2 - 5 Data Analysis of the Schottky Mass Measurements of ^{152}Sm Fragments*

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Precision mass measurements of neutron-deficient ^{152}Sm projectile fragments were conducted in 2005 at the FRS-ESR facility at GSI Helmholtz centre[1, 2], employing the time-resolved Schottky Mass Spectrometry[3]. A new mass evaluation method has been developed in the data analysis. The systematic error in the mass determination was significantly reduced with the new method[4].

Exotic nuclei, produced by projectile fragmentation of a 615 AMeV ^{152}Sm primary beam in a 4.009 g/cm^2 beryllium target, were transmitted and $B\rho$-separated by the fragment separator FRS and then injected and stored in the experimental storage ring ESR. In ESR the electron-cooling process was continuously applied to the stored ions. To first order approximation, the revolution-frequencies (f) of the stored ions in the ESR are related to their velocities (v) and mass-to-charge ratios (m/q) of the ions in rest frame:

$$\frac{f_i - f_j}{f_i} \approx -\alpha_p \frac{(m/q)_i - (m/q)_j}{(m/q)_i} + (1-\alpha_p\gamma^2)\frac{v_i - v_j}{v_i} \quad , \tag{1}$$

where α_p is the momentum-compaction-factor of ESR and γ is the Lorentz factor of the ions.

In the first step of data analysis, the form of α_p was investigated for the entire ESR acceptance[5]. Neglecting the velocity term in Eq. (1), the α_p values can be deduced approximately from the well-known mass-to-charge ratios of ion-pairs of neighbouring peaks in the frequency spectra:

$$(\alpha_p)_i = \frac{[\frac{f_i - f_{i+1}}{f_i}]_{\exp}}{[\frac{(m/q)_{i+1}-(m/q)_i}{(m/q)_i}]_{\mathrm{AME12}}} \quad \text{and} \quad \frac{\sigma(\alpha_p)_i}{(\alpha_p)_i} = \sqrt{\frac{\sigma^2_{f_i}+\sigma^2_{f_{i+1}}}{(f_i - f_{i+1})^2} + \frac{\sigma^2_{m/q_i}+\sigma^2_{m/q_{i+1}}}{(m/q_{i+1}-m/q_i)^2} + \left(\frac{\sigma_{f_i}}{f_i}\right)^2 + \left(\frac{\sigma_{m/q_i}}{m/q_i}\right)^2} \quad . \tag{2}$$

As a result, the velocity spread of the electron-cooled ions were deduced to be $\sigma_v/v = (\sigma_f/f)/(1-\alpha_p\gamma^2) \approx 1.4(3)\times10^{-7}$.

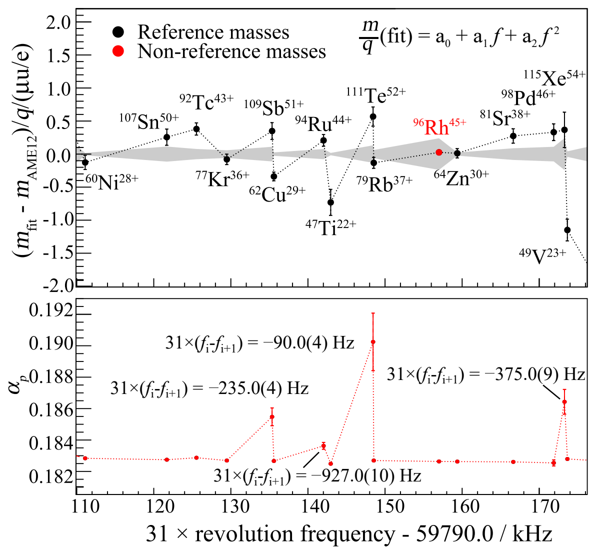

Fig. 1 (color online) Upper panel: the results of the local mass calibration of one spectrum. The calibration was done in the frequency range of 110 kHz $\leq 31\times f - 59790.0$ kHz $\leq$ 176 kHz. The error bars include the contributions from the uncertainties of the measured frequencies and the errors of the calibration coefficients. The grey area shows the 1σ error-band of the ions' tabulated m/q-values from the AME2012[6]. Lower panel: the momentum-compaction factor (α_p) deduced approximately from the measured frequencies and tabulated m/q-values using Eq. (2). It is clearly seen that α_p is nearly constant in the calibration range and there are obvious spikes (more than 3σ deviations) in the obtained α_p-curve. The Figure is adapted from Ref. [4].

