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Addendum to the IS435 experiment

Coulomb excitation of odd-mass and odd-odd Cu isotopes using REX-ISOLDE and Miniball

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Abstract

We propose to study the properties of the low-lying levels in ^{70,72,75}Cu by Coulomb excitation using the REX-ISOLDE facility and Miniball array. During the summer campaigns 2005 and 2006, successful Coulomb excitation measurements with radioactive beams of odd-odd ^{68,70}Cu and odd-A nuclei ^{67,69,71,73}Cu have been performed. For the measurement of the $B(E2; 6^- \to 4^-)$ value in ^{68,70}Cu, isomerically purified 6^- beams were post-accelerated for the first time.

Introduction

In the past few years, Coulomb excitation with radioactive beams became one of the most used technique 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 the Coulomb excitation experiments with radioactive beams were dedicated to the investigation of the structure of the even-even nuclei [1, 2, 3, 4]. The preference for these nuclei comes from the fact that such experiments primarily involve the well-resolved excitation of the first 2^+ state, allowing for a rather accurate measurement of the cross-section. The results of these measurements provided important but incomplete information about the evolution of collectivity far from stability. A consistent understanding of the nuclear force in the neutron-rich systems requires also experimental information in the odd-A and odd-odd nuclei. Investigating these nuclei by Coulomb excitation with radioactive beams is extremely challenging due to the higher density of levels at low-excitation energies and low collectivity of the transitions involved. The study of the odd-odd nuclei by Coulomb excitation is often further complicated by the presence of isomeric states at low-excitation energy. Moreover, although the nuclear states are mainly populated by $E2$ excitations, the Coulomb excitation process does not give any information about the decay mode of these states. For instance, to extract the experimental $E2$ and $M1$ transition probabilities from the observed deexcitation γ-rays, additional information like mixing ratios or lifetimes of the nuclear levels is needed. In the neutron-rich nuclei, such information is rather scarce, therefore assumptions regarding their magnitude have to be made.

The study by Coulomb excitation of the nuclear properties in the neutron-rich nuclei around N=40 subshell and the evolution of collectivity towards N=50 shell gaps has become a key topic in the physics with radioactive beams. The results of these experiments brought additional evidence about the magicity of ^{68}Ni [1] but also proved the fragility of the stabilizing effect of the Z=28 and N=40 gaps when two like-particles are coupled to the ^{68}Ni core [4, 5]. The recent measurements of the $B(E2; 2^+ \to 0^+)$ values in ^{82}Ge and ^{80}Zn [2, 6] were aimed to the investigation of the magicity of the N=50 shell closure.

For a deeper understanding of the underlying microscopic structure of the investigated nuclei, the experimental data are compared with the results of different model calculations. Since the residual proton-neutron interaction is still poorly studied, the attempts to describe the observed properties were only partially successful [1, 2, 4]. At the same time, the different theoretical approaches seemed to have agreed on a few key points regarding the structural changes induced by the extra amount of neutrons with respect to the stable nuclei. It became commonly accepted that the monopole part of the interaction plays an important role in the neutron-rich nuclei since it influences the effective single-particle energies and therefore the energy of the shell gaps [7, 8, 9, 10, 11].

The moderate success of the shell-model calculations for the N=40-50 neutron-rich nuclei is due to the lack of empirical information needed in order to improve the accuracy of the residual interaction used. For instance, electromagnetic properties were measured only in a few even-even nuclei and single-particle energies were experimentally determined in a very limited number of odd-A nuclei.

In 2005 we proposed the investigation of the odd-odd ^{68,70}Cu and odd-A ^{67,69,71}Cu isotopes by Coulomb excitation with Miniball and REX-ISOLDE [16]. With only one valence proton above the Z=28 shell gap, the neutron-rich Cu isotopes are the best candidates for the study of the residual interaction by studying the proton single-particle energies when neutrons start filling the $\nu g_{9/2}$ orbital. More details about the physics case can be found in the original proposal [16]. A total of 29 shifts was allocated to this measurement (Experiment IS435) which were split into two parts. The Coulomb excitation of the odd-odd nuclei ^{68,70}Cu was performed during the summer campaign 2005, whereas a few days during the summer campaign 2006 were dedicated to the measurement of the odd-A nuclei ^{67,69,71}Cu. Both runs were very successful from the point of view of the physics outcome.

In the following, a short report on the status of the analysis of the data taken in each of the two runs is presented.

