The Why and How of Radioactive-Beam Research

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Abstract. Research with radioactive ion beams has entered in the last decade a new era with the advent of energetic beams of radioactive nuclei which can induce nuclear reactions. The why and how of this research is discussed by presenting the open physics questions, the milestones in the exploration of the nuclear chart with special emphasis on obtained insight and knowledge also highlighting the experimental achievements and challenges. An outlook on the next generation of radioactive beam facilities concludes this lecture.

1 Introduction: The Structure of the Nucleus, How Deeply Is It Understood?

Atomic nuclei are quantum systems with a finite number of strongly interacting fermions of two kinds: protons and neutrons. The strong interaction between the nucleons cannot be treated in a perturbative way and the small number of nucleons does not allow the use of statistical methods. Furthermore, both the weak and electromagnetic interaction are at work inside the nucleus. All this makes the atomic nucleus one of the richest and most challenging of quantum systems. Starting from the bare nucleon–nucleon interaction, it has become possible to describe light nuclei up to mass 10 starting from first principles. Going to heavier nuclei the interactions between the nucleons are modified by the medium in which they occur and effective interactions are needed. Nuclear mean fields can be generated in a self-consistent way by using effective two-body nucleon-nucleon forces. The nuclear shell model starts from a different basis by dividing the nucleons into an inert core and a number of valence nucleons. New techniques and increased computer power have resulted in the last decade not only to the description of medium-heavy nuclei but also to the successful reproduction of collective effects in a number of nuclei. Although important progress has been made in recent years a number of crucial, often long-standing questions remain:

- What are the limits for the existence of nuclei?
- How does the nuclear force depend on the proton-to-neutron ratio?
- How can collective phenomena be explained from individual motion?
- Is it possible to explain complex nuclei on the basis of simple building blocks?

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Most of the present-day knowledge of the structure of the atomic nucleus is based on the properties of nuclei close to the line of β-stability where the proton-to-neutron ratio is not so different to that of stable nuclei. But extrapolating this to the region far from stability is quite dangerous and already it is now clear that some of the 'basic truths' of nuclear physics have to be revisited. For instance the nuclear radii of some nuclei do not all scale with a $A^{1/3}$ dependence. Also the well-known magic numbers for Z and N seem to be dependent on N and Z, respectively. Furthermore, nucleon correlations and clustering seem to play a much more important role in nuclear binding than anticipated. The dependence of the nuclear interaction on this specific degree of freedom, the proton-to-neutron ratio (expressed by the quantum number isospin), is believed to shed a new and elucidating light on a number of aspects of the nuclear interaction and dynamics. Studying nuclei under extreme conditions of isospin (completely different from stable nuclei) will not only provide firm guidance for theoretical models but is bound to lead to the discovery of new and exciting phenomena. Such nuclei, far off stability, are often called 'exotic'. In dictionaries one can find that the term 'exotic' means: 1. Originating in a foreign country/ 2. Remarkably strange or unusual/ 3. Of a kind newly brought into use. By moving in the unknown territory of undiscovered nuclei it is likely that the three qualifications of exotic will hold.

2 The Nuclear Chart, Our Road Map from Stable to Exotic Nuclei

How many nuclides exist and how many have been observed? The existence of an atomic nucleus is firstly related to the binding energy of the specific system of protons and neutrons. The binding energy B is defined as the difference in mass energy between a nucleus ${}^{A}_{Z}X_{N}$ and its constituents of Z protons and N neutrons and can be written by using atomic masses (given in atomic mass units) as:

$$B[MeV] = \left[Zm\left({}^{1}H\right) + Nm_{n} - m\left({}^{A}X\right)\right]c^{2} \tag{1}$$

with m(^{1}H) the hydrogen mass, m_n the mass of the neutron and c^2 having the value of 931.50 MeV/u. Information on atomic masses (experimental or calculated ones) can e.g. be found tabulated on the website of the Atomic Mass Data Center [1] and in the recent NUBASE evaluation [2]. Next to the binding energy which is a measure of how much energy has been gained through the strong force by forming the nucleus out of its bare constituents, one also has to consider particle and cluster binding energies of which the neutron and proton binding energies are the most important for delineating the limits of nuclear existence. The neutron (proton) binding energy B_n (B_p) (sometimes called separation energy) is the amount of energy needed to remove the last neutron (proton) from the specific nucleus. Negative binding energy means that the particle is energetically not bound anymore by the

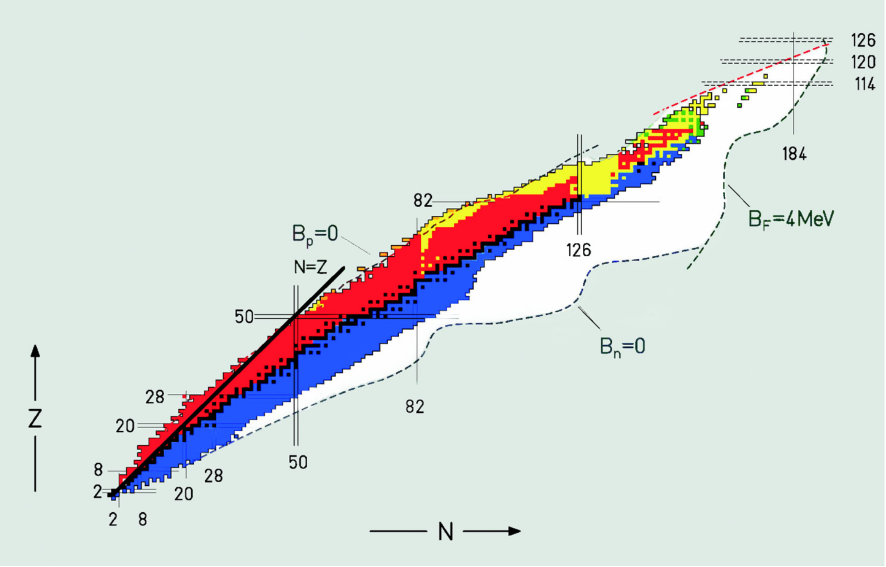

Fig. 1. Chart of the nuclides: within the borderlines defined by the proton (B_p) and neutron (B_n) driplines and the fission barrier (B_f) a 6000 nuclei are believed to 'exist' (the excluded region is given in light grey) of which the stable nuclei form the backbone (black squares). Already studied or observed nuclei are indicated in different grades of grey (depending on the decay mode), most of the unknown nuclei (white area) do lie on the neutron rich side. Also given on the figure as vertical (horizontal) lines are the magic numbers for neutrons(protons) as known close to stability. While for the lighter nuclei the valley of stability follows the N = Z line, heavier nuclei have more neutrons than protons.

nucleus. Coulomb barriers (only for charged particles), centrifugal barriers and nuclear structure incompatibilities could hold the particle or cluster of particles in the nucleus for a longer time than a typical orbit time of the nucleons in a nucleus ($\sim 10^{-21}$ s).

The chart of the nuclides, also called the Segré plot, (see Fig. 1) shows on a grid of proton number versus neutron number the distribution of the stable nuclei and the presently known radioactive nuclides (some 3600). 'Stable' means that the time scale of the possible decay of those nuclei through the strong or weak interaction is of the order of the time scale of our universe or larger. Our present day 'natural' matter consists of these stable nuclei (198 in total) together with the primordial radionuclides, i.e. those radioactive nuclei formed in the build-up of terrestrial matter and having half-lives in the range of 10^9years (86 in total). Since the birth of nuclear physics many short-living radioactive isotopes have been the subjects of extensive studies, first as products in natural radioactive chains or through production in cosmic radiation, and later on artificially created in reactors and accelerators. When adding, as a third dimension, the nuclear mass excess, a landscape becomes visible: the so-called valley of β-stability. The mass excess is the difference between the nuclear mass and A, the mass number:

$$Mass - Excess[MeV] = \left[m\left({}^{A}X\right) - A\right] c^2 \tag{2}$$

Due to the definition of the atomic mass unit as 1/12 of the mass of a ^{12}C atom, the mass excess is 0 for ^{12}C, positive for the lighter masses and becomes tens of MeV negative for the heavier masses. The stable nuclei form the bottom of the valley and can be found by differentiating the Bethe - Weizsäcker semi-empirical mass formula, which can be found in most introductory textbooks on nuclear physics. The cliffs of the valley rise parabolically for a given mass number. It is the weak interaction that brings the unstable nuclei, through β-decay within isobaric chains, back to the bottom of the valley. The time scale of the β-decay ranges from milliseconds to years and strongly depends on the available decay energy: the further away from stability the faster the decay. However, this weak decay process can become obsolete when decay through the strong interaction takes over. This will occur near the drip lines in the Segré plot where the binding energy (B_p or B_n) of the last nucleon (proton or neutron) becomes zero (to have the driplines expressed in integer values of Z and N, the lightest particle-stable nuclide within a family of isotopes or isotones is taken). These lines are accepted as the borderlines of nuclear existence, although for particular cases barriers can slow down the particle emission and lead to the observation and study of nuclei beyond the drip line. Also, direct reactions can be used to study through resonances nuclei across this borderline. Furthermore, as a difference of only a few hundred keV in binding energy can decide whether a nucleus decays by particle emission or beta-decay and as the accuracies on mass models far off stability is in the MeV region, the exact location of the driplines is, for certain isotopes, not well known. For a given isotope, differences up to 16 mass units in the predicted drip lines using different mass models can be the result.

Where does the valley of β-stability end at the heavy mass side? Other decay modes based on cluster emission such as α decay and fission will become faster than β decay and will take over. The partial half life for α decay depends mainly on the available decay energy (Q_a-value, see [1]) compared to the height of the Coulomb barrier although local nuclear structure effects can alter the half life by one to two orders of magnitude (see further down). Different regions where α decay is or will be the main decay mode can be localized on the chart of nuclei. Calculating the half lives of the spontaneous fission process is much more difficult due to the extreme sensitivity to details of the height and shape of the fission barriers and the route in this potential energy surface towards fission. Furthermore, shell effects can stabilize the so-called superheavy elements towards the spontaneous fission process and therefore the question of where nuclear existence ends in the superheavy corner is still open. In Fig. 1 a borderline is drawn where the fission barrier lies around 4 MeV.

