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Search for particle-phonon couplings in ^{65}Cu by the incomplete fusion reaction ^{7}Li+^{64}Ni

S. Leoni[1], A. Bracco[1], S. Bottoni[1], G. Benzoni[1], F. Crespi[1], L. Pellegri[1], V. Vandone[1]
N. Mărginean[2], D. Bucurescu[2], Gh. Căta-Danil[2], I. Căta-Danil[2], D. Deleanu[2], D. Filipescu[2],
I. Gheorghe[2], D.G. Ghiță[2], T. Glodariu[2], R. Lică[2], C. Mihai[2], R.Mărginean[2],
A. Negreț[2], T. Sava[2], L. Stroe[2], S. Toma[2], R. Șuvăilă[2], N.V. Zamfir[2]
C.A. Ur[3]
A. Bruce[4], O.J. Roberts[4]
P.H. Regan[5], Zs. Podolyak[5], P. J. Mason[5], C. Townsley[5]

[1] Università degli Studi di Milano and INFN sez. Milano, Milano, Italy
[2] National Institute for Physics and Nuclear Engineering, Magurele, Romania
[3] INFN sez. Padova, Padova, Italy
[4] University of Brighton, UK
[5] University of Surrey, UK

Spokesperson: S. Leoni
Contact Person: N. Mărginean

Abstract

We propose the measurement of excited states in ^{65}Cu populated by the incomplete fusion reaction of ^{7}Li on ^{64}Ni at energies around the Coulomb barrier. The gamma transitions will be measured using the Bucharest in-beam fast timing array of 8 Ge detectors and 12 $LaBr_3$(Ce) scintillators, possibly in coincidence with the alpha particles detected with 2 E-DE Si telescopes. The aim of the experiment is two folds: in first place we intend to acquire experience in using incomplete fusion reactions with the weakly bound ^{7}Li projectile. Such reactions are in fact considered a very powerful spectroscopic tool to get access to highly excited states in n-rich nuclei, at moderately high spin. For this purpose, an excitation function will be performed, by varying the energy of the ^{7}Li beam between 16 and 22 MeV, in steps of 2 MeV. After determining the optimal beam energy for the population of excited states in ^{65}Cu an in-beam spectroscopy study of this nucleus will be performed. In particular, we intend to focus on particle-phonon coupled 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 will be determined, therefore allowing to estimate their collectivity and to compare with particle-phonon calculations in the weak-coupling limit.

We request 9 days of beam time: *2 for excitation function and 7 for in beam spectroscopy.*

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].

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 [1], but only in few cases clear evidence has been obtained. In addition, it is still an open question 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 particle/hole-phonon coupled states in ^{47,49}Ca, based on the 3^- octupole vibration in ^{48}Ca [3,4]. Furthermore, in ^{67}Cu a fast E3 transition from the $9/2^+$ state to the $3/2^-$ ground state with B(E3)=17(2)W.u. has been measured in a recent ^{64}Ni(α,p)^{67}Cu experiment performed in Bucharest [5], suggesting a strong particle-octupole phonon coupling with the 3^- phonon of ^{66}Ni. In all cases, the key information has been the measurement of the lifetime of the states, which has contributed to shed light on the structure of the levels. The n-rich Cu isotopes are particularly interesting in this context, since they provide valuable information on nuclear structure above the Z=28 shell closure. In addition, they also present a very peculiar situation, which has been tentatively interpreted as a partial breaking of the particle-phonon coupling model. Figure 1 shows a systematic investigation of the first excited $9/2^+$ levels in the odd $^{59-69}$Cu isotopes and their g-ray branching [6]. Dashed lines indicate the energy of the 3^- octupole in the corresponding Ni isotopes. The experimental data on the (a,d) and (^{3}He,d) proton stripping reactions shows that in all odd mass Cu isotopes the first $9/2^+$ states around 2.5 MeV have large spectroscopic factors [7,8], consistent with a single-particle character. On the contrary, inelastic scattering of (α,α'), (e,e') and (p,p') [9-13] give, at least in the case of ^{63}Cu and ^{65}Cu, a significantly large E3 strength (~20 W.u.), compatible with a coupling with the 3^- phonon of ^{62}Ni and ^{64}Ni, respectively. On the other hand, candidates for $\pi p_{3/2}\otimes$Ni(3^-) multiplet were also observed at higher energies, above 3 MeV, in the excitation energy region of the 3^- phonons of Ni. This situation is rather contradictory since it cannot be explained within the usual weak-coupling particle-octupole phonon model. Therefore, further detailed investigation is needed, both theoretically and experimentally. In particular, a firm spin assignment for the states of the multiplet around 3 MeV should be established, together with a more direct determination of the structure of these states (including the $9/2^+$), as follows from lifetime measurements.

In this proposal we intend to focus on ^{65}Cu, which is one proton away from the semi-magic nucleus ^{64}Ni (see Figure 1). In the recent work of Chiara et al. [14], the decay from the $9/2^+$ state has been studied in details by a deep inelastic reaction: four decay branches have been observed, including a very weak, direct decay to the ground state. This $9/2^+$ state has been suggested to arise from a weak coupling between a proton and the ^{64}Ni core. No lifetime measurement has been performed for this state, and no evidence has been found for the states, around 3 MeV, previously interpreted as the $\pi p_{3/2}\otimes$Ni(3^-) multiplet.

