Exotic nuclei: why and how to make them?

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The interaction of neutrons and protons produces an incredible variety of nuclei: all the elements which constitute our universe, from hydrogen, the lightest, to uranium, the heaviest of the natural elements.

Our knowledge of the sub-atomic world has first been constructed by studying the nuclei which we find on Earth, which have been forged by the stars, several billions of years ago.

The stable nuclei are in equilibrium: their cohesion is such that no radioactive transmutation is possible. For a given mass, the proportion of neutrons and protons corresponds to structures strongly bound by the combined action of the various interactions: strong interaction, the pairing, the spin orbit, and the Coulomb repulsion.

Nature, in the processes of nucleosynthesis, and man, with particle accelerators, know how to produce nuclei outside this equilibrium. This is the field of exotic nuclei, the unstable nuclei that do not exist naturally on Earth.

Within the limits of nuclear cohesion, these nuclei will over time join the stable nuclei by transformation of neutrons into protons or inversely. It is the β radioactivity which is responsible for this transformation and the weakness of this interaction explains the very long times for these processes, from several milliseconds to millions of years.

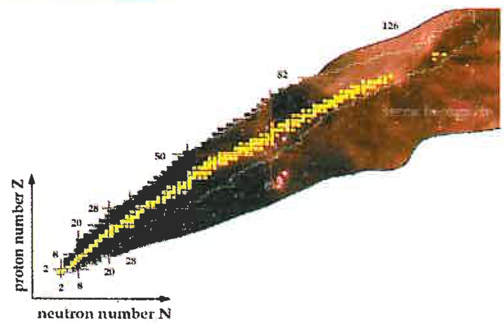
Out of the limits of nuclear cohesion, one or several nucleons are no longer bound, and the system disintegrates quasi instantaneously (in a time of the order of 10^{-21}s) into several pieces. It is this limit of cohesion, called the dripline, which limits the nuclear chart on which each bound nucleus is located by its number of neutrons and protons (figure 1). We seek today to explore this entire chart in order to test our understanding of nuclear cohesion. The goals are clear:

a) Identify the different phenomena at the origin of the nuclear properties;
b) Develop and test models able to describe these phenomena;
c) Establish the foundations of these models.

To explore the "terra incognita" of the exotic nuclei

According to current estimates, between 5000 and 7000 bound nuclei should exist on this chart, but only 2000 of them have been observed to date. In addition, except for the few 250 stable species, very little information could be obtained on these unstable nuclei. For example, the first excited state of only about 550 nuclear species has been observed.

To probe a nucleus and to characterize its properties, it is necessary to subject it to various nuclear reactions. The stable nuclei can be used as targets and can be bombarded with appropriate particles. Unstable and rare, the exotic nuclei do not live long enough to make a target, and to study the reactions with them therefore seems impossible. The revolution came about from the possibility of constituting beams of exotic nuclei. Instead of sending the probe to the nucleus to be studied, it is sufficient to send the nucleus to the probe. The beams of exotic nuclei thus open a vast field of study.



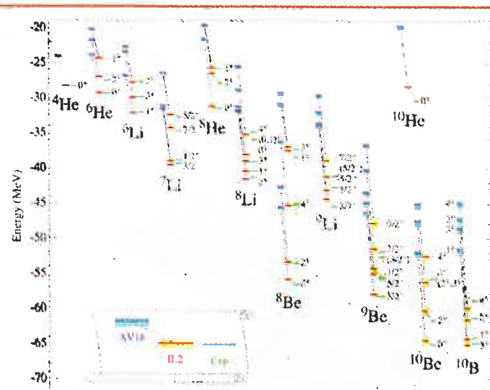
▲ Fig. 1: Chart of the nuclides representing the nuclei according to their number of protons Z and of neutrons N. The clear outline shows the limit of the nuclei observed experimentally, and the outline of the brown zone indicates the theoretical limit of nuclear cohesion. The horizontal and vertical red lines represent the magic numbers (2,8,20,28,50,82,126).

