

NUSTAR - presence and prospects of nuclear structure research at GSI and FAIR

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Abstract. New experimental methods at rare-isotope facilities including in-flight separation, storage rings, and traps, setups for reaction studies with beams of exotic nuclei in reversed kinematics and large gamma arrays give new insights into the structure of atomic nuclei at the limits of stability. The discoveries of new isotopes and elements, as well as new phenomena including one and two proton decay, nuclear halos and skins as well as coexistence of nuclear shapes will be discussed. Workhorses are the UNILAC and SIS accelerators in combination with the in-flight separators SHIP and FRS. Physics at the ESR storage ring at GSI addresses the interaction of atomic and nuclear physics and large-scale explorations of the landscape of nuclear masses. A brief outlook on the future, NUSTAR at FAIR will be given.

1. Introduction

The principal goal of nuclear structure research at rare-isotope facilities is the investigation of atomic nuclei at the limits of existence of elementary matter: along the proton- and neutron driplines where protons and neutrons become unbound and in the region of heavy elements, the limit in mass and charge. Research topics are: nuclear shells and shapes far-off stability, pairing and the proton-neutron interaction, exotic decay modes such as proton emission and new forms of nuclear matter including nuclear skins and halos. Of special interest is the evolution of nuclear structure along the paths of cosmic nucleosynthesis [1,2,3].

New experimental methods at exotic nuclear beam facilities including storage rings and traps offer unique possibilities for the exploration of the nuclear landscape to search for new phenomena. Modern in-flight facilities like FAIR at GSI combine heavy-ion accelerators for intense ion beams with in-flight separators of high transportation efficiency and selectivity. The heavy-ion accelerators deliver beams of all chemical elements up to uranium - including isotopes occurring with low abundance in nature - with energies from the Coulomb barrier to more than 1 GeV/u. In-flight separators deliver isotopic energetic beams of nuclides far-off stability with lifetimes down to microseconds. Efficient detector systems with 4π geometry for particle and γ -detection allow spectroscopy with the highest sensitivity and the capability of single-particle detection and investigation. The high energy of the in-flight separated beams allows reaction studies with unstable short-lived nuclei in reversed kinematics.

A special feature of NUSTAR is the combination of the FRagment Separator FRS and the Experimental Storage Ring ESR opening-up new experimental possibilities such as large-scale direct

mass and live-time measurements of nuclei with half-lives down to microseconds and experiments which involve both, nuclear and atomic physics. The stored atomic nuclei are bare or carry only few electrons, thus allowing nuclear decay studies of highly ionized ions under variable ionization degrees, a scenario of hot stellar media.

After a brief excursion to the upper end of the nuclei chart, the heavy and superheavy elements, we will discuss physics with relativistic beams of unstable rare nuclei, experimental techniques including recent developments, physics results, and prospects on the example of NUSTAR at GSI and FAIR.

2. Heavy and superheavy elements – the upper limit for the existence of elementary matter

With the discovery of nuclear fission by Hahn and Straßmann and its physical interpretation by Meitner and Frisch it became clear that nuclear fission will terminate the number of chemical elements. They predicted the limit for the existence of chemical elements to around $Z = 100$, later refined models predicted this limit for $Z = 104$ to $Z = 106$. With the discovery of the nuclear shells and their relevance to nuclear stability, the question arose as to whether “super heavy” nuclei, can exist at the next doubly magic shell closure after ^{208}Pb beyond the droplet limit estimated by Meitner and Frisch only due to shell stabilization [4]. Most of the early predictions place the island around $Z = 114$ and $N = 184$. Modern calculations with selfconsistent models place the magic proton number at $Z = 120$ or even $Z = 126$. At the same time the progress in accelerator development allowed the acceleration of heavy projectiles. Taking advantage of this new development Y. Oganessian proposed the use of the doubly magic ^{208}Pb as a target and irradiated it with appropriate projectile beams such as the most neutron-rich isotopes of titanium or chromium to create cold compound systems in order to enhance the survival probability of these highly fissile elements at the top of the chart of nuclides. There were however two obstacles: Super heavy nuclei were predicted as an *island* in the “sea of instability”, beginning somewhere beyond rutherfordium, $Z = 104$, and the *extra push* which forbids the fusion of massive systems at the Coulomb barrier. Both problems were solved in SHIP experiments [5]. With the synthesis of rutherfordium in an irradiation of ^{208}Pb with ^{50}Ti cold heavy ion fusion was proven, with the discovery of hassium, $Z = 108$, a new shell region of deformed nuclei was found. It is centred at $Z = 108$ and $N = 162$ and forms the bridge from the transuranium nuclei to the predicted SHE region. The old and the new situation are schematically depicted in Fig. 1.

