REACTION DYNAMICS AND NUCLEAR STRUCTURE STUDIES OF N-RICH NUCLEI AROUND ^{48}Ca VIA DEEP INELASTIC COLLISIONS WITH HEAVY-IONS*

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The population and γ decay of neutron rich nuclei around ^{48}Ca has been measured at Legnaro National Laboratory with the PRISMA-CLARA setup, using deep-inelastic collisions on ^{64}Ni, at 5.9 MeV$/A$. The reaction properties of the main products are investigated, focusing on total cross-sections and energy integrated angular distributions. Gamma spectroscopy studies are also performed for the most intense transfer channels, making use of angular distributions and polarization measurements to firmly establish spin and parity of the excited states. In the case of ^{49}Ca candidates for particle-core couplings are investigated and interpreted on basis of lifetime measurements and comparison with model predictions.

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1. Introduction

In recent years, deep inelastic collisions (DIC) between heavy ions have been proved to be a valuable tool to populate moderately neutron rich nuclei in different mass regions. In particular, the knowledge of these reaction mechanisms provides information on nuclear potentials, spectroscopic factors and multi-nucleon transfer processes, while spectroscopy studies of the populated nuclei allow for the investigation of nuclear structure properties of exotic systems [1, 2]. In this contribution we present a study of the population and γ decay of moderately neutron rich nuclei around $A = 50$ via the deep inelastic reaction $^{48}\mathrm{Ca} + {}^{64}\mathrm{Ni}$, at energy about twice the Coulomb barrier. The experiment has been performed making use of the PRISMA-CLARA setup, which combines the large acceptance magnetic spectrometer PRISMA with the high efficiency Ge array CLARA [3]. This makes possible coincident measurements of particles and γ transitions with rather high

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efficiency, allowing for a detailed study of the reaction mechanisms and of the nuclear structure properties of weakly populated reaction products. In Sec. 2 we briefly describe the experiment and the apparatus, while in Sec. 3 we show selected results from the reaction studies, focusing on the analysis of inclusive angular distributions of one nucleon transfer channels, in comparison with predictions from the semiclassical model GRAZING [4]. Emphasis is given to the study of the transport of the ions in the magnetic spectrometer (*i.e.* the PRISMA response), which is crucial for a proper analysis of the experimental data. In Sec. 4 we present γ spectroscopy studies in coincidence with specific reaction products, showing the possibility of using angular distributions and polarizations of the γ transitions. In particular, we discuss the case of the one neutron transfer channel ^{49}Ca, where the $7/2^-$ and $9/2^+$ states are firmly identified and interpreted on basis of two different type of particle-core coupling schemes, *i.e.* single particle coupled to ^{48}Ca (or ^{50}Ca) simple configurations, and particle-vibration coupled states based on the 3^- phonon of ^{48}Ca.

2. The experiment

The experiment has been performed at Laboratori Nazionali di Legnaro (LNL) of INFN (Italy). 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] and the coincident γ-rays by the CLARA HpGe-array [3]. PRISMA is among the largest acceptance magnetic spectrometers currently operating, with a solid angle of ≈ 80 msr. 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, event by event, after a trajectory reconstruction. In the current experiment PRISMA has been placed at the grazing angle for this reaction, *i.e.* 20°, with an angular acceptance of $\pm 6°$. The Ge array CLARA consisted of 23 composite Ge detectors of EUROBALL Clover type [6], each equipped with Anti-Compton shields, resulting in a total absolute efficiency of $\approx 3\%$ at 1.3 MeV. The Clover detectors were arranged in a hemisphere opposite to PRISMA with the Ge crystals placed in three rings at average azimuthal angles $\theta_{\rm CLA} = 100°$, 130° and 150° with respect to the entrance direction of the spectrometer.

3. Study of the reaction

In the present ^{48}Ca + ^{64}Ni experiment, atomic species from $-4p$ to $+4p$ have been populated and many nucleons transfer channels have been observed, as shown by the E–ΔE and mass spectra displayed in Fig. 1.

