Coulomb Excitation of ^{68,70}Cu: First Use of Postaccelerated Isomeric Beams

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(Received 5 December 2006; published 23 March 2007)

We report on the first low-energy Coulomb excitation measurements with radioactive $I^\pi = 6^-$ beams of odd-odd nuclei ^{68,70}Cu. The beams were produced at ISOLDE, CERN and were post-accelerated by REX-ISOLDE to 2.83 MeV/nucleon. γ rays were detected with the MINIBALL spectrometer. The 6^- beam was used to study the multiplet of states (3^-, 4^-, 5^-, 6^-) arising from the $\pi 2p_{3/2} \nu 1g_{9/2}$ configuration. The 4^- state of the multiplet was populated via Coulomb excitation and the $B(E2; 6^- \rightarrow 4^-)$ value was determined in both nuclei. The results obtained illustrate the fragile stability of the $Z = 28$ shell and $N = 40$ subshell closures. A comparison with large-scale shell-model calculations using the ^{56}Ni core shows the importance of the proton excitations across the $Z = 28$ shell gap to the understanding of the nuclear structure in the neutron-rich nuclei with $N \approx 40$.

DOI: 10.1103/PhysRevLett.98.122701 PACS numbers: 25.70.De, 21.10.Ky, 25.60.−t, 27.50.+e

Radioactive beams provide great opportunities for investigating the nuclear structure away from the stable nuclei. One of the regions of the nuclear chart that has attracted a considerable interest in the past years is the one close to ^{68}Ni [1–8]. Coulomb excitation experiments with radioactive beams of even-even isotopes showed that the coupling of a few extra particles to the ^{68}Ni core induces large polarization effects [2,3]. These effects were associated with a weakening of the $Z = 28$ and $N = 40$ gaps when neutrons start filling the $1g_{9/2}$ orbital [2]. Beyond $N = 40$, results of β-decay measurements in the neutron-rich $^{69-73}$Cu isotopes revealed a dramatic and sudden lowering of the $\pi 1f_{5/2}$ orbital with the increased occupancy of the $\nu 1g_{9/2}$ orbital [4]. Referred to as monopole migration, this energy shift was interpreted as originating from the residual proton-neutron interaction and it is expected to have profound implications on the structure of the doubly magic nucleus ^{78}Ni [4,5].

Shell-model calculations using different effective nucleon-nucleon interactions were used in order to understand the observed properties in the nuclei around ^{68}Ni and predict the evolution of the shell structure towards ^{78}Ni [5–8]. The calculations indicated that the values of the $Z = 28$ and $N = 40, 50$ energy gaps strongly depend on the effective interaction used. A consistent understanding of the evolution of the nuclear structure in these regions requires also experimental information such as excitation energies and transition rates in the odd-A and odd-odd nuclei.

Coulomb excitation experiments provide information on the energies, spins, and parities of the excited levels and reduced transition probabilities. Such experiments are extremely challenging due to the low intensity of the radioactive beams and the possible low collectivity of the transitions involved. Moreover, the very complex level structure of the odd-A and odd-odd nuclei can lead to isomeric states. Apart from being an important probe for nuclear structure, Coulomb excitation might cause an induced isomeric deexcitation, as suggested in [9], leading to triggered γ-ray emission—a field of great current interest.

In this Letter we report on pioneering studies, opening the field for Coulomb excitation and other reaction experiments with odd-odd nuclei, on the structure of ^{68,70}Cu using post-accelerated beams, isomerically purified through selective laser ionization. In a simple shell-model picture, the low-lying level structures of these two nuclei can be regarded as one $2p_{3/2}$ proton plus one neutron particle or hole occupying either the $2p_{1/2}$ or $1g_{9/2}$ orbitals, coupled to the ^{68}Ni core, giving rise to the multiplet of states $I^\pi = (1^+, 2^+)$ and $I^\pi = (3^-, 4^-, 5^-, 6^-)$, respectively. The spins 1^+ and 6^- were assigned to the ground states of ^{68}Cu and ^{70}Cu, respectively. The 6^- state in ^{68}Cu and (1^+, 3^-) levels in ^{70}Cu were found to be β-decaying isomers [10–13]. Prior to this study, the experimental information on the remaining members of the negative-parity multiplet was rather incomplete. Candidates for these states were suggested at 778, 956, and 1350 keV, in ^{68}Cu, and 226 and 506 keV, respectively, in ^{70}Cu [12,14,15].

