Multinucleon transfer reactions in ^{40}Ca+^{124}Sn

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Angular and Q-value distributions for a large variety of charge and mass partitions populated in the reaction ^{40}Ca + ^{124}Sn have been measured at 170 MeV with a new time-of-flight magnetic spectrometer. Reaction channels involving the net transfer of up to six protons and six neutrons have been detected. Population patterns, cross sections, and energy-loss distributions are compared with results of theoretical calculations based on independent single-nucleon transfer modes. The overall agreement is good, but more complex mechanisms may be needed to account for the larger drift towards neutron stripping revealed by the experimental data. [S0556-2813(96)01107-7]

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I. INTRODUCTION

The study of multinucleon transfer processes provides valuable information on particle-particle correlations in nuclei, especially about the pairing interactions that enhance the transfer of nucleon pairs across heavy ions in close contact. In spite of determined experimental efforts it has remained very difficult to collect reliable multinucleon transfer data. Having good nuclear charge, mass, and Q-value resolution and high detection efficiency at the same time is in fact a difficult task. Cross sections are very small and uncertainties—like target impurities and nucleon transfer followed by evaporation—prevent unambiguous identification of the primary reaction products. Moreover, the limited energy resolution hinders a clean separation of the final intrinsic states and, as a consequence, the available cross sections are mostly the result of integrations over wide Q-value windows. A net transfer of six protons has been identified in the reactions ^{144}Sm + ^{88}Sr and ^{144}Sm + ^{208}Pb [1,2], while the transfer of up to four neutrons was reported in the reaction ^{112}Sn + ^{120}Sn [3]. Only very recently has the net transfer of six neutrons been clearly identified in the ^{100}Mo+^{58}Ni reaction [4].

Multinucleon transfer plays a very important role in the description of collisions between heavy ions at energies close to the Coulomb barrier, in particular, at the borderline where peripheral quasielastic reactions and the more central deep-inelastic and fusion processes merge. This transitional regime has been recently approached within a novel theoretical formalism that handles both types of processes on a common ground [5,6]. By using average nuclear properties (e.g., single-particle form factors and single-particle level densities), explicit expressions can be obtained for the characteristic functions describing the distributions of mass, charge, energy, and angular momentum of the outgoing fragments. This yields quantitative estimates for various observables that can be directly compared with experiments. It follows from these calculations that a large number of nucleons may be exchanged between the reaction partners and that a considerable energy loss may occur even outside the Coulomb barrier—with direct consequences for compound nucleus formation. These findings prompted some of us to use this formalism to explore multiple-transfer processes with radioactive beams in order to determine the actual possibilities of producing extremely neutron-rich isotopes of the heaviest elements [7,8].

The idea that multinucleon transfer may be described via a successive transfer of single nucleons has been applied to the analysis of few-nucleon transfer data for the ^{32}S + ^{208}Pb system [9]. In this case, with a good elastic angular distribution, we determined the optical potential and calculated, in the complex-WKB approximation, the angular distributions of the different transfer channels with encouraging results. However, the limited statistics and the difficulty of detecting weak multinucleon transfer events did not allow us to explore in detail the complex mechanisms which might be present in these processes. This objective led us to set up a new time-of-flight (TOF) magnetic spectrometer [10] with

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high detection efficiency and high nuclear mass and charge selectivity.

The new instrument has been used in the present work to investigate the reaction ^{40}Ca + ^{124}Sn for a bombarding energy of 168.5 MeV at the center of the target, corresponding to $\simeq$ 5% above the nominal Coulomb barrier. The choice of the system was dictated by the fact that both nuclei are well known experimentally and theoretically. This combination of projectile and target was also taken as a representative case in the calculations previously mentioned [7,8]. Angular and Q-value distributions have been measured up to the transfer of six neutrons, six protons, and mixed neutron-proton channels; a quantitative comparison with calculations was then possible in a wide range of nuclear charge and mass partitions.

The paper is organized as follows. In Sec. II we give an account of the setup and the experiment. In Sec. III we discuss the results and we compare the experimental and theoretical cross sections and Q-value distributions. Conclusions are given in Sec. IV.

