IN-BEAM GAMMA RAY SPECTROSCOPY OF ^{63,65}Cr

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Abstract: The neutron-rich nuclei ^{63,65}Cr were produced at the RIBF facility at RIKEN in the first campaign of the "*Shell Evolution And Search for Two-plus energies At RIBF*" (SEASTAR) project. The preliminary results of in-beam gamma ray spectroscopy of these nuclei, the detail of experimental setup and the particle identification method are presented. Based on the analysis, new gamma ray transitions were observed at 420, 580 and 730 keV for ^{63}Cr, 392 and 489, 720 keV for ^{65}Cr, respectively. They are the first experimental results on these nuclei.

Key words: *SEASTAR, ^{63}Cr, ^{65}Cr, particle identification, gamma ray transition.*

I. Introduction

Since last years of the 20th century, research on exotic nuclei began being concerned with the most advanced experimental method which aimed at measuring the products of reactions induced by radioactive isotope beams (RIBs) produced by projectile fragmentation and fission of heavy ion beams. The research with RIBs was mainly carried out in big laboratories worldwide equipped with the most advanced facilities such as the RIBF at RIKEN (Japan), the LISE3 at GANIL (France), A1900 at MSU (US) and the FRS at GSI (Germany) [1-4]. Since the availability of RIBs, shell structure of exotic nuclei has been studied and many new phenomena which beyond the explanation of shell model were explored: 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" at N = 40 [10-12] or disappearance of the magic numbers N = 28 [13].

The "*Shell Evolution And Search for Two-plus energies At RIBF"* (SEASTAR, RIBF-Radioactive Isotopes Beam Factory) project aims at a systematic search for new 2_1^+ energies in the wide range of neutron-rich nuclei [14]. By using ^{70}Zn and ^{238}U primary beams at 345 MeV/u in combination with advanced devices, many new isotopes were produced and detected. From the spectroscopic analysis, properties of shell structure of these nuclei can be extracted. The neutron–rich nuclei $^{63,65}Cr$ were recorded at the first SEASTAR campaign. With neutron number N= 39 and 41, studies on $^{63,65}Cr$ will directly contribute to the knowledge and understanding of the "island of inversion" N = 40 at low - Z shore. In this report, experimental setup of this SEASTAR project and preliminary spectra of $^{63,65}Cr$ will be presented, besides that, the analysis of these spectra, including the transition identification, fitting spectra are also discussed.

II. Experimental setup

The first SEASTAR experimental campaign was performed in 2014 at RIBF/RIKEN with the combination of the MINOS [15, 16] active target and array detector DALI2 [17, 18]. A ^{238}U primary beam was accelerated up to energy of 345 MeV/u by the RIBF acceleration system before impinged on a ^{9}Be primary target at the F0 focal plane of the BigRIPS separator [19, 20]. Afterward, the secondary beam – products of fragmentation reactions between primary beam and ^{9}Be target was identified, separated by the BigRIPS detection system before being

