Coulomb excitation of the 3^- isomer in ^{70}Cu

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Post-accelerated isomerically purified radioactive beams, available at the CERN On-Line Isotope Mass Separator facility using the resonant ionization laser technique, have been used to study the Coulomb excitation of the $I^\pi = 3^-$ state in ^{70}Cu ($Z = 29$, $N = 41$). While first results using a $I^\pi = 6^-$ beam were reported previously, the present complementary experiment allows us to complete the study of the multiplet of states (3^-, 4^-, 5^-, 6^-) arising from the $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration. Besides the known γ-ray transition deexciting the 4^- state, a ground-state γ ray of 511(3) keV was observed for the first time and was unambiguously associated with the 5^- state deexcitation. This observation fixes the energy, spin, and parity of this state, completing the low-energy level scheme of ^{70}Cu. $B(E2)$ values for all possible $E2$ transitions within the multiplet were determined. A comparison with large-scale shell model calculations using different interactions and valence spaces shows the importance of proton excitation across the $Z = 28$ shell gap and the role of the $2d_{5/2}$ neutron orbital.

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I. INTRODUCTION

The study of the approximately doubly magic nucleus ^{68}Ni with $Z = 28$ and $N = 40$ and nuclei in its neighborhood has been subject to several experimental, e.g., Refs. [1–8], and theoretical papers, e.g., Refs. [9–11]. The key issues are the importance of neutron and/or proton excitation across the $N = 40$ and/or $Z = 28$ shells and possible changes in the effective interactions when changing the proton-to-neutron ratio. Large-scale shell-model (LSSM) calculations using different effective interactions and different model spaces have been performed and their results compared to ground- and

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isomeric-state properties (like masses and nuclear moments), energy level systematics, and transition probabilities. Recent studies clearly show the stabilizing effect of ^{68}Ni because the structure of its immediate neighbors can, to a large extent, be understood as a proton and/or a neutron coupled to a ^{68}Ni core. It has been shown, however, that when moving away from ^{68}Ni along the isotopic chain toward ^{78}Ni [12] or along the isotonic chain toward lighter Z [5,13], collectivity sets in rapidly.

In the odd-odd mass ^{68}Cu and ^{70}Cu nuclei, the coupling of a proton and a neutron (particle or hole) to ^{68}Ni leads to the existence of multiplets such as the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet that gives rise to different states with spin values from 3^- to 6^- and the $\pi 2p_{3/2}\nu 2p_{1/2}$ multiplet leading to 1^+, 2^+ states. The structure of these multiplets clearly results from a mixing of different proton-neutron configurations. According to the shell-model calculations presented in Ref. [3], however, the lowest 3^- to 6^- states in ^{70}Cu have a dominant $\pi 2p_{3/2}\nu 1g_{9/2}$ component, corresponding to more than 52% contribution in the total wave function. For this reason, in the rest of the text and for simplicity, we will refer to the 3^- to 6^- multiplet as belonging to this configuration.

These structures induce isomerism like the triplet of β-decaying states in ^{70}Cu as the most notorious example [2,3]. The other members of these multiplets in ^{68,70}Cu were tentatively identified using nucleon-transfer reactions [14], mass measurements, and β-decay studies [2,3]. These long-lived isomeric states were also investigated using laser spectroscopy [6,15], whereby the spin and parity were firmly fixed to 1^+, 3^-, and 6^- in the case of ^{70}Cu and 1^+ and 6^- in case of ^{68}Cu.

Thanks to recent developments in resonant-laser ionization and post-acceleration, energetic isomeric beams have been produced; and soon after, this opportunity was used to perform pioneering Coulomb excitation (Coulex) studies of the 6^- state in ^{68,70}Cu [4]. Coulex investigations are an important probe for nuclear-structure studies, as they provide information on electromagnetic ($E2$) transition rates between nuclear states, on energies, and, based on selection rules, on spin and parities of the excited levels. Especially the case of the odd-odd ^{70}Cu isotope, where the existence of several long-lived states at very low energies offers unique possibilities to perform Coulomb excitation within the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet starting from two different states, in particular the 6^- and 3^- states and to compare the results to shell-model calculations.

