New Mass and Lifetime Measurements of $^{152}$Sm Projectile Fragments with Time-Resolved Schottky Mass Spectrometry

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Abstract

The FRS-ESR facilities at GSI provide unique conditions for precision measurements with stored exotic nuclei over a large range in the chart of nuclides. In the present experiment the exotic nuclei were produced via fragmentation of $^{152}$Sm projectiles in a thick beryllium target at 500-600 MeV/u, separated in-flight with the fragment separator FRS, and injected into the storage-cooler ring ESR. Mass and lifetime measurements have been performed with bare and few-electron ions. The experiment and first results will be presented in this contribution.

I. INTRODUCTION

The mass and the half-life of a nucleus are fundamental properties which result from the interaction of all nucleons [1]. Both quantities are essential for the understanding of nuclear structure and also for the nucleosynthesis in astrophysics.

New phenomena in nuclear physics on shell structure, pairing correlations, etc. have been discovered with precise nuclear masses. The driplines, which determine the borders of nuclear existence, are obtained from the mass differences of neighboring nuclei. The actual paths of the nucleosynthesis in stars are governed by the nuclear binding energies and lifetimes.

A very important motivation for measuring new masses of exotic nuclides is the test and improvement of nuclear theories. Although the progress of the theoretical calculations was enormous in the last years [2, 3], especially in the microscopic calculations, their predictive power is still up to a factor of 100 worse compared to our presently achieved experimental accuracy [4, 5].

In this contribution we report on first results from a very recent experiment performed at GSI. The experiment consisted of two parts. In the first part the lifetimes of stored hydrogen-like $^{140}$Pr$^{58+}$ ions have been measured and the objective of the second part were the masses of neutron-deficient $^{152}$Sm projectile fragments.
The indicated primary beam energy, the production target, degrader, and the energy of the injected into the ESR fragment are those used in the first part of the experiment devoted to the lifetime measurements of stored hydrogen-like $^{140}$Pr$^{58+}$ ions.

II. EXPERIMENT

A. Production, separation, storage, and frequency measurement

Proton-rich nuclides were produced via fragmentation of the 508 and 615 MeV/u $^{152}$Sm primary beam, provided by the heavy-ion synchrotron SIS [6], in the 1032 and 4009 mg/cm$^2$ $^9$Be production targets, respectively. The first combination was used for the lifetime measurements of $^{140}$Pr$^{58+}$ ions and the second one was used in the mass measurements. The target was placed in front of the fragments separator facility FRS [7]. The fragments were separated in flight and injected, stored, and electron cooled in the storage ring ESR [8]. The experimental facility is schematically presented in Figure 1. The experimental conditions used in the first part of the experiment are indicated in the figure.

The injection into the ESR was optimized with the primary beam and the electro-magnetic fields of the FRS-ESR facilities were set at a constant magnetic rigidity value during the
measurements. The magnetic rigidity value of $B\rho=7.655$ Tm was required in the first part of the experiment and $B\rho=6.5$ Tm was used in the part of the experiment aimed at mass measurements of neutron-deficient nuclei. In general, the different selections of the secondary fragments were done by changing the primary beam energy impinging on the production target. The selected reference fragment emerging from the target has then to match the prepared ion-optical setting. In this experiment our reference fragment was $^{108}\text{Sb}^{51+}$. In principle, all fragments in same magnetic rigidity acceptance are transmitted as well. This is successfully used in our mass measurements by simultaneously storing the nuclides with unknown masses and with known masses for calibration.

However, applying another separation criterion in addition we can easily reduce and further select the number of nuclear species injected into the ESR. Such a separation is possible with atomic energy-loss in matter and a two-fold magnetic rigidity analysis, $B\rho-\Delta E-B\rho$ method [7]. The $B\rho-\Delta E-B\rho$ method was applied in this experiment for half-life measurements of hydrogen-like $^{140}\text{Pr}$ fragments. In this case we want to avoid that neither the mother nor the daughter nuclei are contaminated by other fragments, such as e.g. helium-like $^{140}\text{Nd}^{58+}$ ions. Moreover, in order to obtain the exact number of $^{140}\text{Pr}^{58+}$ ions decaying via nuclear electron capture to $^{140}\text{Ce}^{58+}$ ions, the amount of injected daughter ions should be kept as small as possible. 731 mg/cm$^2$ aluminium degrader was used at the middle focal plane of the FRS (see Figure 1). The first half of the FRS before the degrader was set to transmit fully-ionized $^{140}\text{Pr}^{59+}$ ions. By applying this FRS setting, and also using the slit systems, no $^{140}\text{Ce}^{58+}$ ions can be transmitted till the degrader. The atomic charge state distribution after the production target is very similar for praseodymium and neodymium and amounts to about 86% in the fully ionized state, about 13% in the hydrogen-like state, and about 0.5% in the helium-like state (GLOBAL [9] calculations). The corresponding charge state distributions after the degrader are also very similar to the one above (the degrader thickness is well above the equilibrium thickness of about 255 mg/cm$^2$ [9]). Thus, setting the second half of the FRS and the ESR on the wanted $^{140}\text{Pr}^{58+}$, we achieved that the intensity of $^{140}\text{Nd}^{58+}$ in the ESR was less than 1 per mill of the praseodymium intensity. No other fragments have been transmitted in this setting.
The ions injected and stored in the ESR were electron cooled. The electron cooling process contracts the phase-space volume of stored beams and the initial velocity distribution is reduced to typically $\Delta v/v \approx 5 \times 10^{-7}$. At the injection only 25% of the ESR acceptance is filled but after electron cooling the circulating ions have exactly the same mean velocity and thus occupy the entire storage acceptance of about $\pm 1.2\%$ due to their different mass-to-charge ratios. By selecting the voltage of the cooler electrodes we define the velocity of the merged electrons and thus the velocity of the cooled ions.

