Development of a Time-of-Flight detector for the Rare-RI Ring project at RIKEN

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Abstract

We have tested the timing properties of several thin plastic scintillators (10-500 μm) designed for the Rare-RI Ring project at the RI Beam factory. The experiments were performed at the heavy-ion synchrotron facility, HIMAC (Heavy Ion Medical Accelerator in Chiba), using a Xe beam with an energy of 200 MeV/nucleon. The scintillation light was read out by fast-timing photomultipliers through standard fishtail-shaped light guides. The resultant timing resolutions reached a few tens of picoseconds, which satisfied our requirement for the project. We also measured charge-state distributions for Xe^{42+} and Fe^{20+} ions penetrating carbon foils of 10-500 μg/cm^2 thickness. The results were compared with a theoretical model calculation for charge-state evolution.

Key words: TOF, Scintillator, Timing resolution, Heavy ion, Charge states
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1. Introduction

Nuclear masses are one of the most essential quantities for understanding nuclear properties. Mapping the mass surface over the nuclear chart provides a crucial test of nuclear models. Nuclear masses also play an important role as basic input for network calculations of element synthesis, such as the r-process in supernovae. The challenge is to precisely measure nuclear masses of exotic nuclei far from stability.

The RI beam factory (RIBF) aims for nuclear structure physics and nuclear astrophysics research programs. The facility consists of a cyclotron complex and a fragment separator, BigRIPS [1]. Various kinds of rare radioactive ions (RI) can be produced via the in-flight fission process of a high-energy uranium beam up to 350 MeV/nucleon. The primary beam intensity will eventually reach up to 1 pμA, which would allow us to study exotic nuclei at and near the driplines, and therefore to stimulate direct mass measurements of such exotic nuclei.

A new scheme, Rare-RI Ring, of direct mass measurements for short-lived rare RI in an isochronous storage ring with a high mass precision ($\frac{\delta m}{m} \sim 10^{-6}$) and a large m/q acceptance ($\frac{\delta(m/q)}{m/q} \sim 10^{-2}$) has recently been proposed [2]. The scheme will efficiently work for extremely low-intensity beams. The applied method was originally developed at GSI Darmstadt, isochronous mass spectrometry (IMS) performed at ESR [3]. In this paper we report a preliminary result from a beam test for Time-Of-Flight (TOF) detectors designed for the mass measurements. The details of the project, itself, can be found elsewhere [4].

2. Principle of mass measurement and specifications required for a TOF detector

The principle is based on the proportionality between the charge-to-mass ratio (q/m) and the cyclotron frequency (f_C) in a magnetic field (B), $f_C = \frac{1}{2\pi}\frac{q}{m}B$. In the case that the storage-ring optics is adjusted to the isochronous

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mode ($B = B_0\gamma_0$) for a primary beam with a known mass ($m = m_0\gamma_0$), the mass-to-charge ratio m_0/q is exactly proportional to the revolution frequency ($1/T_0$), because the γ_0 factor is canceled out. Here, γ_0 is a relativistic factor, defined as $\gamma_0 = 1/\sqrt{1-\beta_0^2}$ and $\beta_0 = v/c$.

For a particle (rare RI to be measured) with a slightly different mass-to-charge ratio, $m_1/q = m_0/q + \Delta(m_0/q)$, $\Delta(m_0/q) \sim 10^{-2}$; however, isochronism is no longer fulfilled, and the mass-to-charge ratio is given by

$$\frac{m_1}{q} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\frac{\gamma_0}{\gamma_1} = \left(\frac{m_0}{q}\right)\frac{T_1}{T_0}\sqrt{\frac{1-\beta_1^2}{1-(\frac{T_1}{T_0}\beta_1)^2}}, \quad (1)$$

where T_1 is the revolution time for a particle with m_1/q. The mass precision also depends on the precision of the velocity β_1. The relative differential of m_1/q is given as

$$\frac{\delta(m_1/q)}{m_1/q} = \frac{\delta(m_0/q)}{m_0/q} + \frac{\delta(T_1/T_0)}{T_1/T_0} + k\frac{\delta\beta_1}{\beta_1}. \quad (2)$$

