RECENT RESULTS FROM FRS EXPERIMENTS WITH EXOTIC NUCLEI PRODUCED WITH URANIUM PROJECTILES AND PERSPECTIVES WITH THE SUPER-FRS

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Relativistic exotic nuclei have been produced via uranium projectile fragmentation and fission and investigated with the in-flight separator FRS directly, or in combination with either the storage-cooler ring ESR or the FRS Ion Catcher. 60 neutron-rich isotopes have been discovered in the element range from Nd to Pt and their production cross sections have been measured. In another experimental campaign the fragments were separated in flight and injected into the storage-cooler ring ESR for accurate mass and lifetime measurements. Pioneering experiments have been carried out with the FRS Ion Catcher. Results from these different FRS experiments will be presented in this overview together with perspectives for the next-generation facility Super-FRS.

1. Experimental

Heavy neutron-rich nuclei in the neighborhood of and at the N=126 shell closure are of great interest for nuclear spectroscopy and astrophysics. Experimentally it is a challenge to produce and identify these nuclei because of the small production cross sections, short lifetimes and difficult separation in flight due to the charge-state population. From these considerations it is clear that both a high luminosity and high kinetic energies are desired. Using relativistic uranium projectiles and the present fragment separator FRS [1] at GSI, one has unique experimental conditions for this task. The experimental facilities applied to obtain the presented results are shown in Figure 1.

The fragment separator FRS with its four magnetic dipole stages and its high ion-optical resolution is ideally suited to perform experiments with exotic nuclei created with an incident uranium beam [2,3]. The final focal plane is used for the identification and spectroscopy of relativistic fragments and also for thermalized ions in combination with the FRS Ion Catcher (FRS-IC). In the latter experimental scenario the fragments produced at about 1000 MeV/u are slowed down with shaped degraders, placed in different focal planes, to the eV range for precision spectroscopy studies. Experiments with stored and cooled exotic nuclei have been performed with the combination of the FRS with the storage ring ESR [4]. Along with accurate mass and lifetime measurements, new isotopes have been discovered [3].

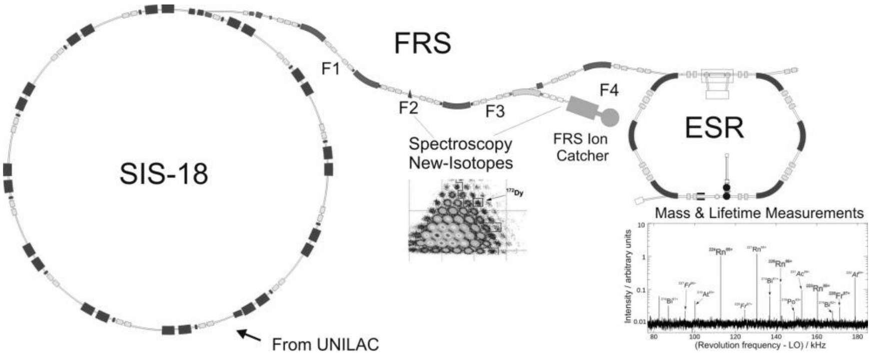

Figure 1. Experimental facilities used to obtain the results in this contribution. The synchrotron SIS provides the primary beam, which is converted into interesting exotic nuclei by the in-flight separator FRS. The spatially separated fragment beams are injected into the storage-cooler ring for accurate mass and lifetime measurements. At the focal plane F4 spectroscopy of exotic nuclei are performed from relativistic energies down to the eV range in combination with the FRS Ion Catcher.

An overview of the investigated exotic nuclei and the corresponding experiments are illustrated on the chart of nuclides in Figure 2.

