SUMMARY REPORT

YEARS 2011-2016

The study of isomeric states using gamma spectroscopy in nuclei close to the doubly magic ^{78}Ni represent an important topic of the nuclear physics research. The experimental results obtained in this project have allowed to test the different theoretical approaches, as well to study the evolution of nuclear shape with increasing neutron number. Nevertheless, by comparing the experimental values with the theoretical predictions new constrains can be developed, such that the prediction power is increased. In the present report are presented the main results obtained in experiments performed at the GANIL facility (the study of ^{72,75}Cu) and IPNOrsay laboratory (^{69}Cu).

Experimental methods

The ^{72,75}Cu nuclei were studied in the fragmentation reaction of a primary beam of ^{86}Kr on a Be target at the energy of 60.4 MeV/A. For selection we have use the in-flight separation tehnique and the implantation of the ions in a thin foil of Kapton (75 μm). This methods requires the use of additional materials to stop completely the studied fragments. The incoming ions were identified in a time of flight-energy loss matrix. The energy loss information was from a silicon detector placed at the focal plane of LISE2k spectrometer [1]. In order to have a better control of the implantation procedure an Aluminium degrader was placed after this detector, its thickness was 115 μm and it could be rotated, such that its effective thickness was varied. The γ-ray detection consisted in three HPGe detectors placed in a very compact geometry, one of them was used for detecting low-energy gammas (LEPS). Due to this configuration the efficiency of the detectors had a strong dependence on the implantation profile of specific ions. For this reason, in order to reconstruct the spatial distribution of the fragments we used a position sensitive silicon detector after the degrader, its active area was 63 mm X 63 mm. Moreover for rejection the events associated with nuclei that were not stopped in the implantation foil, a veto detector as mounted after it.

In the preparatory phase of the experiment, LISE++ [2] simulations were performed to determine the optimal thickness of the Al degrader and to establish the best conditions for selection and transmission of the ^{75}Cu through the spectrometer. In addition, Monte Carlo simulation were performed using GEANT4 toolkit [3] to have an estimation of the efficiency of the detectors in the experimental conditions. The simulation program, required to know very precise all the detector characteristics, as well as the geometry in which they were placed with respect to the Kapton foil. By comparing the simulation results with the experimental ones obtained for a ^{133}Ba source placed in several points on the Kapton foil, the code was validated.

The experimental results obtained in the next section were obtained using γ-γ coincidences technique and by determining the half-lives of the identified transitions.

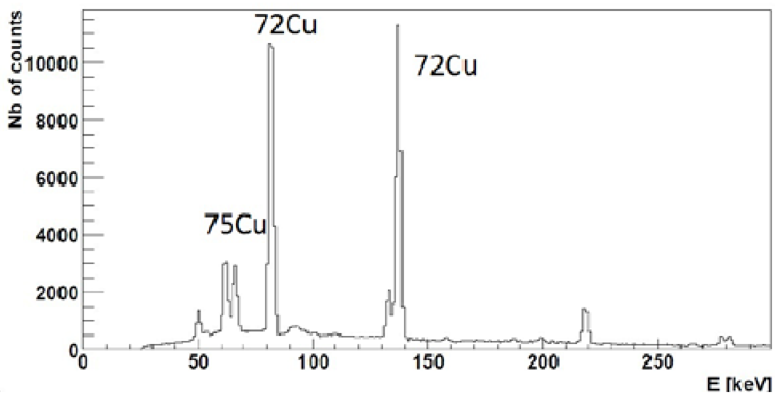

Figure 1: γ spectrum conditioned by the implantation of ^{75}Cu incoming ions.

Results

Due to relatively low energy of the primary beam, most of the nuclei were produced in several charge states, this fact made possible to have in the identification matrix nuclei that overlapped, having the same value of A/Q. For example, ^{72}Cu^{+1} nucleus overlapped with the ^{75}Cu fully stripped, thus by conditioning the γ spectrum with the ^{75}Cu nuclei we will find also the peaks corresponding to the isomer decay of ^{72}Cu - see Figure 1.

By applying a gate on different transitions observed in the γ spectrum, information regarding the half-life could be determined. For this the time distributions were fitted with a function that represents the convolution between an exponential and a Gaussian distribution. An example of the fit results can be observed in Figure 2, representing the time distributions of the two isomeric transitions of ^{75}Cu.

