Magnetic moment of the 13/2+ isomeric state in Cu69: Spin alignment in the one-nucleon removal reaction

著者別名	小沢 顕
journal or publication title	Physical review C
volume	93
number	5
page range	054313
year	2016-05
権利	(C)2016 American Physical Society
URL	http://hdl.handle.net/2241/00143100

doi: 10.1103/PhysRevC.93.054313

Magnetic moment of the $13/2^+$ isomeric state in ^{69}Cu: Spin alignment in the one-nucleon removal reaction

A. Kusoglu,[1,2,*] G. Georgiev,[1] C. Sotty,[1,3] D. L. Balabanski,[4] A. Goasduff,[1,5] Y. Ishii,[6] Y. Abe,[7,8] K. Asahi,[6] M. Bostan,[2] R. Chevrier,[9] M. Chikamori,[6] J. M. Daugas,[9] T. Furukawa,[7,10] H. Nishibata,[11] Y. Ichikawa,[6,7] Y. Ishibashi,[7,8] R. Lozeva,[12] H. Miyatake,[6] D. Nagae,[7,8] T. Nanao,[6] M. Niikura,[13,14] T. Niwa,[8] S. Okada,[8] A. Ozawa,[8] Y. Saito,[8] H. Shirai,[6,7] H. Ueno,[7] D. T. Yordanov,[14,15] and N. Yoshida[6,7]

[1]*CSNSM, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France*
[2]*Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Fatih, 34134, Istanbul, Turkey*
[3]*Horia Hulubei National Institute for R&D in Physics and Engineering, 077125 Magurele, Romania*
[4]*ELI-NP, Horia Hulubei National Institute of Physics and Nuclear Engineering, 077125 Magurele, Romania*
[5]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*
[6]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[7]*RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*
[8]*Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan*
[9]*CEA, DAM, DIF, 91297 Arpajon cedex, France*
[10]*Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan*
[11]*Department of Physics, Osaka University, Osaka 560-0043, Japan*
[12]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, 23 rue du Loess F-67037 Strasbourg, France*
[13]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[14]*Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay, France*
[15]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*

(Received 29 October 2015; revised manuscript received 21 February 2016; published 10 May 2016)

We report on a new measurement of the g factor of the $(13/2^+)$ isomeric state in the neutron-rich nucleus ^{69}Cu. This study demonstrates the possibility of obtaining considerable nuclear spin alignment for multi-quasiparticle states in single-nucleon removal reactions. The time-dependent perturbed angular distribution (TDPAD) method was used to extract the gyromagnetic factor of the $(13/2^+)$ $[T_{1/2} = 351(14)$ ns] isomeric state of ^{69}Cu. Its g factor was obtained as $g(13/2^+) = 0.248(9)$. The experimentally observed spin alignment for the state of interest was deduced as $A = -3.3(9)\%$.

DOI: 10.1103/PhysRevC.93.054313

I. INTRODUCTION

Magnetic moment measurements of isomeric states provide valuable information on the composition of their nuclear wave functions. In the immediate vicinity of ^{68}Ni they can probe both the robustness of the $Z = 28$ shell closure as well as a possible enhancement of the $N = 40$ subshell gap. The nuclear structure in this region is not yet fully understood. Comparing ^{68}Ni to the doubly-magic ^{56}Ni it can be observed that it has high excitation energy of its first 2^+ state [1] and a very small $B(E2; 0^+ \rightarrow 2^+)$ transition probability [2]. Both those features could be considered as a signature of doubly-magic character. On the other hand, the two-neutron separation energies are quasiconstant around $N = 40$ [3,4] and do not show a kink, characteristic for a shell closure. Another possible explanation for the high 2^+ excitation energy in ^{68}Ni could be looked for in the parity change between the neutron pf orbitals (below $N = 40$) and $\nu g_{9/2}$ [2,3]. Even if the energy gap between those might be relatively small at least two neutrons need to be excited to $\nu g_{9/2}$ in order to obtain a positive parity state. The fragility of the $N = 40$ stabilization effect and its delicate influence on the structure around ^{68}Ni is supported by recent large-scale Monte Carlo shell-model calculations, which demonstrate the importance of the proton excitations across the $Z = 28$ shell gap [5,6] for the correct description of the nuclei in the region. Furthermore, adding or removing two or more protons leads to the disappearance of the magicity at $N = 40$ in the iron ($Z = 26$) and zinc ($Z = 30$) isotopes [7,8]. Studies of the properties of ^{69}Cu, a single proton above the ^{68}Ni core, should allow for an additional test of the $N = 40$ subshell closure. By measuring the g factor of the $(13/2^+)$ isomeric state in ^{69}Cu, and comparing it to large-scale shell-model calculations, we aimed at probing the purity of its wave function.