Taking the different borderlines into account more than 6000 nuclides are believed to exist of which some 3600 have been observed (but not all of them have been studied in full detail!). Within this vast number, a wealth of information on the forces active in the nuclear medium is present and the purposeful exploration from the stability line to the most exotic nuclei is believed to lead to a deep understanding of the nucleus and its structure.

2.1 Milestones in the Exploration of the Nuclear Chart

Unravelling the internal structure of a complex system is traditionally done by submitting the system to an external signal. The way the system then responds will yield information on its constituents and their interaction. In nuclear physics the external probes can be of electromagnetic, weak or strong character. The response can be categorized as follows:

- the complex structure survives but the extra energy is radiated away in a specific manner,
- the complex structure breaks up into smaller fragments,
- the complex system fuses with (part of) the probe.

A general term we can use here for this kind of approach is *reaction work*. In 1919 E. Rutherford was the first to artificially transmute one element into another: he observed the production of hydrogen by firing alpha particles in a nitrogen gas. Collimated energetic α particles emitted in the decay of ^{226}Ra, purified out of ores of uranium, were used for this purpose. In 1932 J. Cockroft and E. T. S. Walton repeated this experiment but now with an accelerated alpha beam.

From the early days of nuclear physics, it became clear that the spontaneous decay of unstable nuclei back on their way to stability provides an alternative source of nuclear structure information. For many years this *decay work* was limited to natural radioactive nuclei and their decay products. In 1934, I. Curie and J.F. Joliot were the first to produce in the bombardment of boron and aluminum foils with alpha particles artificial radioactive isotopes: ^{13}N (10 minutes) and ^{30}P (2.5 minutes). A nuclear reaction between two stable nuclei is thus used to produce a radioactive one. In 1942 E. Fermi built the first controlled fission reactor and this was the start for the identification and study of many neutron-rich radioactive isotopes produced through neutron-capture reactions and through neutron-induced fission. Ten years later the number of known nuclei had almost doubled (see Fig. 2).

The advent of powerful accelerators has been crucial for the exploration of the nuclear chart. First light-ion and later on heavy-ion induced fusion reactions could be used for the production and study of new isotopes. In particular, heavy-ion fusion reactions are very successful to intrude deeply in unknown territory since due to the specific N/Z dependence of the line of stability most combinations of stable projectile and stable target end up in the neutron-deficient region. Fusion reactions are still rather selective as

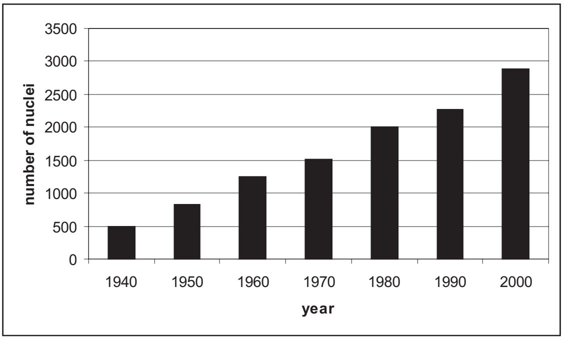

Fig. 2. Evolution of the number of discovered isotopes as a function of year: the first column summarizes all known nuclei before 1940, the other values are given per decade: e.g. 1960 means from 1951 till 1960.

only a limited number of reaction channels are open and a careful choice of the bombarding energy can further reduce the number of nuclei produced. This is no longer the case for spallation, fragmentation and fission reactions where hundreds of isotopes are produced. Next to the basic question on how to produce exotic nuclei, an increasingly important question emerged on how one can study the main characteristics of the produced nuclei.

In 1951 a new method of studying nuclei far from stability was developed. O. Kofoed-Hansen and K. O. Nielsen bombarded an uranium target with fast neutrons coming from the break-up of a 11 MeV d beam. Neutron-rich, noble gas isotopes produced through fission were, after thermalization in the target, swept into the ion source of an electromagnetic isotope separator. The whole process of production, ionization, mass-separation, implantation into a detector set-up and subsequent detection of the emitted decay radiation was performed in a continuous way: the so-called 'Isotope Separation On Line' (ISOL) technique was born. The most neutron-rich isotope studied at that time was 10 s ^{91}Kr [3]. Since then many ISOL facilities came on-line (the right part of Fig. 3 down to the mass separator schematizes the method) and significantly contributed to the exploration of the chart of nuclei. The scientific community organized for the first time a conference around this exploration in 1966 with the Lysekill, Sweden conference 'Why and How should we investigate nuclides far off the stability line' [4]. From then on different 'Nuclei Far From Stability' conferences have been organized. In the nineties this conference series merged with the 'AMCO: Atomic Masses and Fundamental Constants' Conference series under the name 'ENAM: Exotic Nuclei and Atomic Masses'. The latest ENAM conference was held in 2001 at Hämeenlinna, Finland [5]. The technical aspects of on-line mass separation were discussed for the first time in the context of the conference series on Electromagnetic Isotope Separators (the EMIS conferences) at Aarhus, Denmark in 1965 [6]. Since then on-line mass separation and, more generally,

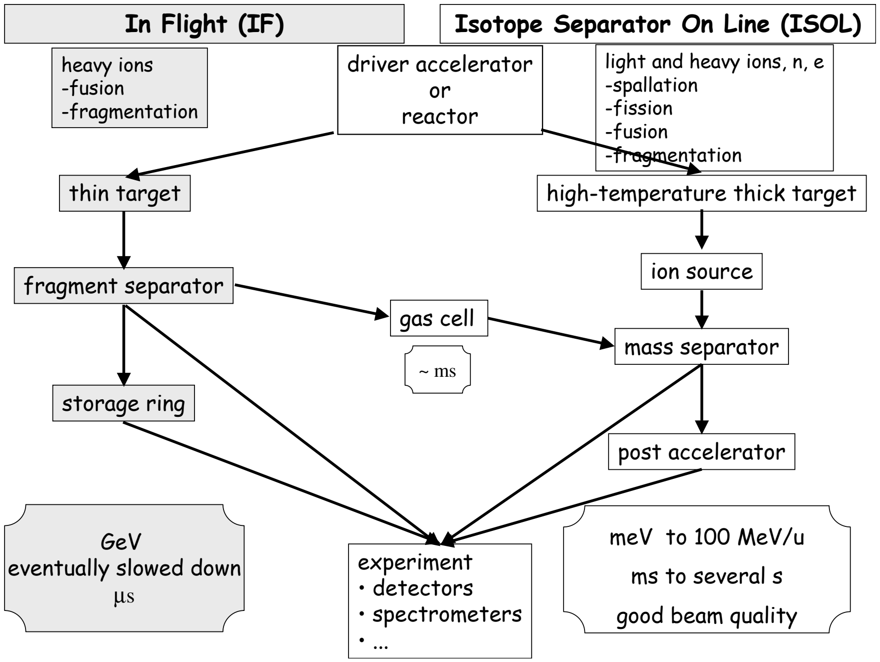

Fig. 3. A generic description of the In-Flight and Isotope Separator On Line methods. A driver accelerator or reactor provides the particles inducing nuclear reactions in a target. In the In-Flight method the primary particles have to be heavy and energetic and the target has to been thin in order to have the reaction products recoiling out of the target (fission is an exception to the statement of heavy and energetic particles as the reaction also can be induced by photons, electrons and light particles; the energy released in fission is high enough for the fragments to leave the thin target). The In-Flight method is applicable to very short-living nuclei (μs) as only the flight time from the production target to the measuring station induces decay losses. With the In-Flight method the radioactive ions are energetic and can eventually be slowed down and stored. In the ISOL method the radioactive products have to be thermalized in a catcher and then re-accelerated. The resulting beams are ion-optically (emittance, energy resolution, timing structure) of excellent quality but the thermalization process and the eventual re-ionization in the ion source can be slow and even inefficient leading to severe losses for short-living nuclei or for isotopes from refractory elements. If the slowing down process happens in a gaseous catcher leaving the ions in a 1^+ charge state (eventually after re-ionization by resonant laser light), these deficiencies of the target-catcher-ion source systems in the conventional ISOL can be avoided. This is also the way how the best of both (In Flight and ISOL) worlds can be obtained and a high-quality beam of short-living radioactive ions can be produced.

all technical aspects on the production of nuclei far from stability became the dominant part of the conferences. The latest conference in this series was held in Victoria, BC, Canada in 2002 [7].

Instead of going through the process of thermalization, ionization, acceleration and mass analysis of the reaction products, the kinematics of the production of the radioactive isotopes can also be used to separate the reaction products. When for example inducing fission of a heavy nucleus, the two fission fragments have each a kinetic energy around 100 MeV. If the target is thin enough, these radioactive isotopes will recoil out the target in a charged state. In heavy-ion induced nuclear reactions such as fusion or fragmentation, the conservation of mass and momentum demands that the reaction products are emitted in the beam direction. By using different magnetic field combinations, eventually further combined with electrical fields and/or with solid degraders, where the energy loss is dependent to the atomic number, or with gas-filled sections, where velocity focussing takes place, the reaction products can be separated from the beam and in certain cases specific isotopes can be select out according to A and Z. Throughout this text the term 'In-flight separators' will be used to describe the complete class of kinematic separators (the left part of Fig. 3 gives the generic features of the In-Flight technique). During the Lysekil meeting P. Armbruster already reviewed the possibilities of In-Flight separators for the study of fission products [8]. The first In-Flight separator used was a gas-filled magnetic separator at the graphite reactor of Oak Ridge, USA [9]. Applying deflection in magnetic *and* electric fields to fission products was pioneered in 1964 at the research reactor in Garching, Germany [10]. In 1969 a gas-filled magnetic separator was used at the Dubna, Russia heavy ion cyclotron for fusion reactions [11]. Next to fission and fusion, In-Flight separators were also later developed for spallation and fragmentation (see also the lecture of D.J. Morrissey and B.R. Sherrill in this volume [12]). The In-Flight separators are highly successful in exploring the limits of stability, thanks to their short flight time, their high transmission and their good particle identification. The role of the velocity filter SHIP at GSI, Darmstadt, Germany [13] in particular should be mentioned for the identification of a series of superheavy elements (see further down and [14]).