The measurement reported in Ref. [4] was performed with a 6^- laser-purified beam and revealed the prompt transition $4^- \to 3^-$ of 127 keV allowing the spin, parity, and relative position of the 3^-, 4^-, and 6^- members of the multiplet to be fixed. However, the information gathered in this first experiment was limited, mainly because the radioactive ion beam used consisted of a mixture of 6^- and 3^- long-lived states in the ^{70}Cu beam. For the estimation of the $B(E2; 6^- \to 4^-)$ value in ^{70}Cu, the population of the $I^\pi = 4^-$ level through an $E2/M1$ excitation of the 3^- contaminant needed to be considered. The incomplete experimental information did not allow for the determination of both the reduced transition matrix elements involved in the excitation of the 4^- state. Therefore a relative ratio of $\langle 6^- || E2 || 4^- \rangle = 0.94 \langle 3^- || E2 || 4^- \rangle$ was assumed based on an extreme single-particle model describing the 3^-, 4^-, 5^-, and 6^- levels as a pure $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration. With this assumption, a value of $41(5) e^2$ fm^4 [2.4(3) W.u.] for the reduced transition probability $B(E2; 6^- \to 4^-)$ was estimated. Second, the population of the 5^- state of the multiplet that was proposed at an excitation energy of 506(6) keV above the 6^- ground state [3,14] was not observed in that experiment, preventing the investigation of this state.

To provide this crucial information about the energy levels and reduced $E2$ transition probabilities for all the connecting transitions between the states of the (3^- - 6^-) multiplet, a new Coulomb excitation experiment was performed with a ^{70}Cu beam whose intensity was enhanced in the 3^- isomeric state. Also in this case, the beam of interest was tainted with the other isomers. However, by combining the data from the two Coulex experiments on ^{70}Cu, the intrinsic imprecision due to the isomeric impurity of the beam could be overcome.

In this paper we report on the new results obtained by the comparative analysis of the two data sets that allows the features of the low-energy states of ^{70}Cu to be completed. Moreover, in the last years, developments in the procedure and tools for the data analysis have been carried out. These improvements mainly determine adjustments on the γ-peak integrals analysis and on the kinematic cuts to distinguish projectile and target detection. The set of data reported in Ref. [4] have been therefore reanalyzed on the basis of the new analysis procedure, and more reliable values have been extracted. This also ensures that the data acquired in the two ^{70}Cu experiments are treated coherently. A detailed description of the analysis procedure can be found in Ref. [16].

II. EXPERIMENTAL SETUP

The ^{70}Cu radioactive ion beam was produced at CERN On-Line Isotope Mass Separator (ISOLDE) facility by combining the 1.4 GeV proton induced fission in a 45 g/cm^2 UC$_x$ target with the resonant ionization laser ion source (RILIS). The isomeric beams were produced in a similar way as in Refs. [2–4,15], where narrow-band laser scans provided the optimum values of the laser frequency that maximize the ionization of the different isomers [17]. The 6^- and 3^- beams of ^{70}Cu, post-accelerated by the radioactive beam experiment (REX) at ISOLDE [18] up to 2.8 MeV/nucleon, were used to bombard a ^{120}Sn 2.3 mg/cm^2 target inducing Coulomb excitation. Typical total ^{70}Cu beam intensities at the detection setup were on the order of 10^4–10^5 pps. The experimental setup used in the present work is identical to the one described in Refs. [4,16]. γ rays following the deexcitation of the levels populated by Coulomb excitation were detected by the MINIBALL HPGe array [19], while the scattered projectile and recoiling target nuclei were detected in an annular Compact Disk (CD)-shaped double-sided silicon strip detector [20].