A number of nuclear-moment studies of exotic nuclei in the vicinity of shell closures have been performed using projectile fragmentation reactions [9–16]. Although the spin orientation in these reactions can be considered as well established, the amount of the orientation, especially as a function of the number of the removed nucleons, is still being investigated (see, e.g., [16]). In the present study we have used for the first time a single-nucleon removal reaction for the population of multi-quasiparticle state. In a previous measurement of the same $(13/2^+)$ isomer in ^{69}Cu [17] $[|g| = 0.225(25)]$ the state of interest was populated from the fragmentation of ^{76}Ge thus removing seven nucleons from the primary beam nucleus. In the same study a 300 μm Si detector, positioned

*Corresponding author: kusoglu@istanbul.edu.tr

a few millimeters upstream the implantation host, was kept constantly in the beam for an event-by-event ion identification. This resulted in a significant electron pick-up of the ions before their implantation. The interaction, in vacuum, of the randomly oriented electron spins $\boldsymbol{J}$ with the nuclear spin ensemble $\boldsymbol{I}$ causes a significant decrease of its orientation [18]. Therefore the amount of the experimentally observed spin orientation in that experiment is significantly lower, compared to that observed in a latter study [11].

II. EXPERIMENTAL DETAILS

In the present experiment, the ^{69}Cu nuclei were produced at RIKEN, Japan, by a single-proton removal from the primary beam. The ^{70}Zn beam, having an energy of 63.13 MeV/u and an intensity of $\sim$ 20 pnA, was impinging on a 101.46 mg/cm^2 ^{9}Be production target which was positioned at the entrance of the RIPS separator [19]. An Al achromatic wedge-shaped degrader of 84.99 mg/cm^2 was placed at the first focal plane (F1) of RIPS in order to select the fragments of interest. The purity of the secondary beam was further adjusted by specific slits openings at the second and third focal planes with typical values of ± 10 mm for F2 and ± 70 mm for F3. A Si detector was used for the beam identification, applying the standard ΔE vs time-of-flight technique. This detector was removed from the beam during the data taking and was replaced by a 50 μm thin plastic scintillator. This allowed to increase considerably the implantation rate without deterioration of the detector. More important the amount of fully stripped ions was increased to 98%. This plastic scintillator detector was used as well for providing the start $t = 0$ signal for the isomeric lifetime measurement.

The nuclear spin alignment depends strongly on the momentum distribution ($\Delta p/p$) of the secondary beam [9]. Therefore, in order to look for the optimum experimental conditions, we performed measurements at several different momentum-selection regions, denoted as A, B, C, D, and E in Fig. 1. The width of the momentum selection $\Delta p/p = \pm 0.15\%$ was set up by using the momentum slits on the first focal plane of RIPS by opening them to ± 3 mm (F1). As it can be observed from Fig. 1, the ^{69}Cu momentum distribution lies between two primary beam charge states, namely a fully stripped ($Q = 30^+$) and a hydrogen-like ($Q = 29^+$). The intensity of the fully stripped primary beam charge state, if fully transmitted up to the implantation point, is practically identical to the one at the production target ($\sim$ 20 pnA) and the intensity of the hydrogen-like charge state is one to two orders of magnitude less intense. Therefore during the secondary-beam tuning (using the Si detector) the momentum slits were set considerably narrower compared to the data-taking time, when the Si detector was replaced with the thin plastic scintillator. This did not allow us to get a quantitative figure for the beam purity in the specific experimental conditions.

Four coaxial HPGe detectors were used for detecting the γ ray of interest. Ion-γ coincidences were registered in a time interval of 2 μs with a start signal provided by the plastic scintillator and a stop signal from the Ge detectors. The isomeric γ rays of ^{69m}Cu were observed only for the C, D, and E momentum-selection regions. The ions of interest were

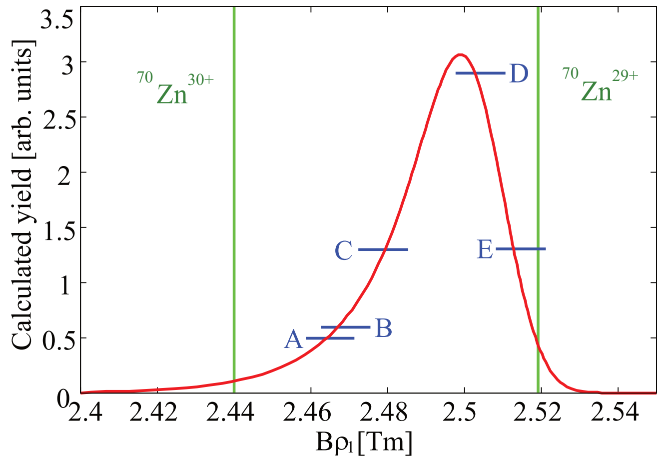

FIG. 1. Calculated momentum distribution of ^{69}Cu by the LISE++ program [20]. A(-1.30%), B(-1.19%), C(-0.80%), D($+0.16\%$), and E($+0.75\%$) correspond to the different momentum selections. The values in the brackets correspond to the central values of each momentum selection with respect to the center of the momentum distribution. The width of the momentum selection was 0.5% in each of the cases.

implanted in an annealed 1 mm thick Cu foil, positioned at the center of the set-up between the poles of an electromagnet, as illustrated on Fig. 2. An electromagnet provided an external magnetic field of 0.50(1) T in vertical direction pointing upwards at the Cu foil position. The four coaxial HPGe γ-ray detectors were placed in a horizontal plane (perpendicular to the magnetic field direction) at polar angles $\theta = \pm 135^\circ$ and $\theta = \pm 45^\circ$ with respect to the beam axis.

