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Exotic nuclei/Les noyaux exotiques

Introduction: The Terra Incognita of exotic nuclei

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Abstract

Atomic nuclei are made of nucleons, protons and neutrons, composed of quarks strongly interacting via gluons. "How such complex objects as particles and nuclei are built?", remains a fundamental question. A new 'frontier' of subatomic physics is the exploration of exotic nuclei, elements and isotopes not stable enough to have survived on Earth. Exotic nuclei populate vast unknown regions of the nuclear chart where many unexpected structures have recently been discovered. Exotic nuclei synthesized in laboratory allow large variation of the neutron and proton chemical composition of nuclear systems needed to uncover the true nature of the subatomic structures and to understand the origin of elements in the Universe. ***To cite this article: P. Chomaz, C. R. Physique 4 (2003).***

Résumé

Les noyaux exotiques une nouvelle Terra Incognita. Les noyaux atomiques sont formés de nucléons, protons et neutrons, composés de quarks interagissant fortement via des gluons. « Quelle est la structure de ces objets complexes, particules et noyaux ? » demeure une question fondamentale qui a d'importantes conséquences pour notre compréhension du Cosmos. Le nouveau défis de la physique subatomique est l'exploration des noyaux exotiques, élément et isotopes pas assez stable pour avoir survécu sur Terre. Les noyaux exotiques peuplent de vastes régions de la carte des noyaux où de nombreux phénomènes inattendus ont récemment été découverts. Les noyaux exotiques actuellement synthétisés en laboratoire permettent de très grandes variations de la proportion de neutrons et de protons qui sont nécessaires pour révéler la véritable nature du monde subatomique. ***Pour citer cet article : P. Chomaz, C. R. Physique 4 (2003).***

1. Introduction

At the very end of the XIX century, the discovery of radioactivity by Henri Becquerel and Pierre and Marie Curie marked the beginning of the exploration of the atomic world. In 1901, Ernest Rutherford and Frederick Soddy showed that radioactivity is associated with the transmutation of chemical elements. In 1911, Ernest Rutherford discovered the atomic nucleus. This event can be seen as the beginning of Nuclear physics. Eight years later he showed that every nuclei contains protons, the nucleus of the lightest element, the hydrogen atom. In the 1932, Sir James Chadwick demonstrated that the new penetrating radiations reported by Frédérique and Irène Joliot-Curie, were neutral twin brothers of protons: neutrons. Since then, we know that nuclei are complex systems of nucleons: protons and neutrons. In 1934, Frédérique and Irène Joliot-Curie discovered artificial radioactivity. This first identification of man-made isotopes can be considered as the beginning of the search for exotic nuclei, isotopes and elements which are not found (in abundance) on Earth and which must be artificially synthesized in order to be studied. In 1938, Hans Bethe understood the role of nuclear reactions in stars such as our Sun, starting the field of nuclear

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astrophysics and the study of nucleosynthesis. Few years later, after the end of the war, Georges Gamow used the primordial nucleosynthesis, the creation of light elements in a hot and dense primordial soup, as an argument in favor of the Big-Bang theory.

At the same time, Maria Goepper-Mayer realized that the severe laws of quantum mechanics are ruling nuclei and ordering them according to magic numbers. In the 1970s, following the important work of Aage. Bohr and Ben Mottelson [1], it was generally believed that the global properties and the structure of nuclei were understood in terms of a nuclear theory relying on an effective mean-field approximation: nucleons are almost independent particles orbiting in a potential well created by their assembly, the self-consistency of which is responsible for their collective behavior [2]. However, during the following decades, many unexpected observations as well as theoretical developments have forced nuclear physicists to introduce new concepts and to bring up new questions about the true nature of dense matter under strong interactions.

On the one hand, nucleons seem to not always be in simple quantum orbitals but rather strongly correlated, leading to deformations and clusterisation. The nucleus is a complex object the properties of which cannot be reduced to the simple sum of the individual properties of its constituents. As any composite matter, nuclei are more often ruled by universal structuring principles such as symmetries rather than by the details of the specific characteristics of the constituting bodies in interaction.

On the other hand, in the 1970s, our present understanding of elementary particles and interactions, the so-called standard model, has been elaborated. Nucleons are built out of Quarks interacting through a gluon field. Since then, the validity of this elementary description of matter has been continuously substantiated. However, the understanding of particles and nuclei in terms of elementary degrees of freedom is far from being completed. Hopefully, it seems that the different degrees of description of nuclei are largely decoupled, so the understanding of nuclei can be decomposed into three steps:

(1) Identifying the pertinent degrees of freedom and size/energy scales needed to understand a specific property of the nucleus. Depending upon the phenomenon studied, the nucleus can be considered as formed of quarks and gluons, of baryons and mesons, of protons and neutrons or of clusters of nuclei;
(2) Built the ‘effective’ theory which govern the dynamics of these ‘effective’ degrees of freedom and try to understand this effective description in terms of the elementary theory;
(3) Deduce the structural properties of the systems as a combination of these degrees of freedom and effective interaction.

These approaches, as well as bridges between the different levels of description, are still under construction. Therefore, to progress, attention should be focused on well-defined issues at a particular level of description.

The ensemble of exotic nuclei constitutes today a huge Terra Incognita since only a few of them are actually known. Considering the present status of our understanding of the atomic nucleus, several regions of the chart will be the focus of the research effort in order to address specific questions. In each region different observations are combined to infer the studied properties. The different series of nuclei of special interest can be spotted around different regions (see Fig. 1):

– The drip lines, the limit of the nucleon binding in nuclei, especially for low and moderate mass where halo and cluster/molecular structures have been identified;
– The $N = Z$ line where proton-neutron pairing and quartetting and, in general, consequences of the proton-neutron (isospin) symmetry and symmetry breaking can be studied;
– Different isotopic (or isotonic) chains from drip line to drip line, for magic proton (or neutron) numbers over which the pertinence and the persistence of shell effects can be followed; one example can be the Sn isotopes and the Ni isotopes together with the $N = 28$ isotones;
– The paths of various nucleosynthesis processes and cycles with a special emphasis on the rapid proton or neutron capture expected to be responsible of the creation of heavy elements (see Fig. 15);
– The heavy and super-heavy region, where a new island of stability is expected.

One can also stress specific properties, which deserve particular interest in the light of the novel exotic nuclear edifices. First, the decay processes should be reconsidered; the radioactivity and the fission are still mysterious and the discovery of new phenomena such as the 2-proton radioactivity [3] or the progress of our understanding of nuclear structure may allow us to uncover their true nature. Second, our knowledge of the nuclear matter thermal and mechanical properties is still too limited. The fact that nuclei are two fluid (protons and neutrons) systems, which undergo phase transitions, are studied and used [4].

In the present issue of the C. R. Physique we present new results and review article in order to illustrate the important field of exotic nuclei. Let me first give an overview of the key questions and progress expected from the theoretical point of view. In such a way, the research program on exotic nuclei can be put in perspective with global physics issues.