In 1981, at the 4th International Conference on Nuclei Far From Stability held at Helsingør, Denmark, T.J.M. Symons reported the first experiments on the production of exotic nuclei by fragmentation of high-energy heavy ions [15]. He pointed to the fact that '... the fragments are so well focused that they can be prepared into a secondary beam thereby extending the study of heavy ion collisions to systems with unusual neutron to proton ratios'. The real impact of this new technique was only apparent with the measurements of the total interaction cross section for He and Li isotopes at Berkeley, USA showing the existence of halo states in ^{6}He and ^{11}Li [16]. The secondary beams of radioactive nuclei, further used to induce nuclear reactions, were obtained by using the In-Flight technique. In 1989 secondary beams of radioactive nuclei were also obtained using the ISOL method: by coupling the

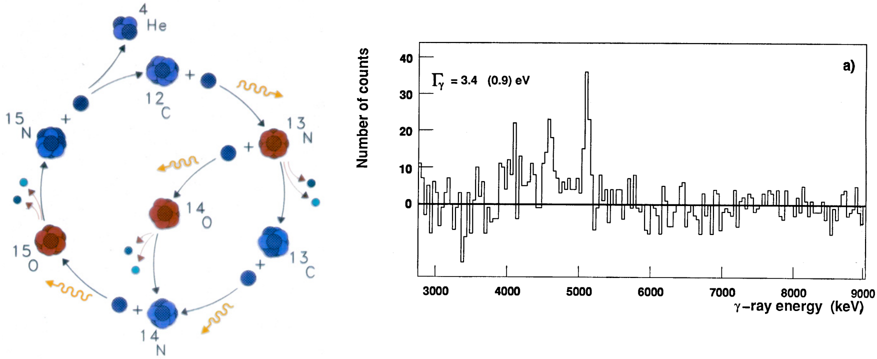

Fig. 4. The so-called cold CNO burning cycle where four protons are transformed in one ^{4}He nucleus involving four proton-capture reactions on stable nuclei and two β decays (circle in left panel) can transform in the hot CNO cycle when the proton-capture reaction on ^{13}N leading to ^{14}O is faster than the β decay of ^{13}N (for more information see the lecture of Langanke, Thielemann and Wiescher [17]). The cross-section of this reaction at stellar energies has been measured directly by impinging a post-accelerated ^{13}N beam [18] on a ^{1}H target and recording the emitted γ ray (see right panel)[19]. The three peaks in the γ ray spectrum are coming from the photopeak, the first escape and second escape of the 5.173 MeV γ line.

two cyclotrons of Louvain-la-Neuve, Belgium through an on-line mass separator, intense beams of post-accelerated ^{13}N were obtained [18]. The intensity and good beam quality made it possible to measure the astrophysical important proton-capture reaction on ^{13}N [19], see Fig. 4. A generic description of the two methods including eventual cooling and/or post acceleration is given in Fig. 3. With the advent of In-Flight and ISOL-based secondary beams a new field was born and a new series of conferences started. The first conference on 'Radioactive Nuclear Beams' was held at Berkeley, USA in 1989 [20], the most recent one at Argonne, USA in 2003 [21]. The current situation of Radioactive Nuclear Beams projects in Europe is given in Fig. 5. Recent references to these projects and the projects in North America and Asia can be found in [5,7,21]. In 1993, a school was started to train Ph.D students and young postdocs in this new discipline. From the start, the 'Euroschool on Exotic Beams' was funded by the EU and while in the first years the schools took place at the University of Leuven, Belgium, from 2001 on the yearly school travelled through Europe. The lecture notes presented in this volume are all written by former lecturers or directors of the school.

The term 'Radioactive *Nuclear* Beams' was introduced to specify that the energy of the secondary beam is such that a nuclear reaction can be induced. One often finds the abbreviation RNB in articles. The more general term 'Radioactive Ion Beams' (abbreviated as RIB) is also sometimes used for this purpose. Also the term 'Rare Beams' can be encountered, mainly in the USA. Of course not only the milestones in the production of (beams of) exotic

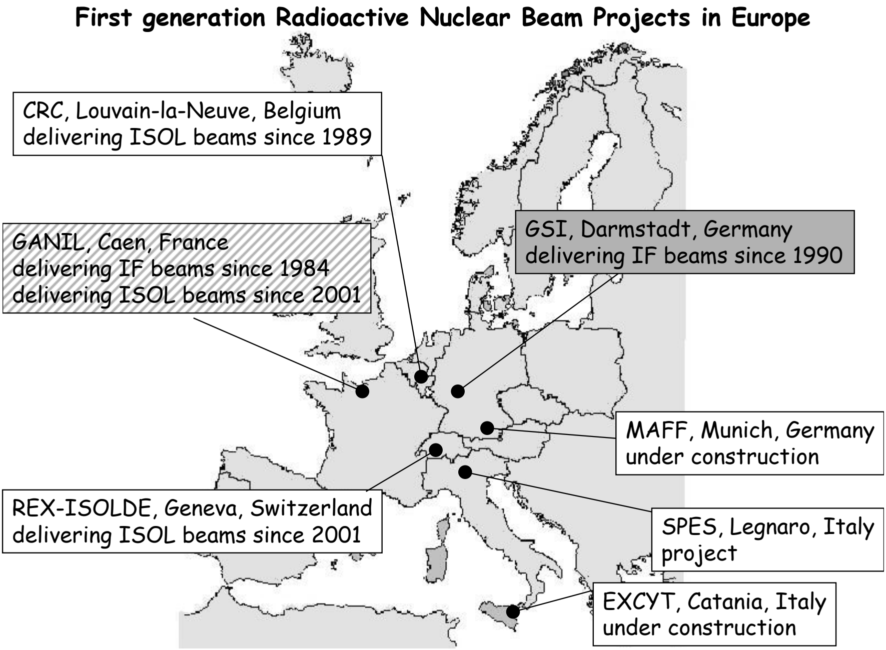

Fig. 5. The first generation of Radioactive Nuclear Beam projects in Europe. As discussed in the text, the development of radioactive beams is already more than half a century going on. The possibility to use beams of radioactive ions for inducing secondary reactions has only more recently been explored and a number of pioneering projects emerged in Europe, North America and Japan. The same coloring code is used here as for Fig. 3: grey for In-Flight projects, white for ISOL (at Ganil both methods are used). Next to this running projects also a number of projects under construction or planned are included in this figure: they form together the first generation of RNB projects in Europe. Such a first generation is also present in North-America and Japan. While excellent physics is coming from these projects, a next generation is planned. As the quality factor (intensity, ion-optical quality, selectivity, sensitivity) is bound to be improved by several orders of magnitude, this next generation can only be realized by strong international collaborations.

nuclei are important. The kind of experiments which can be done with such beams are of matching importance. Ingenious techniques have been developed to manipulate the radioactive nuclei and to detect their radiation. These techniques will not be reviewed here but will be mentioned when discussing the important discoveries which resulted from the study of nuclei far from stability.

2.2 Important Discoveries

Starting from the Lysekil conference in 1966 [4] the field of nuclei far from stability has been characterized by a steady flow of important discoveries, some of them predicted by theory but most of them unexpected and therefore sometimes dramatically changing the understanding of nuclear structure. Many of these discoveries were the result of innovative techniques and therefore the choice of the examples given here is not only guided by the mere nuclear physics importance but also by a pedagogical concern to introduce to the reader the important arsenal of experimental tools available for the exploration of the field of exotic nuclei.

This section is organized as follows: firstly the newly observed decay modes from groundstates or long-living isomers in exotic nuclei are presented, this is then followed by a discussion on the most important groundstate properties. Although the groundstates already contain vital nuclear structure information, the richness of the nuclear many-body system emerges when excited levels are also characterized. To guide us through the wealth of new phenomena and the changes in our understanding we will use the three classes of structural benchmarks, discussed by Casten and Sherrill in their review article on exotic nuclei [22]: magicity, symmetry and transition. The first orientation in the chart of nuclei comes from the presence of magic proton and neutron numbers yielding such anchor points as doubly-closed shell nuclei (see Fig. 1). Symmetries are naturally ordering concepts that play an extremely important role in nuclear physics. In many cases they lead to observables whose values follow simple analytical relations. Nuclei that exhibit excitation spectra as e.g. described by a harmonic vibrator or a symmetric rotor can be found in specific parts of the nuclear chart. The changes in structure such as from spherical to deformed or from one deformed shape to another, form the third benchmark. The systematic exploration of the nuclear chart by going from nuclei near stability to exotic nuclei allows to detect this structural evolution and to unravel the underlying mechanisms.

New decay modes. In 1896 radioactivity was discovered by H. Becquerel and quite soon three types of nuclear decay (α, β and γ) were identified. These different types of decay were observed in the naturally occurring radioactive series and due to the fact that in some cases excited levels were populated. Also, sequential decay modes such as β-delayed γ and α emission and α-delayed γ emission were observed. In 1939 the pioneering experiments of O. Hahn and F. Strassmann [23], where evidence was found that barium isotopes were formed in the bombardment of uranium by neutrons, led L. Meitner and O.R. Frisch [24] to the interpretation of this process as neutron-induced fission. In the same fruitful year R.B. Roberts, R.C. Meyer and P. Wang [25] reported on the observation of delayed neutron emission while N. Bohr and A. Wheeler [26] predicted the possibility of spontaneous fission. One year later spontaneous fission was discovered by K. Petrzhak and G. Flerov [27].