III. DATA ANALYSIS

The TDPAD method was used for the g-factor study of the ($13/2^+$) isomeric state in ^{69}Cu [21]. This technique is based on the measurement of the intensity variation of the γ rays as a function of time. That variation is directly related to the nuclear spin axis sweeping past the γ-ray detectors. Taking the intensity difference of two detectors, positioned at 90° with respect to each other in a plane perpendicular to the external magnetic field, and normalizing it to their sum gives

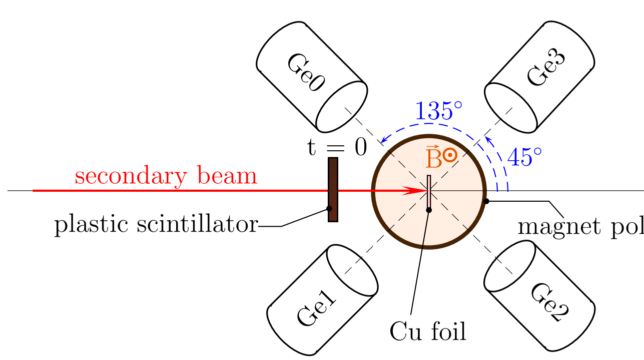

FIG. 2. Schematic drawing of the experimental arrangement of the TDPAD set-up.

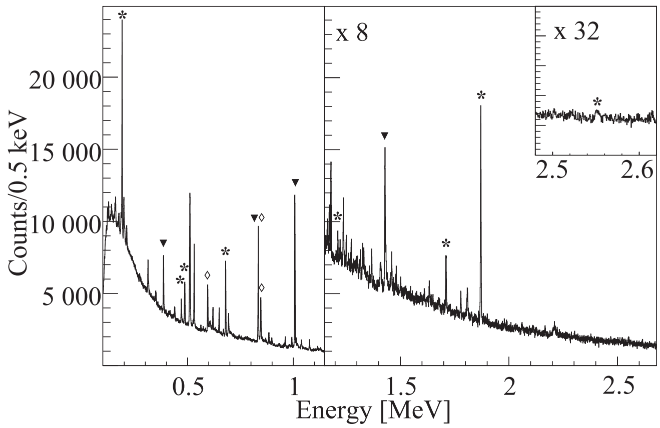

FIG. 3. Typical γ-ray energy spectrum in 160–1460 ns time window. Only the most intense γ lines are marked. The asterisks, the triangles, and the diamonds indicate, respectively, γ rays of ^{69m}Cu, contamination from β decay, (n,n') γ rays, or natural radioactivities γ rays.

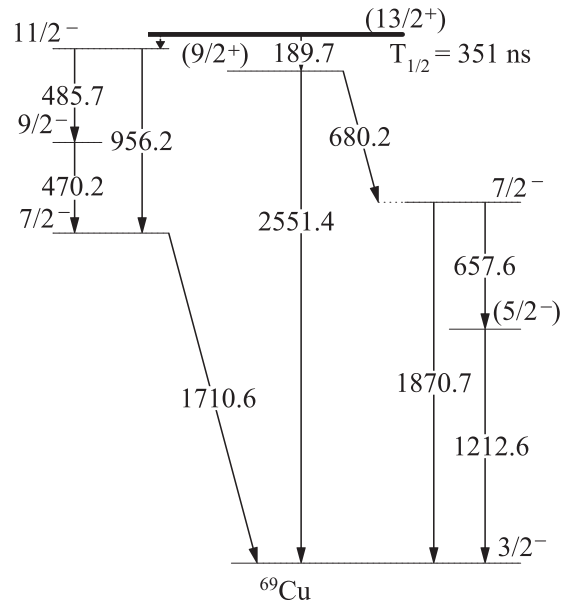

FIG. 4. Level scheme of ^{69}Cu below the $(13/2^+)$ isomeric state.

the standard $R(t)$ function [21]. It is defined as

$$R(t,\theta,\vec{B}) = \frac{I(t,\theta,\vec{B}) - \epsilon I(t,\theta+\pi/2,\vec{B})}{I(t,\theta,\vec{B}) + \epsilon I(t,\theta+\pi/2,\vec{B})} = \frac{3A_2B_2}{4+A_2B_2}\cos\{2(\theta-\vec{\omega}_L t-\alpha)\}, \quad (1)$$

where A_2 is the angular distribution coefficient, which depends on the nuclear spin of the state emitting the γ ray and the multipolarity of the emitted radiation; $\vec{\omega}_L = -(g\mu_N/\hbar)\vec{B}$ is the Larmor frequency; B_2 is the orientation parameter; θ is the angle between the beam axis and the detector position; and α is the rotation angle between the secondary beam direction and the symmetry axis of the spin-aligned ensemble at the implantation point. It can be expressed as $\alpha = -\theta_C(1-(gM/2Q))$ [17], where θ_C is the deviation angle of the secondary beam through the fragment separator ($\theta_C = -\pi/2$ in the specific case of RIPS), M is the mass number, and Q is the charge state of the ions.

