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# Proposal to the INTC Committee

## 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 odd-mass and the odd-odd neutron-rich Cu nuclei applying the Coulomb excitation technique and using the REX-ISOLDE facility coupled to the Miniball array. The results from the Coulex experiments accomplished at REX-ISOLDE after its upgrade to 3 MeV/u during the last year have shown the power of this method and its importance in order to obtain information on the collective properties of even-even nuclei. Performing an experiment on the odd-mass and on the odd-odd neutron-rich Cu isotopes in the vicinity of N=40 should allow us to determine and interpret the effective proton and neutron charges in the region and to unravel the lowest proton-neutron multiplets in $^{68,\ 70}$Cu. This experiment can take the advantage of the unique opportunity to accelerate isomerically separated beams using the RILIS ion source at ISOLDE.

## Introduction

The Coulomb excitation technique has proven its power on gaining experimental information on the transition probabilities in the even-even isotopes throughout the stable nuclides in the nuclear chart during many years. A number of experiments have been performed also on odd-mass nuclei. However, out of the nine odd-odd nuclei existing in the nature, stable or radioactive with long half-life, only in two cases ($^{50}$V and $^{176}$Lu) transition probabilities have been studied using the Coulomb excitation technique [1]. With the fast developments of the post-accelerated radioactive beams at low energies many more species are becoming available for this type of studies in inverse kinematics.

An exciting new direction of the Coulomb excitation technique can be developed using isomerically enriched or pure beams. This will allow us to choose one of the long-living isomeric states in the same nucleus as a starting point for the excitation and in this way to derive nuclear structure information on specific parts of the nuclear levels. In relation with this, the presently available at ISOLDE isomeric beams of $^{68}$Cu and $^{70}$Cu [2,3] provide very interesting possibilities for such a study. Using the hyperfine splitting for the different isomers in the RILIS one can obtain about 20 times suppression of the laser-ionization efficiency for a specific state. Our aim is to use this laser selectivity for the cases of $^{68}$Cu and $^{70}$Cu and to produce beams with strongly enhanced $J^{\pi}=6^{-}$ and respectively $J^{\pi} = 6^{-}$ and $J^{\pi} = 3^{-}$ compositions.

## Physics motivation

The region around N=40 in the neutron-rich part of the nuclear chart has been a subject of extensive experimental and theoretical interest during the last twenty years. Some theoretical studies on the influence of the neutron excess on the structure of the nuclei far from stability [4] suggest that the harmonic oscillator magic numbers should become dominant going towards the neutron drip line. The observation of the relatively high excitation energy of the $2_1^+$ state in $^{68}$Ni [5] was proposed to be a signature of this effect and subsequently $^{68}$Ni was considered as a doubly-magic nucleus. However, there is no signature of a (sub) shell closure in the two-neutron separation energies [6] which was explained by quadrupole shape correlations [7]. The experimentally observed very low B(E2) value in $^{68}$Ni [8] was interpreted as a washing out of N = 40 due increased probability for pair scattering. K.H. Langanke et al. [9] questioned the shell closure at N=40 claiming that the E2 strength is distributed mainly within states lying above 4 MeV and it is not exhausted by the first $2^+$ state in $^{68}$Ni.

