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Isospin symmetry investigation of the proton-unbound nucleus $T = 3/2$ ^{55}Cu

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A B S T R A C T

This study reports the status of the first in-beam γ-ray spectroscopic study of excited states in the exotic neutron-deficient T_z =-3/2 nucleus ^{55}Cu. The nucleus was produced via knock-out reactions at the Radioactive Isotope Beam Factory, located at the RIKEN-Nishina Center. Several γ-ray transitions were detected using the DALI2$^+$ γ-ray detector array. The comparison with isobaric analogue states in the mirror nucleus ^{55}Fe will provide valuable insights into isospin-non-conserving effects beyond nuclear stability. The proton occupation of the $1p_{3/2}$ orbital is expected to play a significant effect on the orbital's charge radius due to the isovector monopole polarizability, which can be linked to the measured mirror energy differences.

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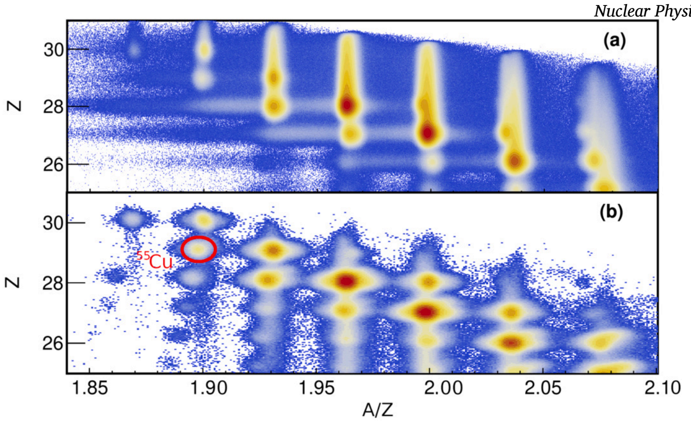

Fig. 1. Particle identification (PID) spectra for secondary beam ions (a) and reaction products (b). In the bottom panel, the recoil of interest ^{55}Cu is highlighted in red. The event-by-event identification of particles detected through the beam line allows the correlation between ions in the secondary beam and their reaction products. As a result, a selection of the nucleus of interest in the PID spectrum of the ZeroDegree spectrometer can be used to identify the isotopes in the secondary beam that impinged in the target and produce it. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

1. Introduction

Isospin symmetry is a key concept in nuclear physics [1]. It can offer insights into exotic nuclei by applying knowledge from systems near stability. The symmetry is broken by the electromagnetic interaction, leading to Coulomb energy differences (CED) of several tens of keV [2]. The breaking of isospin symmetry and its effects on nuclear structure can be inferred by comparing excitation energy differences in isobaric analog states (IAS) in mirror nuclei. Over the past few decades, studies of mirror energy differences (MED) have provided valuable insights into nuclear structure phenomena as a function of angular momentum.

In addition to Coulomb effects, the systematic study of energy differences of IAS has revealed the asymmetry between proton-proton (V_{pp}) and neutron-neutron (V_{nn}) interactions when coupled to angular momentum $J = 0$ or $J = 2$. The reduction in the $J = 0$ V_{pp} diagonal matrix element of ≈ -70 keV provides the best predictions for mirror nuclei in the $0f_{7/2}$ shell [3]. This isospin non-conserving (INC) contribution, denoted as V_B, has been consistently used across various MED studies, demonstrating significant predictive accuracy in the $0f_{7/2}$ shell.

Recent research on $T = 2$ mirror nuclei, including the pairs ^{56}Zn/^{56}Fe and ^{62}Ge/^{62}Zn [4,5], has shown the impact of the $1p_{3/2}$ orbital occupation, particularly its larger spatial extent compared to the $0f_{7/2}$ orbital, affecting Coulomb repulsion and resulting in a residual monopole contribution to the MED. This radial correction to the MED is sensitive to particle occupation variations in p orbitals, with isovector polarization effects reducing the radii of low-ℓ orbits when occupied by one or more particles.

With the advent of exotic beams, it is now possible to extend these studies further from stability, where INC effects are more pronounced. This work aims to investigate the nuclear structure of the proton-unbound T_z =-3/2 nucleus ^{55}Cu, populated through different reactions. The comparison of IAS energies for the $A = 55$ mirror nuclei offers new opportunities to explore nuclear structure further from stability.