In the present work we made use of Coulomb excitation of post-accelerated 6^- beams of ^{68,70}Cu to characterize the states of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet. The beams were produced in a similar way as in [12,13] where narrow band laser scans provided the optimum values of the laser frequency that maximize the ionization of the different isomers.

The 6^- beams of ^{68,70}Cu, post-accelerated by REX-ISOLDE [16] up to 2.83 MeV/nucleon, were used to bombard a 2.3 mg/cm^2 ^{120}Sn target. Typical beam intensities at the detection setup were 3×10^5 pps [^{68}Cu(6^-)] and 5×10^4 pps [^{70}Cu(6^-)]. Scattered projectile and recoiling target nuclei were detected by a DSSSD detector [17], covering the forward angles between 16.4° and 53.3° in the laboratory system.

The detection of the γ rays was performed with the MINIBALL array [18] consisting of 8 clusters each combining three sixfold segmented HPGe crystals. While the γ-ray energy was extracted from the core signal of the individual crystals, the segment with the highest energy deposition determined the emission angle of the γ ray. Doppler correction was applied by combining this information with the direction and velocity of the coincident scattered particle detected in the DSSSD detector.

Experiments with radioactive beams often suffer from the contamination of the beam of interest with other isobars and, in this particular experiment, isomers. The isobaric contamination was investigated by performing measurements with and without laser radiation (laser ON/OFF) at regular time intervals. The amount of Ga contaminant was determined by comparing the yield of elastically scattered particles in the DSSSD detector in the periods with the lasers on (both Ga and Cu present in the beam) and the periods with the lasers off (only Ga present in the beam). Values of 74(2)% and 70(5)% were obtained for the purity of the ^{68,70}Cu beams, respectively.

The isomeric beam contamination stemmed from the broadening of the hyperfine-split resonances of each isomer [12,19]. This introduced a small contamination of the 6^- beam with contributions from the lower spin isomers. The characteristic γ rays produced in their β decay allowed 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, 86(3)% and 85(5)% of the total ^{68,70}Cu ion yield was produced in this spin state, respectively. In ^{70}Cu, the (3^-, 1^+) isomers were found to contribute with almost equal amounts (≈7%) to the total Cu yield.

The upper part of Fig. 1 shows the particle–γ-ray coincidence spectrum observed after 12.3 h of data taking with the 6^- isomeric beam of ^{68}Cu. No Doppler correction was applied to this spectrum. The three peaks at low energies, namely, 84, 178, and 693 keV, were identified as transitions depopulating excited levels in ^{68}Cu [15]. The prompt γ ray of 178 keV deexcites the state at 956 keV, populated in our work by Coulomb excitation. It feeds the 3^- state at 778 keV, which further deexcites via the 693 and 84 keV transitions defining the $3^- \rightarrow 2^+ \rightarrow 1^+$ sequence. A spin