Experiments with radioactive ion beams often suffer from the contamination of the beam of interest with other isobars and, in this particular case, isomers. Because the $B(E2)$ values of the transition of interest are determined relative to the known $B(E2)$ values of the transitions observed after excitation of the

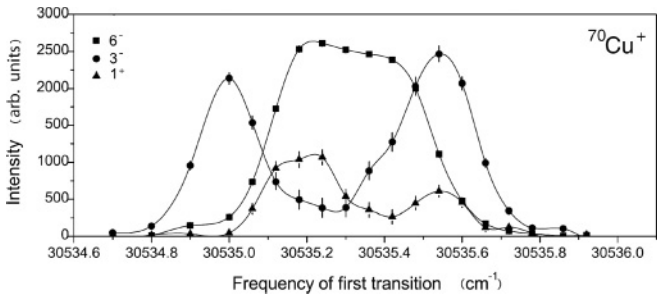

FIG. 1. Intensity of the characteristic γ-decay lines of the three long-lived states of ^{70}Cu as a function of the laser frequency. Note that the γ intensity was multiplied with different factors for the different states. The figure is taken from Ref. [2].

target nucleus (in this case ^{120}Sn), the beam composition is a crucial parameter in the normalization to the target excitation [16].

The isobaric contamination due to gallium was determined as described in Refs. [4,16] by comparing measurements with laser ON and laser OFF. Values of 30(3)% Ga contamination were found in the ^{70}Cu beam when the lasers were tuned to the $I^\pi = 6^-$, while 50(3)% Ga contamination was obtained when the lasers were tuned to the $I^\pi = 3^-$ beam. In the latter case, measurements were performed in laser ON/OFF mode throughout the whole running period. By switching the selective laser ionization periodically ON and OFF on each supercycle of the accelerator chain corresponding to a typical periodicity of 50 s, the observed $2^+ \rightarrow 0^+$ γ transitions in ^{120}Sn, coming from target excitation induced by the gallium beam, could be subtracted in a reliable way. In the former case, the experiment with the 6^- enhanced beam, the excitation induced by the gallium was determined as described in Ref. [16] by considering the ratio of scattered particles detected in laser ON and laser OFF separated runs.

The isomeric beam contamination stemmed from the broadening of the hyperfine-split resonances of each isomer [2,3,15,21], as clearly shown in Fig. 1 taken from Ref. [2]. The characteristic γ rays from the β decay of the three long-lived states that were detected in the MINIBALL germanium array during the off-beam periods [16], allowed us to determine the isomeric content of the beam. The analysis showed that when the laser was tuned to the maximum production of the 6^- beam, 85(5)% of the total ^{70}Cu ion yield was produced in this spin state, while the (3^-,1^+) isomers were found to contribute almost equal amounts ($\approx$7%) to the total Cu beam. Similarly, when the laser was tuned to the maximum production of the 3^- beam, the isomeric composition was found to be 74(7)% and 25(3)% in the 6^- and 3^- states, respectively, with the contribution of the 1^+ isomer less than 1%. Information about the isobaric and isomeric composition of the two ^{70}Cu beams is reported in Table I. For simplicity, the two experiments are referred to as the 6^- and 3^- experiment, hereafter.

III. DATA ANALYSIS

The particle–γ-ray coincidence spectrum acquired after 29 h of ^{70}Cu(3^-) beam on target is presented in Fig. 2(a).

TABLE I. Main characteristics of the ^{70}Cu isomeric beams.

Beam	Energy (MeV/A)	Intensity (pps)	Cu/tot (%)	Isomeric composition (%)		
				6^-/Cu	3^-/Cu	1^+/Cu
^{70}Cu (6^-)	2.83	5×10^4	70(5)	85(5)	7(2)	7(3)
^{70}Cu (3^-)	2.85	9×10^4	50(3)	74(7)	25(3)	< 1

Figure 2(b) shows the same spectrum acquired after 28 h of ^{70}Cu(6^-) beam and already reported in Ref. [4]. Both spectra are Doppler corrected for mass $A = 70$ and random subtracted. It should be noted that the well-known $2^+ \rightarrow 1^+$ transition in ^{70}Ga of 508 keV has been carefully subtracted from the top spectrum by means of laser ON/OFF runs.

