Complete $\gamma$-spectroscopy of n-rich nuclei around $^{48}$Ca
with Multi-Nucleon Transfer reactions

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Abstract. The gamma decay of neutron-rich nuclei around $^{48}$Ca was measured at Legnaro National Laboratory with the PRISMA-CLARA setup, using the multi-nucleon transfer reaction $^{48}$Ca on $^{64}$Ni at 282 MeV. Evidence is found for a large spin alignment which allows to use angular distributions and polarizations of gamma rays to firmly establish, for the first time, spin and parities of several excited states. In the one neutron transfer channels, $^{49}$Ca and $^{47}$Ca, states arising by coupling a single particle to the 3 phonon of $^{48}$Ca are observed, showing the robustness of nuclear collectivity in rather light systems. The work demonstrates the feasibility of complete in-beam $\gamma$-spectroscopy with heavy-ion transfer reactions and provides a method that can be further exploited in the future with heavy targets and radioactive beams.

1. Introduction

One of the most interesting issues in nuclear physics is the study of nuclei far from stability, which represent a test bench for nuclear models and a challenge for the experimental investigation. In recent years, it has been shown that deep inelastic collisions between heavy ions are a valuable tool to populate moderately neutron rich nuclei in different mass regions, allowing to perform spectroscopic studies of exotic systems [1,2]. Experimentally, a key instrument in multi-nucleon reaction studies is a large acceptance magnetic spectrometer coupled to a high efficiency and high resolution multi-detector array for gamma spectroscopy, based on Ge detectors. This results in a very powerful instrumentation which makes possible coincident measurements of particles and $\gamma$ transitions, allowing a detailed study of both reaction mechanisms and nuclear structure properties of weakly populated reaction products.

In this contribution we present an in-beam $\gamma$-spectroscopy study of Ca isotopes populated by the deep inelastic reaction $^{48}$Ca+$^{64}$Ni, at ~6 MeV/nucleon [3,4]. The experiment has been performed at Legnaro National Laboratory of INFN (Padova) using the large acceptance magnetic spectrometer PRISMA [5,6] combined with the high efficiency Ge array CLARA [7]. After demonstrating the possibility of performing complete in-beam $\gamma$ spectroscopy (in terms of angular distribution, polarization and lifetime measurements), we focus on $^{49}$Ca and $^{47}$Ca for which no firm spectroscopic information are available, being hard to reach by standard fusion-evaporation reactions. These nuclei are only one neutron away from the $^{48}$Ca doubly magic core, therefore they are good candidates to search for states arising from coupling a single particle to a phonon, such as the 3$^\pi$ state in $^{48}$Ca. The understanding of particle–phonon and phonon–phonon couplings is indeed 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 particular, the coupling of a single particle to the vibrational motion is the key process at the origin of anharmonicities of the vibrational spectra and a building block of phonon–...
phonon interactions. In nuclear physics, particle-phonon coupled states are responsible for the damping of collective excitations (as giant resonances), effective masses and the quenching of spectroscopic factors [8,9]. Experimentally, several indications have been found of discrete states of particle–phonon nature, mostly in medium-heavy nuclei [8], but only in few cases a 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 this work we give experimental evidence for these type of states in $^{49}$Ca and $^{47}$Ca, showing the robustness of nuclear collectivity in rather light systems.

2. The experiment
The $^{48}$Ca beam, impinging on a 0.98 mg/cm$^2$ thick $^{64}$Ni target, was provided by the Tandem-Alpi accelerators at 282 MeV, with an average current of 1 pnA. The reaction products were measured by the magnetic spectrometer PRISMA [5,6] and the coincident $\gamma$-rays by the CLARA HpGe-array [7]. PRISMA is among the largest acceptance ($\approx$ 80 msr) magnetic spectrometers currently operating. It is based on one quadrupole and one dipole magnets and a system of entrance and focal plane detectors which allow mass and charge identification of the detected ions after a trajectory reconstruction, event by event. In the current experiment PRISMA was placed at the grazing angle for this reaction, i.e. 20°, with an angular acceptance of ± 6°. The Ge array CLARA consisted of 23 composite Ge detectors of EUROBALL CLOVER type, each equipped with Anti-Compton shields and characterized by a total absolute efficiency of ~3% at 1.3 MeV. The CLOVER detectors were arranged in a hemisphere opposite to PRISMA with most of the Ge crystals placed in 3 rings at average azimuthal angles $\theta_{\text{CLA}} =$ 100°, 130° and 150° with respect to the entrance direction of the spectrometer. In this way reaction products detected in the spectrometer focal plane, in coincidence with the $\gamma$-rays, have a forward trajectory with respect to the array.

