Particle identification of $^{69,71}Fe$ in RI beam at RIKEN

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Abstract: The neutron-rich nuclei $^{69,71}Fe$ were produced at the RIBF facility at RIKEN in the first campaign of SEASTAR project. This report presents the method and preliminary results of particle identification (PID) for these nuclei. Besides, particle identification corrections will be discussed. The PID results is a crucial part of analysis process to study the structure of $^{69,71}Fe$ isotopes.

Key words: *SEASTAR, ^{69}Fe, ^{71}Fe, particle identification, PID.*

I. Introduction

Since the 90s of the last century, research on exotic nuclei began being concerned with the most advanced measurement methods in big laboratories worldwide such as the RIBF at RIKEN (Japan), the LISE3 at GANIL (France), A1900 at MSU (US) and the FRS at GSI (Germany) [1-4]. Thanks to the availability of new radioactive isotope beams (RIBs), structure and behavior of exotic nuclei have been studied and many new phenomena which are beyond the explanation of classical models were observed: neutron skin and halo structure [5, 6], appearance of new magic numbers [7] such as neutron number N = 32, 34 [8, 9], a new “island of inversion” around N = 40 in low Z-shore Z = 20 [10-12] or disappearance of the magic numbers N = 28 [13]. These results become new challenges of nuclear physics.

$^{69,71}Fe$ are neutron-rich nuclei which formed by the combination of 26 protons with 43 or 45 neutrons. Although the first productions of these nuclei were performed in 1992 and 1997 at GSI [14,15], there are no structural data of these nuclei have been published because of the difficulties in producing and measuring technique. Up to now, only $T_{1/2}$ values of them are available. In the SEASTAR project, with the combination of modern producing technique and the most advantage devices such as RIBF, a compact system with MINOS target and DALI2 detector, a wide range of neutron-rich nuclei from ^{52}Ar to ^{110}Zr, included $^{69,71}Fe$ at high intensity were produced. Also, their gamma ray spectroscopies were detected and gave us a good chance to extract more structural properties. Basically, the shell structures of $^{69,71}Fe$ could be predicted by $\pi f_{7/2} - \nu g_{9/2}$ configurations but with the discovery of the deformation effect in neutron-rich nuclei and the N=40 island of inversion, these predictions have not been confirmed. Hence, a study on these nuclei is needed and its results will directly contribute to the knowledge of neutron-rich in the Fe chain. Besides, the understanding of shell structure around the "island of inversion" N = 40 [] could be evolved.

By this report, preliminary results of particle identification (PID) based on Bρ – ΔE-ToF method and some corrections for $^{69,71}Fe$ will be presented. Particle identification is one of the most important steps in experimental study of nuclear physics and its accuracy will affect to the precision of further studies: reaction determination, extraction and analyzation of spectrums.

I. Experimental setting of $^{69,71}Fe$ productions.

As note before, at the first time of productions in 1992 and 1997, only several nuclei of $^{69,71}Fe$ were produced by the fragment reactions of $^{86}Kr/^{238}U$. In SEASTAR project, based on the combination of RIBF and modern devices such as MINOS- an active target [17, 18], 69,71Fe were detected in a high-intensity beam of neutron-rich nuclei at RIKEN. Furthermore, their gamma-ray spectroscopic also were recorded by a 4π detector - the DALI2 [19, 20]. The schematic layout of the SEASTAR project which produced $^{69,71}Fe$ is shown in Fig. 1.