With the vigorous exploration of the nuclear chart from the 1960's on, combined with the development of sensitive detection techniques, many new decay modes have been observed. Indeed one of the main characteristics of exotic nuclei is the high decay energy opening up many decay channels. Beta-delayed particle emission occurs in nuclei with high Q_β-values and β-decay daughters with low separation energies for nucleons or clusters. The terminology of this sequential process is as follows: the precursor feeds through β decay excited states in the isobaric nucleus which is called the emitter. In competition with γ decay within the same nucleus, particles such as protons, neutrons or alpha particles can be emitted feeding states in what is called the daughter nucleus. In 1963 V.A. Karnaukhov, G.M. Ter-Akopian and V.G. Subbotin [28] reported on the discovery of β-delayed proton emission. Since then more than a hundred delayed proton precursors have been observed and studied. Next to the now rather common decay modes such as β-n, β-p and β-α, more complex β-delayed radioactivities such as β-2p, β-3p, β-αp, β-2n, β-2n, β-3n, β-4n, β-d and β-t have been observed. A number of excellent review articles can be found on β-delayed particle emission ([29] and references therein). Due to the kinematical conditions in β-delayed proton emission the recoil of the β particle will influence the energy shape of the emitted proton. The energy resolution of proton detectors is good enough to extract from the recorded energy spectrum information on the positron-neutrino correlation in superallowed β decay ([30] and references therein). This can then be used to search for physics beyond the Standard Model. More information on this subject can be found in the lectures of E. Roeckl [31] and N. Severijns [32] to this volume (in particular Figs. 3 and 4 in [31] and Fig. 5 in [32]).

The well-known α radioactivity is a textbook example of quantum mechanical tunnelling and has been known for more than one hundred years. The very strong dependence of the decay rate on the available decay energy, visualized in the so-called Geiger-Nutall plots ($\log T_{1/2}$ versus $(E_\alpha)^{-1/2}$) is one of its most striking features. However strong deviations are observed when particular nuclear structure effects are at play. In Fig. 6 the Geiger-Nutall plot is given for a series of Po isotopes and a deviation for the light masses becomes apparent [33]. This has been explained by a gradual change in deformation of the Po groundstate when going more neutron deficient. This strongly retards the direct α to the spherical groundstate in the corresponding Pb daughter nucleus. Fine structure in the α decay is a common phenomenon where feeding to excited states is observed. Due to the particularities of the selection rules governing α decay and the very selective detection techniques available, fine-structure α decay studies can reach far out and yield unique information. A recent example of such a study where a triplet of 0^+ states has been discovered in ^{186}Pb [34] will be further discussed in the context of shape changes. E. Roeckl treats α decay in his lecture [31] and has also written a review article on this subject [35].

Successfully predicting other direct charged-particle radioactivity will very much depend on the reliability of calculating binding energies of particles and clusters in exotic nuclei. V. I. Goldanskii [36] reviewed in 1965 the theoretical efforts on possible one- or two-proton radioactivity. In 1982 the first case of

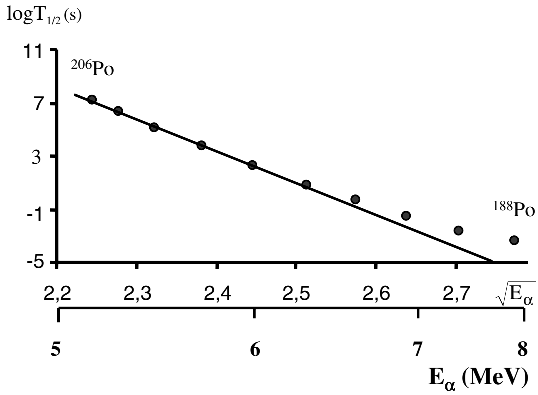

Fig. 6. Geiger-Nuttall plot of the even-even Po isotopes below N=126. A deviation from linearity is observed for the lighter Po isotopes [33].

proton radioactivity from the ground state was observed at the In-Flight separator SHIP [37]: 90 ms ^{151}Lu. Since then this subfield has been blossoming and a number of reviews can be found (see [38] and references therein). The strength of proton spectroscopy lies in the fact that an extremely clear and sensitive signal can be obtained by correlating in a position-sensitive detector the implantation of the radioactive ion from an In-Flight separator with the subsequent particle decay. By further correlating this recoil-decay event with γ and/or electron emission at the target or at the implantation point, one can even obtain information on the level structure above the proton-emitting state. A beautiful example of this technique is the observation of a rotational band on top of the proton emitter ^{141}Ho and can be seen in Fig. 7 [39].

A striking feature of direct proton decay lies in the fact that insight is gained on the world beyond the proton drip line. Indeed although the last proton (or two last protons) is (are) unbound, the tunnelling process through the Coulomb and centrifugal barrier combined with the properties of the involved states make the decay process long enough to be observed in in-flight separators where the whole separation process only takes microseconds. In 2002, almost forty years after the theoretical prediction of its existence, two-proton radioactivity was observed for the first time in the decay of the proton-rich ^{45}Fe [40,41] and see also Fig. 10 in the lecture of E. Roeckl [31]. The first step is now set but further experiments are needed to fully characterize and exploit this decay mode beyond the limits of nuclear existence.

Alpha decay is of course *the* example where a cluster of nucleons tunnels through the energy barrier, but all nuclides with $Z > 40$ are metastable with respect to emission of heavier clusters. However the available decay energy (Q-value) is in most cases not high enough. This, combined with the higher Coulomb barrier (due to the higher Z), means that eventual decay does not proceed at a detectable rate. Shell effects can strongly influence the available decay energy and it is not a surprise that the first example of the so-called

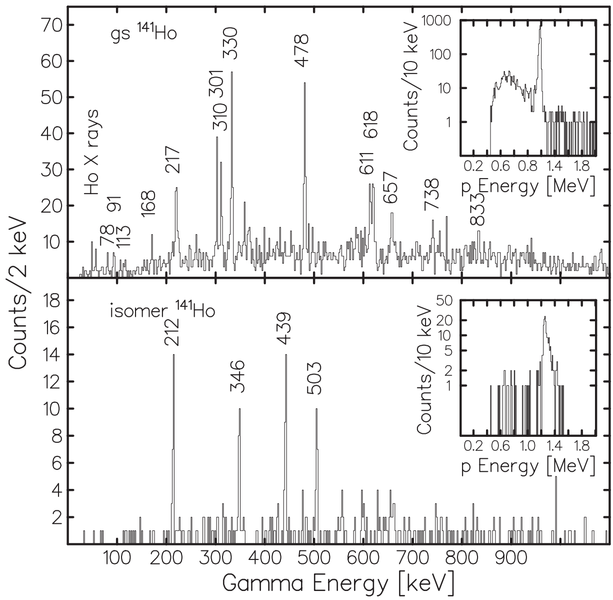

Fig. 7. Prompt γ-ray spectra tagged with protons emitted from the $7/2^-$ ground state (top) and the $1/2^+$ isomeric level (bottom) in ^{141}Ho [39]. In the inserts the respective proton spectra are shown.

heavy-ion radioactivity was reported in the neighbourhood of ^{208}Pb [42]. Some 20 cases of spontaneous emission of heavy-ion clusters ranging from ^{14}C to ^{32}Si have been observed in the trans-lead region. Attempts to detect this decay mode near doubly-magic ^{100}Sn have not been successful yet [43].

Groundstate properties: proof of existence. Presently some 3600 nuclei have been observed (see the NUBASE evaluation [2]) but many more nuclei are believed to exist. On the neutron-deficient side the border formed by the proton dripline is mapped up to the mass A=100 region. A small band of unknown neutron-deficient nuclei with masses heavier than A = 100 is believed to exist but the largest part of 'terra incognita' lies at the neutron-rich side (see Fig. 1). Many of these unknown exotic nuclei were already produced in our laboratories but they remained unidentified as they are submerged in the high background of more stable reaction products. The In-Flight technique with its high efficiency, short flight time and high A and Z selectivity is the method to give the proof of (non)existence of nuclei at the borderlines. In energy-loss versus time-of-flight correlation plots each incoming ion with a specific A and Z can be identified. The production of certain isotopes or in some cases even the mere existence of a particular nucleus is then directly evidenced. With this technique the borderline has been mapped in the neutron-rich O region (see Fig. 8). More examples on this technique can be found in the lecture of Morrissey and Sherill (see Figs. 2 and 3 in [12]).

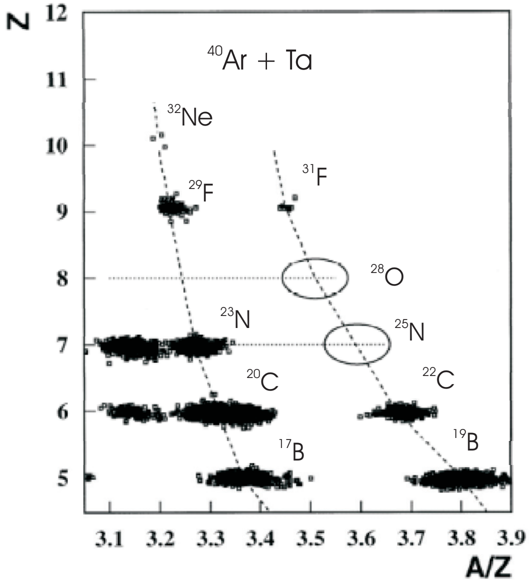

Fig. 8. Using the In-Flight technique each produced isotope gives a signal on a specific position in a Z versus A/Z plot. Given here are the results from the RIPS fragment separator at RIKEN, Japan [44]. From this plot it is clear that the ^{28}O and ^{25}N nuclei are particle unstable as they do not give any signal while they should be produced in the projectile fragmentation of the 94.1 AMeV ^{40}Ar beam. These results confirm the experiments at Ganil, France published two years earlier [45].