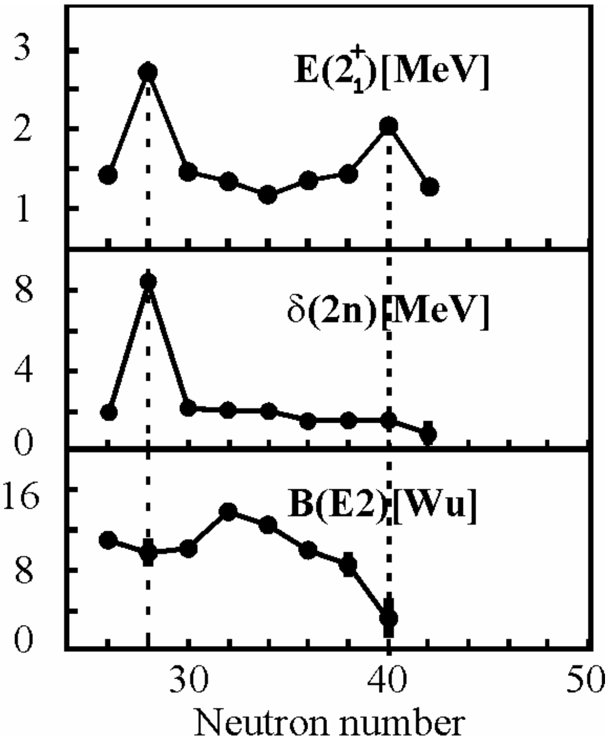

*Fig.1. Energy of $2_1^+$ states, two-neutron separation energies and B(E2) in the Ni isotopes as a function of the neutron number.*

Furthermore, going just two protons [10,11] or one neutron [12] away from $^{68}$Ni the effects of shell closure disappear and deformation starts developing. This can give us the idea that the peculiarity of N = 40 is something quite localized around $^{68}$Ni and should be due to the change of parity between the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ orbitals and the $g_{9/2}$. The influence of the latter can be also observed in the monopole migration of $\pi f_{5/2}$ via the decrease of the energy of the $5/2^-$ states in the odd Cu isotopes starting from N = 42 with the filling of $\nu g_{9/2}$ [13] (see Fig.2). This behavior is very well reproduced by large scale shell model calculations [14].

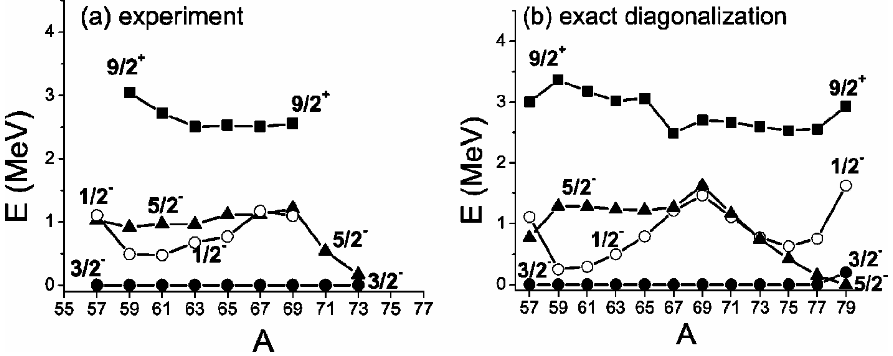

*Fig. 2. a) experimental energies of the 1/2-, 5/2- and 9/2+ states in the odd-mass Cu isotopes; b) relative positions of the same states in shell-model calculations. Figure from Ref. [14].*

An important point in the discussion of the sphericity in $^{68}$Ni and the onset of deformation around it is the knowledge on the effective proton and neutron charges in the region. In the odd-mass and the odd-odd nuclei, especially in the lower lying higher-spin states, one expects strong contributions of single-particle components in the composition of the nuclear wave function and fewer admixtures of collective excitations. From this point of view the Cu isotopes, with a single proton above the Z = 28 shell gap can help us derive indispensable information both on the proton and on the neutron effective charges around $^{68}$Ni. In this proposal our aim is to perform Coulomb excitation on a number of copper isotopes from A = 67 up to A = 71.

