EPJ Web of Conferences **109**, 04008 (2016)
DOI: 10.1051/epjconf/201610904008

A new Time-of-Flight mass measurement project for exotic nuclei and ultra-high precision detector development

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Abstract. The time-of-flight (TOF) mass spectrometry (MS), a high-resolution magnetic spectrometer equipped with a fast particle tracking system, is well recognized by its ability in weighing the most exotic nuclei. Currently such TOF-MS can achieve a mass resolution power of about 2×10^{-4}. We show that the mass resolution can be further improved by one order of magnitude with augmented timing and position detectors. We report the progress in developing ultra-fast detectors to be used in TOF-MS.

1 Introduction

The accurate information on nuclear masses can promote the understanding of atomic nuclide in many aspects. This ranges from the understanding the fundamental interactions governed the many-body nuclear system, to nuclear stability, and to various nuclear phenomena. Meanwhile, nuclear masses of exotic nuclei are one of most decisive properties in revealing the origin of elements from Fe to U in our universe. On the other hand, however, the state-of-art nuclear models, which can reproduce known masses in a precision of less than 500 keV, has been questioned about their reliability in computations with long range extrapolation from the known mass surface. All these arguments are the strong motivations for developing new precision mass measurement techniques and moreover for performing new accurate mass measurements [1-4], in particular for neutron-rich nuclides.

New results with nuclear masses measured for the first time since 2003 are summarized in Fig. 1. It shows the precision of direct mass measurement facilities as a function of the according nuclear half-lives, thus indicating the ability of various methods, time-of-flight mass spectrometry (TOF-MS) and frequency-based spectrometry (Penning trap, SMS-ESR). These two techniques are often quoted as direct mass measurement method, because the masses of unknown are determined directly by well-known calibrators. As can be seen in Fig. 1, Penning traps and storage rings, the two flagship facilities, played the major role in the journey to weigh masses of exotic nuclei over the last ten years. They contribute significantly to the extent of our known nuclear mass surface. TOF-MS, on the other hand, is a pioneering method applied to the study of short-lived nuclei, and now revives due to the development in novel detectors and techniques.

Depending on the available flight path, the operational TOF facilities include the single-pass TOF

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spectrometers at NSCL, the multi-turn instruments at GSI and IMP (i.e., isochronous mass spectrometers), and the multi-reflection TOF (MR-TOF) spectrometers at GSI, CERN, and RIKEN. Of all these TOF facilities, the latter two have a flight time of kilometers by bending the charged ions in a magnetic or electric filed. This results in a significantly increased mass resolving power and mass precision. Currently, both ways achieve a relative mass uncertainty of about 10^{-6}, and can be used to measure nuclei with lifetimes down to ms. However, one has to carefully deal with the efficiency in slowing down the particle, injection and transmission process.

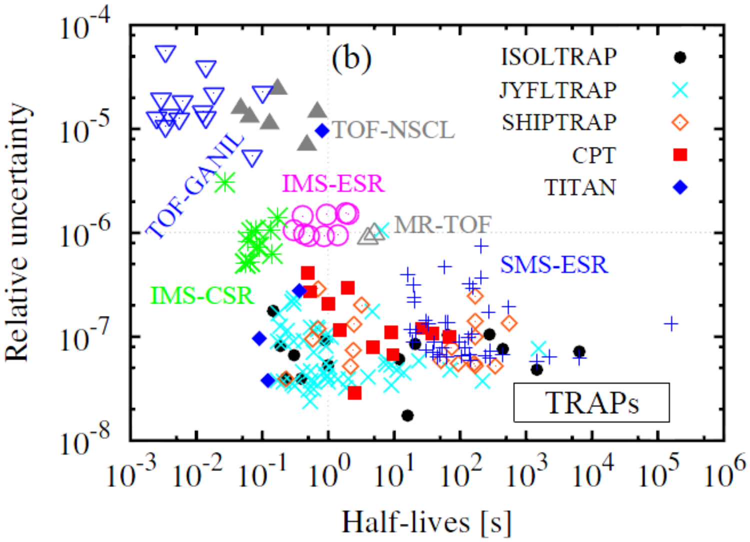

Fig.1 Precision vs. half-lives for different direct mass measurement facilities. Only those nuclei with masses measured for the first time since 2003 are included in this plot. Reproduced from Ref. [3].

In comparison, the conventional single-pass TOF-MS, like the presently running TOF-MS at NSCL [5], is nothing but an optimized in-flight separator. This method, however, provides the most efficient mapping of the nuclear mass surface. As shown in Fig.1, it is especially suitable for weighing short-lived nuclei near the drip line.

We are now working on a new mass measurement project of exotic nuclei based on the TOF method. The key issue in this project is to develop a detector system with ultra-high resolving power in both timing and position. In this contribution, we will discuss the principle of TOF method and the progress in detector development.

