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Particle identification for Z = 25 – 28 exotic nuclei from seastar experimental data

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Abstract: The particle identification (PID) method based on TOF-Bρ-ΔE measurement at RIKEN are discussed, and its application for Z = 25 – 28 neutron-rich nuclei from SEASTAR (Shell Evolution And Search for Two-plus energy At RIBF) experimental data are presented. The results including the PID for beam and residual nucleus at BigRIPS and ZeroDegree, respectively, demonstrate that the reactions of interest are well separated. This ensures the precision in the data analysis later on.

Keywords: SEASTAR, particle identification, BigRIPS, ZeroDegree.

I. INTRODUCTION

The research on unstable nucleonic-rich nuclei has attracted much attention since the availability of radioactive ion beams (RIBs). Many new nuclear phenomena, such as halo and neutron skin [1, 2], intruder states [3, 4] and new magic number [5] which are beyond the explanation of the shell model, …, were explored. As the result, a new research field with RIBs has been opened. In this field, the challenge is that it is essential to produce and accelerate RIBs with high enough intensities which usually have very low production cross sections, leading to low luminosities. The research with RIBs was mainly carried out in big laboratories worldwide where the most advanced facilities exist, for instant the BigRIPS [6] at RIKEN (Japan), the LISE3 [7] at GANIL (France), the A1900 [8] at MSU (USA) and the FRS [9] at GSI (Germany). Even though many efforts have been spent in the development of new accelerators, there were unpractical experiments due to the above mentioning reason. One of the solutions for this difficulty is to combine the advantages of devices that can improve significantly the measuring statistics.

SEASTAR project [10] is such an example which uses the intensive RIB from the BigRIPS, the thick active target MINOS [11], and the highly efficient gamma array detector DALI2 [12] with Doppler correction. According to the calculation, without this combination SEASTAR experiments can be conducted only if the best present RIB intensity (produced at RIKEN) increases by at least one order of magnitude [10] (10^1 times). SEASTAR aims at a systematic search for new 2_1^+ energies in the wide range of neutron-rich nuclei. The spectroscopy of production nuclei, including exotic nuclei, gives the information about the shell structure and properties of sub-shell level in the region far off stability [10, 13-15].

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Particle identification is the first important step in nuclear experimental study. The aim of the PID is to identify clearly incoming and residual nuclei so that contaminants are eliminated. After this step, the reaction is defined because the target made of a stable nucleus is known in advance. Usually, the PID is done by using the time-of-flight (TOF) and energy loss (ΔE) measurements or by letting ionized particles to fly through a magnetic field, namely the TOF-Bρ-ΔE method, because these quantities depend on the intrinsic infromation (A and Z) of the considered isotope. Therefore, the PID can be studied by simulation if the characteristics of detecting devices are known, see Ref. [16] for an example. The PID precision is improved with the improvement of the detecting devices' precision. In this paper, the PID methods of the BigRIPS and ZeroDegree at RIKEN [6] are discussed in details and the PID results for Z = 25 – 28 neutron-rich nuclei measured in the SEASTAR experiments is presented. These results will be served later in the nuclear spectroscopic studies. At the moment, RIKEN is a top worldwide intensive RIB factory. The BigRIPS and ZeroDegree spectrometers have been in operation since 2007 [17] and served to analyze and identify projectiles and residues, respectively. One advance is that the PID, which was carefully checked [18, 19], is provided and integrated within these spectrometers, while normally it is designed and set up by the users (experimentalists) with external detectors [4].

II. EXPERIMENTAL SETUP

In SEASTAR experiment, a ^{238}U primary beam at 345 MeV/nucleon with a mean intensity of 12 pnA was produced and accelerated by the accelerator complex of the Radioactive Isotope Beam Factory (RIBF) [17]. Then, it was driven to collide with a ^{9}Be primary target at F0 (see Figure 1). The secondary beams were obtained by fragmentation. Afterwards, they were selected and transported to the F8 focal point (user location) where the secondary target MINOS was placed. MINOS is an active target which contains a liquid hydrogen (LH2) target and a Time Projection Chamber (TPC) for the vertex tracking purpose [11]. The high-efficiency gamma array detector DALI2 [12] which has 186 NaI crystal was intalled surrounding the MINOS. DALI2 detected prompt gamma rays [13-15]. The PID was done by detectors at two parts: BigRIPS and at ZeeroDgree .