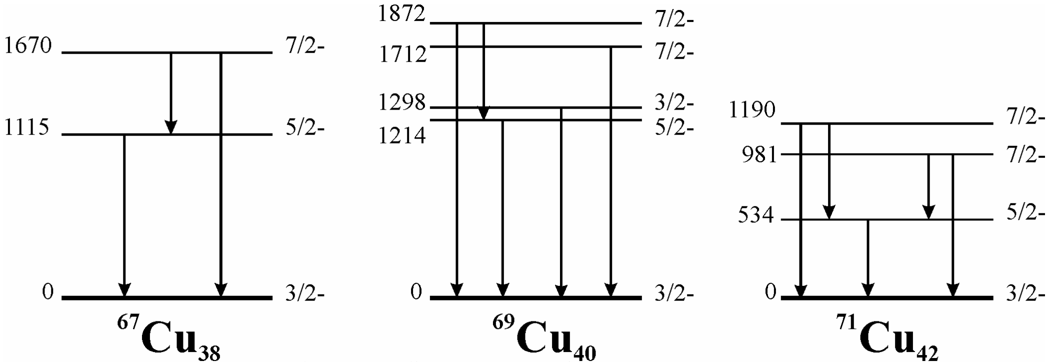

*Fig. 3. Low energy schemes for $^{67}$Cu [16] $^{69}$Cu [13] and $^{71}$Cu [13].*

The low energy structure of the odd-mass Cu isotopes is quite well studied via beta-decay, deep-inelastic reactions and also in projectile-fragmentation due to the existence of μs isomers in $^{69}$Cu and $^{71}$Cu. Among the states, accessible for a Coulomb excitation at low energies, one can identify the $3/2^-$, $5/2^-$ and $7/2^-$ (see Fig. 3). Both in $^{69}$Cu and $^{71}$Cu there are two $J^\pi = 7/2^-$ states experimentally observed. One of them is understood as a single proton coupled to the $2^+$ excitation of $^{68}$Ni, respectively $^{70}$Ni, [13,15] while the other is suggested to represent an $f_{7/2}$ proton-hole in $^{70}$Zn/$^{72}$Zn. To our knowledge in $^{67}$Cu a second $7/2^-$ state is not experimentally observed [16]. Performing a Coulomb excitation on $^{67}$Cu, $^{69}$Cu and $^{71}$Cu one should be able to identify the second $7/2^-$ state in $^{67}$Cu, as well as to shed more light on the structure of these states and determine the proton effective charges right below and above N = 40.

The odd-odd $^{68}$Cu and $^{70}$Cu isotopes provide very rich opportunities for nuclear structure studies based on the existence of several long-lived isomeric states at very low energies. In both cases one of these isomers is identified as a coupling of a proton $p_{3/2}$ to a neutron $p_{1/2}$ ($J^\pi = 1^+$), while the second one is the highest spin member of the proton $p_{3/2}$, neutron $g_{9/2}$ multiplet ($J^\pi = 6^-$). In $^{70}$Cu a third isomeric state, identified as the lowest spin member of the above mentioned multiplet ($J^\pi = 3^-$), has been observed as well [17]. This gives us the unique opportunity to perform Coulomb excitation within the $\pi p_{3/2} \otimes \nu g_{9/2}$ multiplet starting from two different states, in particular the $6^-$ and the $3^-$ states. In large scale shell model calculations the nuclear wave functions of the states in the $(3, 4, 5, 6)^-$ multiplet appear to be rather pure [18] with about 50% of its components coming from a single-particle $\pi p_{3/2} \otimes \nu g_{9/2}$ coupling. Therefore, provided that we determine the proton effective charges from the odd-mass Cu isotopes, from the measurement on $^{68}$Cu and $^{70}$Cu we should be able to derive the neutron effective charges in the region as well.

