Proc. 13th Int. Conf. on Nucleus-Nucleus Collisions
JPS Conf. Proc. **32**, 010047 (2020)
https://doi.org/10.7566/JPSCP.32.010047

Magnetic moment of the isomeric state of ^{75}Cu measured with a highly spin-aligned beam

Yuichi Ichikawa[1], Hiroki Nishibata[1,2], Yusuke Tsunoda[3], Aiko Takamine[1], Kei Imamura[1,4], Tomomi Fujita[1,2], Tomoya Sato[1,5], Satoru Momiyama[6], Yohei Shimizu[1], Deuksoon Ahn[1], Koichiro Asahi[1,5], Hidetada Baba[1], Dimiter L. Balabanski[1,7], Florent Boulay[1,8,9], Jean-Michel Daugas[1,8], Tsuyoshi Egami[10], Naoki Fukuda[1], Chikako Funayama[5], Takeshi Furukawa[11], Georgi Georgiev[12], Aleksey Gladkov[1,13], Naoto Inabe[1], Yoko Ishibashi[1,14], Takafumi Kawaguchi[10], Takayuki Kawamura[2], Yoshio Kobayashi[15], Shuichiro Kojima[5], Asli Kusoglu[7,12,16], Ish Mukul[17], Megumi Niikura[6], Taishi Nishizaka[10], Atsuko Odahara[2], Yuichi Ohtomo[1,5], Takaharu Otsuka[1,3,6,18], Damian Ralet[12], Gary S. Simpson[19], Toshiyuki Sumikama[1], Hiroshi Suzuki[1], Hiroyuki Takeda[1], Longchun Tao[1,20], Yasuhiro Togano[5], Daiki Tominaga[10], Hideki Ueno[1], Hiroki Yamazaki[1] and Xiaofei Yang[18]

[1] *RIKEN Nishina Center for Accelerator-Based Science, Wako, Saitama, Japan*
[2] *Department of Physics, Osaka University, Toyonaka, Osaka, Japan*
[3] *Center for Nuclear Study, University of Tokyo, Bunkyo, Tokyo, Japan*
[4] *Department of Physics, Meiji University, Kawasaki, Kanagawa, Japan*
[5] *Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[6] *Department of Physics, University of Tokyo, Bunkyo, Tokyo, Japan*
[7] *ELI-NP, Horia Hulubei National Institute of Physics and Nuclear Engineering, Măgurele, Romania*
[8] *CEA, DAM, DIF, Arpajon, France*
[9] *GANIL, CEA/DSM-CNRS/IN2P3, Caen, France*
[10] *Department of Advanced Sciences, Hosei University, Koganei, Tokyo, Japan*
[11] *Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo, Japan*
[12] *CSNSM, CNRS-IN2P3, Université Paris-sud, Orsay, France*
[13] *Department of Physics, Kyungpook National University, Daegu, South Korea*
[14] *Department of Physics, University of Tsukuba, Tsukuba, Ibaraki, Japan*
[15] *Department of Informatics and Engineering, University of Electro-Communication, Chofu, Tokyo, Japan*
[16] *Department of Physics, Faculty of Science, Istanbul University, Istanbul, Turkey*
[17] *Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
[18] *Instituut voor Kern- en Stralingsfysica, K. U. Leuven, Leuven, Belgium*
[19] *LPSC, CNRS/IN2P3, Univerisité Grenoble Alpes, CNRS/IN2P3, INPG, Grenoble, France*
[20] *State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, Beijing, China*

E-mail: yuichikawa@riken.jp

(Received July 19, 2019)

The magnetic moment of the isomeric state of the neutron-rich ^{75}Cu nucleus was measured using a highly spin-aligned beam produced via a two-step reaction scheme. In the experiment carried out at the BigRIPS at RIBF, we achieved to produce spin alignment reaching 30% by employing the one-proton removal from ^{76}Zn to produce ^{75}Cu. In the magnetic moment measurement, a method of time-differential perturbed angular distribution (TDPAD) was employed. Precession of the isomeric state with spin parity of $3/2^-$ was clearly observed with significance larger than 5σ in the TDPAD spectrum. The magnetic moment of the isomeric state of ^{75}Cu was determined to be $\mu = 1.40(6)\mu_N$.

KEYWORDS: nuclear moment, spin, RI beam, . . .