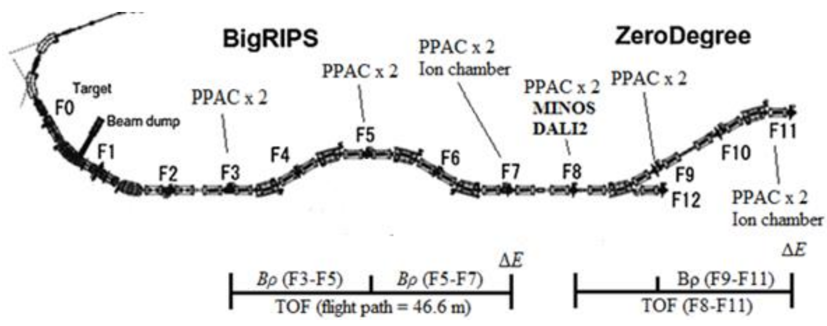

Fig. 1. Schematic layout of the BigRIPS and ZeroDegree spectrometers. The labels Fn indicate the positions of the focal planes. There are two-stage for particle identification at BigRIPS: from F0 to F2 and from F3 to F7. The ZeroDegree spectrometer is from F8 to F11.

The BigRIPS is spectrometer from F0 to F7. It has two-stage structure: the first stage is from F0 to F2 and the second one is from F3 to F7. While the first stage of BigRIPS is used for production, collection, and separation of RIBs, the second one is used for particle identification and/or further separation. The ZeroDegree spectrometer is from F8 to F11. At each focal plane, the PID parameters are measured by plastic scintillators, position-sensitive Parallel Plate Avalanche Counters (PPAC) [21] and MUlti-Sampling Ionization Chamber (MUSIC) [22]. The plastic scintillators were used to measure the time of flight. The coordinates were measured by the PPACs which were used for the particle trajectory reconstruction. MUSIC detectors were used to identify the particle atomic number from its energy loss measurement. At the BigRIPS, there were two plastic scintillators placed at F3 and F7, three PPACs at F3, F5 and F7, and a MUSIC detector at F7. Similarly, two plastic scintillators were placed at F8 and F11, three double PPACs at F8, F9, F11, and a MUSIC detector at F11 at ZeroDegree.

III. PID METHOD AND RESULTS

The particle identification in BigRIPS and ZeroDegree was performed event by event. The PID for the secondary beam at BigRIPS and for the residue at ZeroDegree was based on the Bρ-ΔE-ToF method according to position, energy loss and time of flight measurements. As mentioned before, the time of flight and energy loss were measured by plastic scintillators and energy loss detectors. This information was dependent on the magnetic rigidity set up. The trajectory of the particle were reconstructed by using position-sensitive detectors along the beam line.

The particle identification is based on the atomic number (*Z*) and the mass-to-charge ratio (*A/Q*) of the RIB which are deduced using the equations [23]

$$B\rho = \frac{P}{Q} \rightarrow A/Q = \frac{B\rho}{\beta\gamma}\frac{c}{m_u}, \tag{1a}$$

$$TOF = \frac{L}{\beta c}, \tag{1b}$$

$$\Delta E = \frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz\left[ln\frac{2m_e v^2}{I} - ln(1-\beta^2) - \beta^2\right]. \tag{1c}$$

In these above equations, *TOF, B, ρ* and *ΔE* are the time of flight, magnetic field, the radius of the particle’s tracjectory and energy loss, respectively. *L* is the flight-path length, *υ* is particle velocity, $\beta = \upsilon/c$, $\gamma=1/\sqrt{1-\beta^2}$, *c* is the light velocity, m_u = 931.494 (MeV) is the atomic mass unit, m_e is the electron mass and *e* is the elementary charge. *N, z* and *I* are the atomic density, atomic number and mean excitation potential of the material. *Z, A, P* and *Q* represent the atomic, mass, momentum and charge number of the particle, respectively.

