Mass Measurements of Short-lived Nuclides at the Heavy-ion Storage Ring in Lanzhou

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ABSTRACT

Isochronous Mass Spectrometry (IMS) has been established at the experimental Cooler Storage Ring (CSRe) at the Heavy Ion Research Facility in Lanzhou (HIRFL), of the Institute of Modern Physics (IMP), Chinese Academy of Sciences. Based on the IMS technique, a series of experiments have been performed employing the fragmentation of the energetic beams of 36,40 Ar, 58 Ni, 78 Kr, 86 Kr, and 112 Sn projectiles. Masses of short-lived nuclides on both sides of the stability valley are measured. Relative mass precision of down to 10^{-6} – 10^{-7} is routinely achieved. The mass values are used as an input for dedicated nuclear structure and astrophysics studies. In this article, we briefly review the experiments that have been conducted up to now and the main results that have been achieved. We also outline the plans for future experiments.

INTRODUCTION

Nuclear binding energy is a fundamental quantity of an atomic nucleus, which reflects the net effect of complex interactions among its constituent protons and neutrons. The binding energies are straightforwardly derived from the experimentally determined nuclear masses. Precise and systematic measurements of nuclear masses provide not only indispensable information on nuclear structure, but also deliver important input data for applications in nuclear astrophysics [1–3]. Historically, the well-known shell structure and pairing correlations were discovered in stable nuclei via nuclear masses [4]. Similarly, new nuclear structure effects may be seen as irregularities on a generally smooth nuclear structure is to understand shell structure evolution at extreme neutron-to-proton

ratios, where the well-known magic numbers may disappear and new shell closures may form [6–8].

More than 7000 nuclides are theoretically expected to exist while only 2496 masses are known experimentally [9]. The nuclides with still unknown masses lie far away from the valley of β -stability. The challenge today is to achieve measurements of very exotic nuclei, which are produced with small cross-sections and have short life-times.

New mass measurements inevitably require very efficient and fast experimental techniques [10]. One of the techniques is mass spectrometry based on heavy ion storage rings [11]. In this article, we present a brief introduction to the facilities and the characteristic experiments performed in the Cooler Storage Ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) [12]. Selected recent results and their impact for nuclear physics and astrophysics are reviewed. Planned technical developments and the envisioned future experiments are outlined.

ISOCHRONOUS MASS SPECTROMETRY

Isochronous Mass Spectrometry (IMS) was pioneered at the GSI Helmholtz Centre for Heavy Ion Research (GSI) in Darmstadt [13]. For ions stored in a storage ring, their revolution times, T, are related to the mass-to-charge ratios m/q via the following expression:

$$T = \frac{L}{c} \sqrt{1 + \left(\frac{mc}{q}\right)^2 \cdot \frac{1}{\left(B\rho\right)^2}} \tag{1}$$

where L is the orbit length of the circulating ion, c the speed of light in vacuum, and $B\rho$ the magnetic rigidity. Since the ions within a certain acceptance of magnetic rigidity, $\Delta B\rho$, are all stored and circulate in the ring, their orbit lengths are not the same. In the first order approximation, the relative time changes, $\Delta T/T$, are determined by [13–16]:

$$\frac{\Delta T}{T} = \frac{1}{\gamma^2} \cdot \frac{\Delta(m/q)}{m/q} + \left(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}\right) \cdot \frac{\Delta(B\rho)}{B\rho}$$
(2)

where γ is the relativistic Lorentz factor, and γ_t is the socalled transition energy of the ring, which connects the relative change of the orbit length to the relative change of magnetic rigidity of the circulating ions. In order to determine m/q-values of stored ions, revolution times of the ions need to be measured and the second term has to be made negligibly small. One way to achieve the latter is to use a special ion-optical setting of the ring and to inject the ions with $\gamma = \gamma_t$. This is the basis of isochronous mass spectrometry (IMS) [14–16]. Under this isochronous condition, the magnetic rigidity spreads, $\Delta B\rho$, of the stored ions are compensated by the orbit lengths and their revolution times are a direct measure of m/q of the ions. IMS is ideally suited for the mass measurement of short-lived nuclides [17].