2. Experiment

The experiment took place at the Radioactive Isotope Beam Factory (RIBF) at the RIKEN-Nishina Center (Japan), where a 345 MeV/A ^{78}Kr beam was fragmented on a ^{9}Be target. The resulting reaction products were separated and identified using the BigRIPS separator [6], ensuring precise identification of the secondary beam via the TOF-Bρ-ΔE method [7]. This secondary beam is transmitted to another ^{9}Be beryllium target. Knock-out and inelastic reactions contribute to the formation of the ^{55}Cu nucleus of interest. The γ radiation emitted at this stage was detected using the DALI2^{+} NaI(Tl) detector array [8,9]. Calibration and Doppler-correction accuracies were confirmed using known γ-ray transitions from other isotopes. The γ-ray spectra are analyzed by comparison with Monte Carlo simulations using the Geant4 toolkit [10], to estimate the energies and intensities of the detected transitions. Systematic uncertainties related to calibration and lifetimes of the detected radiation are included in the estimates of the γ-ray energies. The final identification of the reaction products is performed by the ZeroDegree spectrometer. The event-by-event-based identification of beam particles (panel (a)) and reaction products (panel (b)) is illustrated in Fig. 1. Special emphasis is placed on ^{55}Cu observed in the exit channel, highlighted by the red circle.

3. Preliminary results and discussion

By analyzing the event-by-event correlation of radioactive-ion beam particles impinging on the target and their corresponding reaction products, it becomes possible to determine which reactions contribute to populating the nucleus of interest, ^{55}Cu. In this case, the knock-out of a neutron from ^{56}Cu is identified as the dominant channel for producing ^{55}Cu. Several distinct γ rays originating from excited states in ^{55}Cu were observed following this reaction. To trace the origin of these transitions and reconstruct the excitation

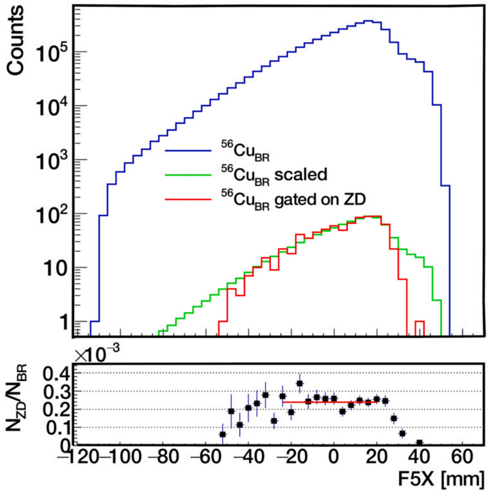

Fig. 2. Momentum distributions at the BigRIPS focal point denoted F5X for the incoming ^{56}Cu ions (blue) and for the same ^{56}Cu projectiles, but with the additional condition of detecting ^{55}Cu in the ZeroDegree spectrometer (red). The blue distribution (^{56}Cu in BigRIPS) is displayed also in green after being scaled to match the red one. The bottom panel reports the ratio between the red and blue distributions, which is proportional to the reaction (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

pattern of the $T_z = -3/2$ nucleus, a comparison with well-known γ-ray transitions in its mirror nucleus ^{55}Fe [11] and shell-model calculations can be employed. Additionally, based on the reaction dynamics, it is anticipated that the low-lying yrast states will be primarily populated.

From the reconstructed γ-ray spectrum and the measured γ-ray intensities, the direct feeding of the excited states populated in ^{55}Cu can be evaluated. Experimentally, σ_{exc} can be estimated as

$$\sigma_{exc}(J^{\pi}) = \frac{(\sum_i I(J^{\pi} \rightarrow J_i) - \sum_j I(J_j \rightarrow J^{\pi}))}{N_{out}} \sigma_{inc} \tag{1}$$

where i runs over all the existing branchings de-exciting the state of interest and j accounts for all the γ rays directly feeding it, while N_{out} represents ^{55}Cu ions detected in the ZeroDegree spectrometer after the reaction. To estimate the reaction cross section, $\sigma_{inc} \propto \frac{N_{ZeroDegree}(^{55}Cu)}{N_{BigRIPS}(^{56}Cu)}$, we evaluated the transmission of ions through the beam line, accounting for losses due to the magnetic settings in BigRIPS and the acceptance of the ZeroDegree spectrometer, as well as interactions within the target. The resulting transmission factor was applied to adjust the measured counts of the outgoing ^{55}Cu reaction product, enabling the determination of an inclusive cross-section for the neutron knock-out reaction from ^{56}Cu. An overall efficiency of 78(1)% is obtained for transmission of ^{55}Cu in the beam line and through the target material. Fig. 2 compares the momentum profiles of ^{56}Cu beam ions and that of the ^{55}Cu ions produced from the knock-out of a neutron from ^{56}Cu. The ratio of these two distributions is displayed in the bottom panel of Fig. 2. It is proportional to σ_{inc}.