In the second step of data analysis, local mass calibrations of the frequency spectra were performed in the selected frequency range where α_p was nearly constant. In this step, a second order polynomial function was used

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to establish the relation between the m/q ratios of the ions and their revolution frequencies. As an illustrative example, Fig. 1 shows the mass calibration results of one spectrum. The same data are also plotted in Fig. 2, but are sorted differently. Note that the mass of the ions were deduced from the corresponding atomic mass $m_{\rm AME12} = m^{\rm Atom}_{\rm AME12} - q \times m_{\rm e} + B_{\rm e}(q)$, where $m^{\rm Atom}_{\rm AME12}$ is the adjusted atomic mass value in the latest Atomic Mass Evaluation AME2012[6], $m_{\rm e}$ is the rest mass of the electron and $B_{\rm e}(q)$ is the electron binding energy of the q electrons that have been removed from the atomic shells[7–9]. The results show that the differences between the fitted mass values and the literature mass values systematically depend on the charge states of the ions; see the upper panel of Fig. 1 and more clearly the left-hand panel of Fig. 2. This observation was similar to, but not the same as, the finding in Ref.[10]. Assuming the tabulated mass-values ($m_{\rm AME12}$) of the ions are correct, the charge-dependent $(m_{\rm fit} - m_{\rm AME12})/q$-values indicate that the revolution frequencies of the ions are charge-dependent. The origin of this charge-dependency phenomenon is still under discussion. Meanwhile, the calculated α_p-values show some points deviating from the normal trend; see the lower panel of Fig. 1 and the right-hand panel of Fig. 2. From Fig. 2, it is clearly seen that the deviating α_p-points are associated with the systematic m/q-deviations: the deviating α_p occurs only when the differences between the frequencies of the neighbouring peaks are very small (*eg.* $31 \times \Delta f < 1000$ Hz) and the $\Delta q = q_i - q_{i+1}$ of the corresponding ions are large. It was also observed in the experiment that if Δf had the same sign as Δq, then α_p would be smaller than 0.1827. If $\Delta q = 0$, which means the ion-pairs of isobars or isomeric and ground states of nuclear species, then there was no α_p deviating from the normal trend. In the case shown in Fig. 2, the slope of the best linear fit in the right-hand panel of Fig. 2 is 0.031(3) μu/e^2, and the normal trend value of α_p is 0.1827(3) in the left-hand panel of Fig. 2. When $|\Delta f|/f$ is as small as $0.3 \times |\Delta q| \times 10^{-6}$, spikes appear in the α_p-curve. The smaller the $|(\Delta f/f)/\Delta q|$ value, the stronger α_p deviates from 0.1827. One way to correct for these spikes is to add a velocity term $\Delta v = v_i - v_{i+1}$ to the calculation of α_p in Eq. (2). This would mean, for example, the mean velocity of the $^{111}{\rm Te}^{52+}$ ions would be different from that of the $^{79}{\rm Rb}^{37+}$ ions by $\Delta v/v \approx -0.95 \times 10^{-7}$, the value by which one can remove the corresponding spike in the α_p-curve in the lower panel of Fig. 1. More investigations are needed to confirm and explain how could this tiny velocity difference systematically appears in the electron cooled ions in the ESR. If the effect is due to the charge-dependent velocities of the electron cooled ions, as proposed in Ref. [10], this will improve our understanding of the electron-cooling process.

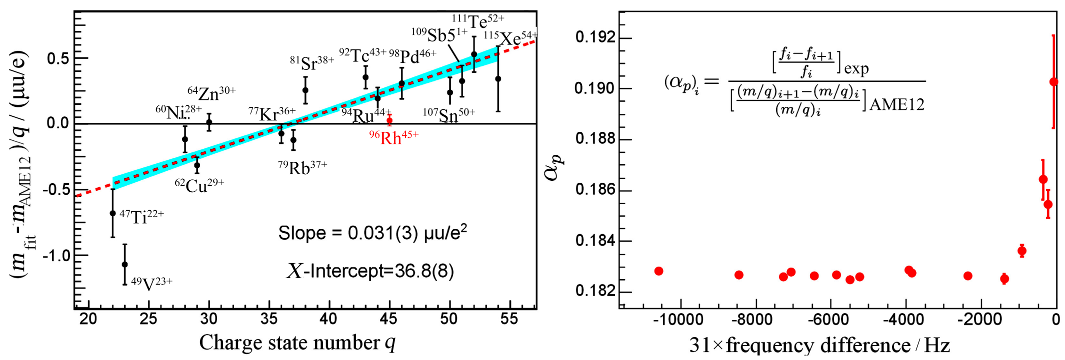

Fig. 2 (color online) Left-hand panel: Fitting residuals as a function of the ion's charge state. The red dotted line and the green area are the results of the best linear fit and the corresponding 1σ error-band, respectively. Right-hand panel: The calculated α_p values as a function of the frequency differences. The data points are the same as those in Fig. 1, but are sorted in a different way.

In the third step of data analysis, the systematic $(m_{\rm fit} - m_{\rm AME12})/q$-deviations were corrected by adding a linear q-term in calibration function and a typical mass uncertainty of 20 keV has been achieved in the experiment. Ten new masses have been experimentally determined for the first time[11]. The mass surface measured in this experiment largely overlapped with previous measurements[3], and results could be used for a consistency check of data.

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