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Particle identification for neutron rich nuclei $^{63,65}Cr$ from knockout reactions

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Abstract: This paper presents the identification for $^{63,65}Cr$ isotopes as the products of knockout reactions for the first time, measured at RIKEN, Japan, within the framework of the "*Shell Evolution And Search for Two-plus energies At RIBF"* (RIBF- Radioactive Isotope Beam Factory) project, in short SEASTAR. Based on the Bρ-ΔE-ToF method, these nuclei were well separated. The results will be used in the spectroscopic study on $^{63,65}Cr$ contributing data to the structural study around the N=40 "island of inversion".

Keywords: *SEASTAR, BigRIPS, ZeroDegree,neutron - rich nuclei of Cr, PID Correction.*

I. INTRODUCTION

The neutron-rich nuclei near N = 40 have attracted much attention due to the magicity of $^{68}_{28}Ni_{40}$. This nucleus has high energy of the first excited 2^+_1 state [1] and a low B(E2; 2^+_1-> 0^+_1) rate [2] which indicate a subshell closure at N=40. However, this subshell closure is very fragile if protons are removed from ^{68}Ni. The collectivity in even-even Fe and Cr isotopes were conducted as the decrease in energies of the 2^+_1 states [3, 4] and the increase in B(E2) values [5, 6] along these isotopic chains. In the odd-A Cr and Fe, as well as the odd-odd Co and Mn isotopes, the onset of the collectivity leading to the prolate deformation has been attributed to the proton ($\pi f_{7/2}$)-neutron ($\nu f_{5/2}$) attractive interaction [7]. The N=40 shell gap is narrower resulting in the high probability of neutron excitation out of pf shell [7]. Up to now, the experimental information on the neutron-rich odd-A Cr isotopes is scarce. The available data are $^{55,57,59}Cr$ in Refs. [8-11], and $^{61,63}Cr$ in Ref. [12]. Heavier odd Cr isotopes were not studied yet due to the difficulty in the Radioactive Isotope Beam (RIB) production because of their very low productive cross sections and short lifetimes. As aforementioned, more data on odd-A neutron rich nuclei are requested to verify the $\pi f_{7/2}$-$\nu f_{5/2}$ isospin interaction in the N=40 "island of inversion".

In the SEASTAR project [13], thanks to the combination of advanced BigRIPS, ZeroDegree facilities [14] and MINOS [15], DALI2 [16] devices, many new neutron-rich isotopes were produced and their gamma spectroscopies were detected. The particle identification (PID) method and the correction procedure for some exotic nuclei with Z>24

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from SEASTAR experimental data were discussed in Ref. [17]. However, the correcting parameters are not universal over the whole data. In this paper, the identification for $^{63,65}Cr_{24}$ is reported. Firstly, the PID procedure described in Ref. [17] was applied. One can see in Fig. 1 that the Cr_{24} isotopes are not aligned in atomic number Z. Therefore, this correction for the Cr isotopes was done in addition to enhance the PID quality and, thus, for the spectroscopic study later on.

