EXOTIC NUCLEI AND SUPERHEAVY ELEMENT RESEARCH ON ITS WAY FROM GSI TO FAIR

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Exotic nuclei and superheavy element research is in a transition phase from experiments at the existing facilities of GSI towards the construction and exploitation of new instruments at the international facility FAIR. Prospective physics opportunities are outlined and illustrated by highlight results from the ongoing research programme together with novel instrumental developments and strategies.

Introduction

The ultimate goal of modern nuclear physics is to obtain a unified picture of nuclei, to understand the complex interaction of protons and neutrons and to describe the large variety of phenomena, structure and dynamics of nuclei with ab initio theories. This will allow one to make reliable predictions to unknown territory in the chart of nuclei, including regions which will possibly never be reached experimentally, and to explain the limits of nuclear existence. In a more applied view, the aim is to explain the macroscopic universe with the same forces and the same constituents in a consistent way, like energy generation of stars, to understand why and how they explode, and finally how, when and where the existing chemical elements were synthesized. The approach used at GSI, and lateron at FAIR, is to explore the "Terra Incognita" using intense primary beams and nuclear fusion, fission and fragmentation reactions to produce exotic beams and to study them with a variety of dedicated cutting-edge instruments, such as storage rings, spectrometers, highly-specialized detectors and last but not least nuclear theory. The latter is indispensable for the interpretation of experimental results and also for guidance of the future programme.

The NuSTAR collaboration at GSI and FAIR

The NuSTAR collaboration aims at nuclear structure, astrophysics, reaction studies and superheavy element research. It will drive and perform the transition from GSI to FAIR in close collaboration and exchange with the bodies and boards of the laboratory. The main result of this effort shall be a unique research programme at the Super-FRS, a superconducting fragment separator, where properties, structure and dynamics of many new, especially neutron-rich isotopes can be studied, and at a new continuous-wave linear accelerator ("cw-linac") plus vacuum separator, where the next-generation experiments on superheavy elements (SHE), possibly beyond Z=120, can be carried out. Figure 1 illustrates key results of exotic nuclei and superheavy-element research obtained at GSI. Several new elements and many new isotopes have been synthesized, and a variety of new phenomena was found, such 2-proton radioactivity, beta-decay to bound final states or deeply bound pionic states in nuclei. All these findings are the basis for the future experimental programme of the NuSTAR collaboration at FAIR.

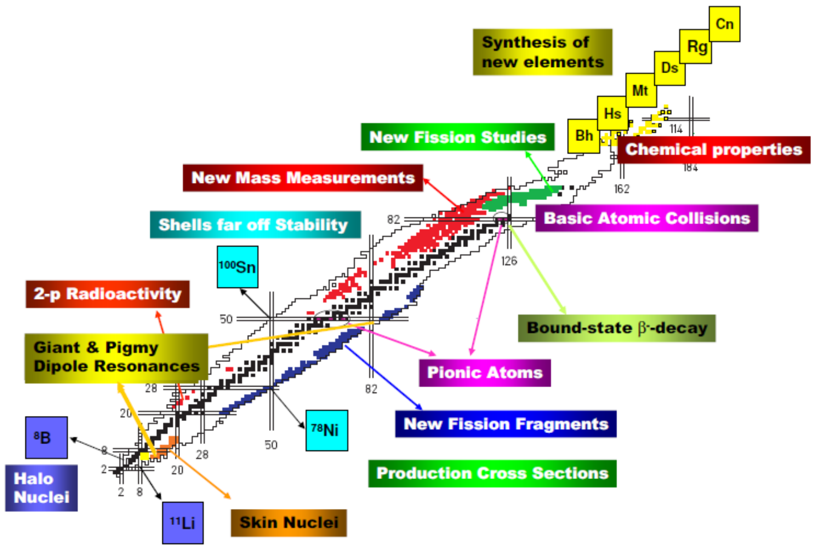

Figure 1. Chart of nuclei, where the black solid line embraces presently known isotopes. Key results of superheavy element and exotic nuclei research, which was carried out at UNILAC and SIS at GSI during the last decades, are indicated.

