GSI-Preprint-97-67
November 1997

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AT GSI- FROM HALO NUCLEI TO SUPERHEAVY
ELEMENTS**

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(To bäh published in 'Il Nuovo Cimento')

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Perspectives for Nuclear Structure Research at GSI- from Halo Nuclei to Superheavy Elements

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(ricevuto ?; approvato ?)

Summary. — After a brief overview on recent advances in the investigation of nuclei at the driplines and the upper end of the nuclear table key issues of nuclear structure research as addressed by new theoretical developments will be discussed in context with new developments in heavy-ion accelerators and experimental techniques.

PACS 21.10.-k – General and average properties of nuclei.

PACS 21.60.-n – Nuclear-structure models and methods.

1. – Introduction

In the past decade significant progress has been made in the exploration of hitherto inaccessible regions of the nuclear chart at the limits of stability and by the further development of nuclear models. Key contributions from GSI were the production of the heaviest elements known today [1, 2] with $Z = 107$ to 112 , the discovery of the proton radioactivity from the groundstate[3] and the first observation of the doubly magic nuclei[4, 5] ^{100}Sn and ^{78}Ni . A region covering more than hundred new masses was measured with high precision. In nuclear reactions at relativistic energies the enhancement of matter radii towards the driplines and the halo dynamics in light exotic proton- and neutron rich nuclei[6, 7] such as ^8B and ^{11}Li were investigated (Fig. 1). Prerequisites to these studies were new experimental techniques such as separation ion-flight, beams of exotic nuclei at relativistic energies, 4π -detector systems of high efficiency, and storage and cooling.

A new access to nuclear structure was opened up by isotope separated projectile fragments at intermediate and high energies. After the first pioneering experiments at Berkeley[8, 9] this field started growing fast. At present the existing facilities at NSCL(MSU,USA), GSI (Darmstadt, Germany) and ARENAS (Louvain-la-Neuve) - the pioneering laboratory for post-acceleration of secondary beams - are currently upgraded. A small projectile fragmentation arena at Dubna (Russia) recently went into operation. The ambitious upgrade and extension of the the RIKEN laboratory has

Fig. 1. – The chart of nuclei with the recent achievements in nuclear structure research at GSI.

been approved. A new generation of facilities based on acceleration of on-line separated exotic beams driven by proton or heavy-ion accelerators are SPIRAL (GANIL, France), REX-ISOLDE (CERN, Suisse), EXCYT (CATANIA), HRIBF (Oakridge, USA), ISAC (TRIUMF, Canada), and INS (Tokyo). They started operation or are being completed. The fission fragment accelerators PIAFE (Grenoble, France) and at the Munich reactor are discussed [10, 11, 12].

To explore the future perspectives of nuclear structure research specifically the new possibilities with intense energetic beams of exotic beams, a number of working groups has been established for instance by NuPEEC and GSI. Results of the latter are partly discussed in this contribution [13].

2. – GSI-Accelerator Schemes

The key to the investigation of exotic nuclei at the limits of stability in decay and reaction studies are powerful high-current accelerators. This consideration led to the new generation of ISOL facilities for accelerated beams of exotic nuclei. For GSI it was decided to keep to the fragmentation concept due to several advantages, such as the experience in in-flight separation. Moreover this scheme provides high separation efficiency independent from target and ion source chemistry: Fast and clean isotopic separation gives access to the most exotic species.

The GSI scheme is based on a high-current injector accelerating low ionic charges. Beam intensities of up to $3 \cdot 10^{14}$ /s are expected at energies near the Coulomb barrier. Straightforward is the replacement of the UNILAC by a linac with a minimum

Fig. 2. – Intensities for the tin isotopes produced in fragmentation of xenon isotopes and ^{238}U fission in-flight as expected for the GSI high-intensity accelerator.

energy of 150 A MeV most suitable for light nuclei up to tin. These are of specific interest as the driplines can only be accessed in the low-mass region. Such an accelerator could deliver intensities of the order of $10^{14}/\text{s}$ and alternatively serve as an injector into SIS for higher energies and the heavier elements. The disadvantage of such a linac is the low duty factor due to high energy consumption. The short pulses are not very suitable for reaction experiments.

The optimum solution would be a synchrotron of high magnetic stiffness, about 100 Tm (SIS100) to accelerate high intensity beams of low charged ions. This synchrotron could provide beams of $10^{12}/\text{s}$ at energies above 1 A GeV. The secondary beam intensities would be comparable to those of the linac due to thicker production targets and a kinematic focusing of the projectile fragments. Both solutions would be competitive to the upgraded facilities in MSU and RIKEN. Fig. 2 displays the expected secondary beam intensities for the production of tin isotopes by fragmentation or fission in-flight.

A great advantage is that a 100 Tm synchrotron, loaded with highly charged ions, would access energies sizeably above those of SIS and in addition open up a broad field for high-energy heavy-ion physics.

2.1. Key Issues in Nuclear Structure Research. – Nuclei are quantum systems governed by the interaction of all forces except gravitation. These determine the limits for the existence of matter towards the driplines and in the region of the superheavy elements. While light nuclei as few-nucleon systems can be described in terms of exact nucleon-nucleon interactions, for the heavier ones mean-field theories are used. Exotic nuclei allow the study of in-medium interactions at large isospin, the medium dependence of the pairing strength, the influence of the continuum in weakly bound proton- and neutron rich systems, and their manifestation in nuclear structure[14].

