Present and Future Experiments with Stored Exotic Nuclei at Relativistic Energies

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Abstract. Recent progress is presented from experiments on masses and lifetimes of bare and few-electron exotic nuclei at GSI. Relativistic rare isotopes produced via projectile fragmentation and fission were separated in flight by the fragment separator FRS and injected into the storage ring ESR. This worldwide unique experimental technique gives access to all fragments with half-lives down to the microsecond range. The great research potential is also demonstrated by the discovery of new isotopes along with simultaneous measurements of mass and lifetime. Representative results from time-resolved Schottky mass spectrometry are compared with modern theoretical predictions. The measured isospin dependence of pairing-gap energies is not reproduced by conventional mass models. The first direct observation of bound-state beta decay has been achieved. Single particle decay measurements and the continuous recording of both stored mother and daughter nuclei open up a new era for spectroscopy. The combination of stochastic and electron cooling has allowed us to measure Schottky analysis for the first time short-lived isomers. The future international NUSTAR facility at FAIR consisting of a new large-acceptance in-flight separator (Super-FRS) will be an ideal tool to study the r- and rp-process nuclei.

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**EXPERIMENTAL**

The combination of the in-flight separator FRS \[1\] and the cooler storage-ring ESR \[2\] at GSI provides unique experimental conditions with bare and few-electron ions for all elements up to uranium. Relativistic fragments of several hundreds MeV/u were produced and separated in flight with the FRS. The separated reaction products were injected into the ESR with a selected fixed magnetic rigidity or fixed velocity depending on the operating mode of the ring. The fragment regions of interest were selected by varying the incident energy of the projectiles extracted from the synchrotron SIS.

Due to their stochastic creation process the fragments have an inevitable velocity spread on the order of one percent which would aggravate precision measurements in flight. However, a storage-cooler ring presents ideal tools to overcome this disadvantageous property. For example, the large phase space is reduced by electron cooling which enforces all stored ions to the same mean velocity and reduces the velocity spread to roughly $3 \times 10^7$ at low intensities. Time resolved Schottky analysis is ideally suited to determine the revolution frequency and the intensity of the circulating ions thus providing mass and lifetime data, respectively \[3, 4\].

Applying time-resolved Schottky Mass Spectrometry (SMS) we can correct for possible drifts and thus to achieve higher resolution plus the feature to record the dynamics of the circulating ions. This method enables us to achieve an improved mass accuracy of 30 keV and a resolution of $2 \times 10^6$ \[3, 5\]. Tracing in time the isotope peaks in the Schottky spectra down to a single stored ion, ground or isomeric states can be assigned even for very small excitation energies which cannot be resolved under the condition when both states are simultaneously present \[3\]. 285 new and more than 300 improved mass values of neutron-deficient isotopes in the range $36 \leq Z \leq 85$ have been contributed by SMS to the present knowledge of the mass surface. The research potential of SMS has been extended in our recent experiments with neutron-rich uranium fragments where we measured the mass of hitherto unknown isotopes. This experimental success, illustrated in figure 1, is based on our high sensitivity, resolution, and unambiguous particle identification.

**FIGURE 1.** Discovery of the new isotope $^{235}\text{Ac}$ along with its mass and lifetime measurements applying SMS. The mass value has been extracted by calibrating with the well known mass for $^{235}\text{Th}$ (panel a), whereas the half-life has been extracted from the time evolution of the peak area (panel b).
RESULTS

The large set of new mass values offers seminal comparisons with theoretical predictions. For example, in figure 2, the absolute mass values and the one-proton separation energy ($S_p$) of Bi isotopes are compared to different modern mass models. An extensive comparison of all our new masses yields for the $\sigma_{\text{rms}}$ deviations of the $S_p$ values 379, 525, and 280 keV corresponding to the models of HFB[7], HF+BCS[7] and FRDM[8], respectively. The accuracy for the separation energies is almost a factor of 2 better than the prediction for the corresponding absolute masses which yield $\sigma_{\text{rms}}$ values of 650, 960, and 372 keV for the HFB[7], HF+BCS[7] and FRDM[8] models, respectively. Besides this global characterization in terms of rms deviations the corresponding comparison for single isotopes over the mass surface covered by our experiments has been presented in reference [9].

The accuracy achieved in the present experiment is the basis for the observation of a new isospin dependence of nuclear pairing energies. The pairing energies are calculated from measured mass values using the 5-point formula. In figure 3 the experimental pairing results are compared to the model predictions and it is clearly seen that the observed isospin dependence cannot be reproduced by the current mass models. This conclusion holds also for the other elements covered in our measured range of masses [10].