Comparing the two spectra clearly shows evidence that in the 3^- experiment a new transition at 511(3) keV was observed that was not present in the 6^- experiment. A state at 506(6) keV appeared strongly populated in the (t,^{3}He) reaction on ^{70}Zn reported by Sherman *et al.* [14] and therefore has been claimed to have a $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration. A spin $I^\pi = 5^-$ was proposed in Ref. [2] for this state. The fact that this state is populated in Coulomb excitation from a 3^- state where $E2$ excitation dominates, leads to (1^- - 5^-) as possible spins and parities. Moreover, since deexcitation is mainly dominated by faster $M1$ transitions, the direct decay toward the 6^- ground state firmly fixes the spin and parity of the 511 keV state to 5^-. The $5^- \rightarrow 3^-$ $E2$ transition at 410 keV was not observed due to its lower absolute transition probability compared to the $M1/E2$ character of the 511 keV transition. The prompt peak at $E_\gamma = 127$ keV is clearly present in both spectra. The

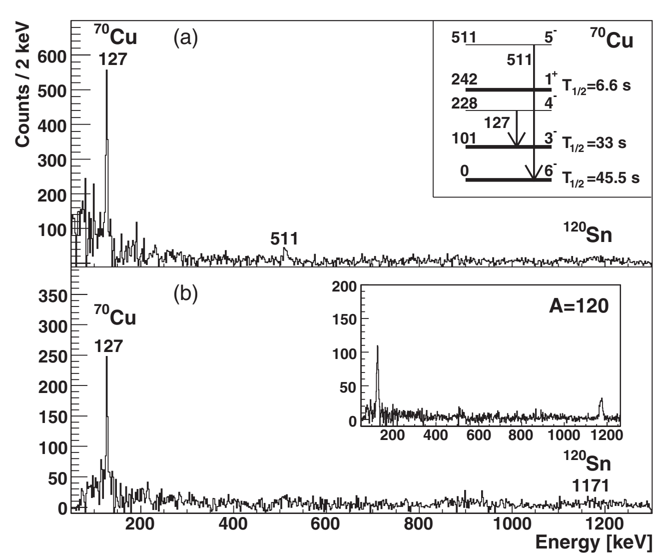

FIG. 2. Particle–γ-ray coincidence spectrum obtained with (a) 3^- beam and (b) 6^- beam. The spectra are Doppler corrected for mass $A = 70$. The inset in the bottom panel shows the spectrum Doppler corrected for mass $A = 120$. The partial level scheme and deexcitation γ rays shown in the upper right corner are based on Refs. [2–4] and this work. Energies are given in keV. Levels drawn with thick lines represent the isomeric states.

TABLE II. Experimental and theoretical excitation energies of ^{70}Cu. Energies are in keV. Details on the theoretical calculations are given in Sec. IV.

I^π	E_{expt}	SMI E_{theor}	SMII $fpgd$ E_{theor}	SMII fpg E_{theor}
6^-	0	0	107	23
3^-	101.1	87	0	0
4^-	228.5	336	352	354
5^-	511	582	589	583
1^+	242.2	383	249	514
2^+	320.7	317	109	304

fact that we do not observe the population of the 5^- state in the experiment with the 6^- beam indicates a small reduced $E2$ transition probability $6^- \rightarrow 5^-$.

The experimental energies corresponding to the two lowest multiplets in the ^{70}Cu level scheme are summarized in Table II and compared with large-scale shell-model calculations. Details on the SMI and SMII calculations are given in Sec. IV. The calculated energies are in good agreement with the experimental values. Even if the SMII calculation does not reproduce the experimental spectrum as well as the SMI, still the agreement is satisfactory given the complexity of the model.