The $R(t)$ function provides information both on the g factor of the state of interest (through the Larmor frequency) and on the degree of spin alignment A which is related to its amplitude. The spin alignment A can be calculated as

$$A = \frac{\sqrt{I(I+1)(2I+3)(2I-1)}}{\sqrt{5}|\alpha_2(\max)|}\frac{4R_{\rm amp}}{A_2(3-R_{\rm amp})}, \quad (2)$$

where $R_{\rm amp} = 3A_2B_2/(4+A_2B_2)$ is the oscillation amplitude and $\alpha_2(m) = I(I+1) - 3m^2$ is defined in such a way, that $-1 \leqslant A \leqslant 1$ [22]. For maximum oblate or prolate alignment, all nuclei are produced, respectively, in the lowest $m=0$ or $\pm 1/2$, or the highest $m = I$ substate. Thus, $\alpha_2(m)$ is described in Ref. [23].

A typical γ-ray energy spectrum obtained in the present experiment is shown in Fig. 3. The level scheme for the $(13/2^+)$ isomeric decay is displayed in Fig. 4 and the measured efficiency-corrected γ-ray intensities are presented in Table I. The 485.7-keV γ-ray transition was contaminated from the β decay of ^{71}Zn. The time spectrum which sums all decay transitions below the isomer in ^{69}Cu is shown in Fig. 5. The half-life of the isomer, considering statistical uncertainty only, was obtained as $T_{1/2} = 351(14)$ ns, which agrees well with a previous measurement [17].

Energy-gated time spectra were used to construct the experimental $R(t)$ functions for all decay transitions for different detector combinations as defined in Eq. (1). For the 189.7-keV transition, the observed oscillation phase is consistent with a pure $E2$ transition. It allows us to fix the multipolarity of this transition as listed in Table I. An $R(t)$ function with reasonable statistics was observed for the sum of the 189.7-keV and the 1710.6-keV $E2$ transitions for the HPGe detectors placed at $\theta = \pm 135^\circ$ [see Fig. 6(a)].

The g factor of the isomer of interest was obtained by fitting the experimental data (Fig. 6) with the theoretical curve [Eq. (1)] and applying a χ^2 minimization procedure. The oscillation amplitude ($R_{\rm amp}$) and the Larmor frequency

TABLE I. Levels and γ-ray transitions of ^{69}Cu below the $(13/2^+)$ isomeric state. The efficiency-corrected γ-ray intensities, I_γ, are normalized to the observed 189.7-keV isomeric transition. No conversion-electron corrections were taken into account. Spins and parities have been taken from Ref. [24].

E_{ex}(keV)	E_γ (keV)	$I_i^\pi \to I_f^\pi$	I_γ	Multipolarity
1212.6(3)	1212.6(3)	$(5/2^-) \to 3/2^-$	91(1)	$(M1)$
1710.6(2)	1710.6(2)	$7/2^- \to 3/2^-$	332(2)	$E2$
1870.7(2)	1870.7(2)	$7/2^- \to 3/2^-$	1328(2)	$E2$
	657.6(4)	$7/2^- \to (5/2^-)$	53(1)	$(M1)$
2180.8(1)	470.2(1)	$9/2^- \to 7/2^-$	341(1)	$M1$
2551.4(5)	2551.4(5)	$(9/2^+) \to 3/2^-$	38(3)	$(E3)$
	680.2(1)	$(9/2^+) \to 7/2^-$	1287(2)	$(E1)$
2666.8(4)	956.2(4)	$11/2^- \to 7/2^-$	120(2)	$E2$
	485.7(1)	$11/2^- \to 9/2^-$	590(1)	$M1$
2741.1(4)	189.7(1)	$(13/2^+) \to (9/2^+)$	1000(1)	$E2$

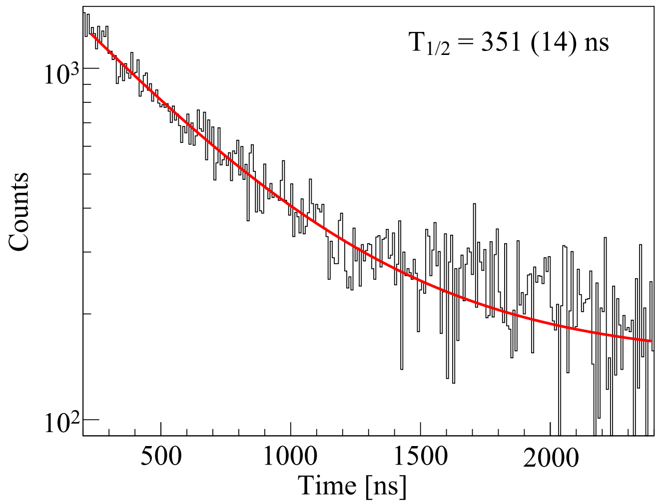

FIG. 5. Decay curve for the sum of all transitions below the $(13/2^+)$ isomeric state in ^{69}Cu.