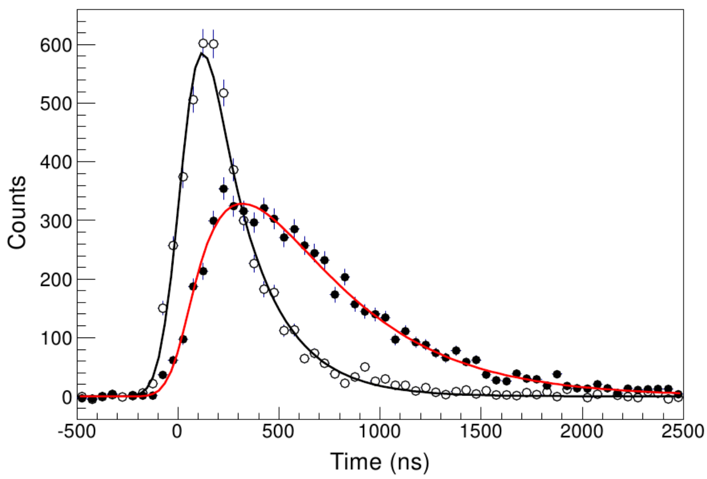

Figure 2: Time distributions conditioned with the energies of 61.7 (red line) and 66.2 keV (black line) of ^{75}Cu.

The existence of two low energy isomeric states is a specific feature of the nuclear structure of ^{75}Cu. The spin and parity of these two states are unknown. In the experiment

Table 1: γ energies and their corresponding conversion coefficients compared with theoretical estimations for ^{72}Cu.

$E_\gamma(keV)$	α_{exp}	$\alpha(E1)$	$\alpha(M1)$	$\alpha(E2)$
50	8.5(5)	4.45×10^{-1}	3.64×10^{-1}	8.33
82	$8.6 \times 10^{-2}(5)$	1.00×10^{-1}	9.18×10^{-2}	1.14
138	$6.5 \times 10^{-2}(3)$	2.07×10^{-2}	2.28×10^{-2}	1.81×10^{-1}

the conditions were maximize to study the ^{75}Cu, therefore the obtained statistics allow to do γ-γ coincidences for the first time, the result has shown that the two transitions are not in coincidence as originally thought [4], but they are parallel to each other in the level scheme. Considering this new result and the systematic behavior of the $1/2^-$ and $3/2^-$ states for neutron-rich copper isotopes, a new level scheme with two possible scenarios for the spin assignment is proposed in Figure 3.

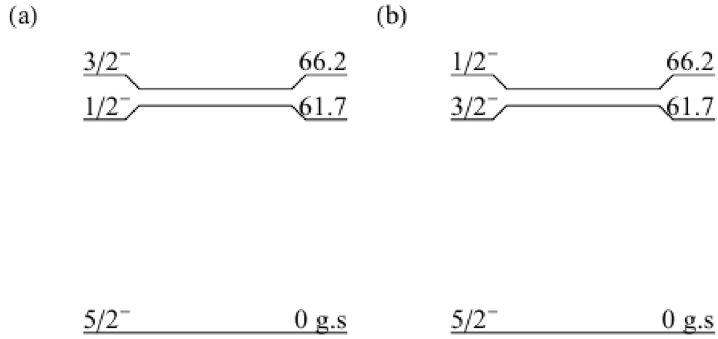

Figure 3: Proposed scenarios for spin and parity assigment of the two isomeric states of ^{75}Cu.

The same γ-γ coincidence method was applied to determine the conversion coefficients of the low energy states of ^{72}Cu. The experimental values are compared with the theoretical estimation of BRICC calculator [5] in Table 1. The isomeric states with the energy of 270 keV and a half-life of 1.54 μs deexcite only by the emission of a 50 keV transition. The experimental value of the conversion coefficient was measured to be 8.5(5), this value is in good agreement with the value of 7.74 expected for a E2 transition, thus an E2 character is consider to be most probable for the transition. By applying the same procedure we established an M1 character for the 82 and 138 keV transitions. Knowing the sin and parity of the ground state [6] and using this new information a new level scheme was proposed (Figure 4).

The experimental results were compared with theoretical predictions of shell model calculation using two interactions developed for this mass region. The code used for these calculations was NUSHELLX [7]. In a simple approach of the shell model, the nuclei with Z=29 and N=40 can be treated as a single particle outside of a ^{56}Ni core. Thus, in a simple configuration the protons outside the closed shell Z=28 will occupy the $\pi p_{3/2}$ orbital. For nuclei with N<40 neutrons are located in the $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ orbital, while for those with N>40 the $g_{9/2}$ begins to be filled. Thus, the low energy spectrum of odd-odd Copper isotopes should be dominated by $\pi p_{3/2} \nu g_{9/2}$ configurations. A second multiplet that is expected to appear is

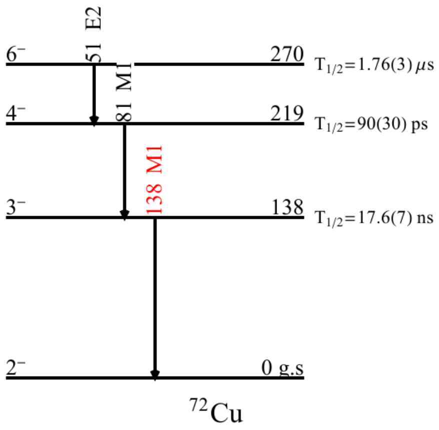

Figure 4: Proposed level scheme of ^{72}Cu.