Status of the Experiment IS435

Coulomb excitation of the odd-odd ^{68,70}Cu isotopes (Summer campaign 2005)

The aim of this experiment was the study of the effects induced by the coupling of the odd proton particle and odd neutron particle/hole to the ^{68}Ni core, by measuring the reduced transition probabilities within the states I^{π}=$(3^-, 4^-, 5^-, 6^-)$ of the configuration with predominant $\pi 2p_{3/2}\nu 1g_{9/2}$ character. The states with the single-particle angular momenta fully aligned (6^-=$9/2^+ \otimes 3/2^-$) or anti-aligned (3^-=$9/2^+ \otimes 3/2^-$) are long-lived. The isomeric nature of the 6^- state in ^{68,70}Cu and 3^- state in ^{70}Cu was experimentally determined in previous works [17, 18]. Transfer reaction studies fixed the energy of the 6^- isomer at 721 keV in ^{68}Cu [19]. The other members of the multiplet were proposed at 778 (3^-), 956 (4^-) and 1350 keV (5^-) [19, 20]. Spins were assigned to these states based on the parabolic rule for proton-neutron multiplet suggested by Paar [21]. In ^{70}Cu, spin and parity 6^- were assigned to the ground-state based on the observed β-decay pattern. Candidates for the remaining members of the multiplet were proposed at 101 (3^-), 226 (4^-) and 506 keV (5^-) [13, 22]. The presence of the long-lived isomer 6^- in ^{68,70}Cu and 3^- in ^{70}Cu led to the development of isomeric beams that were used for the study of the magnetic moments and nuclear masses in both nuclei [18, 22]. The isomeric separation was obtained through selective laser ionization [23]. In summer 2005, these isomeric beams were post-accelerated for the first time up to 2.9 MeV/A and used for Coulomb excitation studies with Miniball.

The particle-γ coincidence spectrum obtained in the measurement with 6^- isomeric beam of ^{68}Cu revealed the prompt transition of 178 keV and the delayed γ-rays of 693 and 84 keV, defining the sequence $(4^-) \rightarrow 3^- \rightarrow 2^+ \rightarrow 1^+$ (see upper part of fig. 1). The (3^-, 4^-) states are the member of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet whereas the (1^+, 2^+) states result from the $\pi 2p_{3/2}\nu 2p_{1/2}$ configuration. The (4^-) state is populated by an $E2$ excitation with 6^- isomeric beam, thus fixing the spin 4^- for this level. The preference for the $4^- \rightarrow 3^-$ decay path can be understood from the comparison of the partial decay lifetime for the 4^- level. The partial decay lifetimes of a $M1$ transition is in the picoseconds range, in agreement with the observation of the Doppler broadened peak of 178 keV, while an $E2$ transition would have a partial lifetime four orders of magnitude higher, based on Weisskopf estimates.

The particle-γ coincidence spectrum obtained in the measurements with 6^- isomeric beam of ^{70}Cu revealed the prompt transition $4^- \rightarrow 3^-$ of 127 keV. The spectrum and partial level-scheme showing the observed γ-ray are shown in fig. 2.

Before extracting the experimental $B(E2)$ values, the purity of the beam had to be determined. In both cases, the 6^- isomeric beam was contaminated with contributions from the low-spin isomers: 1^+ in the case of ^{68}Cu and (1^+, 3^-) in the case of ^{70}Cu. The isomeric beam contamination stemmed from the broadening of the hyperfine-split resonances of each isomer [22, 23]. The characteristic γ-rays produced in their β-decay allowed to determine the isomeric content of the beam. Moreover, the ^{68,70}Cu were also contaminated with the Ga isobars, produced by surface ionization in the ISOLDE laser ion-source. The amount of Ga isobar was determined in each case by performing laser ON/OFF runs and comparing the number of scattered particles in the CD-detector in the periods with the lasers ON (Cu and Ga present in the beam) and periods with the lasers OFF (only Ga present in the beam). Information about the quality of the ^{68,70}Cu 6^- isomeric beams is summarized in Table 1. It is worthwhile to mention that due to the fact that a W transfer line was used at the primary ISOLDE ion-source, the intensity of the beam obtained in both runs was by an order of magnitude lower than expected.

In the case of ^{68}Cu, the contribution of the 1^+ isomeric contaminant to the spectrum given in the upper part of fig. 1 was checked by setting the laser frequency to the value found to produce the maximum ionization of this low-spin isomer [18]. The Coulomb excitation spectrum acquired with 1^+ isomeric beam is shown in the bottom part of the figure. 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 experimental Coulomb excitation cross-section $\sigma_{CE}(6^- \rightarrow 4^-)$ was determined in both nuclei relative to the known cross-section for exciting the 2^+ state in the ^{120}Sn target. The $B(E2; 6^- \rightarrow 4^-)$ value extracted for ^{68}Cu is 68(6) e^{2}fm^4 (4.1(4) W.u.). 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 needed to be considered. The insufficient experimental information did not allow for the determination of both reduced matrix elements involved in the excitation of the 4^- state, therefore we assumed the relation $\langle 6^- || E2 || 4^- \rangle = 0.94 \langle 3^- || E2 || 4^- \rangle$, as predicted by the shell-model calculation for a pure $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration [24]. With this assumption, a value of $B(E2; 6^- \rightarrow 4^-) = 41(5)$ e^{2}fm^4 (2.4(3) W.u.) was determined in ^{70}Cu.

