Interplay between Single-Particle and Collective Effects in the Odd-A Cu Isotopes beyond $N = 40$

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(Received 3 December 2007; published 21 March 2008)

Collective properties of the low-lying levels in the odd-A $^{67-73}$Cu were investigated by Coulomb excitation with radioactive beams. The beams were produced at ISOLDE and postaccelerated by REX-ISOLDE up to 2.99 MeV/u. In ^{67,69}Cu, low-lying $1/2^-$, $5/2^-$, and $7/2^-$ states were populated. In ^{71,73}Cu, besides the known transitions deexciting the single-particle-like $5/2^-$ and core-coupled $7/2^-$ levels, γ rays of 454 and 135 keV, respectively, were observed for the first time. Based on a reanalysis of β-decay work and comparison with the systematics, a spin $1/2^-$ is suggested for these excited states. Three $B(E2)$ values were determined in each of the four isotopes. The results indicate a significant change in the structure of the odd-A Cu isotopes beyond $N = 40$ where single-particle-like and collective levels are suggested to coexist at very low excitation energies.

DOI: 10.1103/PhysRevLett.100.112502 PACS numbers: 25.70.De, 21.10.Ky, 21.60.Cs, 27.50.+e

The evolution of the single-particle states around shell closures when moving into the region of nuclei with unusual proton-to-neutron ratio is a topic of great current interest. Understanding this evolution is crucial for determining the capabilities of the nuclear models to predict properties that are, e.g., relevant for a number of explosive nucleosynthesis scenarios [1] or for explaining the swift onset of collectivity near closed shell nuclei, as observed below $Z = 28$ [2]. Because of the continuous development of the radioactive ion beam facilities, it recently became possible to follow this evolution over long chains of isotopes or isotones and systematic energy shifts of specific single-particle levels in different mass regions have been observed [3]. Such energy shifts, referred to as monopole migration, were found to have a major influence on the collective properties of the atomic nuclei, as the modification of the relative spacing between the single-particle orbitals affects the size of the shell gaps [4–6].

Shell-model calculations employing different nucleon-nucleon interactions were compared to the experimental data available in the nuclei far from stability and the role played by the proton-neutron monopole term [7], tensor force [8], or pairing correlations [9] was investigated.

One of the regions of the nuclear chart where important tensor effects are expected to be observed is that around $Z \sim 28$, $N > 40$ [8]. In this mass region, the valence protons occupy the fp shell while the neutrons fill the $1g_{9/2}$ orbital. Calculations predict the lowering of the $\pi 1f_{5/2}$ and the raising of $\pi 1f_{7/2}$ orbitals with increasing neutron number [8]. This leads to a decrease of the relative spacing

$\pi 1f_{5/2}$-$\pi 1f_{7/2}$ resulting in a reduction of the $Z = 28$ shell gap and therefore an increased collectivity beyond $N = 40$. Furthermore, the repulsion between the $1g_{9/2}$ neutrons and $2p_{3/2}$ protons pushes up the proton orbital, which is expected to cross the downsloping $\pi 1f_{5/2}$ around $N = 45$ [8].

The best candidates for investigating the predicted tensor effects for this mass region are the neutron-rich Cu isotopes ($Z = 29$). In fact, evidence for an unusual behavior of the energy levels when increasing the occupancy of the $\nu 1g_{9/2}$ orbital was already reported in ^{71,73}Cu, investigated by β decay [10,11]. The experimental study revealed a strong compression of their level schemes when compared to the lighter odd-A Cu isotopes. In particular, the sharp decrease of the energy of the low-lying $5/2^-$ state was considered as a clear indication for monopole migration [10,11]. Based on the observed β-decay pattern, this level was interpreted to correspond to the $1f_{5/2}$ proton excitation that is pushed down by the attractive interaction with the $1g_{9/2}$ neutrons [10,11]. Another unusual feature of the level schemes in neutron-rich Cu isotopes is the presence of the microsecond isomers at 62 and 128 keV observed in ^{75}Cu [12].