The experimental Coulomb excitation cross section σ_{CE} to populate the 4^- level was determined relative to the known cross section for exciting the 2^+ state in the ^{120}Sn target. By the coupling of the two values of Coulomb-excitation cross section σ_{CE} obtained separately in the two experiments with the known isomeric-beam composition, a disentanglement of the $\sigma_{\mathrm{CE}}(6^- \rightarrow 4^-)$ and the $\sigma_{\mathrm{CE}}(3^- \rightarrow 4^-)$ was possible. The difference between the measured values can be indeed directly related to the different isomeric composition of the beams.

The CLX code [22], based on the Winther-De Boer theory [23], was then used to determine the set of matrix elements for reproducing the observed excitation cross sections. A quadrupole moment equal to zero was assumed in the calculations. The $B(E2;\, 6^- \rightarrow 4^-)$ and $B(E2;\, 3^- \rightarrow 4^-)$ extracted are 69(9) e^2 fm^4 [4.0(5) W.u.] and 73(10) e^2 fm^4 [4.1(6) W.u.], respectively. It should be noted that the new value of $B(E2;\, 6^- \rightarrow 4^-)$ is larger than the one reported in Ref. [4]. Indeed the measured ratio $\langle 6^- || E2 || 4^- \rangle / \langle 3^- || E2 || 4^- \rangle$ of 1.35(26) is larger than 0.94 assumed in Ref. [4] for a pure $\pi 2p_{3/2} \nu 1g_{9/2}$ configuration. The excitation strengths originating from the 3^- isomer were therefore overestimated in Ref. [4], leading to a smaller value of the $6^- \rightarrow 4^-$ transition strength.

Similarly, the $\sigma_{\mathrm{CE}}(3^- \rightarrow 5^-)$ was also measured, ignoring the contribution of $6^- \rightarrow 5^-$ transitions. The extracted $B(E2;\, 3^- \rightarrow 5^-)$ value is 136(15) e^2 fm^4 [7.9(9) W.u.]. An upper limit can be put on the $B(E2;\, 6^- \rightarrow 5^-)$ of 11(2) e^2 fm^4 [0.6(2) W.u.] assuming that 40 counts in the spectrum of Fig. 2(b) is below the observation limit. The influence of this upper limit on the $B(E2;\, 6^- \rightarrow 5^-)$ matrix element leads to a reduction of the $B(E2;\, 3^- \rightarrow 5^-)$ value to 112(12) e^2 fm^4 [6.5(7) W.u.].

The new analysis method has been also applied in the reanalysis of the ^{68}Cu data set from Ref. [4]. For this isotope, a $B(E2;6^- \rightarrow 4^-)$ value of 68(6) e^2 fm^4 [4.1(4) W.u.] was reported in Ref. [4]. The new extracted value is 77(8) e^2 fm^4 [4.7(4) W.u.].

IV. DISCUSSION

The $B(E2)$ values determined in this work are summarized in Tables III and IV together with results of the LSSM calculations. It is interesting to compare the experimental $B(E2)$ values with the extreme single-particle model prediction originating from the $|\pi 2p_{3/2} \nu 1g_{9/2}; JM\rangle$ configurations. This is illustrated in Fig. 3(a). As expected, only an approximate agreement with the results from this simple approach is observed.

To reach a microscopic understanding of the observed variation within the multiplet, LSSM calculations have been carried out using two different interactions and model spaces [11,24]. In the first approach, labeled SMI, the shell-model calculations were performed using the realistic interaction determined in Ref. [25], also used for the calculation of the levels in $^{70-78}$Cu [4]. The model space consists of the $(1f_{5/2}2p_{3/2}2p_{1/2}1g_{9/2})$ orbitals for both protons and neutrons outside the ^{56}Ni inert core. The theoretical values are reported in Table III for effective charges $e_\pi = 1.9e$ and $e_\nu = 0.9e$.