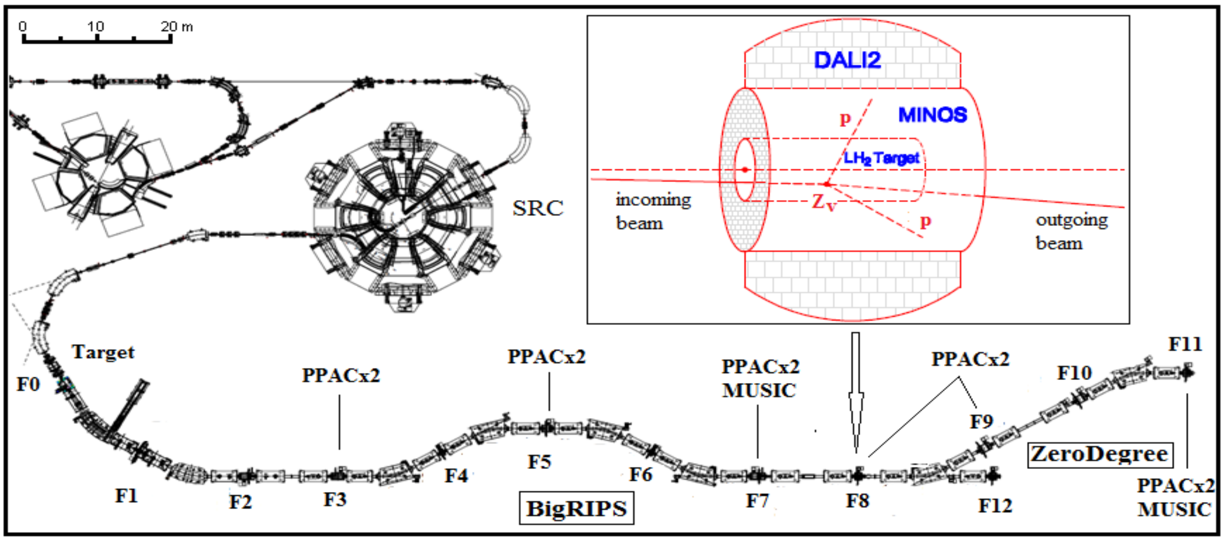

Figure 1. Scheme of SEASTAR's experimental setting. The label Fn are indicate the position of focal planes. The BigRIPS is from F0 to F7 and ZeroDegree is from F8 to F11.

By using by the RIBF, a $^{70}Zn/^{238}U$ beam in role of primary beam was accelerated up to energy of 345 MeV/u before bombarded a thin ^{9}Be target at the F0 of the BigRIPS separator [21, 22]. Then fragmentation products of the primary beam and the ^{9}Be target should be identified, separated and purified by the BigRIPS detection system before being transported to the F8 focal plane - user location. At the F8, while residual nuclei of knock-out reactions between secondary beam and MINOS target were transported to and identified by ZeroDegree [22, 23], exited gamma rays which emitted from excitation states of these nuclei were recorded by DALI2.

As discussed in previous, identification parameters of secondary beams at BigRIPS and residual nuclei at ZeroDegree were recorded in event-by-event mode [24, 25]. To measure PID parameters (ΔE, Bρ and ToF), MUSIC, PPAC and plastic-scintillation detectors were installed along the BigRIPS/ ZeroDegree path. The TOF values were measured by a couple of plastic-scintillators which located at the entrance and exit of measurement locations while the PPACs and MUSIC detectors were used for trajectory and energy loss measurements. At the BigRIPS, two thin plastic- scintillator detectors were installed at F3, F7; three double-PPACs [26] were placed at F3, F5, F7 while only one MUSIC detector [27] was installed at F7. Similarly, a MUSIC detector was installed at F11, two thin plastic scintillators located at F9 and F11, and three double-PPACs located at F8, F9, F11 of ZeroDegree. After selection and optimization steps, beam of interest was transported to F8 and impinged on the proton target inside the MINOS at 200 – 300 MeV/u of energy. Finally, the residual nuclei of nuclear reactions at the MINOS target were identified by ZeroDegree spectrometer while their emitted gamma rays were recorded by DALI2 (see Fig. 1). After these measurements, output signals of beamline detectors such as trajectory of beam, Bρ, ΔE, ToF values and energies, trajectory of gamma- ray in individual crystal of DALI2, vertex positions of nuclear reactions which were reconstructed by MINOS were treated by electronic devices of RIBF and stored into independent branches of a tree-structure data in event by event mode.