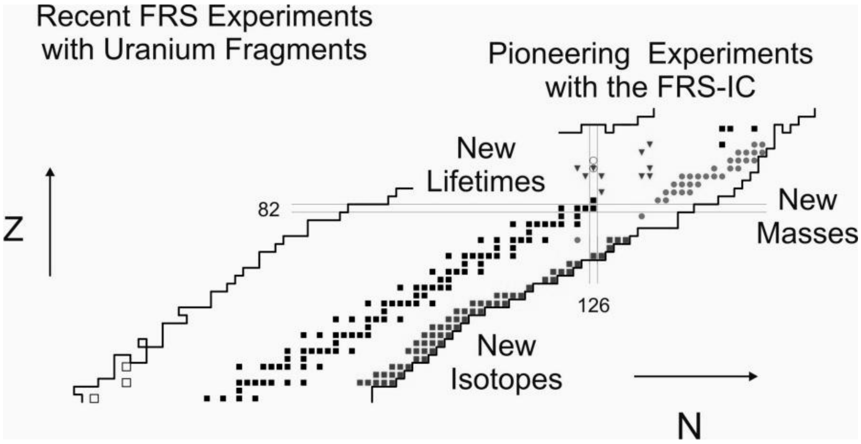

Figure 2. Chart of nuclides indicating the range of isotopes discovered and investigated in the different experimental campaigns performed with the FRS and described in this overview. In the search for the most neutron-rich nuclides close to the N=126 shell 60 new isotopes have been discovered and their production cross sections measured [5]. Pioneering experiments with the FRS Ion Catcher have been performed with different alpha emitters close to the uranium primary beam. Accurate new mass measurements [6] have been achieved with stored and cooled exotic nuclei by the application of a new time resolved Schottky noise analysis.

2. Discovery of New Neutron-Rich Isotopes

A 1000 MeV/u ^{238}U projectile beam with an intensity of 10^9/s impinged on a 1.6 g/cm^2 thick beryllium target placed at the entrance of the FRS [5]. The heavy reaction products Z>60 were separated with the FRS operated in an overall achromatic ion-optical mode. Two degraders, located at the first (F1) and second (F2) focal planes were used. In this way, the reaction products are spatially separated. The complete particle identification in-flight was performed on an event-by-event basis with time-of-flight, energy deposition and magnetic rigidity measurements. In this way unambiguous isotope identification was achieved [5]. Only fully-stripped isotopes have been considered in the particle identification but all charge states have been taken into account for the cross section determination [7] . The ion-optical transmission has been calculated by the Monte-Carlo simulation program MOCADI [8] taking into account the different kinematics of projectile fragmentation and fission. The contribution of each reaction type was determined for the observed nuclides by the ABRABLA code [9]. In Figure 3 an example is shown for Sm and Ir isotopes compared with different theoretical predictions.

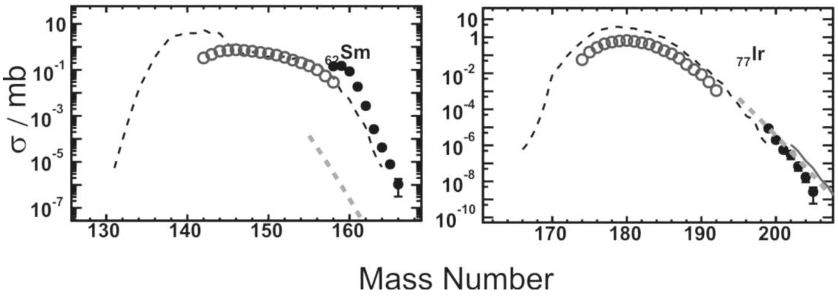

Figure 3. Measured production cross-sections of Sm and Ir fragments [5] created in the reaction of 1000 MeV/u ^{238}U projectiles with a beryllium target in this experiment (black filled circles). The dashed line represents the predictions of the ABRABLA model [9] and the continuous line shows the results of COFRA [10] (Z=73-78). The dotted line shows the prediction of EPAX-3 model [11]. The predictions of EPAX-3 for Sm isotopes is multiplied by a factor of 100.

For the most neutron-rich isotopes of europium covered in this experiment the fission reaction completely dominates the production, whereas for platinum fragmentation dominates and fission is negligible. The ABRABLA predictions show an overall good agreement with the experimental data measured in the present work. Based on the results of ABRABLA calculations, we can state that the observed new neutron-rich isotopes of the elements between $60 \leq Z \leq 66$ are produced mainly by fission, while fragmentation plays the major role in the production of the isotopes of the elements above Z=72.