In the second approach, labeled SMII, a larger valence space outside the ^{48}Ca core has been used, including $(1f_{7/2}1f_{5/2}2p_{3/2}2p_{1/2})$ orbitals for protons and $(1f_{5/2}2p_{3/2}2p_{1/2}1g_{9/2}2d_{5/2})$ for neutrons. Such a model space has been recently used to describe the collectivity of the island of inversion around $N = 40$ [11] and allows us to study the role of the proton and neutron core excitations. The two-body matrix elements used in the present work are based on the interaction of Ref. [11]; however, further modifications have been applied to account for the evolution of the proton gap between ^{68}Ni and ^{78}Ni.

We performed the calculations allowing both proton and neutron core excitations, which comprises the $2d_{5/2}$ neutron orbital, and proton core excitations only. The notations SMII *fpgd* and SMII *fpg*, respectively, will be used to denote them. In these calculations, reported in Table IV, a standard polarization charge $0.5e$ ($e_\pi = 1.5e$ and $e_\nu = 0.5e$) was used. All the calculations were performed using the m-scheme shell-model code ANTOINE [26]. Complete diagonalizations were achieved with the ^{56}Ni core (SMI). However, using the ^{48}Ca core (SMII), up to 7p-7h excitations were considered, relative to the $\pi 1f_{7/2}$ and $\nu 2p_{3/2}$ orbitals.

TABLE III. Experimental and calculated (ANTOINE) $B(E2)$ values and matrix element (ME) values for the observed transitions. The calculations (SMI) use the *fpg* valence space outside the ^{56}Ni core for protons and neutrons. Effective charges $e_\pi = 1.9e$ and $e_\nu = 0.9e$ were used in the calculations.

	$B^{\mathrm{expt}}(E2)$ (e^2 fm^4)	$B^{\mathrm{theor}}(E2)$ (e^2 fm^4)	ME (e fm^2)	ME$_\pi$ (e fm^2)	ME$_\nu$ (e fm^2)
$3^- \rightarrow 4^-$	73(10)	72.9	22.6	6.8	10.7
$6^- \rightarrow 4^-$	69(9)	66.7	29.4	12.9	5.5
$3^- \rightarrow 5^-$	136(15)	112.5	28.1	11.8	6.2
$6^- \rightarrow 5^-$	$\leqslant$11(2)	19.2	15.8	9.7	−3.0

TABLE IV. Experimental and calculated (ANTOINE) $B(E2)$ values and ME values for the observed transitions. The calculations (SMII) use the valence space outside the ^{48}Ca core. Two sets of results are reported: including both proton and neutron core excitations (*fpgd*), and considering proton core excitations only (*fpg*). In both cases, a standard polarization charge of 0.5e is used.

	$B^{\text{expt}}(E2)$ (e^2 fm^4)	*fpgd*		*fpg*	
		$B^{\text{theor}}(E2)$ (e^2 fm^4)	ME (e fm^2)	$B^{\text{theor}}(E2)$ (e^2 fm^4)	ME (e fm^2)
$3^- \to 4^-$	73(10)	51.4	19.0	59.9	20.5
$6^- \to 4^-$	69(9)	57.4	27.3	38.9	22.5
$3^- \to 5^-$	136(15)	122.2	29.3	85.1	24.4
$6^- \to 5^-$	$\leqslant$11(2)	3.55	6.8	5.15	8.2

The comparison with the theoretical calculations is shown in Fig. 3(b). The SMI calculations assuming the ^{56}Ni core with the polarization charge of 0.5e show the correct trend but underestimate the $3^- \to 4^-$, $6^- \to 4^-$, and $3^- \to 5^-$ matrix elements. The best agreement within SMI is obtained by using effective proton and neutron charges of $e_\pi = 1.9e$ and $e_\nu = 0.9e$, to compensate for the large ^{56}Ni core polarization that is clearly present. It is interesting to