$(\vec{\omega_L})$ were considered free parameters. The result obtained was $g(13/2^+) = +0.248 \pm 0.008$, where only statistical uncertainties are included. In addition systematic uncertainty of about 2% need to be added due to the variation of the magnetic field at the target position. As a result, the experimental g factor for the $g(13/2^+) = +0.248 \pm 0.008(\text{stat.}) \pm 0.005(\text{syst.})$ or $g(13/2^+) = +0.248(9)$ is deduced in the present measurement.

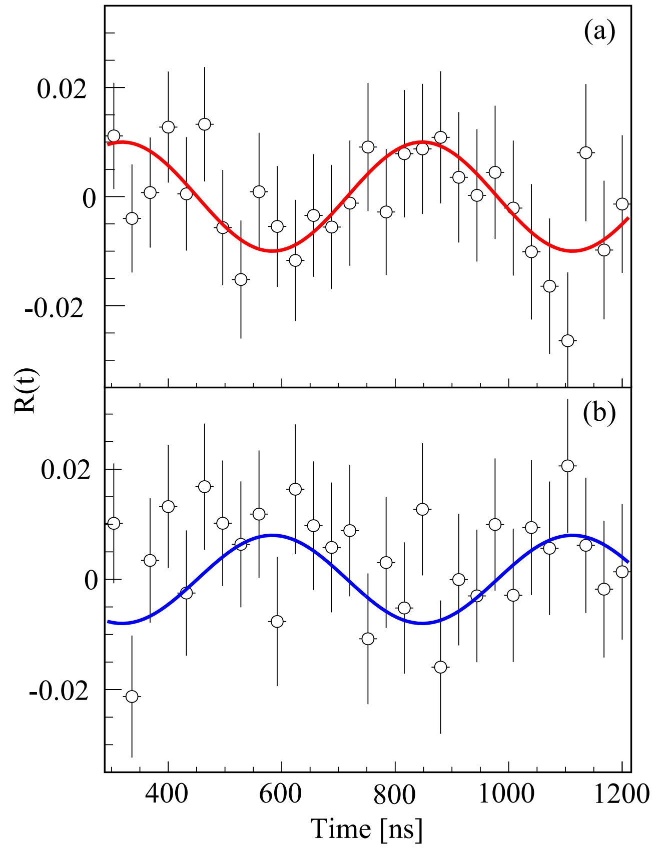

FIG. 6. $R(t)$ functions for (a) the sum of the $E2$ transitions and (b) the sum of $M1$ transitions following the decay of the $(13/2^+)$ isomer in ^{69}Cu for $\theta = \pm 135^\circ$detector combination.

IV. RESULTS AND DISCUSSION

The positive sign of the obtained g factor can be determined taking into account the sign dependence of the nuclear spin alignment as a function of the momentum distribution [9] and the $E2$ multipolarity of the isomeric 189.7-keV transition. It is in agreement with the large-scale shell-model calculations (see further). In Fig. 6(b), the $R(t)$ function for the sum of all $M1$ transitions is presented for the same detector combination as for the $E2$ transitions in Fig. 6(a). The signal-to-noise ratio is not sufficient to achieve a reliable fit based only on these data. However, the solid line drawn on the figure using the fit parameters of Fig. 6(a) demonstrates that the $R(t)$ function of the $M1$ transition has an opposite sign compared to that of the $E2$ transitions as expected.

The degree of spin alignment obtained in the single-nucleon removal reaction was deduced from the amplitude (R_{amp}) of the $R(t)$ function of the 189.7-keV γ-ray transition assuming a pure $E2$ transition ($A_2 = -0.3962$ [25]). From the deduced amplitude of the $R(t)$ function [$R_{\text{amp}} = 0.011(3)$] we could obtain a spin alignment of $A = -3.3(9)\%$ for ^{69}Cu. So far spin alignment in single-nucleon removal reaction has been measured only for the case of ^{12}C(^{13}C, ^{12}B) [26]. The value obtained in that measurement for the center of the momentum distribution, $A = 4.7(1.6)\%$, is in line with our present observations.