2 TOF mass measurement method

To address many open questions of rare isotopes, it is desired to have a clean and confined secondary beam in purity, energy and space. Combined measurements in energy loss, position, and TOF measurements are indispensable tools in in-flight separators to define the quantities -- trajectory, mass, energy – of the species of interest. Typical transmission type beam tracking detectors with time resolutions as good as 100 ps and position resolutions of about 1mm (in two dimension) are widely equipped in fragment separators over the world.

If the mass resolution is high enough, the in-flight separator can be used to directly determine masses of very exotic nuclei. Indeed, this idea was already realized at SPEG/GANIL [6] and NSCL/MSU [5]. Although limited by mass resolution, TOF-method provides the most efficient way to measure exotic nuclei with short life times and low yields. Moreover, it is worth to mention that the

TOF method can be easily extended by including other well-developed techniques, e.g. γ-ray spectroscopy of stopped beam. In this case, enriched information on prompt γ-decays can be obtained for exotic nuclei. The detection of delayed γ-rays from long lived isomers is especially valuable for identifying ground state and isomeric state that are impossible (in most of cases) to separate due to their close mass-to-charge ratios.

In principle, nuclear mass can be determined by measuring at least two out of the three correlated quantities: momentum P, kinetic energy K and velocity *v*. For heavy ions with energies of several hundreds of MeV/u, however, direct measurements of total kinetic energy with good precision become almost impossible. Thus a particle with a rest mass of m_0 can only be deduced from the basic relationship:

$$m_0 = \frac{P}{v} = \frac{P}{c\beta\gamma} = \frac{P}{c}\sqrt{\frac{1}{\beta^2}-1} = P\sqrt{\left(\frac{t}{L}\right)^2-\frac{1}{c^2}} \quad , \tag{1}$$

where β is the particle's velocity normalized to that of light in vacuum *c*, and γ is the Lorentz factor. The velocity *v* is achieved by means of time of flight *t* in a certain flight path *L*, namely, $v=L/t$. Hereafter we refer to this method as TOF-P-MS.

The measurement of the curvature of the particle trajectory in a static magnetic field can provide the momentum,

$$P = B\rho q \, . \tag{2}$$

$B\rho$ is the magnitude rigidity and *q* is the charge state. For medium and heavier nuclei, ionization energy loss measurement is also essential for providing absolute charge information.

Following Eq. (1) the mass resolution in the TOF-P-MS is

$$\left(\frac{\sigma_{m_0}}{m_0}\right)^2 = \left(\gamma^2\frac{\sigma_\beta}{\beta}\right)^2 + \left(\frac{\sigma_P}{P}\right)^2 = \left[1-\left(\frac{L}{ct}\right)^2\right]^{-2}\left(\frac{\sigma_t^2}{t^2}+\frac{\sigma_L^2}{L^2}\right)+\frac{\sigma_P^2}{P^2} \, . \tag{3}$$

Therefore, the mass resolution is fully determined by the precisions in velocity (thus time-of-flight) and momentum. In reality, they can be measured with the time-of-flight technique and position measurement at the dispersive focus plane in a magnetic field.

The *TOF* part in TOF-P-MS is especially challenging, because the reaction products to first order retain their initial velocities in a fragmentation process. On a few meters distance the *TOF* differences between reaction products is on the order of ns, implying the need for excellent timing resolution. Taking the TOF-MS at NSCL as an example, the final time resolution (one standard deviation) achieved is about 80 ps for a total flight time of about 500 ns, and a position resolution is about 500 μm measured at a dispersion plane with about -11 cm/%. Omitting the small variance in path length *L* (this can also be confined to a large extend e.g. by mechanical slits and vetoes), the calculated mass resolution of about 2×10^{-4} from Eq.(3) agrees well with experimental results [5]. The main uncertainty to $\delta m_0/m_0$ in the TOF-P-MS at NSCL is from the relatively large timing precision of about 1.9×10^{-4}. It is about a factor of four larger than the momentum determination.

Ideally, when the precisions of both time and position were improved by one order of magnitude, namely 8 ps for time and 50 μm for position, the mass resolution would be improved to about 2.0×10^{-5}. This corresponds to about ±500 keV of the mass excess for a single nucleus with A = 50. Moreover, the final mass uncertainties are governed by the statistical law. Depending on the number of detected particles, the precisions can be a few tens of keV for thousands of events (nuclei relatively close to β-stability line) , and about 100 keV for twenty events (nuclei approaching the ends of isotopic chains). As shown in Fig. 1, the expected relative mass precision will be then comparable to IMS and MR-TOF.