In the lighter odd-A Cu isotopes, the $5/2^-$ state remains rather constant around 1 MeV excitation energy. The energy of the lowest-lying $1/2^-$ state, containing an important component from the $\pi 2p_{1/2}$ orbital, decreases from 1.06 MeV in ^{57}Cu$_{28}$ to 0.47 MeV in ^{61}Cu$_{32}$ and rises again to 1.09 MeV in ^{69}Cu$_{40}$. However, results of Coulomb excitation experiments in the stable ^{63,65}Cu isotopes showed that the lowest-lying $I = 1/2^-$, $5/2^-$, and $7/2^-$ states are rather collective [$B(E2; I \rightarrow 3/2^-_{\mathrm{g.s.}}) > 10$ W.u.] [13]. The observed properties were found to be consistent with the predictions of the weak coupling model [14]. Within the framework of this simple model, these low-lying levels were described as states arising from the coupling of the $2p_{3/2}$ valence proton to the 2^+ state in the ^{62,64}Ni cores [13].

Beyond ^{65}Cu, transition rates were not known experimentally prior to the present work. However, the study of the low-lying states in ^{63,65,67,69}Cu by transfer reactions [15] indicated similar spectroscopic factors in all nuclei, suggesting that the proposed weak coupling scenario might be valid up to ^{69}Cu. Recently, experimental evidence for enhanced collectivity above $N = 40$ was reported in ^{70}Ni [16]. The large $B(E2; 2^+ \rightarrow 0^+)$ value found experimentally is believed to contain an important contribution from proton excitations across the quenched $Z = 28$ shell gap. It is therefore not clear whether the sharp drop of the energy of the $5/2^-$ state in ^{71,73}Cu originates from the attractive $\pi 1f_{5/2}$-$\nu 1g_{9/2}$ interaction or is caused by an increased mixing with collective degrees of freedom, which, as shown in [16], becomes significant beyond $N = 40$.

To answer the above question we employed Coulomb excitation with radioactive beams of ^{67,69,71,73}Cu as a means to probe the nature of their low-lying states and investigate the impact of the $N = 40$ subshell closure on the evolution of collectivity in this mass region.

The ^{67,69,71,73}Cu radioactive ion beams were produced at the ISOLDE facility by combining the 1.4 GeV proton induced fission in a 45 g/cm^2 UC$_x$ target with resonant laser ionization RILIS [17]. After mass separation, the beams of interest were postaccelerated by REX-ISOLDE [18] up to 2.99 MeV/A and used to bombard a 2 mg/cm^2 target of either ^{104}Pd (^{67,69,71}Cu) or ^{120}Sn (^{71,73}Cu).

The experimental setup used in the present work is similar to that described in Ref. [19]. Gamma rays following the deexcitation of the levels populated by Coulomb excitation were detected with the MINIBALL Ge array [20] while the scattered projectiles and recoiling target nuclei were detected in a double sided silicon strip detector Si detector [21].

The resonant laser-ionization technique employed in this work proved to be a very efficient and selective method for producing neutron-rich Cu beams, as no isobaric contaminants other than Ga were present in the beams. The amount of Ga isobar in each of the beams of interest was determined as described in [19].

Information concerning the beam intensity and purity achieved for each of the four isotopes of interest is summarized in Table I. The quality of the data can be seen in Fig. 1. The figure shows the Doppler corrected particle-γ coincidence spectra obtained for mass $A = 73$, which is the most challenging case studied in the present work, as the beam intensity and purity are the lowest (see Table I). The strongest transitions observed in the spectrum arise from the deexcitation of the levels in the ^{73}Ga isobaric contaminant. The γ lines of 166 and 961 keV, present in the laser ON spectrum only (see Fig. 1, top), were identified earlier in the β decay of the ^{73}Ni isobar and placed in the level scheme of ^{73}Cu as ground-state transitions from the $(5/2^-)$ and $(7/2^-)$ states, respectively [10,11]. The γ- ray of 135.4(1) keV, observed for the first time in our work, is clearly related to laser ionization. This indicates the existence in ^{73}Cu of an excited state at 135 keV. The alternative

TABLE I. Beam intensity (ions/s) and purity (% Cu/total) at the MINIBALL target achieved in the present work.