EXPERIMENTAL MEASUREMENTS

HIRFL-CSR is an acceleration complex that consists of a Separated Sector Cyclotron (SSC, K=450), a Sector Focusing Cyclotron (SFC, K = 69), a main Cooler Storage Ring (CSRm) operating as a heavy-ion synchrotron, and an experimental storage ring (CSRe). The two storage rings are coupled by an in-flight fragment separator, RIBLL2. The high-energy part of the facility is schematically shown in Fig. 1. The CSRm has a circumference of 161 m and a maximum magnetic rigidity $B\rho$ =12.05 Tm. ¹²C⁶⁺ and ²³⁸U⁷²⁺ ions can typically be accelerated to about 1 GeV/u and 400 MeV/u, respectively. The CSRe has a circumference of 128.8 m and a maximal magnetic rigidity of 9.4 Tm [12, 18]. γ_t of the CSRe is changeable from 1.30 to 1.40.

Accelerated in the main cooler-storage ring (CSRm) to typically 350–480 MeV/u, stable ion beams of $\sim 1 \times 10^8$ particles per spill are fast extracted and focused upon a 10–15 mm thick beryllium target placed in front of RIBLL2. The reaction products from projectile fragmentation are selected and analyzed [19] by RIBLL2 and a cocktail beam is injected into the CSRe. The optical settings of RIBBL2 and the CSRe are tuned for the ion species of interest. All other nuclear species within the $B\rho$ acceptance of $\pm 0.2\%$ of the RIBLL2-CSRe system are transmitted and stored as well. In order to fulfil the requirements of IMS, the primary beam energy has been selected according to the LISE++ simulations [20], such that the ions of interest have the most probable velocity with $\gamma = \gamma_t$ at the exit of the target after the production target. In typical IMS experiments at the CSRe, a total of less than 40 ions are usually stored in each injection.



Fig. 1: (a) The high-energy parts of the HIRFL-CSR complex at IMP including the synchrotron CSRm, the in-flight fragment separator RIBLL2, and the experimental storage ring (CSRe) [18]. (b) Schematic view of the timing detector [21].

The revolution times are measured using a dedicated time-of-flight (TOF) detector [21] (see Fig. 1) that is equipped with a 40 mm diameter, 19 µg/cm2 carbon foil. Each time an ion passes through the foil, secondary electrons are released from the foil and transmitted isochronously by perpendicularly arranged electric (E) and magnetic (B) fields to a microchannel plate (MCP) counter. The signals from the MCP are guided without amplification directly to a fast digital oscilloscope at a sampling rate of 50 GHz. The typical rise time of the signals ranges from 0.25 ns to 0.50 ns. The time resolution of the TOF detector is about 50 ps, and the detection efficiency varies from $\sim 20\%$ to $\sim 70\%$ depending on the charge and overall number of stored ions (see Refs. [21, 22] for more details). The recording time is usually longer than 200 µs, corresponding to more than 300 revolutions of the ions inside the ring.

The revolution time of each individual ion is extracted

from the measured periodic timing signals [21, 22]. The full data analyses, including time shift correction and particle identification, have been conducted following the procedures described in Refs. [22–24]. Figure 2 shows a typical revolution time spectrum for the ⁵⁸Ni projectile fragments zoomed in at the time window of $608 \le T \le 619$ ns [25]. The standard deviation of the time peak for ⁵²Co is σ_t =0.7 ps, corresponding to a resolving power of 3.7×10^5 .



Fig. 2: Part of the revolution time spectrum zoomed in at a time window of $608 \le T \le 619$ ns. The red and black peaks represent the $T_z = -1$ and -1/2 nuclei, respectively. The insert shows well-resolved peaks of the ground state and the low lying 2⁺ isomer of ⁵²Co [25].

