COULOMB EXCITATION OF THE ODD-A ^{67,69,71,73}CU ISOTOPES WITH MINIBALL AND REX-ISOLDE

I. STEFANESCU

Instituut voor Kern en Stralingsfysika, KU Leuven, 3000 Leuven, Belgium,
Department of Chemistry and Biochemistry, University of Maryland,
College Park MD 20742 , USA

G. GEORGIEV

CSNSM, CNRS/IN2P3; Univ. Paris-Sud, UMR8609, F-91405 ORSAY-Campus, France

N. BREE, T.E. COCOLIOS, J. DIRIKEN, M. HUYSE, O. IVANOV, N. PATRONIS, P. VAN DUPPEN, J. VAN DE WALLE

Instituut voor Kern en Stralingsfysika, KU Leuven, 3000 Leuven, Belgium

MINIBALL AND REX-ISOLDE COLLABORATIONS

Collective properties of low-lying states in the neutron-rich ^{67,69,71,73}Cu isotopes were investigated by Coulomb excitation with radioactive beams produced at ISOLDE and postaccelerated by REX-ISOLDE up to 2.99 MeV/A. Experimental B(E2; $½^- \rightarrow 3/2^-_{g.s.}$), B(E2;$5/2^- \rightarrow 3/2^-_{g.s.}$) and B(E2;$7/2^- \rightarrow 3/2^-_{g.s.}$) were determined in all four investigated isotopes. Results show that the low-lying level schemes of these nuclei are governed by three different configurations: the expected proton single-particle excitations, core-coupled states and a surprisingly low-lying collective mode.

1. Introduction

In the past few years, Coulomb excitation with radioactive beams became one of the most used techniques for the study of the nuclear properties at low-excitation energies in exotic nuclei. Such experiments provide information on the electromagnetic transition rates between nuclear states as well as on the energies, spin and parities of the excited levels. Most of these experiments were dedicated to the investigation of the collective properties of even-even isotopes [1,2,3,4]. The preference for these nuclei come from the fact that such experiments mainly involve the well-resolved 2_1^+ state, allowing for a rather accurate measurement of the excitation cross-section. The investigation of the odd-A and odd-odd isotopes by Coulomb excitation is more challenging due to the fact that these nuclei show a high density of states at low excitation energies and, in most of the cases, excited levels are connected by low-collectivity transitions. Moreover, the study of the odd-odd isotopes is further complicated by the presence of isomeric states at low excitation energies.

In a recent paper we reported on the first use of post-accelerated isomeric beams for the investigation of the collective properties in the odd-odd ^{68,70}Cu by Coulomb excitation [5]. The beams were produced at the ISOLDE facility and postaccelerated by REX-ISOLDE. The present proceeding reports on the results of the follow-up Coulomb excitation experiment with radioactive beams of odd-A ^{67,69,71,73}Cu. With only one proton outside the Z=28 closed shell, the low-lying level schemes of the odd-A Cu isotopes provide an excellent means for studying the evolution of the proton single-particle energies with increasing neutron number. The discovery by Franchoo et al., of the sharp drop of the $5/2^-$ state in ^{71,73}Cu [6,7] provided the first experimental evidence that the filling of the $g_{9/2}$ orbital can cause significant shifts in the energy of the $f_{5/2}$ and $f_{7/2}$ proton orbitals, similar to the $h_{11/2}$ and $g_{7/2}$ in the odd-A Sn and Sb isotopes, respectively [8]. The observed systematic energy shifts were recently attributed to the tensor part of the nucleon-nucleon interaction which is believed to play an important role in the evolution of the shell structure away from stability [9]. For the neutron-rich nuclei with Z~28 and N between 40 and 50, the calculation predict that the tensor force lowers the $f_{5/2}$ and $f_{7/2}$ proton orbitals with respect to $\pi p_{3/2}$ leading to a quenching of the Z=28 shell gap with increasing neutron number [9].