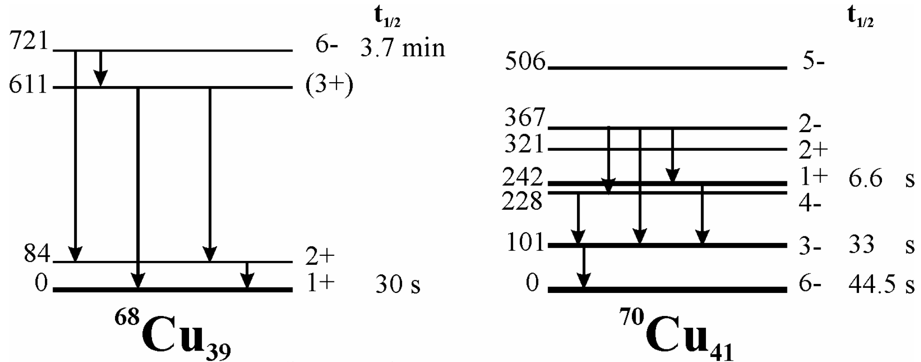

*Fig. 4. Low energy level schemes of* $^{68}$*Cu and* $^{70}$*Cu*

One should note that all four members of the (3, 4, 5, 6)$^-$ multiplet in $^{70}$Cu are experimentally determined. However, this is not the case for $^{68}$Cu where, from a transfer reaction measurement [19], one has a hint for the group of $3^-$,$4^-$,$5^-$ states but their relative positions are not known. Comparing the results from the Coulomb excitation of $^{70}$Cu and $^{68}$Cu one should be able to clearly identify the above mentioned states.

## Experimental details

The neutron-rich copper beams are usually produced using a uranium carbide target and ionized in the resonance ionization laser ion source. A laser shutter and a ΔE-E ionization chamber will be used in order to identify the isobaric contaminants in the beam. The gamma rays from the Coulomb excitation will be detected with the Miniball array. The coincident scattered particles will be detected in the double-side silicon strip detector (CD) of which the 3 inner strips will be shielded from the elastically scattered beam particles. The segmentation of the Ge detectors will allow performing Doppler corrections of the gamma-ray spectra.

In this experiment we plan to use a 2.3 mg/cm$^2$ $^{120}$Sn target for most of the cases. The target excitation will be used as normalization for obtaining the transition probability for the studied nuclei. The gamma ray from the Coulomb excitation of $^{120}$Sn (1171 keV) is quite far in energy from most of the studied cases except for $^{71}$Cu for which a $^{108}$Pd target will have to be used.

In order to estimate the beam intensities one should take into account that for $^{68}$Cu and $^{70}$Cu we will demand an isomeric separation in RILIS (see Fig. 5). In order to get the required spectral resolution of the hyperfine structure one has to reduce the laser power applied for the respective atomic transition. The minimization of the saturation broadening will cause a reduction of the ionization efficiency by a factor of about 2 [3]. At appropriate settings of the laser frequency one of the isomeric states can be suppressed by an additional factor of 20 (see Fig. 5). To estimate the total intensity of the different isomers extracted after the separator one should also account for their different initial production rates. For example for $^{68}$Cu, after the in-source separation one can expect a $^{68m}$Cu/$^{68g}$Cu ratio similar to 100:1, since $^{68m}$Cu ($6^-$) is about 5 times more abundantly produced.

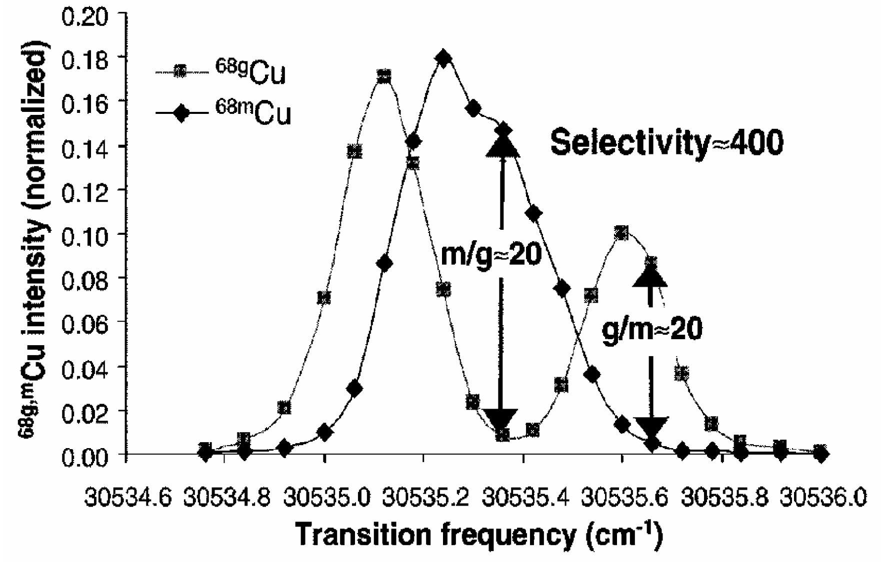

*Fig. 5. Separation of $^{68m}$Cu and $^{68g}$Cu using their hyperfine splitting. Figure from Ref[3].*

