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2011 J. Phys.: Conf. Ser. 312 092037

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## Reaction dynamics and nuclear structure studies via deep inelastic collisions with heavy-ions: spin and parity assignment in $^{49}\text{Ca}$

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**Abstract.** The population and gamma decay of neutron rich nuclei around  $^{48}\text{Ca}$  has been measured at Legnaro National Laboratory with the PRISMA-CLARA setup, using deep-inelastic collisions (DIC) on  $^{64}\text{Ni}$ , at an energy approximately twice the Coulomb barrier. The reaction properties of the main products are investigated, focusing on total cross sections and angular distributions both integrated in energy and associated to the population of specific excited states. Gamma spectroscopy studies are also performed, giving evidence, for the first time in transfer reactions with heavy ions, of a large spin alignment ( $\sim 70\%$ ), perpendicular to the reaction plane. This makes possible the use of angular distributions and polarization measurements to firmly establish the spin and parity of excited states populated in nucleon transfer channels, as in the case of  $^{49}\text{Ca}$ , where candidates for particle-core coupling are investigated. Both reaction and gamma spectroscopy studies demonstrate the relevance of DIC with heavy ions for a detailed investigation of moderately neutron rich systems.

## 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, deep inelastic collisions 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 gamma decay of moderately neutron rich nuclei around  $A = 50$  via the deep inelastic reaction  $^{48}\text{Ca}+^{64}\text{Ni}$ , at energy approximately twice the Coulomb barrier. The experiment has been performed making use of the PRISMA-CLARA setup which consists in the combination of the large acceptance magnetic spectrometer PRISMA with the high efficiency Ge array CLARA [3]. This results in a very powerful instrumentation which makes possible coincident measurements of particles and gamma transitions, allowing a detailed study of the reaction mechanisms and of the nuclear structure properties of weakly populated reaction products.

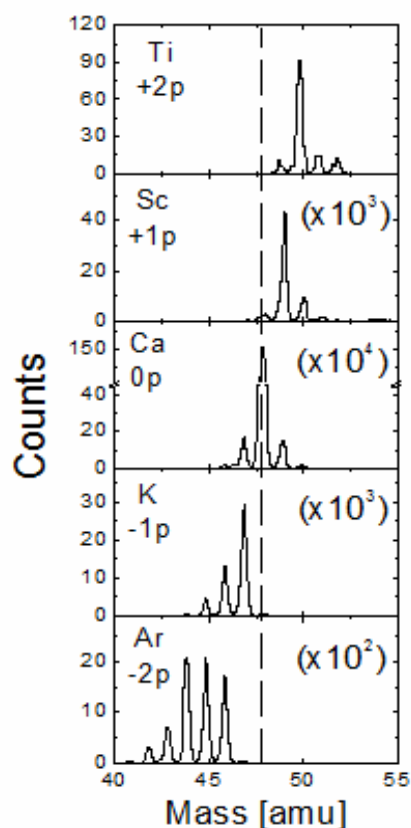
In Section 2 we show selected results from the reaction studies, mainly focusing on the analysis of inclusive angular distributions of one nucleon transfer channels, in comparison with predictions from the semiclassical model GRAZING [4]. In this connection, the study of the transport of the ions in the magnetic spectrometer (i.e. to the response function of PRISMA) is discussed, since it is crucial for a proper analysis of the experimental data. In Section 3 we discuss the analysis of the gamma transitions measured in CLARA, in coincidence with specific reaction products. For the first time we give evidence, in transfer reactions, of a large spin alignment perpendicular to the reaction plane, which makes possible the use of angular distributions and polarizations of the gamma transitions to firmly establish the spin and parity of the nuclear states. Special emphasis will be given to the one neutron transfer channel  $^{49}\text{Ca}$ , where spin and parity assignments of the most strongly populated states and lifetime analysis allow to distinguish between different type of core-coupled states.

## 2. The Experiment

The experiment has been performed at Laboratori Nazionali di Legnaro (LNL) of INFN (Italy). The  $^{48}\text{Ca}$  beam, impinging on a  $0.98 \text{ mg/cm}^2$  thick  $^{64}\text{Ni}$  target, was provided by the Tandem-Alpi accelerators at 282 MeV, with an average current of 1 pA. The reaction products were measured by the magnetic spectrometer PRISMA [5] and the coincident  $\gamma$ -rays by the CLARA HpGe-array [3]. PRISMA is among the largest acceptance ( $\sim 80 \text{ msr}$ ) 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 has been placed at the grazing angle for this reaction, i.e.  $20^\circ$ , with an angular acceptance of  $\pm 6^\circ$ . The Ge array CLARA consisted of 25 composite Ge detectors of EUROBALL CLOVER type [6], each equipped with Anti-Compton shields, characterized by a total absolute efficiency of  $\sim 3\%$  at 1.3 MeV. The CLOVER detectors are arranged in a hemisphere opposite to PRISMA with most of the Ge crystals placed in 3 rings at average azimuthal angles  $\theta_{\text{CLA}} = 100^\circ, 130^\circ$  and  $150^\circ$  degree 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, will have a forward trajectory with respect to the array.