We employed Coulomb excitation with radioactive beams in order to test to which extent the collectivity at low excitation energies in the odd-A $^{67\text{-}73}$Cu isotopes is affected by the observed energy shifts. The predicted quenching of the Z=28 shell gap leading to enhanced collectivity beyond N=40 should be clearly reflected in the experimental B(E2) values.

2. Experimental details

The radioactive Cu beams were produced at the ISOLDE facility by combining the proton-induced fission of an UC_x target with resonant laser ionization. After ionization, the Cu atoms were mass separated and postaccelerated by REX-ISOLDE to up to 2.99 MeV/A. The Coulomb excitation of the beams was induced by a 2 mg/cm^2 target of either ^{120}Sn or ^{104}Pd. Gamma-rays were detected with the segmented MINIBALL array while the scattered projectile and recoiling target nuclei were detected in a double-sided silicon detector (DSSD) which covered the angular range between 15° and 53° in the laboratory system. Typical beam intensities of ~10^5 ions/s were obtained for all four investigated isotopes. However, the Cu beams were contaminated with the Ga isobars, produced by surface ionization at the primary ISOLDE target-ion source system. The Ga contaminants were monitored by performing measurements with and without laser ionization (laser ON/OFF runs) on a regular basis. The amount of Ga isobar in each of the beams of interest was determined by comparing the yield of elastically scattered particles in the DSSD detector in the periods with the lasers switched on (both Ga and Cu present on the beam) and the periods with the lasers switched off (only Ga present in the beam). Values of 97% (^{67}Cu), 95% (^{69}Cu), 65% (^{71}Cu) and 17% (^{73}Cu) were obtained for the purity of the beams investigated in the present work.

3. Results

The Coulomb excitation spectrum obtained with beam of ^{67}Cu showed clear evidence for the population of the states at 1115 ($1/2^-$), 1170 ($5/2^-$) and 1670 keV ($7/2^-$). Similarly, the measurement with beam of ^{69}Cu revealed the transitions deexciting the levels at 1096 ($1/2^-$), 1214 ($5/2^-$) and 1871 keV ($7/2^-$). Based on the measured spectroscopic factors and comparison with particle-core calculations, the observed $7/2^-$ states were interpreted to be dominated by the $\pi 2p_{3/2} \otimes 2^+(^{66,68}\text{Ni})$ configurations, respectively, while the $\pi(1f_{7/2}^{-1}\ 2p_{3/2}^{2})$ structure was assigned to the $7/2^-$ levels at 2340 keV in ^{67}Cu and 1711 keV in ^{69}Cu [10,11], not populated in the present work.

The Doppler corrected particle-γ coincidence spectra obtained with beams of ^{71,73}Cu are displayed in Fig. 1. The spectrum with ^{71}Cu beam on the ^{104}Pd target revealed the transition depopulating the $7/2^-$ state at 1190 keV, see top spectrum of Fig. 1. A γ-ray of 454 keV was also observed. The comparison of the spectra acquired with and without laser radiation (top spectrum of Fig. 1, black and grey colors, respectively) showed that this transition is present only in the on-resonance spectrum, therefore it was assigned to ^{71}Cu. It is worth mentioning that a gamma-ray of 454 keV was also identified in the $\beta\gamma$-spectrum obtained in the measurement reported in [6,7] but it was not placed in the level scheme of ^{71}Cu as no $\gamma\gamma$ coincidences were observed.