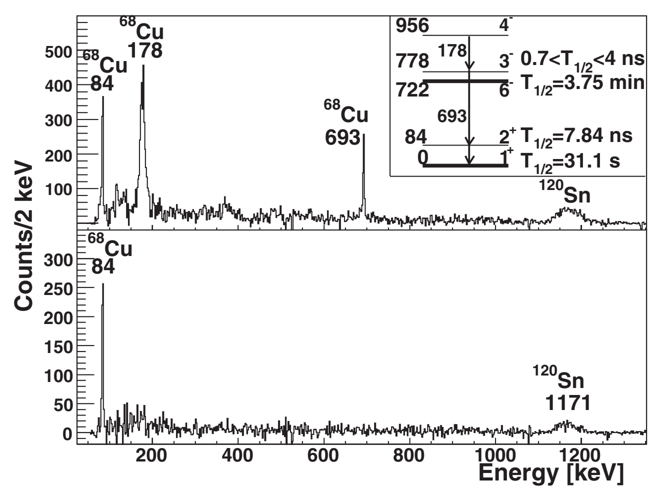

FIG. 1. Top: particle–γ-ray coincidence spectrum acquired with the 6^- beam of ^{68}Cu. The partial level scheme and deexcitation γ rays shown in the upper right corner are based on Refs. [15,21] and this work. Energies are given in keV. Levels drawn with thick lines represent the β-decaying states. Bottom: particle–γ-ray coincidence spectrum acquired with the 1^+ beam. No Doppler correction was applied to these spectra.

$I^\pi = 4^-$ was suggested in Refs. [14,15] for the state at 956 keV, based on the parabolic rule for proton-neutron multiplets proposed by Paar [20]. Such a spin assignment would imply a $M1$-$E2$ multipolarity for the 178 keV γ ray. The fact that this γ ray is Doppler broadened in the Coulomb excitation spectrum of Fig. 1 indicates a lifetime of the order of picoseconds for the level at 956 keV. This fixes the spin of the level to $I^\pi = 4^-$, in agreement with Refs. [14,15], as the partial decay lifetimes of the $M1$ transitions are indeed in the picoseconds range, while $E2$ transitions would have a partial lifetime 4 orders of magnitude higher, based on Weisskopf estimates. Furthermore, the fact that in the same spectrum, the transitions of 84 and 693 keV are not Doppler broadened indicates that these γ rays were emitted after the ^{68}Cu ions were implanted in the particle detector. A half-life of $T_{1/2} = 7.84$ ns was measured in Ref. [21] for the $I^\pi = 2^+$ state, whereas a value between 0.7 and 4 ns was reported in Ref. [15] for the half-life of the $I^\pi = 3^-$ level.

It is interesting to note that by the Coulomb excitation of the 6^- isomer in ^{68}Cu, we demonstrated the induced instantaneous depopulation of a nuclear isomer. The triggered γ emission of an isomer was extensively investigated in K isomers via Coulomb excitation and photoabsorption experiments (see [9] and references therein). These experiments are extremely challenging since the isomer depopulation can only proceed through weak transitions arising from K mixing [22,23]. In this work, an alternative scheme is revealed, based on the multiplet structure of an odd-odd nucleus. The $E2$ Coulomb excitation feeds a member of the multiplet which deexcites faster through $M1$ than $E2$ transitions, eventually bypassing the isomer. In the present experiment, an isomer depopulation cross section of 42 ± 4 mb was observed. A higher cross section can be obtained by, e.g., increasing the beam energy.

There is a possible contribution to the spectrum shown in Fig. 1 from Coulomb excitation arising from the contamination of the 6^- isomeric beam with the 1^+ ground state. This was checked by setting the laser frequency to the value found to produce the maximum ionization of the ground state [12,13]. The spectrum acquired after 5 h of ^{68}Cu(1^+) beam on target is shown in the bottom part of Fig. 1. Apart from the Coulomb excitation peak of 1171 keV of the ^{120}Sn target, the only γ ray present in the spectrum is the transition $2^+ \rightarrow 1^+$ of 84 keV.