III. Data Analysis and results

3.1. Particle identification detectors and method

Particle identification of exotic nuclei was performed at BigRIPS and ZeroDegree based on Bρ - ΔE - ToF method [22] and its results are used for the reaction determination: the incoming/outgoing particles were identified at 2 areas: from F3 to F7 of BigRIPS and from F8 to F11 of ZeroDegree, respectively. Where, Bρ is magnetic rigidity and was achieved via trajectory reconstruction while ΔE and ToF are energy loss and time of flight, respectively, and could be obtained via direct measurements. As mentioned before, these values were stored in a tree-structure data with independently branches and could be extracted to identify interested nuclei. In the PID step, the energy loss, time of flight and magnetic rigidity, atomic number (Z) and mass-to-charge ratio (A/Q) of particle are deduced as:

$$ToF = \frac{L}{\beta c} -> \beta = \frac{1}{c}\frac{L}{ToF} \tag{2.1}$$

$$B\rho = \frac{P}{Q} \rightarrow A/Q = \frac{B\rho}{\beta\gamma}\frac{c}{m_u} \tag{2.2}$$

$$\Delta E = \frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[ln \frac{2m_e v^2}{I} - ln(1-\beta^2) - \beta^2 \right] \quad (2.3)$$

Where, *TOF, B, ρ* and *ΔE* are the time of flight, magnetic field, the radius of the particle's tracjectory and energy loss, respectively. These values were measured by scintilations, PPACs, MUSSIC detectors and could be extracted from measured data while *L* is the flight-path length, υ is particle velocity, β = υ/c, *c* is the light velocity, γ = 1/, 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. In order to improve the PID resolutions at the ZeroDegree, some corrections are required. The PID procedures at the BigRIPS and ZeroDegree have been already described in detail on preferences [22, 24, 25]. In the next sections, PID results for Fe isotopes at BigRIPS and ZeroDegree as well as some PID corrections at ZeroDegree will be discussed.

3.2 Preliminary results of PID at BigRIPS and ZeroDegree

As mentioned in previous, exotic nuclei were identified at BigRIPS and ZeroDegree based on Bρ - ΔE – ToF method. The particle identification at the BigRIPS separator was performed when neutron rich nuclei passing through 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.

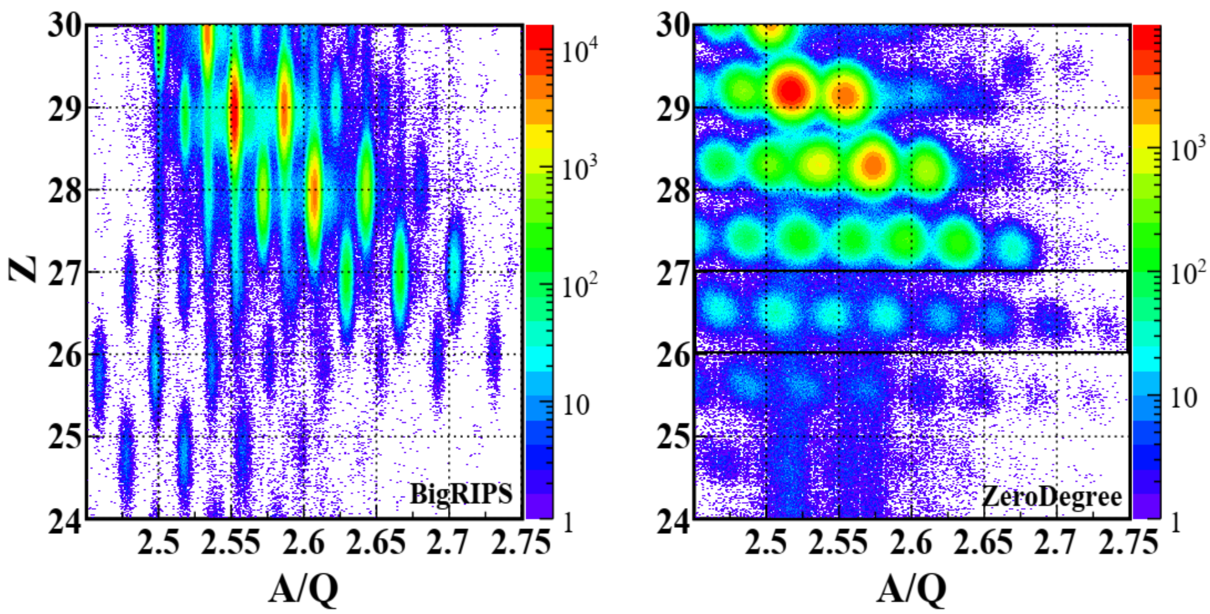

Figure. 2. Particle identification for incoming particle at the BigRIPS (left panel) and residuals at the ZeroDegree (right panel). Events of Fe isotopes (Z=26) are marked by the rectangle.

