Population and γ-decay studies of neutron-rich nuclei around ^{48}Ca with deep inelastic collisions

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Abstract

The population and γ-decay of n-rich nuclei around ^{48}Ca has been measured with the PRISMA-CLARA setup using deep-inelastic collisions (DIC) on ^{64}Ni, at energies ~2.5 times above the Coulomb barrier. After a careful analysis of the response of the PRISMA magnetic spectrometer, a detailed investigation of the reaction properties is carried out. This provides total cross sections and energy integrated angular distributions of the most relevant transfer channels, which are compared with predictions from a semiclassical multi-nucleon transfer model. Good agreement is found for the 0p, ±1p and ±1n channels. In few cases, angular distributions of the first excited states are also measured and the experimental results are interpreted in terms of DWBA calculations, providing information on the basic ingredients of the theoretical models.

1   Introduction

One of the most interesting issues in nuclear physics is the study of nuclei far from stability. High energy collisions between heavy ions have been proved to be a valuable tool to populate neutron rich nuclei. Furthermore, the knowledge of these reaction mechanisms provides information on nuclear potentials, spectroscopic factors, pair transfer and particle-vibration couplings, which are the starting points toward the study of the nuclear structure of exotic nuclei.

In this contribution we present a study, with the PRISMA-CLARA setup, of the population of moderately neutron rich nuclei around A = 50 via the deep inelastic reaction ^{48}Ca+^{64}Ni, at ~ 2.5 times above the Coulomb barrier. Particular emphasis is given to the study of the transport of the ions in the magnetic spectrometer (i.e. to the response function of PRISMA), which is crucial for a proper analysis of the experimental data. Experimental results have been obtained for the energy integrated angular distributions of the most intense reaction products, which have been compared with predictions from the semiclassical model GRAZING [1].

2   Experimental Setup and Response Function Calculations

The experiment has been performed at the Laboratori Nazionali di Legnaro, (Padova, Italy). The ^{48}Ca beam has been provided by the Tandem-Alpi accelerators at 270 MeV and impinged on a 0.98 mg/cm^2 thick ^{64}Ni target. The reaction products have been measured by the magnetic spectrometer PRISMA and the coincident γ-rays by the CLARA Ge-array [2]. The large acceptance magnetic spectrometer (≈ 80 msr) was placed at the grazing angle for this reaction, i.e. 20°, with an angular acceptance of ± 6°. Atomic species from -4p to +4p have been populated and many nucleons transfer channels, pick-up or stripping, have been observed.

To obtain a proper evaluation of the cross sections, the transmission of the ions into the magnetic spectrometer has been carefully evaluated. The study has been performed by a Monte Carlo simulation of the transport of the ^{48}Ca ions, starting from a uniform distribution in θ, ϕ and kinetic energy E 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. This is done on 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 means of the Finite Element Method [3,4]. As a first step, the optics of the magnets has to be adjusted according to the experimental conditions under analysis. This requires a tuning of the intensity of both the quadrupole and dipole magnetic fields on basis of the position of the different charge states at the focal plane for ions with a given kinetic energy. Figure 1 demonstrates the good agreement obtained between the experimental and simulated charge state distribution at the focal plane of PRISMA.
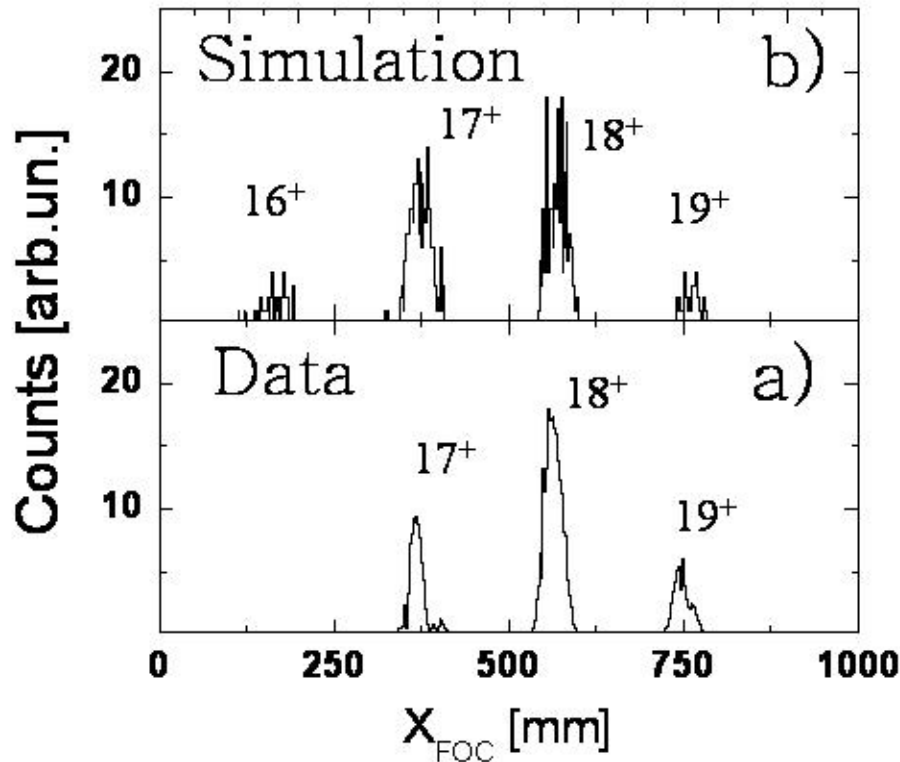