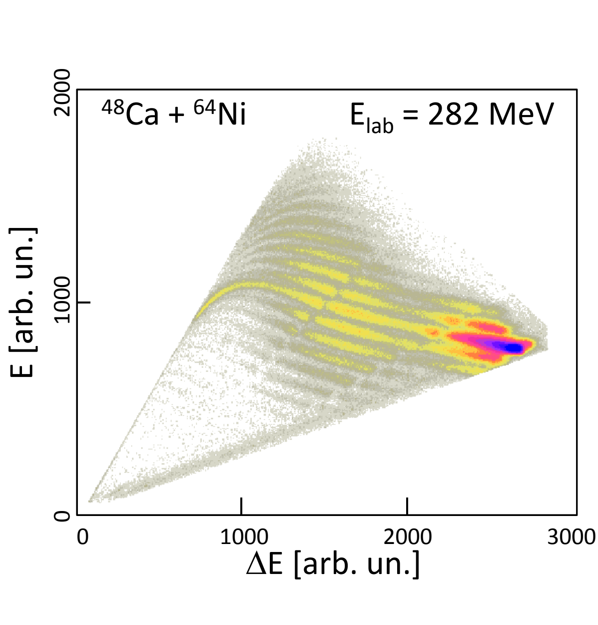

Fig. 1. Left: E–ΔE spectrum of the ^{48}Ca + ^{64}Ni reaction, as measured by the ionization chamber of PRISMA. The most intense distribution is associated to $Z = 20$. Right: Mass spectra of the most intense isotopic chains produced in the experiment. The dashed line is placed at mass $A = 48$.

To obtain a proper evaluation of the cross-sections, the transmission of the ions into the magnetic spectrometer was carefully evaluated [7]. The study was performed by a Monte Carlo simulation of the transport of the ^{48}Ca ions, starting from a uniform spatial and kinetic energy distribution of the incoming particles. The trajectories of the ions into the spectrometer were calculated, event by event, transporting the ions up to the focal plane, on the basis of a detailed knowledge of the magnetic fields (including the fringe fields) and of the geometry of the instruments. The procedure employs a ray tracing code, which uses numerical integrators to determine the trajectories of individual ions through the electromagnetic fields. Figure 2 shows the ($\theta_{\rm lab}$,$\phi_{\rm lab}$) angular distributions obtained for the 16$^+$ and 18$^+$ charge states for different kinetic energies. In the figure, the dashed lines indicate the acceptance of the spectrometer, which corresponds to the area of the microchannelplate (MCP) entrance detector seen by the ions reaching the focal plane. As one can see, the angular distribution is found to vary substantially with the energy of the incoming ion, which demonstrates the importance of the evaluation of the spectrometer response.

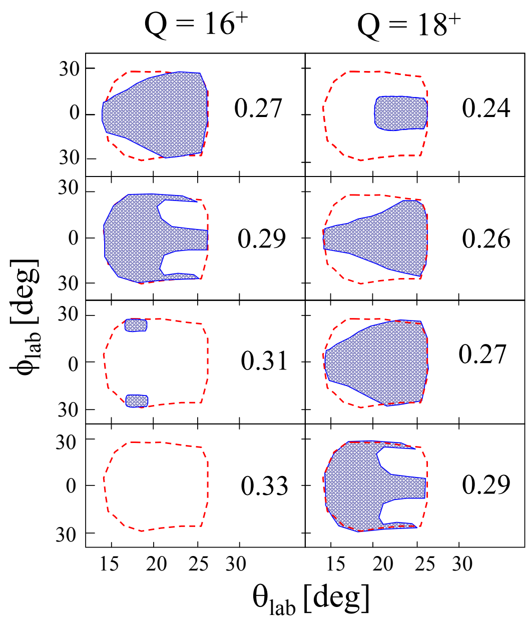

Fig. 2. Angular distributions (dark areas) of the $Q = 16^+$ and 18^+ charge states of ^{48}Ca for different kinetic energies of the incoming ions, from 207 MeV in steps of 30 MeV. Each frame is labelled by the p/Q value expressed in GeV/c. The dashed lines indicate the acceptance of the spectrometer, *i.e.* the area of the entrance MCP detector seen by the particles reaching the focal plane.

The response function of PRISMA was calculated for the total charge state distribution, for each value of energy and angle, as the ratio of the transported events over the initial ones. Its inverse provides directly the factor $f(E_{\rm K}, \theta_{\rm lab})$ needed to correct the experimental yields. As shown in Fig. 3, major corrections are found at the edge of the angular acceptance, with a clear dependence on the kinetic energy of the transported ions.

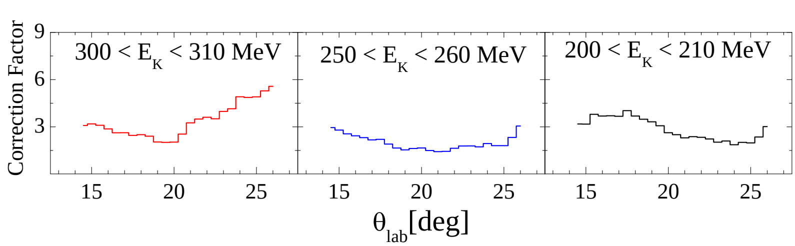

Fig. 3. Cuts in kinetic energy ($E_{\rm K}$) on the correction factor $f(E_{\rm K}, \theta_{\rm lab})$ to the transmission in the PRISMA spectrometer, as obtained by the Monte Carlo simulations for ^{48}Ca ions [7].