At present two ways to produce elements beyond seaborgium ($Z = 106$) are known, Fig. 3. The cold heavy ion fusion with ^{208}Pb and ^{209}Bi targets which was successful in the discoveries of elements 107 to 112 at SHIP (Fig. 2) and element 113 at RIKEN, Japan, and the hot fusion with ^{48}Ca beams and appropriate actinide targets bred in the reactor, which was successful in producing the new elements 114 to 118 at JINR Dubna. Both methods were proposed and pioneered by Y. Oganessian. The theoretical basis for the production of heavy elements in cold fusion was laid by Sandulescu et al. [6].

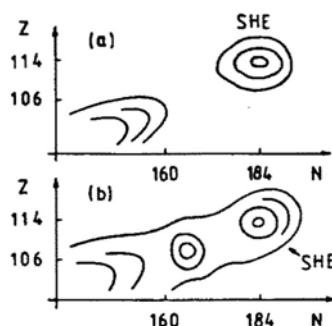


Fig. 1. The shell region around hassium, a bridge to SHE. Upper panel: situation before and lower panel after the discovery of the shell region around ^{270}Hs . Courtesy A. Sobiczewski.

The key to the discoveries of the heaviest elements beyond $Z = 106$ (seaborgium) is the combination of a powerful heavy-ion accelerator delivering intense projectile beams with separation of reaction products in-flight and single-atom detection and identification. These methods were pioneered at GSI with the UNILAC heavy ion accelerator and the velocity filter SHIP [5]. SHIP, a two stage velocity filter with large acceptance (Fig. 2), separates the heavy fusion products by their kinematic properties from the projectile beam and background from other reactions. The energetic fusion products are implanted into a position sensitive silicon surface barrier detector where their decay history is observed in situ. The heavy and superheavy elements were identified by their long α -decay chains leading to known nuclides on the basis of individual nuclei.

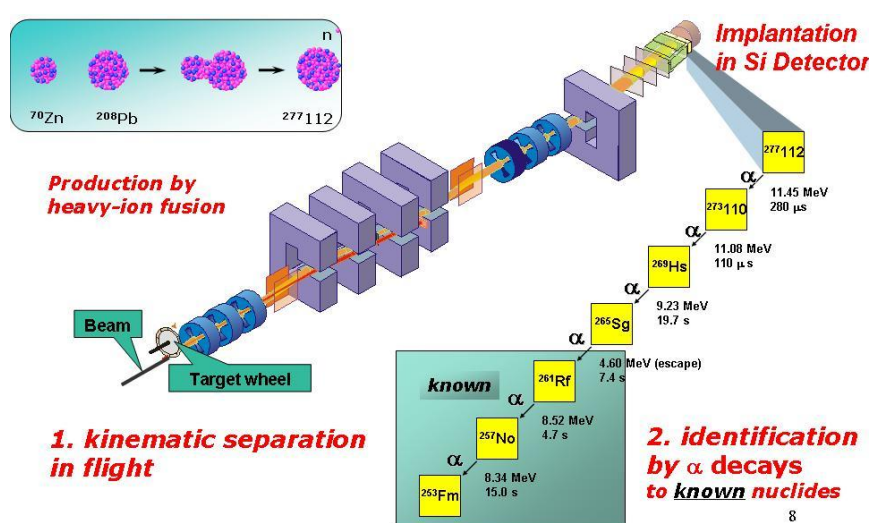


Fig. 2. The velocity filter SHIP. Insets: upper left: the fusion reaction, lower right: the α -decay chain of a single atom of copernicium running down to known nuclides indicated by the box.