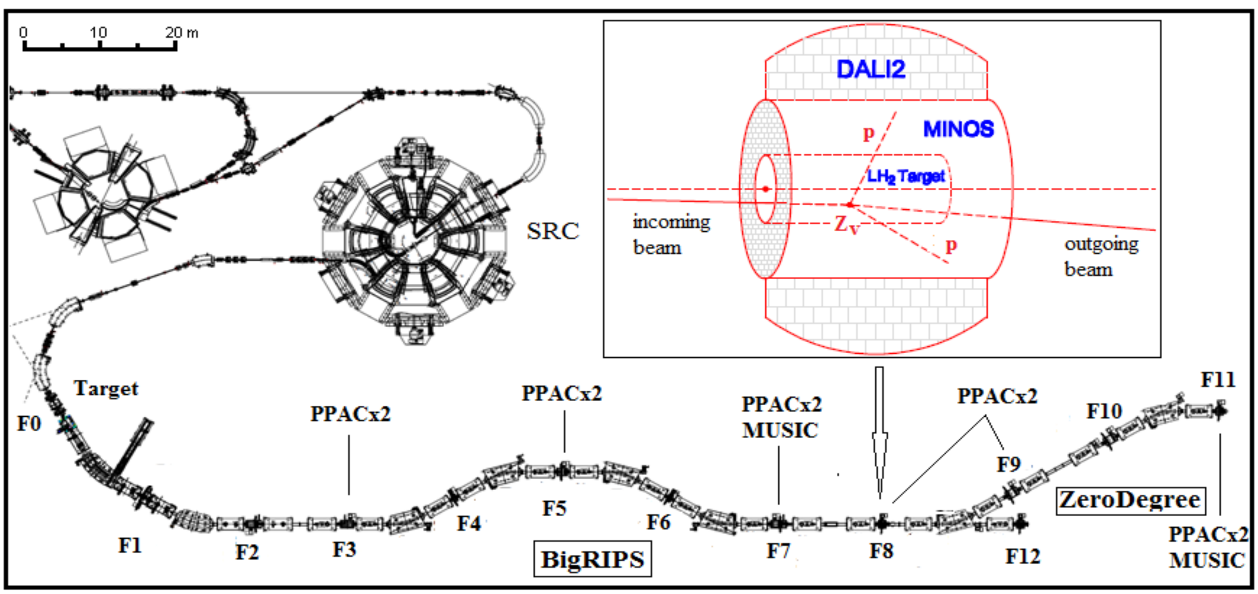

Figure 1. Scheme of SEASTAR's experimental setting. The label Fn are indicate the position of focal planes. The BigRIPS is from F0 to F7 and ZeroDegree is from F8 to F11.

transported to the user locations and interacted with the MINOS proton target at the F8 focal plane. While residual nuclei after the reactions were identified by ZeroDegree [20, 21], excited gamma rays of these nuclei were recorded by DALI2. The schematic layout of the SEASTAR experimental setup is shown in Fig. 1.

During the SEASTAR experiments, particle identification of secondary beams was performed in event-by-event mode at the BigRIPS based on Bρ - ΔE - ToF method. The BigRIPS is a two-stage separator from F0 to F7: the first stage is from F0 to F2 used for producing, collecting and separating the RIBs; while the second stage is from F3 to F7 used for particle identification (PID) and/or further separating, optimizing the nuclei of interest via the magnetic optimization. At each focal plane of the BigRIPS, PID parameters including energy loss (ΔE), magnetic rigidity (Bρ) and time of flight (ToF) were measured by MUSIC, PPAC and plastic-scintillation detectors, respectively. For these measurements, there were two thin plastic-scintillation detectors placed at F3 and F7, three double-PPACs [22] placed at F3, F5 and F7 and only one MUSIC detector [23] placed at F7 (see Fig. 1). After the optimization, beam of interest was transported to F8, impinged on the MINOS target at 200 – 300 MeV/u of energy. Then, produced neutron-rich nuclei were produced by scattering or knock-out reactions. The MINOS is an active target including of 2 components: A liquid hydrogen (LH2) volume playing the role of a reaction target and a Time Projection Chamber (TPC) used for the vertex reconstruction and tracking purpose. After creating at the MINOS target, the residual nuclei decay into more stable states by releasing gamma rays while traveling at kinetic energy of about 200 - 270 MeV/u. These in-beam gamma rays were recorded by DALI2. Outgoing particles were identified by ZeroDegree spectrometer which was installed from F8 to F11. At the ZeroDegree, particles were identified event-by-event basing on Bρ - ΔE – ToF method, similar to that at BigRIPS. For the measurement of PID parameters, 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.

In the next section, the data analysis procedure and its preliminary results will be discussed.

III. Data Analysis and results

$^{63,\,65}$Cr were obtained from the first SEASTAR experimental campaign focusing on the spectroscopy of ^{66}Cr, $^{70,\,72}$Fe and ^{78}Ni. In this part, the reconstruction of the variables of events of interest from the recorded data will be described. Firstly, the particle identification is performed to specify the reaction channel of interest. Secondly, the MINOS detector will be calibrated to reconstruct the trajectory of knock-out protons and obtain vertex positions of knock-out reactions. Beside the DALI2 array will be also calibrated in energy. Thirdly, the DALI2 response functions to gamma energy will be simulated and used for fitting gamma rays spectra.