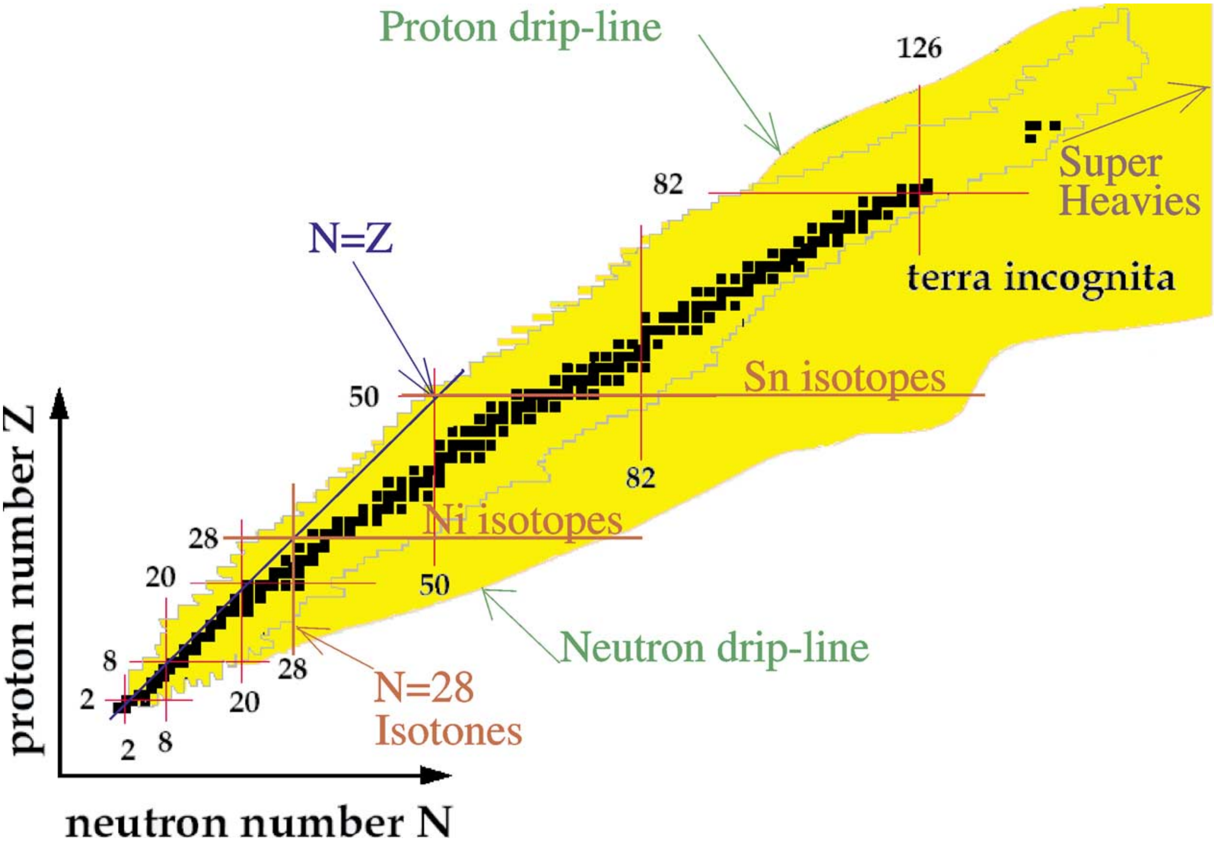

Fig. 1. Chart of nuclei showing in green the ridge of the approximately 250 stable nuclei on the island of several thousand of nuclei bound by the strong interaction but radioactive (yellow area) which constitute a real Terra Incognita since only a few percent of them have been observed up to now (thin line).

2. Quarks and gluons in nuclei

At the most elementary level of description, nuclei are made out of quarks bound by gluons. Our understanding of quark and gluon dynamics in the strong interaction regime of low-energy nuclear physics is still incomplete, even if it is progressing [5]. In particular, the nucleon structures and their interactions are not yet understood from a microscopic point of view. The influence of elementary particles on nuclear structure phenomena is, as yet, unclear. Hopefully it seems that there exists an important decoupling of the elementary level of organization of matter with the next one of nuclear structure, so that valuable information about the subatomic world can be obtained using effective concepts of particles, such as protons and neutrons, in interaction. Then the problem can be considered in two steps:

- use the nuclear structures and reactions studies to infer nucleons and particle properties and interactions in nuclei;
- relate these observations to the underlying quark structure.

2.1. 2-body and more body interactions between nucleons

Low energy nuclear processes involving a modification of the quark structure of nucleons do occur. This is the case of spin and isospin interactions, excitations or decay. The Gamow–Teller strength is a typical example of this phenomenon, since in a charge exchange reaction a valence quark should change flavor from Up to Down or vice versa. The various terms of the nucleon-nucleon interaction, in particular those involving spin and charge exchange, are also related to the underlying quark structure. Recent results on exotic nuclei are pleading in favor of a stronger spin-isospin interaction [6]. Indeed, such an interaction may change the energy of two orbitals, which differ by the orientation of the spin (spin orbit partners) and thus may transform the shell structure and shell closures leading to a modification of magic numbers as observed in exotic nuclei.

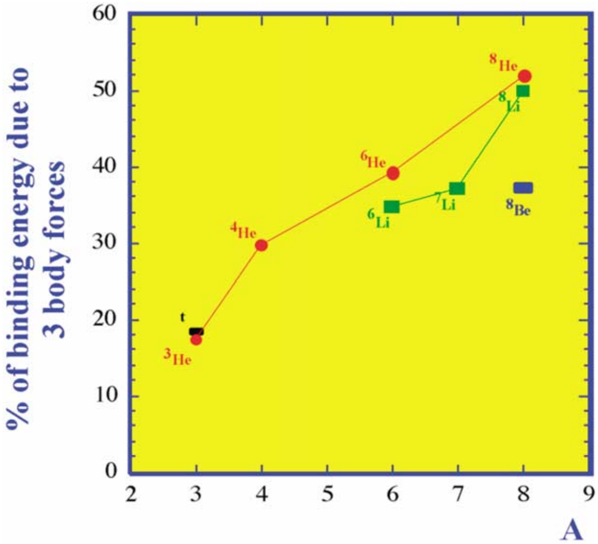

Fig. 2. Proportion of the total binding energy of light nuclei coming from the 3-body force included in the best actual ab-initio calculations (adapted from [8]).