The $B(E2)$ values measured in the present work are summarized in Table 2 and compared to the predictions of the shell-model. The value deduced from the assumed $(6^-) \rightarrow (4^-)$ transition in ^{72}Cu [26, 27] is also included in the table. The valence space

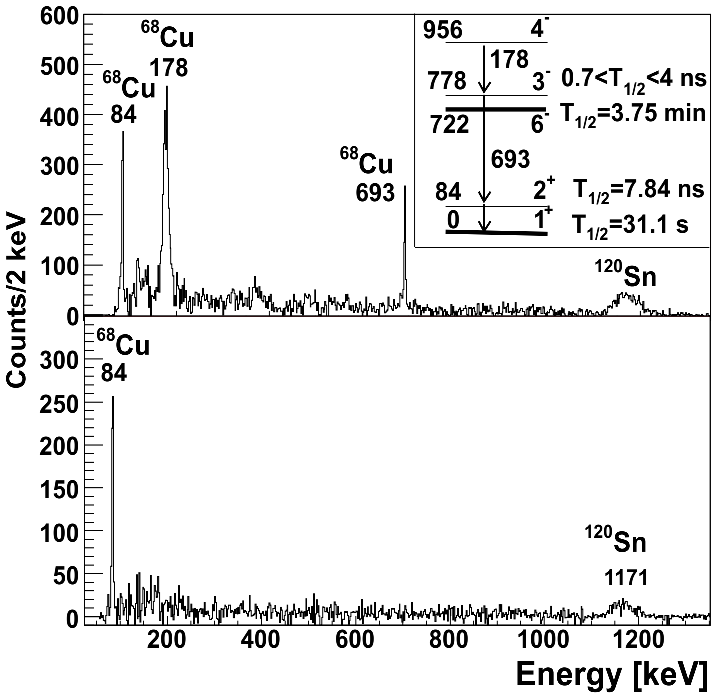

Figure 1: *Top: Particle-γ coincidence spectrum acquired with the 6^- beam of ^{68}Cu. The partial level scheme and deexcitation γ-rays shown in the upper right corner are based on Ref. [20] and this work. Energies are given in keV. Levels drawn with thick lines represent the β-decaying isomers. Bottom: particle-γ coincidence spectrum acquired with the 1^+ beam of ^{68}Cu. No Doppler correction was applied to these spectra.*

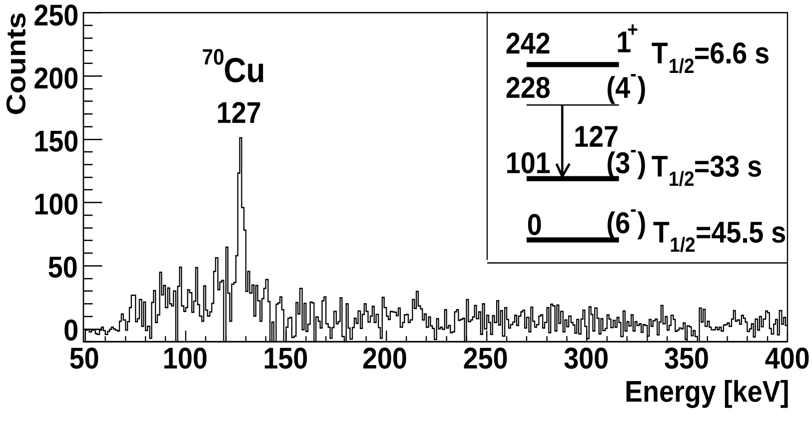

Figure 2: *Particle-γ coincidence spectrum obtained from the measurement with the 6^- isomeric beam of ^{70}Cu. The spectrum is Doppler corrected for mass A=70. Upper right corner: partial level scheme of ^{70}Cu taken from Ref. [22]. Levels drawn with thick lines represent the β-decaying isomers. The gamma-ray observed in this work is also drawn. Energies are given in keV.*

Beam	Energy (MeV/A)	Beam Intensity (REX) (pps)	Time (h)	Contaminant (%)		
				Cu/total	1^+/total	3^-/total
^{68}Cu (6^-)	2.83	$3{\cdot}10^5$	12.3	74(2)	14(3)	-
^{70}Cu (6^-)	2.83	$5{\cdot}10^4$	28	70(5)	7(2)	7(3)

Table 1: *Information concerning the quality of the ^{68,70}Cu 6^- isomeric beams: energy, intensity, total measuring time, contamination. Both isotopes were produced by bombarding an UC_x target with 6 equidistant proton pulses per PS booster supercycle (1 supercycle=12 proton pulses). A W transfer line was used and the mass separation of the Cu ions was performed with the HRS.*

considered in the calculations for both protons and neutrons consist of the fpg orbitals outside the ^{56}Ni inert core, without any restriction on their occupation.