Fig. 1: Focal plane positions of the charge states of ^{48}Ca with kinetic energy equal to 244 MeV. Panel a) refers to the reaction ^{48}Ca on ^{64}Ni at 270 MeV [2], while panel b) has been obtained by the simulation of the transport of PRISMA.

As a second step, one million events, uniformously distributed in E, θ and ϕ, have been generated in such a way to cover the entire experimental ranges, namely, E between 150 and 400 MeV, θ between 10° and 40° and ϕ between -40° and 40° with respect to the beam axis. The charge states distributions have been first studied individually and then as a whole. Figure 2 shows the (θ,ϕ) angular distributions (dark areas) observed for the most probable 18[+] charge state 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. This is determined by the entrance hole of the quadrupole magnet. As one can see, the angular distribution is found to vary substantially with the energy of the incoming ion, which demonstrates the importance of an accurate evaluation of the spectrometer response.
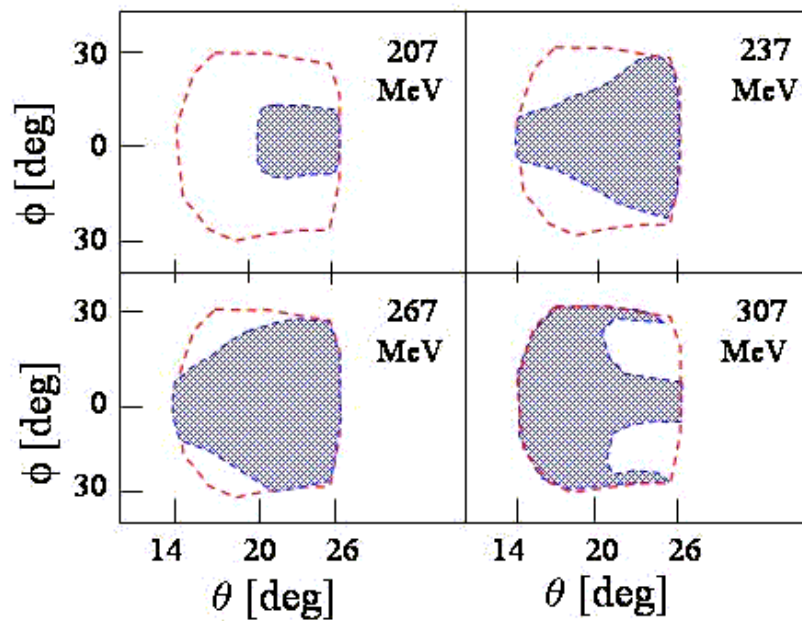