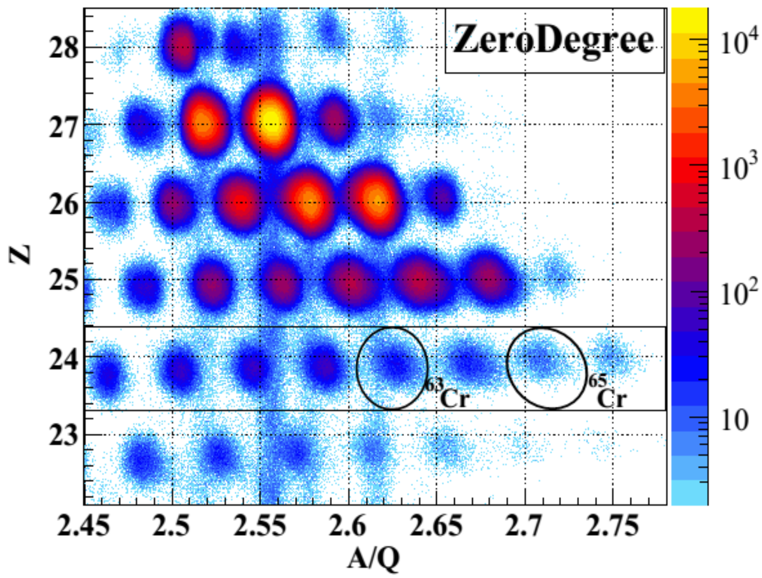

Fig. 1. The correlation between atomic number Z versus the ratio of mass and charge A/Q of particles at ZeroDegree. The Cr isotopic crowds are marked by a rectangle, in particular by circles for ^{63,65}Cr. This figure is taken from Ref. [17]

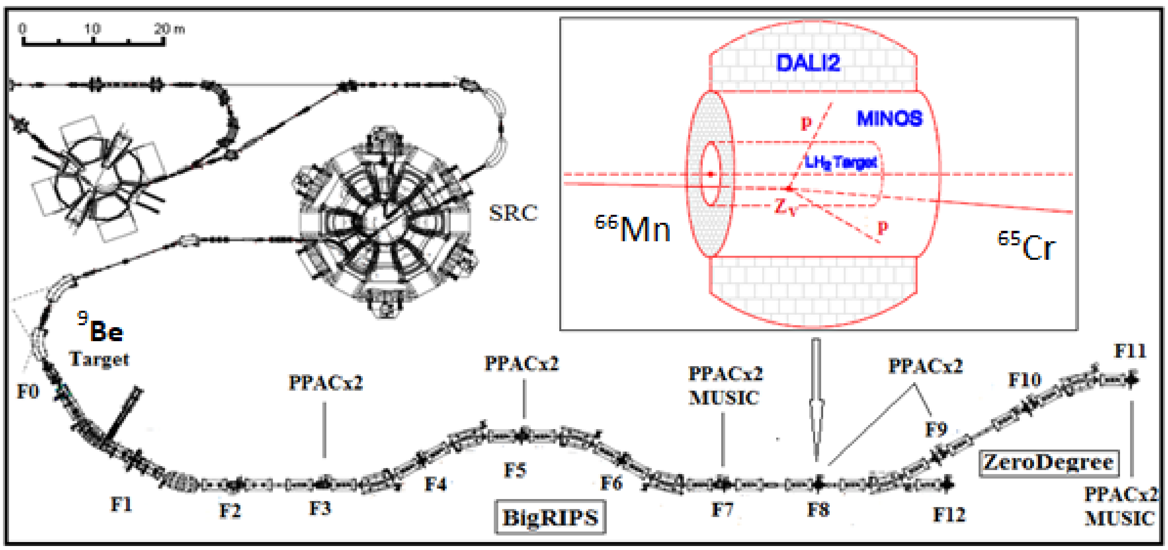

Fig. 2. Experimental setup. The labels Dn and Fn indicate the positions of dipole magnet and foci, respectively. BigRIPS is from F1-F8. ZeroDegree is from F9-F11. PPACs and MUSICs were used for tracking and identifying purpose. The inset is a sketch of the main detectors MINOS and DALI2 with an illustration for ^{66}Mn(p,2p)^{65}Cr. Z_v is the vertex point. More details are explained in text

II. EXPERIMENTAL SETUP AND PID METHOD

The experimental setup is described in Fig. 2. A ^{238}U primary beam with the mean intensity of 12 pnA was accelerated up to 345 MeV/*u* energy by the Superconducting Ring Cyclotron (SRC) before impinging on a ^{9}Be primary target at the F0 focal plane of the BigRIPS separator.

The secondary beam was created as the products of fragmentation reactions, transported to the user location at the F8 focal plane and interacted with MINOS LH_2 active target [15] to induce knockout reactions. The target was a cylindrical cell (see the inset on Fig. 2). Its effective thickness and length were 735(8) mg/cm^3 and 102(1) mm [18], respectively. The secondary beam's energy at the entrance of the MINOS target was about 260 MeV/*u*. Prompt gamma de-excitation from residues was detected by the DALI2 NaI crystals [16] surrounding the target. Measuring gamma-ray energies emitted from particles of interest were the aiming information of the SEASTAR experiments.