The existence of very heavy nuclei is determined by the nuclear stability against spontaneous fission. In the beginning of the 1980's it was realized that an island of superheavy elements (SHE) was present around Z = 114 and N = 184 stabilized by spherical shell configurations. This island was believed to be separated from the lighter, known elements by a swamp of instability due to fast spontaneous fission. Heavy-element research had so far been conducted by fusing heavier and heavier projectile- target systems and recording the α decay of the new isotope to known daughter nuclei. This step by step approach seemed deemed to end due to the big gap between the last known element (Z = 106) and the superheavy elements island around Z = 114. However, magic nucleon numbers do not only exist for spherical configurations but also for deformed shapes. Theoretical efforts [46] and experimental work at SHIP [13] did show that the swamp of spontaneous fission was more stable due to deformed shell stabilization and led to the discovery at GSI of six new elements (for a review see [48]). An example of such an identification is given in Fig. 9. The group of Yu.Ts. Oganessian in Dubna is also very active in the synthesis and identification of superheavy elements reaching up to element Z = 115 in the island of stability (see [49] and references in there).

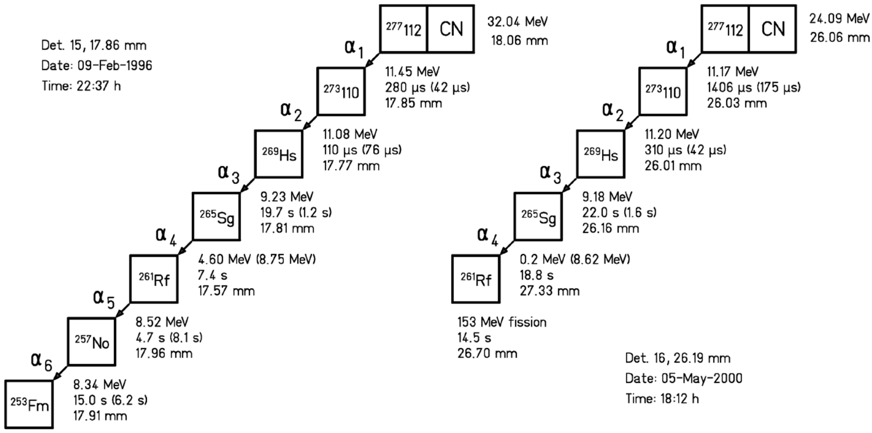

Fig. 9. The element 112 was identified in 1996 at SHIP in the reaction of ^{70}Zn particles with a ^{208}Pb target [47]. One decay chain involving the observation of the decay radiation of 5 daughter nuclei was observed. The date and time of the event together with the energy and time relative to the implantation are given. In the year 2000 this discovery was confirmed in a second experiment where one decay chain was observed.

Table 1. Correlation between the relative uncertainty on the measured mass and the physics questions addressed.

relative precision (δm/m=10^{-5})	relative precision (δm/m=10^{-6})	relative precision (δm/m=10^{-7})	relative precision (δm/m=10^{-8})
astrophysics major shells	sub-shells pairing	pairing halos	fundamental interactions level schemes

Groundstate properties: masses. The groundstate properties of an exotic nucleus such as half life, decay mode(s), decay energy and subsequently the mass are often the first experimental information obtained. The groundstate mass is of particular importance as all interactions and correlations contribute to it. By experimentally mapping the mass surface and improving the theoretical mass formulae it becomes evident that clustering and nucleon correlations do create more binding than previously anticipated and therefore more exotic nuclei are expected to be bound. While a decade ago most of the masses of radioactive nuclei were deduced from their decay characteristics (such as α- and β- decay energies) and closer to stability from reaction work (such as energy thresholds for transfer reactions), the manipulation of radioactive beams has advanced so much that superior mass measurements are now possible in traps, accelerators, dedicated spectrometers and storage rings (for a recent review see [50] and for the Atomic Mass evaluation [1,2]).

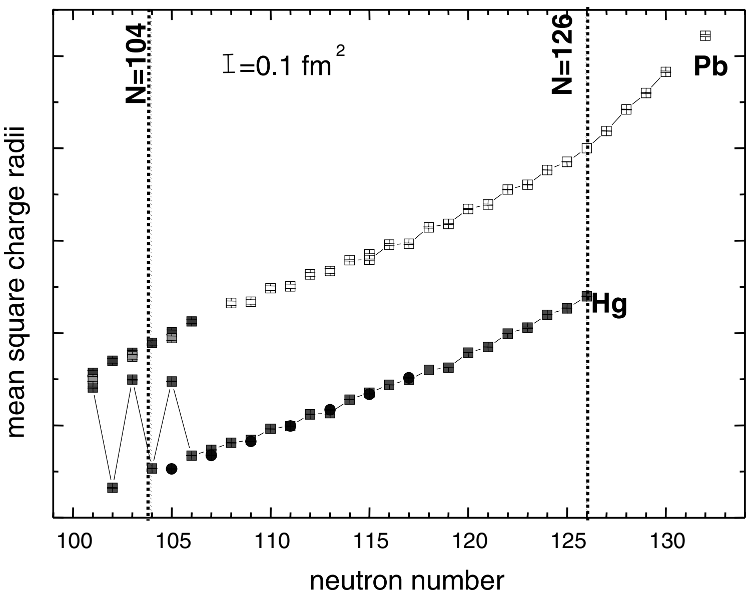

Fig. 10. The mean square charge radii in the Pb-Hg region measured with optical methods. Within an isotopic chain, the mean square radii are given relative to a reference value at N=126 (the difference between the Pb and Hg chain has been chosen arbitrarily). References to the different measurements can be found in [56]; the values for the neutron-deficient Pb isotopes from ^{188}Pb on are preliminary results from an experiment at Isolde using resonant laser ionization [57]. In the neutron-deficient Hg isotopes the mean square charge radii of the odd-mass nuclei are considerably larger than for the even neighbors.

In the review article of D. Lunney [50] the precision needed for investigating different physics questions is discussed. Table 1 summarizes this discussion. Two chapters in the present Lecture Notes are partially devoted to mass measurements: G. Bollen describes traps [51] while F. Bosch discusses the use of storage rings [52]. As an example of the state of the art, the recent mass measurements at ISOLTRAP on 98 ms ^{32}Ar and 173 ms ^{33}Ar achieve on such short-living nuclei relative uncertainties of 6.0x10^{-8} and 1.4x10^{-8}, respectively [53]. Another example is given in the subsection 'Groundstate properties: spins and moments' where the relative precision of 10^{-8} is needed to confirm the particular complicated decay pattern of ^{70}Cu [54]. Precise measurements are not only of nuclear structure interest but are also necessary ingredients for low energy tests of the Standard Model. The improved accuracy for the mass of ^{32} Ar for instance will allow for a re-evaluation of the β - ν correlation data obtained by Adelberger et al. [53,30], discussed above in the context of β-delayed proton emission (see also the lecture of N. Severijns to this book [32]).

Groundstate properties: radii. In textbooks on nuclear physics it is stated that the density in the atomic nucleus, as well as the diffuseness of the surface, are nearly constant and as a consequence the nuclear radius varies with mass number as $R_0A^{1/3}$ with R_0 ranging from 1.2 to 1.25 fm. Furthermore, the protons and neutrons are mixed homogeneously in the nucleus. One can then calculate the change in the mean square radius by adding one neutron to a nucleus, assuming a uniformly charged, spherical liquid drop. Around mass A = 100 this is typically of the order of 0.3 percent. This is small compared to the change in the mean square radius induced by a deformation of the spherical shape: a typical quadrupole deformation, $\beta_2 = 0.3$, causes an increase of $<r>^2$ of 3 percent. Such changes can be deduced accurately by measuring the isotope shift of a spectral line between two isotopes. Historically the first series of isotopes measured by optical means at an on-line mass separator, and still the textbook example, is the Hg chain [55]. This pioneering work reached deep into the region far from stability and lead to the observation of shape staggering and shape isomerism (see Fig. 10 and also below). Meanwhile an impressive number of isotopic chains have been measured using ingenious laser techniques and as a result with a wealth of information on the groundstate properties (for a recent review see [56]).

Nucleon density distributions can also be measured in scattering experiments. The advent of radioactive beams made it possible to measure interaction cross sections of radioactive ions and surprisingly large root mean square radii were observed in the first experiments in Berkeley carried out by Tanihata et al. [16] for ^{6}He and ^{11}Li. As J. Al-Khalili describes in his lecture [58] the large size of these particular nuclei was explained as due to the halo effect, which arises from the weak binding of the last valence nucleons. The particular situation of nuclear radii in the beginning of the nuclear chart is depicted in Fig. 11.

Groundstate properties: spins and moments. The groundstate spin and parity, together with the nuclear electromagnetic moments such as the magnetic dipole moment and the electric quadrupole moment, provide crucial information on the nucleus, as on the specific single-particle characteristics of the valence nucleon(s), as well as on the collective properties of the underlying core. A compilation in the Atomic and Nuclear Data Tables of experimental measurements of these observables dates from 1989 [60] but a new compilation is being prepared by N. J. Stone [61] (a preprint can be found on the website of the National Nuclear Data Center: http://www.nndc.bnl.gov/). The knowledge of spin and parity of a groundstate often comes from its decay characteristics provided the structure of the daughter nucleus is well known. But in many cases the selection rules for the specific decay mode(s) only limit the possible spin range and therefore other methods have to be developed to have a unique spin and parity determination. The magnetic dipole moment is directly related to the nuclear spin through the gyromagnetic ratio.

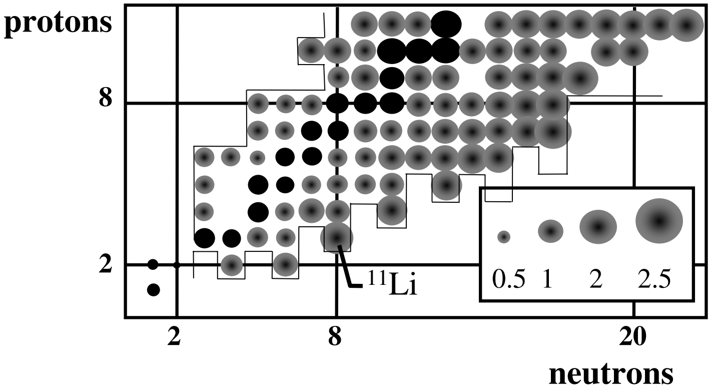

Fig. 11. The nuclear radii of the exotic nuclei (grey) symbolized by circles (in the inset the scale in fm is given) are larger than the ones near stability (stable nuclei are in black). The proton and neutron dripline is also given. This picture is based on [59].