II. THE EXPERIMENT

The experiment was performed at the XTU-Tandem accelerator facility of the Laboratori Nazionali di Legnaro. A ^{40}Ca beam was extracted as a CaH_3^- molecule from an ion sputter source and delivered at 170 MeV with intensities of 5–10 pnA onto a ^{124}Sn target with a thickness of 180 μg/cm^2 and an isotopic enrichment of 97.5%. Light ejectiles have been detected by the new TOF spectrometer, with geometrical characteristics similar to the setup of Ref. [11] and equipped with two microchannel plate detectors (MCP's) for TOF signals, and a multiparametric ionization chamber of ΔE-E type, for nuclear charge and energy measurement. Between the two MCP's we installed two magnetic quadrupole doublets, which focus on the focal plane ions with a magnetic rigidity up to $B\rho$=1.5 T m (with an acceptance in the range $\pm$5%), still achieving a large effective solid angle of $\simeq$ 5 msr, about a factor of 10 larger than what was available previously [12]. Moreover, the TOF distance being $\simeq$ 3.5 m, we can get a mass resolution $\Delta A/A$ $\simeq$ 1/100 for medium mass ions in the energy range of 1–2 MeV/u, which is essentially limited by the energy resolution of the ionization chamber ($\leqslant$1%). The mass resolution could be further improved by the use of kinematic coincidences. Therefore the new instrument is also an ideal tool for detecting very weakly populated channels. More details of the setup will be given in a paper presently in preparation.

The spectrometer is connected to a rotating scattering chamber, and angular distributions have been measured at six angles near the grazing one, in the range $\theta_{\rm lab}$=69° −105°, so as to cover most of the total transfer flux. Absolute normalization of the cross sections and relative normalization between different runs were ensured by two silicon detectors placed at $\theta_{\rm lab}$=$\pm$20° with respect to the beamline and at 15 cm from the target. Figure 1 shows an example of a Z-A matrix and its projection on the mass axis for calcium isotopes. One clearly sees the population of transfer channels up to the pickup of six neutrons and the stripping of six protons, with the presence of numerous charge exchange channels. A few events of seven and eight neutron pickup

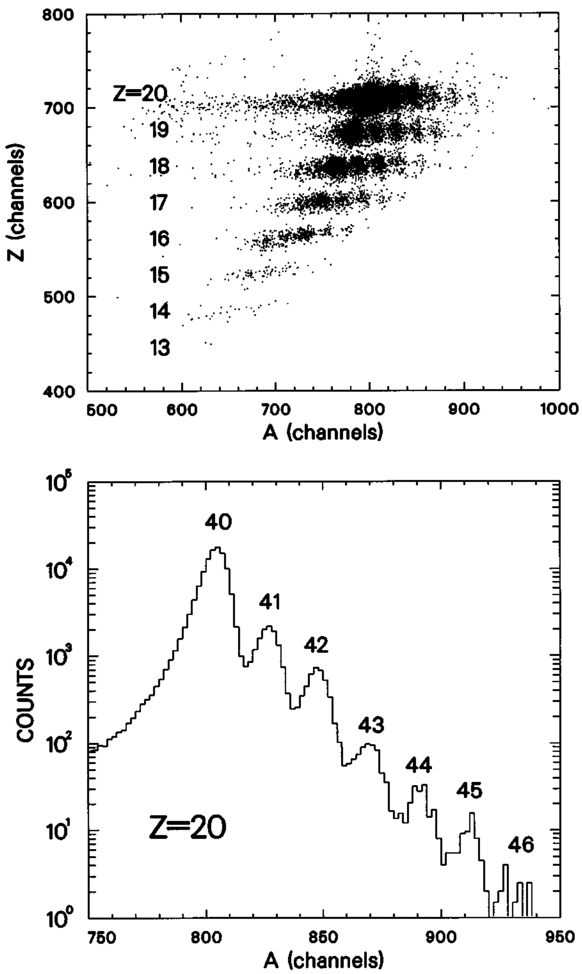

FIG. 1. Z-A matrix obtained at 75° (top) and its projection on the mass axis for the calcium isotopes (bottom). In the matrix, and not in the projection, only a part of the total accumulated statistics is shown.

and proton stripping, and of one proton pickup have also been observed. Cross sections have been measured over a range of four orders of magnitude, down, e.g., to $\simeq$ 28 μb/sr for the $+6n$ channel at 75°.

In order to check that no bias exists on the data due to the distributions of momenta and charge states of the detected ions (focused by the magnetic quadrupoles), Q-value distributions obtained with the quadrupoles switched on and off have been compared for each exit channel at 69°, 75°, and 100°. The centroids and shapes of the spectra are very similar within statistical uncertainties, with an intensity ratio of 22 $\pm$ 2 with and without magnetic fields for all transfer channels and independent of angle. This turns out to be consistent with the $B\rho$ transmission function determined during test experiments and calculated with the code TRACE2D [13].