Inclusive and exclusive cross sections can be compared to theoretical predictions using Eikonal reaction theory and shell-model spectroscopic factors. A systematic study of one-neutron and one-proton knock-out cross sections in well-bound nuclei revealed a consistent reduction in experimental reaction cross sections compared to theoretical estimates, as noted in Ref. [12]. For both one-neutron and one-proton knock-out reactions, significant discrepancies between measured and predicted values were observed, with the reduction increasing with the asymmetry between the proton and neutron numbers in the projectile. In this context, the valence proton in ^{56}Cu is bound by only a few hundred keV, $S_p = 583(6)$ keV [13], while its neighbor ^{55}Cu is proton unbound in its ground state [13]. This makes the study of ^{55}Cu particularly relevant for comparisons with existing trends and provides insights into the behavior of nuclei near the proton drip line. Additionally, inelastic excitations and proton knock-out from ^{56}Zn also populated states in ^{55}Cu, although the latter one occurred with limited statistics.

The reconstructed level scheme of ^{55}Cu can be compared with that of the mirror nucleus ^{55}Fe to extract the MED. These MED can be compared with shell-model predictions, which have previously demonstrated the ability to accurately reproduce experimental data in the fp and sd shells [3,4,14–16]. For ^{55}Cu, we anticipate a non-zero contribution from a residual monopole interaction to play a significant role in the MED reproduction, as noted in previous studies [4,5,17,19]. This effect is expected to arise from the halo-like nature of low-ℓ orbits [18], which, in our case, involves the p orbits. This characteristic enhances the impact of the residual monopole interaction, contributing to the observed deviations in the MED.

4. Summary

We present some preliminary results of the first γ-ray spectroscopic study of the proton-unbound isotope ^{55}Cu. By employing a highly intense primary radioactive ion beam, we successfully probed the T_z =-3/2 nucleus through multiple reaction channels.

This approach facilitated the observation of several excited states, allowing for a more comprehensive understanding of this exotic nucleus.

In ^{55}Cu, studied through neutron knock-out from ^{56}Cu, several γ rays from excited states were observed, shedding light on its nuclear structure. By comparing the measured experimental cross sections with theoretical predictions, we aim to gain a deeper understanding of nuclear structure and reactions near the proton drip line. This comparison will shed light on the behavior of nuclei in this region, where discrepancies between theory and experiment can reveal important insights into nuclear dynamics and correlations.

CRediT authorship contribution statement

S. Pigliapoco: Data curation, Formal analysis, Conceptualization, Writing – original draft, Writing – review & editing. **M.L. Cortés:** Supervision, Writing – review & editing, Investigation. **F. Recchia:** Supervision, Conceptualization, Writing – review & editing, Investigation. **S.M. Lenzi:** Project administration, Conceptualization, Methodology, Writing – review & editing, Investigation. **M.A. Bentley:** Project administration, Conceptualization, Investigation. **P. Doornenbal:** Project administration, Conceptualization, Writing – review & editing, Investigation. **A. Jungclaus:** Investigation. **K. Wimmer:** Investigation. **L. Zago:** Formal analysis. **D. Rudolph:** Writing – review & editing, Investigation. **F. Browne:** Investigation. **T. Koiwai:** Investigation. **H. Sakurai:** Investigation. **T. Arici:** Investigation. **A. Fernández:** Investigation. **J.A. Tostevin:** Methodology, Investigation. **N. Imai:** Investigation. **N. Kitamura:** Investigation. **B. Longfellow:** Writing – review & editing, Investigation. **R. Lozeva:** Investigation. **B. Mauss:** Investigation. **D.R. Napoli:** Investigation. **M. Niikura:** Investigation. **J. Periera Lopez:** Investigation. **P. Ruotsalainen:** Investigation. **R. Taniuchi:** Investigation. **S. Uthayakumaar:** Writing – review & editing, Investigation. **V. Vaquero:** Investigation. **R. Wadsworth:** Investigation. **R. Yajzey:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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