Superheavy element research

SHE research at GSI addresses trans-uranium nuclei and is carried out at the UNILAC. It benefits not only from the intense stable beams and target techniques, including production and handling of actinide targets, but also from the highly-specialized instruments. The world-class separators SHIP (velocity filter) and TASCA (gas-filled separator), which simultaneously provide large transmission and highest primary-beam suppression capabilities, are combined with the selectivity of implantation detectors and chemistry apparatus. Besides this, there are mass- and gamma-ray spectrometers which allow for unique atomic and nuclear structure studies. Last but not least, there is a strong theoretical chemistry contribution. This wide spectrum of instruments and techniques, which is illustrated in figure 2, makes GSI a unique place for SHE synthesis and studies. Meanwhile, the search for the new elements 119 and 120 has been completed at GSI. The analysis is going on and publications of the results are in preparation [1]. As long runs, with durations of the order of several months, are not planned for the next few years, the SHE programme at GSI will concentrate on shorter runs, where physical and chemical highlight experiments shall be performed. Plans exist for e.g. the direct atomic number determination of superheavy nuclei through the observation of X-rays, detailed chemical and atomic structure studies by employing organo-metallic compounds, direct mass measurements of trans-fermium nuclei, and the study of deformed and spherical „islands“ by nuclear decays and spectroscopy.

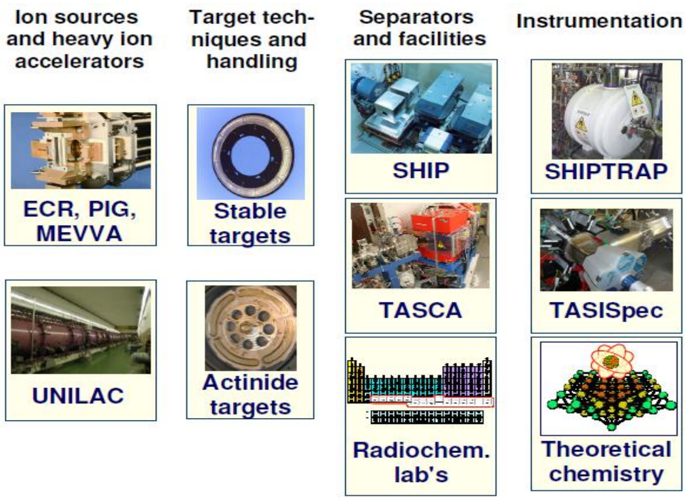

Figure 2. Key techniques and instrumentation, including nuclear and atomic theory, for superheavy element research at GSI.

Furthermore, the programme will comprise reaction studies, e.g. multi-nucleon transfer, cold and hot fusion with new projectile-target combinations, exploiting the worldwide uniquely available long-term stable and intense ^{50}Ti beam. On the mid term, laser spectroscopy studies are being prepared for the study of nobelium isotopes, and the possibility for mass-number identification is being discussed, e.g. by using the existing Penning-trap setup or by means of a multiple-reflection time-of-flight mass spectrometer (MR-ToF-MS) or by means of bolometric detectors. Such experiments require typically of the order of one to two weeks beamtime, so that they are quite appropriate in the coming years and they will yield prominent results and maintain GSI's SHE programme on the forefront of the world scene.

The planned reaction studies can provide insights to cross section systematics, reaction dynamics and kinematics of the nuclear reaction products. They are a first and preparatory step, which will yield important information for the design of GSI's next-generation vacuum separator, in order to extend the SHE island further towards the "north-east", i.e. to new elements, and "south-west", in particular towards more neutron-rich isotopes. This separator has the aim to cope with the 100 to 1000 time higher intensities, provided by the next-generation cw-linac, which is presently under preparation [2].

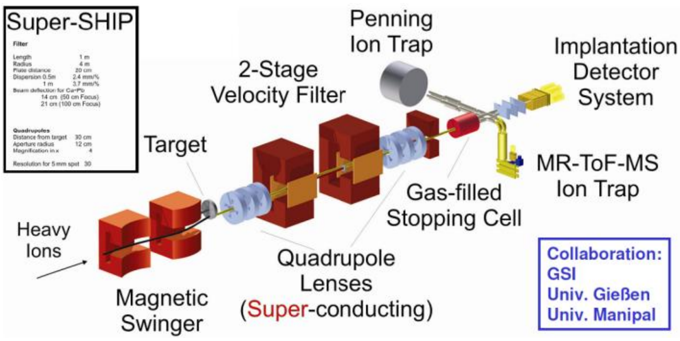

Figure 3. Preliminary sketch of the next-generation, superconducting vacuum separator for transfer and fusion products including advanced instrumentation. It shall be coupled to the planned superconducting cw-linac.