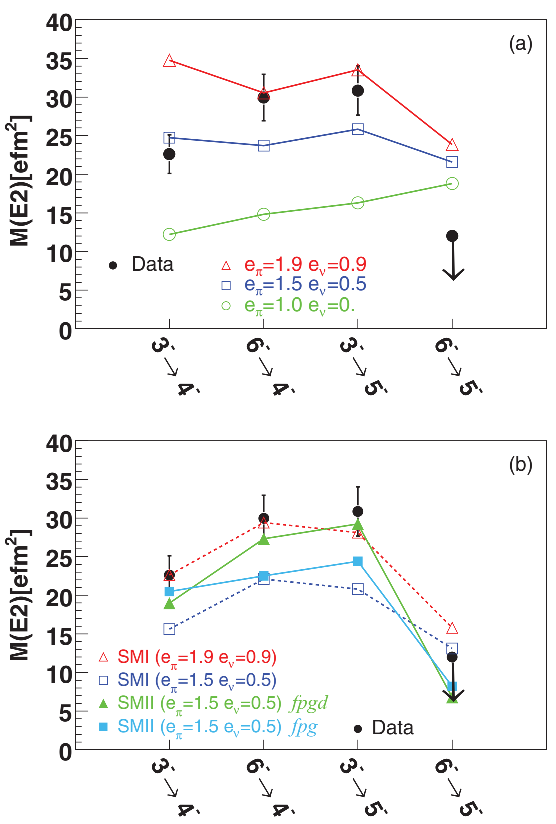

FIG. 3. (Color online) Experimental transition matrix elements measured in ^{70}Cu compared to results from (a) the extreme single-particle approach for a pure $\pi 2p_{3/2} \nu 1g_{9/2}$ configuration and (b) LSSM calculations using different interactions and valence spaces. See text for details. Different effective proton and neutron charges are used.

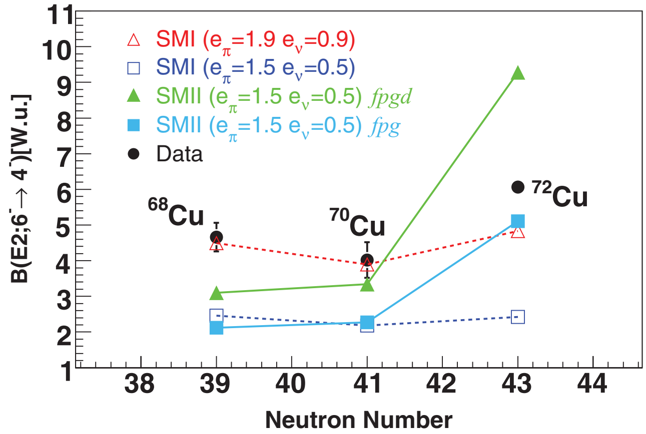

FIG. 4. (Color online) Experimental $B(E2;\, 6^- \to 4^-)$ for the odd-odd Cu isotopes compared to LSSM calculations using different interactions and valence spaces (see text for details).

note that when using these effective charges and in contrast to the extreme single-particle approach, the LSSM calculations reproduce the experimental values for all the transitions within the multiplet in ^{70}Cu except for a slight overestimation of the $6^- \to 5^-$ matrix element. This large polarization of the ^{56}Ni core is accounted for in the calculations allowing core excitations. Indeed, the SMII calculations in the fpg space, using effective proton and neutron charges of $e_\pi = 1.5e$ and $e_\nu = 0.5e$, improve slightly the agreement when compared to the SMI calculations with the same effective charges. However, it appears that the $fpgd$ model space, which also includes neutron excitations across $N = 50$, is necessary to obtain the right order of magnitude of the matrix elements in ^{70}Cu.

In Fig. 4 the $B(E2;\, 6^- \to 4^-)$ reduced transition probabilities for the neutron-rich odd-odd copper isotopes are shown as a function of the neutron number N and compared with the calculations. The $B(E2;\, 6^- \to 4^-)$ value for ^{72}Cu and the spin and parity assignment of the low-lying energy levels are deduced from lifetime measurements [27–30]. However, recent measurements of the ground-state nuclear moment of ^{72}Cu [6,31] firmly fix the spin and parity of the ground state as $I^\pi = 2^-$. According to this result, the level scheme of ^{72}Cu proposed in Refs. [29,30] should be revised. It should therefore be considered that as the 51 keV transition potentially does not correspond to $6^- \to 4^-$ as claimed in Ref. [30], the $B(E2;\, 6^- \to 4^-)$ value of ^{72}Cu might be incorrect.