Fig. 2: Angular distributions (dark areas) of the Q=18[+] charge state of ^{48}Ca for different kinetic energies of the incoming ions. The dashed line in each panel indicates the acceptance of the spectrometer, namely the area of the entrance detector seen by the particles reaching the focal plane.
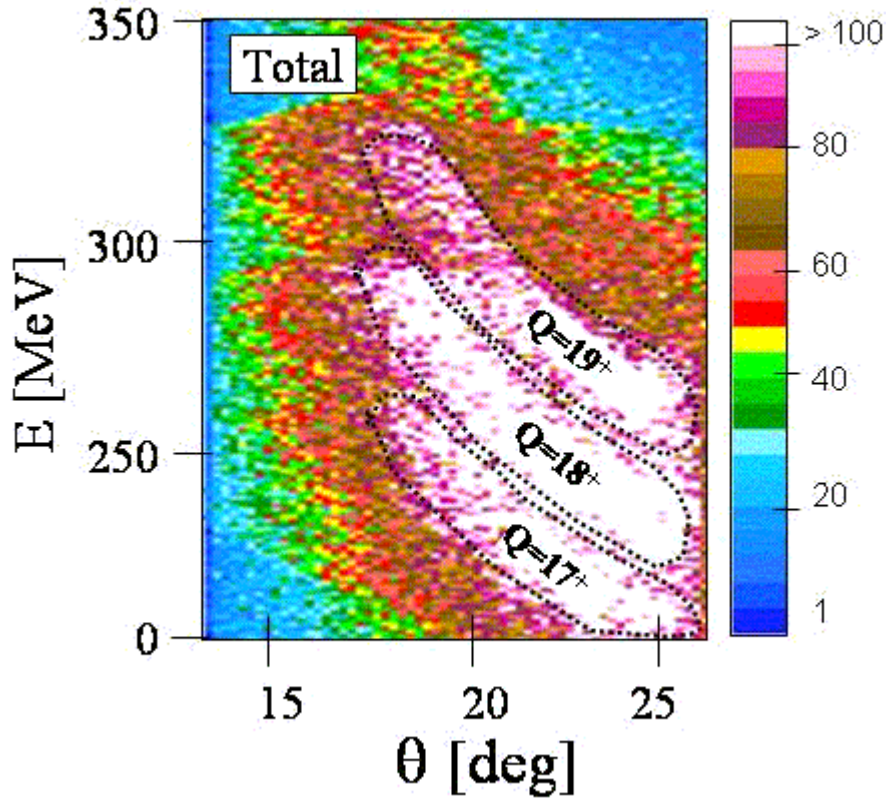
Fig. 3: Kinetic energy and dispersion angle θ distribution of the ^{48}Ca ions obtained after the transport of 5×10^6 events through the magnetic spectrometer PRISMA. Regions corresponding to the most intense charge states are indicated by dotted lines.

The total charge state distribution of the ^{48}Ca ions reaching the focal plane detectors is illustrated in Figure 3, as a function of kinetic energy E and dispersion angle θ. The distribution is integrated over the polar angle φ over which the binary reactions under study are symmetric. The figure clearly illustrates a non uniform transport of the different charge states, although the input distribution was generated uniform both in energy and angular distribution.

The ratio between the uniform (E,θ) input distribution and the corresponding distribution of the transported ions at the focal plane (shown in Figure 3) allows to define a function f(E,θ) which can be used to correct the experimental differential cross sections $d^2\sigma/d\Omega dE$, measured with the PRISMA spectrometer.

The validity of the response obtained by the previous Monte Carlo simulation has been tested making use of input distributions corresponding to differential cross sections calculated with a semiclassical model, implemented in the code GRAZING [1]. First, one million input events have been produced by Monte Carlo for the ± 1n and ± 1p transfer channels following the reaction ^{48}Ca on ^{64}Ni at 270 MeV, according to the (E,θ) correlated differential cross sections given by the GRAZING model. Secondly, each event has been transported through PRISMA by the ray tracing code [3], providing the event distribution expected at the focal plane. Finally, the focal plane distributions were corrected by the function f(E,θ), previously calculated starting from a uniform distribution in energy

and angles. The results of the analysis are shown in Figure 4 in the case of the $\pm 1n$ channels: the solid lines give the input cross section projected on the kinetic energy (left column) and dispersion angle θ (right column), the open circles the distributions transported up to the focal plane and the full circles the same (focal plane) distributions after the correction function $f(E,\theta)$ has been applied. The agreement with the original input calculation demonstrates the validity of the PRISMA response here calculated.
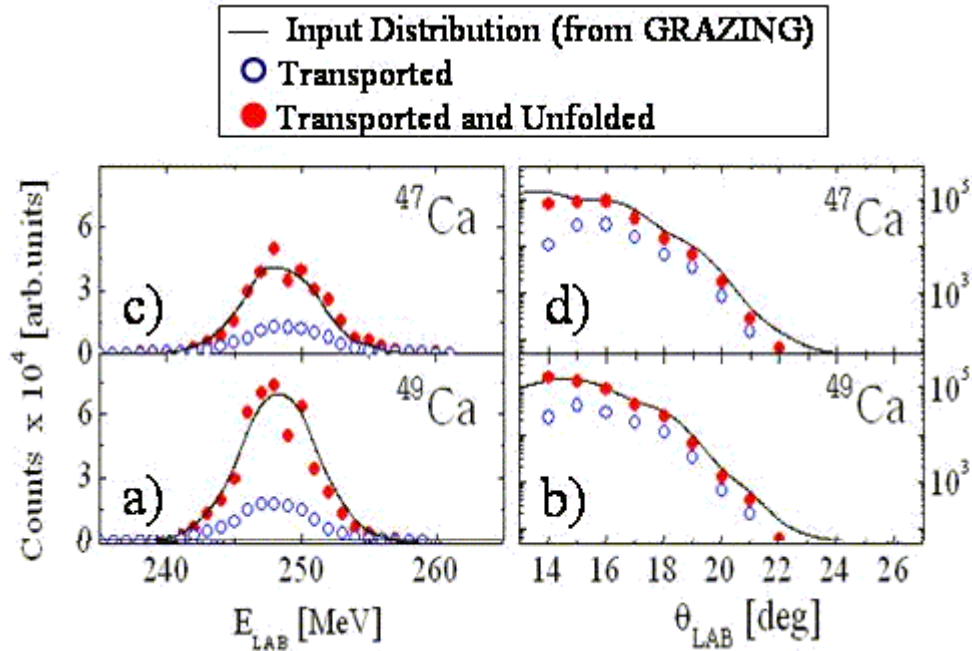