Besides the electron cooling the ESR is also equipped with a stochastic cooling device which provides fast precooling at a fixed fragment velocity, corresponding to 400 MeV/u, and allows to access shorter-lived nuclei as demonstrated in our previous experiments. This fixed velocity results in a magnetic rigidity of $B\rho=7.655$ Tm in the part of the run devoted to lifetime studies in which we have applied the stochastic cooling. However, for the mass measurements we reduced the magnetic rigidity of the ESR to stay in the optimum operating domain of the electron cooler which was employed throughout the present experiment.

The masses and lifetimes have been measured with the time-resolved Schottky mass spectrometry (SMS). It is based on the Schottky-noise spectroscopy, which is widely used for non-destructive beam diagnostics in circular accelerators and storage rings. The stored ions were circulating in the ESR with revolution frequencies of about 2 MHz. At each turn they induced mirror charges on two electrostatic pick-up electrodes. The 30th-31st harmonics of the signals were down-shifted to the frequency range from 0 to 300 kHz, digitized with a 640 kHz sampling rate, and stored as 16-bit words on a hard-disk for the off-line analysis.

Fast Fourier Transformation is applied to the stored data leading to the revolution frequency spectra. The frequencies provide information about the mass-over-charge ratios of the ions. The area of the frequency peak is proportional to the number of stored ions, which is the basis for lifetime measurements. The details of the data acquisition system and of the data analysis can be found in Ref. and references therein.
B. Magnetic rigidity acceptance of the ESR

It is important to know the range of the mass-over-charge values which can be simultaneously stored in the ESR with given electron cooler parameters such as electron current and cooler voltage. Therefore, we have measured the $B\rho$ acceptance of the ESR.

The $B\rho$ value of any stored ion is defined by its mass-over-charge ratio $m/q$ and its velocity $v$ via:

$$B\rho = \frac{mv\gamma}{q},$$

where $\gamma$ is the relativistic Lorentz factor. For this calibration measurement we used the primary beam $^{152}\text{Sm}^{62+}$ ions with precisely known mass-over-charge ratio [14]. Since the velocity is defined by the electron cooler voltage and electron current, the magnetic rigidity can be determined.

![Calibration of the ESR acceptance with the $^{152}\text{Sm}$ primary beam at different velocities (see text). Beyond the presented data points no orbiting ions were observed.](image)

FIG. 2: Calibration of the ESR acceptance with the $^{152}\text{Sm}$ primary beam at different velocities (see text). Beyond the presented data points no orbiting ions were observed.
The revolution frequency $f$ of the primary beam has been measured with SMS for different beam velocities and the length of the corresponding closed orbit $L$ was then calculated via $f = v/L$.

The experimental data points are shown in Figure 2. The error bars of each point are within the symbol size. The linear fit was used to parameterize the data.

It is obvious that with this calibration one can exactly select the measured mass-over-charge range of stored fragments by varying the cooler parameters.

III. PRELIMINARY RESULTS

A. Mass measurements of neutron-deficient nuclides

The present mass accuracy of the time-resolved SMS is about $30 \, \mu u$ \[4\]. Therefore, the objective of this experiment was the mass surface which is presently unknown or experimentally known but with error bars larger than the SMS accuracy. The present status of knowledge of nuclear masses was taken from the Atomic Mass Evaluation (AME) 2003 \[14\].

The production yields, ionic charge-state distribution, transmission through the FRS, and injection into the ESR have been calculated with the MOCADI \[15\] and the LISE++ \[16\] codes. The optimum setting was obtained for $^{108}\text{Sb}^{51+}$ ions being at the magnetic rigidity of 6.5 Tm corresponding to the central orbit of the FRS.

Using the calibration curve from Figure 2 the cooler voltages were calculated which are needed to cover the mass surface aimed at in the experiment. The voltage was varied in steps of 2 kV from 190 kV till 220 kV. The cooler current was kept constant at 0.4 A, a relatively high current chosen for fast electron cooling. With these parameters, the nuclei with half-lives longer than one second are expected to be recorded in the frequency spectra.