Usually, quite a few nuclides with well-known masses [9] are present in the revolution time spectrum. These nuclides are used to calibrate the time spectrum employing a polynomial function of up to the third order [23]. The unknown m/q values of the nuclides are determined by interpolating or extrapolating with the fitted function of m/q versus T. Details on the data analysis can be found in Refs. [22–24].

EXPERIMENTAL RESULTS

A series of experiments have been conducted using 36,40 Ar, 58 Ni, 78,86 Kr, and 112 Sn primary beams. Figure 3 shows the summary of masses measured at the CSRe. Typical relative mass uncertainties of $\delta m/m = 10^{-6}-10^{-7}$ are achieved. While the data analysis for the neutron-deficient 112 Sn projectile fragments and the T_z=-2 pf-shell nuclides using a 58 Ni beam are still in progress (T_z stands for the isospin projection defined as T_z=(N-Z)/2), some results have been published in Refs. [23, 25–39] and the new mass values have been included into the latest Atomic Mass Evaluation AME'16 [9]. Based on the precision mass values, some issues in nuclear

structure have been studied, such as a) the A-dependence of vector and tensor Coulomb energies in $T_z=-1$, fp-shell nuclei, the residual proton-neutron interactions around doubly magic nuclei and the predictive power of different nuclear mass models [23]; b) the validity of isobaric multiplet mass equation in pf- and sd-shell nuclei [23, 25, 27, 34, 35, 37]; c) the N=32 neutron shell closure in scandium [30, 38]; d) the isospin non-conserving forces [29, 34]; and e) the test of conserved vector current (CVC) hypothesis [32]. In addition, we have addressed the waiting point [26, 31], the Ca-Sc and Zr–Nb cycles [28, 36] in the rp-process of stellar nucleosynthesis. Readers can refer to the above-mentioned papers for details, as some selected topics are addressed in the listed works. Earlier reviews of our work can be found in Refs. [3, 40–42].



Fig. 3: A summary of isochronous mass measurements performed at IMP (see Refs. [22, 23, 25–30, 32, 36–38]).

A. Test of nuclear mass models

The masses of the $T_z = -1$, -3/2, -2 pf-shell nuclei have been measured using IMS in the CSRe (see Fig. 3). The highest precision of 5 keV for ⁵⁴Ni has been achieved, corresponding to the relative uncertainty of $\delta m/m = 1 \times 10^{-7}$. These new results allow us to test the accuracy and the predictive power of different mass models. The accuracy of the current theoretical nuclear mass models has been recently investigated in Ref. [43]. Among the ten often-used models of various natures, the macroscopicmicroscopic model of Wang and Liu [44, 45], with the latest version labeled WS4 [46], and the Duflo and Zuker (DZ28) mass model [47] have been found to be more accurate in various mass regions with the smallest rms (root-mean square) values of 250–500 keV. Their mass predictions are compared with the experimental masses for the T_z =-1 nuclei in Fig. 4. We also plot the calculated results from the ETFSI-Q mass table [48]. One can see the prediction powers and accuracies of the models. We noticed that the differences between model predictions and the experimental masses, ME_{th}-ME_{exp}, show oscillations for all models. Only the WS4 model yields a regular zig-zag staggering around zero (see Fig. 4). This may indicate that the smooth A-dependence of nuclear masses have been properly described in WS4 with respect to the other models, leading to a more accurate description of the nuclear masses. Of course, refined treatments of nuclear pairing are still needed in order to reduce the staggering.



Fig. 4: Differences of the experimental mass excesses (ME) and the model predictions for the $T_z = -1$ nuclei.

The masses of lighter neutron-deficient nuclei can be more precisely predicted by using the local mass relationships such as the well-known Garvey and Kelson (GK) [49] mass relation and the isobaric multiplet mass equation (IMME). The GK mass relation has been used here to predict the masses of T_z =-1 nuclei and compared with the experimental ones in Fig. 4. One sees that the simple GK mass relation predicts more accurate masses than any mass model calculations, and the regular staggering in the model calculations has been nearly removed in the GK mass predictions.