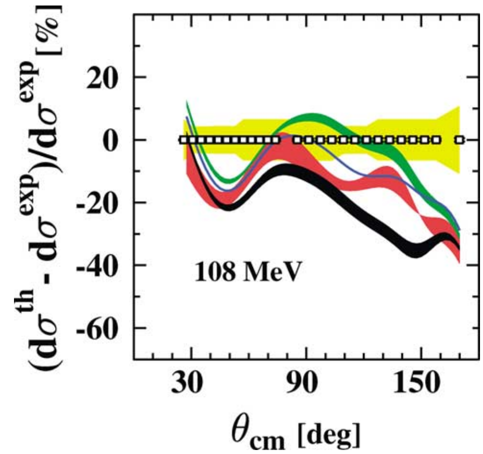

Fig. 3. The difference between the measured and theoretical differential cross sections of the p + d reaction at 108 MeV per nucleon. The yellow bands are the errors. The calculations are those with NN potentials alone (black), two NN heuristic two and three-body force (blue) (from [47]) and the green band the results from chiral perturbation theory [9].

The deduced properties of the nucleon-nucleon interaction involving quark flavor modifications are a constraint on the quark dynamics in nucleons and nuclei.

As shown by the recent ab initio calculation of the light nuclei ground states [7], the understanding of nuclei containing more than two nucleon needs the introduction of three-body forces (see Fig. 2). The same holds for reaction studies involving three nucleons, such as proton on deuteron scattering (see Fig. 3). The determination and the understanding of this unusual type of more then 2-body interaction is one of the challenges of modern nuclear physics. Some attempts have been recently reported to try to update the previously heuristically derived two- and three-body forces by taking into account more elementary constraints such as chiral symmetry in effective approaches [10]. A simultaneous derivation of the 2- and 3-body interactions has also been tried within the framework of Chiral Perturbation theory [11]. However, this field of understanding the properties and interactions of nucleons in nuclei from a more microscopic point of view of more elementary particles remains an essential open question for the future works in nuclear structure and reactions.

2.2. β-decay studies

Another example in which the quark degrees of freedom are directly at play in nuclei is their radioactive β-decay. In this respect nuclei can be used to infer properties of elementary particles, quarks and neutrinos, and weak interactions. However, to do so the nuclear structure should be well understood in order to unfold its influence from the observed properties [12,13]. For example, a proper understanding of isospin mixing is important because it enters as a correction to the Fermi decay-matrix element, which determines the vector-coupling constant of the weak interaction. This in turn can be used to verify the unitarity of the Cabibbo–Kobayashi–Maskawa matrix, which defines the mixing of the three families of quarks in the weak interaction. This type of measurement constitutes a test of the standard model of elementary particles and interactions.

3. Fields in nuclei

Introducing the effective concept of composite particles, nuclei can be described in terms of baryons and mesons in interaction [14,15]. Since electric and magnetic (i.e., vector) fields of different interactions are at play between nucleons, and since the particle velocities are large, one should consider the problem from a relativistic point of view. Also, in a relativistic quantum description, particles and antiparticles are intimately related. In principle all types of particles (baryons, anti-baryons and mesons) should be considered and quantized to directly determine the structure of nuclei. However, models have not yet

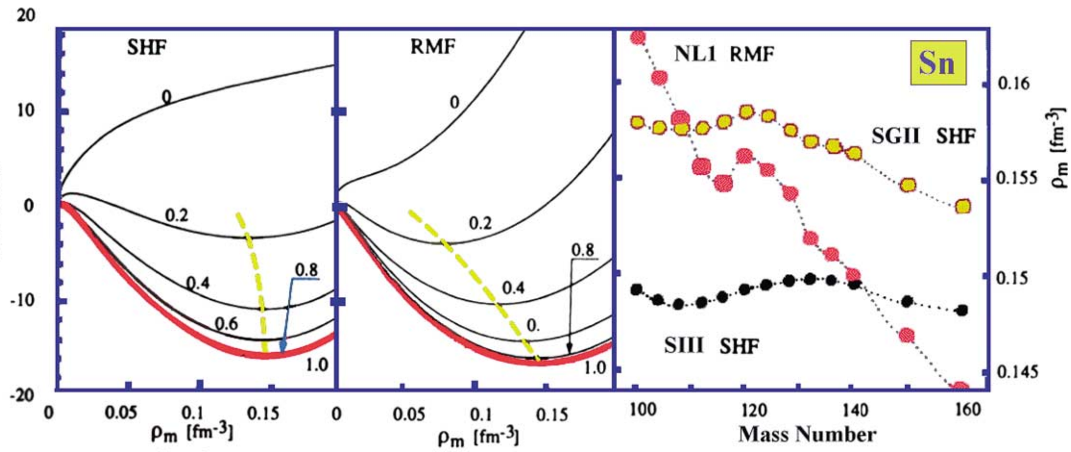

Fig. 4. The 2 left parts show the nuclear matter energy for various protons over neutrons ratios as a function of the total density as predicted by the Hartree–Fock theory with the SIII Skyrme interaction (SHF) (left) and relativistic mean-field (RMF) approach with the NL1 interaction (middle). The saturation point variation as a function of Z/N is shown in yellow. Right part prediction of the central density in the Sn isotopes as predicted by various SHF theory with SGII and SIII forces and a RHF approach with the NL1 interaction (adapted from [18–20]).

reached this degree of sophistication and, up to now, the mesons are considered as classical fields and antiparticles and the Dirac sea are often partly neglected.

Relativistic mean field theory is a microscopic description, which explicitly takes into account the strong field dynamics [16]. Since an explicit link with the quark–gluon substructure is not yet constructed, an effective Lagrangian is assumed and fitted to the data. To constrain this phenomenological model a broader knowledge of nuclear properties is required.

Relativistic approaches are of particular importance for the understanding of the nuclear matter-mechanical properties. Indeed, different calculations of the saturation point are showing that a classical approach is unable to explain the observed values of a maximum binding energy around 16 MeV per nucleon for a density of 0.17 nucleon per fermi cube while relativistic approaches allowing a field dynamics and the creation of antiparticles can go through the saturation point. The evolution of the saturation point as well as the associated equation of states as a function of the isospin is still an open question [17]. The isospin dependence of the saturation point directly influences the central density and radii [8] of nuclei such as illustrated in Fig. 4 for the Sn isotopes.

Several generic properties of the strong-interaction fields are essential for the structure of nuclei and for the properties of nuclear matter. Firstly the strong fields contain electric and magnetic components, which transform one into the other when the particle is in motion, while a scalar part remains constant. The spin gets coupled with the interaction fields as the particle orbits inside the nucleus. This spin-orbit coupling plays an important role in the binding and structure of nuclei [21] since it produces a splitting of nucleon orbital pairs $j = l + 1/2$ and $j = l - 1/2$ associated with a given angular momentum l. Indeed depending upon the relative orientation of the spin and the orbit, levels are either pushed up or down in energy. This effect is so strong that in heavy nuclei the order of the orbitals is strongly modified, some levels being pushed so far from their original location that they become intruder states in an other energy domain. This reorganization of the nuclear orbitals explains the observed sequence of magic numbers which are essential for the understanding of the nuclear shell model.