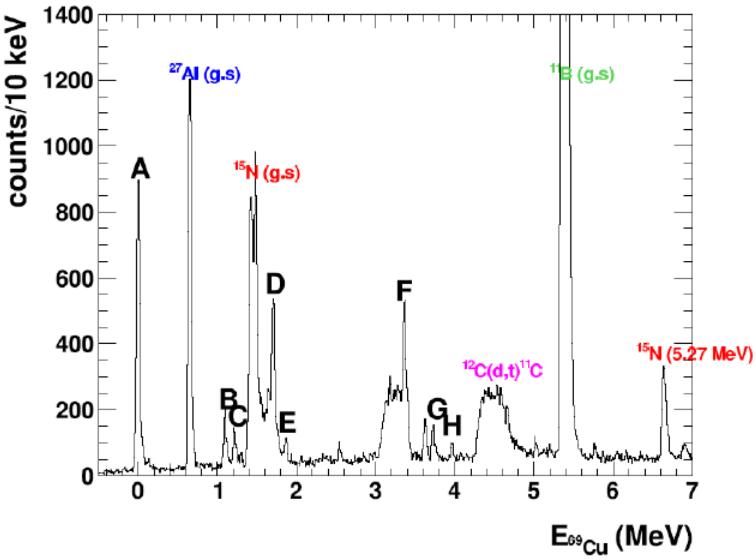

Figure 5: Excitation energy spectrum ^{69}Cu.

$(2-7)^-$, due to the $\pi f_{5/2}\nu g_{9/2}$ configuration. The existence of these two multiplets is predicted by both of the interactions used: jj44b [8] and JUN45 [9], however the comparison between the experimental reduced transition probabilities and the theoretical values have shown an better agreement with the predictions of jj44b interaction.

As already mentioned in the beginning of this report, the main objective of this project is represented by the study of nuclear structure evolution of the neutron-rich copper isotopes. A second experiment having this motivation ,was the study of the ^{70}Zn(d,^{3}He)^{69}Cu reaction. The experiment took place at IPNOrsay and the detection of the ^{69}Cu nuclei was made with the Split-Pole magnetic spectrometer. The excitation spectrum was reconstructed starting from the position of the detected particle in the focal plane of the spectrometer. With this detection setup the excitation energy spectrum could be measured up to 7 MeV, while the typical energy resolution was about 18 keV. By placing the spectrometer at different angles, the angular distribution of the observed state could be measured. An example of an energy spectrum obtained at 21° is illustrated in Figure 5

The states belonging to ^{69}Cu are marked with letters from A to H. The peaks with a larger resolution correspond to the reaction with target contaminants, and they are due to the different kinematics of the reaction. The strength of the $\pi f_{7/2}$ was establish to be at 2.45 MeV from the values of the spectroscopic factors. This information is extremely useful to the theoreticians, that now can develop new interaction starting from this value.

Disseminating Research Findings

The results were presented at several conferences and published in two articles:

- Sesiunea Anuală de Comunicări Științifice a Facultății de Fizica, ”Gamma spectroscopy of isomers in neutron rich nuclei: ^{75}Cu”
- Carpathian Summer School of Physics; Exotic Nuclei and Nuclear’Particle Astrophysics (IV) From Nuclei to Stars, ”Study of isomeric states using gamma spectroscopy around N=40”
- Dynamics of open nuclear systems, ”Low energy isomeric levels of nuclei near N=40”
- Zakopane Conference on Nuclear Physics 2012, ”Gamma spectropscopy of isomeric states in neutron rich nuclei: ^{75}Cu”
- Zakopane Conference on Nuclear Physics 2014, ”Single-particle Strengh in Neutron-rich ^{69}Cu”
- ”Single particle strengh in neutron-rich ^{69}Cu from the ^{70}”Zn(d,^{3}He)^{69}Cu proton pick-up reaction”, P. Morfouce et al., Physical Review C 93, 064308 (2016)
- ”Nearly degenerate isomeric states of ^{75}Cu”, C. Petrone et al., Physical Review C 94, 024319 (2016)

Moreover, this project offered the chance to young researches to gain knowledge on the nuclear structure field, more precisely the results obtained were contained in the PhD thesis of Cristina Petrone (defended in 2013 at the University of Bucharest) and Pierre Morfouace (defended in 2014 at the University of Paris Sud XI).

References

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