3 Detector developments

Several requirements have to be met for the detectors in TOF-P-MS: (i) compatible to in beam use, (ii) a large transmission and a minimal straggling of ions induced by the detectors, (iii) a high detection efficiency and single-particle sensitivity. In principle, a rate capability up to several kHz is fairly enough considering the low yields of most exotic nuclei. In many cases, a reasonably large active detector area is also needed to cover the spatial spread of reaction products, e.g. the position detectors at the dispersive focus plane. An energy loss detector is often needed for accessing heavier systems, because the *TOF-P* technique itself does not allow unambiguous identification of exotic nuclides with similar *m*/*q* values. In this section, we will briefly report our latest results in detector developments for TOF-P-MS.

3.1 TOF measurement

The *TOF* is normally measured by means of a thin scintillation counter telescope consisting of two scintillates spaced at a certain distance. The organic scintillation counters are relatively simple, well understood and robust. We tested several types of plastic scintillator detectors for heavy ions at a few hundred MeV/u. A typical detector arrangement is shown in Fig.2, where six detectors are tested simultaneously with heavy ions. The best intrinsic time resolutions obtained amounts to be about 5 ps, or about 10 ps for *TOF* determination [7]. Fast plastic scintillator with optimized size and thickness, fast PMT readout, and fast, accurate electronics are crucial for this improvement.

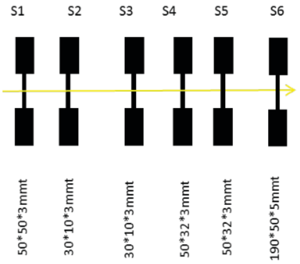

Fig.2 Plastic scintillator detector arrangement in tests with heavy ions. Indicated are various plastic scintillators with different combinations of plastic scintillators (with different size and/or thickness, types) with phototubes (types).

Other approaches for fast timing include the diamond detector (but costly) and MCP-based secondary electron emission detectors. The latter is operated under good vacuum and a resolution of 20 ps has been achieved recently [8].

3.2 Momentum measurement by position determination

Another source that limits the mass resolution of TOF-P-MS is the precision of momentum. Besides, momentum is also essential to correct the total flight length of each ion. A pair of position-sensitive gas detectors (e.g. multi-ware parallel chamber) or MCP detectors placed at a large dispersive focus plane was used for such purpose[5,6].

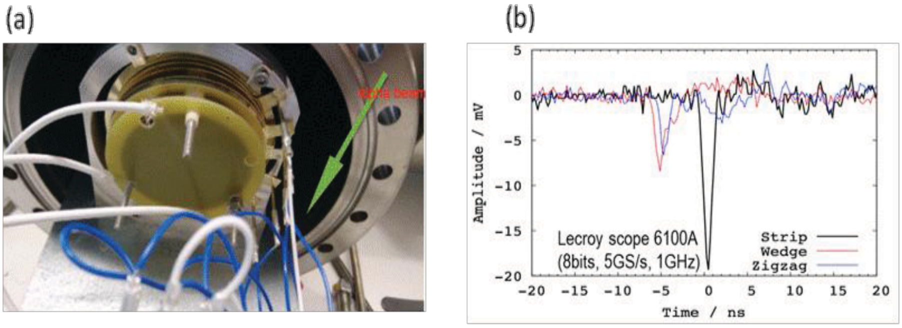

Fig.3 (a) First prototype of the MCP detector with an anode of wedge-strip type for position readout; (b) Typical signals from the anode.

Currently, we are developing a position sensitive anode in a wedge-strip type [9]. The first prototype of this detector is shown in Fig.3(a). Two MCPs in the Chevron configuration are put right in front of the anode. In offline tests, the position of incoming α rays are first passed on to the MCPs. Secondary electrons, which are released in the fired channels of MCP, are then guided and focused to the anode for position readout. Preliminary results show that this anode can provide both time and position information with good precision. Typical signals from three readouts of this anode, strip, wedge and zigzag, are shown in Fig.3(b). After integrations of the total charges from each readout, it is possible to decode the position information carried by electron clouds, and accordingly the position of α particles. Meanwhile, we are investigating a novel way for position determination with a high-gain digital camera with an image intensifier.

4 Summary

TOF-P-MS is a natural coupling of fast particle tracking system with high-resolution, high-transmission magnetic spectrometers. It uses a precise measurement of the flight time t, within which an ion travels a known flight path length L along a static magnetic beam line system. With augmented timing and position detectors, we show that TOF-P-MS even can achieve a similar mass resolution as storage ring mass spectrometer IMS and MR-TOF. In this paper, we reported the progress in fast detector development that is suitable for TOF-P-MS.

Acknowledgement:

We would like to thank D. Diwisch for helping in the first anode test, and Z.Q. Chen, H. Ong, T. Yamaguchi for plastic scintillator detector test.

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