Several ingenious techniques have been developed to measure nuclear electromagnetic moments and they have recently been reviewed by G. Neyens [62]. Many examples illustrating the physics that can be deduced can be found there. One highlight is given here as it has direct impact on the understanding of the phenomenon of haloes in nuclei. The magnetic dipole and electric quadrupole moments of ^{11}Li and ^{9}Li, and thus the proton distributions, are very similar which proves that the extended radius in ^{11}Li is due to the extra neutron pair [63].

With the advent of energetic radioactive ion beams, a number of reactions can also be used to obtain information on the spin and parity of the groundstate of the projectile and of the populated states. N. Alamanos and A. Gillibert discusses this further in their lecture [64].

An interesting spin-off of the optical techniques that have been developed to measure electromagnetic moments is the laser ion source. Laser light can be used to ionize efficiently and selectively the radioactive isotopes of a specific element produced in nuclear reactions. Several contributions on this matter can be found in the proceedings of the last EMIS conference (see [7]). The influence of the nuclear properties on the atomic optical transitions through the hyperfine interaction can be probed with the resonant laser ionization technique by scanning over the laser frequency. In the case of long-living isomerism it is then consequently also possible to enhance the ionization of one particular isomer, which then leads after mass separation to radioactive ion beams that are not only Z and A selected but also isomerically pure. Such isomerically pure beams were crucial in solving the decay puzzle in ^{70}Cu [54]: three long-living states are present, decaying by Internal Transitions and/or β decay. The obtained level scheme of ^{70}Cu was further confirmed by high-precision mass measurements in an ion trap. In Fig. 12 the intensity

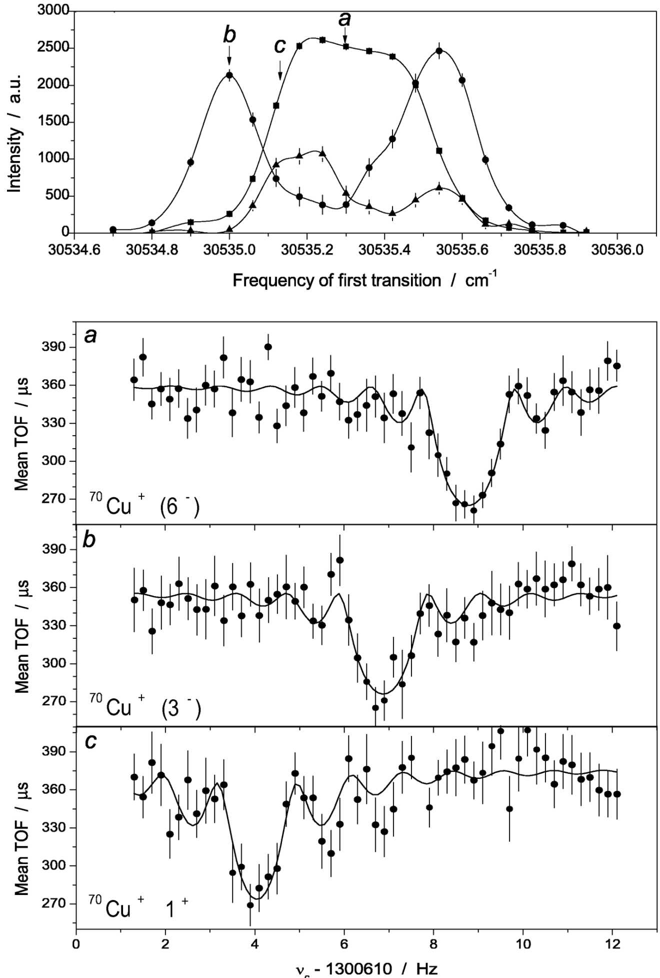

Fig. 12. Top: The intensity of different sets of γ lines observed in the decay of ^{70}Cu strongly varies as a function of the frequency of one of the lasers used for ionization. Bottom: Time-of-flight resonance curves as a function of cyclotron frequency for the laser settings marked with the arrows in the top figure [54]. The spectrum labelled as c was obtained after additional purification in the trap by removing the unwanted ^{70}Cu 6^- and 3^- ions.

of different γ lines is given in function of the laser frequency. By selecting a particular laser frequency an isomerically pure beam can be injected in ISOLTRAP and the mass difference of the three isomers can be measured. To illustrate the possibilities of the combined methods, one can compare the energy difference obtained for the first isomer obtained from the γ decay (101.3 (3) keV) and from the mass measurement (100.7 (2.6) keV).

Structural benchmarks: magicity. The atomic nucleus is a quantum system with a finite number of interacting particles of two kinds. The first ordering system is of course the number of protons and neutrons and consequently the neutron to proton ratio. At the light end of the chart of nuclides this ratio lies for the stable nuclei around unity but in the heavier mass region the line of stability lies more at a neutron to proton ratio around 1.44. This ratio can be understood by describing the nucleus as a liquid drop. But the nucleus can also be described with a central potential where neutrons and protons fill their respective well and specific numbers of protons and neutrons create extra stabilization. H. Grawe introduces this in his lecture on the shell model with special emphasis on a practioner's point of view and on the evolution of the shell structure towards exotic nuclei [65]. The so-called magic numbers effectively divide the chart of nuclei in different zones where certain shell orbits are active (see Fig. 1 where the proton (neutron) magic numbers are given as thick horizontal (vertical) lines). When the proton and the neutron magic lines cross, a so-called doubly-magic nucleus is the result. Only a limited number of stable doubly-magic nuclei are available: ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca and ^{208}Pb. These nuclei have been studied extensively as they form the anchor points for the nuclear shell model. Different experimental tools have been used to study the groundstate properties and the level structure built on top of these groundstates but also to study the neighboring nuclei as their properties will mainly originate from the valence particles or holes added to the doubly-magic core. Also, a number of radioactive doubly-magic nuclei have been identified over the years: ^{48}Ni, ^{56}Ni, ^{78}Ni, ^{100}Sn and ^{132}Sn. However few of them are known in great detail as their production, identification and study involves important technical challenges. Some of these nuclei lie very far from stability with extreme proton to neutron ratios, e.g. ^{48}Ni has a neutron to proton ratio of 0.71 while ^{78}Ni has a ratio of 1.79. The influence of these extreme ratios on the stability of the shells is being actively discussed (see also [65]). Ideally, the same experimental techniques as used for the stable doubly-magic nuclei should be applied and for a number of cases this becomes possible as the intensity and quality of the radioactive beams from doubly-magic nuclei is improving continuously. As an example, doubly-magic ^{132}Sn will be used in the near future as a beam to induce transfer or stripping reactions populating single-particle states in the neighbouring isotopes. At the Holifield Radioactive Ion Beam Facility in Oak Ridge such experiments near ^{132}Sn recently started up by using the ^{9}Be(^{134}Te,^{8}Be)^{135}Te reaction [66]. By gating on the two α particles from the break-up of ^{8}Be, a clean γ-ray spectrum is obtained from this neutron-transfer reaction (see Fig. 13).

Also, singly-magic nuclei and their neighbours with one valence particle or hole are extremely useful to test the validity of the shell-model. The availability of extended systematics within a series of isotopes or isotones on the behavior of particular orbits makes it possible to trace back the importance of specific terms in the nucleon-nucleon interaction (see Sect. 5.1 in [65]).

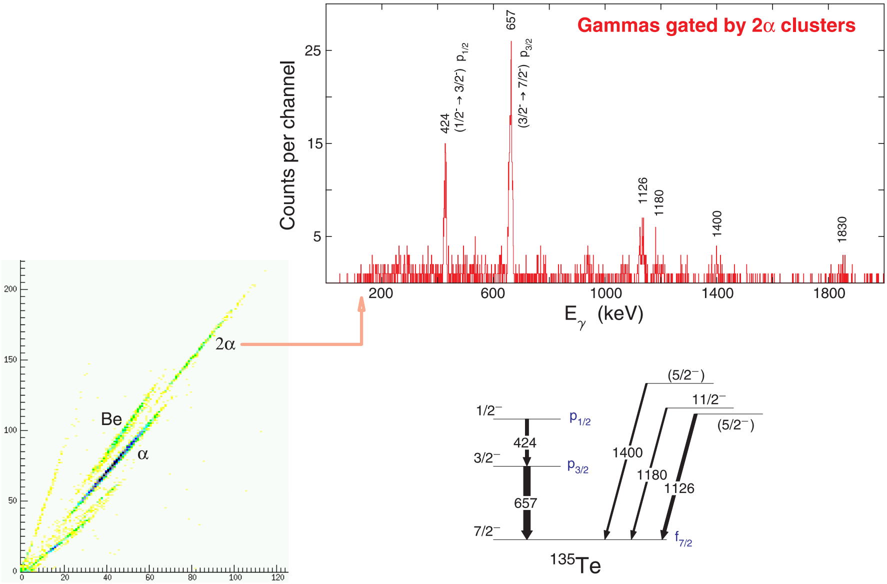

Fig. 13. Level scheme of ^{135}Te based on the gamma-ray spectrum obtained in the one-neutron transfer reaction using the radioactive ^{134}Te beam. The trigger for the γ-ray spectrum is given from the two alpha particles from the break-up of ^{8}Be as selected in the ΔE-E plot down in the left corner [66].

The magic numbers given in Fig. 1 originate from the spherical shell model, but a deformed shell model also generates specific nucleon numbers leading to extra stabilization for a deformed structure. It is such a stabilization which has drained the swamp of instability leading to the discovery of superheavy elements up to Z=115.