However, since fields can be charged and can carry quantum numbers, in particular isospin, the isospin content of the surrounding matter influences the dynamics. Therefore a weakening of the spin-orbit splitting is expected in neutron rich nuclei but this has not yet been confirmed experimentally. One way to directly measure the spin-orbit coupling is to study reactions with polarized nucleons. Another expected effect is the modification of the shell structure, which can be experimentally tested by looking for magic numbers far from stability. An indirect indication of the weakening of shell effects is the heavy-element abundances in the Universe. Indeed, it is generally believed that heavy elements are produced in the important flux of neutrons surrounding the core of exploding supernovae. There the rapid capture of a neutron in competition with the beta decay of neutrons into protons is increasing the size and the atomic number of nuclei present and produced in the heavy stars before the implosion of the iron core. This competition is strongly influenced by the presence of shell closure so that magic numbers become waiting (and accumulation) points of the process producing peaks in the relative abundances. The distribution of the daughters of the radioactive isotopes produced in this fast neutron capture, known as the r-process nucleosynthesis, presents weaker structures if the shell structure are not as strong as initially expected. Fig. 5 shows that this might well be the case, since a weaker spin-orbit coupling is needed in order to reproduce the observed r-process abundances [22].

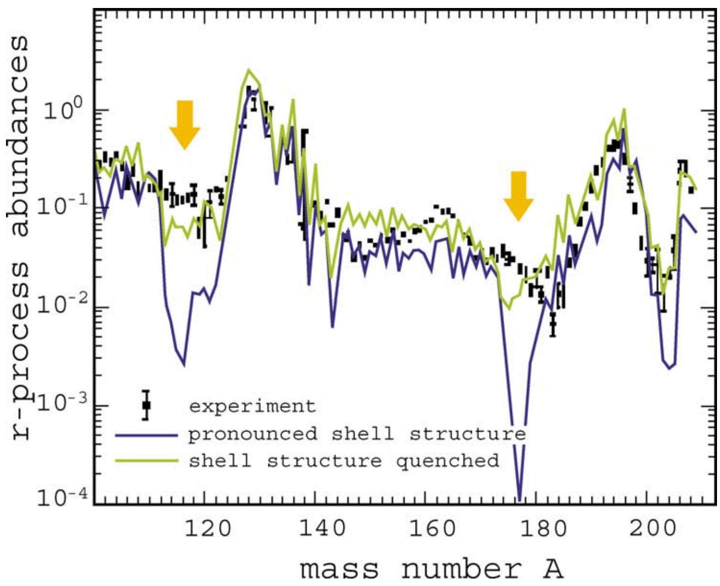

Fig. 5. r-process abundance (black dots) compared to two calculations, which differ by the strength of the spin-orbit interaction. A weaker spin-orbit interaction (green line) gives a better agreement with the data than the previously supposed strong spin-orbit interaction (blue line) (adapted from [22]).

4. Nucleons in nuclei

In the 1970s, a microscopic model of the nucleus in terms of its nucleonic degrees of freedom became operational [2]. For nucleons in nuclei the free nucleon–nucleon interaction must be modified to take account of the surrounding nuclear medium. The theory to carry out this modification (known as Brueckner G-matrix theory) can be applied to a few specific cases but not to nuclei in general [17]. Moreover, the presence of many-body interactions is now known to be important (see Figs. 2 and 3), but is still largely unknown, so that its introduction in the calculation of an effective interaction is far from being satisfactory. Therefore, the currently accepted procedure is to postulate a phenomenological effective nucleon-nucleon interaction, depending on a few parameters controlling terms suggested by the underlying microscopic theory.

4.1. Nuclear forces and equations of state

Different parameterizations of the effective interaction (Skyrme, Gogny, ...) are available today and the theory has now reached a high degree of sophistication. Experimental inputs, in particular from well-defined regions of the nuclear chart, are essential in order to adjust the phenomenological parameters. The isospin dependence of the effective interaction is one of the poorly known aspect of the nuclear forces. In particular, one must worry about the isospin dependence of the nuclear compressibility, which in turn is related to the density dependence of the nuclear asymmetry (see Fig. 4).

Important phenomena, which can bring information on the interaction and structure, are collective states. The breathing modes (giant monopole resonances) give access to the compressibility while the giant dipole modes test the nuclear shape and may help to determine the properties of the asymmetry energy. New modes, in particular, at low energy are expected to appear in exotic nuclei.

The level density parameter deals with the nucleus entropy. The level density is an essential information about complex systems. It can provide information on the particle properties in medium (e.g., effective masses) and on the averaged structure. This is, in particular, the case if one looks for the shell correction compared with the fermi liquid drop expectations (see Fig. 6). Such a kind of experiment can provide a global picture about shell closure and magic numbers [23]. The entropy also contains information about the phase transitions that the system can encounter. At low energy one expects to observe the breaking of nucleon Cooper pairs associated with the super fluid to normal fluid transition. Such a phenomenon has been recently observed looking at the convexity of the entropy deduced from the gamma decay of inelastically excited nuclei [24].

At higher excitation energies, a liquid–gas phase transition is also expected in nuclear matter. It should be studied as a function of the isospin degree of freedom. Because of the presence of Coulomb forces the variation of the equation of states in finite systems may be enhanced. The fact that the nucleus is a two fluid system implies a specific phenomenology for the phase

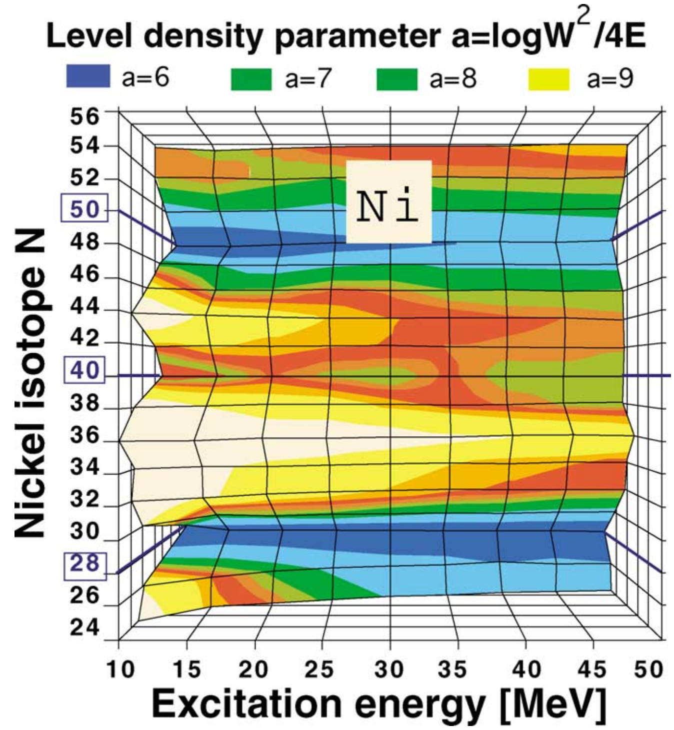

Fig. 6. Evolution of level density parameter as a function of the excitation energy and of the neutron number of various isotopes of Ni: the darker regions correspond to a lower density parameter $a = 6$ while the lighter area is associated to $a = 9$ (adapted from [23]). One can see that the magic numbers 28 and 50 appears as deep valleys in this level density landscape. A smaller reduction of the level density is also visible around $N = 40$.

transition. In particular, a phenomenon analogous to the neutron matter distillation (fractionation) is expected and should be looked for in experiments varying the N/Z ratio of the excited system (for a review see [4]).