The PIDs for the secondary beam at BigRIPS and residue at ZeroDegree were performed via the correlation between *A/Q* and *Z*. These quantities were determined according to time-of-flight (*ToF*), particle trajectory's radius (*ρ*), and energy loss (*ΔE*) using below equations:

$$\beta c = \frac{L}{\mathrm{ToF}} \tag{1}$$

$$A/Q = \frac{B\rho}{\beta\gamma}\frac{c}{m_u} \tag{2}$$

$$\Delta E = \frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz\left[ln\frac{2m_e v^2}{I} - ln(1-\beta^2) - \beta^2 \right], \tag{3}$$

Where, *B* and *L* are magnetic field and the flight-path length, respectively. *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 and *e* are the electron mass and the elementary charge. *N*, *z* and *I* are the atomic density, atomic number and mean excitation potential of the material, respectively. The *ToF* was measured by two thin plastic scintillators installed at *L* distance apart [17]. The magnetic rigidity (*Bρ*) was conducted by using positions and angles measured by position-sensitive Parallel Plate Avalanche Counters (PPAC) [17]. Finally, *ΔE* was measured by MUlti-Sampling Ionization Chambers (MUSIC) [17]. This method is called *Bρ–ΔE–ToF* method. More details are discussed in Refs. [14, 17].

III. PID CORRECTION AND RESULT

During the SEASTAR experiments, the PID correction at BigRIPS was carried out by the BigRIPS experts. At ZeroDegree, the correction needed to be performed according to the particles of interest. For $^{63,65}Cr$ identification, the A/Q values were corrected following the procedure in Ref. [17]. The argument is that the dependence of A/Q on position (X) and angle (A) measured by the PPACs should be removed because this is an intrinsic value of a particle. As the results, the A/Q vs. X (A) plot should be a straight-like line. The A/Q correction of ^{63}Cr was made by adding higher order dependences on X and A as follow:

$$A/Q_{correct} = A/Q + 35x10^{-5}.\ F9X - 18x10^{-8}.\ (F9X)^2 + 6x10^{-9}.\ (F9X)^3 + 7x10^{-4}.\ F9A - 2x10^{-5}.\ (F9A)^2 + 2x10^{-4}.\ F11X + 16x10^{-6}.\ (F11X)^2 - 5x10^{-7}.\ (F11X)^3 + 10^{-4}.\ F11A + 10^{-5}.\ (F11A)^2 \tag{4}$$

Where, F9(11)X and F9(11)A denote the position and angle, respectively, measured at the F9(11) focal plane. A comparison between uncorrected (upper panels) and corrected (lower panels) A/Q vs. X(A) correlation is shown in Fig. 3. Because the statistic for ^{65}Cr is low (see the crowds at A/Q≈2.71 in Fig. 3). The PID quality was not significantly improved by the correction. Therefore, the above correction for ^{63}Cr was also used for the case of ^{65}Cr.

As mentioned before, the Z-correction is necessary because it is not aligned for all Cr isotopes as shown in Fig. 1. In principle, Z is an intrinsic value of nuclei. Therefore, it is not dependent on the measured velocity divided by the speed of light of these particles (β). Similarly to the correction for A/Q, higher order dependences on β was introduced to remove the dependence as:

$$Z_{correct} = 0.87Z + 6.43\beta - 0.52 \tag{5}$$

The result, $Z_{correct}$, is presented in the right panel of Fig. 4 with the centroid of 23.994(4) for Cr isotopes improving from that of 23.862(5) without correction shown in the left panel. The PID quality is estimated by the resolution of the Z distribution which is the projection of these plots on the Z axis. The resolution in σ after the correction is 0.14, much better than that of 0.19 without correction.