Isotope	$B^{exp}(E2)$ (e^2fm^4)	$B^{th}(E2)$ (e^2fm^4)	ME (efm^2)	M_π (efm^2)	M_ν (efm^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)*	43.2	23.7	11.5	12.9

*Refs. [26, 27]

Table 2: *Experimental and calculated $B(E2;6^-\to4^-)$ 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 $e_\pi = 1.5e$ and $e_\nu = 0.5e$ were used in the calculations.*

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 indicate 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.

The results of this run are presented in a paper submitted to Physical Review Letters.

Coulomb excitation of the odd-A ^{67,69,71}Cu isotopes (Summer campaign 2006)

In the summer campaign 2006, the Coulomb excitation experiment with radioactive beams of ^{67,69,71}Cu was performed. The aim of the measurement was to investigate the nature of the low-lying negative-parity states I^π=$1/2^-$, $5/2^-$, $7/2^-_1$, $7/2^-_2$ by Coulomb excitation. Prior to this work, the level-structure of these nuclei was studied in β-decay, transfer and fragmentation reactions [12, 13, 14, 15]. The experimental spectroscopic factors determined for the $3/2^-$ (g.s.), $1/2^-$ and $5/2^-$ states in ^{67,69}Cu indicated large components of $2p_{3/2}$, $2p_{1/2}$, $1f_{5/2}$ single-proton excitations, respectively, whereas the two states with proposed spin and parity $7/2^-$ were interpreted as $(\pi 2p_{3/2})^2_{0^+} 1f^{-1}_{7/2}$ (2p-1h excitation) and $2^+_1(^{66,68,70}\mathrm{Ni}) \otimes \pi 2p_{3/2}$, respectively [12, 14, 25].

Beam	$T_{1/2}$	Target	Energy (MeV/A)	Beam intensity (REX) (pps)	Time (hours)	Cu/total (%)
^{67}Cu	61.9 h	^{104}Pd	2.9	$^{\star}1.2 \cdot 10^5$	30	97(1)
^{69}Cu	3 min	^{104}Pd	2.9	$^{\star}1.5 \cdot 10^5$	40.9	94(1)
^{71}Cu	19.5 s	^{104}Pd	2.9	$^{\star\star}1.5 \cdot 10^5$	12.4	66(1)
^{71}Cu	19.5 s	^{120}Sn	2.9	$^{\star\star}1.9 \cdot 10^5$	8.12	76(1)

*Intensity obtained with 3 proton pulses per supercycle, 10^{13} protons/pulse.

**Intensity obtained with 5 proton pulses per supercycle, $3 \cdot 10^{13}$ protons/pulse.

Table 3: *Information concerning the quality of the ^{67,69,71}Cu beams: half-life, energy, intensity, total measuring time (only laser ON data), contamination. All isotopes were produced by bombarding an UC_x target with 14 proton pulses/supercycle and using a Ta transfer line. Mass separation was performed with the GPS. The fluctuation in the Cu/total ratio extracted in the two measurements with ^{71}Cu beam is due to technical problems with the lasers.*

The identification of the $5/2^-$ state in ^{71,73}Cu indicated a sudden drop in energy with respect to its position determined in the lighter odd-A Cu isotopes. This was interpreted as being caused by the monopole part of the nuclear interaction acting between the neutrons filling the $1g_{9/2}$ orbital and the odd-proton occupying the $1f_{5/2}$ single-particle orbital [12, 25]. The energy shift was rather well reproduced by the shell-model calculations [7]. Theory predicts the same effect for the $2p_{1/2}$ single-particle orbital. However, the experimental energy of the $1/2^-$ single-particle state is not known experimentally in the odd-mass Cu nuclei with A$\geq$71. Such a lowering of the $2p_{1/2}$ and $1f_{5/2}$ orbitals are expected to give rise to an erosion of the Z=28 shell gap [9], leading to an increased collectivity in the odd-mass Cu isotopes beyond N=40. The measurement of the reduced transition probabilities in these nuclei will definitely help clarifying this issue.

Information about the energy, intensity and quality of the ^{67,69,71}Cu beams is summarized in Table 3. The ^{67,69}Cu beams were copiously produced at the primary ISOLDE target, therefore their intensity had to be limited by reducing the number and intensity of the proton pulses used by this experiment.

Figure 3 shows the particle-γ coincidence spectra obtained with radioactive beams of ^{67,69,71}Cu, Doppler corrected for the mass of the projectile. The spectra show the γ-rays depopulating the known $5/2^-$, $1/2^-$ and $7/2^-$ levels in ^{67,69}Cu. The coulex spectrum obtained for ^{71}Cu revealed a new transition of 454 keV which was assigned to the decay of the $1/2^-$ state. The measurement with the ^{120}Sn target did not allow the observation of the transition depopulating the $7/2^-_2$ state at 1190 keV, since this peak was very close in energy with the $2^+ \rightarrow 0^+$ transition of 1170 keV in the target. For the determination of the $B(E2; 7/2^-_2 \rightarrow 3/2^-)$, in the second part of the measurement with ^{71}Cu beam, the ^{120}Sn target was replaced by a ^{104}Pd target.

