Zr. Whether these trends are due to the low-energy structure of the target isotopes (quadrupole and octupole vibrations) and/or to neutron transfer couplings, is a matter of current discussion.

![Fig. 3.2: (left) Fusion excitation functions of the three systems $^{40}$Ca + $^{90,94,96}$Zr, and (right) extracted barrier distributions. See text.](image)

In order to give just some examples, very neutron-rich RIB of $^{132-134}$Sn, $^{126,128}$Cd might fruitfully be used on $^{40,44,48}$Ca targets to measure fusion cross sections near and below the barrier, with the purpose of clarifying the situation, even if barrier distributions will be difficult to extract. In such cases the large neutron excess of the beam leads to huge and positive ground state Q-values for few- and multi-neutron transfer. These studies of near- and sub-barrier fusion reactions using the exotic beams from SPES will require the development of a new dedicated set-up with higher efficiency and background rejection capabilities than is available now at LNL.

At very low energies, fusion excitation functions usually show an exponential decrease [31]. For several systems, however, a different behaviour (called a "hindrance" effect) was found in recent years [32,33]. It was suggested [34] that fusion cross sections are sensible, at far subbarrier energies, to the nuclear potential in the inner side of the Coulomb barrier, in particular to a repulsive core [35] of the nuclear potential arising from nuclear incompressibility K. A good fit was obtained for $^{64}$Ni + $^{64}$Ni [35] using $K=228$ MeV, that is, the value extracted for cold nuclear matter in the “soft” equation of state [36]. Since K depends on the neutron excess, one expects the low-energy behaviour of the fusion excitation functions to be different in systems involving large number of neutrons especially near the nuclear surface. This would be very interesting to investigate with reactions like, e.g., $^{132,134}$Sn beams on $^{48}$Ca or $^{64}$Ni.
1.4 Dynamics and Thermodynamics of exotic nuclear systems

Experiments performed with stable beams have produced hot nuclear systems and their decay modes have been extensively investigated. From the properties of the emitted particles (energy spectra, isotopic yields, multiplicity), information about the excitation energy and the temperature of these hot systems has been extracted [37] giving access to a detailed study of the evolution of NEOS up to non-equilibrium conditions. In particular, studies of the isospin degree of freedom in nuclear matter have already started in Italy at LNS with the CHIMERA detector and at LNL with the GARFIELD and 8πLP apparatuses. Important contributions of Italian groups have been also obtained from collaborations at GSI, at GANIL and at MSU, in particular in the study of the liquid-gas phase transition.

The n-rich ion beams of SPES will allow to further extend the investigation of the NEOS along the isospin coordinate, in a region where the it is largely unknown even at low excitation. In the following we focus the discussion on two main topics that should be effectively investigated with the availability of the SPES beams.

1.4.1 Limiting temperatures in hot N/Z asymmetric nuclear systems

Theoretical calculations have predicted and experiments have observed the existence of a limiting temperature, $T_{\text{lim}}$ [38-46]. Below this temperature, the nuclear system can be described as a nuclear drop evaporating light particles, whereas above $T_{\text{lim}}$, the thermodynamically equilibrated nuclear drop cannot survive anymore and breaks up.

From a theoretical standpoint, calculations based on Skyrme-type nucleon-nucleon interactions and other parameterizations have predicted mass-dependent limiting temperatures [41, 43, 44], with heavier nuclear systems being characterized by a lower $T_{\text{lim}}$ value. Such A-dependence of $T_{\text{lim}}$ is predicted to provide important information about the critical temperature, $T_C$, of infinite nuclear matter and about the isoscalar part of the nucleon-nucleon effective interaction [41, 43, 44]. Experimentally, a systematic study of limiting temperatures has been performed by J. Natowitz et al. [47]. By collecting all the available data on nuclear caloric curves (i.e. the correlation between measurements of excitation energy and temperature), a decreasing limiting temperature with increasing mass of the hot nuclear system has been experimentally observed.

The mass-scaling of $T_{\text{lim}}$ has been associated to an effect of Coulomb instabilities becoming more and more important as the number of protons is increased [47]. These studies were performed with stable beams leading to the production of hot nuclear systems with small N/Z asymmetries. Systems close to the stability line are characterized by high limiting temperatures ($T_{\text{lim}}$~6-9 MeV) [47,48]. However, theoretical calculations predict that $T_{\text{lim}}$ decreases significantly as one moves away from stability. The authors of Refs. [39, 48] have mapped $T_{\text{lim}}$ as a function of N and Z, predicting that very N/Z asymmetric nuclear systems are expected to be characterized by a significantly lower limiting temperature. The attenuation of $T_{\text{lim}}$ away from stability is predicted to be induced by a combined effect of Coulomb instabilities and the symmetry energy [39, 48]. These predictions suggest that it will be possible to achieve and explore the limiting temperature regime of exotic nuclei with large N/Z asymmetries even at the relatively low incident energies available with SPES. By populating compound nuclei with the same mass number, A, and different N/Z asymmetries, the effects of the symmetry energy is enhanced as one moves towards more neutron rich species, on the other hand the effects of the Coulomb instabilities are evidenced approaching the proton-rich side of the nuclear chart.