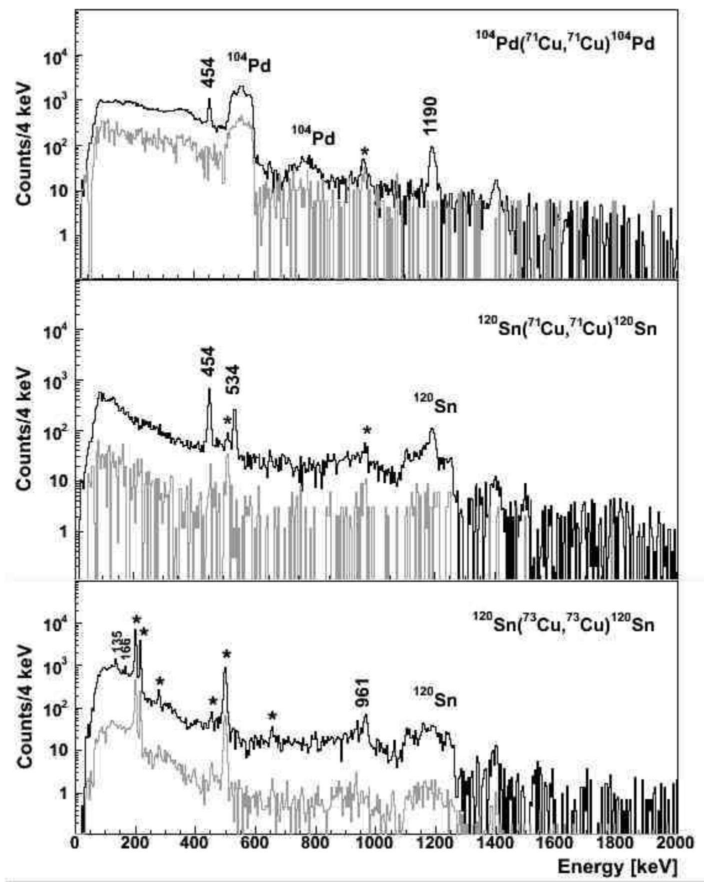

Figure 1. Laser ON (black) and OFF (grey) Doppler corrected particle-γ coincidence spectra obtained with beams of mass A=71,73. Gamma-rays arising from the deexcitation of the levels in ^{71,73}Cu are noted on the figure with their energies. The transitions from the Ga contaminants are marked with a star.

In the top spectrum of Fig. 1, the 534 keV transition arising from the decay of the $5/2^-$ level in ^{71}Cu could not be resolved from the Doppler broadened peak at 555 keV, deexciting the 2^+ state in ^{104}Pd. Thus, in the second part of the measurement with ^{71}Cu beam, the ^{104}Pd target was replaced by ^{120}Sn. The middle spectrum of Figure 1 displays the resulting particle-γ coincidence spectra obtained with and without laser radiation (black and grey lines, respectively). The on-resonance spectrum shows the 534 keV γ-ray as well as the newly identified 454 keV transition.

The bottom spectrum of Figure 1 shows the particle-γ coincidence spectra obtained with beam of ^{73}Cu (black: lasers ON, grey: lasers OFF) incident on the ^{120}Sn target. The strongest transitions observed in the spectra arise from the deexcitation of the levels in the ^{73}Ga isobaric contaminant. The gamma-lines of 166 and 961 keV, present in the on-resonance spectrum only, 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 [6,7]. The activity of the γ-ray of 135 keV, observed for the first time in our work, is clearly related to laser ionization, therefore it was assigned to the level-scheme of ^{73}Cu.

The particle-core model proposed the $7/2^-$ states at 1190 keV in ^{71}Cu and 961 keV in ^{73}Cu as candidates for the $\pi 2p_{3/2}\otimes 2^+(^{70,72}\mathrm{Ni})$ configurations while the $\pi(1f_{7/2}^{-1}\, 2p_{3/2}^{2})$ structure was assigned to the levels located at 981 and 1010 keV, respectively [11]. No γ-rays with these energies were observed in our spectra, indicating a low collectivity for the emitting states, in agreement with the suggested *2p-1h* character [11].

The deexcitation yields of the observed γ-rays 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 [12].

The top panel of Figure 2 shows the systematics of the levels in the odd-A $^{67-73}$Cu isotopes populated by Coulomb excitation in the present work. The new $(1/2^-)$ states at 454 keV in ^{71}Cu and 135 keV in ^{73}Cu are also represented. The analog levels in the stable ^{63,65}Cu as well as the 2^+ states in the Ni cores are included for comparison. The newly assigned levels are very close in energy with the $5/2^-$ states at 534 and 166 keV, respectively. This trend is very similar to that observed in the lighter ^{67,69}Cu, where the $5/2^-$ and $½^-$ states, separated by less than 130 keV (see top panel of Fig. 2), were both populated in our work. Thus, the energy systematics suggests a spin $½^-$ for the new levels in ^{71,73}Cu, assignment which is also in supported by the shell-model and particle-core calculations [11,13].