3.1. Particle identification

As mentioned before, the PIDs were performed at BigRIPS/ZeroDegree and its results are used for selecting the reaction channel of interest. Incoming/outgoing particles are identified from F3 to F7 of BigRIPS and from F8 to F11 of ZeroDegree, respectively. The PID is based on Bρ - ΔE - ToF method [20]. Where, Bρ is magnetic rigidity and could be achieved via the trajectory reconstruction while ΔE and ToF are energy loss and time of flight, respectively, and could be obtained via direct measurements. At the BigRIPS, the trajectory reconstruction was performed by using 3 double-PPACs at F3, F5 and F7. Two thin plastic detectors at F3, F7 were used for time of flight (TOF) measurement. The energy losses (ΔE) were measured by MUSIC at F7. Similarly, the ZeroDegree spectrometer used a MUSIC detector at F11. Two thin plastic scintillators at F9, F11 were used for (ΔE) and (TOF) measurements. The trajectory reconstruction at the ZeroDegree was performed by using 3 double-PPACs at F8, F9 and F11. By using the energy loss, time of flight and magnetic rigidity, atomic number (Z) and mass-to-charge ratio (A/Q) of particle are deduced as:

$$B\rho = \frac{P}{Q} \rightarrow A/Q = \frac{B\rho}{\beta\gamma}\frac{c}{m_u}, \tag{2.1}$$

$$TOF = \frac{L}{\beta c}, \tag{2.2}$$

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

Where, *TOF, B, ρ* and *ΔE* are the time of flight, magnetic field, the radius of the particle's tracjectory and energy loss, respectively. *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 (Fig. 3). The PID procedures at the BigRIPS and

ZeroDegree as well as the PID correction at the ZeroDegree have been already described in detail on preference [24]. Figure 4 shows the PID results in BigRIPS and ZeroDegree ^{63,65}Cr are marked in the right panel.

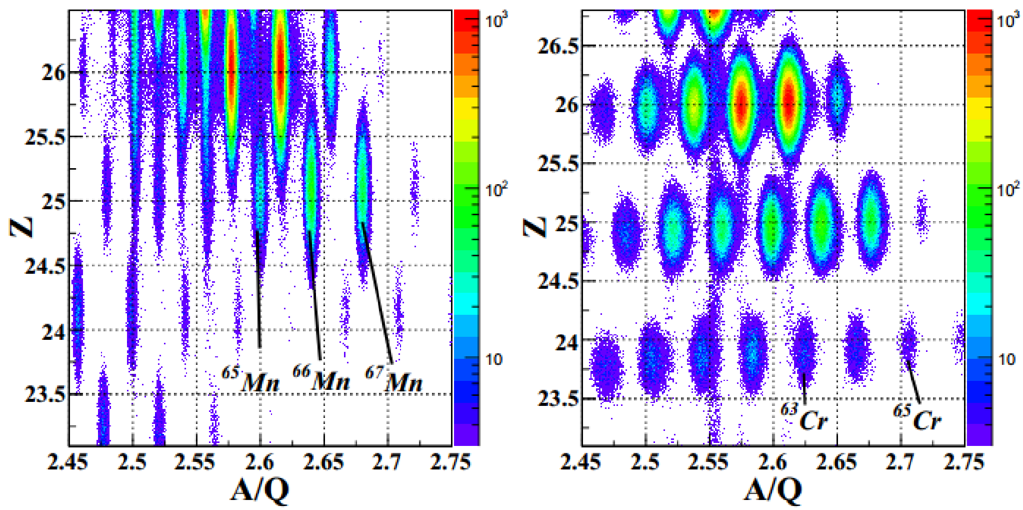

Figure 2. Particle identifications via the correlation A/Q versus Q at the BigRIPS (left) and ZeroDegree (right). At the BigRIPS, events of exotic nuclei from Cr to Ni are showed and incoming-particle of interested channels are marked. At the ZeroDegree, events of exotic nuclei from Cr to Ni are showed. Events of $^{63,\,65}$Cr are marked.