Structural benchmarks: symmetry. Away from the doubly-magic nuclei, the rigidity of the core weakens and the nucleus can exhibit collective excitations such as vibrations and rotations. Geometrical and dynamical symmetries can be used to structure the observed excitations in different schemes of which the harmonic vibrator and the rigid rotor are the simplest ones. Band-structures develop and can be studied with the help of powerful detector-arrays up to very high spin. Heavy-ion fusion reactions with all possible stable target - stable projectile combinations have been the workhorse for these studies for many years. The development of the ultra-selective recoil-decay-tagging technique has extended these studies to exotic nuclei where the production rates are very low. Figure 7 gives an example of such a study using direct proton emission as the decay signal. R. Julin in his lecture [69] discusses tagged gamma-ray and conversion-electron spectroscopy in the Z=82 and Z=102 region. In these studies the nucleus of interest is made in a reaction involving a stable target and a stable projectile but the selection of the very weak channel is done by the in-flight separation of the recoiling nucleus and its subsequent decay after implantation in the focal-plane detector. Using beams of radioactive nuclei to induce a nuclear reaction and observing the emitted γ-rays has become possible in recent years as well with radioactive beams produced with the ISOL method as well as with the In-Flight method. The n-transfer results from Oak Ridge are an example for ISOL-based facilities (see e.g. Fig. 13). However the intensity of the secondary beam is still orders of magnitude lower than intensities of stable beams and therefore only strong channels will be observed. Competition with the whole wealth of different bands and states populated in stable-beam reactions is not the purpose of radioactive beam experiments, instead radioactive beams are opening up previously unaccessible regions of the nuclear chart and allow the use of nuclear reactions that till now were only possible with stable beams. A good example is Coulomb Excitation (Coulex). Due to the Coulomb interaction between a projectile and a target, the nucleus can be electromagnetically excited. Coulomb excitation selectively populates collective shape degrees of freedom with cross-sections that are a direct and sensitive measure of the electric moments. This technique has been extensively used with stable nuclei but the advent of energetic radioactive ion beams now makes it also possible for the incoming projectile to be radioactive. The first experiments involving Coulomb exciting radioactive nuclei were performed at intermediate energies (10–100 Mev/amu) at projectile fragmentation facilities. Figure 14 shows a number of γ-ray spectra obtained at Michigan: out of the intensity of the 2^+ to groundstate transition the B(E2) can be obtained. In this particular experiment evidence was found for a new region of deformation in the neutron-rich S isotopes [67]. Recently low-energy Coulomb Excitation also became possible at the Radioactive Beam Facilities of Oak Ridge, GANIL and Rex-Isolde [68,70,71]. Figure 14 shows the γ-ray spectrum obtained at Ganil when Coulomb exciting a ^{76}Kr beam on a Pb target [68]. Important to notice here is that not only the production of the particular radioactive beam is of prime importance but that also the detection set-ups have to be especially designed to work in conjunction with a *radioactive* beam with *limited* intensity. An example of a γ-detector array reaching a high granularity through segmentation and a high efficiency is given in Fig. 15 [72]. From these first experiments on Coulomb Excitation with radioactive beams it becomes clear that although only a limited number of observables are touched (e.g. energy and B(E2) of the first 2^+ state in even-even nuclei) important nuclear structure information can be obtained. Not anymore limited by the availability of the nucleus of interest in nature (as stable isotope) systematic studies over a wide range of isotopes or isotones can now be started.

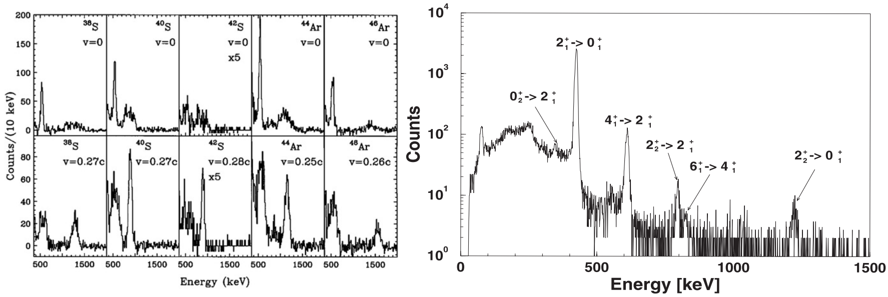

Fig. 14. Left panel: intermediate-energy Coulomb Excitation of the radioactive beams $^{38-42}$S and ^{44,46}Ar [67]. Upper panels contain background subtracted photon spectra in the laboratory frame. The 547 keV (7/2 to g.s.) transition in the gold target is visible as a peak, while the (2^+ to g.s.) transitions in each projectile are very broad. Lower panels contain Doppler-corrected, background-subtracted γ-ray spectra; as a result the (2^+ to g.s.) transitions become more visible as peaks. Right panel: γ rays from Coulomb Excitation of a 4.4 MeV/u ^{76}Kr radioactive ion beam on a Pb target. Peaks are all E2 transitions and are labelled by initial and final spin (the subscript indicates the place in the level scheme: 1 first level with the particular spin, 2 second level ...). The γ spectra were obtained with the EXOGAM γ array in coincidence with scattered Kr particles in a Si detector and are Doppler corrected [68].

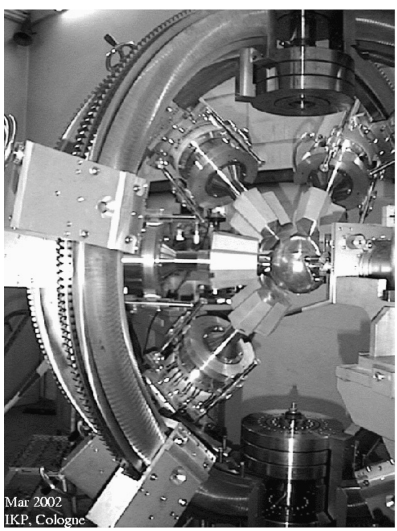

Fig. 15. The Miniball array is a γ-detector array developed for reaction studies with the post-accelerated beams from Rex-Isolde [73]. The array consists of 24 6-fold segmented, individually encapsulated, hyperpure Ge detectors arranged in 8 triple cryostats. In the arrangement shown here the photopeak efficiency (for the ^{60}Co lines) amounts to 10% [72].

Structural benchmarks: transition and evolution. Clear-cut demonstrations of specific aspects of the nuclear force active in nuclei are of prime importance to guide experimenters and theoreticians through the nuclear landscape. But the real challenge is to understand how the structure changes from one paradigm to another and, even more difficult, to predict the evolution. Inspecting Fig. 10 once more, a smooth evolution of the mean square charge radii is observed in the Pb and Hg isotopes when emptying the neutron shell. But, from ^{185}Hg on, an odd-even staggering is observed. The mean square radii of the ^{181,183,185}Hg groundstates are bigger than their even-even neighbours due to a difference in deformation. This dramatic change in shape can be related to the behaviour of specific orbitals. The Pb nuclei do not manifest any such effect in their groundstate, the stabilizing effect of the Z=82 shell closure seems to be so strong that even when the neutron shell is half-filled (N=104) the groundstates of the even-even and odd-mass nuclei remain spherical. But out of a combination of α-decay experiments and in-beam experiments it became clear that this apparent stability is rather fragile as the nucleus ^{186}Pb with its 104 neutrons changes its shape from spherical to oblate deformation or to prolate deformation, all within an energy window of 650 keV, below the excitation energy of the first excited 2^+ state [34]. The driving mechanism is believed to be the interaction of valence neutrons with proton particle-hole excitations through the Z=82 shell closure. In Fig. 16 the relevant information on the coexistence at low energy of three different shapes in ^{186}Pb is collected. The fine structure in the α decay of ^{190}Po provides crucial information as it is possible to compare the l=0 feeding to the three 0^+ states. The W_α values (see the discussion in the lecture of E. Roeckl [31]) in the figure are a measure for this, the higher they are the faster the decay. The slow decay towards the groundstate of ^{186}Pb is the reason why in Fig. 6 the α decay of ^{190}Po is not on the straight line in the Geiger-Nutall plot. An interesting experiment would be to measure the evolution of the mean square radii in a wide range of Po isotopes as around N=104 shape staggering should also be observed. This has so far not been done due to specific problems with the atomic structure of Polonium. Another fingerprint for shape coexistence would be to measure two-particle transfer reactions on even-even Pb and Hg nuclei. This technique was very successful in establishing shape coexistence in another series of single-magic nuclei, the Sn isotopes (see e.g. [75]) and their neighbors. The elements Sn and Cd are the champions in the chart of nuclides concerning stable isotopes (10 resp. 8) and thus a wide range of targets is available. The Pb and Hg isotopes have only a limited number of stable isotopes, all far away from N=104, such two-particle transfer reactions on the relevant nuclei will thus only be available with the development of intense radioactive Pb and Hg beams. This particular choice of shape coexistence in the Pb region is to illustrate the need for systematic studies over a wide range of isotopes and the need for combining different experimental probes.

