New Algorithms for Particle Mass Number Identification and Time-of-Flight Calibration for Secondary Beams Produced via Projectile Fragmentation

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Abstract

This paper presents new data analysis algorithms for identifying the mass number and calibrating the time of flight (TOF) for secondary beams produced via projectile fragmentation at incident energies of several hundred MeV per nucleon. The algorithms need only conventional measurements of TOF in the beam line, the energy deposit (ΔE), and the hit positions in the entering and exiting foci of the beam line for unambiguous identification of the mass number of the secondary cocktail beams, and also the calibration of TOF with a precision of about 0.2ns. The algorithms are implemented by fitting the transfer matrix elements under linear beam optics to extract the central magnetic rigidity $B\rho_0$ with the assumed mass $A_{\rm a}u$ (u is the atomic mass unit) of the nuclei. This procedure is implemented for each chosen nuclide in the secondary beam respectively so that a $B\rho_0$-A scatter plot is obtained. The deviation δA of the assumed mass $A_{\rm a}u$ and the real value Au $\delta A \equiv A_{\rm a} - A$ are evaluated by fitting the $B\rho_0$-A scatter plot with a function $A_{\rm a}/(A_{\rm a} - \delta A)$, from which one obtains $A = A_{\rm a} - \delta A$. The calibration of TOF follows a similar method. The algorithms are tested to give a satisfactory and consistent particle identification for fragments of 350MeV/nucleon Kr-78 in a beam test conducted at the External Target Facility (ETF) of the second Radioactive Ion Beam Line in Lanzhou (RIBLL2) in HIRFL-CSR.

Full Text

Preamble

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This paper presents new data analysis algorithms for identifying the mass number and calibrating the time of flight (TOF) for secondary beams produced via projectile fragmentation at incident energies of several hundred MeV per nucleon. The algorithms need only conventional measurements of TOF in the beam line, the energy deposit (ΔE), and the hit positions in the entering and exiting foci of the beam line for unambiguous identification of the mass number of the secondary cocktail beams, and also the calibration of TOF with a precision of about 0.2 ns. The algorithms are implemented by fitting the transfer matrix elements under linear beam optics to extract the central magnetic rigidity B $_0$ with the assumed mass A u (u is the atomic mass unit) of the nuclei. This procedure is implemented for each chosen nuclide in the secondary beam respectively so that a B $_0$-A scatter plot is obtained. The deviation δA of the assumed mass A u and the real value Au δA A $-$ A are evaluated by fitting the B $_0$-A scatter plot with a function A /(A $-$ δA), from which one obtains A = A $-$ δA. The calibration of TOF follows a similar method. The algorithms are tested to give a satisfactory and consistent particle identification for fragments of 350 MeV/nucleon ^{78}Kr in a beam test conducted at the External Target Facility (ETF) of the second Radioactive Ion Beam Line in Lanzhou (RIBLL2) in HIRFL-CSR.

Keywords: Particle identification algorithm, Projectile fragmentation, Radioactive ion beam line

INTRODUCTION

Radioactive ion beams (RIBs) produced via projectile fragmentation at several hundred MeV per nucleon have been employed as a sensitive and potent probe to systematically study the single-particle structure of unstable nuclei since the 1980s [1–6], and opened a vast new testing ground for nuclear structure models and reaction theories to develop [7–14]. The particle identification (PID) of the secondary beams (fragments) is the premise for their applications to further physical studies. The B -ΔE-TOF method is prevalent for this purpose, which is adopted in major international radioactive ion beam lines, such as A1900 [15, 16], BigRIPS [17–20], FRS [21, 22], and RIBLL2-ETF [23, 24]. The particle positions at the focal planes of the RIB line are recorded to help extract the trajectory radius and the magnetic rigidity B . The time of flight (TOF) through the RIB line is measured to obtain the velocity v = βc (c is the light speed in vacuum) and the Lorentz factor γ. The mass-to-charge ratios A/Q of the beam particles are obtained following Eq. 1:

$$B\rho = \frac{Au}{Q}\beta\gamma c \cdot \mathrm{TOF}$$

where Au is the ion mass in kg, with u = $1.66053906660(59) \times 10^{-27}$ kg being the atomic mass unit. e is the elementary charge, and L the flight length. Q = Z e represents the charge carried by the ion, with Z denoting the charge number, differing from the atomic number Z by a prime. For fully stripped ions, we have Z = Z. The last step of Eq. 1 is for a convenient numerical evaluation of B , where uc/e = $3.1071299 \cdots$ T · m is a constant, and A/Z · $\beta\gamma$ is dimensionless.