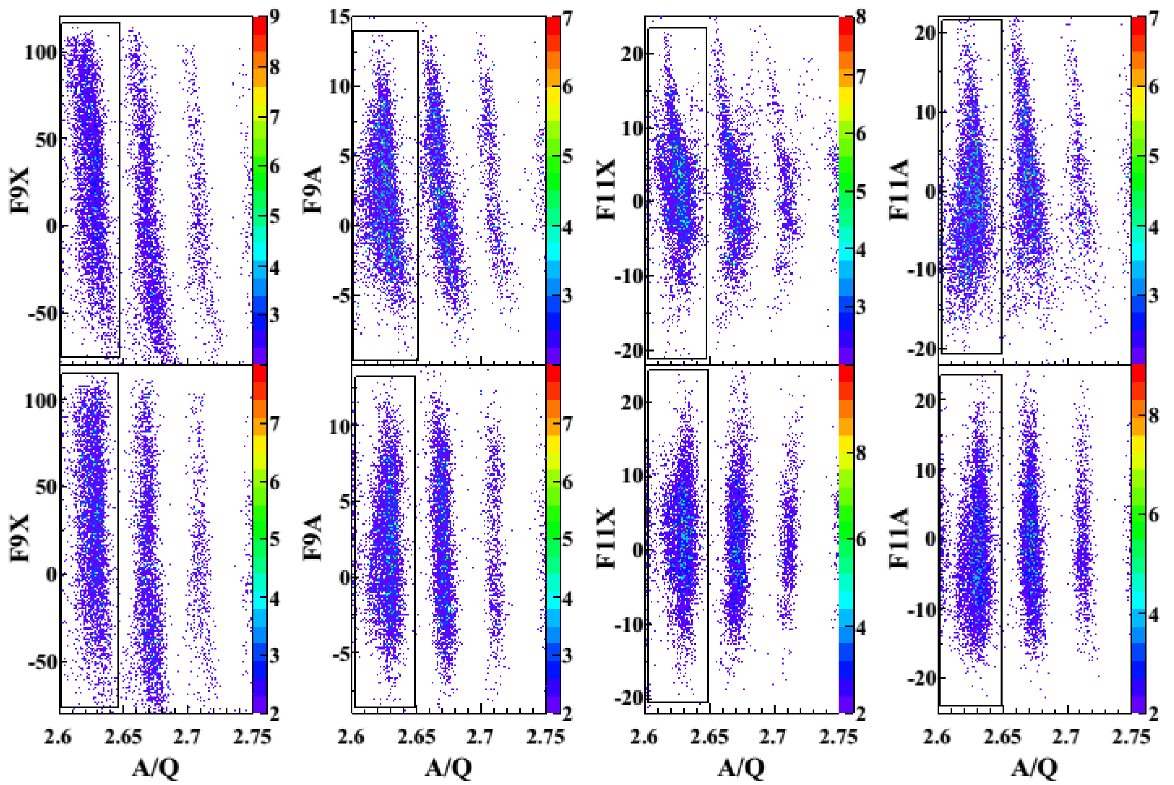

Fig. 3. The dependence of A/Q versus position (X) and angle (A) at F9 and F11. The upper panels are for uncorrected A/Q. The lower panels are for the corrected ones. The correction was performed to select ^{63}Cr events marked by the rectangles

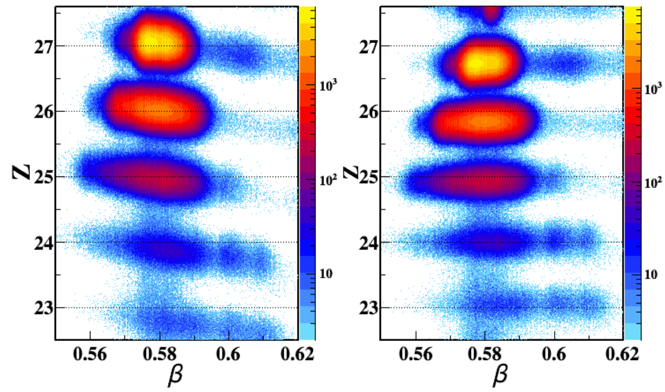

Fig. 4. Correlation between atomic number Z and the velocity divided by the speed of light β before (left) and after (right) the correction

Taking into account both A/Q- and Z-corrections in Eqs. (4) and (5), the PID plot is displayed in Fig. 5a. The projection of this plot on the abscissis shown in Fig. 5b. The A/Q resolution (σ) is 0.114 and 0.118 for ^{63,65}Cr, respectively. Before the correction these values are 0.180 for ^{63}Cr and 0.156 for ^{65}Cr (obtained from Fig. 1).

