Exotic Nuclei

Björn Jonson*,#

*Department of Physics, Chalmers University of Technology, Göteborg, Sweden
#e-mail: bjorn.jonson@chalmers.se

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Abstract—The paper is dedicated to a very interesting and rapidly developing field of nuclear physics—the generation and study of exotic nuclei in the vicinity of the driplines. The history of this field is presented with methods of obtaining such nuclei in the accelerators of the world’s leading research centers—the European Organization for Nuclear Research (CERN) in Switzerland and the Helmholtz Center for Heavy Ion Research (GSI) in Germany. The structure of the nuclei, as they change greatly approaching the driplines of neutron and proton stability, is given, as well as the results of experimental research of neutron- and proton-rich nuclei and the formation of neutron halos in isotopes of helium, lithium, beryllium, and boron, strongly enriched with neutrons. Information on medical applications of radionuclide beams is presented.

Keywords: radioactive beam, nuclear dripline, exotic nuclei, ISOLDE facility, heavy ion accelerator, fragment separator, beta-delayed proton emission, nuclear halo, neutron- and proton-rich nuclei, FAIR project, Borromean nucleus, CERN-MEDICIS project.

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In my presentation, here at the annual General meeting of the Russian Academy of Sciences, I have selected the title “Exotic Nuclei” for my talk. This title reflects, to a major extent, my scientific life over the past 50 years [1–5]. But, what is an exotic nucleus? As illustrated in Fig. 1 atomic nuclei may be organized in a nuclear chart, which is a grid of squares, where each square represents one individual nuclear species, consisting of a certain number of protons (Z) and neutrons (N). Nature around us is built up by the some 280 stable nuclides, marked in black colour, and grouped along a line ranging from the lightest to the heaviest elements. On both sides of this line we find nuclides that are radioactive, and only very few of these are present in nature around us. The major part of them is only known from laboratory experiments, where they are synthetically produced. The radioactive nuclides range from the stable ones out, on both sides of stability, to the so-called driplines, where no more nucleon can be added to form a radioactive nuclide. The nuclei in the vicinity of dripline are referred to as exotic—they have proton-to-neutron ratios deviating strongly from the stable ones and they are characterized by half-lives ranging from some minutes down below microseconds [1, 3, 5].

In the early days of nuclear science the understanding of the structure of nuclei was built up from experiments, where radioactive decays of nuclei were studied. Natural radioactivity, with only some decay chains among heavy elements available, was not enough. One therefore started to produce new radioactive isotopes in nuclear reactions by bombarding different materials with protons and heavier isotopes from accelerators. The different produced nuclides were then first purified by chemical methods and finally separated in an electromagnetic separator to obtain a pure sample of one single isotope. This method had one major problem—the time required to perform each single step before a measurement could start. With the highest possible speed for the different steps only isotopes with half-lives down to minutes became accessible. It was first in the year 1951, at the University of Copenhagen in Denmark (later called the Niels Bohr Institute) that the first steps towards more short-lived, exotic nuclei were taken. There, one of the physicists, Otto Kofoed-Hansen, worked with investigations of nuclear beta-decay with the aim to shed more light into the Pauli neutrino hypothesis. To increase the number of isotopes for his experiments Kofoed-Hansen then, together with Karl-Ove Nielsen, invented a new production method, which gave an important increase in the number of accessible isotopes. They irradiated uranium oxide with neutrons, produced by bombarding a Be target with deuterons from their accelerator, to produce fission products. In order to catch the more short-lived nuclides, the target was directly connected to the ion source of an isotope separator via a long tube. By keeping the ion source side cold a pressure gradient between target and ion source was created so that the gaseous fission products were swept directly into the ion source and subsequently separated. With
this techniques isotopes of noble gases with half-lives down to the second region could be studied. Soon, however, this experiment at Copenhagen ended. But the idea of Kofoed-Hansen was not forgotten! It had sown a seed in the minds of the European Nuclear Physics Community, a seed that grew up to become the ISOLDE experiment at the 600 MeV proton synchro-cyclotron at the CERN laboratory in Geneva. An international collaboration proposed a dedicated experiment, called ISOLDE, to produce and investigate short-lived nuclides. The ISOLDE experiments were approved and a new, underground hall was built for the new installation.