In order to compare our g-factor results to the theory, we performed shell-model calculations using the ANTOINE code [27,28]. The energy levels and electromagnetic moments were calculated using the JUN45 [29] and jj44b[1] [30] interactions. They are having the same model space, including $1f_{5/2}$, $2p_{1/2}$, $2p_{3/2}$, and $1g_{9/2}$, both for protons and for neutrons above a ^{56}Ni inert core. The calculated level scheme is presented in Fig. 7 and compared to the experimental one. The detailed structure of the ^{69}Cu is not precisely reproduced by either of the two interactions. In particular our calculations are unable to reproduce the positions of the $7/2^-$, $9/2^-$, and $11/2^-$ states which might arise from proton excitation across $Z = 28$. It has been shown that those excitations are of particular importance for the understanding of the structure of the $N = 40$ shell gap in ^{68}Ni [6]. In the present paper we will focus on the results obtained for the $(13/2^+)$ isomeric state observed at 2741 keV. A good agreement is obtained for the excitation energy using the JUN45 interaction with a theoretical value of 2731 keV, while with the jj44b interaction the theoretical value (2917 keV) is slightly above the experimental one. In the two calculations the wave function of the isomeric state

[1]The jj44b Hamiltonian was obtained from a fit to about 600 binding energies and excitation energies with a method similar to that used for the JUN45 Hamiltonian. Most of the energy data for the fit came from nuclei with $Z = 28$–30 and $N = 48$–50. With 30 linear combinations of the good J-T two-body matrix elements varied, the rms deviation between experiment and theory for the energies in the fit was about 250 keV.

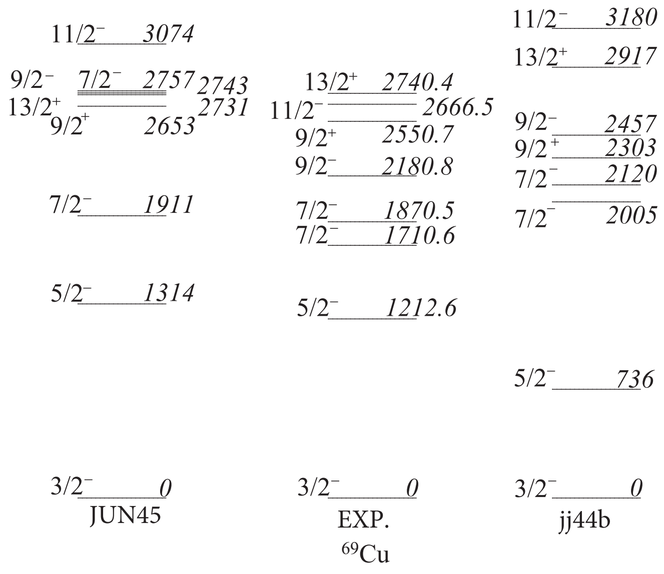

FIG. 7. Experimental levels of ^{69}Cu below the $(13/2^+)$ isomeric state compared to shell-model calculations using the JUN45 and jj44b interactions.

is dominated by two main components: $\pi p_{3/2}^1 \otimes \nu p_{1/2}^1 g_{9/2}^1$ (C1) and $\pi p_{3/2}^1 \otimes \nu f_{5/2}^4 p_{1/2}^1 g_{9/2}^3$ (C2). The total contribution of these two components corresponds to $\sim 55\%$ of the total wave function on average and varies between the JUN45 and jj44b interactions. In JUN45, the ratio C1/C2 is about 4.1 whereas with jj44b this ratio decreases to ∼1.7.

Two sets of g factors were used in the calculations of the magnetic dipole moment of the isomeric state. In the first one the standard free-nucleon g factors, $g_s^{\text{free}} = 5.586(-3.826)$ and $g_l^{\text{free}} = 1.0(0.0)$ were used for the protons (neutrons). For the second set the quenched effective g factors were used with $g_s^{\text{eff}} = 0.7 g_s^{\text{free}}$ and $g_l^{\text{eff}} = g_l^{\text{free}}$ for both protons and neutrons as suggested in Ref. [29]. The results are presented in Table II. All theoretical g factors are within three standard deviations from the experimental value. However, taking into account the small differences between the free-nucleon and effective g factors for the two interaction no clear preference can be given to either. In order to give a qualitative indication of the complexity of the wave function and the sensitivity of the g factors to the configuration mixing, we performed extreme single-particle calculations (no configuration mixing included) for the aforementioned C1 configuration. The values obtained $g_{\text{free}} = 0.387$ and $g_{\text{eff}} = 0.317$ differ considerably from the experimentally obtained g factor of the $(13/2^+)$ isomer in ^{69}Cu [$g_{\text{exp}} = 0.248(9)$]. This indicates that, although isomeric states next to shell closures are expected to have quite simple configurations, this clearly is not the case for the present three-quasiparticle isomer. The mixed configuration of the isomeric state reinforces the evidence that ^{68}Ni is not a good magic core.

TABLE II. Comparison between experimental and theoretical values for the g factor of the $(13/2^+)$ state in ^{69}Cu using the JUN45 and jj44b shell-model (SM) interactions.