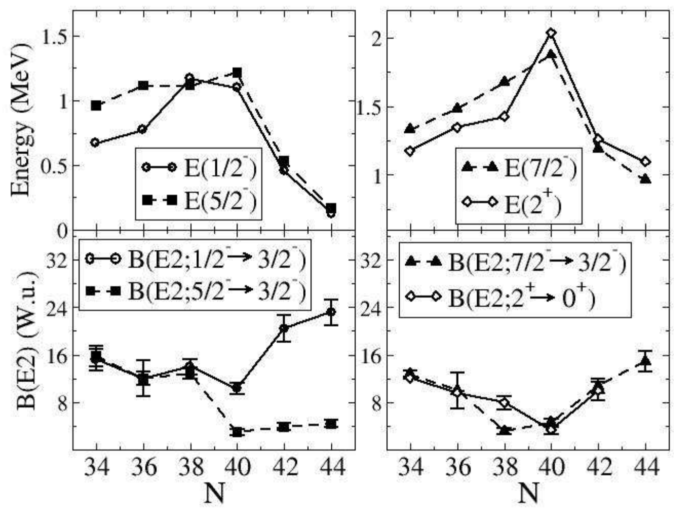

Figure 2. Top: Systematics of the energies of the ½$^-$, 5/2$^-$ and core-coupled 7/2$^-$ states in $^{63-73}$Cu along with the 2$^+$ levels in the even-even $^{62-72}$Cu. Bottom: Experimental B(E2) values in ^{63,,65}Cu [14], ^{67,69,71,73}Cu (present work) and $^{62-70}$Ni [4,15].

The B(E2) values extracted from the analysis of the deexcitation yields of the γ-rays observed in the present work are indicated in the bottom panel of Fig. 2. For comparison, the corresponding B(E2) values in the stable ^{63,65}Cu and the B(E2;$2^+\rightarrow0^+$) strengths in the even-even adjacent Ni isotopes are also included. In ^{67}Cu, the B(E2) values measured for the transitions depopulating the ½$^-$ and 5/2$^-$ states are found to be very similar to those measured in the stable ^{63,65}Cu, suggesting that the two extra neutrons in ^{67}Cu do not induce any important modifications in the structure of these two levels. In ^{69}Cu, however, the 5/2$^-$ state shows a significant loss in collectivity, most likely related to the presence of the N=40 subshell closure. However, neither the energies of the 5/2$^-$

and ½$^-$ states nor the B(E2;1/2$^-$→3/2$^-$) strength show any significant change when compared to ^{67}Cu.

In ^{71}Cu, the sharp drop of the energy of the proposed ½$^-$ state is found to lead to an important gain in collectivity while the decrease of the energy of the 5/2$^-$ level induces only a slight increase of the corresponding B(E2) value. In ^{73}Cu, however, the energies of the (1/2$^-$) and 5/2$^-$ states continue descending without affecting significantly the B(E2) transitions rates.

The large difference found experimentally between the B(E2;5/2$^-$→3/2$^-$) and B(E2;1/2$^-$→3/2$^-$) value beyond ^{67}Cu suggests a single-particle-like character for the 5/2$^-$ level and a deformed-like structure for the ½$^-$ state. Surprisingly, the very different nature is not reflected also in the energies of the two states, which are found to remain close together in all four investigated isotopes. This illustrates clearly the sensitivity of the transitions 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.