## 3. Reaction Study

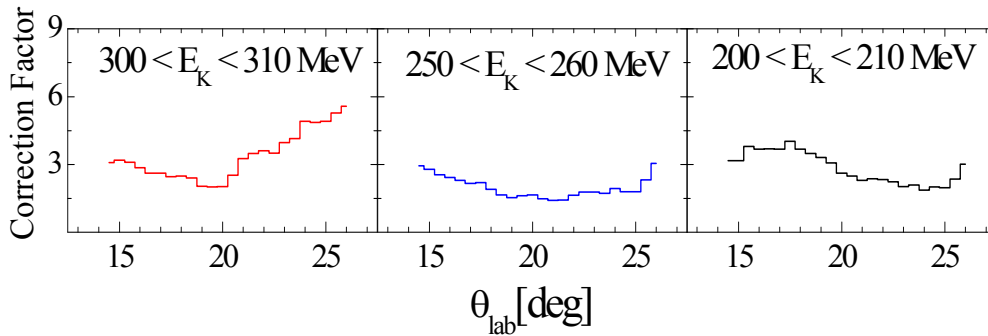
In the present  $^{48}\text{Ca}+^{64}\text{Ni}$  experiment, atomic species from  $-4p$  to  $+4p$  have been populated and many nucleon transfer channels, pick-up or stripping, have been observed, as shown by the mass spectra displayed in Fig. 1.



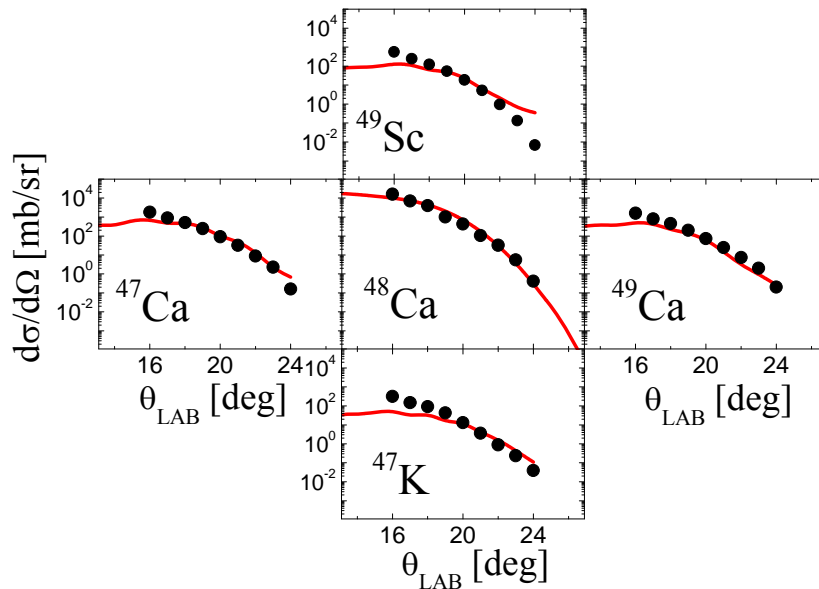
**Figure 1.** Mass spectra ranging to -2p to +2p transfer channels, populated in the  $^{48}\text{Ca} + ^{64}\text{Ni}$  reaction. The dashed line corresponds to the projectile nucleus  $^{48}\text{Ca}$ . For presentation purposes the mass spectra of Sc, Ca, K and Ar have been scaled by the factors given in the corresponding panels.

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  $^{48}\text{Ca}$  ions, starting from a uniform spatial and kinetic energy distribution of the incoming particles. The trajectories of the ions into the spectrometer are 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, the latter being calculated by the Finite Element Method. The response function of PRISMA is then calculated for each value of energy and angle, as the ratio of the transported events over the initial ones. Its inverse provides directly the factor  $f(E_K, \theta_{\text{lab}})$  needed to correct the experimentally measured yield. As shown in Fig. 2, major corrections are found at the edge of the angular acceptance, with a clear dependence on the kinetic energy of the transported ions. This demonstrates the importance of the accurate treatment of the distortion and aberration of the transmission into the spectrometer.

The study of the reaction mechanisms has been focused mostly on the energy integrated angular distributions of the most intense channels, in comparison with the theoretical calculations of the semiclassical grazing model of Ref. [4]. The experimental results for the elastic cross section and the  $\pm 1n$  and  $\pm 1p$  channels are shown in Fig. 3 by full symbols, while theoretical values are represented by the solid red 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 experimental analysis has been carried out on a number of transfer channels between  $-4p$  to  $+2p$ , showing the need for additional reaction mechanisms, such as evaporation and pair transfer, to interpret the data.