For the most neutron-rich nuclei, predictions of the analytical COFRA code have been used for the range of elements where fragmentation is dominant. The COFRA model is in general also in good agreement with the experimental data, although gradual deviations from the experimental results can be observed for the heaviest (Os-Pt) nuclei. The EPAX-3 predictions are also quite good in the region of neutron-rich nuclei where fragmentation dominates.

For the neutron-rich low-Z nuclides EPAX-3 cannot predict the cross sections because fission is not included in the parameterization.

3. First Measurements with the FRS Ion Catcher

In general, in-flight separators provide spatially separated fragment beams characterized by an emittance determined by the kinematics of the production reaction convoluted with the atomic interaction of the ions in the target material. In addition, one has to take into account the interaction with the necessary matter such as detectors, stripper foils and energy degraders within the separator. Shaped degraders placed in dispersive focal planes are well established ion-optical elements which can, for example, preserve the achromatism or bunch the momentum distribution such that the separated exotic nuclides can be implanted in thin layers of matter. A special implantation medium is a gas-filled Cryogenic Stopping Cell. (CSC) [12] characterized by an areal density of a few mg/cm^2 pure He gas (e.g. 5 mg/cm^2 under the condition of 100 mbar, 100 K and an effective length of 1 m). This extremely-small thickness represents a challenge for the range compression of relativistic fragments with a monoenergetic degrader. The goal is to stop effectively the isotopically separated exotic nuclei in the He gas volume. In the first experiments of the FRS Ion Catcher (FRS-IC) (see Figure 4.) with uranium projectile fragments produced at 1000 MeV/u, the stopping efficiency after range-bunching with a monoenergetic degrader system placed at the central focal plane of the FRS was about 15 % [13]. This experimental result is deduced from range measurements of ^{223}Th fragments. Including the survival and extraction efficiency, the total efficiency of the CSC in the described pioneering experiments was 8 %. Besides the stopping and extraction efficiencies, the extraction time from the CGC is another key parameter.

The main goal is to access with the FRS-IC rare short-lived isotopes which cannot be reached with an ISOL system. The measured extraction time with ^{221}Ac ions was a few tens of ms. These experimental results are very promising and clearly show the potential of the FRS-IC for the investigation of short-lived exotic nuclides which cannot be accessed by other experimental techniques. The third component of the FRS-IC, the multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) [14] has been also applied for the first time to projectile fragments [15]. The extracted ions from the CSC have been mass analyzed with the MR-TOF-MS with the first goal to characterize the performance of the CSC. In the second step high-accuracy mass measurements ($m/\delta m > 10^6$) of short-lived isobars with mass number of A=211 and A=213 have been successfully carried out.

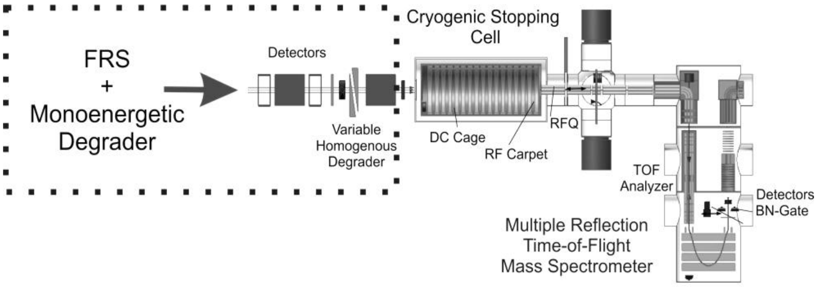

Figure 4. Layout of the FRS Ion Catcher consisting of a monoenergetic degrader system, a cryogenic stopping cell filled with helium gas and a multiple-reflection time-of-flight spectrometer [12, 13, 14, 15]. In the first measurements the monoenergetic degrader was placed at the dispersive central focal plane of the FRS and the final slowing down in front of the cryogenic gas cell was performed with a variable homogenous degrader at the final focal plane.

4. New Mass Measurements of stored Exotic Nuclei

Uranium fragments have been separated in flight with the FRS and injected into the storage-cooler ring ESR [4]. Electron cooling was applied to the stored ions. This forces the circulating ions to the same mean velocity, which is determined by the chosen terminal voltage of the electron cooler. In the present experiment, the injected velocity of the ions was about 70% of the velocity of light, corresponding to kinetic energies in the range of 360 to 400 MeV/u.