4.2. Shell structure and magic numbers

Once a certain (effective) nucleon–nucleon interaction is obtained, there still remains the problem of the self-organization of the nucleus as a quantal many-body system. From the study of stable nuclei, it has been demonstrated experimentally that some edifices of nucleons are more tightly bound than others.

This occurs for given numbers of protons (Z) or neutrons (N), which are equal to 8, 20, 28, 50, 82 and 126. These numbers are the nuclear magic numbers. The strength of this magicity can be characterized by the energy that is required for a nucleus to be excited into its first excited state. In Fig. 7, this energy are shown for the $_{20}$Ca, $_{16}$S and $_{12}$Mg isotopes as a function of their neutron enrichment. ^{40}Ca contains $Z = 20$ protons and $N = 20$ neutrons and is thus a doubly magic nucleus. The sudden rise in energy at $N = 20$ clearly establishes the difficulty to excite ^{40}Ca to its first excited state. A similar – large – energy is required to excite ^{36}S, which is composed with four protons less than ^{40}Ca. When removing again four protons, the nucleus ^{32}Mg exhibits a large neutron excess and is thus unstable by β-decay. It is remarkable to see that it is much more easily excited than the other $N = 20$ isotones even if it contains fewer nucleons and thus fewer degrees of freedom. This reveals a drastic change in the structure of this nucleus, which has to be understood. Indeed, many phenomena affects the shell structure from a modification of the interaction, in particular of the spin-orbit or spin-isospin terms as discussed before, to the occurrence of a neutron skin and halos. In exotic regions the shell structure may melt because a strong reorganization of the nucleus structure with the increase of correlations might be leading to deformation and even clustering. Indeed, some theoretical interpretations put forward that this nucleus minimizes its intrinsic potential energy by adopting a strong quadrupole deformation. Being deformed, the rotational excitation is possible and thus is the easiest excitation. It is interesting to note that the doubly magic nucleus ^{28}O, which corresponds to a removal of four protons from ^{32}Mg, is most probably unbound. This feature, together with the low excitation energy in ^{32}Mg supports a disappearance of $N = 20$ magic number when a large N/Z ratio is encountered. Hence, the well-established concept of nuclear magicity must be reconsidered by taking into account more specifically the role of proton or neutron enrichment.

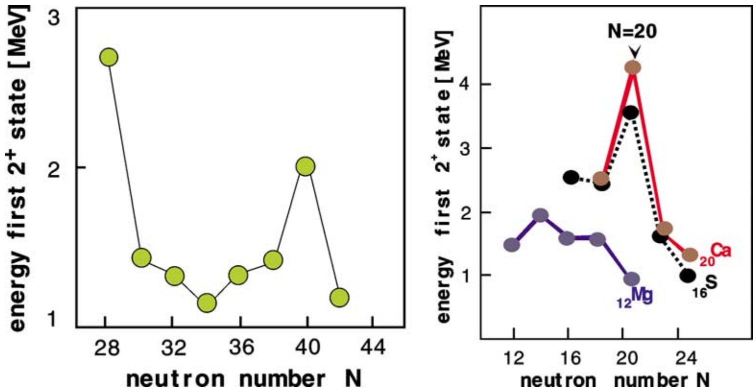

Fig. 7. Energies of the first excited states of Ni (left, adapted from [25]) and Mg, S and Ca (right, adapted from [26]) isotopes as a function of their neutron numbers. The peak at $N = 28$ (left) and $N = 20$ (right) corresponds to the known magic number while the second one at $N = 40$ (left) is a new phenomenon. It may be due to the presence of a diffuse surface which modifies the nuclear potential and hence the shell structure. On the right one can see that for Mg isotope the number $N = 20$ is no more magic since less than an MeV is needed to excite ^{32}Mg.

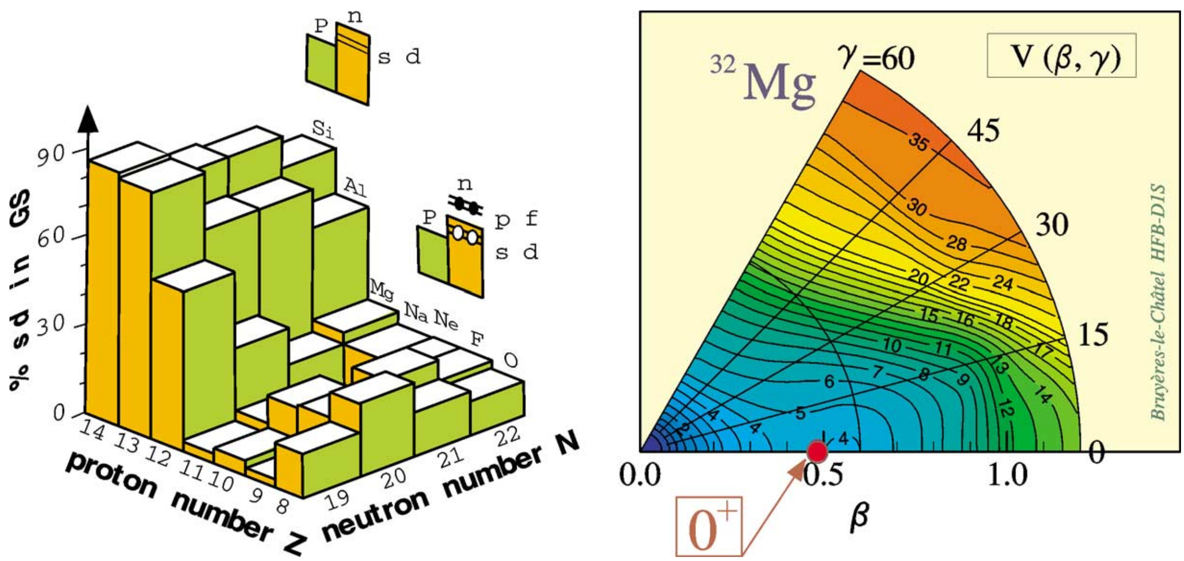

Fig. 8. Left: Ground state probability of s–d shell occupation as a function of N and Z of light nuclei as a result of a shell model calculation (adapted from [27]). For large neutron excess the probability to be in the simple configuration where the lowest energy states (the s and d orbitals) are occupied suddenly becomes rather improbable (see probabilities on the vertical axis). At least two nucleons are excited in the nest shell (p and f).
Right: Hartree–Fock–Bogolioubov (HFB) calculation of the ^{32}Mg energy (in MeV) as a function of its ellipsoidal deformation defined by the parameter β and the angle γ. While the minimum energy correspond to a spherical configuration ($\beta = 0$) the calculation of the ^{32}Mg ground state taking into account the mixing of all deformations appears in average deformed (adapted from [28]). In both cases the predicted strong mixing indicates a complex structure with deformations and even clustering. This may explain the absence of magicity of the ^{32}Mg.