The analysis of the data taken during this run is in progress.

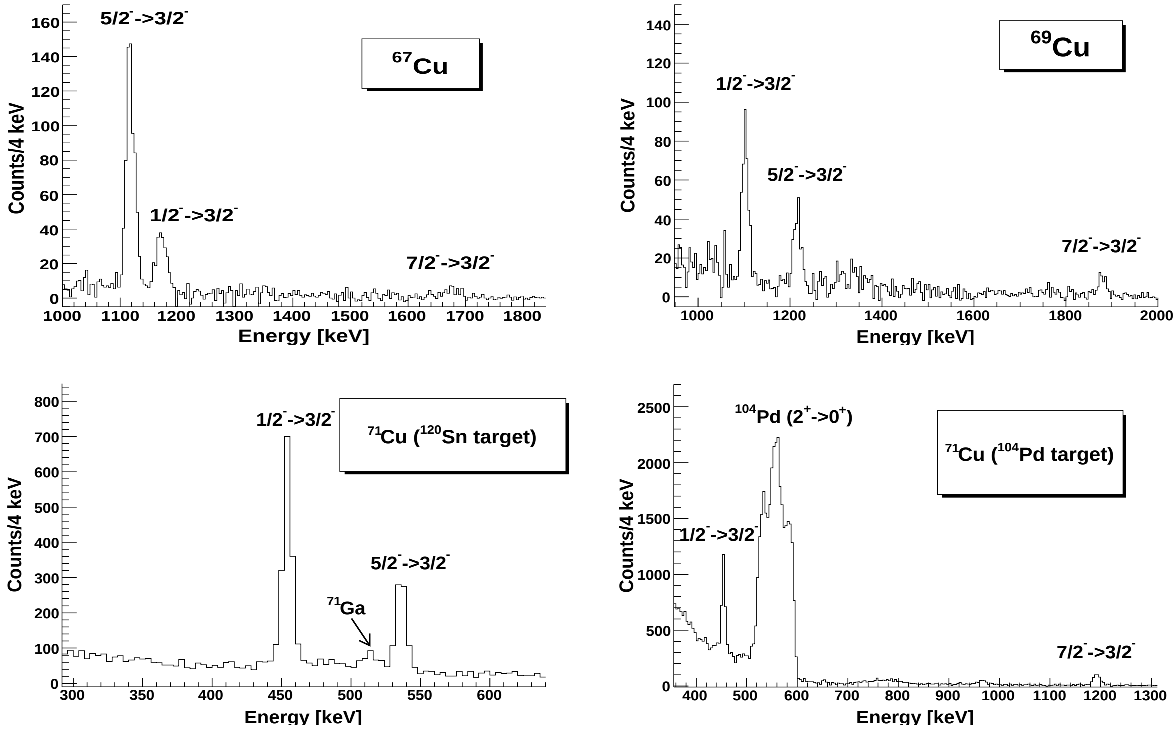

Figure 3: *Particle-γ coincidence spectra obtained with radioactive beams of ^{67,69,71}Cu. Spectra are random subtracted and Doppler corrected for the mass of the projectile.*

Testing the Coulomb excitation of ^{73}Cu at REX-ISOLDE (Summer campaign 2006)

The successful measurement of ^{67,69,71}Cu gave us confidence that the investigation by Coulomb excitation of the low-energy levels in the heavier ^{73}Cu is also feasible at REX-ISOLDE. At the end of the beamtime allocated for the measurement of ^{67,69,71}Cu nuclei, one shift was used for testing the production, post-acceleration and coulex of ^{73}Cu. The observation of the surprisingly high coulex cross-sections for populating the levels in ^{71}Cu together with the identification of the $1/2^-$ state strongly motivated the test of the heavier ^{73}Cu. In this nucleus, the levels of interest are located at excitation energies lower than those of the corresponding levels in ^{71}Cu [12, 25]. Also, the presence of the two extra-neutrons in the $g_{9/2}$ orbital is expected to induce an increase in collectivity by core polarization. Thus, the decrease in the intensity of the beam with respect to that of ^{71}Cu was expected to be partially compensated in ^{73}Cu by the gain in excitation cross-section due to the enhanced collectivity and higher efficiency for detecting the lower-energy γ-rays.