The analysis of the $\gamma$ rays measured by the CLARA array was performed in coincidence with some of the most intense reaction products. In particular, we have studied the angular distributions of the most intense transitions taking advantage of the ring geometry of the Ge detectors. For several known stretched E2 transitions in $^{46,50}$Ca and $^{51}$Sc nuclei, the intensities measured in the three rings at 100°, 130° and 150° have been normalized to the one at 100°, and fitted by the angular distribution function $W(\theta) = 1 + a_2 P_2(\cos\theta)$ (with $P_2$ the Legendre polynomial and $a_2$ the fitting parameter). It is found that the ratio $a_2/a_{2\text{max}}$ is approximately 70%, being $a_2$ the measured coefficient and $a_{2\text{max}}$ the maximum value allowed for the corresponding $\gamma$ decay with fully aligned spin. The presence of a strong spin alignment also allows the measurement of the linear polarization of the gamma rays, making use of the most efficient CLOVER detectors at 100°. Figure 4 shows, as an example, the $\gamma$ spectrum of $^{50}$Ca (panel a), with the angular distribution and the linear polarization of the stretched quadrupole transition $2^+ \rightarrow 0^+$ at 1027 keV given in panels b) and c). The analysis demonstrates the possibility to firmly establish spin and parity of the excited states by performing $\gamma$-spectroscopy studies with low energy heavy-ion transfer reactions [4,10]. In the following Sections we apply these techniques, together with lifetime measurements, to the study of $^{49}$Ca and $^{47}$Ca nuclei.

3. $\gamma$ Spectroscopy of $^{49}$Ca and $^{47}$Ca: Particle-vibration coupling in medium-light nuclei
Nuclei only one nucleon away from doubly magic systems are ideal candidates to search for states arising by coupling a particle/hole to a phonon. In the case of the doubly magic nucleus $^{48}$Ca, the 3$^-$ state at 4.507 MeV exhibits a sizable collectivity, with a measured B(E3) of 6.8±1 Wu [11]. On the contrary, the 2$^+$ state at 3.832 MeV is less collective, with a B(E2) value of ~2 Wu [12]. The rather strong collective character of the 3$^-$ suggests the existence of multiplets of positive parity states arising by coupling the 3$^-$ phonon with the unpaired p$_{3/2}$ neutron of $^{49}$Ca and the f$^+_7/2$ neutron hole of $^{47}$Ca. Experimentally, candidates for this type of states have been found both in $^{49}$Ca and $^{47}$Ca by low resolution particle spectroscopy studies: their common features are largely reduced spectroscopic factors and “anomalous” angular distributions of the detected particles [13,14]. For these states, no
firm spin and parity assignments have been obtained, so far, and no lifetime analysis has been performed in order to establish their collectivity.

**Figure 1.** Panel a): Gamma spectrum measured in the CLARA array in coincidence with $^{50}$Ca ions detected in PRISMA. The angular distribution of the $2^+ \rightarrow 0^+$ quadrupole transition at 1027 keV is shown in panel b): points refer to data, lines to the fit by the angular distribution function $W(\theta)$ with $a_2 = 0.51 \pm 0.06$ (see text for details). Panel c) shows the linear polarization of the 1027 keV transition, as measured by the CLOVER detectors at 100°. Solid and dashed lines give the expected values for a pure electric and magnetic quadrupole decay, respectively [4].

Figure 2 shows in the bottom panel the γ spectrum measured in coincidence with $^{49}$Ca ions detected in PRISMA. All strong transitions correspond to the decays from states identified as single particle excitations, besides the 660- and 3357-keV lines which depopulate the levels at 4017 keV and 3357 keV, with the tentative spin assignment $9/2^+$ and $7/2^-$, respectively [2]. In particular, the 4017 keV state is expected to originate from the $p_{3/2}$ neutron coupled to the $3^-$ phonon of $^{48}$Ca. In the present experiment these spin assignments have been proven by measuring the angular distribution and polarization of both transitions, resulting in $a_2$ coefficients and asymmetry values consistent with electric stretched dipole for the 660-keV line and electric stretched quadrupole for the 3357-keV γ ray (cfr. Fig. 2). In addition, to firmly establish the nature of the states, a lifetime analysis has been performed by applying a differential plunger technique to the heavy-ion transfer reaction $^{48}$Ca$^{+}$208Pb, measured with PRISMA-CLARA [15]. As shown in Fig. 2 b), the lifetime of the 660-keV line, depopulating the 4017 keV level, is $\tau = 8.5 \pm 2.0$ ps. Taking into account the branching from the 4017 keV state (of the order of 9% for the direct decay to the ground state) one obtains the reduced transition probability $B(E3) = 7.9 \pm 2.0$ Wu, which is very close to the measured strength of the $3^-$ phonon of $^{48}$Ca.
Figure 2. Bottom panel: Gamma spectrum of $^{49}$Ca, with contaminant lines from $^{63}$Ni marked by stars. Panels a): Angular distribution of the 660-keV transitions. The lines represent the fit by the function $W(\theta)$, with parameter $a_2 = 0.072 \pm 0.05$ (consistent with a stretched dipole with ~4% admixture of quadrupole decay). The inset of panel a) shows the polarization of the 660-keV $\gamma$ ray, in comparison with prediction for a pure electric or magnetic dipole. Panel b) shows, in the inset, the Doppler corrected $\gamma$-ray spectrum around 660 keV, as measured in the differential plunger experiment [15]. From the relative intensity of the high- and low-energy peaks, corresponding to the decay after and before the degrader, as a function of the target-to-degrader distances, the lifetime of the state is obtained [4].