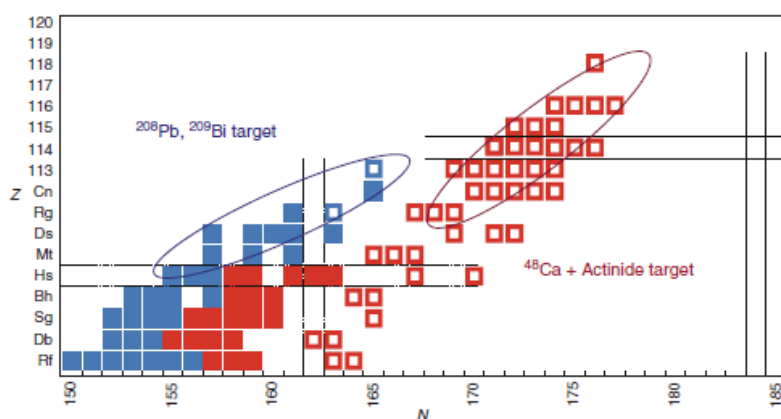


Fig. 3. Production of superheavy elements by cold (blue color) and hot (red color) fusion. The subshell at $Z = 108$ and $N = 162$ and the spherical shell closure at $Z = 114$ and $N = 184$ are indicated.

What did we learn? The idea of superheavy nuclei has been confirmed: nuclei can exist only by shell stabilization in “the sea of instability” beyond the liquid drop limit. The heaviest element reported up to now is element 118 [7], searches for element 120 are under way at SHIP and TASCA, GSI. Though the magic number 114 has already been passed, there is no indication for spherical superheavy nuclei. The explored region is too far away from the magic neutron number 182 (Fig. 3). Future work will concentrate on SHE chemistry to place the chemical elements in the periodic table, structure research, and, most important, the search for the spherical superheavy nuclei. Intensity upgrades of accelerators and new separators with the capability of mass identification are under way, e.g. the design study in the GSI-Giessen-Manipal collaboration.

3. The GSI accelerators with SHIP, FRS, and ESR

As a typical example of a first-generation rare isotope facility, the UNILAC-SHIP and SIS-FRS-ESR setup at GSI Darmstadt, is displayed in Fig. 4. Heavy-ion beams of all chemical elements from hydrogen to uranium are accelerated by the UNILAC to energies near and above Coulomb barrier for the production of exotic nuclei and heavy elements by complete fusion reactions. SHIP is located in the straight beam line. In parallel operation beam bunches are alternately injected into the Heavy-Ion Synchrotron SIS where they are accelerated to energies of typically 1 GeV/u. They are impinged onto the production target of the FRS for the production of radioactive nuclei at relativistic energies by projectile-fragmentation or -fission. The nuclides of interest are separated, event wise identified in flight, either implanted into a detector system for nuclear spectroscopy, or injected into the Experimental Storage Ring ESR where they are stored and cooled, or directed to the setup for reaction studies in complete kinematics (Fig. 4). Challenges are:

- Single-atom in-flight identification in mass A and nuclear charge Z
- Reactions with short-lived species in complete kinematics
- Physics with stored and electron-cooled beams and atomic nuclei.

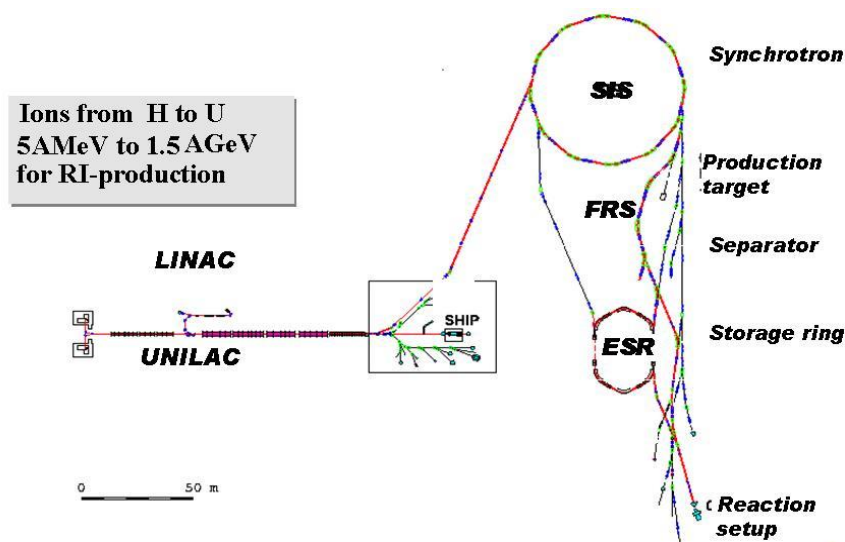


Fig. 4. The GSI accelerators UNLIAC and SIS with the in-flight separators SHIP and FRS, and ESR