Nuclear models used at present have predominantly been developed from nuclei close to β -stability well bound and with balanced neutron and proton distributions. The Fermi surfaces for protons and neutrons are well below zero and protons and neutrons cover the same volume. Far-off stability new phenomena such as the nuclear halo[7] have been

Fig. 3. - Neutron and proton radii for the tin isotopes from various predictions [15].

discovered allowing the study of matter in the transition regime from bound to unbound and the increasing importance of continuum interactions. Neutron- and proton skins offering the possibility to study pure neutron- and proton matter are predicted in regions far-off stability along the entire nuclear table. Fig. 3 shows a compilation of predictions of proton- and neutron radii [15] for the tin isotopes, compared to data (filled symbols).

It has been deduced from r -process abundances [16] that shells far-off stability are quenched. The question is whether all nuclei far-off stability are structureless spherical nuclear droplets. As all nucleosynthesis paths pass through regions of unstable nuclides, astrophysics will profit from the investigation of the structure of nuclei far-off stability. Towards the heaviest systems the Coulomb repulsion between the increasing number of protons grows faster than the nuclear forces. The heavy nuclear systems are macroscopically unstable, their existence is determined by shell effects. A key question is the location of the next spherical double shell closure beyond ^{208}Pb and its importance for the extension of the number of elements [18, 19].

The β -decay is a testing ground for fundamental physics such as β -neutrino correlations β -asymmetry, or the weak vector coupling constant and the quark mixing element of the Kobayashi-Maskawa matrix [20]. At high energy, well above the present limit of about 2 GeV/u beams of exotic nuclei would contribute to the investigation of isospin effects in highly compressed nuclear matter and the extension of structure physics into the region of hypernuclei [21], topics still under discussion but beyond the scope of this contribution.

Separation in-flight has proven to be fast and efficient [17], the limit in separation time is of the order of microseconds, the unambiguous identification of single atoms is suited for the investigation of nuclei at the very limits of nuclear stability [11]. This technique has been used successfully for heavy element research, the investigation of proton emitters, and the first identification of ^{100}Sn and ^{78}Ni . Another important development is the storage and cooling of heavy nuclei in traps and storage rings, allowing experiments of highest precision and sensitivity [10]. The new generation of highly efficient 4π -arrays such as the new germanium balls for highly efficient γ detection or large area neutron detectors will increase the sensitivity of spectroscopy far-off stability and reaction studies with exotic nuclei.

Fig. 4. - Cross section systematics for the production of heavy and superheavy elements with cold and hot fusion.

Heavy element research would tremendously profit from the increased beam intensities which are the prerequisite to proceed to new elements[22] (Fig. 4) and to investigate the spherical proton shell closure[18, 19], predicted at $Z = 114, 120$, or 126 . Bolometric detectors would allow direct mass determination, necessary for longlived species and in regions where the α -chains now used for identification pass through unknown regions. Systematic reaction studies at high sensitivity to search for new paths to heavy elements become possible. The long half-lives of the heaviest elements allow the application of trapping techniques to investigate nuclear and atomic properties and to extend the region of elements for chemical research. Coulomb fission of unstable nuclei created by fragmentation of uranium gives new insights into the fission process and the influence of closed shells in the heavy uranium fragments and the fission fragments as well, leading to a better understanding of the production of superheavy shell nuclei.

The new and efficient germanium arrays, combined with particle detectors are considerable progress for decay and reaction studies of exotic nuclei. High precision spectroscopy would allow to already detect phenomena which fully exhibit at the limits of stability such as Coulomb distortion and shell quenching. Coulomb excitation allows systematic investigation of nuclear deformations. A powerful tool for the investigation of nuclei at and beyond the driplines are reactions with exotic nuclear beams. The combination of a CRYSTALBALL, the ALADIN magnet, and the LAND large area neutron detector allow kinematically complete experiments appropriate to investigate the structure of nuclei at and beyond the driplines. Momentum distributions and correlation among halo nucleons are measured, above Fermi velocity the fragments emerging from the collision reflect the frozen wavefunction.

In a first generation of experiments, a region of more than hundred atomic masses in the gold region were measured with high precision by using storage and cooling of projectile fragments in the ESR[23]. Next generation experiments will be elastic and inelastic scattering at the internal gas target with cooled beams of highest luminosity circulating in the ESR to investigate matter distributions and nuclear structure with

highest precision, free from atomic interactions. An electron-/proton storage ring of comparatively small size is a completely new tool to measure matter- and charge radii. A mini electron-heavy-ion collider, first discussed in the frame of the Dubna K4-K10 project, was further discussed with members of this group at GSI. Electrons provide a clean electromagnetic probe for nuclear matter distributions and excitations. With the application of stacking techniques a broad range of exotic nuclei[24] is accessible.

In conclusion high-current accelerators, combined with new experimental methods will allow to extend our knowledge of nuclear structure to nuclei at the limits of stability, helping us on the long range to develop a better and more fundamental understanding of the nucleus closer to the grounds of the fundamental forces[25].

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