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Lifetime Measurements of particle-phonon coupled states in ^{61}Cu

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Abstract

We propose the investigation in ^{61}Cu of excited states of particle-phonon nature, populated by the fusion reaction $^{48}Ti(^{16}O, p2n)\,^{61}Cu$ at 50 MeV. The γ-transitions will be measured using the Bucharest ROSPHERE array, consisting of 14 Ge detectors and 11 $LaBr_3(Ce)$ scintillators, coupled to a plunger setup for lifetimes measurements in the ps up to several tens of ps range.
Aim of the experiment is, in particular, to study the multiplet of particle-phonon coupled states arising by coupling the 3- phonon of ^{60}Ni and the unpaired $p_{3/2}$- proton of ^{61}Cu. At present, candidates for such states exist, although with large uncertainties in spin and parities and scarce/no information on their decay schemes and lifetime. In particular, the 9/2+ member of the multiplet is, possibly, the known 2721 keV state, for which only a lower limit of ≈4 ps is given and no direct branching to the ground state is measured. Therefore, we here propose, firstly, to perform a high-resolution γ-spectroscopy experiment, making use of a thick ^{48}Ti target, in order to establish the full decay branching of the 9/2+ state. This will be followed by a plunger measurement to determine the lifetime of the 9/2+ state and its B(E3) value, to be compared to the one of the 3- state of the ^{60}Ni core.
The experimental findings will be compared with particle-phonon calculations in the weak-coupling limit. The present proposal is part of a series of experiments, carried out in Bucharest, aiming at a systematic investigation of octupole coupled phonon states, along the Cu isotopic chain, which are instrumental to shed light on the evolution of the shell structure, associated to the Z=28 magic Ni core.

We request 12 days of beam time: *2 days for in beam spectroscopy with a thick target and 10 days for the plunger measurement. One additional day is also requested to align target and stopper.*

Physics motivation

The understanding of particle–phonon and phonon–phonon couplings is a very important issue, since this phenomenon is at the basis of fermionic many-body interacting systems, both in solid state and nuclear physics. In nuclear physics, the coupling between a particle/hole and a vibration is a key ingredient to explain important phenomena, such as the observed reduction of spectroscopic factors, the anharmonicity of vibrational spectra, the damping of Giant Resonances, etc. [1,2].
It is well known that the best place to search for particle-phonon coupled states is around magic or doubly magic nuclei, where collective vibrations are expected to be quite robust. Until few years ago, indications have been found of discrete states of particle-phonon nature, mostly in medium-heavy nuclei [1], while the question is still open whether states of particle-phonon nature can be considered a general nuclear property, down to the region of medium-light systems with reduced collectivity.

In recent works, evidence has been found for the existence of particle/hole-phonon coupled states in ^{47,49}Ca, where the excitation are based on the 3^- octupole vibration in ^{48}Ca [3,4]. Moreover, in a series of experiment performed in Bucharest with the ROSPHERE array, n-rich Cu isotopes have been studied, in order to obtain valuable nuclear structure information above the Z=28 shell closure. In particular, a lifetime investigation of the $9/2^+$ state in ^{65}Cu [5] and ^{67}Cu [6] has been carried out by fast-timing technique [7], to probe the nature of such states and to establish whether or not they can be viewed as a single proton $\pi p_{3/2}$, coupled to the 3- phonon of the corresponding ^{64}Ni and ^{66}Ni cores (see Fig. 1).