A part of the chart of nuclides with the mass surface expected to be covered in this experiment is shown in Figure 3. The developed single particle method \[4, 17\] is the base for precise mass determination of even a single stored ion. Thus, particle yields in the ESR as low as one ion in one hundred injections could be measured. The analysis of the data is in progress. The presently identified nuclides are indicated in the figure with white crosses.
FIG. 3: Part of the chart of nuclides showing the mass surface which is expected to be covered in this experiment. The rp-path [18], the stable nuclei, and the nuclides with very well known mass values [14] are indicated in the figure. Nuclides so far identified in the frequency spectra of this work are indicated with white crosses.

One can see from Figure 3 that the expected mass surface as well as some of the presently identified nuclides lie close to the calculated rp-process path [18].

An example of a measured Schottky frequency spectrum is shown in Figure 4. Two nuclides with presently unknown mass values [14] are indicated.
FIG. 4: Part of a Schottky frequency spectrum. Known and unknown masses are indicated according to the AME 2003 [14].

B. Lifetime Measurement with Single Stored Fragments

Already in previous experiments we have proven that we are sensitive and selective to single particles stored and cooled in the ESR. SMS is ideally suited to measure decay properties of bare and few-electron fragments if the Q-value and the change in $B\rho$ are not exceeding the storage acceptance of the ESR [19, 20, 21]. In case the change of $B\rho$ values in the decay is too large, the daughter nuclei can be intercepted by detectors placed outside the storage orbits of the fragments. In this experiment we aimed at investigating the decay of a nucleus with a strong electron capture (EC) branch and a half-life in the order of a few minutes. The selected nucleus was $^{140}$Pr$^{58+}$ characterized with a $Q_{EC}$ value of 3388 keV. Mother and daughter nuclei are well resolved in the Schottky spectrum and we specifically aimed our measurements on the study of single particle decay such that we observed mother and daughter nuclei discretely changing the area of the corresponding Schottky frequency peaks. This is really a unique measurement and can be only performed with our facilities under the described conditions. An example of measured decays with only a few mother...
More than 4 particles
4 particles
3 particles
2 particles
1 particle

**FIG. 5:** A series of subsequent-in-time Schottky frequency spectra of mother $^{140}$Pr$^{58+}$ and daughter $^{140}$Ce$^{58+}$ ions. About six mother nuclei were initially stored. Two out of them decayed via nuclear electron capture into $^{140}$Ce$^{58+}$. The correlated intensity changes are clearly seen. Other ions decayed via $\beta^+$ decay or were lost e.g. due to interaction with the residual gas.

nuclei is illustrated in Figure 5 where a series of subsequent-in-time Schottky frequency spectra are plotted. Goals of this experimental study are to check the SMS with nuclei of well-known lifetimes down to a few stored ions and to investigate the decay statistics under these extreme conditions.

**IV. TOWARDS PURE ISOMERIC BEAMS FOR THE ILIMA PROJECT**

Although the present experimental program at the SIS-FRS-ESR facilities has been quite successful and has led to several basic discoveries, the field of research is expected to be
drastically extended by the next-generation facility FAIR. It will consist of a more powerful driver accelerator, a large acceptance in-flight separator Super-FRS, and a new storage-cooler ring system specially adapted to the large phase space and short half-lives of the exotic nuclear beams. Within the FAIR framework, ILIMA is an accepted proposal which will be an extension of the present successful program at the FRS-ESR. One goal is to provide pure isomeric beams circulating in the new storage ring system to be investigated and used in reactions with the internal target or collision zones with other stored particles as electrons or antiprotons. An important demonstration of the feasibility in this direction has been achieved in the present experiment by scraping off one component of the mother and daughter nuclei recorded with SMS. The goal was achieved by a precise mechanical scraper at a dispersive plane in the ESR. This mechanical separation in the micrometer range brought the success as demonstrated in Figure 6. The technique which

FIG. 6: Schottky frequency spectra of well resolved mother and daughter ions characterized by a Q value of about 3 MeV. Note, that we can inject monoisotopic fragment beams in the ESR as we have proven many years ago. Left panel: undisturbed mother and daughter traces in time recorded for about 520 s. Right panel: 170 s after the injection into the ESR, the primary beam of mother ions was eliminated by mechanical scraping. This is a demonstration for the feasibility to provide pure isomeric beams in the storage rings.
has been applied is very similar to one developed for the measurements of the horizontal beam size of cooled ion beams with micrometer resolution [26]. More sensitive methods to achieve the micrometer separation [26] can be done by moving the stored beam towards a fixed position of the scraper.

V. CONCLUSION

The time-resolved Schottky Mass Spectrometry has again proven its great potential for precise mass determination of short-lived nuclides [4]. In this work the technique was now applied to neutron-deficient nuclides below samarium. The covered mass surface is very close to the astrophysical rp-process path. Thus our results will contribute to a better understanding of this nucleosynthesis process.

Unique results have been achieved in the present experiments with lifetime measurements of a few mother nuclei stored in the ESR.

An important step towards the future has been achieved with the demonstration of a method to provide pure isomeric beams. The spatial separation of ground states or isomeric states with excitation energies of at least 3.5 MeV is now a realistic perspective.

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