The separation scheme of GSI projectile fragment separator FRS is explained in Fig.5. The relativistic heavy ion beam from SIS hits the production target where it is transmuted by fragmentation to a beam of radioactive isotopes preserving the kinematic properties of the beam. In the first part of the separator we have a kinematic separation according to the magnetic rigidity. As all fragments have approximately the same velocity as the projectiles and are fully stripped at the high energy they are separated in A/Z . A is the mass number and Z the element number. The inset in Fig. 5 shows the

example of ^{78}Ni produced by an ^{86}Kr beam. All fragments with $A/Z = 78/28$ are separated. The second separation uses the energy loss $\Delta E \sim Z^2$ in matter (degrader in Fig. 5) which is analyzed in the second separator stage. As a result the isotopic clean energetic beam of ^{78}Ni is obtained at the exit of FRS. It can be implanted in detector systems, directed to the ESR or to a reaction setup for reaction studies with radioactive nuclei. It should be noted here that the number of separated isotopes can be adjusted by the degrader thickness. Thin degraders are used to produce cocktail beams.

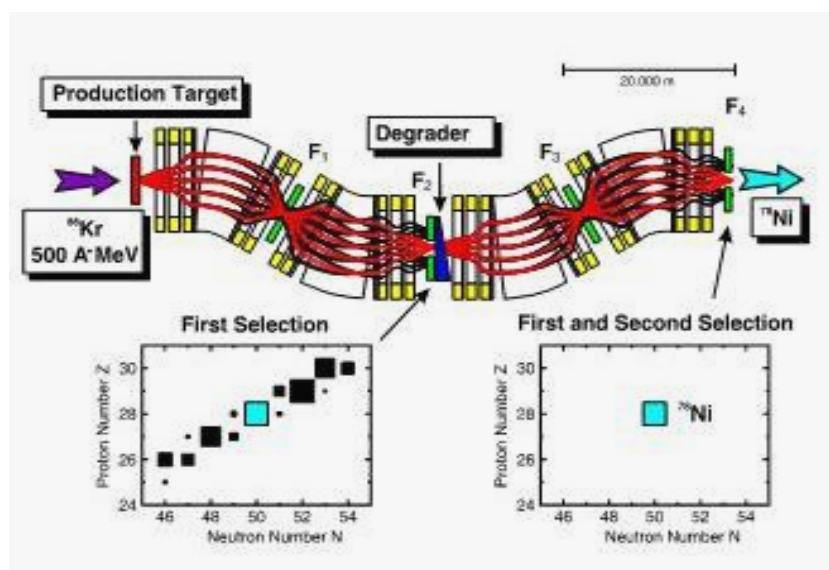


Fig. 5. Isotope separation with FRS

4. Research with nuclear beams at the limits of stability – some highlights from FRS and SHIP

At present 118 chemical elements are known, 80 of them are stable. All elements above the doubly magic lead, $Z = 82$, are unstable. The 254 stable isotopes form only a small band in the chart of nuclei within the more than 3000 unstable isotopes known at present. The region within which atomic nuclei can exist is limited by the proton- and neutron driplines, beyond they are proton and neutron unbound, the upper end is terminated by prompt fission.

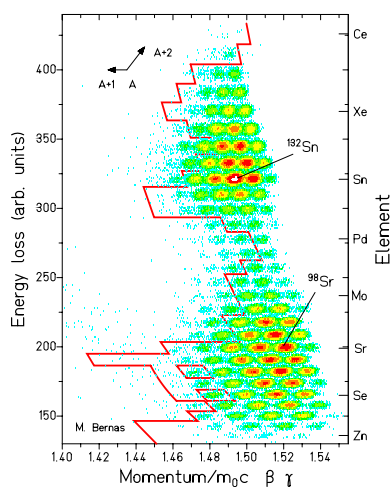


Fig. 6. Projectile fission (including abrasion-fission) of ^{238}U

Fig. 6 displays an example of isotope production, separation, and identification with FRS by projectile fission in-flight of ^{238}U . The heavy and the light fission group are collected in one spectrum. With the FRS such spectrum could be achieved for the first time [9]. Each dot in the spectrum represents an atomic nucleus, each cluster an isotope. Right of the red line we find isotopes discovered in this experiment. Some highlights and discoveries obtained with the in-flight separators at GSI are illustrated in Fig. 7.