A. Particle identification in BigRIPS

The particle identification in the BigRIPS spectrometer is performed in the second satge which is subdivided into 2 sections: from F3 to F5 and from F5 to F7. The trajectory reconstructions of the beam in these sections were done via the positions and angles measured by the PPACs at F3, F5, and F7 [23]. The results were used to determine $B_{35}\rho_{35}$ and $B_{57}\rho_{57}$. The *A/Q* were obtained as:

$$\left(\frac{A}{Q}\right)_{35} = \frac{B_{35}\rho_{35}}{\beta_{35}\gamma_{35}}\frac{c}{m_u}, \tag{2a}$$

$$\left(\frac{A}{Q}\right)_{57} = \frac{B\rho_{57}}{\beta_{57}\gamma_{57}}\frac{c}{m_u}. \tag{2b}$$

where, the subscripts 35 and 57 imply the quantities measured in the F3-F5 and F5-F7 sections correspondingly. Becausse the *A/Q* value does not change in BigRIPS, we have:

$$\frac{\beta_{35}\gamma_{35}}{\beta_{57}\gamma_{57}} = \frac{B_{35}\rho_{35}}{B_{57}\rho_{57}}. \tag{3}$$

The time of flight from F3 to F7 can be written as the sum:

$$TOF_{37} = \frac{L_{35}}{\beta_{35}c} + \frac{L_{57}}{\beta_{57}c}, \tag{4}$$

From the Eqs. (3) and (4), the velocities β_{35} and β_{57} are calculated as [24]

$$\beta_{35} = \frac{(a_1 \times L_{35} + cL_{57} \times TOF_{37})}{\left(a_1 c \times TOF_{37} + \left[1 - \left(\frac{B\rho_{57}}{B\rho_{35}}\right)^2\right] \times L_{35} L_{57}\right)}, \quad (5)$$

$$\beta_{57} = \frac{(a_1 \times L_{35} + cL_{57} \times TOF_{37})}{\left(c^2 \times TOF_{37}^2 + L_{35}^2 \left[\left(\frac{B\rho_{57}}{B\rho_{35}}\right)^2 - 1\right]\right)}, \quad (6)$$

where,

$$a_1 = \sqrt{c^2 TOF_{37}^2 \left(\frac{B\rho_{57}}{B\rho_{35}}\right)^2 + \left[\left(\frac{B\rho_{57}}{B\rho_{35}}\right)^4 - \left(\frac{B\rho_{57}}{B\rho_{35}}\right)^2\right] L_{35}^2 + \left[1 - \left(\frac{B\rho_{57}}{B\rho_{35}}\right)^2\right] L_{57}^2} \quad . \quad (7)$$

From these above equations, the velocities β_{35} and β_{57} will be determined if TOF_{37} is known. In fact, this quantity is measured by two thin plastic scintillators installed at F3 and F7 (Fig. 1). Finally, the *A/Q* can be calculated according to either Eq. (2a) or (2b). The TOF typical resolution is 0.017% for a 300 MeV/nucleon particle [24].

The energy loss (*ΔE*) was used to deduce *Z* according to Eq. 1c as:

$$Z = \frac{\sqrt{m_e c^2 \beta_{35}^2}}{\sqrt{4\pi e^4 N z \left[\ln \frac{2m_e c^2}{I} - \ln \frac{\beta_{35}^2}{1-\beta_{35}^2} - \beta_{35}^2\right]}} \quad (8)$$

The correlation between Z and *A/Q* is used for the particle identification.

The result of PID plot in BigRIPS spectrometer from the SEASTAR experimental data is presented in the bottom panel of Fig. 2. It is seen that the isotopes with Z = 25-28 including $^{65-67}$Mn, $^{66-68}$Fe, $^{68-71}$Co, and $^{69-71}$Ni are clearly identified. The top panel of Fig. 2 is the projection of the bottom panel on the *A/Q* axis to see the quality of the isotopic separation. The average *A/Q* resolutions for the Mn, Fe, Co and Ni isotopes in the BigRIPS are 0.092(4)%, 0.086(8)%, 0.075(1)% and 0.068(2)%, respectively.