Similarly, residuals particle at the ZeroDegree were identified by using same method with PID process for incoming particle at the second stage of BigRIPS. Here, two thin plastic scintillators were installed at F8 and F11 while a MUSIC detector was placed at F11 to and 3 double- PPACs were placed at F8, F9, F11. By using recorded parameters from these detectors as inputs for equations (2.1) - (2.3), Z and A/Q values of individual event could be deduced. Fig. 2 shows the PID plot of neutron-rich nuclei, include $^{69, 71}$Fe. At the BigRIPS, neutron rich nuclei were clearly separated while the PID plot at ZeroDegree was shown with overlap areas. Hence, corrections at ZeroDegree are needed. Corrections could be performed via both Z, A/Q values and will be discussed in the next parts.

3.2.1 Z Correction

As discussed in section 3.1, Z values could be achieved from velocity and energy loss of particle by using (2.2) and (2.3) equations. Principally, Z values should not depend on velocity – β but isotopic chains in the raw ZeroDegree PID exhibited a slight slope, due to a dependence in beam velocity- β (see left panel on Fig. 4). Therefore, the dependence of Z in β should be eliminated and Z – β correlation should be straight. Fig. 4 displays the correlations between Z values and velocity – β before and after corrected by using:

$$Z_{corrected} = 1.15279 * Z_{raw} - 7.25698*(\beta - 0.65) - 5.10286 \quad (3.1)$$

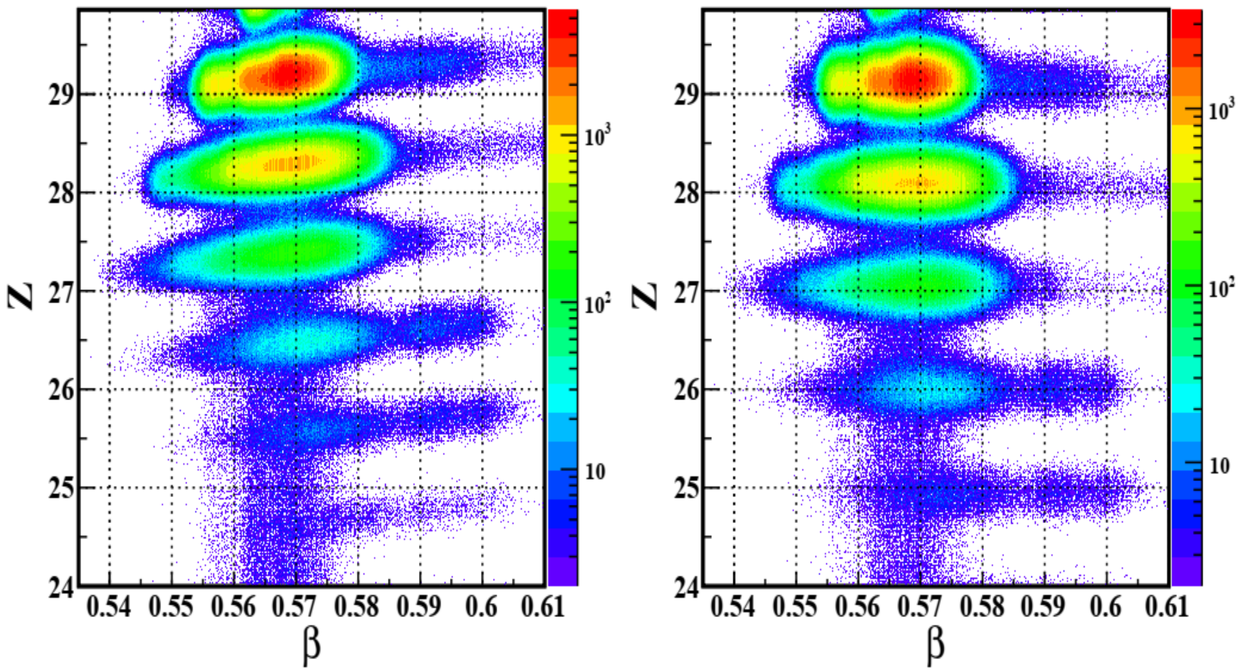

Figure.3. Z – β correlations before (left panel) and after Z corrected (right panel) for Fe isotopes.

