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New Results with Stored Exotic Nuclei at Relativistic Energies

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Recently, much progress has been made with stored exotic nuclei at relativistic velocities ($\frac{v}{c} = 0.7$). Fragments of ^{208}Pb and ^{209}Bi projectiles and fission fragments from ^{238}U ions have been produced, separated in flight with the fragment separator FRS, and injected into the storage-cooler ring ESR for precision measurements. Precise masses of neutron-deficient isotopes in the lead region have been measured with time-resolved Schottky Mass Spectrometry (SMS). A new isospin dependence of the pairing energy was observed due to the improved mass accuracy of typical 1.5×10^{-7} (30 keV). New masses of short-lived neutron-rich fission fragments have been obtained with Isochronous Mass Spectrometry (IMS). An innovative field of spectroscopy has been opened up with lifetime measurements of stored bare and few-electron fragments after applying both stochastic and electron cooling.

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1. Introduction

Experiments with stored exotic nuclei at relativistic energies have a rich discovery potential for nuclear structure research and nuclear astrophysics [1]. Mass and lifetime measurements are key contributions to test the basic nuclear models and to improve the understanding of the nucleosynthesis in stars. The combination of the in-flight separator FRS [2] and the cooler storage-ring ESR [3] provides unique experimental conditions with bare and few-electron ions for all elements up uranium. This allows for the first time investigations in the laboratory under conditions which prevail in stellar plasmas. Changes in the decay characteristics, like lifetime and enhanced or suppressed decay branches, are direct consequences of the ionic charge states.

2. Mass Measurement

2.1. Schottky Mass Measurements of Cooled Fragments

Relativistic fragments have been produced and separated in flight with the FRS. The separated reaction products are injected with a fixed magnetic rigidity of 6.5 Tm into the storage ring ESR. Applying SMS [4,5] the phase space of the ions is reduced by electron cooling which enforces all the stored ions to have the same mean velocity and reduces the velocity spread to roughly 5×10^{-7} dependent on the number of stored ions. The masses are determined via precise measurements of the revolution frequency and the absolute calibration is obtained by the frequency determination of well-known masses.

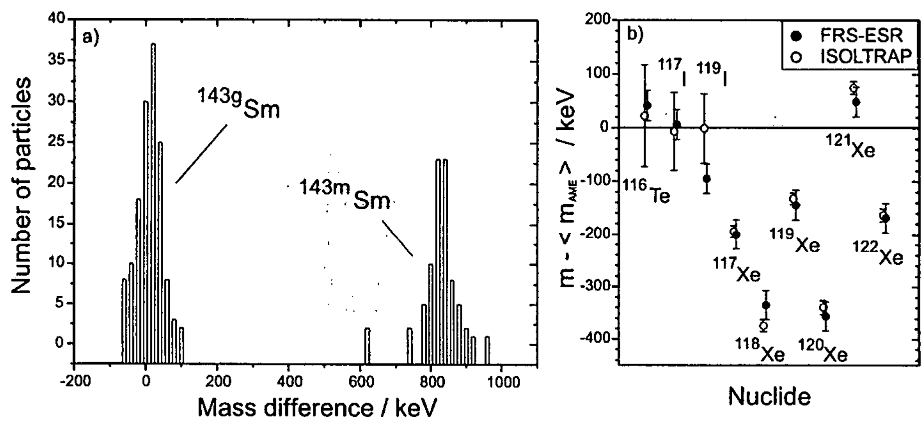

Figure 1. Illustration of the improved accurracy and resolution of SMS. a): the resolving power of SMS is demonstrated for the case of ^{143}Sm ions in the ground and isomeric states. A resolving power of 2×10^6 has been achieved [8,9] by tracing down to single particles. The origin of the horizontal axis represents the corresponding value of AME [7]. b): The measured data from our SMS experiment and from ISOL-Trap [6] are both compared with the prediction of the AME table [7].