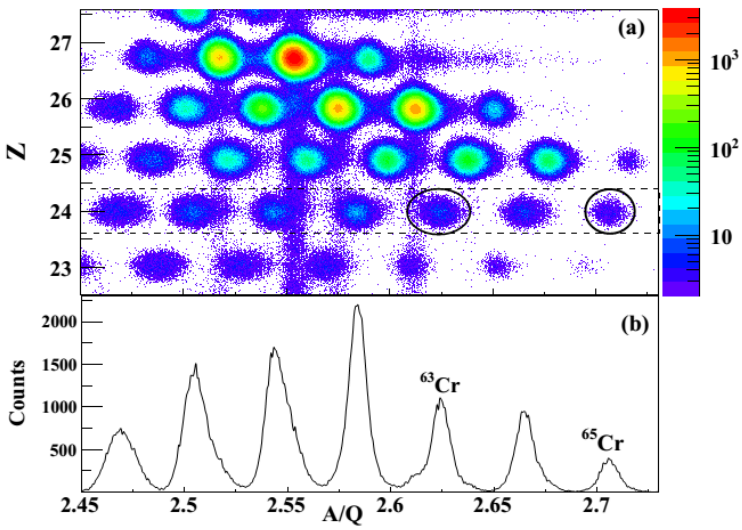

Fig. 5. Particle identification via Z vs. A/Q for ^{63,65}Cr is marked by the circles in panel a). Panel b) is the projection of panel a) on the abscissis

IV. CONCLUSIONS

In this paper, the identification for ^{63,65}Cr from the SEASTAR experimental data based on *Bρ-ΔE–ToF* method has been reported. Following the procedure described in Ref. [17], the A/Q correction was carried out. The PID correcting parameters in the case of ^{63}Cr was used for identifying ^{65}Cr. The Z correction was necessary to improve the PID resolution of these nuclei. As the results, ^{63,65}Cr were well separated from the other isotopes. These PID results will be used in the study on the spectroscopy of ^{63,65}Cr.

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REFERENCES

[1]. R. Broda et al., Physical Review Letters 74, 868, 1995.

[2]. O. Sorlin et al., Physical Review Letters 88, 092501, 2000.

[3]. M. Hanawald et al., Physical Review Letters 82, 1391, 1999.

[4]. A. Gade et al., Physical Review C 81, 051304(R), 2010.

[5]. W. Rother et al., Physical Review Letters 106, 022502, 2011.

[6]. T. Baugher et al., Physical Review C 86, 011305(R), 2012.

[7]. S. M. Lenzi et al., Physical Review C 82, 054301, 2010.

[8]. H. Junde, Nuclear Data Sheets 109, 787, 2008.

[9]. A. N. Deacon et al., Physics Letters B 622, 151, 2005.

[10]. S. N. Liddick et al., Physical Review C 72, 054321, 2005.

[11]. S. J. Freeman et al., Physical Review C 69, 064301, 2004.

[12]. S. Suchyta et al., Physical Review C 89, 034317, 2014.

[13]. P. Doornenbal and A. Obertelli, RIBF NP-PAC-13, 2013.

[14]. N. Fukuda et al., Nuclear Instruments and Methods in Physics B 317, 323, 2013.

[15]. A. Obertelli et al, The European Jour. Phys. A 50, 8, 2014.

[16]. P. Doornenbal, Progress of Theoretical and Experimental Physics, 03C004, 2012.

[17]. B. D. Linh, N. D. Ton, L. X. Chung et al., Nuclear Science and Technology 7, 08-15, 2017.

[18]. C. Santamaria, L. X. Chung et al., Physical Review Letters 115, 192501, 2015.

[19]. H. Kumagai et al., Nuclear Instruments and Methods in Physics A 470, 562, 2001.

[20]. K. Kimura et al., Nuclear Instruments and Methods in Physics A 538, 608, 2006.