The particle charge Q is given by the energy deposit ΔE, and is in many cases much easier to be identified than A/Q, e.g., by a careful calibration of the ΔE detector. In comparison, according to Eq. 1, the A/Q identification entails accurate B and TOF information, which are susceptible to offsets. B offsets to nominal values may come from small deviations of beam-line working conditions from design values in a certain run, particularly for beam lines composing of many magnets. On the other hand, the fragment velocity carries a considerable dispersion width, and usually the estimation of its central value relies on simulation. The simulated TOF may be even more unreliable when new timing configurations (e.g., timing thresholds in leading edge discrimination) are used in the detector electronics of the experiment. Moreover, it is difficult to directly use secondary beams for their own TOF calibration as their velocities are not known.

The RIB experiments will benefit from a convenient and effective method for identifying the mass number of the secondary beams via projectile fragmentation, with TOF that is easy to calibrate for each experiment run with their own electronics configurations.

The A/Q identification for fragments of very light projectiles (typically A < 20)

is trivial. Firstly, with Z around 10 and below, and at fragmentation energies of several hundred MeV per nucleon, these RIBs are usually fully stripped. Since the product nucleus species are so few and the PID spectrum possesses so distinctive characteristics (e.g., the absence of certain particle-unstable products such as ^{9}B and ^{8}Be, and specific features of the relative positions of A/Z, such as the A/Z = 2 vertical line in the A/Z-Z PID spectrum), that the (A, Z) of the fragments are definitely resolved [25–29]. Other A assignments by adding or removing the same number (δA) of neutrons from all the product nuclei result in disparate PID spectra that contradict with physical reality. For a typical example the readers are referred to Fig. 9 [Figure 9: see original paper] of Ref. [24].

As the projectiles come from a heavier region in the nuclear chart, the aforementioned advantages soon vanish. The limited dynamical range of the ΔE detector restricts the minimal Z that can be measured while keeping the high Z in its measurable range for fully stripped beams. This results in a much higher starting Z in the PID spectrum, easily exceeding B and Be isotopes. The PID spectra obtained by applying a δA mass number offset to the real PID as formerly mentioned are not guaranteed to be so non-physical to rule themselves out. A definitive A identification in this scenario usually requires the measurement of characteristic γ-rays emitted from the known isomer of a specific nucleus, a technique known as isomer tagging [18, 30].

Given that γ-ray detectors are cumbersome to construct and operate, an identification method independent of any γ-ray detector is highly appealing for practical applications. On the other hand, uncalibrated TOF may easily distort the PID spectrum so much that it may affect our judgment in A identification. So the TOF calibration is necessary with the absence of a γ-ray detector.

This paper introduces a fragment mass number identification algorithm using only as input the conventional measurements of TOF, ΔE and positions at the focal planes of the beam line. Another algorithm for the calibrations of TOF is also given. They are formulated in detail in the chapter to follow. An application of the algorithms to beam test data analysis of 350-MeV/nucleon ^{78}Kr impinging on a 10-mm beryllium target are presented afterwards.

II. THE ALGORITHMS

To facilitate the formulation of the algorithms, we assume that the beams are fully stripped in the following text. The issues involving different charges states of not-fully-stripped (or the so-called hydrogen-like) ions will be discussed separately in the end of Sec. III A.