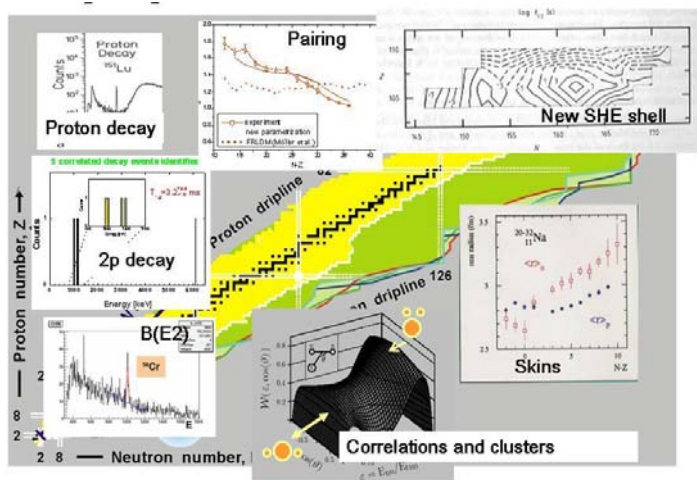


Fig. 7. Highlights and discoveries with SHIP and FRS

4.1 Nuclear masses

Mass measurements led to the discovery and understanding of basic properties of nuclear matter. The present generation of experiments employ time-of flight spectrometers, traps, and storage rings for

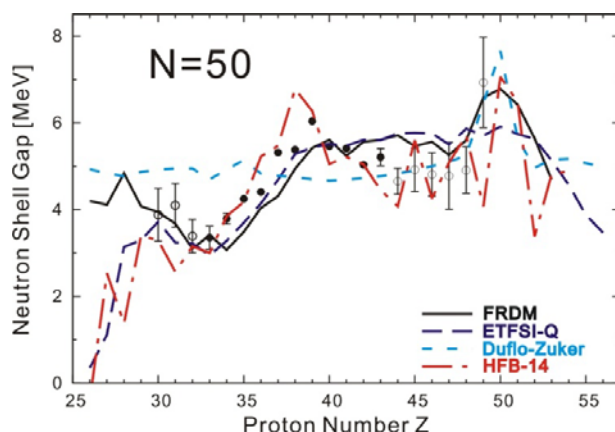


Fig. 8. The neutron shell gap for $N = 50$ isotones

direct mass measurements of short-lived nuclei at the limits of stability with a precision of better than 10^{-6} and half-lives down to 100 nanoseconds, and the exploration of large areas of the nuclear chart. Large-scale mass measurements as we performed at the ESR allow crucial tests of nuclear models [10]. As a typical example in Fig. 8 displays the experimental and theoretical mass values in the

representation of shall gaps for $N = 50$ isotones which cross two proton shells: at nickel ($Z = 28$) and tin ($Z = 50$). The theories reproduce well the proton-rich species including the doubly magic ^{100}Sn but diverge for the neutron-rich species around the doubly magic ^{78}Ni . This result suggests that the exploration of neutron-rich species will reveal new nuclear properties.

4.2 Nuclear Shapes

A nuclear liquid drop is spherical. Structure effects may create non-spherical nuclei. Nuclides may even co-exist in different shapes. Such an example of shape coexistence is ^{186}Pb [11]. The decay of ^{190}Po feeds three 0^+ states: prolate, oblate, and spherical (Fig 9). Such deformations are measured by decay spectroscopy.