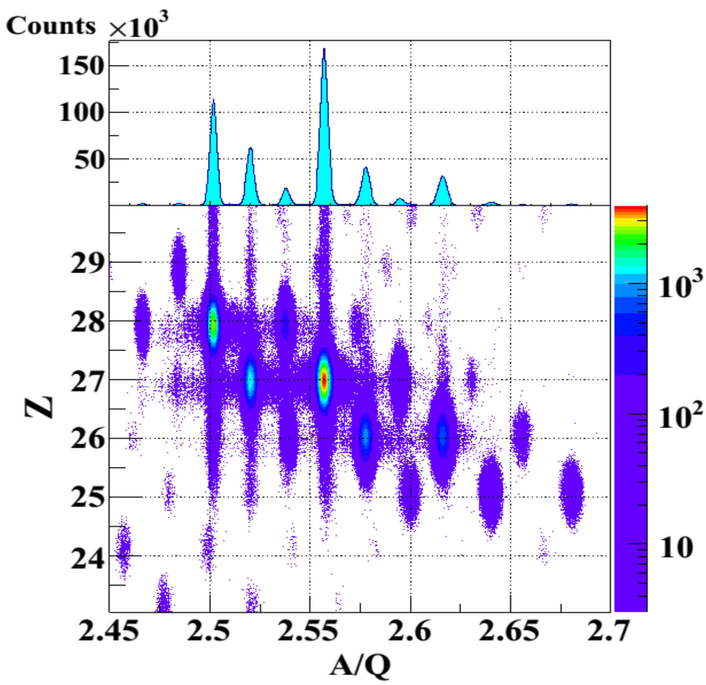

Fig.2. BigRIPS particle identification, A/Q vs Z (Bottom); and its projection on A/Q axis (Top) to see the quality of the isotopic separation.

B. Particle identification in ZeroDegree

The same identification method was applied in the ZeroDegree spectrometer. Here, the TOF was measured by two thin plastic scintillators which were installed at F8 and F11. A MUSIC detector was installed at F11 to measure the energy loss. Two PPACs were placed at F8 (before the secondary target) for the reaction point reconstruction. Two PPACs at F9 and Two PPACs at F11 were used to measure the $B\rho$ of the residue in ZeroDegree. The PID result from the SEASTAR experimental data is shown in Fig. 3 for $^{62-67}$Mn, $^{64-69}$Fe, $^{67-70}$Co, and $^{70-71}$Ni isotopes. They have the average *A/Q* resolution of: 0.223(15)%, 0.201(13)%, 0.198(9)% and 0.162(12)%, respectively.

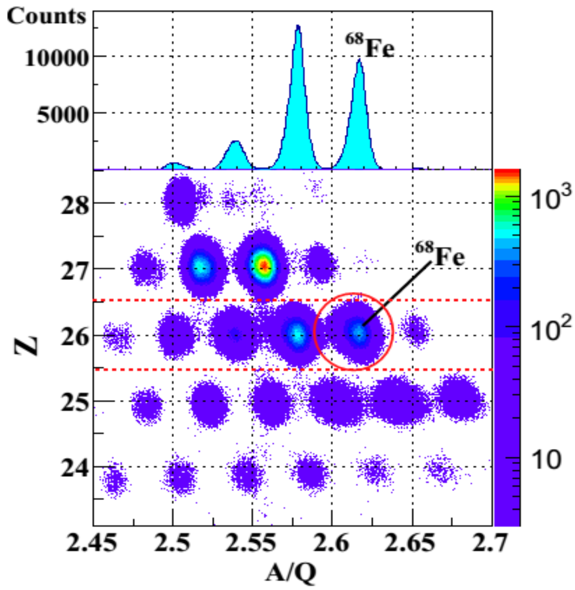

Fig. 3. Particle identification in ZeroDegree (Bottom) and its projection on A/Q axis for Fe isotopes with Z=26 (Top).