A. The Fragment Mass Number Identification

We first introduce the algorithm for the identification of fragment mass number A. According to linear beam optics [31], the transverse motion of the beam in horizontal plane can be expressed as:

$$x(s) = C(s)x_i + S(s)x_i' + D(s)\frac{\Delta p}{p_0}$$

where s is the arc length of the reference orbit, and x the transverse position of the beam particle in the horizontal plane relative to the reference orbit. x = dx/ds represents the momentary angle in the horizontal plane. x_i and x _i are the initial values of these optical coordinates at s = s_i. p_0 is the momentum of the reference particle, and $\Delta p = p - p_0$ is the momentum deviation of the beam particle from p_0. For beam transfer from focal plane 0 (x_0) to focal plane 1 (x_1) realizing point-to-point image, the angular dependence S = 0, as in the case of beam transfer from the dispersive focal plane F1 to the ETF [24] terminal of RIBLL2 [23, 33]. We have in this situation:

$$x_1 = Cx_0 + D\frac{\Delta p}{p_0} = Cx_0 + D\frac{B\rho - B\rho_0}{B\rho_0}$$

where Eq. 1 has been applied in the last step, with B_0 the magnetic rigidity of the reference particle, or the central magnetic rigidity of beam. Then B can be expressed as a linear combination of x_0, x_1, and B_0:

$$B\rho(x_0, x_1) = B\rho_0 + ax_0 + bx_1.$$

It is sometimes necessary to include higher-order x_0 dependence in Eq. 5 so that B (x_0, x_1) are accurate to our satisfaction. Using A and A = A + δA as the real and the assumed mass number of a certain fragment nuclide respectively, we can get the assumed magnetic rigidity following Eqs. 1 and 5:

$$B\rho(\beta)_a = \frac{A_a}{A} \cdot (B\rho_0 + ax_0 + bx_1) \equiv B\rho_0(\delta A) + a(\delta A)x_0 + b(\delta A)x_1.$$

where

$$B\rho_0(\delta A) \equiv B\rho_0 \frac{A_a}{A_a - \delta A}, \quad a(\delta A) \equiv a\frac{A_a}{A_a - \delta A}, \quad b(\delta A) \equiv b\frac{A_a}{A_a - \delta A}.$$

Eq. 6 shows that the magnetic rigidity calculated with the assumed fragment mass number has A -dependent coefficients. δA is estimated by fitting experimental $B_0(\delta A)$-A plot with Eq. 7, which then gives A = A − δA.

It turns out in practice that $B_0(\delta A)$ is the best option to do this job. a and b are not recommended because their absolute values are so small that the change in values brought about by the A /(A − δA) factor is easily overwhelmed by their fluctuations (e.g., due to difference in statistics) among different A . As a result, the error of the fitted δA is too large for A identification. $B_0(\delta A)$ with

a series of δA and using B $_0 = 7$ T $\cdot$ m is shown in Fig. 1 [Figure 1: see original paper]. The curves with $\delta A \neq 0$ exhibit trends distinct from that with $\delta A = 0$.

Another noteworthy feature is that the δA resolution ability will be significantly improved as the collection of nuclides in the secondary beam starts from a lighter nuclide.

As the extraction of B $_0(\delta$A) needs to be done for each fragment respectively, one firstly has to separate the fragment nuclides from each other. This is achieved by computing preliminary A/Z via Eq. 1, with B calculated by Eq. 5, for which the preliminary assignments of the transfer matrix elements a and b are needed. They can be made from beam optics calculations, beam line design parameters, or fitted from experiment data [18, 33]. We recommend a and b fitted from experiment data, because it is both reliable [18] and self-contained. All fittings in this paper are implemented by minimizing the fitting ^{2}.

The fitting of a and b follows the steps below:

1. Draw the $\beta\gamma$-x$_0$ plot, where we can find several discrete stripes. Equating Eq. 1 with Eq. 5 we have:

$$\beta\gamma = \frac{uc}{e} \cdot \frac{A}{Z} \frac{1}{B\rho_0 + ax_0 + bx_1}$$

which shows that $\beta\gamma$ takes discrete values corresponding to discrete A once x$_0$, x$_1$, and Z are fixed. So each of the stripes corresponds to an isotope. An example of such a plot is shown in Fig. 2 [Figure 2: see original paper].

2. Keep in mind that x$_1$ is a constant and fit one of the stripes with Eq. 8 to get a. uc/e $\cdot$ A/Z is also obtained by the way. Note that here A has to be roughly assumed (namely, A has to be given a value) to obtain a. Practically it is not required that A be very close to real A, as long as the fragments are clearly separated so that the fitting can be implemented on each nuclides without contamination from each other. δA as large as 5 has been tested to work fine. Still we do recommend making the A assignment with the help of extra information, e.g., nominal B $_0$ provided by the accelerator crew or measurements of B and central , so that A is close to A.