The SMI calculations with the ^{56}Ni core and 0.5e as the polarization charge predict a nearly equal, slightly underestimated value for this transition in all considered isotopes. Enhancing the effective charges improves the agreement at $N = 39$ and $N = 41$, but it still is not enough to reproduce the increase observed at $N = 43$. This, however, can be understood, because with the filling of the $1g_{9/2}$ orbit, no more pf holes can appear, and consequently the transition value saturates.

The increase observed experimentally between $N = 41$ and $N = 43$ may be due to the weakening of the $Z = 28$ proton gap with increasing neutron number from $N = 40$ to $N = 50$ as shown in Ref. [10]. Indeed, the calculations with the ^{48}Ca core predict a rapid increase of this $B(E2)$ value between

$N = 41$ and $N = 43$ using a standard $0.5e$ polarization. It is interesting to note that the SMII-$fpgd$ model, which does rather well up to $N = 41$, seems to overshoot considerably the measured value in ^{72}Cu. Such a rapid growth of collectivity, similar to what is observed between ^{68}Ni and ^{70}Ni, or ^{69}Cu and ^{71}Cu, seems not to be the case for the $B(E2; 6^- \rightarrow 4^-)$ transition in odd-odd copper isotopes. However, as mentioned above, the experimental result for ^{72}Cu needs to be revised.

One should also point out that the increase of the $B(E2)$ value in the SMII-$fpgd$ calculations depends on both the size of the proton gap and the excitations to the $2d_{5/2}$ orbital. While the size of the proton gap can be constrained from experiment, at least in ^{68}Ni, very little is known on the position of the $2d_{5/2}$ orbital and its evolution close to $N = 40$. The role of this orbital at $N = 40$ merits further experimental investigation. $B(E2)$ values for the $3^- \rightarrow 4^-$ and $3^- \rightarrow 5^-$ transitions in other neutron-rich odd-odd copper isotopes have not yet been measured.

V. CONCLUSIONS

Level energies and $B(E2)$ values within the low-lying energy members of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet in ^{70}Cu have been measured using Coulomb excitation of post-accelerated $I^\pi = 6^-$ and $I^\pi = 3^-$ beams. This part of the level scheme was already studied in a previous experiment, and data were reported in Ref. [4] where a post-accelerated $I^\pi = 6^-$ beam was used. The $B(E2)$ values reported in Ref. [4] have been revised, because the new experimental data allow one to determine them without relying on theoretical assumptions. Moreover, the observation of a 511 keV transition fixes the energy, spin, and parity of the 5^- member of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet.

The experimental results have been compared with two large-scale shell-model calculations using different valence spaces and different values of the effective residual proton-neutron interaction. Calculations starting from a ^{56}Ni core (SMI) reproduce quite well both the absolute $B(E2)$ values and their trend, provided $e_\pi = 1.9e$ and $e_\nu = 0.9e$ effective charges are used.

The large polarization of the ^{56}Ni core is explicitly taken into account in the SMII-$fpgd$ calculation starting from a ^{48}Ca core and including the $2d_{5/2}$ orbital for neutrons. Indeed this calculation reproduces the absolute values and their trend using a standard $0.5e$ polarization charge. From the comparison with the SMII-fpg calculation, the inclusion of the $2d_{5/2}$ orbital appears necessary. However, when including the $2d_{5/2}$ orbital, the calculation predicts an enhancement in collectivity in ^{72}Cu not observed experimentally. In view of the recent spin and parity determination of the ^{72}Cu ground state [6,31], the experimental result needs revision. The effect of the $2d_{5/2}$ deserves further investigation.

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