	^{67}Cu	^{69}Cu	^{71}Cu	^{73}Cu
Beam intensity	1.2×10^5	1.6×10^5	2.3×10^5	8×10^4
Purity	97.5(7)	95.2(5)	65(1)	17.4(2)

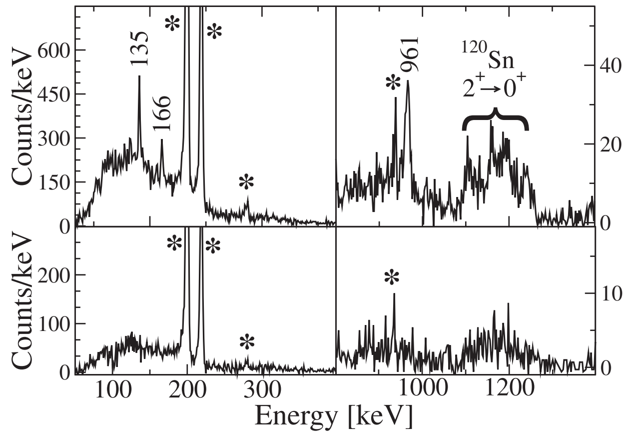

FIG. 1. Laser ON (top) and OFF (bottom) Doppler corrected particle-γ coincidence spectra obtained with beam of mass $A = 73$. The Coulomb excitation was induced on a 2 mg/cm^2 ^{120}Sn target. γ rays arising from the deexcitation of the levels in ^{73}Cu are noted on the figure with their energies. The transitions from the Ga isobaric contaminant are marked with a star.

scenario where the 135 keV line belongs to a cascade deexciting a level populated by multistep Coulomb excitation can be disregarded, as the probability of such a process is at least an order of magnitude lower and the observed intensity of the 135 keV transition is larger than that of the known 166 and 961 keV γ rays.

Also in the lighter ^{67,69,71}Cu isotopes, Coulomb excitation resulted in the observation of three ground-state transitions, all but one already identified in previous studies [10,11,15]. The particle-γ coincidence spectrum obtained with a beam of ^{71}Cu revealed a transition of 454.2(1) keV indicating the existence in this nucleus of an excited state at this energy. In fact, the reanalysis of the ^{71}Ni β-decay data obtained by this collaboration at the LISOL separator [10,11] also showed the presence of a 454 keV line. Because of the lack of $\gamma\gamma$-coincidence relations, this transition was not placed in the level scheme of ^{71}Cu reported in [10,11].

A summary of the levels populated by Coulomb excitation in ^{67,69,71,73}Cu is given in Table II. The newly observed states at 454 keV in ^{71}Cu and 135 keV in ^{73}Cu are also included. The weak or missing feeding of these levels in the β decay of the ^{71,73}Ni isobars, respectively [10,11], suggests a low spin for these states in both nuclei, most probably a $1/2^-$ state.

The deexcitation yields of the observed γ rays in ^{67,69,71,73}Cu were used to extract the experimental Coulomb excitation cross sections, normalized to the known cross section for exciting the 2^+ state in the ^{104}Pd or ^{120}Sn target. The fit of the experimental data was performed with the Coulomb excitation code GOSIA [22]. The code calculates the experimental γ yields integrated over the scattering angle of the detected particle and corrected for the energy loss of the beam in the target, angular distributions of the γ rays, and internal conversion coefficients. GOSIA predicts that the population of the $1/2^-$ and $5/2^-$ levels via Coulomb excitation from the $3/2^-$ ground state proceeds mainly through $E2$ transitions, as the probability for $M1$ excitations is 3 orders of magnitude lower.