Fig. 4: Monodimensional plots showing the kinetic energy E, left panels, and the dispersion angle θ, right panels, distributions of $\pm 1n$ channels. Solid lines are theoretical calculations, open circles are the transported events and filled circles are the transported events after the unfolding by the response function of the PRISMA spectrometer.

3 Data Analysis and Theoretical Interpretation

The analysis of the data has been focused mostly on the energy integrated angular distributions of the most intense reaction channels, in comparison with the theoretical calculations of the GRAZING code [1]. The experimental results for the $\pm 1n$ and $\pm 1p$ channels are shown in Fig. 5 by full symbols, while theoretical values are represented by the solid red line. The central panel shows the experimental elastic cross section for ^{48}Ca obtained as described in ref. [5], i.e. as a difference between the total kinetic energy loss (TKEL) measured in PRISMA and the one requiring a γ-coincidence. In this way, the elastic scattering distribution provides an absolute normalization for all the reaction products. A similar experimental analysis has been carried out on a number of transfer channels between -4p to +2p. This provides valuable experimental information for theoretical modelling, including additional reaction mechanisms such as evaporation and pair transfer.
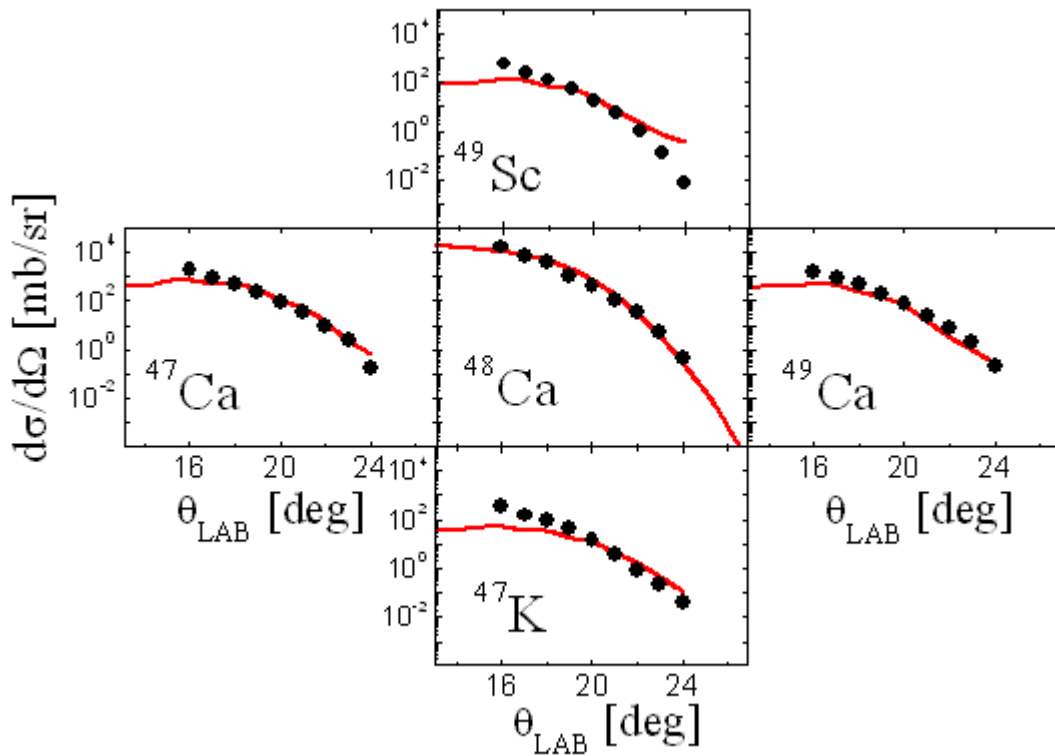
Fig. 5: Angular distributions for the ^{48}Ca elastic channel and for the ±1n channels and the ±1p channels. Experimental data are shown in full symbols while solid lines give theoretical predictions from the semiclassical grazing model of ref. [1].