A similar type of analysis has been performed on the $^{47}$Ca reaction product. Figure 3 shows in the bottom panel the $\gamma$ spectrum, with labels indicating transitions de-exciting states of single particle nature [2]. In addition, a very weak transition at 437 keV is also observed, which has been established to depopulate a state at 3999 keV. Such state has been proposed to be the 11/2$^-$ or 13/2$^-$ member of the multiplet of states arising by coupling the 3$^-$ phonon of $^{48}$Ca with the $f^{17/2}$ neutron hole of $^{47}$Ca. Due to the limited statistics collected for this transition no angular distribution and polarization measurements could be performed to firmly determine spin and parity of the 3999 keV level, however an attempt was made to measure the lifetime of this state using the same differential plunger technique applied to the case of $^{49}$Ca (cfr. panels a) and b) of Fig. 3). It is found that the lifetime is $\tau = 64\pm16$ ps. Therefore, taking into account the decay branch of ~58% to the ground state, the reduced transition probability becomes equal to $B(E3)=7.4\pm1.9$ Wu, again very similar to the 3$^-$ phonon strength of $^{48}$Ca.

Theoretically, a weak coupling model, originally proposed by Bohr and Mottelson [8], can be applied to predict the excitation energy spectrum arising from coupling a particle/hole to a phonon. This type of calculation have been performed for $^{47}$Ca and $^{49}$Ca, making use of both an Skx and Sly5 interaction, and the obtained results are very similar [10]. As shown in Fig. 4, the model predicts, at the lowest perturbative order, multiplet of states with energies shifted with respect to the 3$^-$ phonon. In
particular, in the case of $^{49}\text{Ca}$ the levels are found to be quite closely spaced and moved down in energy, with very good agreement with the experimental energy for the $9/2^+$ state. On the contrary, in the case of $^{47}\text{Ca}$, a larger energy spread is found within the multiplet, with the $13/2^+$ state being the only one lifted up. This strongly favors the spin assignment of $11/2^+$ to the 3999 keV level, experimentally observed. At the same perturbative order, the calculations predict that the reduced transition probability $B(\text{EL})$ to the ground state should be associated to the same multipole of the vibrational state and should have the same value of the core nucleus ($B(\text{E3}) \approx 7 \text{ Wu}$ in this case). The fact that, experimentally, the $B(\text{E3})$ values of the ground state decay from the 3999-keV level in $^{47}\text{Ca}$ and from the 4017-keV level in $^{49}\text{Ca}$ is the same (within the error) of the 3' phonon of $^{48}\text{Ca}$ is a strong evidence that these state have a particle-phonon coupled nature. Indication for similar type of states have been recently found also in $^{41,43}\text{Ar}$ nuclei [16].

![Figure 3. Bottom panel: Gamma spectrum of $^{47}\text{Ca}$. Panels a) and b): Lifetime analysis of the 437-keV line, de-exciting the 3999-keV level, extracted from the relative intensity of the high- and low-energy peaks (panel a)), corresponding to the decay after and before the degrader, as a function of the target-to-degrader distances (panel b)). To improve the selectivity to $\gamma$ decays from states around 4 MeV, only events with large Total Kinetic Energy Loss were considered, as shown in the inset of panel b) [10].](image)

4. Conclusion
Based on the study of the binary reaction $^{48}\text{Ca} + ^{64}\text{Ni}$ at ~6 MeV/nucleon, we have demonstrated the possibility of performing complete $\gamma$ spectroscopy studies (i.e. angular distribution, polarization and lifetime analysis) with low energy heavy-ion transfer reactions. This opens up the possibility to investigate in great detail the properties of moderately neutron rich systems moving away from stability and provides a method that can be further exploited in the future with heavy targets and radioactive beams. In the specific cases of $^{49}\text{Ca}$ and $^{47}\text{Ca}$, evidence is given for particle-phonon coupled states based on the 3' excitation of $^{48}\text{Ca}$. These are among the few fully established examples
of particle-phonon coupled states in rather light nuclear systems. They are, in general, of great importance for the understanding of the origin of the anharmonicity of vibrational spectra, for damping phenomena and for the quenching of spectroscopic factors.

Figure 4. Partial level scheme of $^{49}$Ca (right) and $^{47}$Ca (left) showing the positive parity states arising by coupling one neutron ($p_{3/2}$) or one neutron-hole ($f_{-1}^{17/2}$) to the collective $3^+$ phonon of $^{48}$Ca (center). Experimental data refer to this work, theoretical prediction are obtained by the weak coupling model of Ref. [8] using the Skx skyrme interaction.

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