The proposal was approved and the first experiment at ISOLDE took place on October 16, 1967. This may be considered as the beginning of a new era in nuclear science, giving access to large numbers of earlier unexplored radioactive nuclei. The name ISOLDE, is an acronym for Isotope Separation On Line. At ISOLDE one rapidly got access to intense beams of isotopes with half-lives down to the millisecond region. It was in particular the 600 MeV primary proton beam from the CERN SC that resulted in tremendously increased production cross sections for exotic nuclei all over the nuclear chart.

In the beginning of 1970, when working on my thesis, I was offered to move with my young family to Geneva to work at ISOLDE at CERN for a period of about two years. It turned later out that this stay became much longer, and I returned to Sweden only in the middle of 1985 when I was offered a chair in physics at Chalmers University of Technology. Already from the beginning of my stay at CERN I started to work with P. Gregers Hansen and our first joint experiment was to study the, at that time, exotic process of beta-delayed proton emission. This process occurs in the beta decay of nuclei where excited daughter states above the proton separation energy may be populated. The experiments were immediately quite successful and several precursors for the beta-delayed proton decay mode could be observed in earlier unknown isotopes of the elements Ar, Xe, and Hg. The new data could be understood from model calculations in a statistical-model approach. At the same time period there were similar work going on at the Joint Institute of Nuclear Research in Dubna, where V.A. Karnau-

**Fig. 1.** Central in this figure is the chart of nuclides showing the different isotopes of the elements as known today. They are organized in a grid of squares, each of which represents a certain number of protons (vertically) and neutrons (horizontally). This chart, or nuclear landscape, is the working field for radioactive beam experiments, where the main emphasis is the most exotic nuclei. These nuclei provide important new insight into the complex nuclear many-body system. They give clues to the simplicity hidden in the complexity, they tell us about the elements that build up the nature around us, about their cosmic origin, and play a prominent role in our understanding of the formation of the chemical elements.
khov and his group made similar progress in studies of beta-delayed proton emission in Ba and Cs isotopes. In 1971, I was invited to the international conference on Heavy Ion Physics in Dubna (Fig. 2) to present our CERN data. There I also had opportunity to meet and discuss with Dr. Karnaukov. It was also during this conference I first met Prof. G. Flerov. I learnt to know him quite well over the years. The last time I met him was in 1985, when he was visiting Chalmers in Göteborg to present an invited talk. My wife and I had then also the honour to see him, together with some my Swedish colleagues, at a dinner party in our home, in Göteborg.

The ISOL technique had a lot of successes during the seventies and eighties. Not only the nuclear landscape was widened, but several new exciting experimental discoveries were done [2]. The ISOLDE experiment at the CERN SC soon grew into a major international facility and is today the leading on-line facility in the world. Important for the success of ISOLDE is, and has always been, the painstaking development work on new, ingenious target-ion-source systems, that allowed ISOLDE to conquer new territories of the nuclear chart. One such development, that in retrospect can be considered as the starting point in a new era in the field of exotic nuclei, was the development of a target system with a uranium carbide, UC, target matrix, which gave very interesting opportunities to produce and study isotopes from many different elements produced in spallation, fission and fragmentation reactions.

In particular, high yields of Li isotopes were found all the way out to the last particle stable one, $^{11}\text{Li}$. With its very high Q-value for beta decay, and the low separation energies for a variety of possible beta-delayed decay modes, it gave interesting prospects for new experiments as illustrated in Fig. 3. The presence of beta-delayed neutrons in the decay of $^{11}\text{Li}$ was already known. At ISOLDE the focus was therefore to search for the more exotic decay modes that were energetically possible, starting with beta-delayed two-neutron emission, beta-delayed three-neutron emission and finally beta-delayed triton emission.