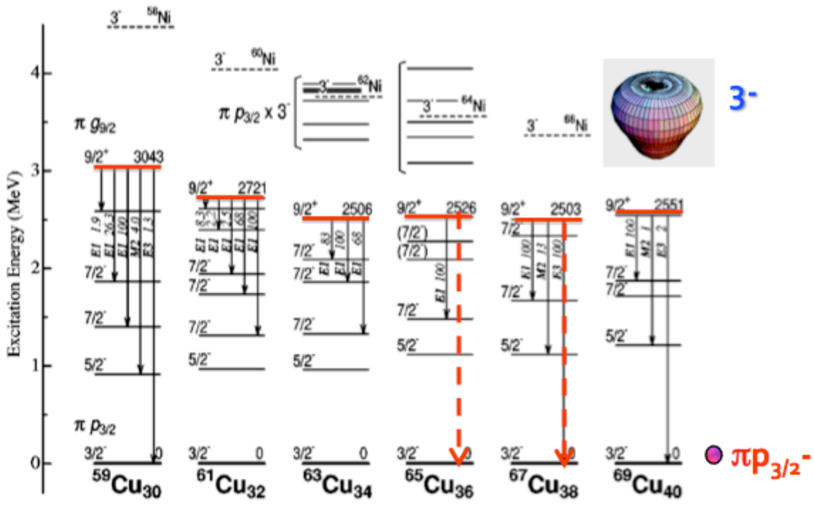

Fig. 1. *Energy levels and γ-ray branching for the first excited $9/2^+$ states in $^{59-69}$Cu isotopes. The 3^- octupole states in the corresponding Ni isotopes are indicated by dashed lines Ref. [8]. In the case of $^{63-65}$Cu, the lifetimes of the $9/2^+$ state (which are candidates for being $\pi p_{3/2} \otimes Ni(3^-)$ coupled states) have been measured in Bucharest by fast-timing techniques.*

In the experiment on ^{65}Cu (Spokeperson S. Leoni), the nucleus of interest was populated by the ^{7}Li+^{65}Ni reaction, at 32 MeV of beam energy. Making use of several start and stop combinations, the lifetime of the $9/2^+$ state at 2534 keV has been determined by the centroid shift method (see Fig. 2), resulting in the value τ = 37(3)ps. This corresponds to the octupole strength B(E3)=8.89 ± 1.65 W.u., which is, within the error, very close to the experimental strength of the octupole phonon of ^{66}Ni (of the order of 11 W.u).

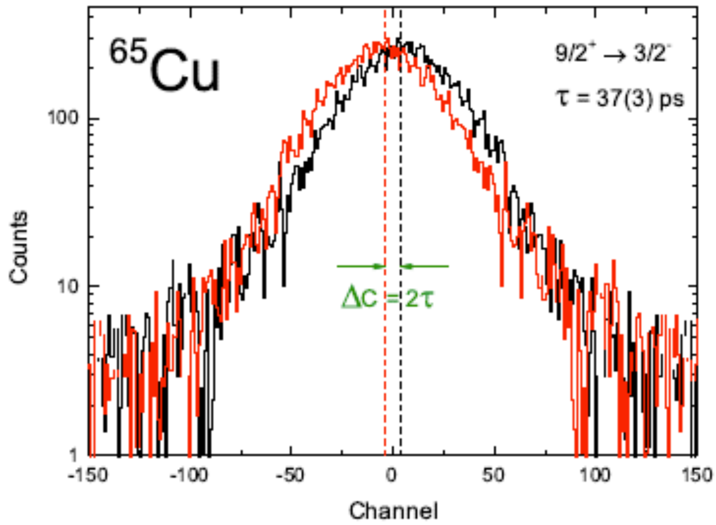

Fig. 2. *Time spectrum relative the 9/2+ state of ^{65}Cu. The red (black) distribution is obtained by considering the time difference* $\boldsymbol{t}_{stop} - \boldsymbol{t}_{start}$ *(*$\boldsymbol{t}_{start} - \boldsymbol{t}_{stop}$*.), based on several start γ–γ combination measured in the LaBr$_3$ detectors.*
The lifetime value, extracted by the centroid shift method, is reported in the legend [5].

In order to interpret the data, Random Phase Approximation calculations have been firstly performed to reproduce the octupole phonon of ^{66}Ni. As a second step, a particle-phonon weak coupling model [1] was employed to reproduce the data for the specific nucleus ^{65}Cu. At this stage, Hartree Fock-BCS calculations have been done to obtain the proton single particle levels of ^{64}Ni. In particular, two different forces (SkX and Sly5) have been considered and in the neutron channel the pairing interaction was taken into account. As reported in Fig. 3, the calculations are able to reproduce quite well the B(E3) strength of the $9/2^+$ state of ^{65}Cu, confirming the particle-phonon nature of this nuclear configuration.