The coefficient k in the third term is on the order of 10^{-2} for $\Delta(m_0/q) \sim 10^{-2}$. One can determine the mass value of a non-isochronous particle with a precision of 10^{-6} by measuring the velocity with a precision of $\delta\beta_1/\beta_1 \sim 10^{-4}$, and by measuring the revolution time with a precision of $\delta T_1/T_1 \sim 10^{-6}$. A mass precision on the order of 10^{-6} will be achieved for all particles within a m/q difference of 10^{-2}. The storage-ring optics is designed for the fixed energy of 200 MeV/nucleon [4].

For this purpose, both the revolution time in the storage ring and the beam velocity should be precisely measured for all particles. The timing resolution required for the revolution time is estimated to be less than 100 ps for a total revolution time of around 1 ms (∼3000 turns in a period of 330 ns for a beam of 200 MeV/nucleon). For a beam velocity measurement, a long beam-transport line, ∼180 m from the fragment separator to the storage ring will be utilized, which would provide around a 1 μs flight time for ions with the energy of 200 MeV/nucleon. In addition, the detector material should be thin enough to maintain the charge states and the emittances of the incoming particles, because of the tuning sequence of the isochronous optics for the storage ring [4].

A plastic scintillator with photomultiplier readout can provide one of the fastest timing response for heavy ions [5]. Typical plastic scintillators are available to achieve such high precision for both revolution time and beam velocity measurements.

3. Experimental

The experiment was performed at the secondary beam line, SB2 course [6] in the heavy-ion synchrotron facility, HIMAC (Heavy Ion Medical Accelerator in Chiba) at National Institute of Radiological Sciences (NIRS).

A primary beam of Xe^{42+} was accelerated to 200 MeV/nucleon and delivered to the final focus (F3) of the SB2 course with a typical intensity of 2×10^3 particles per pulse. The beam size at F3 was less than ϕ10 mm. We closely arranged three sets of scintillation counters after a vacuum window of 100 μm-thick aluminum. Photomultipliers were connected on both ends of the scintillators through standard fishtail-shaped light guides (50 mm long) to cancel out any position dependence of the timing response.

We used several plastic scintillators and fast photomultipliers. The thicknesses of the plastic scintillators were 10, 50, 100 and 500 μm, all of which, except 10 μm, were model EJ230 made by ELJEN Technology. Model EJ232 was used for a thickness of 10 μm. The size of all scintillators was 100 × 50 mm^2, relatively large to fully cover the beam size of secondary beams. In the present dimensions, the minimum thickness for plastic scintillators might be 10 μm, due to technological limitations. The photomultipliers used were models H1949, H2431 and R4998, made by HAMAMATSU.

We also measured the charge-state distributions for partially stripped Xe^{42+} and Fe^{20+} ions penetrating carbon foils at an energy of 200 MeV/nucleon. Carbon foils with thicknesses of 10, 50, 100, 518 μg/cm2 were installed at the target position (F0) at the SB2 course; 518 μg/cm^2-thick foils were provided from ACF-metals, and the others from YISSUM Research Development Company. The present measurement can be a basic input in designing the thinnest detectors, and also would improve a database of the charge-state distributions for heavy ions at medium energies. So far, the charge states of heavy ions at this energy range have not been measured in detail. It should be noted that the thinnest 10 μm-thick plastic scintillator is almost equivalent to a 1000 μg/cm^2-thick carbon foil.

4. Data analysis and results

4.1. *Timing resolutions of plastic scintillators*

We tested several combinations of the plastics and the photomultipliers under different conditions. The timing signals measured with leading-edge type discriminators were corrected by the pulse-height information as a walk effect. The function for the walk-effect correction was the same as given in Ref. [5]. Typical TOF and pulse-height spectra are shown in Fig.1.