The production of secondary beams implies a very big intensity loss when compared to the primary beam, of typically 6 to 12 orders of magnitude. Therefore key experimental requirements are high intensity accelerators and high efficiency detection systems. This review will illustrate their interest with several examples.

Light nuclei

An approach to the description of nuclei, which seems obvious and which is entirely satisfactory for atomic physics, consists in trying to consider the nuclear force as the sum of the forces between the individual nucleons. The interaction between two nucleons is currently not understood starting from fundamental principles, but it can be modeled with a high degree of accuracy by adjusting it on a broad basis of experimental data for p-p, p-n and n-n scattering, corresponding to two body forces. Recently, it has become possible to do exact ab initio calculations for the systems of n-bodies up to A=12 with these realistic forces.

These model calculations show that it is necessary to include in the models a three-body force to reproduce, for example, the binding energies of these nuclei. Just as the two-body force, this three-body force cannot be calculated from fundamental principles. Figure 2 illustrates the results obtained. In this region, only 5 stable nuclei exist, not enough to fix the parameters of the model.



▲ Fig. 2: Binding energies of ground states and of the first excited states calculated using a two body interaction labelled AV18 on the figure, and using a three body interaction labelled IL2, are compared to experimental results (from S. Pieper *et al.*, Phys. Rev. C64, (2001), 014001 and private communication).

features

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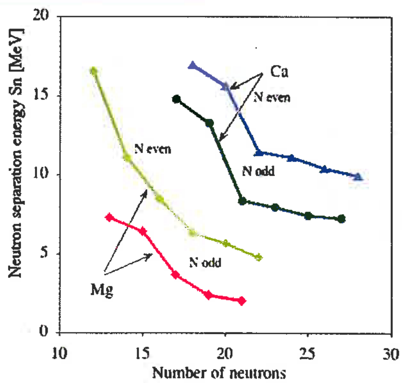
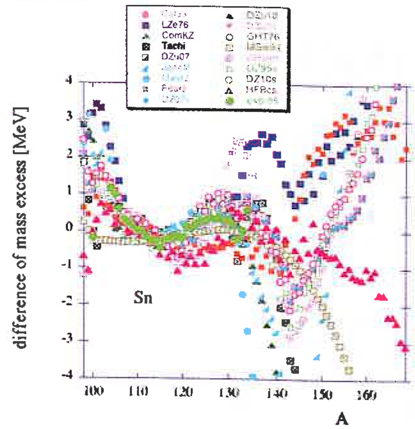


◀ **Fig. 3:** Evolution of the energy of separation of the last neutron for the isotopes of Ca and of Mg, according to their number of neutrons. The closing of shells in the case of the Ca is visible by the discontinuity observed for N=20 but absent in the case of the Mg.



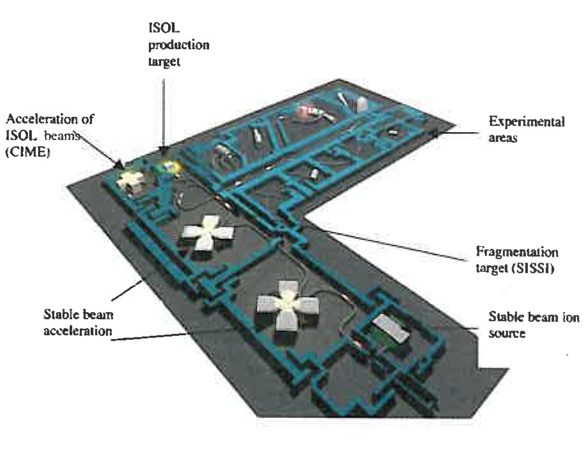
▲ **Fig. 4:** Difference of binding energy of various models and experimental results with respect to the predictions of the model of Møller et Nix, taken as reference, for the chain of isotopes of Sn. The green points are experimental results that extend up to ^{132}Sn. The other curves correspond to different model calculations.