Information concerning the quality of the ^{73}Cu beam is summarized in Table 4. The high contamination of the beam with the ^{73}Ga isobar was also due to a malfunctioning of the lasers during the test. In fig. 4 the particle-γ coincidence spectrum obtained in the measurement with the lasers ON (top) and lasers OFF (bottom) is shown. The known γ-ray of 166 keV and the newly observed transition of 135 keV were attributed to ^{73}Cu. Both γ-rays contain sufficient statistics for an accurate determination of the

Beam	$T_{1/2}$	Target	Energy (MeV/A)	Yield$^{Cu}_{REX}$ (pps)	Time (h)	Cu/total (%)
^{73}Cu	3.9 s	^{120}Sn	2.9	$^{\star}1.5{\cdot}10^{4}$	12	19(1)

*Intensity obtained with 6 proton pulses per supercycle, $3{\cdot}10^{13}$ protons/pulse.

Table 4: *Information concerning the quality of the ^{73}Cu beam: half-life, energy, yield, total measuring time (only laser ON data), contamination. The beams was produced by using an UC_2 target and a Ta transfer line. Mass separation was performed with the GPS.*

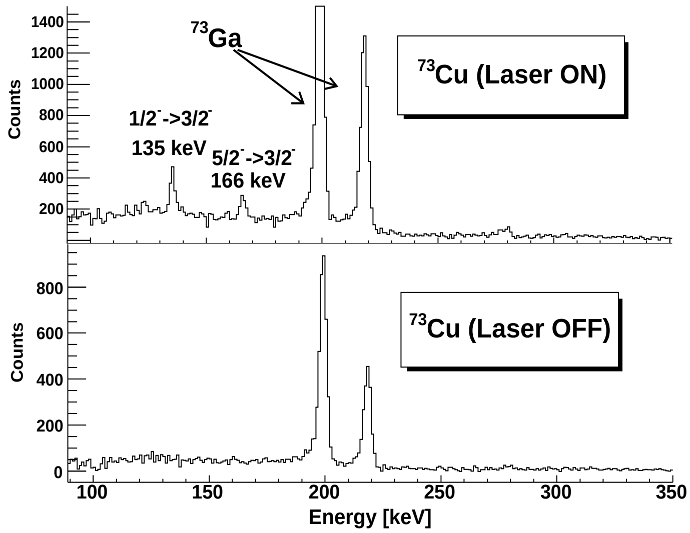

Figure 4: *Particle-γ coincidence spectra obtained with radioactive beam of ^{73}Cu. Spectra are random subtracted and Doppler corrected for the mass of the projectile. The gamma-ray of 135 keV is observed only in the laser ON data therefore it was assigned to ^{73}Cu.*

reduced transition probabilities. Thus, the test run with ^{73}Cu proved to be extremely successful not only from the point of view of the production and post-acceleration of the beam, but also for the rich physics outcome.

Figure 5 shows the systematics of the $5/2^-$, $1/2^-$ and $7/2^-$ states in the odd-A $^{61-73}$Cu isotopes. The $7/2^-$ states plotted are those suggested to result from the coupling of the odd proton in $2p_{3/2}$ orbital to the 2^+ state of the even-even neighboring Ni nuclei. Thus, the $B(E2; 7/2^- \rightarrow 3/2^-)$ values in ^{69,71,73}Cu are expected to be very similar to the $B(E2; 2^+ \rightarrow 0^+)$ values in ^{68,70,72}Ni. It is worthwhile mentioning that the $B(E2; 2^+ \rightarrow 0^+)$ value in ^{72}Ni was not yet experimentally determined, therefore the $B(E2; 7/2^- \rightarrow 3/2^-)$ value measured in ^{73}Cu will provide an initial estimate for the amount of collectivity at low-excitation energy in this even-even nucleus. The systematics presented in fig. 5 also shows that the newly observed $1/2^-$ states in ^{71,73}Cu closely follow the energy of the $5/2^-$ levels, in agreement with the shell-model calculations [7].

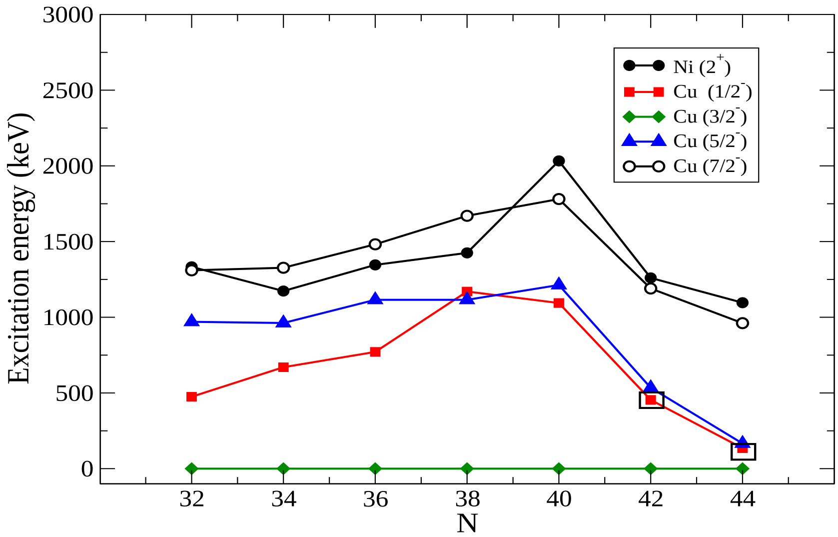

Figure 5: *Systematics of the low-lying energy levels in the odd-A* $^{61-73}$*Cu isotopes. For comparison, the energy of the* 2^+ *states in the even-even Ni isotopes is also presented. The newly identified* $1/2^-$ *states in* ^{71,73}*Cu are marked by a square.*

