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Recent results on mass measurements of exotic nuclides in storage rings

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for ESR & CSRe Collaborations on In-Ring Mass Measurements

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Abstract. Storage ring mass spectrometry allows for simultaneous measurements of masses of a large amount of nuclides. Two measurement techniques, isochronous and Schottky mass spectrometry, are applied. The clear advantage of the storage ring mass spectrometry is that only a few particles are required to measure their mass with high accuracy. In this contribution we address the most recent results obtained at the two presently operating facilities, namely the Experimental Storage Ring (ESR) in Darmstadt and the Experimental Cooler-Storage Ring (CSRe) in Lanzhou.

1. Introduction

It is well known in physics that the total energy of a closed system is its fundamental constant which results from all interactions and correlations of the constituent particles. In this respect nuclei are fascinating many-body objects in which the strong, weak, and electromagnetic fundamental interactions take place by acting between two types of nucleons, protons and neutrons. Via the famous equation of A. Einstein, the total energies of the nuclei can directly be connected to their masses.

Nuclear masses are indispensable quantities for investigations of nuclear structure [1, 2] as well as for our understanding of nucleosynthesis processes in stars [1, 3, 4]. For the latter, nuclear masses determine – through nucleon separation energies – the paths of various processes on the nuclidic chart [3, 4]. Today the nuclei of interest with yet unknown masses lie typically far away from the valley of β -stability. We emphasise, that many of nuclei, which for instance are involved in the rapid-neutron capture process (*r*-process), are not accessible at the present radioactive ion beam facilities and their masses have thus to be obtained from theory. Such nuclides can be characterised by a strong asymmetry of their proton-to-neutron ratio and can reveal unexpected nuclear structure effects. Therefore new experimental nuclear masses are essential to test and improve nuclear models. However, these nuclei are difficult to investigate due to their small production cross-sections and short lifetimes (see, e.g., [5]). Hence, their studies require very efficient and fast experimental techniques [6, 7]. Two highly complementary



experimental techniques are routinely used. These are the Penning trap [1] and storage ring mass spectrometry [8].

In this contribution we briefly review recent results obtained with storage ring mass spectrometry.

2. Experimental facilities

Two ion storage ring facilities conducting in-ring mass measurements of exotic nuclides are in operation today [9]. One of these facilities is located at the GSI Helmholtz Center in Darmstadt, Germany (GSI) [10] and the other one is built at the Institute of Modern Physics, Chinese Academy of Sciences in Lanzhou, China (IMP) [11]. The high energy parts of both facilities are based on a similar principle. The driver accelerators are heavy-ion synchrotrons, SIS-18 [12] at GSI and CSRm [13] at IMP, which are respectively connected to the Experimental Storage Ring ESR [14] and the experimental Cooler-Storage Ring CSRe [13] via in-flight fragment separators FRS [15, 16] and RIBLL2 [13]. The storage rings are schematically illustrated in Figure 1.