The 7 unstable nuclei such as ^{6,8,10}He are therefore essential to establish and control the model. An unexpected result is obtained: the contribution of the three body forces reaches 50% of the binding energy for A=8. The light exotic nuclei are therefore an excellent test bench for our understanding of the nuclear forces. It is why a significant experimental and theoretical effort is being made at the moment to understand the structure of these nuclei and to explore the properties of new systems such as ^{5,7}H, or the quadrineutron 4n, even further from equilibrium. This illustrates the interest of exotic nuclei as a testing ground to establish the foundations of models.

Nuclei of intermediate mass and the shell model

New experimental results (binding energy, properties of first excited states,...) question increasingly our understanding of the shell structure of nuclei such as was developed for the stable nuclei. At the moment, the dependence of independent-particle orbits as a function of the neutron excess and of the binding energy is the most commonly used explanation for the disappearance of magic numbers valid for the nuclei close to stability and for the appearance of new shell closures. The most studied example at the present time is the ^{32}Mg nucleus for which the experiments clearly show that this nucleus is very deformed, contradicting all the theoretical models which predict it as spherical, according to its neutron magic number N=20. This loss of magicity of ^{32}Mg is illustrated in figure 3, where the evolution of the binding energy of the last bound neutron is plotted as a function of the number of neutrons, for the isotopes of Ca and of Mg. In the case of the ^{40}Ca (20 protons, 20 neutrons), located in the valley of stability, the shell closure appears as an abrupt change of slope for N=20, whereas for the ^{32}Mg (12 protons, 20 neutrons), with a large excess of neutrons, this behaviour is not observed. More recent shell model calculations interpret this disappearance of the magic number N=20 by the inversion of the order of the shells due to the dependence of the neutron-proton interaction on the combination of their spin in the nucleus (nucleon-nucleon spin-isospin $V_{\sigma\tau}$interaction). These calculations also predict that the magic number N=20 should be replaced by N=16 for the nuclei in this region very far from stability, and that this phenomenon should occur over all the chart of the nuclei. In particular, the non-observance of ^{28}O, a doubly magic nucleus in theory, could also be explained by this modification of its shell structure.

The experimental results obtained in this area of nuclei have already therefore brought many surprises, have permitted a better understanding of the underlying physical phenomenon and consequently a better use of the models. For example, the discovery of the importance of the spin-isospin coupling mentioned above, has opened new directions for nuclear mean-field theories. These results could only be obtained thanks to an increase in the sensitivity of the experimental devices and to the availability of high beam intensities. This made it possible to reach areas of the chart of nuclei previously inaccessible.



◀ **Fig. 5:** To produce exotic nuclei and to make beams of them, two methods are used. In the first, often called the 'in flight method', the secondary beams are produced in relatively thin targets, so that they retain on exit from the production target a significant part of the speed of the primary beam. They can therefore be directly transported in the beam lines towards the experimental room, after being focused and sorted. This method is that used at GANIL on the LISE separator, and SISSI, which allows the sending of secondary beams to all the experiment rooms of GANIL. The selection of the nucleus of interest is achieved with the help of magnetic sorting and the properties of energy loss of the ions in materials. The second method is the on-line separation, often called the ISOL method (Isotope Separation On Line). It is this, that is used in SPIRAL (Système de Production d'Ions Radioactifs Accélérés en Ligne), inaugurated in 2001 at GANIL. Just as in the preceding method, the beam of stable ions delivered by the GANIL cyclotrons is sent onto a target where the exotic nuclei required are produced. The target is heated to around 2000°C, which makes it possible to extract in a relatively short time these nuclei by the phenomenon of diffusion. On leaving the target, they will be ionized. The CIME cyclotron accelerates the ions and at the same time carries out the selection, so that only the exotic nucleus of interest is sent to the experiment room.