The accuracy and resolution of time-resolved SMS have been substantially improved as demonstrated in figure 1 [8]. Tracing the isotope peaks in the time-resolved 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 populated. Additionally, time-resolved SMS provides also an inherent check for the correct isotope identification because the observed decay characteristics has to agree with the assignment from reference masses. The mass accuracy achieved was 30 keV (standard deviation) which represents an improvement of a factor of about three compared to our previous results [4,5]. In figure 1 we present a comparison of our results with the measured data from the Penning trap system at ISOLDE (ISOLTRAP) [6,9]. The agreement between the data sets is excellent which reflects the accuracy of the two experimental methods and also the reliable calibration masses in this mass region. The extended comparison of about 77 mass values measured with SMS and ISOLTRAP is characterized by a reduced χ^2 of 1.12 [9].

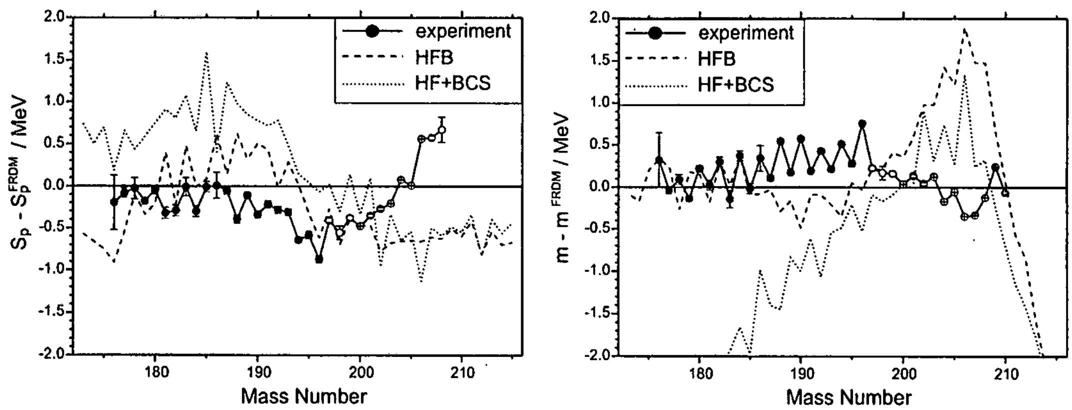

Figure 2. Proton separation energies (left panel) and mass values (right panel) of Tl isotopes compared with the HFB [10], HF+BCS[10] and FRDM[11] mass models. The full circles represent our new mass values.

The large set of new mass values offers an important comparison with theoretical predictions. For example, in figure 2, the one-proton separation energy (S_p) and the absolute mass values of Tl isotopes are compared to different modern mass models. An extensive comparison of all new masses measured since the publication of the AME [7] yields for the deviations of the S_p values 379, 525 and 280 keV corresponding to the models of HFB[10], HF+BCS[10] and FRDM[11], respectively. The accuracy for the separation energies is almost a factor of 2 better than the prediction for the corresponding absolute masses which yield σ_{rms} values of 650, 960 and 372 keV, for the HFB[10], HF+BCS[10] and FRDM[11] models, respectively. Besides this global characterization in terms of rms deviations we present the corresponding comparisons for single isotopes over the mass surface in figure 3.