3. b is fitted similarly.

Inserting the preliminary a and b thus obtained into Eq. 5 and equating it with Eq. 1 for all the fragments, we can extract A /Z and get an A /Z-Z PID plot, where different fragment isotopes are separated.

After the separation of the fragment isotopes, the fitting of a and b for each fragment isotope follows a simpler procedure [18, 33]:

1. Fix x$_1$ by narrowing it down to a small range.

2. Draw the B (β) -x_0 plot, with B (β) evaluated by the first line of Eq. 6. Fit the plot to get a. An example is illustrated in Fig. 5 [Figure 5: see original paper] of Sec. III A, where a second-order term of x_0 is also added.
3. b is fitted similarly (namely by fixing x_0 and fitting the B (β) -x_1 plot).
4. The B $_0(\delta A)$ is then evaluated according to Eq. 6 as B $_0(\delta A)$ = B (β) − ($ax_0 + bx_1$) with a and b using the fitted values.
5. Finally we get a B $_0(\delta A)$-A data point.

The above procedure is repeated for all fragments, so that the B $_0(\delta A)$-A plot is obtained. It is then fitted with the first formula of Eq. 7, with B $_0$ and δA as the fitting parameters.

It is worth noting that this A identification algorithm is robust against moderate offsets in TOF. It has been tested that the above procedure is still effective with (unknown) systematic error in TOF of the order of several ns. This is explained in Sec. II B.

B. The TOF Calibration

The TOF calibration follows a similar procedure. Using similar notations, by denoting the real and the assumed time of flight by TOF and TOF TOF + Δt respectively, we have:

$$B\rho(\beta_a) = \frac{\mathrm{TOF}_a}{\beta_a(\Delta t)\gamma_a(\Delta t)}\frac{Au}{Qc} \equiv \frac{\mathrm{TOF}}{\beta_a(\Delta t)\gamma_a(\Delta t)}\cdot(B\rho_0+ax_0+bx_1) \equiv B\rho_0(\Delta t)+a(\Delta t)x_0+b(\Delta t)x_1.$$

where

$$B\rho_0(\Delta t) \equiv B\rho_0\frac{\mathrm{TOF}_a}{\beta_a(\Delta t)\gamma_a(\Delta t)}\frac{1}{\mathrm{TOF}} = B\rho_0\left(1-\frac{\gamma^2\Delta t}{\mathrm{TOF}_a}\right)$$

will be used to fit Δt, due to similar reasons with Sec. II A. β and γ are those correspond to TOF . B $_0(\Delta t)$ with a series of Δt and using B $_0$ = 7 T $\cdot$ m and L = 30 m are drawn in Fig. 3 [Figure 3: see original paper].

Like the situation in Sec. II A, we also observe the distinct trends of B $_0(\Delta t)$ with $\Delta t \neq 0$ compared with that of $\Delta t = 0$, although they are not as prominent. The overall TOF spread of the fragments is of the order of, say, 20 ns. The relative B $_0$ change, as can be told from Fig. 3, is only around 1%, for TOF changing from 120 ns to 140 ns, for $\Delta t = 3$ ns. This imposes a B $_0$ dispersion of at most the same magnitude to the B $_0$-A plot, because for data points with the same A , their TOF can vary at most from 120 ns to 140 ns in the case discussed here. The relative change of B $_0$ is about 1 to 2 orders of magnitude smaller than that with A changing from 7 to 100 for nonzero δA, as can be told from Fig. 1. Moreover, moderate nonzero Δt (e.g., 3 ns discussed here) has a very limited effect on the overall trend of B $_0$-A plot, since while A /Z

is positively related to TOF, A barely changes with it (see Eqs. 1 and 2). So it is feasible and suggested to kick start the fragment mass number identification algorithm using (un-calibrated) TOF estimated from, e.g., simulation or simple calculations, given that small Δt give sharp B $_0$-A plots. However, the converse is not valid. Non-zero δA will impose dispersion in B $_0(\Delta t)$ that easily overwhelms the trends brought about by Δt and spoils Fig. 3.