*Table 1. Estimated transition probabilities, weighted cross-sections and gamma-ray yields for the nuclei under investigation.*

| | $J_i \rightarrow J_f$ | B(E2) [$e^2fm^4$] | $E\gamma$ [keV] | $\sigma$ [b] | **ISOLDE yield /μC** | **Events in photopeak /hour** | **shifts** |
|---|---|---|---|---|---|---|---|
| $^{67}$Cu | $3/2^- \rightarrow 5/2^-$ | 48 | 1115 | 0.011 | 3.0 E8 | 69 | 3 |
| | $3/2^- \rightarrow 7/2^-$ | 59 | 1670 | 0.003 | | 14 | |
| | $5/2^- \rightarrow 7/2^-$ | 81 | 555 | 0.059 | | 52 | |
| $^{69}$Cu | $3/2^- \rightarrow 5/2^-$ | 34 | 1212 | 0.007 | 1.0 E8 | 14 | 4 |
| | $3/2^- \rightarrow 7/2^-$ | 31 | 1871 | 0.006 | | 8 | |
| | $5/2^- \rightarrow 7/2^-$ | 94 | 658 | 0.060 | | 170 | |
| $^{71}$Cu | $3/2^- \rightarrow 5/2^-$ | 46 | 534 | 0.040 | 5.0 E7 | 40 | 3 |
| | $3/2^- \rightarrow 7/2^-$ | 14 | 1189 | 0.020 | | 29 | |
| | $5/2^- \rightarrow 7/2^-$ | 54 | 655 | 0.014 | | 20 | |
| $^{68}$Cu | $6^- \rightarrow 4^-$ | 44 | 229 | 0.047 | 1.0 E8 | 164 | 1 |
| | $6^- \rightarrow 5^-$ | 5 | 629 | 0.003 | | 8 | |
| $^{70}$Cu | $6^- \rightarrow 4^-$ | 38 | 228 | 0.042 | 4.0 E7 | 58 | 2 |
| | $6^- \rightarrow 5^-$ | 13 | 506 | 0.016 | | 20 | |
| $^{70}$Cu | $3^- \rightarrow 4^-$ | 35 | 127 | 0.040 | 2.0 E6 | 3.0 | 12 |
| | $3^- \rightarrow 5^-$ | 25 | 405 | 0.060 | | 3.9 | |

The above considerations have been taken into account in the estimated ISOLDE yields. Additionally, the total efficiency of REX-TRAP, REX-EBIS and the REX-LINAC which should be of the order of 1% is to be taken into account. The Miniball gamma-ray efficiency has been taken from Ref. [20]. Large scale shell model calculations [18] have been used to estimate the expected transition probabilities. They were afterwards used as an input to the CLX program [21] in order to determine the weighted cross-sections and the expected photo-peak count-rates for each of the studied nuclei. In the calculations an energy loss of 17.7 MeV/(mg/cm$^2$) of the beam in the target was considered. The integration of the cross-section is made over the whole CD range (16.4$^o$ - 53.3$^o$). This gives us the overall picture presented in Table 1.

In summary we need **10 shifts** of beam on target for the odd-mass Cu isotopes in order to determine the proton effective charges in the $^{68}$Ni region. Additional **15 shifts** will be necessary to perform the Coulomb excitation on the odd-odd $^{68}$Cu and $^{70}$Cu which should allow us to determine also the neutron effective charges in the region and to fix the positions of the members of the (3,4,5,6)$^-$ multiplet in $^{68}$Cu. This sums up to a **total 25 shifts of beam on target.**

Additionally we will need time for the laser scans and tuning on the isomers in $^{68}$Cu and $^{70}$Cu, which we estimate to **3 shifts**, and for the changes in the tuning of REX-ISOLDE on the 5 different masses, about **6 shifts**.

A **total of 34 shifts** are asked for the entire measurement.

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