3.2 Gamma spectra of $^{63,\,65}$Cr

As noted previously, because of statistical limitation, only spectra of ^{63}Cr from reactions channel $^{64+X}$Mn(p,2pXn)^{63}Cr (X = 1, 3) and spectra of ^{65}Cr populated from $^{65+Y}$Mn(p,2pYn)^{65}Cr (Y = 0, 1) will be showed. Note that $^{63,\,65}$Cr emitted gamma rays during flight, the energies of these gamma rays were shifted. The shifted energy is dependent on the emitted angle and the velocity of the residual nucleus. The angle was determined by using the vertex position. The gamma energy was corrected for the Doppler broadening as:

$$E_{Dopp} = E_{\gamma} \frac{1-\beta\cos\theta}{\sqrt{1-\beta^2}} \tag{3.1}$$

Where, E_{Dopp} is the energy of the gamma ray after corrected, E_{γ} is the energy recorded by DALI2, β is the beam velocity at the vertex position and θ is the gamma emitted angle with respect to the beam direction. The angle is calculated by using vertex point and position of DALI2 crystal fired by the emitted gamma because each DALI2 crystal was located at a certain position in the space. After the correction, gamma spectra were fitted with a function being a sum of the DALI2 response function simulated with SHOGUN package [25] and a background of an exponential function. A transition is accepted if its width agree with the expected resolution (i) and its intensity obtained from the fit must be at least twice greater than its statistical uncertainty (ii).

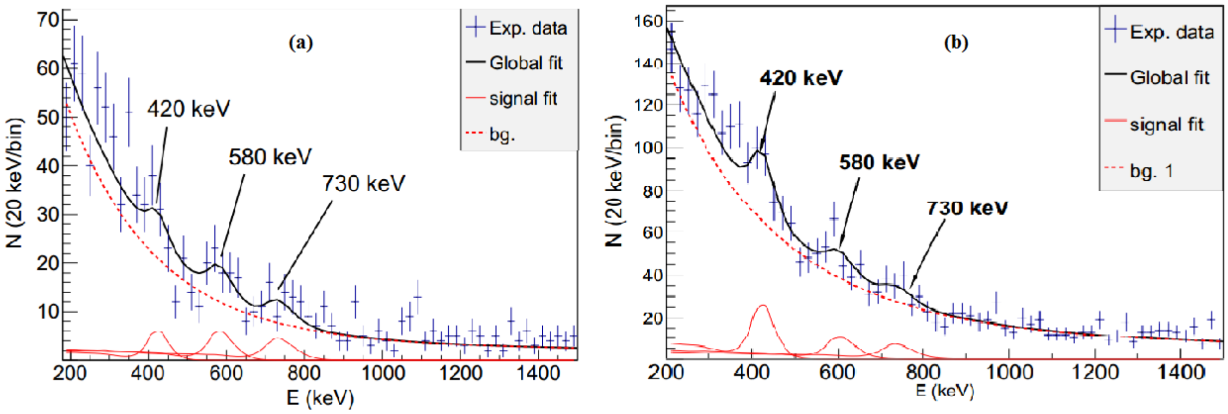

Figure 3. Doppler corrected spectra of ^{63}Cr populated from reaction channels ^{65}Mn(p,2pn)^{63}Cr (panel a) and ^{67}Mn(p,2p3n)^{63}Cr (panel b). Black are fitting curves. Red-smooth curves are the DALI2 simulating responses to the gamma energies indicated in the plot. Red- dash line is the background function.

The gamma spectra of ^{63}Cr populated from ^{65}Mn(p,2pn)^{63}Cr and ^{67}Mn(p,2p3n)^{63}Cr reactions are shown in Fig. 3. They contain the same 3 transitions at 420 and 580 and 730 keV. The gamma transition at 420 keV has been previously reported via beta decay of ^{63}V into ^{63}Cr [24].