This disappearance of the magic number $N = 20$ can be due to the deformation of the protons. Experimental investigations should be made in this mass region aiming to demonstrate the decoupling of these two fluids, which may result in the appearance of new deformed regions of nuclei or new excitation modes between protons and neutrons. Also, the surface of these neutron-rich nuclei may be composed essentially of a diffuse neutron surface, which may result in a modification of the structure of the nucleus and in the appearance of new magic numbers. Many theoretical approaches have been used to understand the properties of the $N = 20$ exotic nuclei. In particular, large scale shell model calculations including the mixing of many configurations such as two particles excited in the next shell above the $N = 20$ core as well as calculations going beyond mean field approximations are now predicting that ^{32}Mg are in fact deformed. The p–n interaction can also be responsible for the observed modification of the shell structure (Fig. 8).

A different example is the chain of Nickel isotopes, which contain a magic number of protons $Z = 28$ which should prevent them from deforming. With the new observations of ^{48}Ni (see, e.g., [29]) and ^{78}Ni [30], on both extreme sides of the chart of nuclides, it is in principle feasible to test the evolution of the magic numbers $N = 20$ and $N = 50$ with respectively large proton or neutron excess. The hitherto accessible energies of the first excited states in Ni isotopes are shown in Fig. 7. Increases of this energy are found at $N = 28$ and more surprisingly at $N = 40$. It is expected that with large neutron excess, magicity would increase at $N = 40$ and subsequently decrease at $N = 50$. Therefore, the study of $^{78}Ni_{50}$ and of $^{60}Ca_{40}$ will be of key interest to prove this expected new organization of the nucleons in extremely neutron-rich nuclei with $N = 40$ or $N = 50$ neutrons. As discussed in the previous section the study of the density of levels (see Fig. 6) is also a way to test the nuclear magicity. This can only be investigated with a new generation of exotic nuclear beams with increases in intensities of some orders of magnitude.

The existence of heavy elements above Rf_{104} is the most spectacular consequence of the shell structure of nuclei [31]. Indeed, would these nuclei be only liquid drops of charged nuclear matter, would they undergo fission immediately when one tries to form them? The additional shell effects modify the balance between the repulsive Coulomb and attractive nuclear forces as a function of elongation, thereby creating a barrier against fission and allowing the nucleus to exist. It was first expected that nuclei would cease to exist on some range of Z, then exist again, forming an ‘island’ around the next magic numbers of protons and neutrons. Actually the end of the nuclide chart will rather form a peninsula, since calculations predict – and experiments confirm – a continuous region of shell-stability extending from nuclei around Hassium ($Z = 108$), which have a deformed neutron shell at $N = 162$, towards the next spherical doubly magic nucleus. While there is agreement about the calculated location of the next neutron shell, $N = 184$, the next proton magic number was first thought to be 126, then 114 was a long time favorite and now it may be 114, 120 or 126. The experiment should settle this down in the future.

5. Deformations, pairing, quartetting and clustering

While shells and magic numbers are crucial to the atomic nucleus, they alone do not suffice to determine its structure. Specifically, there are collective effects and correlations involving several to all nucleons in the nucleus. 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 and their subtle dependence on nucleon numbers [32].

5.1. Complex pairing and quartetting, new superfluidities

One of the most important correlations between nucleons is pairing. Self-conjugate $N = Z$ nuclei might show effects of isoscalar ($T = 0$) neutron–proton pairing. Unlike the usual isovector ($T = 1$) pairing, which involves either neutrons or protons with antiparallel spins, isoscalar pairing requires a neutron and a proton with parallel spins. Collective effects associated with this pairing mode remain hitherto unseen but considerable efforts are currently being made to unravel their experimental signatures. If successful, it can be considered as a new type of superconductivity that amounts to the formation of a deuteron condensate.

The formation of a deuteron condensate will be in competition with that of an α-particle condensate, i.e., a quartetting. Both types of correlation, isoscalar pairing and quartetting, have an effect on the masses of $N = Z$ nuclei (see Fig. 9). An even more exciting possibility is that, because of specific shell structures, a new symmetry involving protons and neutrons in different

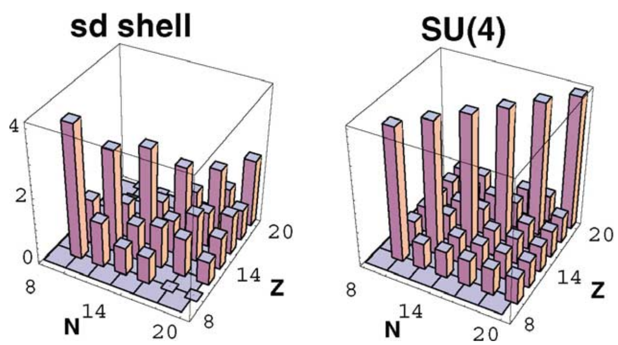

Fig. 9. Left quartetting energy experimentally extracted using four neighboring nuclei compared with the expectation from a pure spin-isospin symmetry (SU(4) symmetry). The data confirm the occurrence of this new type of Bose condensation (adapted from [43]).

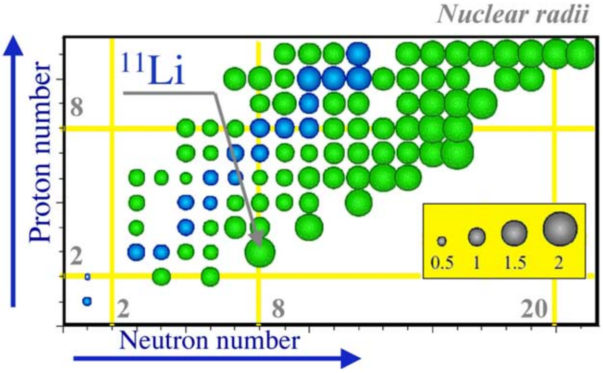

Fig. 10. Circles symbolizing the nuclei radii for the light nuclei referenced as a function of their neutron and proton numbers. One can see that exotic nuclei (in green) are systematically larger than the stable one (in blue). The drip-line nuclei (especially on the neutron rich side) appear much larger then their neighbors because of the presence of a nucleon halo (adapted from [41]).

shells may appear so that the quartetting effect will be enhanced for heavy $N = Z$ nuclei even particles are not in the same type of orbitals. This pseudo SU(4) symmetry would be a completely novel type of Bose condensation in nuclei.