After electron cooling, we have achieved a velocity spread for low intensity stored fragments of $5\cdot10^{-7}$ [6]. The mass values are deduced from the revolution frequencies of the stored and cooled ions with time-resolved Schottky noise analysis (SMS) [16]. For the measurement of the revolution frequency spectra, the current signals induced by the circulating few-electron heavy ions at each revolution on two metallic pick-up plates were recorded. SMS is able to record simultaneously many different ion species, including nuclides with known masses and nuclides with hitherto unknown masses. An additional advantage is that the circulating fragments are bare or with one or two electrons bound in the broad band frequency spectrum. SMS can detect single ions [6] which gives the advantage that the ground and low-lying isomeric states can be resolved in an elegant way. In this experiment we have obtained accurate new mass values of

33 neutron-rich nuclei in the element range from platinum to uranium [6]. In total more than 150 nuclides including references with well-known masses have been covered in this large-area SMS measurement. A novel data analysis has been applied which reduces the systematic errors to about 10 keV by taking into account the velocity profile of the cooler electrons and the residual ion-optical dispersion in this part of the storage ring [6].

A representative comparison of our new experimental mass values to the widely-used and most accurate macroscopic-microscopic model FRDM (P. Möller) , the semi-empirical complex mass formula of Duflo and Zuker, and two microscopic Hartree-Fock-Bogoliubov theories (S. Goriely), namely HFB-14 and HFB-17 is shown in Figure 5 [6].

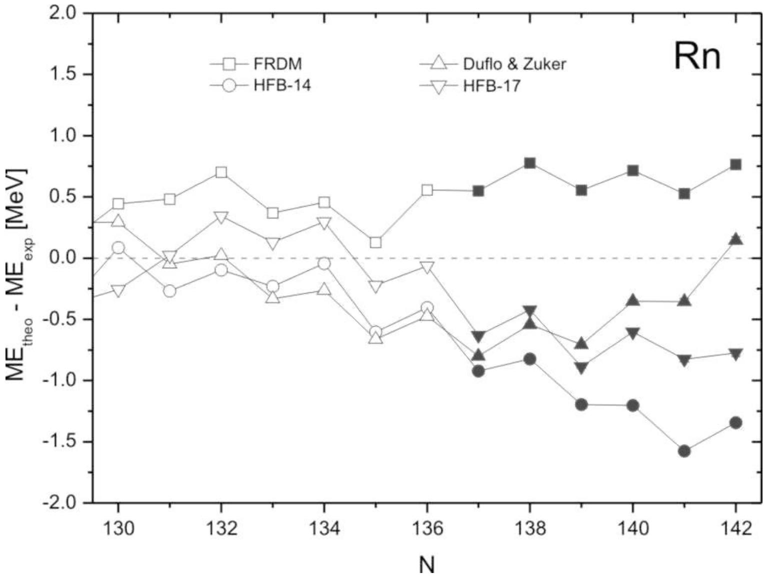

Figure 5. Comparison of experimental Mass Excess (ME) data for Rn isotopes with different theoretical models [6]. The experimental data are taken from ref.[17] and the present experiment indicated by filled symbols [6].

The comparison clearly shows the deficiency of the models. The deviations from the experimental data systematically increase with increasing neutron number, i.e., with the distance from the previously measured mass values. Presently, the status with respect to accurate prediction of mass values is that our data are in general one order of magnitude better. Besides the generally-valid observation of the stronger deviation for the more n-rich isotopes, the odd-even fluctuation in the comparison reveals another shortcoming in the theoretical models. These statements also hold for other elements within the mass area mapped in our experiment [6].

A key question in nuclear physics is, how much the nuclear decay characteristics are modified for ions in different charge states. This question is relevant also for nuclear astrophysics because in hot stellar matter the atoms are highly ionized or even bare. With the FRS-ESR facilities we can study this topic for the first time in the laboratory for all ions up to uranium. In previous experiments we have investigated this topic mainly with ions which decay via weak interaction (beta-decay) [18]. Recently, we have performed a pilot experiment with neutral and stored H-Like ^{213}Fr fragments [19]. The experiment with neutral ^{213}Fr atoms was carried out via implantation in a position-sensitive silicon detector placed at the F4 focal plane. The measurement with H-like ^{213}Fr fragments was performed in combination with the ESR. The experiment has demonstrated that the half-lives of the alpha-emitter are in agreement, within the uncertainties, for the different ionization degrees. This result contradicts earlier theoretical predictions (A. Erma, C. Rolfs).