Heavy nuclei and mean-field models

For heavy nuclei, the shell model does not provide reliable calculations. However, an evolution is possible in the future with Monte-Carlo shell model calculations. Self-consistent mean-field calculations give a good reproduction of the properties of medium mass and heavy nuclei, in particular average properties such as the radii, the binding energies and deformations. Figure 4 presents a comparison between different theoretical calculations and the experimental results for the binding energies of Sn (tin) isotopes. If a good agreement is obtained between the different models and the experimental results for the nuclei relatively close to stability, the predictions diverge when one moves away from the zone where measurements were feasible. This stresses the necessity to extend the experiments to a larger area of the chart. With respect to deformation, the series of the isotopes of Kr constitute an excellent test for the models which predict transitions between spherical nuclei in the vicinity of the valley of stability and very deformed nuclei when one moves away both to proton and neutron rich isotopes.

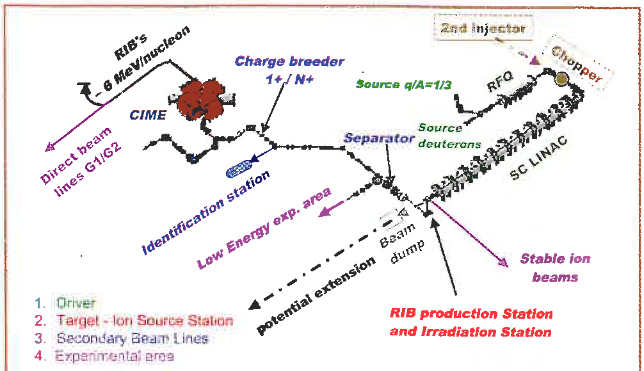
Furthermore, the understanding of the nucleosynthesis implies a precise description of nuclei very far from stability, often out of experimental reach. For example, the r-process, responsible for the formation of the heavy nuclei in the Universe, by a rapid succession of neutron captures and β decays, implies the existence of nuclei far from stability, such as ^{192}Dy and ^{240}Pb, whereas at the present time the last nuclei known in these regions are ^{173}Dy et ^{214}Pb.

For such exotic nuclei, the only means of having a good description of these processes is therefore to have reliable nuclear models, established and checked over as large as possible region of the chart.

Accelerators

Nuclear reactions are the tools to produce exotic nuclei in the laboratory. Various mechanisms are used, depending on the nature of the primary beam and its energy, and the nuclei to be produced. With the heavy ion beams of GANIL, fragmentation reactions occur when the primary beam has an energy greater than several tens of MeV/nucleon, which correspond to speeds of the order of 30 to 50 % of the speed of light. In these reactions, the projectile and the target loose part of their nucleons, thus producing all sorts of nuclei lighter than the beam particles, of which some can be very exotic. The fragments of the beam produced during this process keep kinematic characteristics relatively close to those of the primary beam (slightly lower speed, angle of emission concentrated in a forward angle cone). With lower energy, the reactions of fusion-evaporation make it possible to form heavy nuclei very deficient in neutrons, because in a fusion reaction mainly neutrons are evaporated from the compound nucleus, that is already neutron deficient due to the curvature of the valley of stability in the N-Z diagram. From a technical point of view, two methods are used: the in-flight method and the on-line method or ISOL (see figure 5). These two methods have their advantages and their drawbacks, but are perfectly complementary.