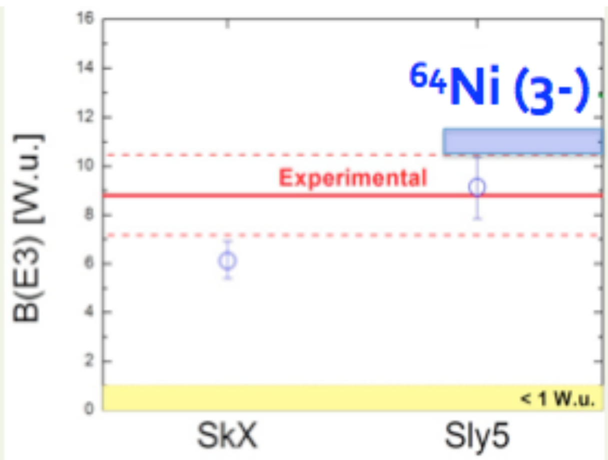

Fig. 3. *Experimental results for the B(E3) strength of ^{64}Ni (blue bar) and ^{65}Cu (red bad), as obtained in the Bucharest experiment of S. Leoni et al.. Calculations performed by the weak-coupling model (considering the coupling between the 3- phonon of ^{64}Ni and the unpaired $p_{3/2}$ proton of ^{65}Cu) are given by symbols, considering two different forces (SkX and Sly5) [5].*

Similar type of calculations have been performed for the case of ^{67}Cu, recently measured in Bucharest by N. Marginean et al., employing the ^{64}Ni(α,p)^{67}Cu reaction. In this case, the B(E3) strength of the $9/2^+$ state at 2503 keV has been also determined by fast-timing techniques, yielding a much larger value of 17 W.u.. As reported in Tab. 1, this result can not be reproduced by the weak-coupling model, indicating a significant configuration change going from ^{65}Cu to ^{67}Cu. This could be related to a severe variation in the core structure, underlying the particle-phonon coupling scheme, for example due to a shape change/onset of deformation. This is consistent with the experimental observation of a coexistence of different type of structures in heavier Cu isotopes at low and medium excitation energies, such as single particle, intruder and collective states, as reported in a recent ISOLDE experiment [9]. A similar situation has also been reported in Co isotopes, i.e. in the hole proton nuclei with respect to the Ni core [10].

We also note that the B(E3) strength of the 3- state is not known in ^{66}Ni, therefore the present study of Cu isotopes in terms of particle-phonon couplings becomes important also in connection with a systematic investigation of structural evolution of the cores.

^{67}Cu

		E [MeV]	B(E3) [W.u]
3^-	Exp.	3.370	- *
	Theory (SkX)	4.4	7.9
	Theory (Sly5)	5.2	7.5
$9/2^+$	Exp.	2.503	17.0 ± 2.0
	Theory (SkX)	2.9	5.4
	Theory (Sly5)	2.9	5.2

Table 1. *Top panel: Experimental and theoretical (RPA) results for the 3- state of ^{66}Ni. We notice that the B(E3) strength is experimentally not known. Bottom panel: Experimental and theoretical results for the 9/2+ state of ^{67}Cu. The theoretical predictions are obtained by the weak coupling model of Ref. [1].*