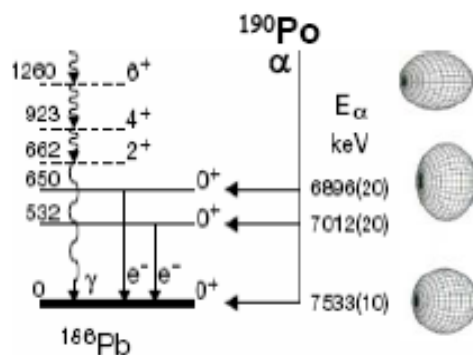


Fig. 9. The coexistence of nuclear shapes in ^{186}Pb

4.3 New Decay Modes

When crossing the proton dripline, protons become unbound and proton emission from the ground state can be observed. This new decay mode was discovered by S. Hofmann et al. in 1981 in the decay of ^{151}Lu [12]. Presently about 30 ground state proton emitters are known. Ground state proton emission is an excellent example for quantum tunnelling. The proton energy and the half live of the decay yield information on the initial quantum state. Fine structure in the proton decay spectrum, first observed in ^{131}Eu , yields more details on nuclear structure and provides a stringent test for nuclear models at the limit of stability.

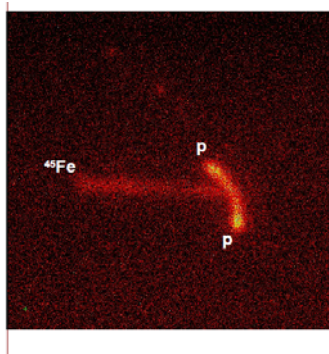


Fig. 10. Image of two proton decay observed with an optical CCD camera

For proton-dripline nuclei with an even number of protons, two-proton decay is observed. The first ground state two-proton emitter ^{45}Fe was discovered in 2002 by M. Pfützner et al. [13] and

independently B. Blank et al.. Fig. 10 shows an example of a two-proton decay of ^{45}Fe observed with a CCD camera looking at an optical ionization chamber from a recent experiment. A theoretical analysis of the observed tracks shows that the two protons are emitted neither fully correlated nor uncorrelated. The decay is a three - body decay.

4.4 New Forms of Nuclear Matter

In 1985 Tanihata et al. at the Berkeley BEVALAC made reaction studies with relativistic beams of ^{11}Li . They measured a large interaction cross section [14], which they interpreted as large nuclear radius explained by Hansen and Jonson as a neutron halo [15]. The weakly bound two outer neutrons of ^{11}Li surround the nuclear ^9Li core as dilute neutron matter.

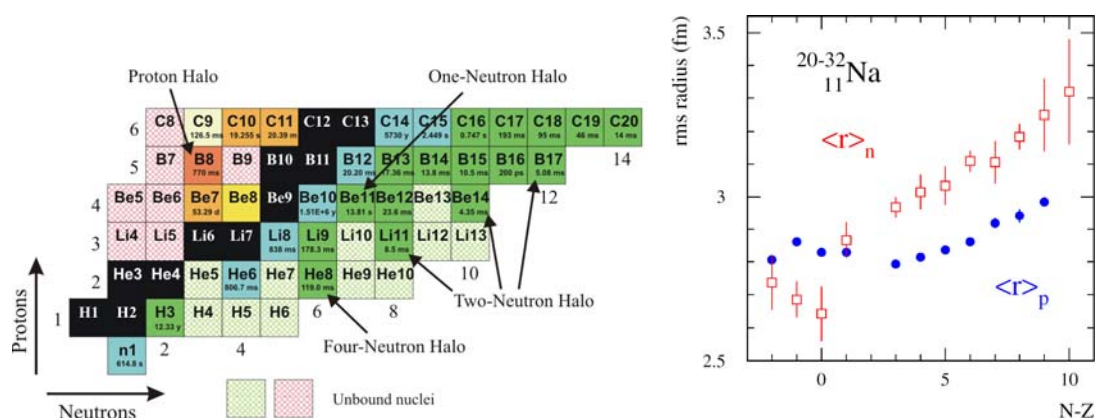


Fig. 11. Chart of neutron and proton halo nuclei (left), neutron skin in sodium isotopes (right)

In the meantime one-neutron halo, four neutron halo, and proton halo nuclei have been observed (Fig. 11). Because of the large reaction cross section the halo neutrons can be individually removed in a nuclear collision and give a frozen picture of their nuclear state.

The tendency of excess-neutrons to separate from the nuclear core is also observed in heavier nuclear systems where they form a neutron skin. Fig. 11 shows the evolution of a neutron skin towards the neutron rich isotopes for sodium [16]. The radii of neutron matter are from experimental interaction cross section values employing Glauber scattering theory (matter radii), the radii of the proton distribution are deduced from the hyperfine structure measured in a laser experiment. Neutron skins are a testing ground for the nuclear equation of state and the neutron crust in neutron stars as the crust of the neutron stars has the same matter density as the neutron skin.