Gregers Hansen and I were in then in year 1986 invited to write a review article, “Beta-delayed particle emission from light neutron-rich nuclei”, a review that was felt to be very timely, mainly due to the successes with new beta-delayed decay modes observed in light nuclei and, in particular, in $^{11}\text{Li}$. At the time of writing our review we had noted another interesting paper by I. Tanihata and his team from experiments performed at the LBL laboratory in Berkeley. By
deriving nuclear matter radii from measured interaction cross-sections from energetic radioactive beams of He and Li isotopes they had observed a stunning result for just $^{11}\text{Li}$. They observed that the smooth trend of the radii, with the expected $A^{1/3}$ slope for the lighter bound Li isotopes, suddenly was interrupted with a dramatic increase, of about 30%, for the $^{11}\text{Li}$ radius. Some discussions about a possible onset of deformation of $^{11}\text{Li}$ was put forward, but no firm theoretical understanding of the phenomenon was given. We looked into this problem and realized some interesting facts that turned out to become the key to the understanding of the large radius: $^{11}\text{Li}$ is the last bound Li isotope and its lighter neighbor $^{10}\text{Li}$ is unbound, further the separation energy for the last bound neutron pair in $^{11}\text{Li}$ is very low, $S_{2n} = 365$ keV, which means that the last neutron pair is barely bound to the $^{9}\text{Li}$ nucleus (see illustration in Fig. 3). With some calculations in a model where the last two neutrons were approximated as a “di-neutron” we could show that the observed radius could be explained, mainly be a consequence of the low two-neutron separation energy. The proposed structure of $^{11}\text{Li}$ was that it is built up from a $^{9}\text{Li}$ core nucleus surrounded by a dilute tail of neutron matter [4]. This novel structure, which we referred to as a nuclear halo, created a worldwide interest in investigations of halo structure both experimentally and theoretically. The discovery of the nuclear halos gave an unprecedented attraction towards the physics of, not only halo nuclei, but towards the entire region of exotic nuclei all the way out to and beyond the drip lines. I feel tempted to try to explain the feeling to discover something unexpected, which became sort of a new paradigm in our field of nuclear physics or, as I prefer to call it, subatomic physics. We had something new in our hands and it was up to us to take care of this in the benefit of science. Figure 4 is meant as an illustration of such a feeling.

The Tanihata experiment was not only of importance as the basis for the discovery of the halo structure as a novel phenomenon in nuclear physics. It was actually also the first experiment utilizing an energetic radioactive beam for nuclear reaction studies. It can be said to be the crown of a development at Berkeley, starting in the late seventies and early eighties, when it was demonstrated that beams of relativistic heavy ions were very efficient in producing exotic nuclei. The method starts with a beam of energetic heavy-ions, which is fragmented or undergoes fission in a thin target. The reaction products are subsequently transported to a secondary target after selection of mass, charge and momentum selection in a fragment separator, creating an energetic beam of a certain radioactive isotope. Today we see several dedicated radioactive beam facilities placed at external beams from heavy-ion accelerators worldwide.

A very timely coincidence in the period after the halo discovery was the start of the high-energy experimental programme at the GSI accelerator complex in Darmstadt in Germany. This allowed performing many of the first dedicated experiments to study light neutron-rich halo nuclei. It was realized that performing experiments with Radioactive Ion Beams (RIBs)
at relativistic energies poses a number of challenges as well as advantages; the kinematical focusing of the messengers from the reaction yields excellent solid angle coverage. Furthermore, the heavy remaining fragments will leave the reaction vertex at almost the same velocity as the incoming beam, permitting further tagging and characterization. My group from Göteborg started a very fruitful collaboration with scientists from GSI in 1992 and we were able to perform some early key experiments increasing the understanding of nuclear halos [1].