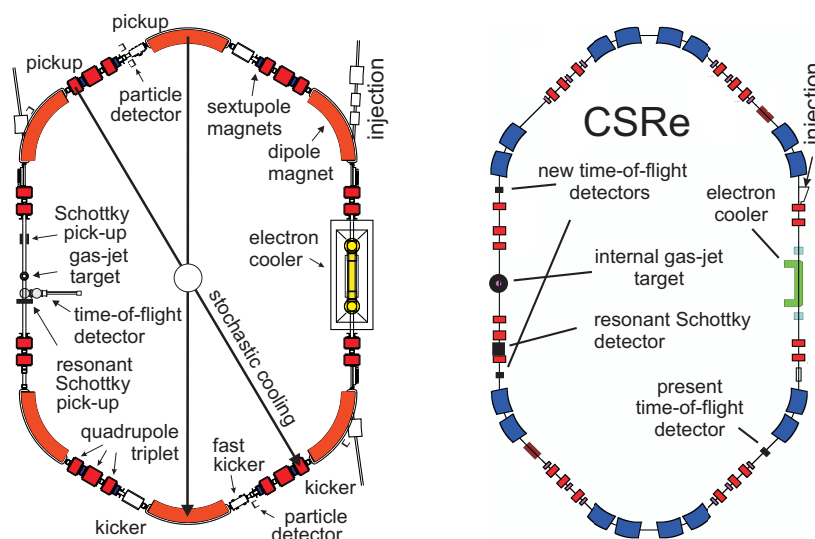


Figure 1. Schematic view of the Experimental Storage Ring (ESR) [14] (left) and the experimental Cooler-Storage Ring (CSRe) [13] (right). The stored beams circulate clockwise in the rings. The rings are equipped with systems for stochastic- [17] and electron [18] cooling, various instrumentations and detection systems [19], internal targets [20], devices for (de)acceleration as well as for bunching of the stored beams [21], etc. Adopted from [9, 22].

The ESR [14] is a storage-cooler ring with two arcs and two straight sections. Its mean circumference is 108.36 m. It consists of 6 dipole magnets (deflection angle is 60°). The ESR can operate up to a maximum magnetic rigidity of 10 Tm and is capable of storing, cooling, accelerating or decelerating stored beams as well as extracting them towards external setups. The CSRe [13] has a mean circumference of 128.8 m and a maximal magnetic rigidity of 8.4 Tm. It has eight 45° bending sections, each of which consists of two dipole magnets. Both storage rings operate under ultra-high vacuum (UHV) conditions of about 10^{-11} mbar, which inevitably requires that in-ring instrumentations are bakeable to about $150\text{--}200^\circ\text{C}$ and have to be made of UHV materials. In addition to direct mass measurements, which will be discussed in more detail below, the rings are routinely used for a broad range of atomic physics experiments [23, 24], dielectronic recombination on stable and radioactive ions [25, 26, 27, 28], studies of nuclear reactions with internal targets [29, 30, 31, 32, 33]. Owing to the UHV and high kinetic energies,

storing and investigations of radioactive decays of highly-charged ions is possible. For more details see, e.g., Refs. [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45].

3. Storage ring mass spectrometry

For ions stored in a storage ring holds the following relationship, which connects the relative revolution frequencies (f) or revolution times (t) of the circulating ions to their relative mass-over-charge ratios and velocities [8, 46]:

$$\frac{\Delta f}{f} = -\frac{\Delta t}{t} = -\alpha_p \frac{\Delta(m/q)}{m/q} + (1 - \alpha_p \gamma^2) \frac{\Delta v}{v}, \quad (1)$$

where α_p is the momentum compaction factor, which characterises the relative variation of the orbit length of stored particles per relative variation of their magnetic rigidity. The $\alpha_p = -1/\gamma_t^2$ is nearly constant over the entire revolution frequency acceptance of the storage ring, and γ_t is the so-called transition point of a ring [8].

From Eq. (1) it follows that in order to determine m/q values of the stored ions, one needs to measure revolution frequencies (or revolution times) of the ions. The magnitude of the second term on the left hand side determines the mass resolving power and it has to be made as small as possible.

One way to minimise the second term in Eq. (1) is to reduce the velocity spread $\Delta v/v$, which can be done by applying beam cooling. This allows for the reduction of the energy spread of the ions induced by the production reaction process. Stochastic [17] and/or electron [18, 47] cooling techniques are applied which enable beams with the highest phase-space density. For electron cooled beams, the momentum spread of stored ions $\delta p/p$ is determined by the equilibrium between the Coulomb interactions with cold electrons in the cooler device and the intra-beam scattering [47]. If the electron cooling is applied to low intensity (below about a thousand ions) fragment beams, then the velocity spread as low as a few 10^{-7} can be achieved [48, 49]. Electron cooling requires at least a few seconds which sets a limit on half-lives of the nuclides that can be studied. Applying the stochastic cooling prior to the electron cooling allows for reducing the cooling time [50, 51]. The revolution frequencies are measured with non-destructive Schottky detectors. The details on the Schottky detector and data acquisition can be found in Refs. [8, 43]. This is the so-called *Schottky Mass Spectrometry* (SMS) [52, 53].

