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Precision Physics with Stored Exotic Ions: Storage Ring Mass Spectrometry

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The mass of an atomic nucleus reflects a net result of complicated interactions between nucleons composing it. Systematic studies of nuclear masses are decisive to elucidate nuclear structure changes and in turn help us to understand the underlying nuclear forces. Although numerous masses have been measured to date, further measurements are needed to benchmark and improve theory. The nuclei with yet unknown masses lie at the outskirts of the chart of the nuclides. They are complicated to produce and are short-lived, which makes their measurements extremely challenging. In this context, storage ring mass spectrometry is one of the promising methods characterized by a very high sensitivity, mass resolving power and speed. Recent developments of storage ring mass spectrometry are briefly discussed.

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1. Introduction

Protons and neutrons in a nucleus are kept together through a highly complicated interaction commonly called *nuclear force*. Since about a century, extensive theoretical and experimental investigations are pursued to understand the clockworks of this force [1]. It is obvious that the nuclear force determines the structure of nuclei, the limits of their existence, their collective properties, reaction rates, halflives, etc. However, it turns to be important also on a macroscopic scale where it governs various processes in stellar environments [2].

The key quantity in this context is the *total energy* of the nucleus, which is directly connected to its *rest mass*. Indeed, historically major breakthroughs in understanding nuclear structure came from systematic studies of masses of neighbouring nuclides. For instance the shell closures, pairing correlations and changes in deformation are seen as irregularities on the otherwise very smooth *mass surface* [1], that is formed by nuclear masses plotted on the chart of the nuclides [3].

In the last 100 years masses of about 2550 nuclei have been measured [3, 4], whereas about 7000 bound nuclei are expected to exist [5]. On the neutron-deficient side of the nuclear chart the known mass surface extends for many elements up to and even beyond the proton dripline, the line at which proton separation energy turns negative meaning that a nucleus can energetically decay via proton emission [6]. The majority of yet unknown masses belongs to nuclei on the neutron-rich side, where the neutron dripline is reached only for a small number of light elements. However, nuclear properties at large neutron excess indicate intriguing modifications: The known shell closures quench while new ones appear [7] or unusual structures develop like neutron halos [8] and skins [9]. Also one of the major nucleosynthesis processes, the rapid neutron capture (r-process), paths along the neutron drip line [10]. This process is responsible for the creation of about one half of nuclei heavier than iron and of entire uranium and thorium. Although numerous nuclear properties are needed to model nucleosynthesis processes, the masses of the relevant nuclei are the principal input. Therefore, the measurements of still unknown masses is highly desired.

So, why not just measure them? Indeed, mass measurement programs exist at basically all present and future radioactive-ion beam facilities [11, 12]. However, severe complications arise from the fact that the nuclei of interest are as a rule short lived (halflives $T_{1/2} << 1$ s) and are produced in nuclear reactions in vanishingly small quantities. It is therefore clear that mass measurements are extremely challenging and demand fast techniques with highest sensitivity. Still, many of the most exotic nuclei will remain inaccessible even at the new-generation facilities, that are being planned or constructed now. As a consequence, for many applications, it is inevitable to employ theory to predict properties of such systems. Due to the complexity of the nuclear force, the predictive power of modern mass models is limited [13, 14]. Hence, an essential goal of experiment is to constrain theory by providing new masses as test grounds for refining its parameters.

Taken its importance, mass spectrometry is a rapidly developing field of research and is well reviewed in the literature [11, 12, 15–20]. This short contribution focuses on the most recent progress in storage ring mass spectrometry (SRMS).

2. Conventional storage ring mass spectrometry

The motion of a relativistic particle with mass-over-charge ratio, m/q, in a magnetic field, B, is described by setting the acting Lorentz and centrifugal forces equal. The momentum of the particle is $p = mv\gamma$, where v is the particle velocity and γ the relativistic Lorentz factor. Assuming a closed trajectory, the revolution frequency $f = v/C$, where C is the orbit length. After some math, one can derive the basic equation of SRMS, which relates the relative f deviation to the relative m/q difference and the velocity spread $\Delta v/v$ [21]:

$$\frac{\Delta f}{f} = -\frac{1}{\gamma_t}\frac{\Delta(m/q)}{m/q} + \frac{\Delta v}{v}\left(1 - \frac{\gamma^2}{\gamma_t^2}\right), \tag{1}$$

where γ_t is the machine parameter called *transition energy*, related to the relative change of the orbit length caused by a relative change of magnetic rigidity, $B\rho = mv\gamma/q$ [22, 23].