The total number of counts for each transfer channel in the different runs has been obtained by simply integrating the events in the corresponding region of the Z-A matrix. Only in the case of the calcium isotopes, due to the larger intensity of the elastic peak, has a multi-Gaussian fit of the mass distribution been used to derive the total counts of the neutron pick-up channels. The mass resolution was anyhow high enough to allow a clean separation of all the channels, in-

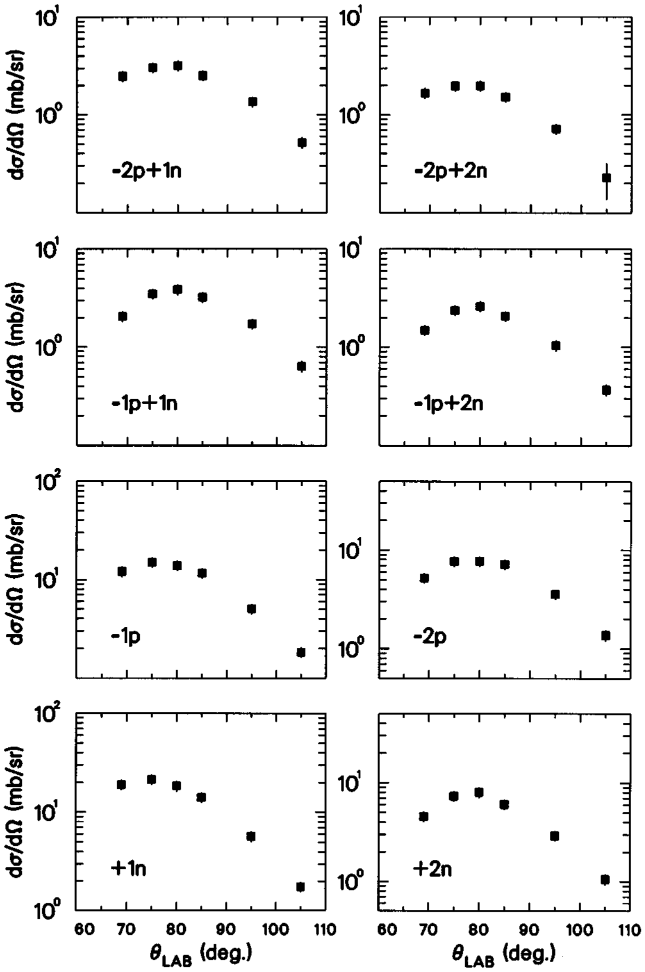

FIG. 2. Angular distributions in the laboratory system for the indicated channels. We notice the slight channel dependence of the maximum of the cross sections.

cluding at backward angles where the energy resolution generally worsens. Taking into account the monitor and the spectrometer solid angles (whose ratio has been further determined with an α source placed at the target position), and the efficiency of the two MCP's (which was $\simeq$ 90%, independent of the nuclear charge of the detected ions), absolute cross sections have been deduced and are discussed in the following section.

III. RESULTS AND ANALYSIS

The angular distributions for some representative channels are shown in Fig. 2. They are generally bell shaped, peaking at the grazing angle ($\theta_{\text{lab}}=75°$) with a small dependence on the channel. They have an average angular width $\Delta\theta_{\text{lab}}\simeq 25°$. The total cross sections have been obtained by integrating the angular distributions via a quasi-Gaussian fit. The fit procedure introduces an error of 5–10 % in the final values of the cross sections, mainly due to the extrapolation at forward angles.

In Fig. 3 we show the Q-value- and angle-integrated cross sections for the different channels. Each plot is the isotope distribution for a particular proton stripping channel. Notice that the data show, after the stripping of more than one proton, a drift toward isotopes whose population should involve neutron stripping channels. This is somewhat surprising since from a simple Q-value analysis one expects for this system only proton stripping and neutron pickup channels. We notice also that the magnitude of the drift increases with the number of transferred protons.

The experimental results are analyzed with the formalism of Refs. [5,6] which, to our knowledge, is the only one that allows a direct comparison with the full body of our data. Since the theory provides estimates for the excitation energy of the outgoing fragments it is possible to take into account the changes in the primary formation rates due to cooling off by particle emission [8]. At this stage only neutron evaporation is considered.

The values of the cross sections for the different exit channels depend on the strength of average form factors for the one-nucleon transfer channels and on the single-particle densities in projectile and target. The values of these quantities are not very well known and estimates exist only for single-particle states close to the Fermi surface [5,6,14]. To obtain the results reported here the strength of the form factor for proton stripping and neutron pickup channels was increased by a factor of 2 with respect to the standard parametrization [14]. The nuclear density parameter has been adjusted to values of 7 MeV^{-1} and 6 MeV^{-1} for neutrons and protons, respectively. The histograms shown in Fig. 3 (full line) display the predicted yields following evaporation. We also display (dashed lines) the primary production yields. The comparison between the two calculations indicates that neutron emission from the primary fragments plays an important role in the understanding of the observed population of the lighter isotopes.