The proposed case of ^{61}Cu

In this proposal we intend to focus on ^{61}Cu, which is one proton away from the semi-magic nucleus ^{60}Ni (see Figure 1). The idea is to continue the investigation of particle-phonon coupled states built on the 3- phonon of the Ni core. The nucleus ^{61}Cu will be produced by the fusion evaporation reaction ^{48}Ti(^{16}O, p2n) ^{61}Cu, which is an ideal mechanism to enhance the population of collective structures. Therefore, we expect to be able to populate more than one member of the $\pi p_{3/2} \otimes$Ni(3$^-$) multiplet.
In the case of ^{60}Ni, the 3- state is at an excitation energy of 4040 keV, with a sizable B(E3) strength, of the order of 14 W.u. This value has been obtained in the '60s [11] from (e,e') experiments, while no γ-spectroscopy measurements exist. Therefore, a detailed spectroscopic work on particle-phonon coupled states in ^{61}Cu would also contribute, in a complementary way, to pin down structural properties of the ^{60}Ni core.
At present, there are several known states in ^{61}Cu in the 2.7 - 4.5 MeV range, with tentative I^{π} assignment, matching the ones of the $\pi p_{3/2} \otimes$Ni(3$^-$) multiplet (i.e. 9/2+, 7/2+, 5/2+ and 3/2+). In particular, we intend to investigate in great details the 9/2+ state at 2721 keV, which is a strong candidate for being the highest spin member of the octupole-phonon multiplet. At present, only a lower limit for the lifetime of this state exists (≥ 4 ps). In this case, to finally estimate the B(E3) value it will be crucial to have established, in a thick target experiment, the branching (or a limit) for the direct ground state decay. This is, so far, still unknown, although ^{61}Cu has been extensively investigated up to rather high spins [12].

The theoretical interpretation of the experimental results will be done in collaboration with our colleagues Gianluca Colò and Pier Francesco Bortignon of Milano University, which have already provided the weak-coupling calculations for ^{65,67}Cu.
It is important to notice that the proposed study of ^{61}Cu, together with the previous work on ^{65,67}Cu, will represent the first systematic investigation of particle-phonon coupled states based on 3$^-$ octupole excitation, along an isotopic chain. This unprecedented work will contribute to extract a rather precise, quantitative assessment on the coupling strength between particle-states and low-lying phonon core excitations, shading lights on the evolution of the underling core structure of Ni isotopes, in this case. It will also provide precious

experimental information for a more advanced, microscopic treatment of the particle-phonon coupling scheme, presently under development by the Milano group [13].

Experimental details

We propose to use the fusion reaction ^{48}Ti(^{16}O, p2n)^{61}Cu at 50 MeV, which according to CASCADE calculations is expected to populate ^{61}Cu with a sizable cross section of 300 mb.
The subsequent γ decay of ^{61}Cu will be detected by the ROSPHERE array, consisting of 14 HPGe detectors and 11 $LaBr_3$ scintillators, with absolute detection efficiency at 1.33 MeV of ~1.5% and ~1%, respectively.

First, we plan to perform a high-resolution γ-spectroscopy run to establish the decay branch to the ground state(or a limit) of the $9/2^+$ state at 2721 keV, which is the candidate for the high spin member of the $\pi p_{3/2} \otimes {}^{60}$Ni($3^-$) multiplet. For this purpose we intend to use a ^{48}Ti target, 10 mg/cm^2 thick, in order to fully stop the recoiling ^{61}Cu isotopes and to well identify γ lines up to 3 MeV. The measurement will be performed acquiring Ge events in singles, in order to accumulate enough statistics in the high energy lines in a short two days run. As a by-product, the use of a thick target will also make it possible to perform DSAM measurements for lifetimes shorter than 1 picosecond.
We will then perform lifetime measurements by plunger techniques, using the fusion-plunger setup available at IFIN-HN, focusing in particular on the 9/2+ state at 2721 keV. For this purpose we will employ a ^{48}Ti target, 1 mg/cm^2 thick, on a Au foil, 4-5 mg/cm^2 thick. In this condition, the recoil velocity of ^{61}Cu is on average just below 2%, which is optimal for plunger measurements. As usual for a plunger experiment, we intend to measure 10 target-stopper distances to obtain a precise lifetime value, therefore we will need 10 days of beam time, i.e. roughly one distance/day. We also point out that the presence of $LaBr_3$ scintillator detectors will offer the possibility to measure the lifetime (or a limit) for states in the 20-30 ps up to few ns range, by fast-timing techniques.

Our total beam-time request is 10 days:
2 days with the thick target, 10 days for the plunger setup. One additional day will also be needed to align target and stopper in the plunger measurement.

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