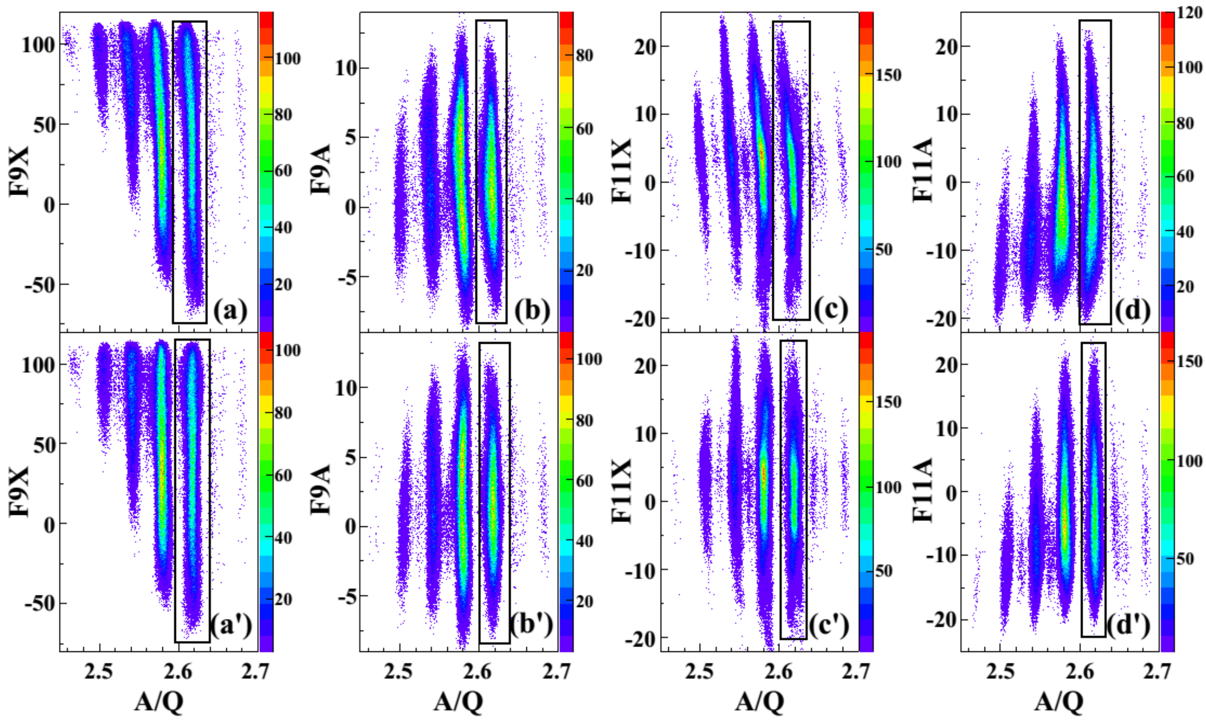

Fig.4. The dependence of A/Q versus the measured position (X) and angle (A) at F9 and F11, respectively: before the PID correction shown in upper panels; after the PID correction shown in lower panels. The correction was done to select ^{68}Fe events which are marked by the rectangles. Details are explained in text.

As discussed above the particle's rigidity $B\rho$ was determined by using the position and angle measured by PPACs. Consequently, the *A/Q* value was obtained according to Eq. (1a). The correlations of *A/Q* versus the position and angle measured at F9 and F11 are shown in panel a, b, c and d of Fig. 4. Here, *X* and *A* are *x*-coordinate and angle, respectively. As seen in these panels, with a certain A/Q value, the dependences are not vertical. This leads to the reduction of the A/Q resolution when they are projected on the x-axis (see upper pannel of Fig. 3 for an overlap around A/Q of 2.6). In oder to improve the PID quality, the A/Q were corrected with higher order dependence on X and A variables [23, 24]. For example, for ^{68}Fe selection at ZeroDegreee, the new value $(A/Q)_{\text{correct}}$ was modified from the old A/Q as:

$$(A/Q)_{\text{correct}} = (A/Q) + 10^{-4}\times F11A + 10^{-5}\times F11A^2 + 25\times10^{-5}\times F11X + 16\times10^{-6}\times(F11X)^2 - 5\times10^{-7}\times(F11X)^3 + 35\times10^{-5}\times F9A - 2\times10^{-5}\times(F9A)^2 + 18\times10^{-6}\times F9X - 18\times10^{-8}\times(F9X)^2 + 6\times10^{-9}\times(F9X)^3 \quad (9)$$

The new results are presented in panel a', b', c' and d' of Fig. 4. Comparing to the upper panels, the dependences are now reduced (presented by vertical lines). It is noted that the selection for ^{68}Fe is considered. The dependences at other isotopes' posititions might not be vertical. For a given particle of interest, the procedure described in Eq. (9) need to be repeated.