After corrected, the dependence of Z in β was removed (see right panel of Fig. 3). In the below part, A/Q corrections will be considered and described.

3.2.2 A/Q correction

As shown in Fig. 3, ZeroDegree PID need to be optimized in order to improve the A/Q resolution. Better separation would allow more reliable and accurate channel of interest. The correction method has already described in Ref. [22, 24, 25, 28, 29] and used to remove the dependence of A/Q in position (X) and angle (A) measurements at the PPACs. The slew was corrected for A/Q of ^{69}Fe by using:

$$A/Q_{corrected} = A/Q_{raw} + 125.10^{64}.\ F11A + 10^{-5}.\ (F11A)^2 + 22.10^{-5}.\ F11X + 8.10^{-6}.\ (F11X)^2 - 5x10^{-7}.\ (F11X)^3 + 85.10^{-4}.\ F9A - 2.10^{-5}.\ (F9A)^2 + 26.10^{-6}.\ F9X - 2.10^{-8}.\ (F9X)^2 + 125.10^{-11}.\ (F9X)^3 \quad (3.2)$$

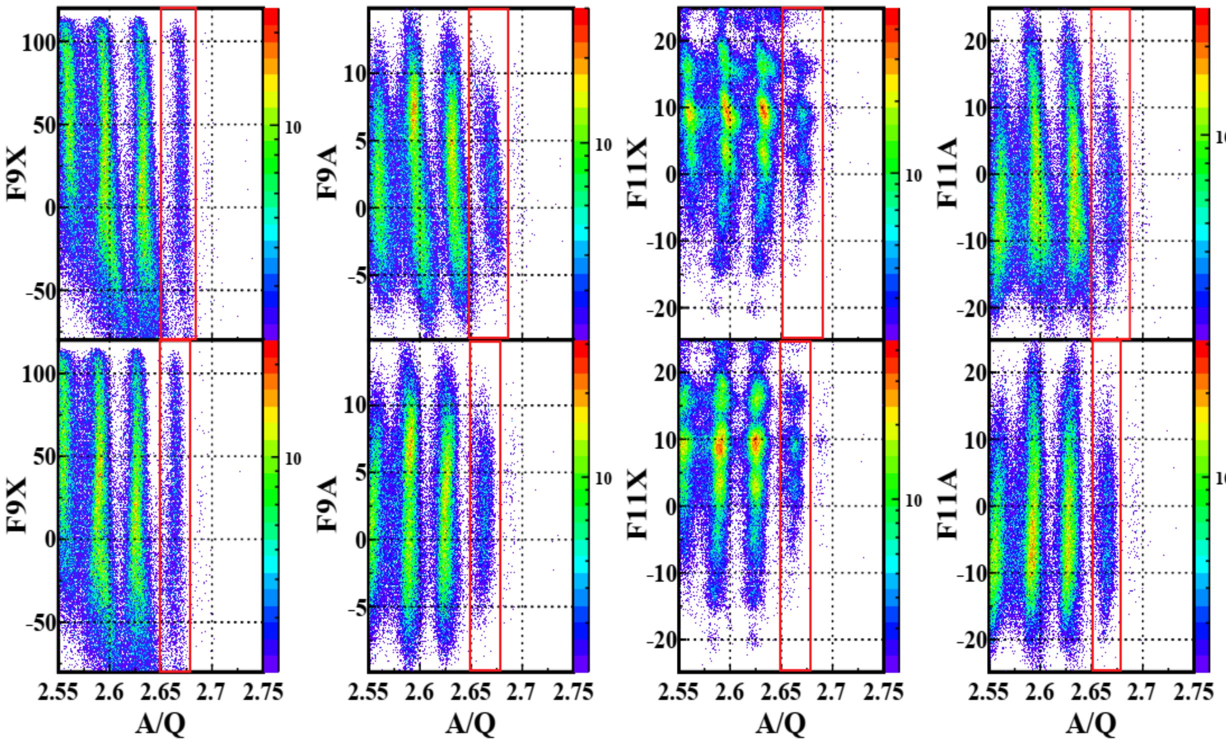

Figure 5. The dependence of A/Q versus position (X) and angle (A) at F9 and F11, respectively: before PID correction shows in upper panels, after PID correction shown in lower panels. The correction was performed to select ^{69}Fe events which are marked by the rectangles.