According to Eq. (1), the revolution frequency is the measure of the particle mass-over-charge ratio if the second term on the right hand side is made negligible. There are two approaches to achieve this. One shall note that (i) the velocity spread of secondary particles produced in a nuclear reaction is huge in the present context and is defined by the acceptance of the transfer line and storage ring and (ii) the acceptance of the ring allows many tens of different nuclear species to be stored in one setting. Typically the masses of the most abundant nuclear reaction products are well known and can be used as references in Eq. (1).

In the conventional Schottky mass spectrometry (SMS) [24–26], see Figure 1 (Left), the velocity spread of the stored ions is reduced by stochastic and electron cooling [27, 28], reaching values as small as $\Delta v/v \approx 10^{-7}$. The revolution frequencies are then measured by non-destructive Schottky diagnostics, which, in an oversimplified picture, can be imagined as a transformer: A charged particle periodically passing the detector induces a tiny current. The output of the detector, which is dominated by thermal noise, is Fourier analyzed, which enables measuring repeating signals. However, the electron cooling takes several seconds, which makes the conventional SMS less suitable for modern mass measurements on short-lived nuclides.

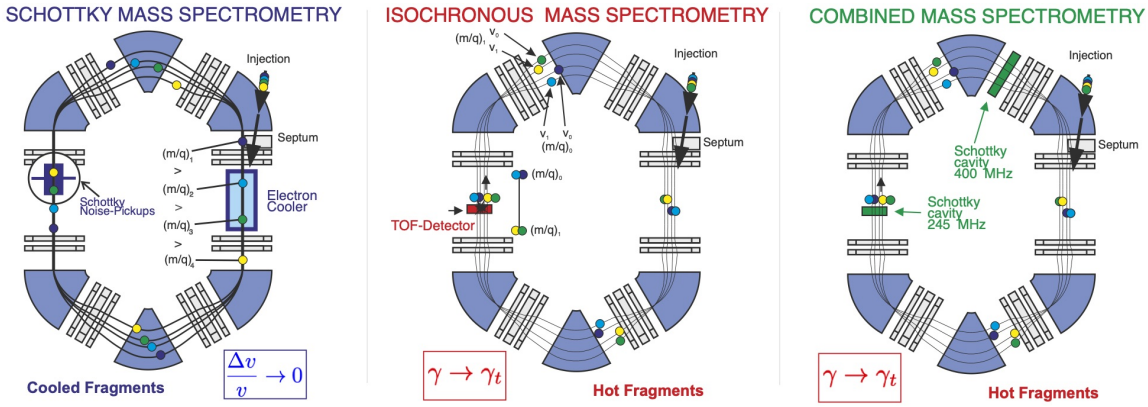

Figure 1: (Color online). Schematic illustration of different techniques of the storage ring mass spectrometry (see text). Courtesy Marc Hausmann, Wolfram Korten, Torsten Radon, and Helmut Weick.

In the conventional isochronous mass spectrometry (IMS) [29, 30], see Figure 1 (Middle), the ring is tuned in a special ion-optical mode, in which two particles with the same m/q ratio but two different velocities travel on such distinct orbits that their revolution frequencies are equal. In this mode the Lorentz factor of the ions $\gamma = \gamma_t$. To achieve very quick measurement of revolution frequencies, a semi-destructive time-of-flight (ToF) detector is employed [31, 32]. It is equipped with a very thin ($< 20\,\mu$g/cm^2) carbon foil inserted into the ring aperture, which is used as a source of secondary electrons created by periodically penetrating it stored ions. The electrons are detected and provide trains of several tens of repeating signals that are relatively easy to convert into the wanted frequencies [33, 34]. The number of secondary electrons depends on the charge of the ion, which is utilized as an additional identification criterion [35–37]. No cooling is required and the overall measurement is merely a few hundreds of microseconds long, which make this technique ideal to measure short-lived ions. However, due to the large velocity spread of stored ions, the condition $\gamma = \gamma_t$ is fulfilled only in a small range of m/q values termed *isochronous window*. Outside of it, the mass resolving power and–in turn–the sensitivity deteriorate rapidly [11, 21, 38, 39].

3. Present storage ring facilities for mass measurements of exotic nuclei

There are three heavy-ion storage facilities in operation worldwide. These are the experimental storage ring (ESR) [40] at GSI, Germany, the experimental cooler-storage ring (CSRe) [41] at IMP, China and the rare-ion storage ring (R3) [42] at RIKEN, Japan. The driver accelerators at GSI and IMP are heavy ion synchrotrons and at RIKEN it is a cyclotron. All three facilities are coupled to *in-flight* fragment separators and employ nuclear production reactions at relativistic energies of a few 100 AMeV [43]. Bunched beams at synchrotrons enable storage of multiple ions at the same time but no particle identification is possible prior to their in-ring investigation. In contrary, the quasi-DC beam from the cyclotron enables identification of every ion and selection of only those of interest to be injected and studied one-by-one [44].