Our mass measurements of neutron-deficient ¹¹²Sn projectile fragments yield new masses for ⁷⁹Y, ⁸¹Zr, ⁸²Zr, ⁸³Nb, and ⁸⁴Nb [36], among which the masses of ⁸²Zr and ⁸⁴Nb were obtained for the first time with a precision of ~15 keV. These results have been used to extract the

 α -separation energies for Mo isotopes and compared to the theoretical calculations of the finite range droplet model (FRDM) [50, 51] (see Fig. 5).



Fig. 5: a-separation energies, S_{α} , for Mo isotopes. The open circle indicates S_{α} from at least one extrapolated mass value. The lines are from different mass models indicated in the figure.

Our new results question the pronounced island of low α -separation energies in neutron-deficient Mo isotopes, which was predicted by FRDM'92 [50, 52] but not supported by, e.g., the WS4 [46] mass model. As seen in Fig. 5, the S_{α} values of ⁸⁵Mo and ⁸⁶Mo in AME'12 [53] follow the predictions of FRDM'92 if the previously known experimental mass of ⁸¹Zr and the extrapolated one of 82 Zr [53] are used. A sudden drop of S_a at 85 Mo was considered as the first evidence of the pronounced low- S_{α} island [54]. However, if our accurate masses of ^{81,82}Zr are used, S_{α} decreases smoothly with A down to ⁸⁵Mo and no sudden drop of S_{α} at ^{85}Mo is observed. It is also the case for Tc isotopes, for which the reported sudden decrease of S_{α} at ⁸⁷Tc [54] is now removed due to our new mass of ⁸³Nb. Fig. 5 shows that the new experimental S_{α} data can be well described by the latest version of FRDM'12 [51] and the WS4 [46] mass models. We note that the extrapolated S_{α} (⁸⁴Mo) agrees well with the prediction by the WS4 model. The facts above indicate that the claimed pronounced low- S_{α} island in neutron-deficient Mo isotopes does not exist.

B. Validity of the Isobaric Multiplet Mass Equation

The isobaric multiplet mass equation (IMME) is based

on the fundamental concept of the isospin symmetry in nuclear physics. It connects the members of an isobaric multiplet via [55, 56]:

$$E(A,T,T_{z}) = a(A,T) + b(A,T) \cdot T_{z} + c(A,T) \cdot T_{z}^{2}$$
(3)

where a, b, and c are parameters depending on the atomic mass number A and the total isospin T. Extra terms such as $d T_z^3$ or $e T_z^4$ can be added to the IMME in order to provide a measure for any deviation from the quadratic form, which has been extensively tested in sd-shell nuclei (see Ref. [57] and references therein).

Mass measurements of neutron-deficient ⁵⁸Ni projectile fragments yield new masses for pf-shell nuclei with $T_z = -2, -3/2$, respectively [30, 35, 36]. These new masses enable us to test the validity of the IMME in the fpshell nuclei [25, 27–29]. In fact, using our newly determined masses of the ground state of ⁵³Ni, we found that the quadratic form of IMME is broken for the A=53, T=3/2 quadruplet. This indicates that at least one of the masses of the corresponding isobaric multiplet should be re-measured. Indeed, a recent experiment has been performed to re-determine the excitation energy of the T=3/2 isobaric analog state (IAS) in ⁵³Co through the measurements of β-delayed γ transitions of ⁵³Ni [58]. It was found that the T=3/2 IAS in ⁵³Co is ~70 keV below the previously assigned IAS based on the measurement of β -delayed proton emissions [59]. The new assignment of the T=3/2 IAS in ⁵³Co leads to the re-validation of the quadratic form of IMME for the A=53, T=3/2 quadruplet [58].

Using the newly determined masses of the ground state and the low-lying 2^+ isomer of ⁵²Co [25], we also pointed out that the previously assigned T=2 IAS in ⁵²Co [59, 60] should be replaced by a new state that is ~135 keV higher than the previously assigned one. The new state should be the expected T=2 IAS of ⁵²Ni. This, again, leads to the re-validation of the quadratic form of IMME for the A=52, T=2 quintuplet [23, 25].