The timing resolutions were determined by fitting the TOF spectra with a Gaussian function. The intrinsic timing resolutions were separated using three sets of TOF data measured with the counters (A, B, C), following equations

$$\sigma^2_{\mathrm{TOF_{AB}}} = \sigma^2_{\mathrm{T_A}} + \sigma^2_{\mathrm{T_B}}, \quad (3)$$
$$\sigma^2_{\mathrm{TOF_{BC}}} = \sigma^2_{\mathrm{T_B}} + \sigma^2_{\mathrm{T_C}}, \quad (4)$$
$$\sigma^2_{\mathrm{TOF_{CA}}} = \sigma^2_{\mathrm{T_C}} + \sigma^2_{\mathrm{T_A}}. \quad (5)$$

Here, it is assumed that the timing broadening, $\sigma^2_{\mathrm{TOF_{AB}}}$, for the TOF between counters A and B consists of a simple sum of the intrinsic timing resolutions of counters A ($\sigma_{\mathrm{T_A}}$)

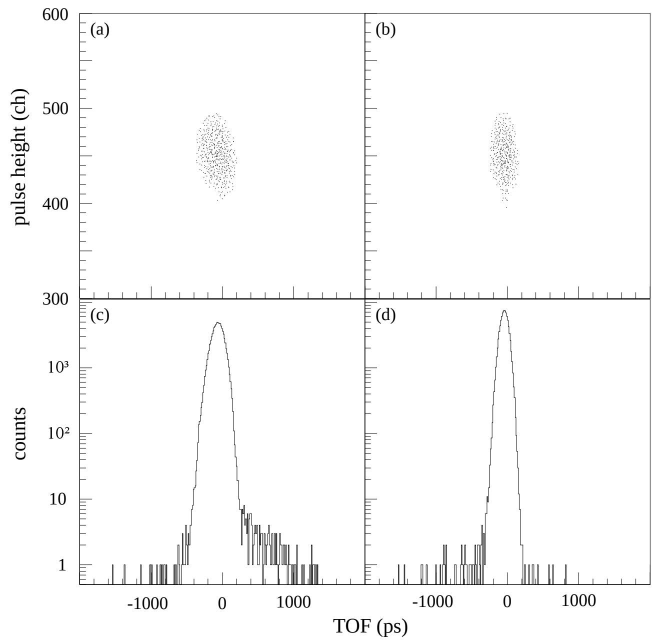

Fig. 1. Typical TOF spectra between 50 μm-thick plastic with H2431 and 500 μm with H1949. Correlations between the pulse height and the TOF are shown in (a) and (b) before and after a pulse-height correction, respectively, and the corresponding TOF spectra in (c) and (d). TOF spectra were fitted by a Gaussian function.

and B ($\sigma_{\mathrm{T_B}}$), and the same assumption is applied to the other quantities as well.

Preliminary results show that the timing resolutions reached a few tens of picoseconds (less than 100 ps) for all combinations. The best was 500 μm thick with H2431, which gave a timing resolution of 10 ps in sigma, as shown in Fig. 2. The results are not sensitive to the variance of the applied high voltage. Model H2431 gave slightly better results, because of a faster rise time of the photomultiplier. Meanwhile, the thinnest case, 10 μm thick with H1949, resulted in 70 ps. The results for 50 and 100 μm thick were both almost 20 ps. It has thus been proved that standard plastic scintillators with fast photomultiplier readout are available in terms of the timing resolution for $Z = 54$. For a practical design, beam tests would also be necessary for lighter ions.

4.2. *Charge-states of heavy ions*

Charge-state fractions were measured by changing the magnetic fields of the SB2 course and counting particles transmitted up to F3. The fractions were then normalized with those of empty-foil measurements periodically repeated so as to avoid any fluctuation of the primary beam intensity.