3.2.3 Effect of PID corrections at ZeroDegree

In this part, PID results at the ZeroDegree and a briefly comparison between before and after corrections will be discussed. As noted in previously, Z and A/Q should be corrected by using Eq. (3.1) and Eq. (3.2), afterward, both (3.1) and (3.2) should be included into Z versus A/Q correlation: $(Z{:}A/Q)_{corrected} = (1.15279*Z_{raw} - 7.25698*(\beta - 0.65) - 5.10286){:}\ \{A/Q_{raw} + 35x10^{-5}.\ F9X - 18x10^{-8}.\ (F9X)^2 + 6x10^{-9}.\ (F9X)^3 + 7x10^{-4}.\ F9A - 2x10^{-5}.\ (F9A)^2 + 2x10^{-4}.\ F11X + 16x10^{-6}.\ (F11X)^2 - 5x10^{-7}.\ (F11X)^3 + 10^{-4}.\ F11A + 10^{-5}.\ (F11A)^2\}$ (3.3)

Fig. 6 displays the PID results at ZeroDegree to make a simple comparison with and without PID corrections.

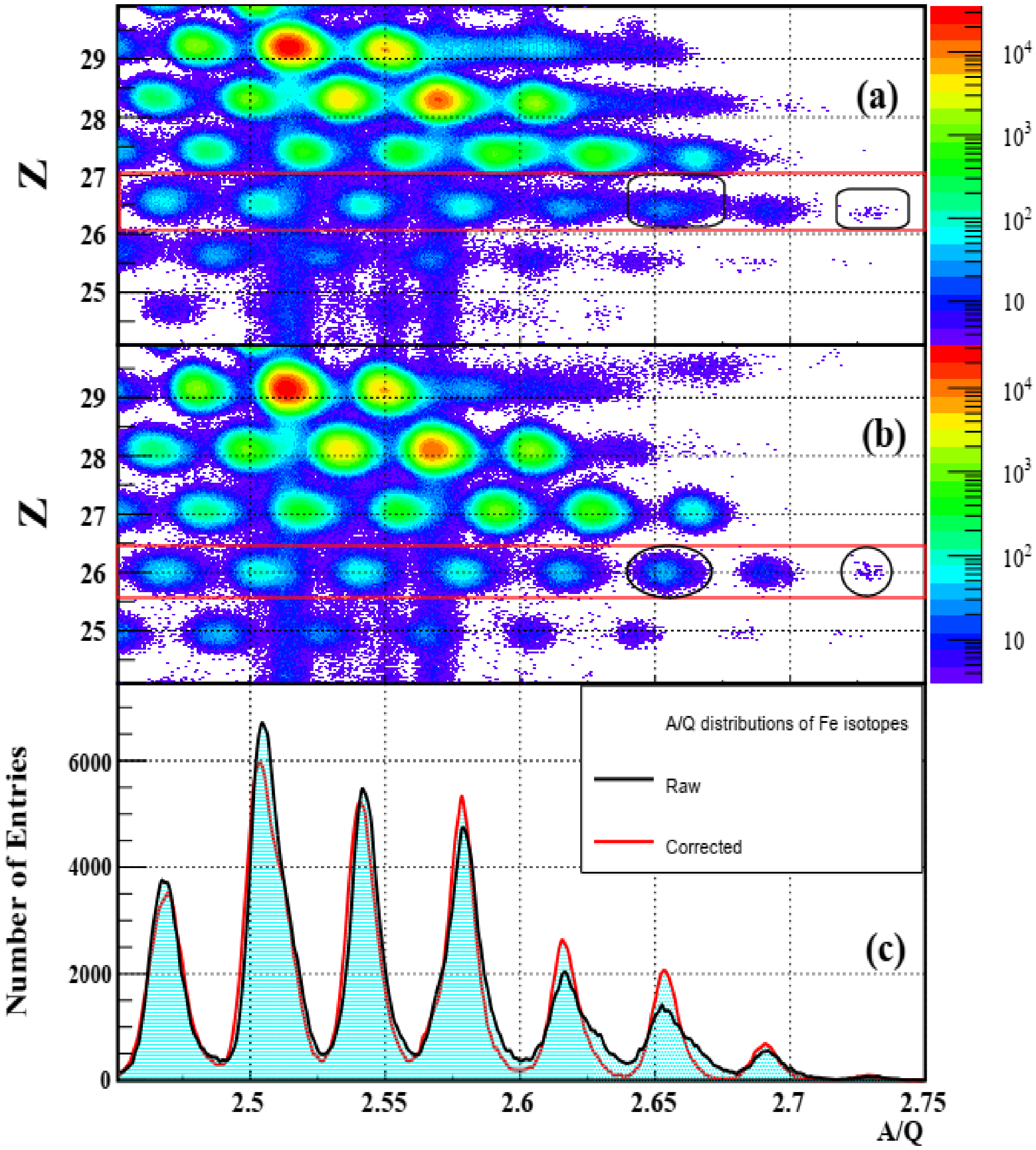

Figure 6. PID results in Z versus A/Q plot (2 upper panels) and A/Q distributions (lower panel) before and after corrected. PID corrections were performed in order to improve resolutions of ^{69}Fe. Event of Fe isotopes are marked by rectangles.

As shown in panel (a), isotopic chains were displayed with some overlaps and therefore, PID corrections are needed. In panel (b), these chains were clearly separated. In panel C, A/Q distributions for Fe isotopes before (black line) and after (red line) PID corrections are shown, these results are projected from panel (a) and panel (b). A briefly comparison of Z, A/Q and corresponding sigma values for ^{69,71}Fe nuclei before and after PID corrections is shown in Table

1. The sigma (σ) values could be taken from Z, A/Q distributions by Gaussian fitting and able to be used for resolution calculations.