The second way to minimise the second term in Eq. (1) is based on a special isochronous ion-optical mode of the ring. The ions are injected into the ring at energies corresponding to $\gamma = \gamma_t$. The γ_t -values are $\gamma_t(\text{ESR}) = 1.41$ and $\gamma_t(\text{CSRe}) = 1.395$ [9]. In this mode the velocity spread is compensated by the orbit lengths of the stored ions. This simply means that faster and slower ions of the same nuclear species are stored on the longer or shorter orbits, respectively, such that they have the same mean revolution frequency. This is the prerequisite for the so-called *Isochronous Mass Spectrometry* (IMS) [54, 55, 56]. Since the IMS does not require beam cooling, it is ideally suited for the mass measurements of the shortest-lived nuclides. The revolution frequencies are obtained by using dedicated time-of-flight detectors [57, 58]. Very recently a novel resonant Schottky detector [59, 60] was developed which will allow for an accurate revolution frequency determination within a few tens of milliseconds and which thus can be employed in the IMS [61, 62]. The dramatic improvement in the speed of measurements enabled now applying SMS also in the isochronous mode.

More than 1000 masses have been measured with the IMS and SMS at the ESR and CSRe, which enabled numerous investigations of nuclear structure and astrophysics questions [46, 52, 56, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79].

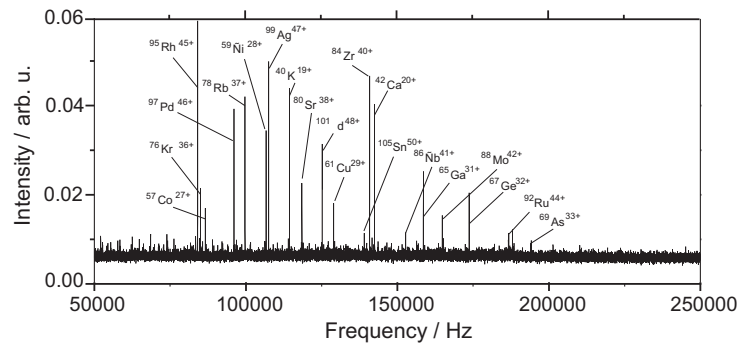


Figure 2. (Colour online) A part of Schottky revolution frequency spectrum of ^{152}Sm projectile fragments. Adopted from Ref. [80].

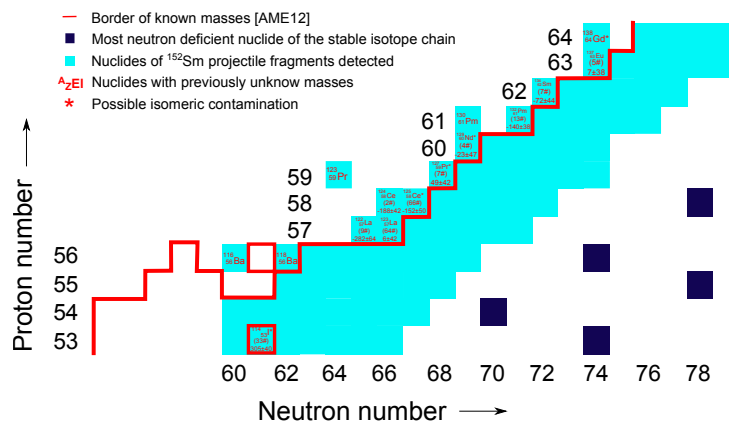


Figure 3. (Colour online) A part of the nuclidic chart above iodine ($Z \geq 53$) with the mass surface measured in this experiment. Fifteen nuclides whose masses were obtained for the first time are indicated. Adopted from Ref. [81].

4. Schottky mass measurements ^{152}Sm projectile fragments in the ESR

To date, the Schottky mass measurements were conducted only in the ESR [8, 62, 82]. For cooled ions the ESR acceptance corresponds to $\Delta(m/q)/(m/q) = \pm 1.2\%$ which allows for simultaneous mass measurements of many nuclides [83]. In the last three years, masses of several tens of neutron-rich heavy isotopes were published [73, 78]. Furthermore, several new isotopes [69, 84, 85] and isomers were discovered [66, 68, 70, 75, 76, 79, 86].