For some of the most intense channels, angular distribution of the first excited states have been also obtained and compared with Distorted Wave Born Approximation calculations, provided by the PTOLEMY code [6,7]. Figure 6 shows the results obtained for the 2^+ first excited states of the inelastic channels ^{48}Ca and ^{64}Ni, which are found to be well reproduced by the model, giving confidence in the basic ingredients of the calculations, such as the nuclear potential.
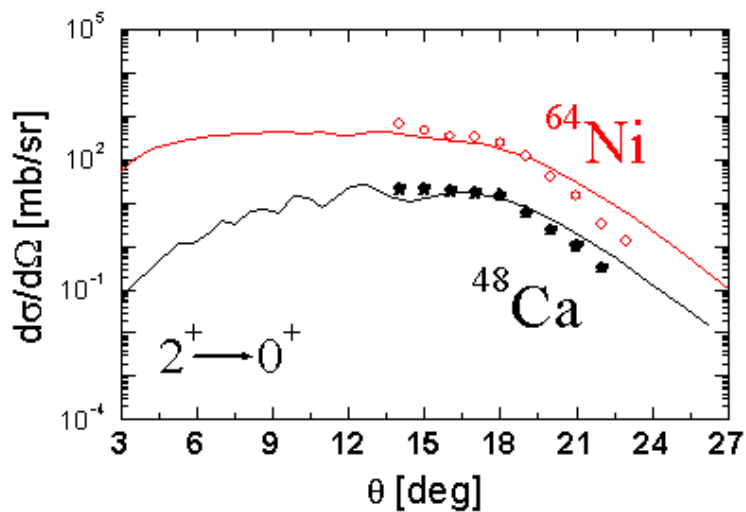

Fig. 6: Angular distributions of the 2^+ excited state of ^{48}Ca and ^{64}Ni. Experimental data are shown by symbols, while solid lines give DWBA predictions with the PTOLEMY code [6,7].

Finally, a preliminary analysis of the γ-spectra measured by the CLARA array in coincidence with some of the most intense reaction products has also been performed, as shown in Figure 7 in the case of [49]Sc and [49]Ca nuclei. A part from the strong peaks already observed in deep-inelastic heavy-ion reactions with thick targets and lower incident beam energies [8], additional transitions are visible, previously observed in transfer reactions with light ions only [9]. A similar pattern is found in other systems, such as [47]Ca and [50]Ca. This is mostly caused by the very short lifetimes of the corresponding states which leads to deexciting transitions emitted in-flight.
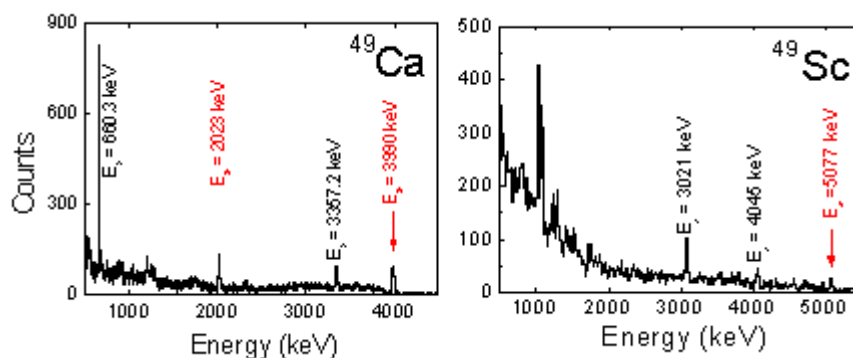

Fig. 7: Gamma spectra of [49]Ca (left) and [49]Sc (right). The arrows indicate the transitions which have been observed in reaction involving light ions only [8].

4   Conclusions

Preliminary results from the deep inelastic experiment [48]Ca on [64]Ni at 6 MeV/A, performed with the CLARA-PRISMA setup, have been presented. After a carefull evaluation of the response function of the magnetic spectrometer, energy integrated angular distributions of the most intense transfer channels have been extracted from the data. The experimental results have been compared with predictions from a semiclassical model, which is found to well reproduce the ± 1n and ± 1p transfer channels. For the more massive transfer channels, presently under analysis, the data indicate the need to include in the calculations additional contributions, such as, for example, pair transfer and evaporation modes.

The γ-spectra display as sharp lines also transitions from short-lived states, in contrary to thick target experiments performed at lower energies.

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