Table 1. Z and A/Q values of ^{69,71}Fe before and after correction.

Data status	**^{69}Fe ((Z=26; A/Q=2.6538)**		**^{71}Fe (Z=26; A/Q=2.7308)**	
	Z(σ)	A/Q(σ)	Z(σ)	A/Q(σ)
Raw data	26.4601(0.1413)	2.655(8.955e-3)	26.4008(0.1410)	2.7299(6.916e-3)
Corrected	26.0101(0.1494)	2.654(5.145e-3)	26.0029(0.1423)	2.7291(4.452e-3)

IV. Conclusion

In this paper, particle identification method based on Bρ - ΔE – ToF measurements at BigRIPS and ZeroDegree at RIBF/RIKEN has been presented. Based on verified method, data of Fe isotopes from SEASTAR experimental data have been extracted, PID corrections for both Z and A/Q were performed and shown the first results. After corrections, accuracy and resolutions of Z and A/Q values of ^{69,71}Fe at ZeroDegree were improved (may up to several tens of percent). These results decide the accuracy of channel selection and will be used in the nuclear spectroscopic study of interested nuclei.

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Nhận diện các hạt nhân ^{69,71}Fe trong chùm đồng vị phóng xạ tại RIKEN

Tóm tắt: Các hạt nhân không bền giàu neutron ^{69,71}Fe được tạo ra trên hệ thống RIBF của Viện nghiên cứu RIKEN trong đợt thí nghiệm thứ nhất của dự án SEASTAR. Báo cáo giới thiệu phương pháp và kết quả ban đầu của quá trình nhận diện các hạt nhân này. Ngoài ra, một số hiệu chỉnh cần thiết nhằm cải thiện độ phân giải nhận diện hạt cũng sẽ được thảo luận. Kết quả nhận diện ^{69,71}Fe là tiền đề quan trọng cho các bước phân tích tiếp theo để nghiên cứu cấu trúc các hạt nhân này.

Từ khóa: *SEASTAR, ^{69}Fe, ^{71}Fe, nhận diện hạt, PID.*