The $B(E2)$ values obtained in the present work are given in Table II and shown in the bottom panels of Fig. 2. For comparison, the corresponding values in the stable ^{63,65}Cu and the $B(E2; 2^+ \rightarrow 0^+)$ strengths in the even-even adjacent Ni isotopes are also included. The top panels present the energy systematics of the $1/2^-$, $5/2^-$, and the core-coupled $7/2^-$ levels in the odd-A $^{63-73}$Cu, as well as the 2^+ states in the Ni cores.

In ^{71,73}Cu, based on the particle-core model [23], the $7/2^-$ states at 1190 and 961 keV, respectively, were interpreted as $\pi 2p_{3/2} \otimes 2^+(^{70,72}\mathrm{Ni})$ configurations, while the $\pi 1f_{7/2}^{-1} 2p_{3/2}^2$ structure was assigned to the $7/2^-$ levels located at 981 and 1010 keV, respectively [23]. The nonobservation of the latter $7/2^-$ states in this Coulomb excitation experiment and the obtained $B(E2)$ values for the former, very similar to the $B(E2)$ strengths in the corresponding Ni cores, is consistent with the proposed interpretation, which can be easily extended over the whole series of $7/2^-$ states presented in Fig. 2. Since the $B(E2)$ transition rate in ^{72}Ni is not known experimentally, our measured $B(E2; 7/2^- \rightarrow 3/2^-)$ value in ^{73}Cu can give a good estimate of the collectivity of the 2^+ state in ^{72}Ni.

TABLE II. Experimental excitation energies (keV) of the levels populated by Coulomb excitation and the corresponding $B(E2)$ values (W.u.) extracted from the analysis of the present data (EXPT.) compared to the results of the large scale shell-model calculations (SM) [7]. Levels marked with a star are newly assigned to the level schemes of ^{71,73}Cu. The shell-model $B(E2)$ values were calculated with the effective charges $e_\pi = 1.5e$, $e_\nu = 0.5e$.

	^{67}Cu		^{69}Cu		^{71}Cu		^{73}Cu	
	EXPT.	SM	EXPT.	SM	EXPT.	SM	EXPT.	SM
$E(1/2^-)$	1170	1118	1096	1325	454.2(1)*	1089	135.4(1)*	776
$E(5/2^-)$	1115	1390	1214	1524	534	1135	166	748
$E(7/2^-)$	1670	1815	1871	2026	1190	1583	961	1428
$B(E2; 1/2^- \rightarrow 3/2^-)$	14.0(13)	7.7	10.4(10)	7.1	20.4(22)	7.3	23.1(21)	7.5
$B(E2; 5/2^- \rightarrow 3/2^-)$	12.5(10)	2.1	3.0(3)	1.6	3.9(5)	1.7	4.4(5)	1.3
$B(E2; 7/2^- \rightarrow 3/2^-)$	3.0(5)	1.9	4.6(7)	1.2	10.7(12)	1.5	14.9(18)	2.3

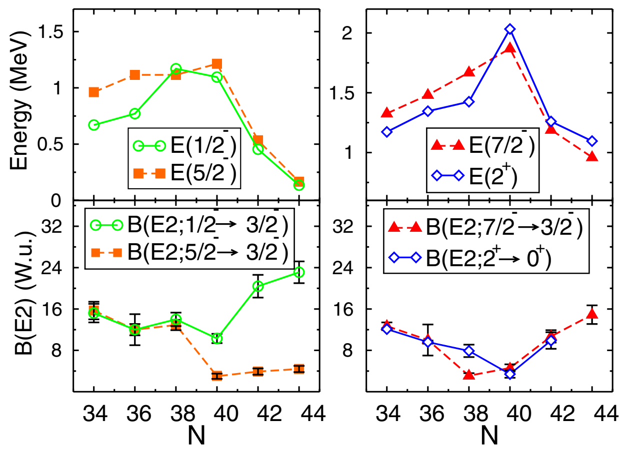

FIG. 2 (color online). Top: Systematics of the energies of the $1/2^-$, $5/2^-$, and core-coupled $7/2^-$ states in $^{63-73}$Cu along with the 2^+ levels in the even-even $^{63-73}$Ni. Bottom: Experimental $B(E2)$ values in ^{63,65}Cu [13], ^{67,69,71,73}Cu (present work), and $^{62-70}$Ni [16,27]. The lines connect the experimental points for the states of same spin but do not imply that the structure remains the same.