The nuclear magnetic dipole moment is one of the fundamental observables a nucleus intrinsically has, and provides us key information about the proton and neutron configurations in the nucleus. In the study of nuclear structure through the measurement of the nuclear electromagnetic moments, a technique to produce spin orientation of rare-isotope (RI) beams has played important roles. Recently, a study of the structure of neutron-rich Cu isotopes from a measurement of the magnetic moment of an isomeric state of ^{75}Cu was reported [1], where a two-step reaction [2] was employed to produce spin alignment (rank-two orientation) in the RI beam of ^{75}Cu. This paper provides complementary experimental details, which were not presented in Ref. [1].

The two-step reaction scheme achieves high-spin alignment by utilizing a close relation existing between the angular momentum transferred to the fragment and the direction of the removed momentum [3] in the second reaction of projectile fragmentation (PF). At the same time, high production yields of RI beams are ensured by combining a technique of momentum-dispersion matching for the ion optics at the beam transportation. It has a clear advantage to produce spin alignment for RIs, for which the spin alignment would have tended to significantly attenuate if the conventional single-step PF reaction was employed. Ref. [2] demonstrated the production of 8% spin alignment in the isomeric state of ^{32}Al with a spin parity of $I^{\pi} = 4^{+}$ from the projectile of ^{48}Ca via ^{33}Al ($I^{\pi} = 5/2^{+}$).

The two-step reaction scheme to produce a highly spin-aligned RI beam was employed in the magnetic moment measurement of an isomeric state of a neutron-rich nucleus of ^{75}Cu. In the neutron-rich Cu isotopes, an intriguing shell evolution was reported, that the ground-state spin parity is changed from $3/2^{-}$ to $5/2^{-}$ at ^{75}Cu, as a result of the migration of the $5/2^{-}$ levels accompanied by the increase in the neutron number [4–6]. The ^{75}Cu nucleus has two isomeric states at 61.7 keV (^{75m1}Cu) and 66.2 keV (^{75m2}Cu) directly decaying to the ground state [7]. They are expected to have spin parities of either $I^{\pi} = 1/2^{-}$ or $3/2^{-}$, the latter of which is based on the ground state of ^{73}Cu. This work aims at measuring the magnetic moment of the $3/2^{-}$ isomeric state which is key to verifying the shell evolution from the viewpoint of the orbital configuration.

In this work, a new scheme of *j*-*I* correspondence was incorporated to the two-step reaction scheme, that the one-nucleon removal from the ground state of an even-even nucleus with spin parity of $I^{\pi} = 0^{+}$ was employed as the second PF reaction. When a proton occupying the $p_{3/2}$ orbital with angular momentum $j = 3/2$ is removed from the 0^{+} ground state of ^{76}Zn, a state with spin $I = 3/2$ ($= j$) in the final fragment of ^{75}Cu should be preferentially populated via a direct process, and the simple relation between the direction of spin and the kinematics maximizes the magnitude of spin alignment.

The experiment was carried out with the in-flight superconducting RI separator BigRIPS [8] at the RIKEN RIBF facility [9]. The RI beam of ^{75}Cu was produced in the process of the two-step reaction from a primary beam of ^{238}U via an intermediate product of ^{76}Zn, as shown in Fig. 1. In the reaction at F0, ^{76}Zn was produced by a fission reaction of a 345-MeV/nucleon ^{238}U beam on a ^{9}Be target with a thickness of 1.29 g/cm^2 chosen to provide a maximum production yield for the secondary ^{76}Zn beam. A wedge-shaped aluminium degrader with a mean thickness of 1.65 g/cm^2 was placed at the first momentum-dispersive focal plane F1.

The secondary ^{76}Zn beam was impinged on a second target of wedge-shaped aluminum with a mean thickness of 0.81 g/cm^2, placed at the momentum-dispersive focal plane F5. Here, the tertiary beam of ^{75}Cu was produced through a PF reaction of the one-proton removal from ^{76}Zn, that populated the isomeric states at the same time. The ^{75}Cu beam was subsequently transported to the double-achromatic focal plane F7 under the condition that the momentum dispersion between F5 and F7 was matched to that between F0 and F5. The momentum selection to produce the spin alignment was performed in the analysis using information from two parallel-plate avalanche counters (PPACs) placed at the double-achromatic focal plane F7. Only events where beam particles were detected within a horizontal region of ± 12 cm were analyzed.