Today, a quarter of a century later, we can look back into a string of different experiments performed at GSI, over the entire region of the nuclear chart, where the uniqueness of the RIBs has been the key to the success. It is also these experiments that have given inspiration and guiding for the developments of new, modern equipment for the future FAIR physics [6].

The first experimental study of halo nuclei at GSI started in 1992. With a 340 MeV/u 11Li beam break-up reactions in C, Al, and Pb targets were studied. The transverse and longitudinal momentum distributions of the 9Li fragments were measured and the data revealed the expected narrow width of the momentum distributions, which is a signal of the large spatial extension of the halo wave function [4]. Here one...
should mention the great success of these experiments were that they were performed in inverse kinematics. Instead of irradiating a certain sample with a stable beam, one uses the radioactive isotope as the beam bombarding a stable target. This creates a situation in that center-of-mass where, for example, the isotope $^{11}\text{Li}$, with a half-life of 8.75 ms, can be analyzed as if it were a radioactive target—but without disappearing immediately!

The nucleus $^{11}\text{Li}$ is the last particle-bound Li isotope. Its lighter neighbour $^{10}\text{Li}$ is, however, unbound towards neutron emission. Even if $^{10}\text{Li}$ is unbound it is still of scientific relevance since it can be shown to possess clear and distinct quantum properties. The most precise data, from neutron knock-out from $^{11}\text{Li}$, have revealed a virtual $s$-state as ground state, with a scattering length of $a_s = -22.4$ fm, and with an excited $p$-wave resonance at 0.566 MeV with a level width of $\Gamma = 0.548$ MeV.

The very exotic nuclear systems $^{12}\text{Li}$ and $^{13}\text{Li}$ could be shown to belong to the family of unbound nuclei in an experiment using a 304 MeV/u $^{14}\text{Be}$ beam, which was directed towards a liquid hydrogen target for studies of the $^{1}_1\text{H}(^{14}\text{Be},2\text{pn})^{12}\text{Li}$ and $^{1}_1\text{H}(^{14}\text{Be},2\text{p})^{13}\text{Li}$ reactions. This type of experiments turns out to be an efficient method to cross the nuclear dripline and to study unbound nuclear systems beyond it [3]. The main principles are depicted in Fig. 5, with a summary of the cases observed so far.

A bound three-body nuclear system, where none of the binary subsystems are bound, is referred to as Borromean\textsuperscript{1} nucleus [4]. An example is the nucleus $^{6}\text{He}$, which has a very simple three-body structure of type $\alpha + n + n$. This nucleus has been studied in a number of different experiments. In one of these experiments, the breakup of a 240 MeV/u $^{6}\text{He}$ beam in carbon and lead targets was studied and the inelastic nuclear and electromagnetic excitation spectra were obtained. The deduced $E1$ strength was found to exhaust both the energy-weighted cluster sum rule and the non-energy weighted one, when integrating the strength up to 10 MeV excitation. From the data the root-mean distance between the $\alpha$-core and the two valence neutrons could be derived to be $r_{\alpha,2n} = 3.2$ fm. At Dubna Radioactive Ions Beams (DRIBs-1) complex, which includes the RIB fragment separator ACCULINNA, the $^{4}\text{He}+^{4}\text{He}$ elastic scattering was studied, at a laboratory energy of 151 MeV for the $^{6}\text{He}$ beam. An open question was whether the two halo neutrons were close in space as a “di-neutron” or rather on each side of the core in a “cigar-like” configuration. The scattering data were compared to theoretical calculations for these to extreme configurations. As seen in Fig. 6 the data favor the di-neutron configuration.