Addendum to Experiment IS435: Coulomb excitation of the odd-N ^{70,72}Cu and odd-A ^{75}Cu nuclei

^{70}Cu

Due to the low intensity of the ^{70}Cu beam obtained in the 2005 run, the Coulomb excitation measurement with the 3^- isomeric beam was not feasible. The measurements with 6^- and 3^- isomeric beams are expected to provide complementary information about the energy levels and reduced transition probabilities of the connecting transitions between the states of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet (see original proposal [16]). For instance, the measurement with the 6^- isomeric beam aimed to the investigation of the 4^- state of the multiplet by fixing its spin and measure the $B(E2; 6^- \to 4^-)$ value while the measurement with the 3^- beam was proposed for the investigation of the 5^- state of the multiplet (see figure 6).

In this addendum we reaffirm our interest in measuring the Coulomb excitation of ^{70}Cu with 3^- isomeric beam. The yields obtained for ^{69,71}Cu during the 2006 run by using a Ta transfer line indicate a gain by a factor of 10 in the ^{70}Cu yield with respect to that obtained in 2005. The higher beam intensity makes such a measurement feasible thereby allowing for the determination of the energy of the 5^- state by observing the deexcitation γ-rays. Furthermore, the measurement of the $B(E2)$ values of the decaying transitions will provide additional information about the underlying structure of the $\pi 2p_{3/2}\nu 1g_{9/2}$ multiplet.

^{72}Cu

The low-lying level scheme of the odd-odd ^{72}Cu was recently investigated in fragmen-

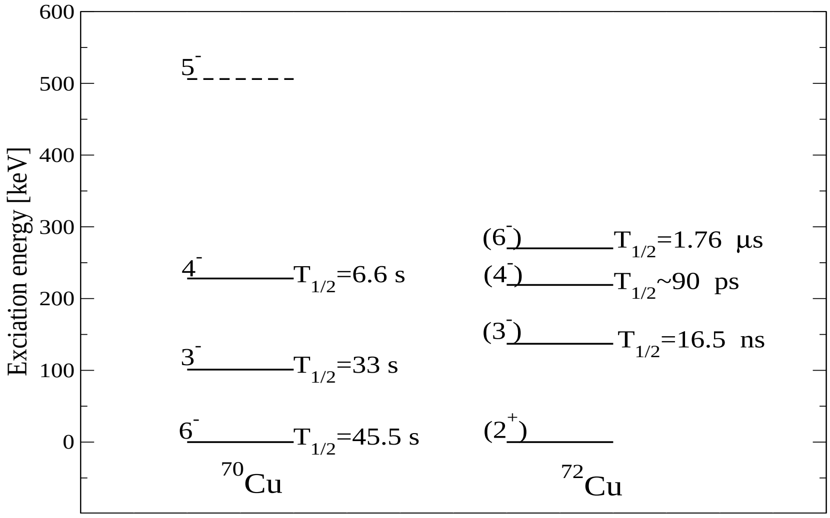

Figure 6: *Partial level schemes of* ^{70,72}*Cu taken from Refs. [13, 27]. The* 5^- *level in* ^{70}*Cu is represented with a dashed line and it was placed at the energy proposed in Ref. [13].*

tation and β-decay studies [26, 27]. The fragmentation of a ^{76}Ge beam of 60 MeV/u allowed for the determination of the energies and lifetimes of the excited levels by employing the time-delayed coincidence technique [26]. In that work, spins were assigned to the observed levels based on the measured lifetime and multipolarity considerations, see fig. 6. The spins $I = (2, 3)$ for the ground and first excited states, respectively, were also suggested by the results of the recent β-decay experiment [27]. However, the positive-parity assigned to the ground-state in the fragmentation study could not be confirmed and the $I^\pi = (4^-, 6^-)$ states were not observed, this being explained by the low-spin and the positive parity of the 0^+ ground-state of the mother nucleus ^{72}Ni [27]. In contrast to ^{70}Cu, no β-decaying isomeric states were identified in ^{72}Cu.