The new assignment of the T=2 IAS in ⁵²Co has a significant impact on the understanding of β^+ /EC-decay properties of ⁵²Ni. Combining the experimental data from the measurements of β -delayed protons and β -delayed gammas [59, 60], we reconstructed the partial decay scheme of ⁵²Ni, as shown in Fig. 6. We found that the level structure of ⁵²Co and the β^+ /EC-decay properties of ⁵²Ni can be well reproduced by state-of-the-art shell model calculations. In particular, the newly assigned IAS in ⁵²Co decays dominantly via γ transitions while proton emissions are almost negligible. This phenomenon can also be reproduced theoretically and could be explained as being due to very low isospin mixing of the IAS.



Fig. 6: Re-constructed partial decay scheme of 52 Ni (left) and theoretical level structure of 52 Co (right). Excitation energies are in keV. The theoretical branching ratios (BR) and logft values based on cd-GXPF1J are deduced from the present Q value. The red levels are deduced from the ground-state mass of 52 Co and the γ -ray energies from Ref. [60]. The black levels are determined from the data of β -delayed proton emissions.

C. N = 32 subshell closure in scandium

In past decades, many efforts have been made to study the shell evolution at N=32 and 34 subshells, where proton (π) and neutron (v) p_{3/2}-p_{1/2} and f_{7/2}-f_{5/2} spin-orbit partners determine the shell structure. It has been elucidated [61, 62] in the framework of the shell model that the monopole component of tensor force acting between the protons in $j = l \pm 1/2$ and the neutrons in $j' = l' \pm 1/2$ orbitals has a key role in describing shell evolution, where l and l' represent orbital angular momenta of protons and neutrons, respectively. In general, this π -v tensor force is attractive for the combinations of $j_> = l + 1/2$, $j'_< = l' - 1/2$, and $j_< = l - 1/2$, $j'_> = l' + 1/2$, while it is repulsive for those with $j_> = l + 1/2$, $j'_> = l' + 1/2$, and $j_< = l - 1/2$, $j'_< = l' - 1/2$. These interactions are strongest between the spin-orbit partners with l = l'.

In the N=32 mass region, the tensor force is attractive between the $\pi f_{7/2}$ valence protons and the $v f_{5/2}$ valence neutrons. Once the protons are removed from the $\pi f_{7/2}$ orbital, that is, when going from $_{26}$ Fe to $_{20}$ Ca, the magnitude of attractive π -v tensor force decreases, consequently resulting in an upshift of the $v f_{5/2}$ orbital. Continuous upshift of the $v f_{5/2}$ orbital while decreasing the number of protons in the $\pi f_{7/2}$ orbital may generate an inversion of the $v f_{5/2}$ and $v p_{1/2}$ orbitals, giving a substantial energy gap between $v p_{3/2}$ and $v p_{1/2}$ orbitals (N=32 subshell closure) or even between $v f_{5/2}$ and the $v p_{3/2}$ - $v p_{1/2}$ spin-orbit partners (N=34 subshell closure).

Experimentally, a local maximum in the systematics of the first 2⁺ excitation energies in even-even nuclei at N=32 were reported in ₁₈Ar [63], ₂₀Ca [64], ₂₂Ti [65], and ₂₄Cr [66] isotopes, remarkably suggesting a new neutron shell closure at N=32. Meanwhile, a local minimum in the systematics of reduced transition probabilities B(E2; $0^{+}_{1} \rightarrow 2^{+}_{1}$) has also provided evidence for the existence of this subshell in Ti [67] and Cr [68] isotopes. Furthermore, a sizable subshell closure with a similar magnitude as the N=32 gap in ⁵²Ca has been unambiguously demonstrated at N = 34 in ⁵⁴Ca [69].

The determination of the upper boundaries of these new subshells at N = 32, 34 provides information on the relative ordering of $vf_{5/2}$, $vp_{3/2}$, and $vp_{1/2}$ orbitals and leads to a better understanding of the role of the tensor force on shell evolution in exotic neutron-rich nuclei.

