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TIME-OF-FLIGHT MASS MEASUREMENTS AND THEIR IMPORTANCE FOR NUCLEAR ASTROPHYSICS*

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Atomic masses play an important role in nuclear astrophysics. The lack of experimental values for nuclides of interest has triggered a rapid development of new mass measurement devices around the world, including Time-of-Flight (TOF) mass measurements offering an access to the most exotic nuclides. Recently, the TOF-$B\rho$ technique that includes a position measurement for magnetic rigidity correction has been implemented at the NSCL. An experiment with a similar TOF-$B\rho$ technique is approved and planned at the next generation radioactive beam facility (RIBF) at RIKEN.

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1. Astrophysical motivation

Atomic masses play an important role in nuclear astrophysics. Neutron and proton capture reactions, together with β-decays, are involved in many astrophysical processes [1]. The neutron capture processes include the s-process and the r-process, which are responsible for nucleosynthesis of most

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of the elements above iron [2]. Meanwhile proton capture powers novae, supernovae or massive second generation star explosions [3], as well ass type I X-ray bursts (rapid proton capture process, rp-process) [4], and might occur in neutrino-driven core-collapse supernovae [5]. At relatively low temperatures and densities the capture reactions occur on stable or very long lived isotopes as the faster β-decays shift the path closer to the valley of stability. Contrary to this, much faster capture reactions during the r-process and rp-process push the paths along very exotic nuclei. Though these processes are too short to establish nuclear statistical equilibrium (NSE), (n,γ)–(γ,n) equilibrium is formed along the isotopic chains in the r-process and (p,γ)–(γ,p) equilibrium is formed along the isotonic chains in the rp-process [1]. The isotonic or isotopic equilibrium between two neighboring nuclei with mass number A (initial nucleus) and $A+1$ (final nucleus) is given by the Saha equation, defining their abundance ratio as

$$\frac{Y(A+1)}{Y(A)} = \rho \frac{G(A+1)}{2G(A)} \left(\frac{A+1}{A} \frac{2\pi\hbar^2}{m_u kT} \right)^{3/2} \exp(S/kT)\,, \qquad (1)$$

where Y are abundances, G the partition functions, ρ is the proton or neutron density, T is the temperature and S is the proton or neutron separation energy. The exponential dependence on separation energy makes knowledge of nuclear masses crucial for modeling the r- and rp-processes.

Another example is the processes taking place in the crust of accreting neutron stars, where the extreme density condition drives the composition of nuclear matter towards the neutron drip line [6]. Nuclear masses are needed to determine electron capture transition strengths as well as neutron capture rates, calculated with the Hauser–Feshbach model [7].

2. TOF-$B\rho$ mass measurement technique

The lack of experimental values has initiated a rapid development of new mass measurement devices around the world. The success of the ISOLTRAP mass measurements [8] has triggered development of Penning trap technique at other radioactive beam facilities that have already covered large areas far from stability with unprecedented uncertainties [9–11].

The Time-of-Flight (TOF) technique, with access to the most exotic nuclides (minimum rate requirement of the order of 0.01 particles/s and a measurement time shorter than ~ 1 μs), is a complementary method to the very precise but more limited Penning trap mass measurements. Generally, TOF methods are categorized as either isochronous and magnetic rigidity (Bρ) measurements, and according to number of passes through the system as single- or multi-turn. Typical uncertainties of 100–200 keV are at least an order of magnitude higher compared to the Penning trap technique, the method is therefore useful only for the nuclides that cannot be measured by a more precise technique, either due to rate restrictions or because of a too short half-life. To reach the exotic nuclides that Penning trap could not reach yet, TOF measurements have to be flexible and done relatively quickly. Single turn Time-of-Flight mass measurements with $B\rho$ correction have proven to fulfill this condition. The first TOF-$B\rho$ mass measurement technique applied at the SPEG spectrograph at GANIL has produced mass values for a number of nuclides mainly on the neutron-rich side below $Z = 20$ [12]. It is limited to lighter nuclei, at the GANIL beam energies the charge state contamination would dominate for heavier nuclei.

Recently, the TOF-$B\rho$ technique has been implemented at the NSCL facility, see the left panel in Fig. 1 [13, 14]. The first experiment, focused on the neutron rich isotopes in the Fe region, important for nucleosynthesis processes by charged particle reactions in the early stages of a type II supernovae explosion as well as for calculations of processes occurring in the crust of accreting neutron stars, has been successfully performed. A resolution of $(1 - 2) \times 10^{-4}$ has been achieved. Mass values with typical uncertainties of 150–500 keV are determined for ^{53}Sc and ^{63}Cr, nuclei with values not known before, and improved for ^{57}Ti, $^{57-59}$V, $^{60-62}$Cr, ^{66,68}Fe and ^{67,69,71}Co. Data is still being evaluated. In future, mass measurement of neutron-rich nuclides around Ca will be proposed.

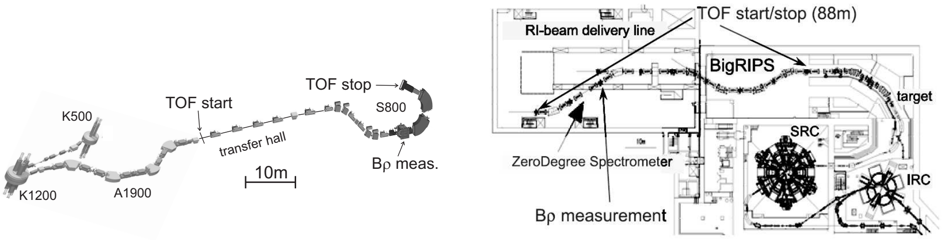

Fig. 1. Left panel: Setup of TOF-Bρ mass measurements at the NSCL. Time is measured along 58 m long path, magnetic rigidity is determined at the dispersion-matched plane of the S800 spectrograph. Right panel: Overview of TOF-Bρ mass measurements planned at RIKEN. The flight path is 88 m long, magnetic rigidity will be measured at the Zero Degree Spectrometer.

An experiment with a similar TOF-$B\rho$ technique for nuclei in the rp-process path is approved and planned by the same collaboration at the next generation radioactive beam facility (RIBF) at RIKEN, see the right panel in Fig. 1 [15]. The BigRIPS separator and the zero degree spectrometer will be used to provide the cocktail beam of interest and the magnetic rigidity correction. If the experiment is successful, a measurement focused on r-process nuclei is planned.

3. Summary and conclusions

TOF-$B\rho$ technique has proven to be an important mass measurement method with many applications in nuclear astrophysics. It has been successfully implemented at the NSCL and is planned at the RIKEN new generation facility.

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