Two theoretical explanations were proposed to justify the spin $I = (2)$ for the ground-state in ^{72}Cu [27]. In both cases, an unexpected drop in energy of either a 2^+ state of $\pi 2p_{3/2}\nu(2p^{-1}_{1/2}1g^4_{9/2})$ configuration or a 2^- state of $\pi 1f_{5/2}\nu 1g^3_{9/2}$ component was invoked. The second scenario suggests a dramatic lowering of the $1f_{5/2}$ proton orbital in ^{72}Cu relative to ^{70}Cu, owing to the addition of the two extra-neutrons in the $1g_{9/2}$ orbital. Neither large-scale shell-model calculations [27] nor the experimental magnetic moment measured for the ground-state of ^{72}Cu by in-source atomic spectroscopy [28, 29] support the $I = 2$ spin assignment. Shell-model predicts that in ^{72}Cu, the states of the $\pi 2p_{3/2}\nu 1g_{9/2}$ configuration are still the lowest in energy and the $I = 6^-$ member of the multiplet is the ground-state, which is in agreement with the measured magnetic-moment [27, 28].

In this addendum we propose to investigate the low-lying level structure of ^{72}Cu by Coulomb excitation. Since $E2$ excitations have the largest probability, only the population of those states which differ from the spin of the ground-state by ± 1, $2\hbar$ units of angular momentum is expected. The selective population of the excited states together with the observed γ-decay pattern and known lifetimes [26] will help us fixing the spins and parities of the levels and extract the reduced transition probabilities of the deexcitation transitions.

^{75}Cu

We are aiming to extend our investigations on the structure of the odd-A neutron-rich Cu isotopes by measuring the Coulomb excitation of ^{75}Cu. Apart from the half-life $T_{1/2}$=1.22 s of the ground-state, nothing else is known for this nucleus. Based on the observed systematics of the low-lying states in the lighter Cu isotopes (see fig. 5) and shell-model calculations [7], in ^{75}Cu the $1f_{5/2}$ and $2p_{3/2}$ orbitals are expected to cross, with the former becoming the ground state. In this case the ground-state will have spin and parity $I = 5/2^-$, the first excited states will be $I = 3/2^-$ and $1/2^-$ or vice versa, expected to be located below 500 keV excitation energy. Relative to ^{73}Cu, the two extra neutrons in ^{75}Cu fill the upper part of the N=40-50 subshell, therefore a reduced collectivity is expected.

By employing Coulomb excitation we expect to populate the first two excited states and therefore determine their energies. Based on the systematics of the $B(E2)$ values measured in the lighter neutron-rich Cu isotopes, we can also draw conclusions about the spin order of the observed states and extract the reduced transition probabilities for the observed deexcitation γ-rays.

Summary

In this addendum we propose to extend our investigations on the low-lying level structures of the neutron-rich Cu isotopes by measuring the odd-odd ^{70,72}Cu and odd-A ^{75}Cu nuclei by Coulomb excitation with Miniball and REX-ISOLDE. The aim of the measurement with ^{70}Cu is to fix the energy of the 5^- state of the multiplet with predominant $\pi 2p_{3/2} \nu 1g_{9/2}$ character and determine $B(E2)$ values of the deexcitation transitions. The experiment with ^{72}Cu beam will fix the spin and parity of the ground state. We also propose to study the odd-A nucleus ^{75}Cu by Coulomb excitation in order to determine the energies and spins of the low-lying states and the reduced transition probabilities of the decaying transitions.

Beam time request

The expected beam intensities at the Miniball set-up for each of the three isotopes of interest and the requested number of shifts are summarized in Table 5. The quoted beam intensities are based on the estimated ISOLDE yields and our experience from the previous runs with beams of neutron-rich Cu isotopes.

For the measurement of ^{70}Cu, 3^- isomeric beam is required.

Beam[1]	Expected intensity at the MB target	Special conditions	Requested shifts
^{70}Cu	$\sim 10^5$ pps	3^- isomeric beam	7+2[2]
^{72}Cu	$\sim 10^5$ pps		6
^{75}Cu	$\sim 10^3$ pps	Cu/total>20%	9
			TOTAL=24 shifts

[1]post-accelerated to the maximum energy that can be achieved

[2]shift allocated for the change of the mass of the isotope and isomeric beam tuning

Table 5: *Expected yields obtained with an UC_2 target and requested shifts for the measurement of the neutron-rich ^{70,72,75}Cu by Coulomb excitation.*

Target development for ^{75}Cu

The success of the ^{75}Cu measurement strongly depends on the ability to suppress the Ga contaminant of the beam. According to the quoted ISOLDE yields obtained with an UC_x target, the ^{75}Ga amount in the beam is expected to be about two orders of magnitude higher than the beam of interest. This requires the development of a new target-transfer-line combination aiming to the reduction of the ^{75}Ga contaminant without causing serious losses in the ^{75}Cu yield. The minimum beam intensity needed such as the experiment becomes feasible is $\sim 10^3$ pps at the Miniball target with a beam purity >20%.

We request a total of 24 shifts of beamtime.

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