A list of key projectile/target combination populating medium mass systems should be:

$^{64}\text{Ni} + ^{78}\text{Zn}, \quad ^{94}\text{Kr} + ^{50}\text{Ti}, \quad ^{96}\text{Sr} + ^{48}\text{Ca}, \quad ^{72}\text{Kr} + ^{50}\text{Ti}$. A similar list for heavier masses should include the reactions: $^{114-145}\text{Xe} + ^{40,48}\text{Ca}, \quad ^{122}\text{Cd} + ^{58}\text{Ni}$ and $^{90}\text{Kr} + ^{90}\text{Zr}$.
With these reactions one can produce chains of isotopes as compound nuclei all with the same $Z$ and different mass number $A$. Furthermore, reactions such as $^{72}\text{Kr}, ^{78}\text{Kr} + ^{28}\text{Si}$ and $^{74}\text{Zn}, ^{80}\text{Zn} + ^{26}\text{Mg}$ allow to produce compound nuclei with the same mass but with different $Z$-values. This is particularly useful to isolate mass and isospin effects in limiting temperature measurements [47].

1.4.2 N/Z dependence of nuclear level densities

The density of nuclear levels is a fundamental quantity in nuclear physics which plays an essential role in understanding compound nuclear reactions. It is also a basic ingredient for the determination of thermonuclear rates for astrophysics, with applications both in nucleosynthesis and supernovae dynamics [49,50]. While the level density around the Fermi surface depends critically on nuclear structure details [51], at higher energy it can be effectively parameterized via a mass ($A$), isospin ($T_3=(N-Z)/2$) and temperature ($T$) dependent level density parameter $\alpha(A,T_3,T)$ and possibly a backshift $\Delta$ accounting for pairing effects [52, 53]. Recently, it has been shown [54] that an isospin dependence of the level density from the quantity $(Z-Z_0)$, where $Z_0$ is the atomic number of the beta stable isotope with the same mass, should be more adequate at least for low excitation energies. Furthermore, the variation with temperature of the effective nucleon mass $m^*$, which is responsible for the level density parameter variation, contribute also to the change of the symmetry energy term in the nuclear binding energy through the dependence on the isospin component: $E_{sym}(T)=b_{sym}(T) \cdot 4T_3^2/A$.

Variations of the nuclear symmetry energy affects the rate of electron capture in a collapsing star, changing the energy of the supernova explosion. It has been shown in Ref. [49] that the dependence of the symmetry energy on the temperature would produce a gain in the explosion energy of the order of $\Delta E_k \sim 0.5-0.7 \times 10^{51}$ erg, value comparable to the explosion energy itself ($E_k \sim 1.5 \times 10^{51}$ erg for the case of the SN1987 supernova). Therefore, the experimental confirmation of this isospin effect would be of great interest in the astrophysical context.

On the basis of the statistical model, the effect of the isospin term on particle evaporation is expected to be relevant in the first steps of the de-excitation chain, where the nuclei involved are relatively far from the stability valley. Therefore, decay channels involving a small number of particles are more effective for this study. This also provides a stringent test of the statistical model, the decay not being integrated on many decay steps. As far as the symmetry energy in concerned, it affects the binding energy of particles involved in the evaporative process, the correction term reaching values up to $\sim 10$ MeV for temperature $T \sim 1$ MeV [49], for the most neutron-rich nuclei. Owing to these predictions, the best condition to observe these effects is to produce composite systems at relatively low excitation energy ($\sim 20$ MeV).
Fig. 4.1: (left) Ratio between 1n and 2n channel cross sections for the composite system $^{109}$Mo as a function of the excitation energy; (right) neutron energy spectra in the c.m. system for the 1n channel, for the same nucleus at $E_x=14$ MeV. Calculations have been carried out by Lilita_N97 code: i) including in the level density the (Z-Zo) (circles) and (N-Z) dependence (square); ii) using standard parameters (triangles). Lines are drawn to guide the eye.

In order to evaluate these effects, statistical model calculations using the code Lilita_N97 have been carried out, for neutron-rich Mo isotopes, whose study is relevant, as they represent an important fraction of the chemical composition of the crust of a collapsing star.

In Fig. 4.1 (left) the calculated ratio between 1n and 2n channel cross sections is shown as a function of the excitation energy for the $^{109}$Mo, taking into account for the Z-Zo and N-Z dependence in the level density. The standard (i.e. isospin-independent) calculation is also reported for comparison. The corresponding neutron spectra at $E_x=14$ MeV are reported in Fig.4.1 (right). Significant effects are observed. Furthermore, the xn channels for this system are predicted to be strongly affected also by the symmetry energy. These results indicate 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. These reactions meet the conditions of providing a high fusion cross section with low excitation energy (15-30 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.

Studies of Mo nuclei at higher excitation energies (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 effects on the evaporation process.

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