5. Super-FRS the Next-Generation In-Flight Facility

Presently, the heavy-ion synchrotron SIS-18 is rather limited to low-intensity relativistic projectile beams due to space-charge effects. A direct solution is to arrange to accelerate the heaviest projectiles in lower charge states and increase simultaneously the maximum magnetic rigidity of the synchrotron. This idea is elegantly applied by the future project FAIR by upgrading the UNILAC and adding a 100 Tm synchrotron, SIS-100.

The Super-FRS [20] will be the most powerful in-flight separator for exotic nuclei up to relativistic energies corresponding to 20 Tm. It is a large-acceptance superconducting fragment separator with three branches serving different experimental areas including a new storage ring complex. The layout of the Super-FRS is shown in Figure 6.

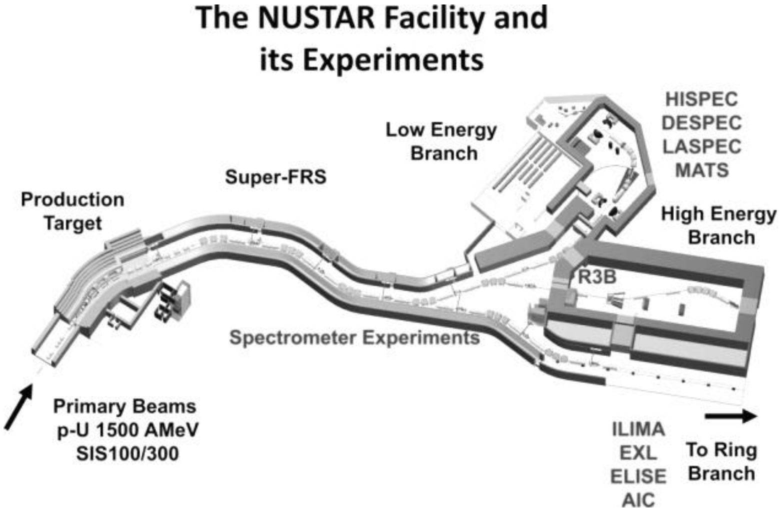

Figure 6. The in-flight separator Super-FRS is the central facility for all NUSTAR experiments [21] which will be performed with the magnet systems directly as Spectrometer Experiments or at the focal planes in the different branches.

The intensity gain for exotic nuclei compared to the present FRS is mainly for fragment beams with a large phase-space population, like fission fragments or projectile fragments far from the mass from the primary beam. A simulation with MOCADI using the ion-optical performance of the Super-FRS shows this gain factor for many interesting exotic nuclides in Figure 7.

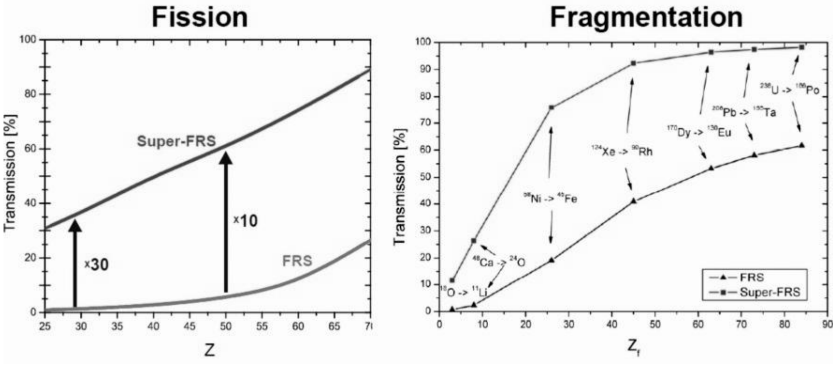

Figure 7. Intensity gain with the large acceptance of the Super-FRS compared to the present FRS. Both for fission fragments and projectile fragments roughly one order of magnitude can be gained for reaction products with large phase space.

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