4. $B\rho$-defined Isochronous Mass Spectrometry

Numerous experiments were conducted at the ESR and CSRe by employing the conventional IMS addressing nuclear structure [45–53] and astrophysics [54, 55]. However, only the data in the isochronous window could be usefully analyzed. To expand beyond it, the knowledge of the particle velocity or magnetic rigidity, $B\rho$, is needed [56, 57]. At GSI this has been verified in the so-called $B\rho$-tagging regime, in which the $B\rho$ spread was physically limited to about 10^{-4} [58]. Indeed, the resolving power was increased and remained constant over the entire ESR acceptance. Although the $B\rho$-cut severely reduces the transmission, several measurements have been conducted [59, 60].

The measurement of particle velocities is realized at the R3 by using standard detectors within the fragment separator and the results of the first masses measurements relevant for the r-process have been reported in 2022 [61].

At the CSRe, two ToF detectors were installed in a straight section [62]. Each stored particle causes two trains of timing signals in them, which are then used to determine the frequency and the velocity of each ion [63]. By assuming that the particles with the same $B\rho$ have the same mean C, a universal calibration curve can be constructed. As a result, high mass resolving power of

about 400000 which is constant over the entire CSRe acceptance was achieved, corresponding to the FWHM of about 5 keV/q [64, 65]. The later quantity means that the mass of a single rare ion can be determined with this precision within 200 μs, which is unprecedented. Striking confirmation of the power of the method has been delivered through measurements of the masses of ^{70}Kr and ^{75}Sr which were produced with rates of below 2 particles per week [37, 66].

5. Combined Isochronous+Schottky Mass Spectrometry

Since the mass-over-charge ratio changes in the decay, non-destructive SMS is ideally suited to study exotic nuclear decays [67–69]. Such, time-resolved SMS has been intensively applied to study decays of long-lived ($T_{1/2}$ >> 1 s) highly charged ions [70–80]. To access shorter-lived nuclei, Schottky detectors have been improved from capacitive copper plates to cavity based resonators, thereby increasing the signal-to-noise characteristics by several orders of magnitude [81, 82]. It is presently possible to measure the frequency of a single stored ion within a very few milliseconds [83, 84]. To avoid the lengthy cooling process, the Schottky diagnostics is applied in the IMS, thus realizing combined Schottky+isochronous mass spectrometry (I+SMS) [85], see Figure 1 (Right). Through the development of the I+SMS, simultaneous mass and lifetime measurements are now enabled. The technique has been verified in the ESR and successfully employed to measure the two-photon de-excitation of the first exited 0^+ state in ^{72}Ge [86, 87].

6. Future Perspectives

Apart from the mass measurement programs at the present ESR, CSRe and R3 storage rings, which will undoubtedly continue [88], there are plans at the next-generation facilities FAIR, Germany and HIAF, China. The collector ring (CR) at FAIR [89] and spectroscopy ring (SRing) at HIAF [90] are dedicatedly designed for mass measurements of short-lived nuclei. Both rings will be equipped with double-ToF detectors realizing the powerful $B\rho$-defined IMS. A variety of Schottky detectors will as well be installed and thus enable the S+IMS technique. In addition, transverse Schottky detectors are being developed for non-destructive in-ring determination of $B\rho$ of every stored particle [91–94]. If successful, this will combine all SRMS techniques together. Such an attractive combination of $B\rho$-defined S+IMS does not yet have a name.

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References

[1] A. Bohr and B.R. Mottelson, *Nuclear Structure*, World Scientific Publ., Singapore, 1998.

[2] E. M. Burbidge, *et al.*, Rev. Mod. Phys. **29**, 547–650 (1957).

[3] W. J. Huang, *et al.*, Chin. Phys. C **45**, 030002 (2021).

[4] K. Blaum, Y. Litvinov (Eds.), special issue, Int. J. Mass Spectr. **349–350**, 1 (2013).

[5] J. Erler, *et al.*, Nature **486**, 509 (2012).

[6] Yu. N. Novikov, *et al.*, Nucl. Phys. A **697**, 92–106 (2002).

[7] R. Kanungo, *et al.*, Phys. Rev. Lett. **102**, 152501 (2009).