Here we report on the mass measurements of neutron-deficient ^{152}Sm projectile fragments, the data analysis of which has been completed. The experiment was performed in 2005 [41, 80]. Primary beam of ^{152}Sm ions was extracted from the SIS at 508 AMeV or 615 AMeV. It was fragmented in 1032 or 4009 mg/cm² ^9Be production targets, respectively. Two about 12 hours long settings have been done in this experiment. The fragments centred around $^{108}\text{Sb}^{51+}$ or $^{140}\text{Ce}^{58+}$ ions were separated in-flight and injected, stored, and electron-cooled in the ESR. The revolution frequencies were measured with a capacitive Schottky detector. The details of the Schottky data processing and the isotope identification can be found in Refs. [46, 52, 65, 83].

A part of a typical revolution frequency spectrum obtained in this experiment is shown in Figure 2. The mass surface covered in this experiment consists of more than 370 different nuclides. Masses of fifteen nuclides were determined for the first time. A relative mass accuracy

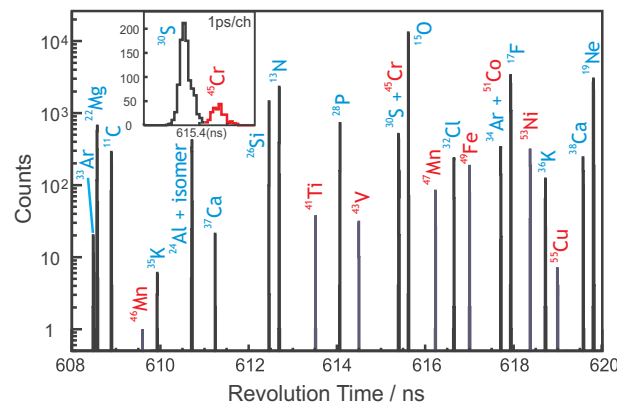


Figure 4. A part of the revolution time spectrum of neutron-deficient ^{58}Ni projectile fragments measured in the CSRe [77]. The insert shows the well-resolved peaks of $^{30}\text{S}^{16+}$ and $^{45}\text{Cr}^{24+}$ nuclei, which have very similar m/q values. Nuclei with masses determined in this experiment and those used as references are indicated with bold and italic letters, respectively. Taken from [74, 77].

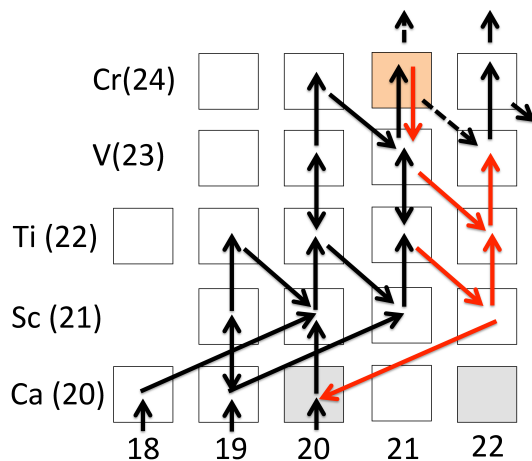


Figure 5. The main time-integrated reaction flow in the Ca-Cr region during an X-ray burst. Black arrows show the reaction flow for the new $S_p(^{45}\text{Cr})$ value. The red arrows indicate the reaction flow for the lowest $S_p(^{45}\text{Cr})$ value allowed by the 3σ uncertainties from AME03 [87]. Flows that disappear for the latter case are indicated as black dashed arrows. Taken from [77].

$\Delta m/m$ of a few 10^{-7} was achieved. The new masses are indicated on the nuclidic chart shown in Figure 3. The preparation of the publication is in progress [81].

5. Isochronous mass measurements ^{58}Ni projectile fragments in the CSRe

Isochronous mass measurements are conducted at the ESR as well as at the CSRe [56, 64, 71, 72, 74, 77]. Since no cooling is applied, the measured spectrum is about a six times broader ($\Delta(m/q)/(m/q) \approx 13\%$) than a typical revolution frequency spectrum of cooled ions. In the last three years a series of experiments addressing neutron-deficient nuclides has been performed at the CSRe [71, 72, 74, 77]. Here we address only the latest results on the mass measurement of ^{45}Cr (see [77]).