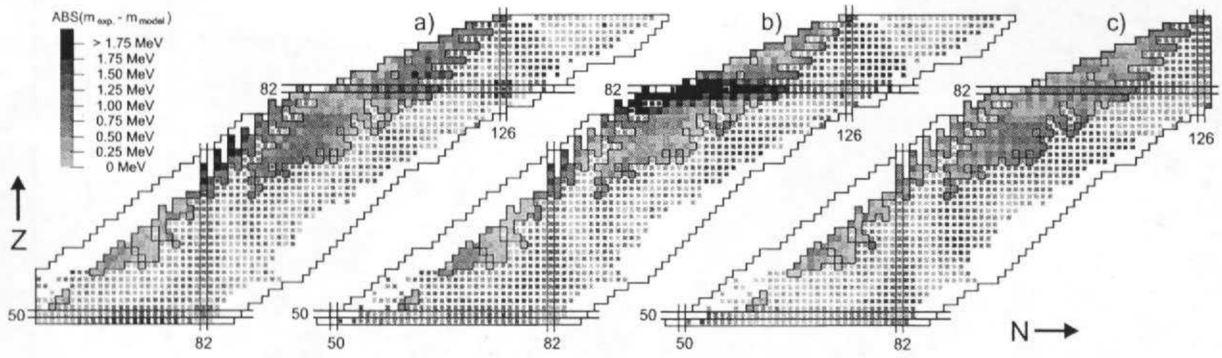

Figure 3. Measured masses compared with models. Absolute deviations of measured masses from the HFB (a), HF+BCS (b) and FRDM (c) models are illustrated on the chart of nuclides. The large squares represent the new masses with respect to the last AME [7]. The comparison yields σ_{rms} values of 650, 960 and 372 keV, for the HFB[10], HF+BCS[10] and FRDM[11] models.

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 as discussed in [12]. In figure 4 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 models. This conclusion holds also for the other elements covered in our measured range of masses [8,9].

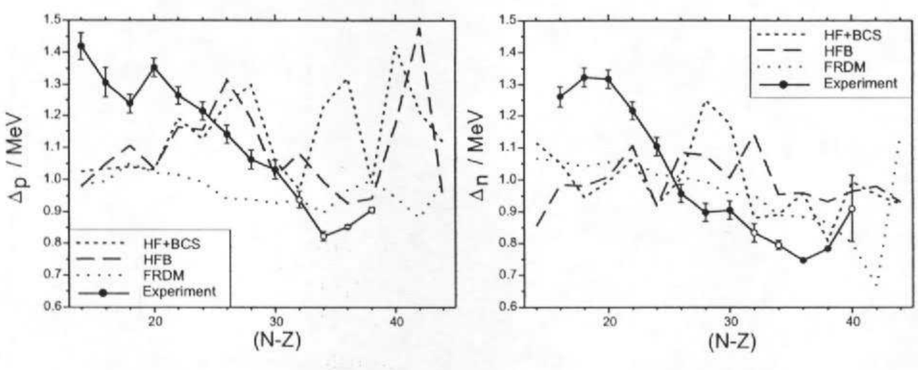

Figure 4. Measured isospin dependence of proton (left panel) and neutron (right panel) pairing-gap energies for even-even tungsten isotopes compared with nuclear models [10, 11]. The experimental values are taken from this work and Ref. [7]. The full circles represent our new values.

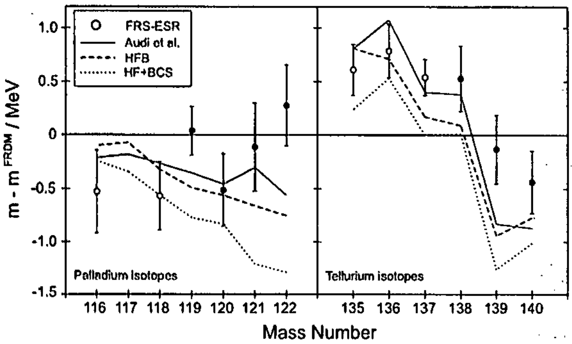

Figure 5. Preliminary experimental data of new masses for Te and Pd isotopes compared with the AME prediction [7] and with theories (HFB[10], HF+BCS[10], FRDM[11]). The isotopes which were measured for the first time are indicated by full circles. The open circles represent previously known masses.