[8] I. Tanihata, *et al.*, Phys. Rev. Lett. **55**, 2676 (1985).

[9] I. Tanihata, *et al.*, Phys. Lett. B **289**, 261–266 (1992).

[10] J. J. Cowan, *et al.*, Rev. Mod. Phys. **93**, 015002 (2021).

[11] Y. H. Zhang, *et al.*, Phys. Scripta **91**, 073002 (2016).

[12] T. Yamaguchi, *et al.*, Prog. Part. Nucl. Phys. **120**, 103882 (2021).

[13] A. Sobiczewski, *et al.*, Phys. Rev. C **89**, 024311 (2014).

[14] A. Sobiczewski, *et al.*, At. Data Nucl. Data Tables **119**, 1–32 (2018).

[15] D. Lunney *et al.*, Rev. Mod. Phys. **75**, 1021–1082 (2003).

[16] K. Blaum, Phys. Rep. **425**, 1–78 (2006).

[17] F. Bosch, *et al.*, Int. J. Mass Spectr. **251**, 212–219 (2006).

[18] F. Bosch, *et al.*, Int. J. Mass Spectr. **349-350**, 151–161 (2013).

[19] Y. Litvinov, *et al.*, Nucl. Instr. Meth. B **317**, 603–616 (2013).

[20] T. Eronen, *et al.*, Prog. Part. Nucl. Phys. **91**, 259–293 (2016).

[21] B. Franzke, *et al.*, Mass Spectr. Rev. **27**, 428–469 (2008).

[22] M. Steck *et al.*, Prog. Part. Nucl. Phys. **115**, 103811 (2020).

[23] M. Zhang *et al.*, Nucl. Instr. Meth. A **1027**, 166329 (2022).

[24] T. Radon *et al.*, Phys. Rev. Lett. **78**, 4701–4704 (1997).

[25] T. Radon, *et al.*, Nucl. Phys. A **677**, 75-99 (2000).

[26] Y. Litvinov, *et al.*, Nucl. Phys. A **756**, 3–38 (2005).

[27] H. Geissel, *et al.*, Nucl. Phys. A **746**, 150–155 (2004).

[28] H. Geissel, *et al.*, Eur. J. Special Topics **150**, 109–115 (2007).

[29] M. Hausmann, *et al.*, Nucl. Instr. Meth. A **446**, 569–580 (2000).

[30] M. Hausmann, *et al.*, Hyperf. Interactions **132**, 289–295 (2001).

[31] W. Zhang, *et al.*, Nucl. Instr. Meth. A **755**, 38–43 (2014).

[32] W. Zhang, *et al.*, Nucl. Instr. Meth. A **756**, 1–5 (2014).

[33] X. Tu, *et al.*, Nucl. Instr. Meth. A **654**, 213–218 (2011).

[34] Y. Xing, *et al.*, Nucl. Instr. Meth. A **941**, 162331 (2019).

[35] P. Shuai, *et al.*, Phys. Lett. B **735**, 327–331 (2014).

[36] X. Zhou, *et al.*, Nucl. Sci. Techniq. **32**, 37 (2021).

[37] M. Wang, *et al.*, Phys. Rev. Lett. **130**, 192501 (2023).

[38] M. Z. Sun, *et al.*, Front. Phys. **13**, 132112 (2018).

[39] J. Liu, *et al.*, Nucl. Instr. Meth. B **463**, 138–142 (2020).

[40] B. Franzke, Nucl. Instr. Meth. B **24-25**, 18–25 (1987).

[41] J. Xia, *et al.*, Nucl. Instr. Meth. A **488**, 11–25 (2002).

[42] A. Ozawa, *et al.*, Prog. Theor. Exp. Phys. **2012**, 03C009 (2012).

[43] H. Geissel, *et al.*, Ann. Rev. Nucl. Part. Sci. **45**, 163–203 (1995).

[44] T. Yamaguchi, *et al.*, Int. J. Mass Spectr. **349-350**, 240–246 (2013).

[45] J. Stadlmann, *et al.*, Phys. Lett. B **586**, 27–33 (2004).

[46] B. Sun, *et al.*, Nucl. Phys. A **812**, 1–12 (2008).

[47] B. Sun, *et al.*, Phys. Lett. B **688**, 294–297 (2010).

[48] X. Tu, *et al.*, Phys. Rev. Lett. **106**, 112501 (2011).

[49] Y. Zhang, *et al.*, Phys. Rev. Lett. **109**, 102501 (2012).

[50] X. Xu, *et al.*, Phys. Rev. Lett. **117**, 182503 (2016).