The ^{75}Cu beam was introduced to an experimental apparatus for the time-differential perturbed angular distribution (TDPAD) measurements. The TDPAD apparatus consisted of an annealed Cu

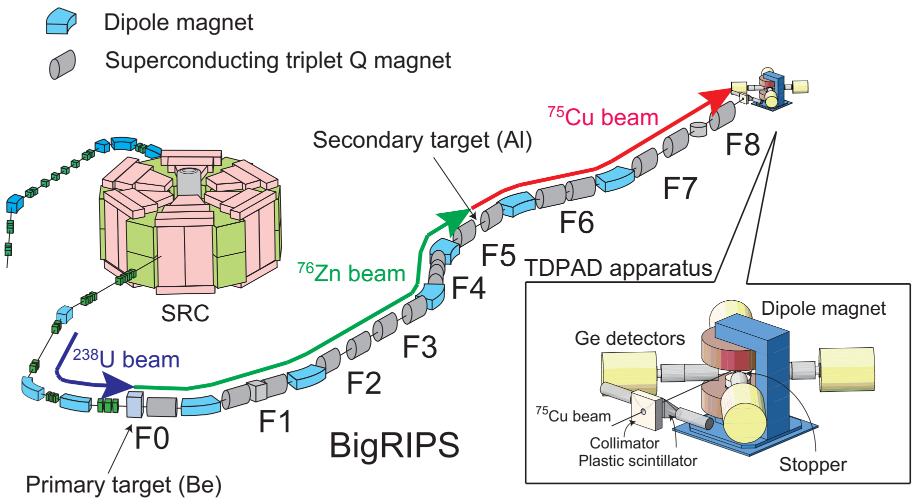

Fig. 1. Production of ^{75}Cu in the two-step reaction scheme along the BigRIPS beam line. A primary beam of ^{238}U was incident on a primary target located at F0. The projectile fragments were analyzed and selected in the BigRIPS beam line, where F1, F4, F5 and F6 are the momentum-dispersive focal planes and F2, F3 and F7 are the double-achromatic focal planes. In the present experiment, a second PF reaction producing ^{75}Cu from ^{76}Zn occurred at F5. The inset shows the apparatus used for the TDPAD experiment that was placed at F8.

crystal stopper, a dipole magnet, Ge detectors, a plastic scintillator and a collimator, as shown in the inset of Fig. 1. The Cu stopper has a thickness of 3.0 mm and an area of 30×30 mm^2, and the dipole magnet provided a static magnetic field of $B_0 = 0.200$ T. Emitted γ rays were detected with four Ge detectors located at a distance of 7.0 cm from the stopper and at angles of ±45° and ±135° with respect to the beam axis. Three of the four Ge detectors were planar-type ones and the remaining one was of coaxial type. The plastic scintillator has a thickness of 0.1 mm and was placed upstream of the stopper, the signal from which provides a time-zero trigger for the TDPAD measurement. The TDPAD apparatus enables us to determine the magnetic moment, by observing the changes in the anisotropy of the de-excitation γ rays, emitted from spin-aligned nuclei in synchronization with the spin precession in the presence of the external magnetic field.

The $R(t)$ ratio representing the change of anisotropy of γ rays synchronized with the spin precession is obtained according to

$$R(t) = \frac{N_{13}(t) - \epsilon N_{24}(t)}{N_{13}(t) + \epsilon N_{24}(t)}, \tag{1}$$

where $N_{13}(t)$ and $N_{24}(t)$ are the sums of the photo-peak count rates at the two pairs of Ge detectors placed diagonally to each other, and ϵ denotes a correction factor for the difference in the detection efficiency. Theoretically, $R(t)$ is also given as

$$R(t) = -\frac{3A_{22}}{4 + A_{22}} \sin(2\omega_{\rm L} t), \tag{2}$$

in terms of the rank-two anisotropy parameter $A_{22} = AB_2F_2$, where A denotes the degree of spin alignment, B_2 is the statistical tensor for complete alignment, and F_2 is the radiation parameter [10]. The rank-four and higher parameters are neglected in Eq. (2). The Larmor frequency $\omega_{\rm L}$ is given by $\omega_{\rm L} = g\mu_{\rm N}B_0/\hbar$, where g is the g-factor, $\mu_{\rm N}$ the nuclear magneton and $\hbar$ the reduced Planck constant.