It is recommended to substitute TOF with A/Z. It is told from Eqs. 1 and 2 that TOF is positively related to A/Z by:

$$\mathrm{TOF} = \sqrt{\left(\frac{uc}{e}\cdot\frac{A}{Z}\frac{L}{B\rho}\right)^2 + \left(\frac{L}{c}\right)^2}$$

The TOF spread for a certain nuclide could be omitted if B is fixed, or limited in a small range compared with the variation of $\beta\gamma$ (around 7%) for different nuclides, which is usually the case due to the limited momentum acceptance (around $\$\pm 1\{0\}(\Delta t) - A/Z data points from the corresponding B\rho\{0\}(\ \$A = 0)$-A data points in the fragment mass identification procedure, which has been implemented in the first place. We only have to replace A with A/Z for each data point.

Note that since B $_0$ changes (although slightly) with TOF (thus also with A/Z) for moderate nonzero Δt, the B $_0$ averaged over all the B $_0(\delta A = 0)$-A obtained in the fragment mass identification procedure could be used for the B $_0$ in Eq. 12. By iteration of the two algorithms, the dispersion of B $_0$ due to Δt will be rapidly diminished along with the minimization of Δt.

The extraction of B $_0(\Delta t)$-TOF data points is somewhat cumbersome. B $_0(\Delta t)$ is calculated via Eq. 11 with factor $\beta\,(\Delta t)\gamma\,(\Delta t)$ given by B $(\beta\,)$/B $(x_0,\ x_1)$, where the B $(\beta\,)$ are calculated separately for each nuclide with their own (A, Z). All the events are then accumulated to constitute the final B $_0(\Delta t)$-TOF scatter plot.

The TOF calibration algorithm is summarized as follows:

1. Complete the A identification following the procedure given in Sec. II A to get B $_0$ with δA = 0 for each A, which will then be used as B $_0(\Delta t)$.
2. Extract Δt by fitting the B $_0(\Delta t)$-TOF scatter plot with Eq. 11. Or fit the B $_0(\Delta t)$-A/Z plot with Eq. 11 and Eq. 12, and using B $_0$ fitted and averaged from step 1.
3. Go to step 1 for another iteration.

Usually Δt satisfactorily converges after two iterations.

III. THE BEAM TEST

The above algorithms for fragment mass number identification and TOF calibration are tested in data analysis of a beam test conducted at the RIBLL2-ETF.

A schematic layout of the experiment setup is illustrated in Fig. 4 [Figure 4: see original paper]. The primary beam of ^{78}Kr was accelerated in the Cooler Storage Ring (CSRm [34]) to 350 MeV/nucleon and fragmented on a primary target of 10-mm thick beryllium at F0. The fragments were transported to ETF through RIBLL2 with its A/Z centered around 2.3. TOF of the secondary beams were measured by the time difference of two plastic scintillators Tstart [33] and Tstop [36] installed at the dispersive focal plane F1 and the achromatic focal plane ETF. A position detector was installed at F1 next to Tstart for x_0 measurement, which is composed of 50 vertical 2-mm wide and 1-mm thick plastic scintillator strips, covering an effective area of 100 × 100 mm [33]. The ΔE of the fragments were measured by a MUlti-Sampling Ionization Chamber MUSIC0 [37]. The beam position x_1 at ETF is given by drift chambers DCTaU0,1. The data analysis is completed using code ETFAna [38].

A. The Fragment Mass Number Identification

Following the algorithm in Sec. II A, we have selected 76 nuclides in the secondary beams with appropriate statistics from an experiment run of 242,919 events. Since the experimental B (x_0, x_1) has shown an appreciable parabolic dependence on x_0, we have added an $x_0{}^2$ term to Eq. 5, which then reads:

$$B\rho(x_0, x_1) = B\rho_0 + ax_0 + a_{2x}0^2 + bx_1.$$

As an example, Fig. 5 [Figure 5: see original paper] shows the fitting of a, a_2 and b for one specific case of ^{44}Ca in the 76 fragment nuclides. The units of the fitted parameters in the figure are deduced when B_0 is in T · m and $x_{0,1}$ in mm for practical convenience in data analysis.