**Figure 2.** Cuts in kinetic energy ( $E_K$ ) on the correction factor  $f(E_K, \theta_{lab})$  to the transmission in the PRISMA spectrometer, as obtained by a Monte Carlo simulations for  $^{48}\text{Ca}$  ions [7].



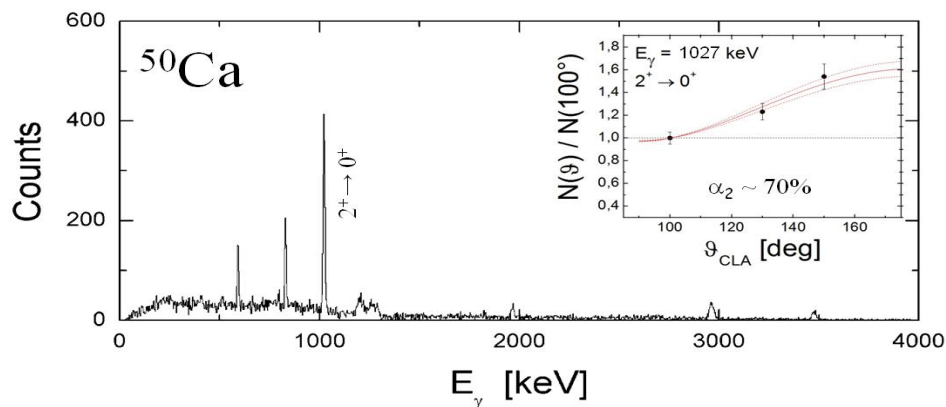
**Figure 3.** Angular distributions for the  $^{48}\text{Ca}$  elastic channel and for the  $\pm 1n$  and the  $\pm 1p$  channels. Experimental data are shown by full symbols while solid lines give theoretical predictions from the semiclassical grazing model of Ref. [4].

For some of the most intense channels, angular distributions of the direct population of excited states have been also studied experimentally and compared with Distorted Wave Born Approximation calculations, provided by the PTOLEMY code [8]. In particular, the angular distributions of the inelastic excitation to the  $2^+$  states of  $^{48}\text{Ca}$  and  $^{64}\text{Ni}$  and to the first excited state of  $^{49}\text{Ca}$  have been obtained by gating on the corresponding  $\gamma$  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  $\gamma$ -arrays are operated in conjunction with magnetic spectrometers.

### 3. Spectroscopy Studies: spin and parity assignment in $^{49}\text{Ca}$

The analysis of the  $\gamma$ -rays measured by the CLARA array was performed for spectra in coincidence with some of the most intense reaction products. In particular, angular distributions of the most intense transitions have been studied, grouping the Ge detectors in rings at azimuthal angles  $\theta_{CLA}$

=100°, 130° and 150° with respect to the entrance direction into the magnetic spectrometer. For several known E2 transitions, the intensities measured in the three rings 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  $\alpha_2 = a_2/a_{2\max}$  is approximately 70%, being  $a_2$  the measured coefficient and  $a_{2\max}$  the maximum value allowed for the corresponding  $\gamma$  decay with fully aligned spin. Figure 4 shows, as an example, the gamma spectrum of  $^{50}\text{Ca}$ , with the angular distribution of the stretched quadrupole transition  $2^+ \rightarrow 0^+$  at 1027 keV given in the inset. Similar results are obtained for a number of known stretched quadrupole transitions deexciting  $^{46,48,50}\text{Ca}$  and  $^{51}\text{Sc}$  nuclei.

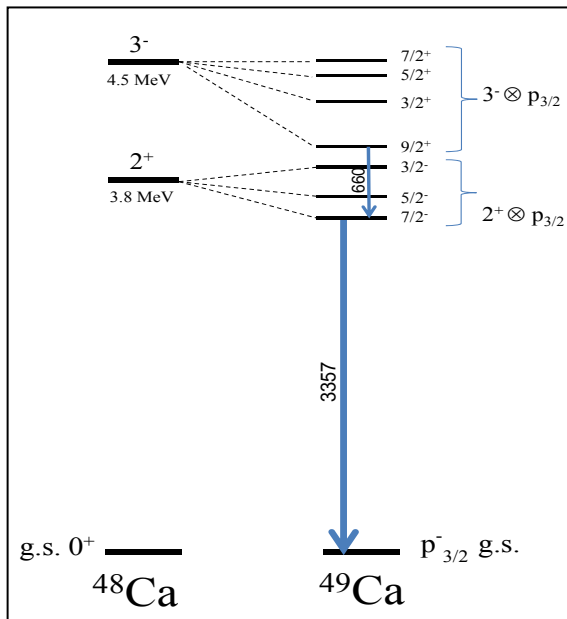


**Figure 4.** Gamma spectrum measured in the CLARA array in coincidence with  $^{50}\text{Ca}$  ions detected in PRISMA. The angular distribution of the  $2^+ \rightarrow 0^+$  quadrupole transition at 1027 keV is shown in the inset: points refer to data, lines to fit by the angular distribution function  $W(\theta)$  with  $a_2=0.51\pm 0.06$  (see text for details).