Next to the rather familiar particle-core states present in the odd-A Cu isotopic chain, two pronounced and distinctive structures emerge from $N = 40$ onwards. The $5/2^-$ state, whose dramatic drop in the excitation energy beyond $N = 40$ is believed to be caused by the monopole migration [7,8,10], shows a low $B(E2)$ value (<5 W.u.), confirming its assumed $\pi f_{5/2}$ single-particle character. The observed sharp drop in energy can indeed be attributed to the lowering of the $1f_{5/2}$ proton state when neutrons start filling the $1g_{9/2}$ orbital, in agreement with the predicted tensor effects for this mass region [8]. The newly identified low-spin states in ^{71,73}Cu, assumed $1/2^-$, show an identical energy evolution but a large $B(E2)$ value (>20 W.u.), which excludes a single-particle character of $\pi p_{1/2}$ type. As shown in Ref. [7], shell-model calculations employing a realistic interaction based on the G matrix [24] and modified by Nowacki for the monopole part [25] show a tendency to reproduce the energy trend of the low-lying states in ^{67,69,71,73}Cu but fail to account for the $B(E2)$ values; see Table II. The particle-core calculations reported in [23] also predict a low-lying $1/2^-$ state in ^{71,73}Cu, but no information on its structure is given. Furthermore, in contrast to the $7/2^-$ state, the $B(E2; 1/2^- \to 3/2^-)$ results do not follow the $B(E2)$ trend in the neighboring Ni isotopes. Thus, the low-energy level schemes of the odd-mass Cu isotopes at and beyond $N = 40$ are governed by three different structures: the expected proton single-particle excitations, particle-core-coupled states and a surprisingly low-lying collective mode. The onset of deformation in these nuclei is clearly related to the filling of the $\nu 1g_{9/2}$ orbital. The presence of this collective structure at such low excitation energies might indeed be responsible for the enhanced core polarization observed in ^{70}Ni [16] and could also explain the low magnetic moment reported recently for the $3/2^-$ ground state of ^{71}Cu [26].

In conclusion, the $B(E2)$ values for the transitions depopulating low-energy $1/2^-$, $5/2^-$, and $7/2^-$ states in the neutron-rich ^{67,69,71,73}Cu have been measured. These odd-proton nuclei span the $N = 40$ neutron subshell and $N = 3$ oscillator shell closure at ^{68}Ni. New low-energy levels with unexpectedly large $B(E2)$ values have been identified at 454 and 135 keV, respectively, in ^{71,73}Cu for which $1/2^-$ spin and parity are proposed. The increased collectivity could indicate significant deformation, although the position of these levels were foreseen in the vibrational model based calculations [23]. Our results indicate a significant drop in the $B(E2; 5/2^- \to 3/2^-)$ value that points to a change from a rather collective to a single-particle-like structure for the $5/2^-$ level at $N = 40$ and beyond. Thus, these new data reveal the presence of both single-particle and collective states at low energy in these neutron-rich Cu nuclei that drop with increasing value of N and lie at approximately the same energy. This behavior clearly illustrates the sensitivity of the transition rates to the details of the wave functions and emphasizes the importance of the present results to the understanding of the evolution of the shell structure in this mass region. Finally, the presence of collectivity at such a low excitation energy is likely to play an interesting role in the evolution of the structure of these Cu nuclei near the doubly magic nucleus ^{78}Ni and beyond.

This work was supported by EU Sixth Framework through No. EURONS-506065, BMBF under Contracts No. 06KY205I and No. 06MT238, BriX Research Program No. P6/23, FWO-Vlaanderen (Belgium), and DFG research cluster "Origin and Structure of the Universe."

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