The B (δA)-A scatter plots with a series of δA are presented in Fig. 6 [Figure 6: see original paper], and fitted with the first formula of Eq. 7 over the region of A (20, 62). The fitted B_0 and δA are listed in Table 1 . δA is the integer nearest to the fitted δA. The δA values are cross-checked to be compatible with beam information from the accelerator, which will be explained later. It shows that the δA of each curve in Fig. 6 are unambiguously solved with the algorithm formulated in Sec. II A.

It is also shown in Fig. 6 and also Fig. 1 that as the fragments start from a heavier region, e.g., by using a degrader for beam purification [18], the distinctions between the trends of different δA will shrink and higher B resolution (higher TOF resolution and position resolution) are expected to compensate for the decrease in the resolving power of δA. The fitted δA being close to an integer and differing by 1 for adjacent δA should be used for the estimation of the applicability of the algorithm.

The deviation |δA−δA | of the fitted δA from its true value δA are directly related to those (off-line) data points that go downwards off the curve constituted by the main body of the data points. The fitted δA thus tends to suppress

the B_0 by increasing its value to minimize the fitting ^{2}. Those off-line data points may be attributed to low statistics, and/or too narrow distributions in x_0 or x_1, which deteriorate the fitting process and result in significant error in the extracted B_0. Still, the δA deviation of around 0.1 as seen in Table 1 is negligibly small in determining δA . The robustness of the algorithm against systematic error in TOF is also tested using $\Delta t = \$\pm\$3$ ns. The fitted δA turn out to have smaller deviations (around 0.03) from their corresponding δA for $\Delta t = +3$ ns, as the positive Δt decreases B_0, reducing the need to increase δA. The $\Delta t = -3$ ns expectedly gives larger δA deviation of around 0.3, which is still acceptable. Besides, by minimizing δA and Δt through iteratively calling of the algorithms, the trouble of non-zero Δt could be solved once and for all.

The PID spectrum with zero δA and calibrated TOF is presented in Fig. 7 [Figure 7: see original paper], with the N = Z + x (x = 0, 1, 2, $\cdots$) lines superimposed for reference. N here is the neutron number. The exact values of A/Z from AME2020 database [39, 40] are also marked in the figure for those nuclides selected in the δA fitting. The y axis represents the charge of the beam particle when they reach MUSIC0. Its calculation only involves the energy deposit ΔE in the detector plus some vertical position-dependence corrections [24]. The x axis is related to the mass over charge ratios of the beams in the beam line, which is totally determined by TOF and horizontal positions. So the two variables in Fig. 7 are independently measured.

As far as we are concerned, it is necessary to discuss the different charge states for the same particle in the beam line from Tstart to Tstop (denoted as Q_0), and in MUSIC0 (denoted as Q_1). For clarity we first talk about the cases of capturing or stripping of one electrons with respect to fully-stripped ions:

1. $\mathbf{Q_0 = Z-1,\ Q_1 = Z-1}$: The spot (A/Z, Z) in the PID spectrum for a fully-stripped ion moves to (A/(Z − 1), Z − 1). Just for the purpose of illustration here, it is equivalent to one proton neutralized by an electron to change to a neutron, so N is incremented by 1, and Z decremented by 1. Then the new spot falls from N = Z + x to N = Z + x + 2 line. Each fragment isotope suffering this issue should exhibit an spot at the point two line rightward and one element down. There is no perceptible presence of such spots in Fig. 7. Since it is the fragment with maximal Z that is most attractive to electrons, the outlier of ^{84}Kr is an optimal example. There is no discernible trace of its spot around (2.4, 35) in Fig. 7. So the possibility of this case is deduced to be negligibly small.

2. $\mathbf{Q_0 = Z,\ Q_1 = Z-1}$: The spot (A/Z, Z) in the PID spectrum for a fully-stripped ion moves down by 1 to (A/Z, Z − 1), sitting next to the left side of its fully-stripped neighbor ((A − 1)/(Z − 1), Z − 1). Similar to case 1, we do not find these spots, with ^{84}Kr still being the most convincing example.

3. $\mathbf{Q_0 = Z-1,\ Q_1 = Z}$: Similar to case 2, Fig. 7 is short of (A/(Z−1), Z)-like spots, which should appear next to the right side of the original fully-

stripped (A/Z, Z), confirming that this case could also be safely neglected.