First of all, with regard to the energy, the in-flight method is well adapted to the production of secondary beams of energy higher than a few tens of MeV/nucleon, whereas the ISOL method produces nuclei at rest, which can then be accelerated to the energy desired. One of the advantages of the ISOL method is the optical quality of the secondary beams, which is as good as that of the primary beams, whereas the beams produced in flight have larger spatial and angular emittance. The purity of the ISOL secondary beams is generally excellent whereas it is often difficult to completely eliminate the contaminants in the beams produced in flight. But all nuclei with a life



▲ Fig. 7: In the project Spiral2, a linear superconducting accelerator provides high intensity primary beams, 5mA of deuterons at 40MeV, and 1mA of heavy ions with a mass over charge ratio M/Q≤3. The deuterons are converted in a carbon target into forward-angle focused neutrons, with energies centered at about 14MeV. These neutrons can be used to induce fission in a fissile material such as Uranium. The fission products can be extracted, ionized, and accelerated(ISOL method referred to in the caption of figure 5). The heavy ion beams can be used to produce fusion evaporation products by the ISOL method or in a recoil spectrometer.

◄ Fig. 6: In order to be able to study nuclei at the limit of stability in good conditions, new detectors of very high detection efficiency were designed and built. The equipment finalized at GANIL for the experiments with secondary beams are the VAMOS spectrometer and the EXOGAM multi-detector dedicated to the detection of γ radiation. The principal characteristic of VAMOS (bottom photo) is its large angle and momentum acceptance. VAMOS is composed of two quadrupoles, a velocity filter and a dipole, these elements being able to function individually or together, which makes it possible to use the spectrometer in different modes (VAriable MOde Spectrometer). The EXOGAM design (top left photo), a powerful γ spectrometer made of 16 Germanium detectors, achieves an efficiency of detection of 20% for a total energy deposition (photo-peak efficiency). EXOGAM and VAMOS can be used separately or together (cf top right photo: EXOGAM assembled around the target point of VAMOS), possibly joined to other detectors, in particular those of charged particles, such as TIARA or MUST2. These two detectors were built within the framework of European collaborations. VAMOS was defined by a European RTD project which involved laboratories in France (GANIL, SPhN Saclay, CENBG Bordeaux, LPC Caen, IPN Orsay), Germany (GSI), U.K. (Liverpool, Manchester, Surrey Universities, CCLRC Daresbury), and Czech (NPI Rez). EXOGAM is the fruit of a vast collaboration involving France, Germany, U.K., Spain, Sweden, Finland, Denmark, Poland and Hungary.

time longer than their time of flight from the production target to the reaction study target, i.e. of the order of 1μs, can be studied if they are produced in flight. This is not the case with the ISOL method where the chemistry of materials plays a significant role since the atoms produced must be extracted from the target and arrive at the source by a diffusion-effusion process. For example, the first beams produced by SPIRAL at GANIL are only rare gases for which the exit times are relatively short. For the other chemical elements, new target-ion source combinations are being studied to optimize this time of diffusion-effusion out of the target. In practice, the ISOL method is mostly limited to nuclei of a life span of the order of 0.1 to 1 second.

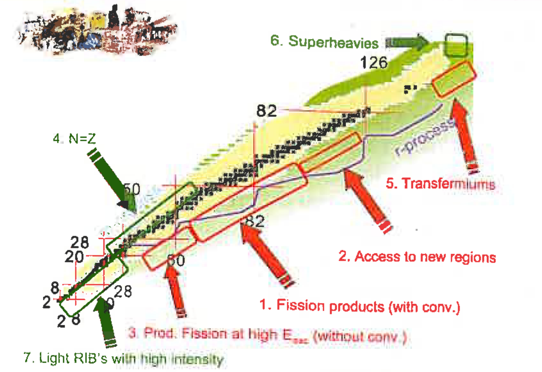
Measuring instruments

Experiments using secondary beams have brought a revival to the discipline, not only with regard to the physics involved, but also because they required a new methodology and the development of new instruments. Indeed, just as in the past, physicists started by sending beams of protons, or at least particles of relatively simple and well known structure, onto targets which they wanted to study, the first experiments relating to reactions induced by exotic nuclei have been made with targets of protons, deuterons or of helium. In this inverse kinematics (the projectile is the heavier nucleus, the target nucleus the lighter), the characteristics of the fragments to be detected are very different from those usually met in the case of direct kinematics.