For the pure neutron-transfer channel (the frame with the $0p$ label) one sees that the theoretical calculations reproduce quite well the population rates of the different calcium isotopes. The cross sections drop by a factor $\approx$ 3.5 per each additional neutron, a value similar to that reported in Ref. [4]. A good agreement is also observed for the isotope distributions of other nuclear charges down to the $-3p$ channel. Beyond that, a discrepancy starts to build up on the neutron stripping side of the distributions.

In Fig. 4 we show—for the scattering angle $\theta_{\text{lab}}=75°$—the experimental energy-loss distributions for some representative channels. These are constructed assuming binary reaction kinematics. As was found in other experiments (see, e.g. [15], and references therein), when more nucleons are transferred the centroids of the spectra move to higher excitation energies, but the average shift per transferred nucleon gets smaller. In addition, the ground state population accounts for only a minor fraction of the total flux, a feature already observed in [4]. With the exception of a few channels, the centroids and the shape of the spectra are quite well reproduced by the theory.

In connection with Fig. 3 we already noticed that—as one moves away from ^{40}Ca in the proton stripping direction—there is a smooth drift of the distributions towards lighter isotopes, which is not described by the calculations. Since neutron stripping is strongly suppressed these deviations could be related to a poor estimate of the evaporation rate that follows nucleon transfer. Although a more accurate treatment of this effect might reduce the discrepancies, these

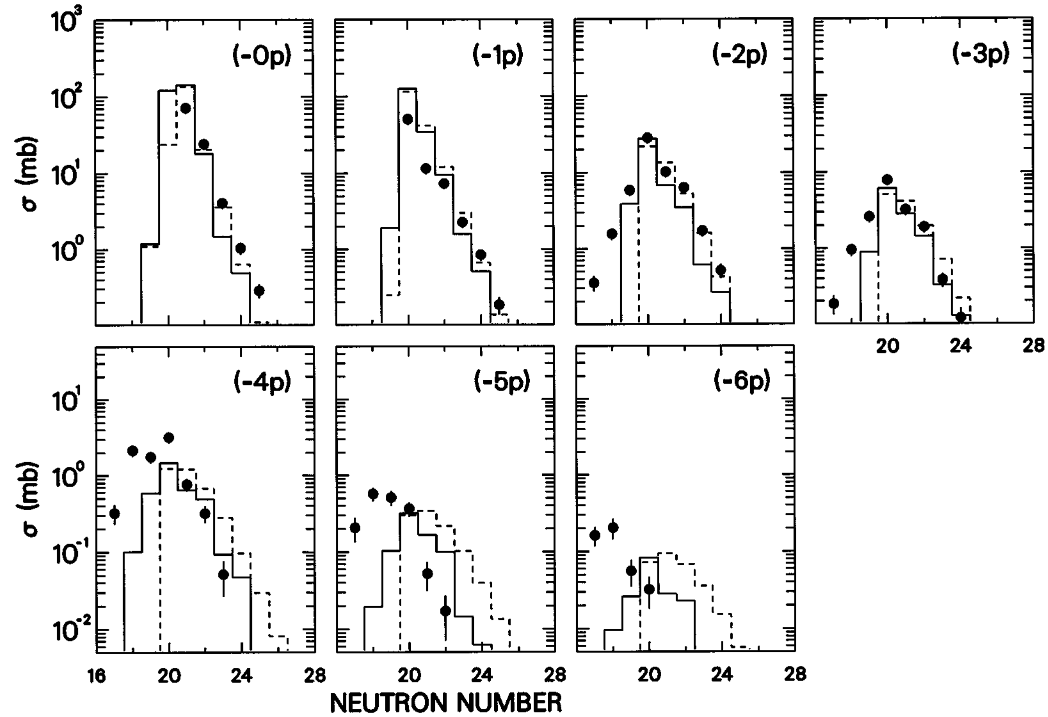

FIG. 3. Experimental (points) and calculated (histograms) total integrated cross sections for the transfer products. Experimental errors take into account statistics and systematic errors coming from monitor and spectrometer solid angle determination, beam focusing, integration of the mass and charge spectra, and integration of the angular distributions. The dashed lines represent the cross section for the primary yields; this has been shown to illustrate the importance of neutron evaporation.