In the article of R. F. Casten and B. M. Sherill [22], different techniques to recognize structural evolution are given and different classifications are

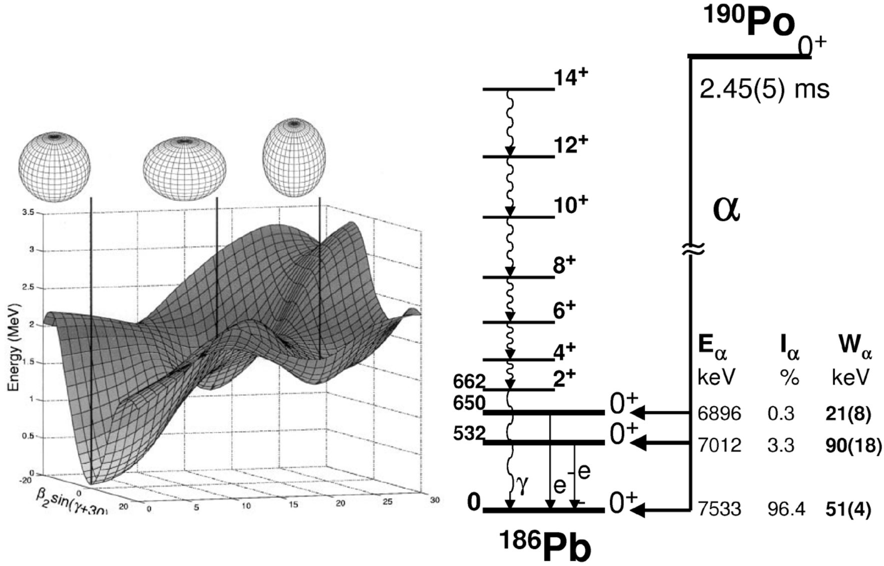

Fig. 16. Evidence for a low-lying spin 0^+ triplet in ^{186}Pb. The left panel shows a calculation of the potential energy surface with the indication of three minima of different shape (spherical - oblate - prolate) [34]. The right panel shows a selection of levels in ^{186}Pb based on in-beam data [74] and fine-structure in the α decay[34].

discussed. In order to see the evolution when approaching the drip lines sensitive methods have to be used as the production rates become extremely low. The success of measurements of the total interaction cross-section has already been discussed in the context of halo nuclei. Another strong signal is provided by one- and two-nucleon knockout reactions using intermediate-energy radioactive beams. P. G. Hansen and J. A. Tostevin discuss in a recent review article the current status and review what has been learned in the past few years [76].

3 Radioactive Beams for Other Fields

So far the importance of radioactive beams for the understanding of the atomic nucleus has been the main emphasis. However having strong beams of certain radioactive isotopes can also be extremely useful for other fields. In this section a short discussion on the use of radioactive beams for the study of fundamental interactions, for nuclear astrophysics, for solid-state physics, and nuclear medicine is presented.

3.1 Fundamental Interactions

Three basic interactions are active in the nucleus and therefore the nucleus has played and still plays a crucial role in determining the basic structure of fundamental interactions, providing the experimental foundations for a large part of the so-called Standard Model. In particular, nuclear beta decay has contributed significantly. N. Severijns in his lecture [32] explains the main aspects of the Standard Model relevant to nuclear β decay and then discusses the role of precision experiments. Within the 6000 nuclei in the chart of nuclei, a number of them do show very specific decay properties which makes it possible to single out specific observables of relevance to precision tests of the Standard Model. A number of examples of such studies have already been briefly discussed above. More information can be found in the lecture of N. Severijns [32].

3.2 Nuclear Astrophysics

Nuclear astrophysics plays a vital role in understanding the structure and composition of the Universe and its constituents. The energy of stars is generated through nuclear reactions between stable as well as radioactive nuclei. This process can be quiescent and last for billions of years. But sometimes it can be explosive involving a timescale of seconds. One of the burning cycles, the so-called CNO cycle has already been briefly presented as example on how intense radioactive beams can be used to measure directly some of the key reactions at the relevant stellar energies. New chemical elements are generated in the different burning stages. Some of the paths of the nucleosynthesis do run in the regions far from stability and it is quite obvious that the complex modelling of nucleosynthesis processes will rely on a number of specific characteristics of exotic nuclei. When available, experimental information is used but otherwise one must rely on extrapolating nuclear models. Radioactive beams can provide this experimental information or can severely test and advance the applicability of the current nuclear models. The lecture of K. Langanke, F-K Thielemann and M. Wiescher [17] is fully devoted to this subject.

3.3 Solid-State Physics

Radioactive ion beams can be used as a superior diagnostic tool to provide detailed information on the environment in which the ions are implanted. Different methods have been developed over the years and a number of them are briefly presented here in order to give a flavor of the nuclear physics parameters involved. The use of radiotracers for diffusion studies in different materials relies on measuring the amount of radiation as a function of specific parameters. A second way is through the hyperfine interaction between the atomic nucleus and its electron cloud. As discussed above, this interaction can yield nuclear physics information such as electromagnetic nuclear

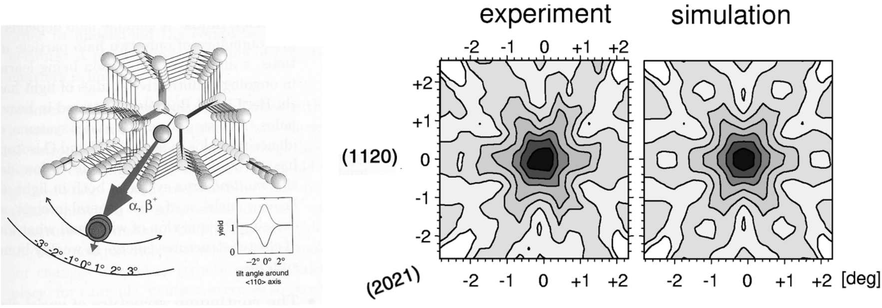

Fig. 17. Emission channeling: the principle (left panel) is based on the angle dependence of the intensity of the emitted radiation as a function of the orientation of the host crystal; the middle panel shows the normalized angle-dependent emission yields of conversion electrons above 88 keV from ^{149}Eu in GaN after vacuum annealing at 900^{o}C (two crystal axes are given); the right panel shows a fit of the simulated channeling patterns for substitutional Ga sites to the experimental yields [77].

moments but vice-versa when knowing the nuclear moments one can deduce information on the host material such as the Electric Field Gradient and the Hyperfine Field. An important facet of these studies, which sometimes provides unique information on the neighbourhood of the implanted ion, is that the required amount of probe material is extremely small and therefore has little influence on the host material properties. Another method uses the emitted radiation to measure the lattice position of the implanted ion in a crystalline host material. This technique is called emission-channeling and complements the well-known Rutherford Back Scattering technique, where an external beam such as a proton or α beam is scattered on a target. Figure 17 shows measured and simulated channeling patterns of ^{149}Eu ($T_{1/2}$ = 93 days) implanted in GaN sample [77]. An important part of the experimental program at Isolde, CERN is devoted to solid-state physics. More information on this program can be found in the special volume of the journal Hyperfine Interactions [78] devoted to Isolde physics. Most of the studies so far have been done with an implantation energy up to 60 keV (the first stage in the generic description of the ISOL technique given in Fig. 3) leading to an implantation depth of the probe ion in the tenths of μm region inside the sample. With the development of post-accelerated radioactive beams deeper implantation profiles are becoming possible.

3.4 Nuclear Medicine

From the early days of nuclear physics, it was realized that nuclear radiation could be used in medicine for diagnostics and therapy. Medical radioisotopes are serving this double purpose. As an example for the intertwining of fundamental research in nuclear physics and nuclear medicine a number of examples will be discussed below. The 70 s ^{14}O isotope of oxygen is a positron emitter which is frequently used in Positron Emission Tomography (PET) cameras visualizing oxygen-consuming processes in the human body. The CYCLONE-30 cyclotron specially constructed for the PET facility at Louvain-la-Neuve is also used as the primary accelerator for the Radioactive Ion Beam facility [18]. In order to reduce negative side-effects in the treatment of cancer using radionuclides, one is now trying to replace less site-specific radiotracers by more selective bio-conjugates. This requires the development of high-purity radionuclides and new isotopes. Fast and efficient physical and chemical separation technologies developed for radioactive ion beam research combined with intense production schemes will lead to spin-offs for the radiopharmaceutical industry. A third example of a medical application is based on the possibility to deliver a well-contoured ionizing dose to specific malicious tissues by making use of the sharp maximum in the energy deposition at the end of a particle's trajectory (Bragg peak). W. K. Weyrather discusses in her lecture the developments in the medical applications of accelerated ions in general, taking some specific examples from the ion therapy program at GSI, Darmstadt [79].

4 Outlook: The Next Generation

With the continuous development of new or better performing schemes for the production and utilization of radioactive ion beams, a considerable step forward has been taken in the last decade. Several facilities producing intense beams of exotic nuclei are now operational. Most of them are based on adaptations, extensions, combinations and/or upgrades of existing facilities. Worldwide serious efforts are devoted to prepare the new generation of radioactive ion beam facilities aiming for an improvement factor of 1000 in their general performance (intensity, selectivity, sensitivity) compared to the facilities presently running. An impressive number of reports from different laboratories and science organizations have been written on these efforts. Rather than referencing all these reports, the websites of the different projects will be given in the short overview of the next-generation projects. In the USA the RIA project [80] is based on a flexible driver accelerator capable of providing beams from protons to uranium at energies of at least 400 MeV per nucleon, with beam power in excess of 100 kW. It will combine the In-Flight with the ISOL technique through the gas cell approach (see Fig. 3). In Japan the RIKEN RI Beam Factory [81] is a major extension of the present facility with a new Superconducting Ring Cyclotron and Fragment Separator. In Europe two complementary projects are proposed. The GSI upgrade (at its heart is a double ring facility with five times the circumference of the current synchrotron SIS) is partially devoted to the research with radioactive ions and is based on the In-Flight technique [82]. The EURISOL project is based on the ISOL technique and has as a baseline option for the driver a 1 GeV, 5 mA proton linac [83].

When aiming for the next generation of radioactive beam facilities it becomes clear that the necessary efforts are so extensive that not only international collaboration within the nuclear physics community is vital but also that synergy with other areas of science and technology is crucial. From the design goals of the ISOL-based facilities, it is clear that a new generation of high-power proton accelerators should be developed. Such a machine also forms the heart of new schemes for the transmutation of nuclear waste and the production of energy (Accelerator Driven Systems), for neutron spallation sources, for intense material irradiation tools and for producing intense sources of muons and neutrinos. The technical requirements set by the In-Flight facilities can only be met with R&D on rapidly cycling, superconducting magnets and beam cooling of ions over a broad energy range, developments which are also crucial for other accelerator-based research programs.

With the exciting physics coming from all operational or nearly completed first generation radioactive beam facilities and with the challenging technological developments needed to design and build the next generation, the field of exotic nuclei is in a mature phase appealing to many different skills and efforts from you, the new generation of physicists.

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