The B(E2) value obtained for the γ-ray depopulating the 7/2$^-$ state in ^{67}Cu is found to be a factor of two lower than what one would expect for a $\pi 2p_{3/2} \otimes 2^+(^{66}\mathrm{Ni})$ configuration. This deviation from the observed systematics and model predictions suggests an important polarization of the ^{66}Ni core by the $2p_{3/2}$ proton. After reaching a minimum at N=38, the B(E2;7/2$^-$→3/2$^-$) values start increasing, following closely the B(E2;2$^+$→0$^+$) strengths in the even-even adjacent Ni isotopes, in agreement with the proposed $\pi 2p_{3/2} \otimes 2^+$(Ni) configuration for the observed 7/2$^-$ states. Since the B(E2) transition rate in ^{72}Ni is not known experimentally, our measured B(E2;7/2$^-$→3/2$^-$) value in ^{73}Cu can give a good estimate of the collectivity of the 2$^+$ state in ^{72}Ni. It is interesting to note that the B(E2;2$^+$→0$^+$) values measured in even-even Zn isotopes also show a minimum at N=38 and not at N=40 like in the Ni isotopic chain. Shell-model calculations performed in [4] indicated that in the Zn isotopes, the pairing correlations start filling the $\nu 1g_{9/2}$ orbital earlier than in the Ni nuclei, with the extra $\nu 1g_{9/2}$ neutrons giving an important contribution to the B(E2) value in $^{70}\mathrm{Zn}_{40}$.

In conclusion, we measured the B(E2) values for the transitions depopulating the low-lying ½$^-$, 3/2$^-$ and 7/2$^-$ states in the neutron-rich ^{67,69,71,73}Cu, isotopes located in the immediate neighborhood of ^{68}Ni, a key nucleus for this mass-region. This is for the first time when Coulomb excitation with radioactive beams is employed for the investigation of the odd-A nuclei in this part of the nuclear chart. The results indicate that below ^{69}Cu, the ½$^-$ and 5/2$^-$ states have properties consistent with the interpretation as levels arising from the $\pi 2p_{3/2} \otimes 2^+$(Ni) multiplet. The drop in the B(E2;$5/2^- \rightarrow 3/2^-$) value in ^{69}Cu points to a change from a rather collective to a single-particle-like structure for the $5/2^-$ state. A new level was identified at low excitation energies in ^{71,73}Cu. Based on systematics and model calculations, a spin $½^-$ was assigned to the new state. The large B(E2;$1/2^- \rightarrow 3/2^-$) strength suggests a deformed structure for this level. Thus, our results indicate a competition of single-particle and collective configurations at low excitation energies in the odd-A Cu isotopes beyond N=40, competition which is expected to play an interesting role for the structure of the neutron-rich nuclei near ^{78}Ni.

Acknowledgments

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

References

1. O. Sorlin et al., Phys. Rev. Lett. **88**, 092501 (2002).
2. E. Padilla-Rodal et al., Phys. Rev. Lett. **94**, 122501 (2005).
3. O. Niedermaier et al., Phys. Rev. Lett. **94**, 172501, (20051,2,3,4]).
4. O. Perru et al., Phys. Rev. Lett. **96**, 232501 (2006).
5. I. Stefanescu et al., Phys. Rev. Lett **98**, 122701 (2007).
6. S. Franchoo et al., Phys. Rev. Lett. **81**, 3100, (1998).
7. S. Franchoo et al., Phys. Rev. **C64**, 054308, (2001).
8. W. B. Walters in *Nuclear Fission and Fission Products Spectroscopy*, AIP Conf. Proc. No. 447 (AIP, Woodbury, NY, 1998), p. 196.
9. T. Otsuka et al., Phys. Rev. Lett. **95**, 232502 (2005).
10. B. Zeidman and J.A. Nolan, Phys. Rev. **C18**, 2122 (1978).
11. A. M. Oros-Peusquens and P.F. Mantica, Nucl. Phys. **A669**, 81 (2000).
12. T. Czosznyka, D. Cline, and C.Y.Wu, Bull. Am. Phys. Soc. **28**, 745 (1983).
13. N. Smirnova et al., Phys. Rev. **C69**, 044306 (2004).
14. R.L. Robinson, F.K. McGowan, and P.H. Stelson, Phys. Rev. **134**, B567 (1964).
15. S. Raman, C.W. Nestor Jr., P. Tikkanen, At. Data Nucl. Data Tables **78**, 1 (2001).