The study of the reaction mechanisms has been mainly focused on the energy integrated angular distributions of the most intense channels, in comparison with predictions from a semiclassical model, implemented in the code GRAZING [4]. The experimental results for the elastic cross-section and the $\pm 1n$ and $\pm 1p$ channels are shown in Fig. 4 by full symbols, while theoretical values are represented by the solid lines. The reasonable agreement between data and calculations gives us confidence in the choice of the nuclear potential and in the theoretical description of the one nucleon transfer channels. A similar analysis has been carried out on a number of transfer channels between $-4p$ to $+2p$, showing the need for additional reaction mechanisms, such as pair transfer, to interpret the data [8].

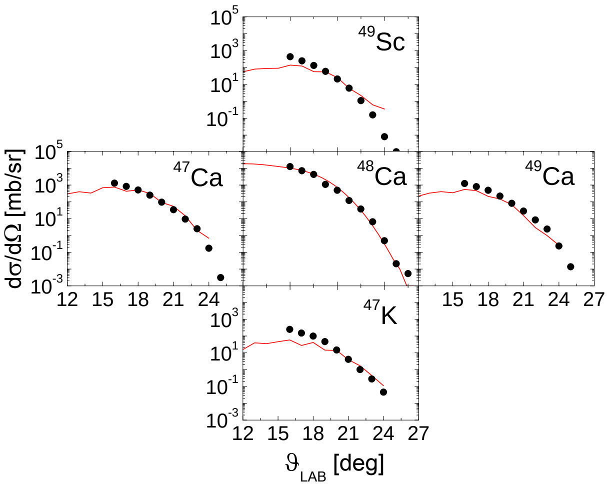

Fig. 4. Angular distributions for the ^{48}Ca elastic channel and for the $\pm 1n$ and the $\pm 1p$ channels. Experimental data are shown by full symbols while solid lines give theoretical predictions from the GRAZING model (see text for details).

For some of the most intense channels, angular distributions of the direct population of excited states have also been studied experimentally and compared with Distorted Wave Born Approximation calculations, provided by the PTOLEMY code [9]. In particular, the angular distributions of the inelastic excitation to the 2^+ states of ^{48}Ca and ^{64}Ni and to the first excited state of ^{49}Ca have been obtained by gating on the corresponding γ-transition measured in the Ge spectrometer. Preliminary results show that the particle distributions are reasonably well reproduced by the model, indicating the possibility of using transfer reaction between heavy ions to extract basic nuclear structure information, such as spectroscopic factors, if high efficiency and high multiplicity γ-arrays are operated in conjunction with magnetic spectrometers.

4. Gamma spectroscopy study

The analysis of the γ-rays measured by the CLARA array has been performed only in coincidence with the most intense reaction products [8]. In particular, we have studied the angular distributions of the strongest γ transitions, grouping the Ge detectors in rings at azimuthal angles $\theta_{\mathrm{CLA}} = 100°$, 130° and 150° with respect to the entrance direction into the PRISMA spectrometer. From the study of known $E2$ transitions evidence was obtained for a large spin alignment perpendicular to the reaction plane. Figure 5 (a) shows, as an example, the γ spectrum of ^{50}Ca, with the angular distribution of the $2^+ \rightarrow 0^+$ transition at 1027 keV given in the inset. The existence of spin alignment makes possible the use of angular distributions and linear polarizations of the γ-rays to determine the multipolarity and electromagnetic character of the transitions. This analysis is particularly important for neutron rich nuclei around ^{48}Ca, whose excited states have in most cases a tentative spin and parity assignment, mostly based on systematics or on comparison with model predictions [2]. In the case of ^{49}Ca, for example, a