Experiment	SM interaction	g^{free}	g^{eff}
+0.248(9)	JUN45	+0.261	+0.226
	jj44b	+0.274	+0.236

V. CONCLUSIONS AND OUTLOOK

In summary, we obtained a more precise measurement of the g factor of the $13/2^+$ isomer in ^{69}Cu, compared to a previous study [17]. We also demonstrated that a useful degree of nuclear spin alignment can be obtained in single-nucleon removal reactions even for multi-quasiparticle states. Shell-model calculations using the JUN45 and jj44b interactions both fall close to the measured g factor, indicating a mixed configuration with excitations across $N = 40$. For more detailed insight into the composition of the wave function from g-factor measurements in this region, it is evident that the choice of the effective $M1$ operator must first be considered because it can be as important as the choice of interaction. Such a study goes beyond the scope of the present work. It will require a detailed comparison of theoretical and experimental magnetic moments in the region. Another direction to explore, in order to get better understanding of the structure around ^{68}Ni, might be to evaluate the effect of proton excitations across the $Z = 28$ shell gap.

ACKNOWLEDGMENTS

The authors thank to RIKEN Nishina Center staff for their cooperation during the experiment. This work was supported by the 2214-TUBITAK (Scientific and Technological Research Council of Turkey) Programme, the Scientific Research Projects Coordination Unit of Istanbul University under Project No. 46811, P2IO (Physique des 2 Infinis et des Origines) laboratory of excellence, Kakenhi (22340071 and 20532089) by JSPS, the Japan-France Hubert Curien partnership PHC SAKURA2011 Project No. 23528UC implemented by the Japan Society for the Promotion of Science (JSPS), the French Ministère de l'Enseignement Superieur et de la Recherche (MESR) et des Affaires Etrangères et Européenes (MAEE), and French Japanese International Associated Laboratory. D.L.B. acknowledges support through the Extreme Light Infrastructure Nuclear Physics (ELI–NP)-Phase I, a project co-financed by the European Union through the European Regional Development Fund and research funded by Bulgarian National Science Fund, Contract No. DID-02/16.

[1] R. Broda, B. Fornal, W. Królas, T. Pawlat, D. Bazzacco, S. Lunardi, C. Rossi-Alvarez, R. Menegazzo, G. deAngelis, P. Bednarczyk, J. Rico, D. DeAcuna, P. J. Daly, R. H. Mayer, M. Sferrazza, H. Grawe, K. H. Maier, and R. Schubart, Phys. Rev. Lett. **74**, 868 (1995).

[2] O. Sorlin, S. Leenhardt, C. Donzaud, J. Duprat, F. Azaiez, F. Nowacki, H. Grawe, Zs. Dombrádi, F. Amorini, A. Astier, D. Baiborodin, M. Belleguic, C. Borcea, C. Bourgeois, D. M. Cullen, Z. Dlouhy, E. Dragulescu, M. Górska, S. Grévy, D. Guillemaud-Mueller, G. Hagemann, B. Herskind, J. Kiener,

R. Lemmon, M. Lewitowicz, S. M. Lukyanov, P. Mayet, F. de Oliveira Santos, D. Pantalica, Yu.-E. Penionzhkevich, F. Pougheon, A. Poves, N. Redon, M. G. Saint-Laurent, J. A. Scarpaci, G. Sletten, M. Stanoiu, O. Tarasov, and Ch. Theisen, Phys. Rev. Lett. **88**, 092501 (2002).

[3] H. Grawe *et al.*, Nucl. Phys. J. A **704**, 211 (2002).

[4] C. Guénaut, G. Audi, D. Beck, K. Blaum, G. Bollen, P. Delahaye, F. Herfurth, A. Kellerbauer, H.-J. Kluge, J. Libert, D. Lunney, S. Schwarz, L. Schweikhard, and C. Yazidjian, Phys. Rev. C **75**, 044303 (2007).

[5] N. Shimizu *et al.*, Prog. Theor. Exp. Phys. **2012**, 01A205 (2012).

[6] S. Suchyta, S. N. Liddick, Y. Tsunoda, T. Otsuka, M. B. Bennett, A. Chemey, M. Honma, N. Larson, C. J. Prokop, S. J. Quinn, N. Shimizu, A. Simon, A. Spyrou, V. Tripathi, Y. Utsuno, and J. M. Von Moss, Phys. Rev. C **89**, 021301(R) (2014).

[7] M. Hannawald, T. Kautzsch, A. Wöhr, W. B. Walters, K.-L. Kratz, V. N. Fedoseyev, V. I. Mishin, W. Böhmer, B. Pfeiffer, V. Sebastian, Y. Jading, U. Köster, J. Lettry, H. L. Ravn, and the ISOLDE Collaboration, Phys. Rev. Lett. **82**, 1391 (1999).

[8] I. Stefanescu, G. Georgiev, F. Ames, J. Äystö, D. L. Balabanski, G. Bollen, P. A. Butler, J. Cederkäll, N. Champault, T. Davinson, A. De Maesschalck, P. Delahaye, J. Eberth, D. Fedorov, V. N. Fedosseev, L. M. Fraile, S. Franchoo, K. Gladnishki, D. Habs, K. Heyde, M. Huyse, O. Ivanov, J. Iwanicki, J. Jolie, B. Jonson, T. Kröll, R. Krücken, O. Kester, U. Köster, A. Lagoyannis, L. Liljeby, G. Lo Bianco, B. A. Marsh, O. Niedermaier, T. Nilsson, M. Oinonen, G. Pascovici, P. Reiter, A. Saltarelli, H. Scheit, D. Schwalm, T. Sieber, N. Smirnova, J. Van De Walle, P. Van Duppen, S. Zemlyanoi, N. Warr, D. Weisshaar, and F. Wenander, Phys. Rev. Lett. **98**, 122701 (2007).