It will employ advanced target techniques and instrumentation for the new SHE synthesis programme at GSI, the search for new elements 119 and 120, and possibly beyond element 120. The draft design of the new vacuum separator is sketched in figure 3. Like the existing SHIP, it will be a velocity filter with two stages in order to yield highest primary-beam suppression. Its acceptance will be increased in transverse direction by using superconducting large-aperture lenses. Its working title is superconducting SHIP, or Super-SHIP. A beam swinger system in front of the target will allow to separate transfer reaction products efficiently, which escape from the reaction under small angles in the laboratory. It will also serve for shaping a beam profile, which illuminates the target area homogeneously in order to distribute the thermal heat load. The possibility of mass determination by a mass spectrometer or new A/q separator is under consideration. Novel detection systems, including fast digital electronics, are under continuous development by the NuSTAR collaboration and will be implemented later.

Exotic nuclei research

At GSI, exotic nuclei are produced and studied at the heavy ion synchrotron and storage-ring complex SIS-ESR by fragmentation or fission reactions of intense primary beams at relativistic energies. The central instrument is the fragment separator FRS. Advantageous is its triple capability to serve for particle identification, to act as high-resolution magnetic spectrometer and to provide isotopic clean separation. The device has been built in the late 80'ies and still offers forefront research opportunities. Several key results are depicted in figure 1. Presently the FRS serves experiments and is the development platform for Super-FRS experiments at FAIR and related equipment. Unique on the worldwide scale is the connection to the storage and cooler ring ESR. Large-area mass measurements and decay studies of highly-charged ions are carried out on exotic nuclei. Two original methods have been developed, isochronous mass spectrometry (IMS) and time-resolved Schottky mass spectrometry (SMS). Masses of more than 400 nuclides have been measured for the first time and many known values could be improved. It will be the goal to further enhance the precision of the method, to access the most exotic nuclei in reach, and to benefit from the single-particle sensitivity, which is tailored for exploring the limits of accessible nuclei with intensities as low as 1 per day. Recently, a novel programme for low momentum-transfer measurements by reactions off gas-jet targets was launched at FRS-ESR. The low-energy target recoils, which can be detected down to few keV kinetic energy, give insights to nuclear structure and bulk properties and allow the study of transitions which are relevant for nuclear astrophysics: using internal targets with densities exceeding 10^{14} atoms/cm^2 and with revolution frequencies exceeding 10^6/s, one can study elastic and inelastic reaction channels of exotic nuclei in inverse kinematics even with moderate secondary beam intensities. In this way, and using a demonstrator setup for the EXL experiment at FAIR, a luminosity of $>10^{27}$/cm^2 s was reached for the reaction ^{56}Ni+H. For the future it is planned to use ^{4}He and ^{3}He as probes. With alpha particles, one can for instance probe the isoscalar GMR and GDR and obtain data for the compressibility of (asymmetric) nuclear matter, which is still poorly known. With the ^{3}He targets, Gamow-Teller resonances can be studied and provide electron capture rates for nuclear astrophysics calculations.

Towards NuSTAR at FAIR

In the coming years, GSI will concentrate its resources on the construction of the FAIR instruments and the preparation of the FAIR experimental programme. On the one hand side, this means that resources need to be saved: some parts of the NuSTAR programme at GSI have been terminated, for instance the online mass separator at the UNILAC has been shut down and dismantled; similarly, the participation in foreign programmes was largely reduced.

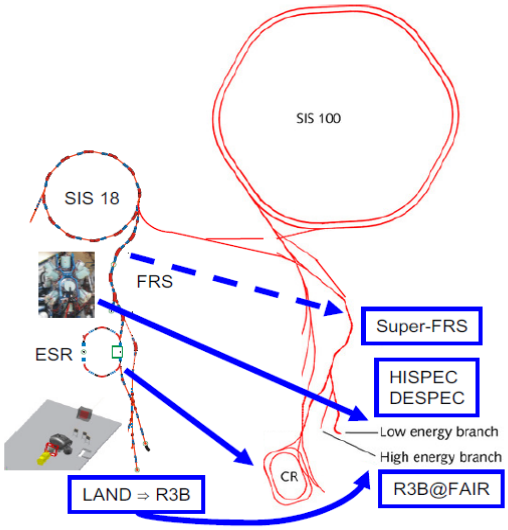

Figure 4. The itinerary of NuSTAR instruments from FRS to Super-FRS is indicated by arrows.