The precision mass measurements of ${}^{52-54}$ Sc and 54,56 Ti nuclides [38] allow us to probe the robustness of the

N=32 subshell closure using the two-proton separation energies, S_{2n} , as an indicator; see Fig. 7.



Fig. 7: S_{2n} values for K, Ca, Sc, and Ti isotopic chains (see legend). The remarkable agreement between the experimental data and VS-IMSRG calculations is clearly seen [38].

As can be seen is Fig. 7, our new mass values completely change the systematic behavior of S_{2n} of the scandium isotopic chain as a function of neutron number N. $S_{2n}(^{52}Sc)$ as well as $S_{2n}(^{53}Sc)$ are now significantly larger than assumed previously, and consequently, a kink at N = 32 emerges clearly. This behavior is in line with the recently established trends for calcium [70] and potassium [71] isotopic chains. Our results undoubtedly indicate the persistence of the subshell N = 32 in scandium. The *ab initio* calculations using the VS-IMSRG approach with NN and 3N interactions from chiral effective field theory confirm the experimental observations for calcium and scandium but predict a persistence of a large N = 32 gap in titanium, at odds with these and other experimental measurements. See Ref. [38] for details.

D. Waiting points and reaction cycles in the rp-process of a Type I X-ray burst

It has been shown that the waiting points at ⁶⁴Ge, ⁶⁸Se, and ⁷²Kr and the Ca-Sc and Zr-Nb reaction cycles in the rp-process (rapid proton capture process) have significant impacts on the reaction path and, consequently, on the light curve and the ashes of the nuclear burning in Type I X-ray bursts [52, 72, 73]. As ⁶⁹Br and ⁷³Rb are known to be strongly proton unbound, ⁶⁸Se and ⁷²Kr are considered to be important waiting points [74, 75].

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Due to its long half-life of $t_{1/2} = 64(3)$ s [9] and since it is encountered first in the rp-process, the ⁶⁴Ge nucleus is considered to be the most important potential waiting point [52]. Before our measurement, only a model dependent lower limit of $S_p(^{65}As) > -250$ keV existed from the observation of the β^+ -decay of ⁶⁵As [76]. Our new $S_p(^{65}As)$ -value, $S_p(^{65}As)$ =-90(85) keV [26] was used in one-zone X-ray burst model [77] calculations, which allowed us to define the temperatures and densities needed to bypass the ⁶⁴Ge waiting point. We find that 89–90% of the reaction flow passes through ⁶⁴Ge via proton capture, thus indicating that ⁶⁴Ge is not a significant rp-process waiting point. See Ref. [26] for details.

As for the reaction cycles, our experiments yield a more precise mass excess $ME(^{45}Cr)=-19515\pm35$ keV [28] and $ME(^{44}V)=-23827\pm20$ keV [23]. These results give an enhanced proton separation energy $S_p(^{45}Cr)=2972\pm45$ keV, rather than the previously recommended value of $S_p(^{45}Cr)=2.1\pm0.5$ MeV [78]; the latter leads to a large uncertainty on the formation of the Ca-Sc reaction cycle in the model calculations for the rp-process. One-zone X-ray burst model calculations using the new $S_p(^{45}Cr)$ value basically excludes the formation of the significant Ca-Sc reaction cycle as shown in Fig. 4 of Ref. [28].

As mentioned above, our mass measurements exclude the predicted pronounced low- S_{α} island in neutron deficient Mo and Tc isotopes [52]. The non-existence of the low- S_{α} island in neutron-deficient Mo isotopes questions the formation of the predicted Zr-Nb cycle in the rp-process of Type I X-ray bursts [52, 54]. Such a Zr-Nb cycle is characterized by large ⁸⁴Mo(γ,α)⁸⁰Zr and ⁸³Nb(p,α)⁸⁰Zr reaction rates, which sensitively depend on $S_{\alpha}(^{84}Mo)$, i.e., the mass difference between ⁸⁴Mo and ⁸⁰Zr. Based on our extrapolated masses of ⁸⁴Mo and ⁸⁰Zr [28], we obtain $S_{\alpha}(^{84}Mo)=2.21\pm0.35$ MeV. This value agrees with the previous extrapolations but is somewhat higher than the values used in the previous Type I X-ray burst model calculations in Refs. [52, 54].