[9] K. Asahi, M. Ishihara, T. Ichihara, M. Fukuda, T. Kubo, Y. Gono, A. C. Mueller, R. Anne, D. Bazin, D. Guillemaud-Mueller, R. Bimbot, W. D. Schmidt-Ott, and J. Kasagi, Phys. Rev. C **43**, 456 (1991).

[10] W. D. Schmidt-Ott *et al.*, Z. Phys. A **350**, 215 (1994).

[11] I. Matea, G. Georgiev, J. M. Daugas, M. Hass, G. Neyens, R. Astabatyan, L. T. Baby, D. L. Balabanski, G. Bélier, D. Borremans, G. Goldring, H. Goutte, P. Himpe, M. Lewitowicz, S. Lukyanov, V. Méot, F. de Oliveira Santos,Y. E. Penionzhkevich, O. Roig, and M. Sawicka, Phys. Rev. Lett. **93**, 142503 (2004).

[12] N. Vermeulen, S. K. Chamoli, J. M. Daugas, M. Hass, D. L. Balabanski, J. P. Delaroche, F. de Oliveira-Santos, G. Georgiev, M. Girod, G. Goldring, H. Goutte, S. Grévy, I. Matea, P. Morel, B. S. NaraSingh, Y. E. Penionzkevich, L. Perrot, O. Perru, S. Péru, O. Roig, F. Sarazin, G. S. Simpson, Y. Sobolev, I. Stefan, C. Stodel, D. T. Yordanov, and G. Neyens, Phys. Rev. C **75**, 051302(R) (2007).

[13] L. Atanasova *et al.*, Europhys. Lett. **91**, 42001 (2010).

[14] L. Gaudefroy, J. M. Daugas, M. Hass, S. Grevy, C. Stodel, J. C. Thomas, L. Perrot, M. Girod, B. Rosse, J. C. Angelique, D. L. Balabanski, E. Fiori, C. Force, G. Georgiev, D. Kameda, V. Kumar, R. L. Lozeva, I. Matea, V. Meot, P. Morel, B. S. Nara Singh, F. Nowacki, and G. Simpson, Phys. Rev. Lett. **102**, 092501 (2009).

[15] R. Chevrier, J. M. Daugas, L. Gaudefroy, Y. Ichikawa, H. Ueno, M. Hass, H. Haas, S. Cottenier, N. Aoi, K. Asahi, D. L. Balabanski, N. Fukuda, T. Furukawa, G. Georgiev, H. Hayashi, H. Iijima, N. Inabe, T. Inoue, M. Ishihara, Y. Ishii, D. Kameda, T. Kubo, T. Nanao, G. Neyens, T. Ohnishi, M. M. Rajabali, K. Suzuki, H. Takeda, M. Tsuchiya, N. Vermeulen, H. Watanabe, and A. Yoshimi, Phys. Rev. Lett. **108**, 162501 (2012).

[16] Y. Ichikawa *et al.*, Nat. Phys. **8**, 918 (2012).

[17] G. Georgiev *et al.*, J. Phys. G **28**, 2993 (2002).

[18] K. Vyvey, G. Neyens, N. Coulier, R. Coussement, G. Georgiev, S. Ternier, S. Teughels, A. Lépine-Szily, and D. L. Balabanski, Phys. Rev. C **62**, 034317 (2000).

[19] T. Kubo *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 97 (2003).

[20] http://lise.nscl.msu.edu/lise.html

[21] G. Goldring and M. Hass, in *Treatise in Heavy Ion Sciences*, Vol. 3, edited by D. E. Bromley (Plenum Press, New York, 1985), p. 539.

[22] N. Coulier, G. Neyens, D. L. Balabanski, D. Borremans, R. Coussement, J. M. Daugas, G. Georgiev, S. Teughels, and K. Vyvey, Phys. Rev. C **63**, 054605 (2001).

[23] G. Neyens *et al.*, Rep. Prog. Phys. **66**, 633 (2003).

[24] C. D. Nesaraja *et al.*, Nucl. Data Sheets **115**, 1 (2014).

[25] E. Dafni *et al.*, At. Data Nucl. Data Tables **23**, 315 (1979).

[26] G. Neyens *et al.*, Phys. Lett. B **393**, 36 (1997).

[27] E. Caurier and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).

[28] E. Caurier *et al.*, Rev. Mod. Phys. **77**, 427 (2005).

[29] M. Honma, T. Otsuka, T. Mizusaki, and M. Hjorth-Jensen, Phys. Rev. C **80**, 064323 (2009).

[30] B. A. Brown (unpublished).