Identification of Time-of-Flight spectra for Isochronous Mass Measurements

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Abstract The Isochronous Mass Spectrometry (IMS) developed at GSI is a very efficient method for direct mass measurements of short-lived nuclides. By taking a recent IMS experiment as an example, the identification procedure of the Time-of-Flight (TOF) spectrum measured in this experiment is discussed.

Key words Isochronous Mass Spectrometry, Time-of-Flight Spectrum, isotope identification

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1 Introduction

Mass measurements of exotic nuclei contribute to a deeper understanding of nuclear structure and also nucleosynthesis in nature. In the last two decades, lots of mass measurement programs were pursued worldwide associated with radioactive-beam facilities. At GSI, two complementary mass measurement methods have been well developed based on the coupling of the experimental storage ring ESR and the in-flight fragment separator FRS, namely, the Schottky Mass Spectrometry (SMS)[1, 2] for electron-cooled beams of relatively long-lived isotopes ($T_{1/2} > 1$ s) and the Isochronous Mass Spectrometry (IMS)[3, 4] for uncooled beams of shorter-lived fragments. Both methods are suitable for large-scale precise mass measurement of stored exotic nuclei. Their mass-over-charge acceptances $\Delta(m/q)/(m/q)$ are about 2.5% and 10%, respectively. In both cases, the circulating fragments generate narrow lines in frequency or time-of-flight (TOF) spectra.

In this paper, we will present the key procedure of the analysis, namely, the isotope identification of the recorded TOF spectrum. This will be done at the example of data from a recent IMS experiment[4].

The paper is organized as follows. In Sec. 2, the experiment and the accumulated spectrum are briefly described. A simulated TOF spectrum for the given experimental condition is discussed in Sec. 3. The identification method is presented in Sec. 4. Finally, a summary is given.

2 Experimental TOF spectrum

In the latest IMS experiment[4], neutron-rich exotic nuclei were produced by projectile fission of 411 MeV/u ^{238}U ions in a 1 g/cm^2 Be target placed at the entrance of the FRS. The energy of the primary beam was chosen such that the mean energy of ^{133}Sn^{50+} fragments corresponded to the relativistic Lorentz factor γ=1.41, which was exactly the isochronous energy of the ESR[3]. All other fragments within the acceptance of the FRS-ESR facility were transmitted and stored as well.

A special thin-foil detection system was developed to record signals from each ion at each revolution. The ions can make several hundred revolutions before they get lost in the ring. Hence each measurement cycle generated hundreds of signals belonging to several stored ions. This raw spectrum was analyzed using

a pattern recognition algorithm that seeks for series of equidistant signals[5]. These signals were then re-grouped and assigned to a certain revolution time. All extracted revolution times were combined into a TOF spectrum which contains more than a hundred TOF peaks. These peaks need to be unambiguously identified. A part of the accumulated TOF spectrum is illustrated in Fig. 1(a).
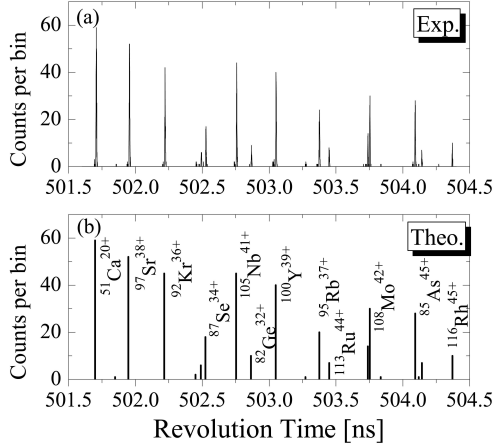

Fig. 1. (a) A part of the TOF spectrum accumulated in the discussed IMS experiment; (b) A simulated TOF spectrum. Only the prominent lines are labelled with the isotope identification.

3   Simulated TOF spectrum

The identification method is based on the comparison of measured and simulated TOF spectra. The first step is to create a list of all nuclides that can be observed in the ESR under the experimental condition. This list includes mass-over-charge ratios (m/q) of nuclides in ground and isomeric states and in all relevant charge states. There are over 16000 nuclear species considering only fully-ionized, hydrogen-like, helium-like and lithium-like ions.

Further restrictions can be made to the m/q list based on the experimental condition as below.

3.1   Ion-optical setting of the FRS

The Monte-Carlo code MOCADI[6] was used to simulate the production and separation of fragments in the FRS. This code has implemented the production cross-sections, the reaction kinematics, the atomic slowing down in matter and the ion-optical properties of the FRS. In this particular experiment the FRS has been tuned to transmit $^{133}Sn^{50+}$ fission fragments. Mainly fission fragments between the neutron shell closures $N = 50$ and $N = 82$, and the pro-

ton shell closures $Z = 28$ and $Z = 50$ are transmitted. However, a small probability of projectile fragments has to be considered which yields nuclides with proton numbers in the range of 10—60.