Network calculations [79] based on the Type I X-ray burst model of Schatz et al. [77] have been performed using the new reaction rates obtained with the Talys code [80]. We define a cycle branching ratio as the fraction of the flow ending at ⁸⁰Zr via the ⁸³Nb(p,α)⁸⁰Zr and the ⁸⁴Mo(γ,α)⁸⁰Zr reactions. Figure 8 shows the branching ratio as a function of typical burst time. Under the favorable conditions of the masses, i.e., the 1 σ upper or lower limits in masses that give the largest Q-value for the



Fig. 8: A fraction of the reaction flow branching into the Zr-Nb cycle under the most favorable conditions (see text for details), using the masses from AME'12 [53] (black line) and from this work (red line). The dashed black line shows the temperature varying within the burst time.

⁸³Nb(p, α)⁸⁰Zr reaction and the smallest α -separation energy of ⁸⁴Mo, the rp-process ends up at the Zr-Nb cycle at the peak temperature of ~1.9 GK using the favorable masses from AME'12 [53] (black solid line in Fig. 8), in agreement with the result in Ref. [54]. The branching ratio is reduced quickly as the temperature decreases to below 1.4 GK. However, if our new masses are taken, the branching ratio into the Zr-Nb cycle is decreased, as demonstrated by the red line in Fig. 8, by several orders of magnitude, even at the peak temperature of ~1.9 GK, leading to a weakening or even disappearance of the Zr-Nb cycle in the rp-process in Type I X-ray bursts.

SUMMARY AND OUTLOOK

In the last several years at HIRFL-CSRe, we have successfully established the research program on direct mass measurements by employing isochronous mass spectrometry (IMS). In this paper, we presented a general review of our work and a few examples of the results that proved to be important for nuclear structure and astrophysics investigations.

Future experiments will inevitably require improvements of the accelerator performance as well as improvements of measurement and analysis techniques. Recent technical developments at the CSRe are discussed in Refs. [24, 81–88]. Since the high resolving power of IMS is achieved in a small range of revolution times, additional information on the velocity or magnetic rigidity of each ion can be used to correct for non-isochronicity effects [89]. In this vein, a proof-of-principle experiment was performed at GSI by restricting the acceptance to $\Delta B\rho/B\rho \sim 10^{-5}$ [90]. In the case of HIRFL-CSRe, two time-of-flight detectors were recently installed in the straight section of the CSRe [84, 85]. Several test experiments have been conducted using two TOF detectors. Preliminary results have shown that the velocity of each stored ion can be measured with a relative uncertainty of 10^{-5} , and the resolving power of the revolution time can be significantly improved, in particular for the ions not within the isochronous window. Future IMS measurements will be conducted using the new technique.

An essential development is also the commissioning of time-resolved Schottky Mass Spectrometry (SMS) [91–93] in the CSRe. In addition to accurate mass measurements, SMS will enable a wide range of unique experiments with stored stable as well as radioactive highly-charged ions [93, 94]. Furthermore, a new resonant Schottky pick-up, which allows for non-destructive frequency as well as intensity measurements of stored ions, has been developed [95]. A similar detector was also installed in the CSRe [96]. Owing to a broad dynamic range, this detector is capable of measuring frequencies of single stored ions as well as high intensity beams of several mA. It is possible that in the future such detectors could replace the time-of-flight detectors in IMS measurements. The intensity measurements will enable studies of radioactive decays of highlycharged ions, e.g., the studies of β -decay, which up to now could only be performed at the experimental storage ring (ESR) at GSI [93, 94]. Furthermore, other nuclear physics experiments, e.g., the studies of nuclear isomers, measurements of β -delayed neutron emission, protonand α -capture reactions for nuclear astrophysics, in-ring nuclear reactions studies, and di-electronic recombination on exotic nuclei, will be pursued in the future [97–99].

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