2.2. Isochronous Mass Spectrometry of Short-Lived Stored Ions

Exotic nuclei with half-lives shorter than the electron cooling time can be investigated with time-of-flight techniques when the ESR is operated in the isochronous mode. For isochronous mass spectrometry (IMS)[13] a special magnetic field setting of the ESR causes that the revolution frequency of an ion species is independent of its velocity spread. IMS has been applied for the first time in an experiment with uranium fission fragments. The mass resolution achieved was 2×10^5 and the accuracy about 200-300 keV. A large number of new neutron-rich masses of fission fragments in the element range of $32 \leq Z \leq 57$ has been measured. The analysis of the data is still in progress and represents a special challenge due to missing reliable reference masses in this area. We present an example of measured masses for neutron-rich Pd and Te isotopes compared with theoretical predictions in figure 5. Even this small subset from the new data indicates that the deviations from the theories (HFB[10], HF+BCS[10], FRDM[11]) and from AME extrapolation [7] are larger than the ones observed for the neutron-deficient isotopes discussed above.

3. Lifetime Measurements

Stored exotic nuclei circulating in the ESR offer unique perspectives for decay spectroscopy. The half-life of the stored nuclei can be measured by detecting the daughter nuclides using the difference of their magnetic rigidity (Bρ) compared to the mother nucleus. 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 leaves the closed orbit and can be detected after a dispersive magnetic dipole stage of the ESR lattice. The possibility to investigate bare nuclei allows the measurement of decay properties under the conditions in hot stellar plasmas, i.e., for the first time bound and continuum β^- decays have been simultaneously measured in the laboratory [14]. The measurements of bound-state beta decay (β_b^-) was pioneered at the ESR with incident stable projectiles [15]. Recently, we have started the spectroscopy of stored bare radioactive beams [16]. As an example to demonstrate the power and potential of this novel spectroscopic tool we present the decay measurements of ^{207}Tl fragments in an isomeric state. Bare ^{207}Tl fragments have been separated in-flight with the FRS and injected into the ESR. Since the lifetime of the isomeric state for the neutral ^{207m}Tl atom is only 1.33 s it is too short to be recorded with standard Schottky spectroscopy. However, as demon-

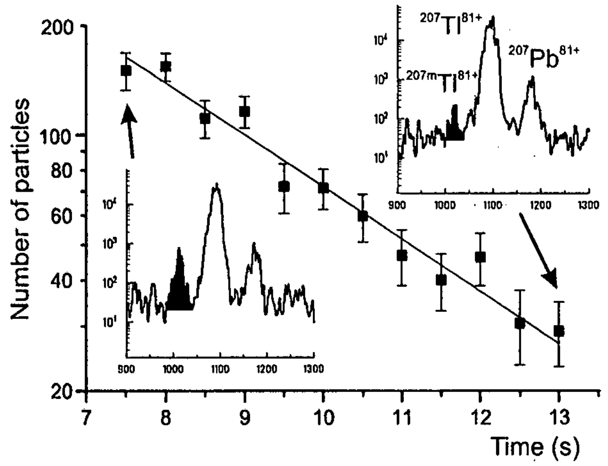

Figure 6. Schottky frequency spectra of the decay of ^{207m}Tl fragments and the corresponding decay curve. The area of the peak in the Schottky spectra is proportional to the number of stored ions. The combination of stochastic and electron cooling yields access to short-lived ions.

strated in figure 6 the combination of stochastic precooling [17] and electron cooling yields access to the spectroscopy of hot fragments with lifetimes in the second range. In the measured Schottky spectrum the ground and isomeric states of ^{207}Tl and the bound-state beta daughter $^{207}Pb^{81+}$ are observed. The half-live of $^{207m}Tl^{81+}$ was determined from the evolution in time of the area of the corresponding peak in the Schottky spectrum, see fig. 6. Our experimental value for bare ^{207m}Tl fragments is 1.48±0.12 s which is in excellent agreement with the calculated prolongation (1.52 s) due to the complete suppression of the internal conversion decay branch.

In summary, we have demonstrated that the experiments with stored exotic nuclei at relativistic energies opens a new range for mass and lifetime measurements and will be extended in the future by nuclear reactions in the internal target.

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