Already in 1960 V.I. Goldansky predicted the existence of proton- and two-proton radioactivity in neutron-deficient isotopes of light nuclei. The existence

\textsuperscript{1} In mathematics Borromean rings consist rings of three topological circles linked together so that no two of the three rings are linked with each other but all three are linked as illustrated in Figure 3. The name “Borromean” comes from their use in the coat of arms of the aristocratic Borromeo family living on Isola Bella in Lago Maggiore in Northern Italy.
The very rapid progress in the understanding of the most exotic nuclear species has to a very large extent been due to a steady development of new, ingenious production methods. Also advanced detector systems have been of key importance. This has given ideas to new, improved experimental setups worldwide. One dare to say that there has never before, in the history of nuclear science been such a rapid development of new and upgraded research facilities as we witness today [5, 7]. Let me here give just three examples to illustrate this.

I. In Darmstadt in Germany at the GSI Helmholtzzentrum für Schwerionenforschung a major upgrade of the existing GSI to a new facility called FAIR (Facility for Anti-proton and Ions Research) is presently in a rapid initial construction phase. One important future programme will be devoted to studies of beams of exotic nuclei. Within a large experimental collaboration, called NUSTAR, one of the main experiments will be the R3B (Reactions with Relativistic Radioactive Beams) setup, which is based on the so successful ALADIN-LAND setup at the fragment separator FRS. The R3B will be installed at the end of a beam-line from the Super FRS. With its extreme broad spatial coverage for detection of the secondary reaction products, it will become something like a facility within the FAIR facility. An outline of the main parts of the future R3B setup and the entire FAIR Facility are shown in Fig. 8.

II. At JINR in Dubna a recent upgrade of the existing fragment separator ACCULINNA has been performed [8]. The new in-flight fragment separator, called ACCULINNA-2 is coupled to the U-400M cyclotron and offers high intensity Radioactive Ion Beams (RIB) for elements ranging from hydrogen (Z = 1) to krypton (Z = 36) in the lowest energy range (10–50 MeV/u) attainable for in-flight separators. Further, this new separator will be the base for the first stage of a new powerful RIB project called DERICA (Dubna Electron Radioactive Ion Collider facility). DERICA will combine in-flight production of RIBs...
Fig. 8. The schematic drawing of the R3B setup, which is under construction as a joint effort from different laboratories in Europe at the future FAIR Facility in Darmstadt. The upper inset shows the entire FAIR accelerator complex.

by projectile fragmentation technique (primary beams up to uranium, energies ~100 MeV/nucleon for A/Z = 3), stopping of radioactive ions in a gas catcher, followed by a re-acceleration in a LINAC-synchrotron combination. This will allow using the re-accelerated RIBs for reaction studies in storage ring experiments. DERICA will cover a broad range of modern nuclear physics experiments such as production of new isotopes, measurements of their masses, lifetimes and decay modes, including nuclear reactions and nuclear spectroscopy. The main emphasis will, however, be storage ring physics with ultimate aim of electron-RIB scattering studies in the collider experiments. This future new facility is expected to be built in the JINR territory next to existing FLNR buildings, as illustrated in Fig. 9. One has here to clearly state that this project, in its full scale, would definitely be world-unique with its combination of in-flight production and separation of exotic nuclear beams with gas cell techniques followed by a LINAC+synchrotron combination for post-acceleration into storage rings with the future possibility for RIB-electron scattering.

III. At CERN the ISOLDE Radioactive Beam Facility had a major boost in the scientific programme when post-acceleration of the broad range of produced radioactive isotopes became possible. The REX-ISOLDE post-accelerator giving the first beams for experiments in 2001, was originally only planned for accelerating light isotopes up to mass around A = 50. It turned, however, out that its capability went far beyond this goal and has over the years provided post-accelerated beams covering the entire mass range from 3He up to 224Ra for nuclear reaction studies. The experiments have mainly profited from the opportunities offered by Coulomb excitation studies in inverse kinematics. REX-ISOLDE has, in its 15 years of operation, delivered accelerated beams of more than 100 different isotopes from more than 30 chemical elements.