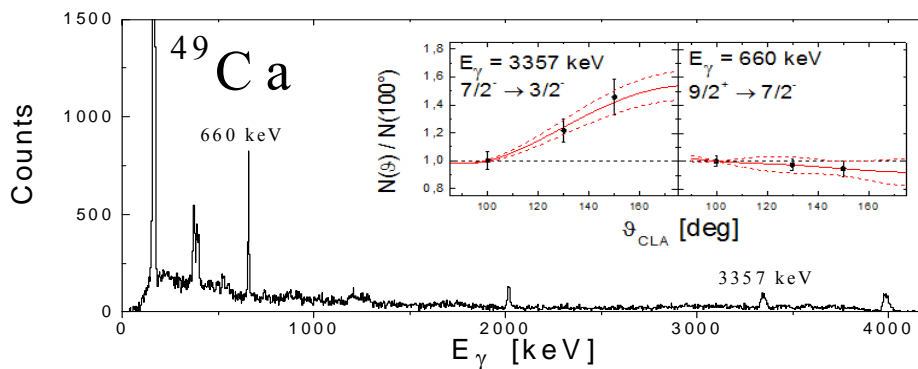
The existence of a large spin alignment makes possible the use of angular distributions and linear polarization of the  $\gamma$ -rays to determine the multipolarity and electromagnetic character of the transitions, therefore fixing the spin and parity of the nuclear states. This is particularly important for neutron rich nuclei around  $^{48}\text{Ca}$ , 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  $^{49}\text{Ca}$ , for example, a particle-core coupling model has been proposed to explain the spectrum at excitation energies corresponding to those of the first excited states in  $^{48}\text{Ca}$  [9]. In particular, the transitions at 3357 and 660 keV are proposed to decay from the states  $7/2^-$  and  $9/2^+$ , which should correspond to the lowest members of the multiplet of states arising, respectively, from the coupling of the  $2^+$  and  $3^-$  levels of  $^{48}\text{Ca}$  with the unpaired  $p_{3/2}$  neutron of  $^{49}\text{Ca}$ . This is schematically illustrated in Fig. 5. Figure 6 shows the gamma spectrum measured in the CLARA array in coincidence with  $^{49}\text{Ca}$  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 suggested in Fig. 5 (see Ref. [11] for more details).

To investigate the microscopic nature of the  $7/2^-$  and  $9/2^+$  states and fully establish the core-coupling scheme, lifetime analysis have been performed, using the differential Recoil Distance Doppler Shift method [10]. The results give support to a core-coupling picture, although the small  $B(E2)$  value ( $\sim 0.05$  W.u.) obtained for the 3357 keV transition leads us to interpret this state as a  $2p-1h$  state produced by coupling a  $(f_{7/2})^{-1}$  neutron hole to the  $0^+$  core of  $^{50}\text{Ca}$ . This analysis provides, for the first time, a complete interpretation of the first excited states in the neutron rich nucleus  $^{49}\text{Ca}$  [11].



**Figure 5.** Level scheme of  $^{49}\text{Ca}$  as obtained from particle-core coupling models with the  $2^+$  and  $3^-$  states of  $^{48}\text{Ca}$ . To be noted that states arising by coupling a  $p_{3/2}$  particle with the  $2^+$  state of  $^{48}\text{Ca}$  can also be generated by coupling a  $(f_{7/2})^{-1}$  hole to the  $0^+$  or  $2^+$  states in  $^{50}\text{Ca}$  (see Ref. [9]).



**Figure 6.** Gamma spectrum measured in the CLARA array in coincidence with  $^{49}\text{Ca}$  ions detected in the PRISMA spectrometer. The angular distribution of the transitions at 660 and 3357 keV are shown in the insets.

#### 4. Conclusions

The binary reaction  $^{48}\text{Ca} + ^{64}\text{Ni}$  at few MeV per nucleon, measured with the PRISMA-CLARA setup at LNL, has been investigated in terms of reaction dynamics and nuclear structure properties of the neutron rich systems around  $^{48}\text{Ca}$ . Evidence is found for a large spin alignment perpendicular to the reaction plane, which makes possible to use angular distributions and polarizations of the  $\gamma$  transitions to firmly establish spin and parities of the excited states. This represents a step forward in binary reaction studies with heavy ions, since it opens up the possibility to investigate in greater details the properties of moderately neutron rich systems away from stability.

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