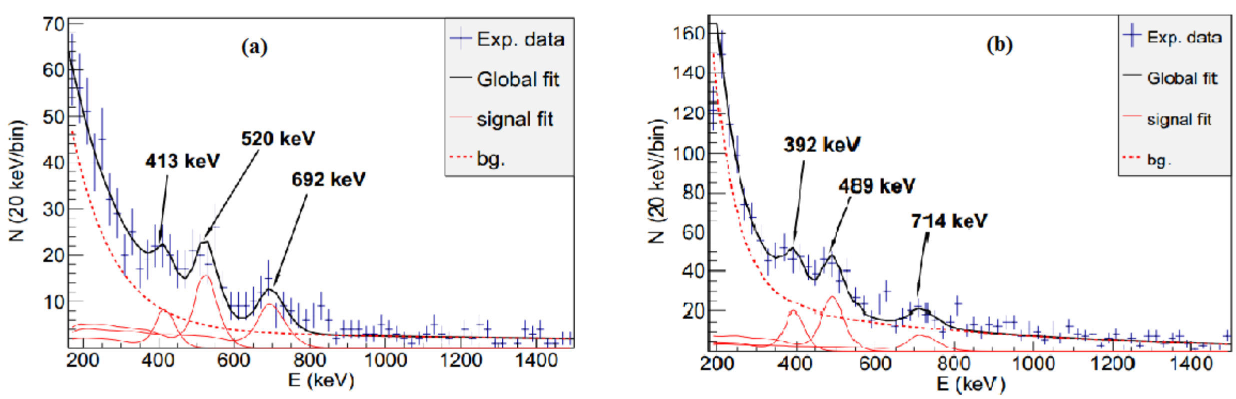

Figure 4. Doppler corrected spectra of ^{65}Cr populated from ^{66}Mn(p,2p)^{65}Cr (panel a) and ^{67}Mn(p,2pn)^{65}Cr (panel b). Black are fitting curves. Red-smooth curves are the DALI2 simulating responses to the gamma energies indicated in the plot. Red- dash line is the background function.

The gamma spectra of ^{63}Cr populated from *^{66}Mn(p,2p)^{65}Cr and ^{67}Mn(p,2pn)^{65}Cr* reactions are presented in Fig. 4. Gamma transitions at 413, 520 and 692 keV are observed in (p,2p) reaction. Meanwhile, the transitions at 392, 489 and 714 keV are observed in (p,2pn) reaction.

IV. Conclusion

This work presents an overview of the SEASTAR experimental setup and preliminary results of data analysis including the PID at BigRIPS /ZeroDegree and gamma spectra of $^{63, 65}$Cr. Based on the analysis gamma spectrum, new transitions of these nuclei were observed. Besides that, the PID principle at the BigRIPS/ZeroDegree and the operation of MINOS and DALI2 were presented.

In the next step, the theoretical predictions for $^{65, 65}$Cr structures should be performed in order to interpret the experimental results. This is also used to place the observed transitions in the level scheme of these nuclei.

The Vietnamese authors would like to thank MOST for the support under Grant Nos. ĐTCB 09/17/VKHKTHN.

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PHỔ GAMMA PHÁT XẠ TRÊN ĐƯỜNG BAY CỦA $^{63, 65}$Cr

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Tóm tắt: Các hạt nhân không bền giàu neutron ^{63,65}Cr được tạo ra trên hệ thống RIBF của viện nghiên cứu RIKEN trong chiến dịch thí nghiệm thứ nhất của dự án nghiên cứu cấu trúc các hạt nhân giàu neutron (SEASTAR). Trong báo cáo này, kết quả ban đầu về phổ gamma tức thời của các hạt nhân ^{63,65}Cr cũng như chi tiết về cấu hình thí nghiệm và phương pháp nhận diện hạt của dự án SEASTAR được trình bày. Thông qua phân tích, chúng tôi quan sát được các chuyển dời gamma có năng lượng 420, 580 và 730 keV của ^{63}Cr, 392 và 489, 720 keV của ^{65}Cr. Đây là các kết quả thực nghiệm đầu tiên của các hạt nhân này.

Từ khóa: *SEASTAR, ^{63}Cr, ^{65}Cr, nhận diện hạt.*