The particle–γ-ray coincidence spectrum acquired after 28 h of ^{70}Cu(6^-) beam on target is presented in Fig. 2. The spectrum was Doppler corrected for mass $A = 70$. The prompt peak at $E_\gamma = 127$ keV was identified as the transition between the state at 228 keV populated by Coulomb excitation and the isomeric state $I^\pi = 3^-$ in ^{70}Cu. A spin $I^\pi = 4^-$ for the state at 228 keV was proposed in Ref. [12], based on the observed β-decay pattern. The observation of the fast 127 keV decaying transition implies a $M1$ character for this γ ray, thus confirming the $I^\pi = 4^-$ spin assignment for the 228-keV level [12], see Fig. 2. In this case, as

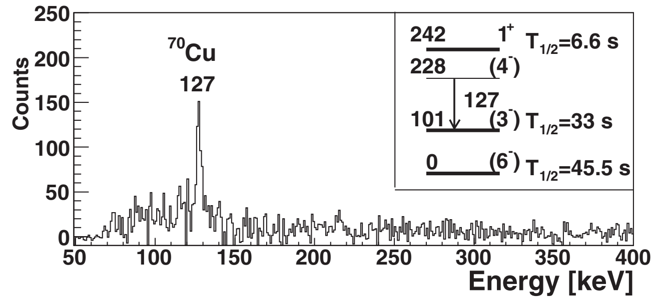

FIG. 2. Particle–γ-ray coincidence spectrum obtained with 6^- beam of ^{70}Cu. The spectrum is Doppler corrected for mass $A = 70$. Upper right corner: partial level scheme of ^{70}Cu taken from Ref. [12].

well as in the case of ^{68}Cu, population of the 5^- state was not observed and therefore will not be considered in the further analysis.

The experimental Coulomb excitation cross section $\sigma_{\rm CE}(6^- \rightarrow 4^-)$ was determined in both nuclei relative to the known cross section for exciting the 2^+ state in the ^{120}Sn target. For the fit of the experimental cross sections and corresponding $B(E2)$ values, the Coulomb excitation code GOSIA [24] was used. The code calculates the experimental γ yields integrated over the scattering angle of the detected particle and corrected for angular distributions, internal conversion coefficients, and energy loss of the beam in the target. In the GOSIA fitting code, the unknown $\langle 6^- \| E2 \| 4^- \rangle$ reduced matrix element was varied so as to reproduce the measured yield of the observed deexcitation $4^- \rightarrow 3^-$. The $B(E2; 6^- \rightarrow 4^-)$ value extracted for ^{68}Cu is $68(6)e^2\text{fm}^4$ [4.1(4) W.u.] (Weisskopf unit). The quoted error is dominated by the statistical errors arising from the determination of the peak area and purity of the beam. The systematic error introduced by the reorientation matrix elements was found to be below 1% when assuming the values for the quadrupole moments predicted by the shell model. For the estimation of the $B(E2; 6^- \rightarrow 4^-)$ value in ^{70}Cu, the population of the $I^\pi = 4^-$ level through an $E2/M1$ excitation with the 3^- isomeric contaminant needs to be considered. From the measured magnetic moment for the 3^- isomeric state in ^{70}Cu [13], a $B(M1; 3^- \rightarrow 4^-)$ value of $6.74\mu_N^2$ could be deduced. This would imply a $M1$ Coulomb excitation cross section of 0.16 mb, which is a factor of 16 less than the cross section for an $E2$ excitation corresponding to a $B(E2)$ value of 1 W.u.; therefore, the $M1$ contribution can be considered negligible. Shell-model calculation for a pure $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration predicts that the two reduced matrix elements are connected by the relation $\langle 6^- \| E2 \| 4^- \rangle = 0.94 \langle 3^- \| E2 \| 4^- \rangle$. Taking into account also the isomeric ratio $6^-:3^- = 85:7$ determined experimentally, we estimated that ~14% from the observed deexcitation yield $4^- \rightarrow 3^-$ is due to the population of the 4^- state by an $E2$ excitation with the 3^- isomer. From the remaining number of counts, a value of $B(E2; 6^- \rightarrow 4^-) = 41(5)e^2\text{fm}^4$ [2.4(3) W.u.] was determined in ^{70}Cu.

TABLE I. Experimental and calculated $B(E2; 6^- \to 4^-)$ values in ^{68,70,72}Cu. The last three columns give the calculated total matrix element ME $= M_\pi e_\pi + M_\nu e_\nu$, $M_\pi = \langle 6^- || E2 || 4^- \rangle_\pi$ for protons and $M_\nu = \langle 6^- || E2 || 4^- \rangle_\nu$ for neutrons. Effective charges $e_\pi = 1.5e$, $e_\nu = 0.5e$ were used in the calculations.