The detectors thus have to be adapted to these new conditions. Another important difference between an experiment carried out with a stable beam and another carried out with a secondary beam is connected to the intensity of the beam. Indeed the intensity of a secondary beam is several orders of magnitude lower than that of the stable beams. As the times allocated for experiments cannot be extended indefinitely, it is therefore necessary to compensate, at least partly, for this loss of intensity by an increased effectiveness of the detectors. Whereas the experiments with stable beams use typically intensities of the order of 10^9 to 10^{12} particles per second, fairly detailed spectroscopic information has already been obtained with beam intensities going down to 1 particle per second, which represents a gain of experimental efficiency of around 10 orders of magnitude, realized in 2 decades. An additional difficulty is related to the radioactive nature of the secondary beams. Their disintegration generates a background noise that can mask the signal sought. The new detection devices have therefore been designed to be able to suppress as far as possible this background noise. The use of several detectors allows, by carrying our coincidences, the reactions of interest to be the tagged (see figure 6).

The future

At present, experimental studies are still often limited to the lightest exotic nuclei, because only these beams are available with sufficient intensities. Future accelerators will make it possible to widen the range of the nuclei which can be studied, and to increase the intensities available to be able to carry out more selective and detailed experiments. This will deepen our understanding of the nucleus, and hence better establish and constrain nuclear models. The SPIRAL II project (see figure 7) proposes the use of fission in a target of uranium carbide for the production of neutron-rich nuclei. The fission will be induced by neutrons produced by a high-intensity beam of deuterons (5 mA, 40MeV) on a carbon converter. The fragments from the fission of the Uranium, extracted by the ISOL method, will make it possible to explore a region of neutron-rich nuclei of mass ranging between 80 and 160, still comparatively unknown. Proton-rich nuclei, on the other side of the valley of stability, can be formed by fusion-evaporation reactions using



▲ **Fig. 8:** The various domains of the nuclear chart are shown. Low energy fission induced by neutrons from a converter gives access to region 1, and reacceleration of these fission products to region 2 by fusion reactions. This will be complemented by the use of heavy ion beams for hot fission (region 3) and for fusion evaporation reactions (region4). The regions 5 and 6 of trans-uranium and super-heavy elements will become accessible by the use of secondary neutron-rich beams, and of high-intensity heavy-ion primary beams. Very high-intensity light radioactive beams are possible by the use of neutron-induced reactions on light targets (region 7), for example ^{6}He with intensities of up to 10^{13}/s.

heavy-ion beams that will be available with very high current, up to 1mA, with energies up to 14MeV/nucleon. The secondary beams can be accelerated in the existing CIME cyclotron to energies up to about 20MeV/nucleon, depending on the charge-state. The domains of the nuclear chart that will be covered with this project are shown on figure 8. SPIRAL II is a first stage to increase the intensities and the variety of the beams at GANIL and integrates present European developments for the medium and long term. In Germany the GSI project, proposing very intense heavy beams of 1GeV/nucleon, has cleared an important decision stage, with an agreement of principle from the Research Ministry. EURISOL is a large project for beams produced by the ISOL method and is the subject of a vast European collaboration.

Different projects are also being studied in other parts of the world. In Japan, the RIBF (Radioactive Ion Beam Factory) is under construction at RIKEN, using the fragmentation of heavy ion beams at several hundred MeV/nucleon. RIA (Rare Isotope Accelerator) is the ambitious American project, in the same field of energy. Extension to existing machines are also in progress in Canada (TRIUMF-ISAAC at Vancouver), in China (Lanzhou), in Russia (Dubna), in Italy (Catania, Legnaro), and at CERN (ISOLDE).

Further reading

Special issue on Research Opportunities with Accelerated Beams of Radioactive Ions, Nucl. Phys. A693 (2001) Nos 1,2 published by I. Tanihata.

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