4.5 Interplay of atomic and nuclear effects

The experimental storage ESR ring offers unique conditions to store atomic nuclei as fully stripped or few-electron systems which allows to study radioactive species under conditions as they exist in the universe [10]. Bound-State Beta Decay is a classical example. If the energy of the emitted β is not sufficient to escape to the continuum, the atomic nucleus can not decay, it is stable. However if the electron orbits are empty it can decay into the K shell. This new decay mode, Bound-State Beta Decay, was observed first for the decay of $^{163}\text{Dy}^{66+}$ in 1992 by Jung et al. [17]. Atomic nuclei in the cosmos undergoing β decay in a hot stellar environment will make such decays and have a different half-life from that observed on earth which has dramatic consequences if e.g. such nuclides are used as cosmic clocks as for instance $^{187}\text{Re}^{75+}$. Decays of bare atomic nuclei are investigated at the GSI storage ring ESR. They are produced at relativistic energies where they are fully stripped, separated in-flight in the FRS, and injected at full energy into the ESR where they are stored and cooled for experimental investigations [10]. In general bound state beta decay decreases the half-lives of heavy

beta emitters by about 15-20 %. New features of nuclear electron capture decay have also been discovered for H- and He-like ions.

5. FAIR – the future of GSI and NUSTAR

Fig. 13 shows the new international GSI facility, FAIR, the Facility for Antiproton and Ion Research [18]. A double ring synchrotron system delivers intense beams of all ions up to uranium. For

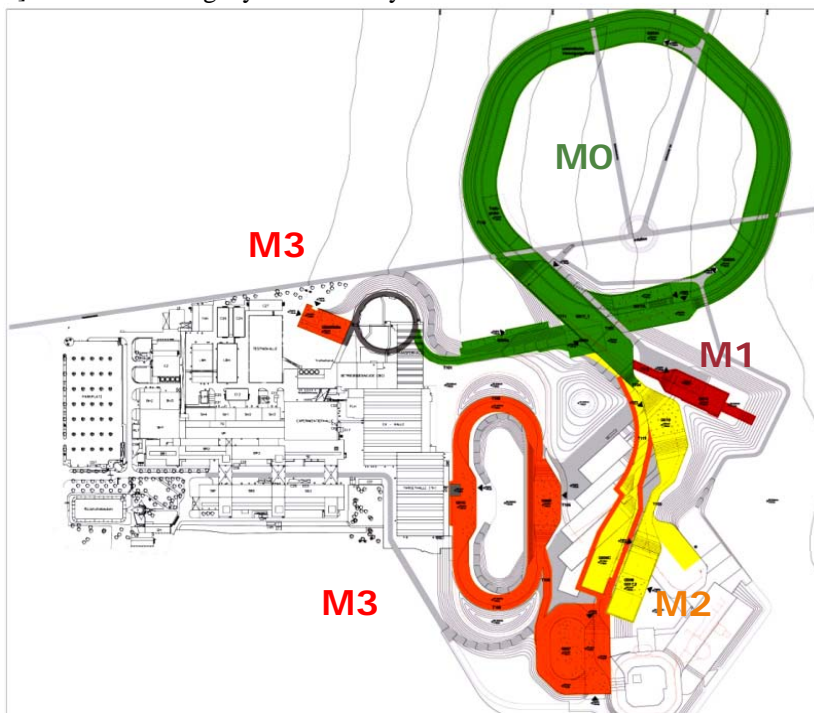


Fig. 13. FAIR-the new GSI project

Energies between 0.5 AGeV to 1.5 AGeV will be used for NUSTAR experiments at GSI-FAIR. Module 2 (yellow) is NUSTAR, the facility for NUClear Structure Astrophysics, and Reactions. The workhorse of NUSTAR [19] is the Super-FRS, a three-stage fragment separator of large acceptance with superconducting magnets. Increased primary beam intensity and separator transmission will increase the intensity of radioactive beams by up to four orders of magnitude, especially for experiments with stored exotic nuclei. This will give access to new regions of the nuclear landscape, to the borderlines of the existence of elementary matter for structure research, astrophysics, and reactions.

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