Although mass measurements may give some hints as to the competition between isoscalar pairing and quartetting, only transfer reactions (of either deuterons or α particles) on $N = Z$ nuclei can clarify the situation.

5.2. Granular structure in nuclei

During many years nuclei have been thought of as the archetype of quantum fluids because it was believed that the uncertainty principle was enforcing a full delocalization of the nucleons in nuclei. However, several arguments are now pleading in favor of a granular nature for nuclei [34–39]. These structures are better displayed in weakly bound nuclei, but may well be present in every nuclei and thus might be at the origin of phenomena like fission and α-particle, Carbon or other nuclei radioactivity (see in particular [3]).

One of the first surprises showing that nuclei might be dominated by clustering effects was the discovery of halo nuclei by I. Tanihata in 1985 [40]. Some light neutron-rich nuclei, close to the drip line, acquire a very large size owing to one or two weakly bound neutrons orbiting far from the nucleus core. Because of the small binding, these last nucleons it can even become so diluted that they resembles to a Halo. Since the discovery of Halo nuclei, the radii of many exotic nuclei have been inferred from various reactions measurements (see Fig. 10). Light exotic nuclei close to drip lines appear systematically very large because of the presence of a nucleon halo [33]. Several of such halo nuclei have already been extensively studied. A less dramatic nuclear exoticity can be envisaged in which a neutron skin develops, that is, a mantle of neutrons that envelops the core of a nucleus, which is presumably of a rather diffuse character.

Halos and skin might decouple from the core of the nucleus. Whether such decoupling actually takes place, is still controversial. If it takes place, one would be confronted with a genuine nuclear three-component system consisting of core neutrons, core protons and skin neutrons, which would display an unprecedented richness in possible excitation modes. For example, simple arguments indicate that such systems exhibit a doubling of dipole resonances, one associated with the oscillation of the neutrons versus the protons in the core (a giant resonance) and the second with oscillations of the skin neutrons versus the core nucleons (a soft resonance). The observation of such soft excitation modes of nuclei certainly represents a significant experimental challenge, but at the same time, opens up an entire new field of research.

A Borromean nucleus is a weakly bound system of a very special kind. It can be considered as a three-body system of which all subsystems are pair-wise unbound. The archetypal example is the weakly bound nucleus lithium-11 considered as lithium-9 plus two neutrons, the subsystem lithium-10 as well as the di-neutron being unbound. A Borromean system is of interest because its very existence is due to correlation effects. In addition, in the limit of zero binding energy its ground state tends to a so-called Efimov state, which has many peculiar properties such as an huge spatial extent.

Borromean systems may exhibit even more original structure since their binding originates from their correlations. In particular, halo nuclei such as lithium-11 (Fig. 11) may in fact look like a water molecule with the two neutrons being at 108° one with respect to one another. This molecular and clustered nature of nuclei might even be more general then initially thought. For example the possible polymerization of halo nuclei is an interesting issue. A binding of quasi-molecular states formed of halo nuclei through their neutron clouds in a way which is analogous to the hybridization of the valence electrons in polymers, is a completely new kind of clusterization. Recent experiments are pleading in favor of such exotic novel structures [37,39] (see also [44]).

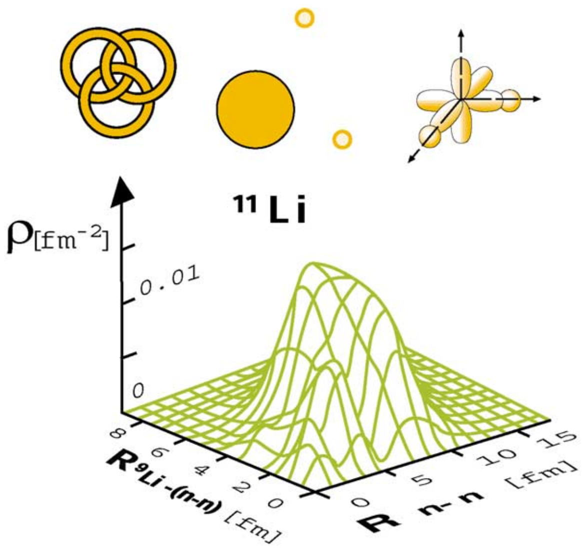

Fig. 11. Predicted probability for a certain distance between ^{9}Li and the neutron pair and the distance between the two neutrons. The peak corresponds to a structure, which resembles to a water molecule (see top). The drawing on the left is the symbols of the Borromee family (adapted from [42]).

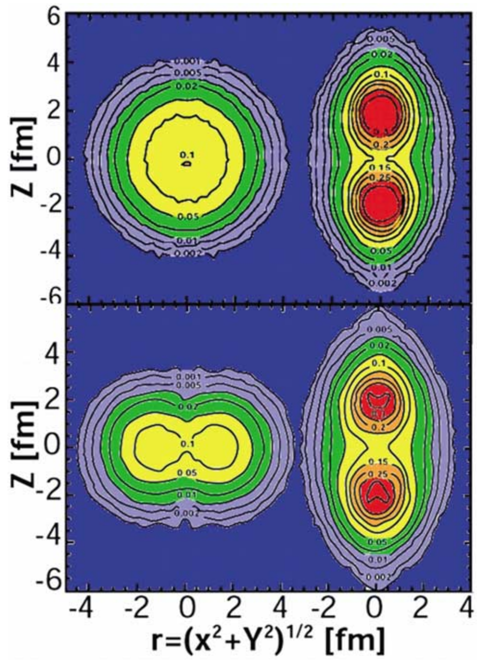

Fig. 12. Ab initio quantum calculations using Monte Carlo techniques of the density contours of 8Be first 0 + (top) and 4 + (bottom). The left part is in the laboratory frame while the right part corresponds to the intrinsic frame (adapted from [45]).

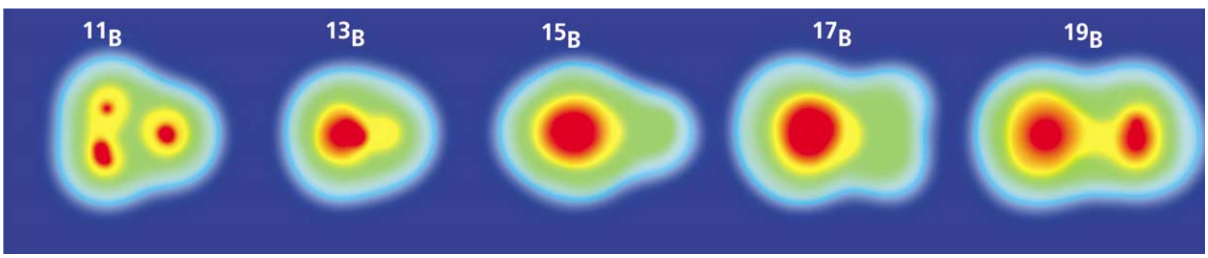

Fig. 13. Anti-symmetrized molecular dynamics calculation of the ground state of light nuclei showing a strongly clustered system (adapted from [41]).