[51] P. Zhang, *et al.*, Phys. Lett. B **767**, 20–24 (2017).

[52] Y. H. Zhang, *et al.*, Phys. Rev. C **98**, 014319 (2018).

[53] X. L. Yan, *et al.*, Phys. Rev. C **107**, 014304 (2022).

[54] X. L. Yan, *et al.*, Astroph. J. Lett. **766**, L8 (2013).

[55] Y. M. Xing, *et al.*, Phys. Lett. B **781**, 358–363 (2018).

[56] H. Geissel, *et al.*, J. Phys. G **31**, S1779–S1783 (2005).

[57] H. Geissel, *et al.*, Nucl. Instr. Meth. B **541**, 305–309 (2023).

[58] H. Geissel, *et al.*, Hyperf. Interactions **173**, 49–54 (2006).

[59] R. Knöbel, *et al.*, Eur. Phys. J. A **52**, 138 (2016).

[60] R. Knöbel, *et al.*, Phys. Lett. B **754**, 288–293 (2016).

[61] H. F. Li, *et al.*, Phys. Rev. Lett. **128**, 152701 (2022).

[62] X. Zhou, *et al.*, Phys. Rev. Accel. Beams **24**, 042802 (2021).

[63] P. Shuai, *et al.*, Nucl. Instr. Meth. B **376**, 311–315 (2016).

[64] M. Wang, *et al.*, Phys. Rev. C **106**, L051301 (2022).

[65] M. Wang, *et al.*, Eur. Phys. J. A **59**, 27 (2023).

[66] X. Zhou, *et al.*, Nature Physics (2023). doi: 10.1038/s41567-023-02034-2

[67] Y. Litvinov, *et al.*, Nucl. Phys. A **734**, 473-476 (2004).

[68] Y. Litvinov, *et al.*, Rep. Prog. Phys. **74**, 016301 (2011).

[69] F. Bosch, *et al.*, Prog. Part. Nucl. Phys. **73**, 84–140 (2013).

[70] Y. Litvinov, *et al.*, Phys. Lett. B **573**, 80–85 (2003).

[71] T. Ohtsubo, *et al.*, Phys. Rev. Lett. **95**, 052501 (2005).

[72] Y. Litvinov, *et al.*, Phys. Rev. Lett. **99**, 262501 (2007).

[73] Y. Litvinov, *et al.*, Phys. Lett. B **664**, 162–168 (2008).

[74] N. Winckler, *et al.*, Phys. Lett. B **679**, 36–40 (2009).

[75] M. W. Reed, *et al.*, Phys. Rev. Lett. **105**, 172501 (2010).

[76] M. W. Reed, *et al.*, Phys. Rev. C **86**, 054321 (2012).

[77] D. R. Atanasov, *et al.*, Eur. Phys. J. A **48**, 22 (2012).

[78] A. Akber, *et al.*, Phys. Rev. C **91**, 031301 (2015).

[79] D. Atanasov, *et al.*, J. Phys. B **48**, 144024 (2015).

[80] Y. Litvinov, *et al.*, Eur. Phys. J. A **59**, 102 (2023).

[81] F. Nolden, *et al.*, Nucl. Instr. Meth. A **659**, 69–77 (2011).

[82] M. S. Sanjari, *et al.*, Rev. Sci. Instr. **91**, 083303 (2020).

[83] P. Kienle, *et al.*, Phys. Lett. B **726**, 638–645 (2013).

[84] F. Ozturk, *et al.*, Phys. Lett. B **797**, 134800 (2019).

[85] X. L. Tu, *et al.*, Phys. Rev. C **97**, 014321 (2018).

[86] W. Korten, *et al.*, Proposal, GSI Program Advisory Committee (2022).

[87] F. Bosch, *et al.*, EPJ Web Conf. **123**, 04003 (2016).

[88] Y. Litvinov, *et al.*, Acta Phys. Polonica B Proc. Suppl. **14**, 4-A25 (2023).

[89] P. Walker, *et al.*, Int. J. Mass Spectr. **349-350**, 247–254 (2013).

[90] J. Yang, *et al.*, Nucl. Instr. Meth. B **317**, 263–265 (2013).

[91] X. Chen, *et al.*, Hyperf. Interactions **235**, 51–59 (2015).

[92] M. S. Sanjari, *et al.*, Phys. Scripta **T166**, 014060 (2015).

[93] X. Chen, *et al.*, Nucl. Instr. Meth. A **826**, 39–47 (2016).

[94] D. Dmytriiev, *et al.*, Nucl. Instr. Meth. B **463**, 320-323 (2020).