Following the above discussion, the capturing or stripping of more electrons involves more abnormal spots in the PID spectrum, which Fig. 7 turns out to do not show in perceptible significance. Moreover, they are naturally more difficult to happen than that involving one electron. So Fig. 7 is taken to be predominantly fully-stripped ions.

The conspicuous outlier of ^{84}Kr is inferred to be unreacted nuclide from the primary beam, as it is seldom possible that the cross section is so large for ^{78}Kr capturing one specific number of neutrons, and at the same time almost zero for the production of the neighboring nuclides [41]. Moreover, the momentum spread of this outlier is nearly an order of magnitude smaller than other fragments, also supporting the notion that it is the unreacted primary beam. So it is not without surprise that our fragment mass identification algorithm suggests that it is ^{84}Kr, instead of ^{78}Kr. With ^{78}Kr^{26+} as the primary beams that were accelerated in the CSRm, it is still possible that the outlier is ^{84}Kr^{28+} contamination in the ^{78}Kr ion source. Since the mass over charge ratios of ^{84}Kr^{28+} and ^{78}Kr^{26+} are almost identical (differ only by 0.003%), these two ion species appear almost the same as far as the accelerator and RIBLL2 concern, according to the equations of motion of beam optics [32]. It is highly possible that ^{84}Kr^{28+} and ^{78}Kr^{26+} were accelerated and delivered to ETF altogether. The suspicion of ion source contamination by ^{84}Kr is corroborated by the much higher natural abundance of ^{84}Kr (57.0%) than ^{78}Kr (0.4%). It is unnecessarily and prohibitively expensive if ever feasible to get rid of every ^{84}Kr atom from the ^{78}Kr ion source. Finally, there exist small deviations of the experimental data spots from the nominal N = Z + x lines and the A/Z values from AME2020 in Fig. 7 for some nuclides. This may be due to the time walk effect in the leading edge timing, which varies for different Z, introducing Z dependence in TOF offset constants. This is not taken care of in the TOF calibration algorithm in this work.

B. The TOF Calibration

The $B\rho_0(\Delta t)$-A/Z scatter plot following procedures depicted in Sec. II B are extracted from the experiment data as shown by Fig. 8 [Figure 8: see original paper]. The five datasets with distinct colors are for five preset Δt values as indicated in the figure. Specifically speaking, for each of the Δt values, we added it artificially to the real TOF of each of all the particles, and see how well the algorithm could reproduce them. The fitted Δt are 2.83(1), 0.98(1), 0.00(1), -1.02(2) and -3.18(2) ns for preset $\Delta t = 3, 1, 0, -1, -3$ ns, respectively. The deviation of the fitted Δt from their preset values are less than 0.2 ns, and increasingly small as Δt approaches zero. This is rather meaningful since we are most interested in eliminating Δt so that TOF is without a constant offset.

The $B\rho_0(\Delta t)$-TOF method shows comparable Δt resolution. The experimental $B\rho_0(\Delta t)$-TOF scatter plot is shown in Fig. 9 [Figure 9: see original paper].

Similarly we used the same preset Δt values, and get fitted Δt of 2.807(1), 0.947(1), 0.035(1), -1.055(2) and -3.126(1) ns for the preset $\Delta t = 3$, 1, 0, -1, -3 ns, respectively.

IV. SUMMARY

New algorithms for mass number identification and the related TOF calibration are introduced. The algorithms make use of the fact that the central magnetic rigidity B_0 of the secondary beam exhibits dependence on mass number A (A/Z) if the corresponding offset δA (Δt) of the assumed mass number A (TOF) off the real value is non-zero. No additional measurements other than the basic TOF, ΔE and beam positions at the entrance and exit of the beam line are required. By iterative calling of the two algorithms, virtually the calibration of A or TOF does not require that the other one has been calibrated. The expressions of the dependence are deduced and employed to fit δA and Δt. The algorithms are tested against experimental data using ^{78}Kr primary beam impinging on a beryllium target. Unambiguous PID and a Δt precision of 0.2 ns are achieved for the secondary beams using our method.

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Note: Figure translations are in progress. See original paper for figures.