Exotic nuclei with half-lives shorter than the cooling time can be investigated with time-of-flight techniques operating the ESR in the isochronous mode. For isochronous mass spectrometry (IMS) [11] a special ion-optical setting causes that the revolution frequency of an ion species is independent of its velocity spread. Previously, IMS was successfully applied in smaller isotope regions with many reference masses in the corresponding spectra [11, 12]. In these pilot experiments the mass resolution achieved was 1:100 (FWHM) and the accuracy about 100-500 keV. Recently, a large number of new neutron-rich masses of fission fragments has been measured [13]. The analysis

FIGURE 2. Mass values (left panel) and proton separation energies (right panel) of Bi isotopes compared with the HFB[7], HF+BCS[7] and FRDM[8] mass models. The full circles correspond to our new mass values [3].
of the data is still in progress and represents a special challenge due to missing reliable reference masses in this area and secondly due to the fact that the isochronous condition is strictly fulfilled only for a part of the stored fragments. An example of IMS results with nuclear astrophysical relevance is illustrated in figure 4. The new mass values contribute to the astrophysical calculations of the rp-process [14]. The possible contribution of exact neutron separation energies to nuclear astrophysics is illustrated in figure 5.

Stored exotic nuclei circulating in the ESR offer unique perspectives for decay spectroscopy [15, 16]. The half-life of the stored nuclei can be measured by detecting the mother and daughter nuclides using the difference of their magnetic rigidity (Bρ). If the Bρ difference is less than 2.5 % both nuclei orbit in the storage ring and can be observed in the same Schottky spectrum. For larger Bρ differences the daughter species leave the closed orbit and can be detected in a dispersive magnetic dipole stage of the ESR lattice. The possibility to investigate bare nuclei allows the measurement of decay properties under the ionization conditions of hot stellar plasmas. For the first time bound and continuum β− decay have been simultaneously measured in the laboratory [4]. The combination of stochastic pre-cooling [17] and electron cooling yields access
FIGURE 5. Illustration of the influence of a single $S_n$ value on the abundance of r-process nuclei. In this case only the $S_n$ value of $^{93}$Br was varied by 1 MeV (see two curves) in the HFB calculation. The assumed conditions for the classical r-process were $10^{20}$ neutrons / cm$^3$ and a temperature $T_9=1.35$ K. The measured Solar System abundances are shown by full circles.

to the spectroscopy of hot fragments with lifetimes down to circa one second. For example, we have measured the ground and isomeric states of $^{207}$Tl$^{81+}$ and the bound-state beta daughter $^{207}$Pb$^{81+}$. The half-life of the $^{207m}$Tl$^{81+}$ isomer was determined from the evolution in time of the area of the corresponding peak in the Schottky spectrum. The determined experimental value for bare $^{207m}$Tl fragments in the rest frame is $1.47 \pm 0.32$ s.

FIGURE 6. Masses presently covered by FRS-ESR experiments and future range with FAIR. For the future the following limits have been assumed: $10^{12}$ projectiles / s, 1 fragment / d, $T_1=10^6$ s. The classical r-process corridor is included for orientation. Different neutron densities ($10^{20,23,26}$ n / cm$^3$) and a temperature $T_9=1.35$ have been assumed. The rp-path has been included according to reference [14].
which is in excellent agreement with the calculated prolongation (1.52 s) due to the complete suppression of the internal conversion decay branch \[18\].

**SUMMARY AND OUTLOOK**

In summary, we have demonstrated that the experiments with stored exotic nuclei at relativistic energies have opened up a new era for mass and lifetime measurements. Our accurate mass measurements with cooled nuclei contribute to improve the theoretical models. The unique experimental condition to select the atomic charge states of the fragments down to bare ions can yield new perspectives for beta decay spectroscopy in general and specifically for bound-state beta decay. The conditions to provide pure isomeric beams have been successfully established in our recent $^{140}$Pr run [19].

Presently, we have severe intensity limitations for the primary beams and also in the injection efficiency of the ESR for hot fragments. The future international Facility for Antiprotons and Ion Research FAIR [20] will overcome these shortcomings. A new double-ring synchrotron system (100 / 300 Tm) will accelerate ions up to uranium with intensities of $10^{12}$. The beam of stable isotopes will be converted to rare isotopes with a large-acceptance superconducting fragment separator (Super-FRS) [21] which will efficiently handle also the large phase space of the fission fragments. A dedicated storage ring system will collect, store and cool the fragment beams with minor losses. These new facilities will allow us to substantially extend the nuclear physics research and also the major set of astrophysical relevant nuclei in the nucleosynthesis paths can be studied for the first time, see figure 6.

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