Many theoretical approaches are now pleading in favor of the existence of strong correlations and clusterisation in nuclei. Fig. 12 presents results of ab initio calculations [45] which correspond to exact solutions of the quantal many-body problem with realistic 2- and 3-body interactions. Fig. 13 is obtained within the recently developed quantum molecular dynamics for fermions [41]. In both cases the clusterisation of the nucleus is obvious.

This possible strongly correlated or even granular nature of nuclei may induce new types of radioactivities. Specific di-proton and deuteron emission can be favored in presence of the associated pairing. It should be noticed that the 2-p radioactivity has recently been discovered [3]. Special decay channels can be observed as well as exotic radioactivity.

It should be noticed that the clustering is deeply related to the more conventional concept of deformation. Indeed, breaking the rotational invariance by allowing nuclear deformation is a alternative way to take into account correlations. Indeed, the restoration of the symmetry together with possible additional mixing of different deformations through more sophisticated approaches leads to a strongly correlated wave function. Fig. 14 gives an example of such type of description [28] in the case of ^{74}Kr, which presents a ground state and an isomeric state with two different deformations.

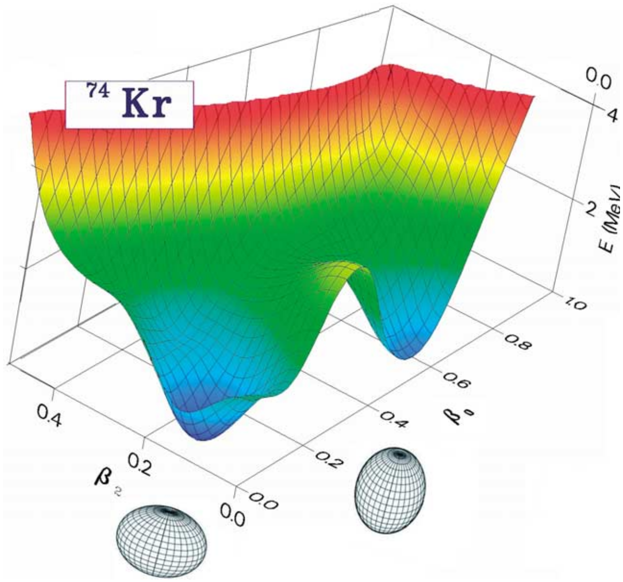

Fig. 14. Hartree–Fock–Bogoliubov calculation of the energy of a ^{74}Kr nucleus as a function of its deformation. The two deep minima correspond to two isomeric states with different shapes (shown below) (adapted from [28]).

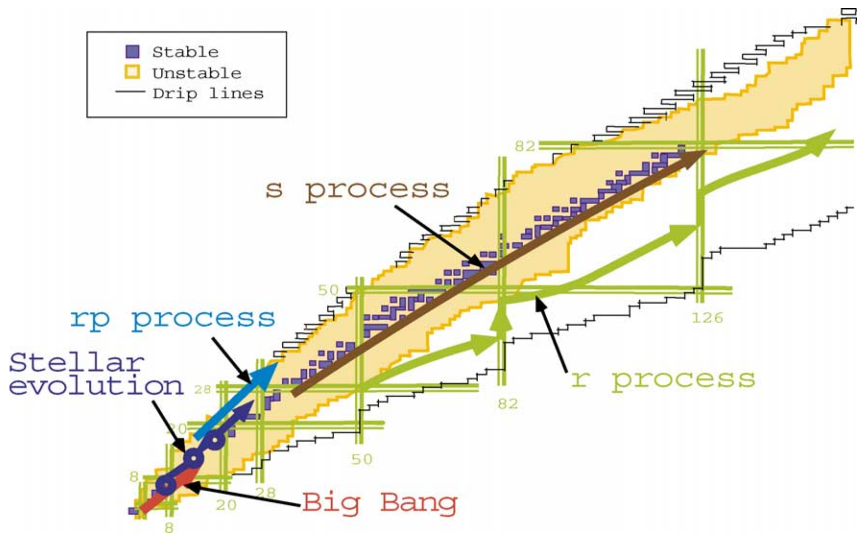

Fig. 15. Various astrophysical processes on the nuclear chart: (i) the primordial nucleo-synthesis (red); (ii) the normal slow stellar evolution with typical cycles (blue); (iii) the slow neutron capture (s-process in black); (iv) the fast one (r-process, green); (v) the rapid proton capture (rp process light blue).

6. Nuclei in the Cosmos

Nuclear Astrophysics is a focal point for nuclear physics, astronomy, geophysics, chemistry and hydrodynamics. Important progress has recently been made in all these disciplines, increasing our understanding of how elements constituting the universe have been synthesized, spread out in the galaxy to form meteorites, interplanetary dust, planets and stars. These elements are continuously formed either in quiescent burning of stars or in very violent events like supernova explosions [46].

Stars results from the balance between the nuclear reactions that tend to blow up matter and the gravitational forces that tend to aggregate it (and even collapse it). Stars transmute matter due to high densities and temperatures prevailing in their deep interior. These newly formed elements are ejected in stellar winds or in supernovae residues. The modern astronomy provides a wide range of observational wavelengths, from radio astronomy to high-energy gamma rays, to ascertain the fate of stars or galaxies.

These new observations have confirmed that nucleosynthesis involving radioactive isotopes is an ongoing process all around the universe. They offer the possibility to deduce the elemental abundances at the surface of exploding stars for a broad range of chemical elements up to uranium. These observations bring the opportunity to compare the observed isotopic abundances at the surface of exploding stars with theoretical predictions. These models take into account the nuclear properties of the involved species. The problem is that these calculations, which involve a large number of unstable isotopes, often rely on crude estimations of nuclear reaction rates and decay properties. To progress, these new nuclear species, which populate the nucleosynthesis paths, should be synthesized and studied in order to understand how their nuclear microscopic properties can influence the abundance and fate of the macroscopic structures like stars and galaxies.

7. Conclusions

From radioactivity to fission, from nucleosynthesis to transmutation, from the Big-Bang to energy sources, the nucleus is an essential object of our Universe. However, it still partly escapes from our understanding. Research programs on mechanical and thermal properties of nuclear matter and associated phase transitions, on nuclear structure and properties of exotic nuclei are very active all around the world. Experiments with Intense Beams of Exotic Nuclei will extend our understanding of nuclei. While unforeseen discoveries undoubtedly will continue to act as catalysts in the development of nuclear physics, many of the main themes of research with Exotic Nuclei have been outlined in this introduction. I have tried to give the perspectives of this very active field together with some selected examples of recent progresses both from the experimental and theoretical point of view. More details on more focused issues can be found in the following articles.

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