On the other hand side, efforts are concentrated towards FAIR experiments. For NuSTAR at SIS energies, this programme evolves in an evolutionary way from the ongoing experiments: detectors, techniques, identification schemes, ion-optical modes will be prepared, tested and used at the FRS, and later-on they will be transferred to the Super-FRS at FAIR. This holds for the transition from FRS to Super-FRS itself, including all its functional elements (like data acquisition, separation schemes, operational procedures, insertions, etc.), but also for its ancillary equipment, and in particular for the large, complex detector systems like R3B (setup for kinematical complete reaction studies using relativistic radioactive beams), HISPEC-DESPEC (a variable setup for gamma-ray and particle decay spectroscopy), MATS and LaSPEC (laser spectroscopy and precision experiments on exotic nuclei) and ILIMA (isomer, mass and lifetime experiments with stored beams) and EXL (scattering and reaction experiments of exotic nuclei off internal targets in storage rings). This process is illustrated in figure 4. Finally, and as a consequence, the remaining resources will be concentrated on scientifically outstanding cases, which can exclusively be studied at GSI. Criteria applying here are, besides scientific top quality on the world scene, uniqueness with respect to beams (like intense Ti beams) and elements/isotopes, beam energies (beyond the minimum of transparency in nucleon-nucleon scattering cross sections), unambiguous identification (fully stripped ions) and GSI-only instruments such as the high-resolution momentum spectrometer FRS or the storage ring ESR. Along these lines, it is clear that the above mentioned reactions off internal targets belong to this category. Also experiments using high-resolution missing-mass spectroscopy, like the discovery of deeply-bound pionic states [3], are to be mentioned here, and there is a very exciting proposal to form η'-mesic nuclei by η' transfer reactions and to derive real and imaginary nuclear potential depths from in-medium mass shifts [4].

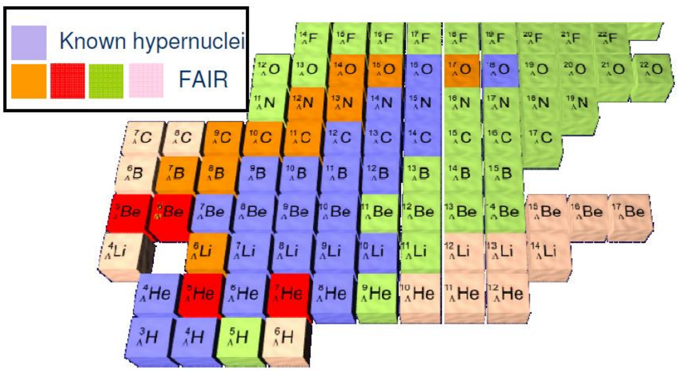

Figure 5. The "third dimension" of the chart of nuclei is opened-up by strange quarks contained in exotic nuclei. The blue colour labels the presently known hypernuclei, whereas other colours indicate exotic nuclei containing hyperons, which can be produced and studied within the various phases of the FAIR project, mainly progressing along the intensity increase and the growing capabilities of the hypernuclei experimental setup.

Another such case is the synthesis and study of exotic nuclei containing strange quarks and thus exploring the "third dimension" of the chart of nuclei. So far, the production of hypernuclei is restricted to pion- and kaon-induced reactions on stable or long-lived isotopes, which can be prepared as targets. In a novel approach, it was recently demonstrated in peripheral nuclear reactions that coalescence is an effective mechanism how hyperons, produced in the overlapping, hot zone of colliding projectile and target nuclei, can stick to the exotic projectile fragment [5]. After this first experiment using ^{6}Li beams, in a next step exotic nuclei containing hyperons will be produced at the FRS, with the goal to study hypernuclei at extreme isospin. The objective of forthcoming studies is the quest of Λ-Σ coupling in the nuclear medium, weak decays, hypernuclear excitations and the measurement of hypernuclear radii. There are ideas for a dedicated hypernuclei separator for experiments at FAIR-SuperFRS.

Conclusion

The construction of the international facility for anti-proton and ion research FAIR has started. All FAIR bodies are implemented and the major fraction of funds was formally approved. Civil construction started in 2012. Technical developments are ongoing, and for most components prototypes exist which are being tested. At GSI, future beam times will largely be used for beam tests of FAIR components, and resources are focussed overall on the construction of the new facilities. From the experimental point of view, NuSTAR detectors and experiments undergo a continuous evolution and transition from GSI to FAIR. This is reflected in a very concentrated research programme, which will be conducted from 2013 on at the UNILAC and at the SIS.

The search for new elements will be on hold for the next few years, but properties of SHE's will be studied exploiting the unique experimental capabilities of GSI for chemistry, direct mass measurements and nuclear structure studies. Simultaneously, exploratory reaction studies like deep inelastic and transfer reactions with heavy and very heavy beams will continue to search for new avenues to produce new isotopes and possibly neutron-rich SHE. The exotic nuclei experiments at SIS will concentrate on "GSI-only" experiments, probing the strong force at the boarder line of nuclear and hadron physics, and detectors and equipment will be upgraded continuously for a smooth and reliable transition from GSI experiments to Super-FRS experiments at FAIR.

References

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