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Search for particle–vibration coupling in ^{65}Cu

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Abstract. The lifetime of the $9/2^+$ state of ^{65}Cu, at 2534 keV, has been measured by fast timing techniques, in order to establish wether such state arises from a weak coupling between a $p_{3/2}$ proton and the 3^- octupole vibration at 3.56 MeV in the ^{64}Ni core.
The ^{65}Cu nucleus was populated by the reaction ^{7}Li + ^{64}Ni at 32 MeV, at the Horia Hulubei National Institute of Physics and Nuclear Engineering (NIPNE) in Bucharest, and its γ-decay was detected by the ROSPHERE array. The measured lifetime coresponds to a B(E3) reduced transition probability to the ground state equal to 8.89 W.u., in agreement with theoretical predictions in the weak coupling limit.

1 Introduction

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 [1] 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 [2], etc..

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. Experimentally, several indications have been found of discrete states of particle-phonon nature, mostly in medium-heavy nuclei, while only few examples are known in lighter mass regions [3,4]. In this context, we have studied the first excited states of the ^{65}Cu nucleus populated by the reaction ^{7}Li on ^{64}Ni. In particular, we focused on the $9/2^+$ state [5] which is supposed to be the highest spin member of the multiplet of states arising by coupling the unpaired $p_{3/2}$ proton to the 3^- octupole phonon of the ^{64}Ni core. By applying fast-timing techniques, the lifetimes of the states of interest has been determined, therefore allowing to estimate their collectivity and to compare with particle-phonon calculations in the weak-coupling limit.

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2 Experimental Analysis

The experiment has been performed at Horia Hulubei National Institute of Physics and Nuclear Engineering (NIPNE) in Bucharest, using the reaction ^{7}Li + ^{64}Ni at 32 MeV [6]. This reaction produced several nuclei, as shown in the inset of Figure 1. It is found that the most intense populated channel is the ^{65}Cu nucleus. The experimental setup consisted of 14 HpGe and 11 $LaBr_3$(Ce) in 4π configuration. The high energy resolution of the HpGe detectors allowed the selection of the reaction products by energy gating, while the excellent timing of the $LaBr_3$(Ce) scintillators allowed precise lifetime measurements, in particular for the $9/2^+$ state of ^{65}Cu.

In order to determine the lifetime of the states of interest, triple γ coincidences are needed, since one transition observed in the Ge array is used as a gate (to cleanly select the decay path) and $\gamma - \gamma$ coincident transitions detected in the $LaBr_3$(Ce) array are needed to construct the time difference spectrum, according to the method described in Ref. [7]. For a precise lifetime measurement, the instrument time response for each $LaBr_3$(Ce) detector and CFD combination in the array requires an off-line correction due to time walk. This correction needs to be done as a function of γ-ray energy, since a significant variation of the centroid position of the time peak is observed, in particular at low energy [7].

The lifetimes of the states of interest have been obtained by the analysis of the time difference spectrum which is the result of a convolution between a Gaussian function and an exponential decay. The

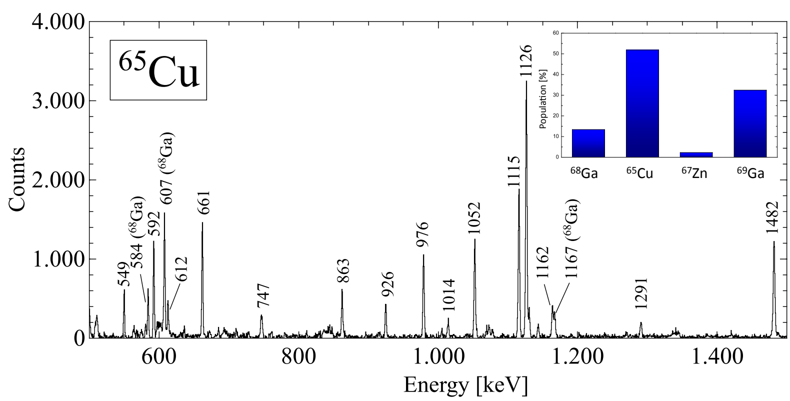

Figure 1. Single γ-ray spectrum of the ^{65}Cu nucleus measured by HpGe detectors for the energy range 500-1500 keV with a coincidence requirement on the 415 keV line of ^{65}Cu. Labels mark the strongest transitions of ^{65}Cu and contaminant lines of ^{68}Ga. The inset shows the population of the most intense products of the reaction ^{7}Li + ^{64}Ni at 32 MeV (normalized to the sum of the four nuclei here considered), obtained by considering the population of the lowest excited states of each reaction product.

first describes the uncertainty in the determination of the temporal event and the second describes the law of the radioactive decay. For values of the lifetime shorter or comparable with the time resolution (as in the present case), the time spectrum suffers a displacement of the centroid with respect to the prompt peak and the exponential slope is not so evident. For this reason one can measure the lifetime directly by the shift of the centroid, as reported in Figure 2.

Following this procedure, a lifetime of 37(3) ps has been obtained for the $9/2^+$ state of ^{65}Cu. This gives the value B(E3)=8.82(165) W.u. for the $9/2^+ \rightarrow 3/2^-$ decay to the ground state, after taking into account the decay branch of the 2534 keV (recently reported in Ref. [5]). Such a result is close to the B(E3) strenght of the 3^- phonon in ^{64}Ni, reported to be 10.83±0.59 W.u. [8].