As time passed it became obvious that a more global upgrade, including increased energy, intensity and beam quality would open another era of scientific possibilities. A project, with the working name HIE-ISOLDE, was launched as a major staged upgrade of the existing ISOLDE facility. It includes an energy increase of the REX post-accelerator first up to 5.5 MeV/u, followed by a further increase up to 10 MeV/u, as well as an upgrade of the REX resonators. The beam quality was improved by installing a new RFQ cooler. The beam intensity will be increased by two independent parts of the injectors. First the production will linearly increase with the enhanced proton intensity delivered by the new Linac-4 and second the fragmentation and spallation cross sections are enhanced by the increase
Fig. 9. The ACCULINNA and ACCULINNA-2 experimental halls. The lower part of the figure shows the new proposed extension of the experimental park with the DERIKA project in its first phase, as described in the text.

Fig. 10. The ISOLDE Radioactive Beams Facility with the recent extensions. The HIE ISOLDE post-accelerator, where the addition of cryogenic-modules (photo in the upper right) enables radioactive beams up to 10 MeV/u. The Class A laboratory for safe handling of radioactive targets and the MEDICIS building are to the upper left.
in energy of the PS Booster to 2 GeV. The HIE-ISOLDE project was approved on September 2, 2009.

The first step of the energy upgrade was tested successfully already 2015 and the first scheduled physics experiment was then performed in October–November 2015 by accelerating beams of exotic Zn ions to an energy of 4 MeV/u. Recently two additional cryogenic-modules were installed which, together with the already installed two, gave an energy of 10 MeV/u. A schematic layout of the ISOLDE Radioactive Beam Facility is shown in Fig. 10.

The use of radioisotopes for medical applications, both for diagnostics and for therapy, has a long tradition at ISOLDE. The possibility to use the know-how on radioactive-beam production and handling at ISOLDE for medical applications in a more continuous and organized way has also been considered over the years. In 2012 a project under the working name CERN-MEDICIS (MEDical Isotopes Collected from ISOLDE) was launched with the aim to produce innovative radioactive isotopes for medical research at ISOLDE. To give some numbers the ISOLDE experiments use about half of the protons from the PS BOOSTER. The proton beam loses only about 10% of its intensity and energy when hitting a standard ISOLDE target. Thus the protons passing through the target can still be used. For CERN–MEDICIS, a second target is placed behind the HRS target to produce dedicated radioisotopes. An automated conveyor, designed for this purpose, carries this irradiated target to isotope the MEDICIS building. There it is attached to the front-end of an isotope separator. After heating the isotopes of interest are separated and collected. In this way the longstanding experience and knowledge of isotope production and separation acquired at ISOLDE over the years will be applied for the production of radioisotopes to be used in innovative medical applications. In September 2013 a ground-breaking ceremony marked the beginning of the construction of the CERN–MEDICIS building that is placed in an extension of the Class A laboratory. The construction work has been completed in 2016, and the first irradiations of the second target took place in 2017.

I have in this contribution discussed the science where we try to understand the salient features of nature on a sub-microscopic length scale. What we learn about nature on the nuclear level is based on experiments where signals sent to us by a multitude of sophisticated detector systems allow us to combine their messages by theoretical calculations to draw conclusions about the basic building blocks of nature around us. And the many steps towards exotic nuclei, where recent years have revealed many new secrets of nature. We may add what they are telling us to with earlier knowledge to take major step towards an increased, but maybe never full, understanding of the world we live in.

To the end I would like to quote my countryman Esaias Tegnér, who was poet and cultural personality, professor in Greece language at the University of Lund, bishop in the town of Växjö and member of the Royal Swedish Academy. At a Master’s Degree Celebration at the University of Lund in 1820 he wrote a beautiful long epilogue, where these five lines can be said to be representative for our field of science:

*This is Man’s wonderful ability: to be able to grasp the inner essence of phenomena, not what they appear to be, but what they mean, and the reality that we see with our eyes is a symbol only of something higher.*

Göteborg, October 9, 2018

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