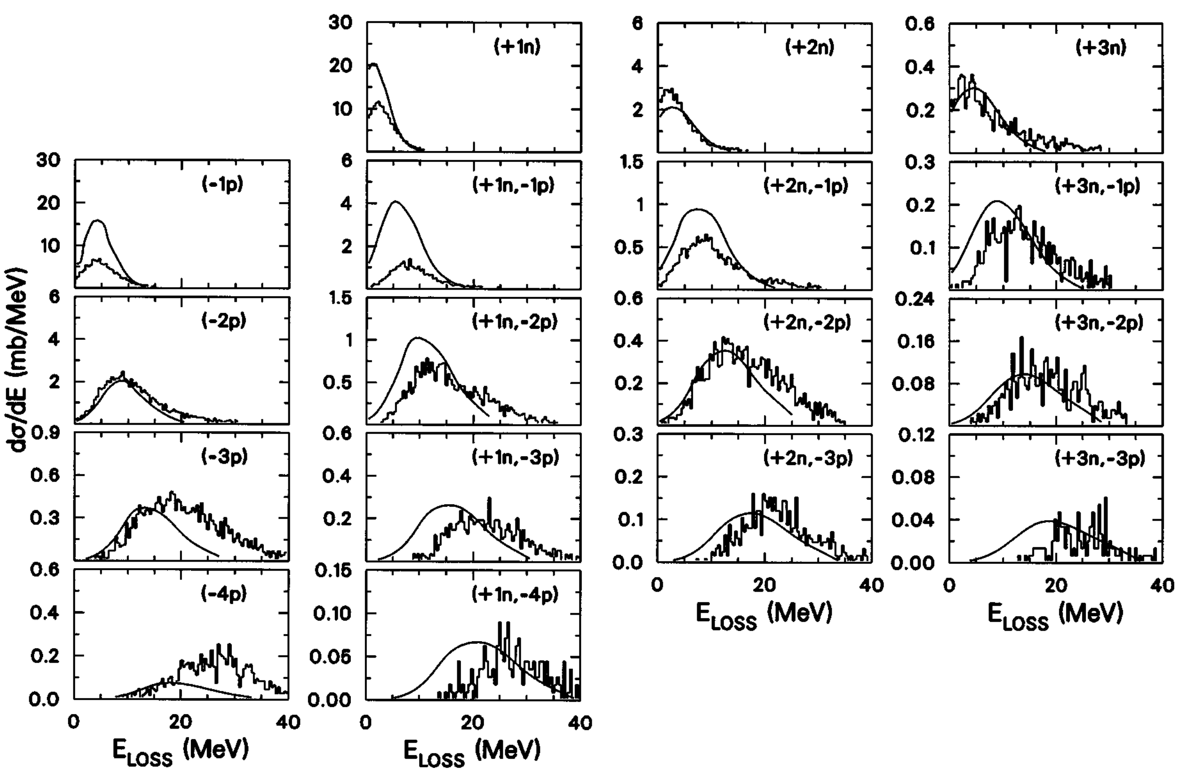

FIG. 4. Experimental (histograms) and calculated (lines) energy-loss distributions. The experimental cross section scale (mb/MeV) has been obtained by normalizing each distribution to its total integrated cross section.

may also indicate the need of including in the formalism degrees of freedom other than the single-particle transfer channels, for instance, the transfer of correlated proton and neutron pairs or even α-transfer channels. A quantitative estimate of the effect of these cluster-transfer channels on the population of the different charge and mass partitions is not available at the moment. Although discussed in another context, coupling to an α-transfer channel seems to be necessary for reproducing in some instances sub-barrier fusion cross sections [16] and elastic scattering data [17].

IV. CONCLUSIONS

In conclusion, we have measured with high efficiency and resolution a large variety of transfer channels in the system ^{40}Ca + ^{124}Sn. Cross sections and energy-loss distributions show a quite satisfactory agreement with calculations for the transfer of few nucleons. The experimental population of nuclei involving a large number of transferred nucleons shows, however, a drift towards neutron stripping which is not well reproduced by the formalism used here. This might be due to a stronger neutron evaporation from the primary fragments or to the presence of more complex transfer channels. A complete investigation of these mechanisms is very important for a general understanding of the many interesting effects which show up at energies close to the Coulomb barrier and calls for a broad, systematic study with other suitable projectile/target combinations; experiments with a ^{48}Ca beam on the same target ^{124}Sn are in progress. With that projectile, nuclei are predicted to be symmetrically populated along the stripping and pickup directions for both neutrons and protons [8] and a comparison among the two systems should help elucidate the role played by the two mechanisms mentioned before.

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