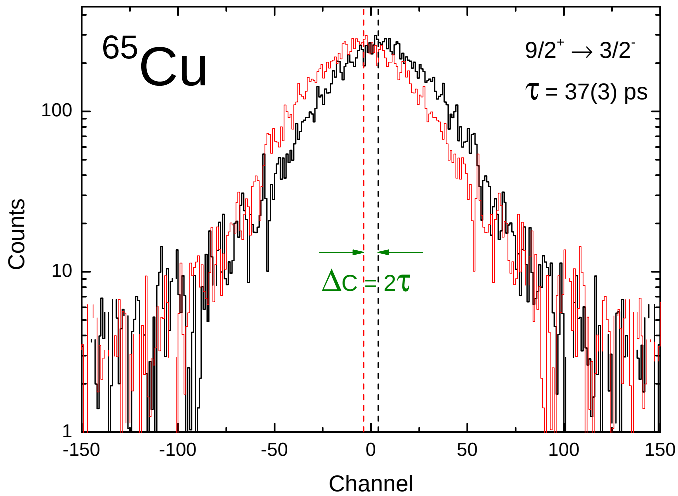

Figure 2. Time difference spectrum of the γ-ray cascade relative to the 2534 keV state in ^{65}Cu. By thin (red) line it is reported the distribution obtained considering the difference $t_{stop} - t_{start}$ while by thick (black) line we report the difference $t_{start} - t_{stop}$. The displacement ΔC is also indicated, from which a direct measure of the lifetime τ is obtained.

3 Theoretical analysis

A theoretical analysis has been performed to interprete the structure of the $9/2^+$ state in ^{65}Cu within the framework of the particle vibration coupling (PVC) model, using the weak coupling approximation. The Particle-Vibration Coupling model (originally developed by Bohr and Mottelson [1] and Hamamoto [9]), in order to predict both the energies and the ground state transition probabilities for the members of the multiplet of states arising from the coupling scheme. In this work it has been considered the so called *weak coupling*, that is a particular condition that occurs in the treatment of nuclei near closed shell. This assumption allowed us to treat the effect arising from the coupling within the perturbation theory. At the leading order, we consider the decay scheme of the multiplet members only to the lower-lying states having a predominant component consisting of a single-particle coupled to the ground state of the core.

At first, the single particle levels of the ^{64}Ni core have been calculated using the Hartree-Fock-BCS formalism employing two different forces: SkX and Sly5. Subsequently, the 3^- phonon of ^{64}Ni has been calculated within the RPA model, properly taking into account the effect of neutron pairing, being ^{64}Ni an open shell nucleus with respect to neutrons.

The results of the weak-coupling calculations for the $9/2^+$ state are shown in Figure 3 and are found in reasonable agreement with the experimental value. The other members of the multiplet (i.e. $7/2^+$, $5/2^+$ and $3/2^+$) are predicted to lie at higher excitation energies and are not identified in this work, since the present reaction favours the population of high-spin configurations.

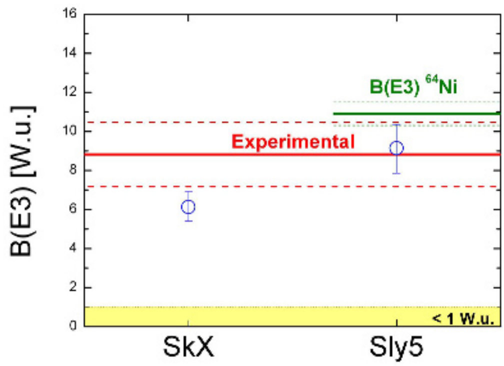

Figure 3. B(E3) reduced transition probabilities for the nucleus ^{65}Cu. Red lines indicate the experimental values (with error bars) obtained from the present lifetime measurement. Blue circles indicate the values obtained from the theoretical calculations with two different forces. For comparison, the B(E3) value of the ^{64}Ni core is reported by the green line [8].

4 Conclusion

Through γ-ray spectroscopy, we have studied the first excited states in ^{65}Cu. This nucleus was produced using the reaction ^{7}Li + ^{64}Ni at 32 MeV.
The lifetime of the $9/2^+$ excited state of the nucleus ^{65}Cu has been obtained using Fast-timing techniques providing the value of 37(3) ps. This corresponds to the reduced transition probability to the ground state $B(E3) = 8.82(165)$ W.u..
The previous result has been compared with theoretical calculations interpreting the structure of the $9/2^+$ state in ^{65}Cu within the framework of the particle-vibration coupling (PVC) model, using the weak coupling approximation. The obtained results are in good agreement with the experimental value, confirming the particle-phonon nature of the $9/2^+$ state of the ^{65}Cu nucleus. This is one of the few established examples of Particle-Vibration Coupled states in medium mass nuclei, therefore providing important information on the robustness of the nuclear collectivity in relatively light nuclei. Similar type of studies performed for the $9/2^+$ state in ^{67}Cu [10] seem to point to a change of structure, moving towards more exotic systems.

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