3.2   Ion-optical setting of the ESR

The acceptance of the ESR has been measured with the primary beam $^{238}U^{90+}$ electron-cooled to different mean velocities. Since the $(m/q)_U$ is well-known and the velocity is defined by the voltage applied to the cooler electrodes, the magnetic rigidity $(B\rho)$ acceptance can be determined[7]. Thus the measured spectrum lines are expected in the m/q range of 2.4—2.8. Moreover, we additionally verify the isochronicity of the ESR by measuring the revolution times T_U. The revolution time for any other ion species T_i with $(m/q)_i$ can be estimated from the following equation

$$T_i = T_U \bigg/ \sqrt{\frac{\dfrac{(m/q)_U}{B\rho} + \dfrac{1}{c^2}}{\dfrac{(m/q)_i}{B\rho} + \dfrac{1}{c^2}}} \, . \qquad (1)$$

3.3   Atomic charge states

The charge state of a fragment after the production target is strongly dependent on its atomic number and kinetic energy. The equilibrium charge state distributions can be estimated with the CHARGE and GLOBAL codes [8]. The following charge states are expected in our case:

$$\begin{aligned} Z &\geqslant 70, \quad \text{with 0, 1, 2, 3 electrons;} \\ 50 &\leqslant Z \leqslant 69, \quad \text{with 0, 1, 2 electrons;} \\ 35 &\leqslant Z \leqslant 49, \quad \text{with 0, 1 electrons;} \\ Z &\leqslant 34, \quad \text{with 0 electrons.} \qquad (2) \end{aligned}$$

3.4   Nuclear half-lives

In principle, the IMS method can access nuclides with half-lives down to tens of µs. Furthermore, nuclear half-lives in high charge states can be significantly different from the ones known for neutral atoms[9—12]. Nuclear species with half-lives longer than 1 µs were considered in the analysis.

Important information on the isotope identification can be also obtained from nuclear decays. A slight change of the m/q in these decays is reflected by the corresponding revolution frequency shift. By monitoring in time the revolution frequency, one is able to identify such decays and therefore the pairs of nuclides[2].

The above selection criteria reduce the list of possible candidates to less than 4000 different nuclear

species. It is now possible to apply a computer assisted pattern recognition algorithm.

4   Identification

For two ions i, j, the relation between their revolution time difference and the m/q difference can be expressed in first order approximation as

$$\frac{T_i - T_j}{T_i} = \alpha_p \frac{(m/q)_i - (m/q)_j}{(m/q)_i} ,\qquad (3)$$

where α_p is the momentum compaction factor, and is close to 0.5 in the experimental setting. Within a narrow range of $\Delta(m/q)/(m/q) \sim 0.5\%$ a linear approximation to this relation is sufficient: $m/q = a_0 + a_1 T$ with a_0 and a_1 being the parameters. An example of the identification process for the part of the IMS spectrum in Fig. 1(a) will be discussed below.

In the peak pattern comparison, we vary the α_p between 0.4 and 0.6 with steps of 0.0001. For each value of α_p the best overlap of the simulated and experimental spectra is searched. This is done by subsequent assignment of all $(m/q)_i$ from the selected (m/q) list to the first TOF peak (with T_1) in the measured spectrum. For each assignment a theoretical TOF spectrum containing T_j $(j > i)$ is created using Eq. (3). The overlap of two spectra is characterized by $\chi^2 = \sum_i^N (T_i^{\mathrm{cal}} - T_i^{\mathrm{exp}})^2$, where T_i^{cal} and T_i^{exp} are the calculated and experimental revolution times, respectively, and N is the total number of peaks. Fig. 2(a) shows the χ^2 as a function of different assignment of T_1 at $\alpha_p = 0.487$. The minimal χ^2 values for different α_p values are illustrated in Fig. 2(b). The best overlap between the measured and calculated spectra is achieved for $\alpha_p = 0.487$ by choosing the 1650th m/q value (corresponding to $^{85}\mathrm{As}^{33+}$) from the list to match the first measured TOF peak. The corresponding calculated revolution times and their isotope identification are displayed in Fig. 1(b).

A complication arises from the fact that α_p is a not constant but slightly depends on the magnetic rigidity. The convergence of the identification algorithm requires 10—20 peaks. Therefore, we divided the measured broad-band TOF spectrum into a few overlapping parts with about 20 peaks each which were identified separately. The overlapping parts with about 10 peaks were used to verify the uniqueness of identification. However, due to limited resolving power some peaks could not be uniquely assigned to a certain species. Such cases can be clarified in the final mass evaluation.
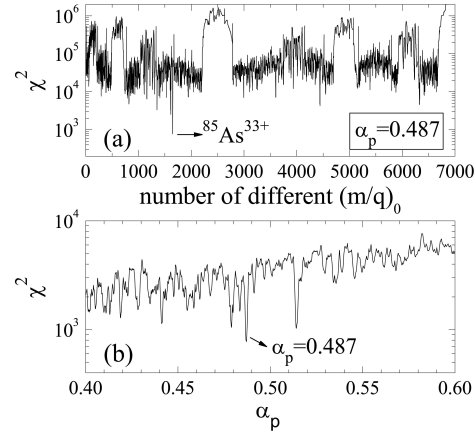

Fig. 2.   Verification of the ion identification. (a) The best overlap between the calculated and the measured frequencies at $\alpha_p = 0.487$ is achieved if the first TOF peak is assigned to $^{85}\mathrm{As}^{33+}$ isotope; (b) The overall minimum is obtained for the $\alpha_p = 0.487$.

5   Summary

The isotope identification of a TOF spectrum from the IMS experiment has been discussed in detail. This method has been widely used for the IMS and SMS data analysis, and is also suitable for the CSR mass measurement project in Lanzhou[13].

The present isotope identification is based on the peak pattern comparison between the measured and the simulated spectra. An additional calibration can be provided by storing the primary beam in a selected charge state matching the correct m/q range together with the investigated fragments[14].

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