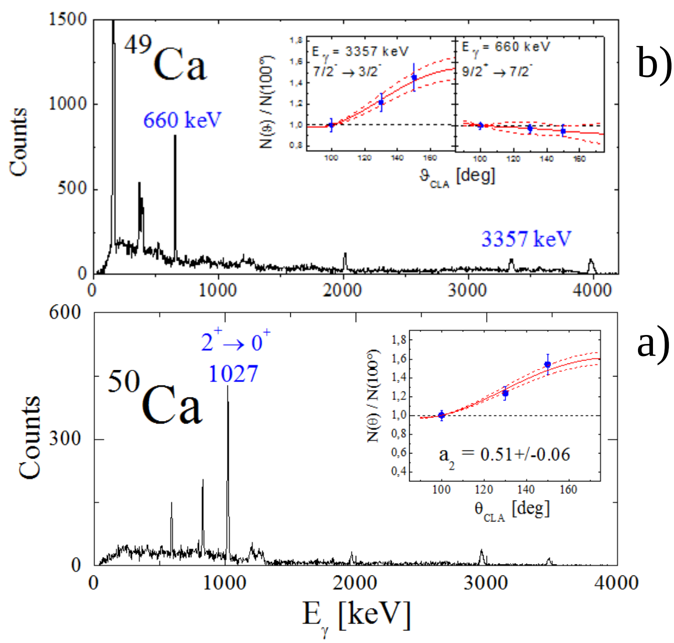

Fig. 5. Gamma spectra measured in the CLARA array in coincidence with ^{50}Ca (panel (a)) and ^{49}Ca (panel (b)) ions detected in the PRISMA spectrometer. In panel (a) the inset shows the angular distribution of the $2^+ \rightarrow 0^+$ transition of ^{50}Ca at 1027 keV, with the a_2 coefficient equal to 0.51 ± 0.06. The inset of panel (b) shows instead the angular distributions of the transitions of ^{49}Ca at 660 and 3357 keV, with a_2 coefficients equal to 0.072 ± 0.05 and 0.47 ± 0.07, respectively.

particle-core coupling model was proposed to explain the spectrum at excitation energies corresponding to the first excited states in ^{48}Ca [10]. In particular, the transitions at 3357 and 660 keV were suggested to decay from the $7/2^-$ and $9/2^+$ states, which could arise from the coupling of ^{48}Ca (or ^{50}Ca) core excitations with a single particle (or hole) state. Figure 5 (b) shows the γ spectrum measured in CLARA in coincidence with ^{49}Ca ions detected in PRISMA. As given in the insets, the angular distribution of the 3357 and 660 keV transitions show anisotropies which are consistent with stretched quadrupole and dipole transitions, respectively. In addition, polarization measurements performed with the CLOVER detectors at 100° indicate an electric character for both transitions, therefore fixing the spin and parity of the states to $7/2^-$ and $9/2^+$, as given in Fig. 6. The microscopic nature of the $7/2^-$ and $9/2^+$ states has been investigated by lifetime analysis, using the differential Recoil Distance Doppler Shift method [11, 12]. The results for the $B(E2)$ values of the ground state decays from the $7/2^-$ and $9/2^+$ levels are also shown in Fig. 6. The experimental values are compared with predictions from shell model and particle-vibration coupling calculations, giving strong support to the previous core-coupling picture: while the $7/2^-$ state is a pure $2p$–$1h$ configuration arising from the coupling of the $f_{7/2}$ hole state with the ground state of ^{50}Ca, the $9/2^+$ state is given by the coupling of the $p_{3/2}$ single particle with the 3^- collective phonon of ^{48}Ca [8].

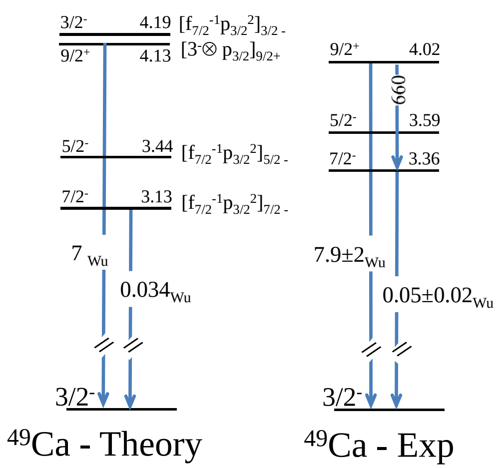

Fig. 6. Partial decay scheme of ^{49}Ca, discussed in this work. Spin, parity and excitation energy are given for each level, as follows from the experimental analysis (right) and theoretical calculations (left), which also provide the configuration of the states. Experimental and theoretical $B(E\lambda)$ transition strengths of the $7/2^-$ and $9/2^+$ ground state decay are reported on the arrows in Weisskopf units (W.u.).

5. Conclusions

The deep inelastic reaction $^{48}\mathrm{Ca}+{}^{64}\mathrm{Ni}$, at few MeV per nucleon, has been investigated with the PRISMA-CLARA setup at LNL. The analysis focuses both on the dynamics of the reaction and on nuclear structure properties of the neutron rich systems around ^{48}Ca. In the latter case, angular distributions and polarizations of the γ transitions are used to firmly establish spin and parities of the excited states. In the case of ^{49}Ca, evidence is given for states resulting from the coupling between core-excitations and the unpaired $p_{3/2}$ neutron of ^{49}Ca, either of single particle nature or based on particle–phonon interaction.

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