Isotope	$B^{\mathrm{expt}}(E2)$ (e^2fm^4)	$B^{\mathrm{theor}}(E2)$ (e^2fm^4)	ME ($e$fm^2)	M_π ($e$fm^2)	M_ν ($e$fm^2)
^{68}Cu	68(6)	40.6	23.0	12.7	7.7
^{70}Cu	41(5)	37.5	22.1	12.9	5.5
^{72}Cu	108(2)[a]	43.2	23.7	11.5	12.9

[a]Refs. [25–28].

The $B(E2)$ values measured in the present work are summarized in Table I and compared to the predictions of the shell model. The value deduced from the assumed $(6^-) \to (4^-)$ transition in ^{72}Cu [25–28] is also included in the table. The shell-model calculations were performed with the ANTOINE code [29] using the realistic force determined in Refs. [30,31], also used for the calculation of the levels in $^{70-78}$Cu [12,25,32]. The valence space considered for both protons and neutrons consist of the fpg orbitals outside the ^{56}Ni inert core, without any restriction on their occupation. The effective proton and neutron charges used in the calculations are $e_\pi = 1.5e$ and $e_\nu = 0.5e$. The calculation predicts that while the main contribution to the $E2$ transition rates is due to protons, the neutron contribution becomes important with the increased occupancy of the $1g_{9/2}$ orbital. However, the $B(E2)$ values calculated with the effective charges $e_\pi = 1.5e$ and $e_\nu = 0.5e$ do not vary significantly as a function of the neutron number, in disagreement with the experimental observations. The values in ^{68,72}Cu are underestimated by the theory pointing to the importance of proton excitations across the $Z = 28$ shell gap that are not included in the used model space. The lower $B(E2)$ value in ^{70}Cu, as well as its agreement with the calculation with a ^{56}Ni core, indicates a stabilizing effect at $N = 40$ and $Z = 28$. This effect appears to be very delicate since the coupling of three quasiparticles to ^{68}Ni induces significant core polarization, as observed in the case of ^{68,72}Cu. Indeed, an increased neutron effective charge $e_\nu = 1.0e$, keeping $e_\pi = 1.5e$, leads to a better agreement with the experiment [$B^{\mathrm{th}}(E2) = 55$, 48, and $70e^2$fm^4 for ^{68,70,72}Cu, respectively] implicitly implying proton p-h excitations across $Z = 28$ through a polarization of the neutrons.

In conclusion, we have determined the $B(E2; 6^- \to 4^-)$ values of the $\pi 2p_{3/2} \nu 1g_{9/2}$ multiplet in ^{68,70}Cu using Coulomb excitation of post-accelerated $I^\pi = 6^-$ beam. The experimental results were compared with large-scale shell-model calculations using ^{56}Ni as a core. The low $B(E2)$ value in ^{70}Cu indicates weak polarization effects induced by the extra-proton and neutron coupled to the ^{68}Ni. However, the results show that the coupling of at least two like quasiparticles to ^{68}Ni weakens the stabilization effects of the $N = 40$ subshell and $Z = 28$ shell gaps, in agreement with [2,3]. The availability of post-accelerated radioactive beams in combination with isomer selective resonant laser ionization opens new possibilities for further investigations as it allows probing the underlying structure of the different configurations present in the same nucleus through Coulomb excitation or transfer reactions. Also, the triggered depopulation of the nuclear isomer in ^{68}Cu using Coulomb excitation with isomeric beams calls for a detailed study of other multiplets in odd-odd nuclei for evaluating the possibility of triggered energy release.

This work was supported by EU Sixth Framework through No. EURONS-506065, BMBF under Contracts No. 06KY205I and No. 06MT238, IAP Research Program No. P5/07, and FWO-Vlaanderen (Belgium).

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