We therefore propose to further investigate the g-decay of this nucleus, by employing a reaction mechanism that is expected to favor the population of excited states based on collective core excitations, such as incomplete fusion of a ^{7}Li beam on a ^{64}Ni target, at energies

around the Coulomb barrier. Incomplete fusion reactions are in fact considered a very powerful, little exploited, tool to get access to highly excited states at moderately high spins in n-rich nuclei [15,16].
The aim of the experiment is two folds: first, by performing an excitation function (varying the ^{7}Li beam energy between 16 and 22 MeV), we intend to study the properties of the reactions and to determine the best experimental conditions for the population of excited states in ^{65}Cu. Then we intend to perform a lifetime analysis of the 9/2^{+} state. If this state has a similar octupole character of the 3^{-} state in ^{64}Ni, as suggested by inelastic scattering reactions [10], its lifetime should be of the order of ~20 ps (assuming the decay branching reported in Ref. [14]). Such a value can be determined by fast-timing techniques, which are able to provide information in the range of tens of picoseconds to few nanoseconds [17].

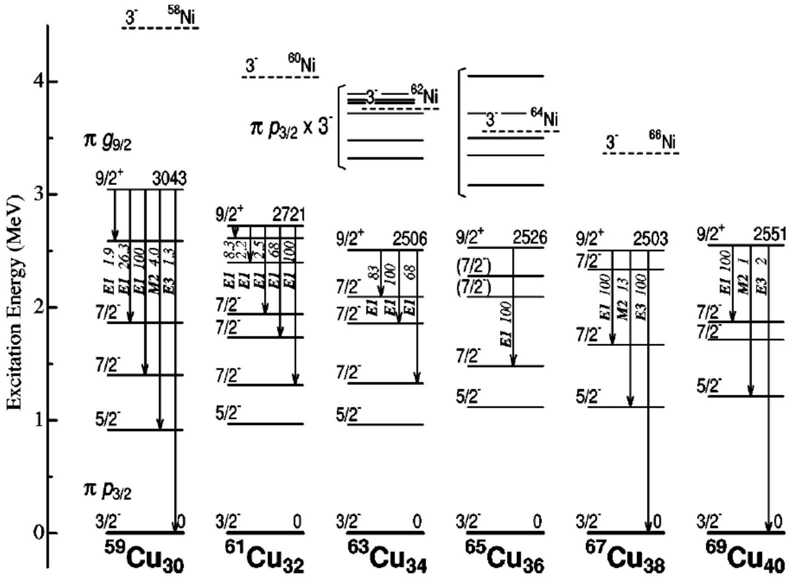

Fig. 1. *Energy levels and g-ray branching for the first excited 9/2^{+} states in $^{59-69}$Cu isotopes. The 3^{-} octupole states in the corresponding Ni isotopes are indicated by dashed lines. In the case of $^{63-65}$Cu, candidates for $\pi p_{3/2}\otimes$Ni(3^{-}) states are also given [6].*

The theoretical interpretation of the experimental results will be done in collaboration with our colleagues Gianluca Colò and Pier Francesco Bortignon of Milano University. It will be based both on a phenomenological approach (originally developed by Bohr and Mottelson [1,3,4]) as well as on a recently developed fully microscopic calculations performed within a self-consistent framework. The latter will be able to provide an exact treatment of the coupling vertex, making use of the whole phonon wave function [18].
It is important to note that the present study forms part of a wider program aiming at a systematic investigation of particle-phonon coupled states in different region of mass and N/Z ratio. It will contribute to extract a precise, quantitative assessment on the coupling strength between particle/hole-states and the low-lying phonon core excitations by comparison with other cases, going from stable to exotic systems. It will also shed light on the observation of an apparent anomalous particle-octupole phonon multiplet, earlier reported in ^{65}Cu [13].

Experimental details
We propose to use the incomplete fusion reaction ^{7}Li on ^{64}Ni at beam energy of 22 MeV, which is ~30% above the Coulomb barrier. The alpha particles resulting from the incomplete fusion will be detected by 2 Si E-DE telescopes of the ISIS array [19] placed in close geometry around the target to grant 10% detection efficiency. The gamma rays coming in coincidence will be measured using an array of 8 HPGe detectors and 12 LaBr$_3$ scintillators, with absolute detection efficiency at 1.33 MeV of ~0.8% and ~1%, respectively.

A reliable estimate of the ^{64}Ni(^{7}Li, α2n)^{65}Cu reaction cross section is not a trivial task. However, based on previous experiences [20] and on simple estimates one can expect a cross section σ~50 mb, mostly peaked at forward angles, around 40°-50°.
For the excitation function study we plan to employ a ^{64}Ni target of 2 mg/cm^2 on a Au backing of 20 mg/cm^2, in order to fully stop the recoiling ^{65}Cu isotopes. This will allow to easily identify the γ lines of ^{65}Cu and to study the population of its excited levels. Assuming a ^{7}Li beam of 3 pnA, we expect to measure ~15 events/s of α-γ coincidences both with the Ge array and the LaBr$_3$(Ce) array. This will be sufficient to perform an excitation function in 2 days, varying the ^{7}Li beam energy between 16 and 22 MeV, in steps of 2 MeV.

After determining the optimal beam energy for the population of ^{65}Cu, we intend to use a ^{64}Ni target with a thickness of 15 mg/cm^2, to perform a spectroscopic study of ^{65}Cu. In order to determine the lifetime (or a limit) of the states of interest, triple gamma coincidences will be needed, since one transition observed in the Ge array will be used as a gate (to cleanly select the decay path) and γ-γ coincident transitions detected in the LaBr$_3$(Ce) array will be needed to construct the time difference spectrum, according to the method described in Ref. [17]. Assuming a population of 10% for the $9/2^+$ state of interest, a total of ~6000 triple gamma coincidences will be collected in 7 days, assuring a meaningful analysis of the time difference spectrum. As a by-product, the use of a thick target will also offer the possibility of performing DSAM measurements for transitions with a lifetime shorter than 1 picosecond.

Our total beam-time request is 9 days
(2 for the excitation function and 7 for in beam measurement)

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