In the present experiment, two γ rays with energies of 61.7 keV and 66.2 keV de-exciting the two isomeric states were observed. The $R(t)$ ratios for both γ rays were evaluated according to Eq. 1, and an oscillation pattern was observed only for the 66.2-keV γ ray, as shown in Fig. 2. As a result of the least χ^2 fitting of Eq. 2 to the experimental $R(t)$ ratios, the statistical significance of the oscillation

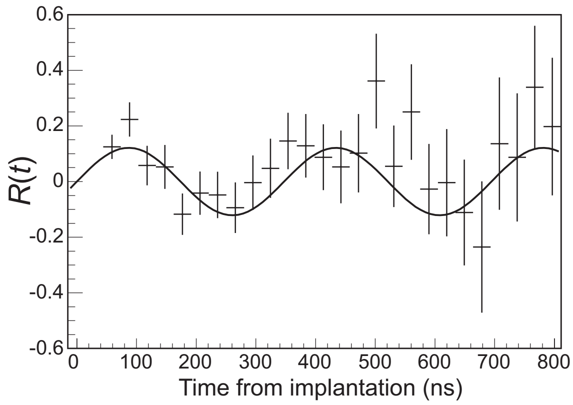

Fig. 2. $R(t)$ ratio deduced from $N_{13}(t)$ and N_{24}(t), according to Eq. 1, for the 66.2-keV γ rays. The solid line represents the theoretical $R(t)$ function in Eq. 2 after fitting the experimental $R(t)$ ratios.

for the 66.2-keV γ ray was found to be larger than 5σ, as $A_{22} = -0.17(3)$. The spin parity of the 66.2-keV level ($^{75\mathrm{m}2}$Cu) was fixed to be $I^{\pi} = 3/2^{-}$ from the clear observation of the oscillation in the $R(t)$ spectrum. On the other hand, the spin parity of the 61.7-keV level ($^{75\mathrm{m}1}$Cu), where no oscillation pattern was observed, is considered to be $I^{\pi} = 1/2^{-}$, because A_{22} in Eq. (2) is identically zero for the $I = 1/2$ system. The g-factor of the 66.2-keV isomer of ^{75}Cu was determined for the first time to be $g = 0.93(4)$, thus the magnetic moment, $\mu = gI\mu_{\mathrm{N}} = 1.40(6)\mu_{\mathrm{N}}$.

The degree of spin alignment produced for $^{75\mathrm{m}2}$Cu was found to be $A = 30(5)\%$, which was derived with $B_2F_2 = -0.602$ for a mixed M1 + E2 transition from the $3/2^{-}$ isomeric state at 66.2 keV to the $5/2^{-}$ ground state assuming a mixing ratio $\delta = 0.41$ [7]. The spin alignment obtained in this experiment, 30(5)%, is much larger than 8% obtained in the case of ^{32}Al [2], owing to the scheme of *j-I* correspondence, where there may be good overlapping between wave functions of a proton in the $p_{3/2}$ orbital removed from ^{76}Zn and a valence proton in the $3/2^{-}$ isomeric state of ^{75}Cu.

In summary, the magnetic moment of $^{75\mathrm{m}2}$Cu was measured at RIBF using a spin-aligned beam produced in the two-step reaction scheme incorporating *j-I* correspondence. Owing to high spin alignment of 30(5)%, the oscillation was clearly observed in the $R(t)$ spectrum for the 66.2-keV state with significance larger than 5σ. The spin parity of the 66.2-keV state was assigned as $3/2^{-}$ and the magnetic moment of this state was determined to be $\mu = 1.40(6)\mu_{\mathrm{N}}$. See Ref. [1] for discussion on nuclear structure based on this experimental value combined with theoretical shell-model calculations.

Experiments were performed under Program No. NP1412-RIBF124R1 at RIBF, operated by RIKEN Nishina Center and CNS, The University of Tokyo. We thank the RIKEN Ring Cyclotron staff for their cooperation during experiments. This work was partly supported by the JSPS KAKENHI (16K05390).

References

[1] Y. Ichikawa *et al.*, Nature Phys. **15**, 321 (2019).
[2] Y. Ichikawa *et al.*, Nature Phys. **8**, 918 (2012).
[3] K. Asahi *et al.*, Phys. Lett. B **251**, 488 (1990).
[4] K. T. Flanagan *et al.*, Phys. Rev. Lett. **103**, 142501 (2009).
[5] S. Franchoo *et al.*, Phys. Rev. Lett. **81**, 3100 (1998).
[6] T. Otsuka *et al.*, Phys. Rev. Lett. **104**, 012501 (2010).
[7] C. Petrone *et al.*, Phys. Rev. C **94**, 024319 (2016).
[8] T. Kubo, T., Nucl. Instrum. Meth. B **204**, 97 (2003).
[9] Y. Yano, Y., Nucl. Instrum. Meth. B **261**, 1009 (2007).
[10] H. Morinaga and T. Yamazaki, *In-Beam Gamma-Ray Spectroscopy.* (North-Holland, Amsterdam, 1976).