Preliminary results are shown in Fig. 3. A theoretical model (GLOBAL) [7] was calculated to plot in the figure as well. The code GLOBAL was originally developed by Scheidenberger *et al.* based on systematic measurements of the charge states for heavy ions from Xe to U at relativistic

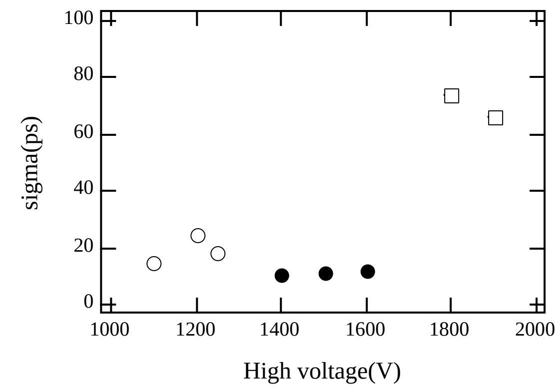

Fig. 2. High-voltage and photomultiplier dependence on the timing resolution. The open and closed circles indicate the timing resolutions of 500 μm-thick plastic for H1949 and H2431, respectively. The open squares show the results for 10 μm thick with H1949.

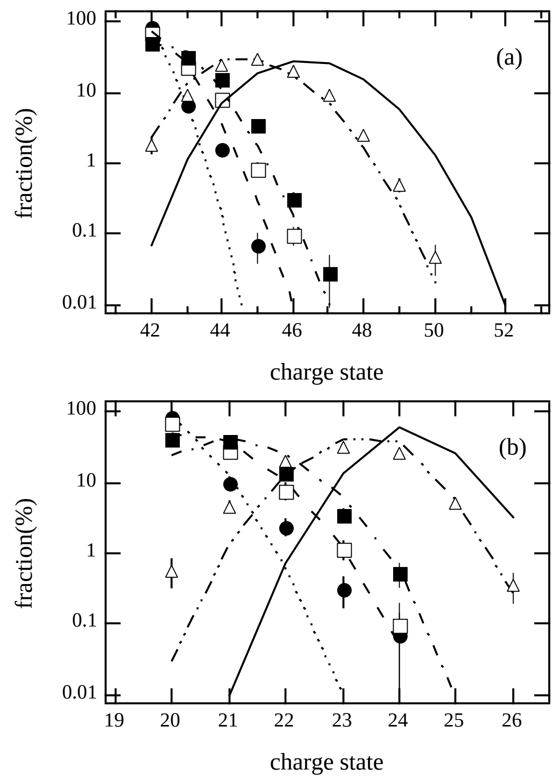

Fig. 3. Charge-state distributions of (a) Xe^{42+} and (b) Fe^{20+} ions penetrating carbon foils. The closed circles, open and closed squares, and open triangles show the results for carbon foils with 10, 50, 100, 518 μg/cm^2 thick, respectively. Corresponding theoretical calculations by GLOBAL are shown with dotted, dashed, dashed-dotted, dashed-two dotted lines. Calculations for 1000 μg/cm^2-thick carbon are shown with solid lines.

energies. The calculation code solves the rate equations numerically with the electron stripping and capture cross sections up to the M shell with screening effects.

One can see an overall good agreement with theoretical calculations and experimental data. It should be mentioned that the calculation for Fe is beyond the application of the code, since the original code was developed for $Z > 29$. A small, but systematic, underestimation observed in both cases might be caused by some approximation methods in the code.

The charge states for 10 μm-thick plastic (calculated as 1000 μg/cm^2 carbon equivalent) are plotted as a reference to demonstrate a thickness dependence of the detector materials on the charge states. The charge equilibrium thickness for a carbon target is estimated in the code to be 95 and 13 mg/cm^2 for Xe and Fe ions at 200 MeV/nucleon, respectively.

5. Summary

The timing properties of several thin plastic scintillators with standard photomultiplier readout were measured using a 200 MeV/nucleon Xe beam. Preliminary results satisfy the TOF requirement of the Rare-RI ring for all combinations down to a 10 μm-thick plastic scintillator. The present study would also be helpful for the general use of TOF detectors in secondary beam experiments. Further technological developments for thinner plastic scintillators are strongly desired.

The charge-state distributions of Xe and Fe ions have been measured as a function of thickness of carbon foils. The theoretical model code GLOBAL well describes the present experimental data.

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