In this experiment, primary beam of $^{58}\text{Ni}^{19+}$ ions accelerated by the CSRm to an energy of 463.36 AMeV was fragmented in about 15 mm thick beryllium target placed at the entrance of the RIBLL2. Neutron-deficient fragments centred around $^{47}\text{Mn}^{25+}$ were separated in flight with RIBLL2 and injected into the CSRe. The CSRe was tuned into an isochronous ion-optical

mode. Typically, about 10 ions were stored simultaneously after each injection. The revolution times of the stored ions were determined with a dedicated timing detector [58]. The details of the detector operation, data acquisition, and data analysis can be found in Refs. [58, 71, 72, 88]. A typical revolution time spectrum is illustrated in Fig. 4. The inset shows the resolved peaks of $^{30}\text{S}^{16+}$ and $^{45}\text{Cr}^{24+}$ ions. The mass of the latter was determined in this experiment for the first time and amounts to $ME(^{45}\text{Cr}) = -19515(35)$ keV, where a contamination by a recently observed isomeric state at $E^* = 107$ keV [89] had to be taken into account.

The new mass of ^{45}Cr has an effect on the modelling the rapid proton capture process (rp -process) in X-ray bursters [90]. The new value of the proton separation energy of ^{45}Cr is $S_p(^{45}\text{Cr}) = 2684(125)$ keV [77]. Figure 5 shows a part of the nuclidic chart around titanium and the path of the rp -process as obtained from a single-zone calculation [91, 92]. The double arrows indicate nuclides which are in $(p, \gamma) - (\gamma, p)$ equilibrium. Important here is the case of ^{44}V and ^{43}Ti nuclides. The flow here is determined by the $^{44}\text{V}(p, \gamma)^{45}\text{Cr}$ reaction rate, the so-called $2p$ -capture process on ^{43}Ti [91]. The value of $S_p(^{45}\text{Cr})$ effects this rate. For a low $S_p(^{45}\text{Cr})$, the $^{45}\text{Cr}(\gamma, p)^{44}\text{V}$ reaction becomes effective and thus reduces the proton capture flow at ^{43}Ti and leads to an increased β -decay branch in ^{43}Ti . The proton capture on the β -decay daughter ^{43}Sc nuclei has a large (p, α) branch which leads to ^{40}Ca (see red arrows in Figure 5). This is a so-called Ca-Sc cycle [93, 94] which limits the reaction flow towards heavier elements. The new $S_p(^{45}\text{Cr})$ value constrains the proton capture flow through ^{43}Ti and allows one to exclude a possible formation of a strong Ca-Sc cycle in X-ray bursts.

6. Summary and Outlook

Storage ring mass spectrometry has been applied to neutron-deficient nuclides. Two examples of mass measurements conducted at the ESR and CSRe are presented here.

Schottky mass spectrometry was applied to ^{152}Sm projectile fragments. Masses for fifteen nuclides were obtained for the first time. The publication of these results is in preparation [81].

Since a few years isochronous mass measurements are successfully conducted at the CSRe [95]. In this contribution we addressed the mass measurement of ^{45}Cr and its impact on the rp -process of nucleosynthesis.

Concerning the future experiments, it is important to emphasise new technical developments which are ongoing. One of them is the commissioning in the ESR and CSRe of the resonant Schottky detectors which have by a factor of about 100 better signal-to-noise characteristics than the older capacitive pickups [59, 60]. Another one is the planned setup of two time-of-flight detectors which is being done in the CSRe and which will enable an in-ring velocity measurement of every stored ion [95, 96]. The latter is an essential quantity to enable a high resolving power over the entire revolution time spectrum [97].

Storage ring mass measurements are planned also at future radioactive beam facilities. A dedicated isochronous storage ring, the RI-Ring [98], is being commissioned at RIKEN Nishina Center in Japan [99], where the highest beam intensities are presently offered. The ILIMA project [100] aims at mass measurements at the future FAIR facility [101, 102]. The key facilities here are the Super-FRS [103] and the collector ring (CR), which is particularly designed for conducting IMS. The CR will be equipped with two ToF detectors installed in one of the straight sections. Employing the novel resonant Schottky detectors will enable simultaneous broad-band mapping by SMS technique of nuclear masses and lifetimes [61, 100, 104]. In China, a concept for a new project, High-Intensity Accelerator Facility, is being prepared where one of the key experiments will be IMS.

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