The result of the PID after the corection is presented in Fig. 5 for the case of the ^{68}Fe events being of interest. Comparing to the PID before the correction in Fig. 3, the PID resolution in Fig. 5 is much better. In particular, the A/Q resolution of ^{68}Fe is improven from 0.194 % down to 0.135% (see upper panels of these figures). The average resolutions for Mn, Fe, Co and Ni isotopes are 0.165(11)%, 0.137(7)%, 0.129(7)%, and 0.135(13)%, respectively. Note that the PID correction is necessary only at ZeroDegree in the offline analysis. At BigRIPS, it has been done already during the beamtime.

Table I presents the PID resolutions before and after the PID correction corresponding to the particles of interest being ^{66}Mn, ^{68}Fe and ^{68}Co. The comparison of the average resolutions of each isotope before and after the PID correction corresponding to the same particles of interest is shown in Table II. It is seen that, with the PID correction, the A/Q resotutions are impreoved in all cases. As the results, the particles of interest are clearly identified.

Table I. Comparison of the resolutions (%) before and after the PID correction corresponding to the particles of interest being ^{66}Mn, ^{68}Fe and ^{68}Co

PID correction	^{66}Mn	^{68}Fe	^{68}Co
Before	0.278(5)	0.194(1)	0.186(1)
After	0.169(3)	0.135(1)	0.121(1)

Table II. Comparison of the average resolutions (%) of the isotopes before and after the PID correction corresponding to the same particles of interest as in Table I

PID correction	Mn	Fe	Co	Ni
Before	0.223(15)	0.201(13)	0.198(9)	0.162(12)
After (^{66}Mn)*	0.176(12)	0.152(11)	0.153(11)	0.174(20)
After (^{68}Fe)*	0.165(11)	0.137(7)	0.129(7)	0.135(13)
After (^{68}Co)*	0.166(11)	0.136(10)	0.127(8)	0.134(13)

**The particles in the parentheses are of interest when performing the PID correction*

IV. CONCLUSIONS

In this paper, the particle identification method based on the *Bρ-ΔE-ToF* measurements at BigRIPS and ZeroDegree at RIKEN, a top worldwide leading acceleration laboratory, has been studied and presented. The PIDs for the neutron-rich isotopes with Z = 25 – 28 from the SEASTAR experimental data have been performed. 13 and 18 neutron-rich isotopes in BigRIPS and ZeroDegree, respectively, were clearly identified. In which, the PID resolution were improved with the correction at Zerodegree. The PID results will be served later in the nuclear spectroscopic study.

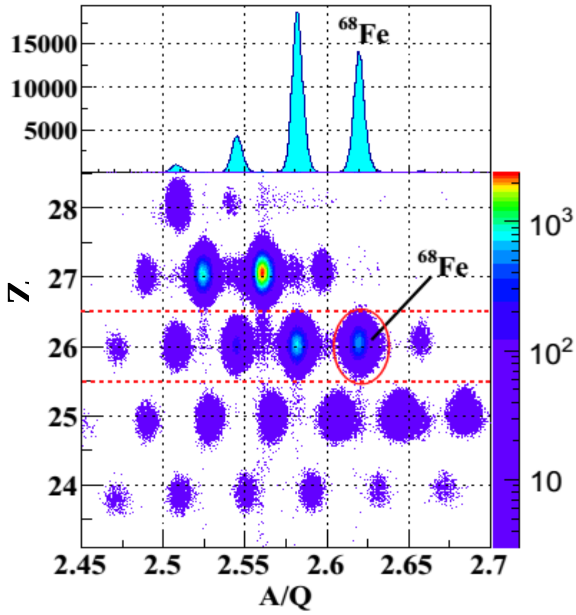

Fig. 5. Particle identification in ZeroDegree (Bottom) and its projection on A/Q asix for Fe isotopes (Top) with the correction to select ^{68}Fe

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