Evidence of complex degrees of freedom in multinucleon transfer reactions of ^{48}Ca+^{124}Sn

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Multinucleon transfer reactions in ^{48}Ca+^{124}Sn have been studied at 174 MeV with a time-of-flight magnetic spectrometer. The pickup and stripping of several protons and neutrons have been observed. The experimental isotope yields for the $-2p$ and $+2p$ channels cannot be reproduced with calculations that incorporate only independent single-nucleon transfer modes. The discrepancies can be accounted for by explicitly including nucleon pair and α-cluster degrees of freedom. [S0556-2813(97)04507-X]

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Multinucleon transfer between heavy ions at energies close to the Coulomb barrier represents an important reaction mechanism for the understanding of the correlation among nucleons [1], for the study of the transition from the quasielastic to deep inelastic regime [2], and also for the understanding of subbarrier fusion [3] reactions. Besides considerable experimental and theoretical efforts, many features of multinucleon transfer are still very poorly understood. The mechanism through which nucleons are transferred becomes extremely complicated as their number increases due to the many paths they can follow. An important, and still unanswered, question to be addressed is the definition of the relevant degrees of freedom one has to include in models in order to have an adequate description of the reaction mechanism. In particular, one would like to know the relative weight of single-nucleon transfer modes compared to the more complicated processes involving transfer of pairs or even clusters of nucleons.

Recent high quality data on neutron transfer cross sections [4,5] exhibit features close to a picture of a multistep single-particle transfer mechanism. On the other hand, data on proton transfer [6–8] indicate the presence of strong pair correlations, as evidenced by the enhancements of 1 and 2 pair transfer probabilities.

In order to better understand the problem, we recently studied the system ^{40}Ca+^{124}Sn [5]; high quality data have been obtained for several multinucleon transfer channels up to the very weak channels of six neutrons pickup $(+6n)$ and six protons stripping $(-6p)$. Calculations have been performed too, with a formalism based on a theoretical approach treating quasielastic and deep inelastic processes on the same ground [9,10]. The calculations consider only independent single-nucleon transfer modes; the philosophy adopted was, in fact, to see how far one can go in the description of the reaction mechanism by including only the simplest degrees of freedom. The comparison of data with theory showed that for channels involving few nucleons the agreement is quite nice. When many nucleons are transferred along the proton stripping chain, a larger drift towards neutron stripping is revealed by the experiment. This may be potentially due to nucleon evaporation from the primary fragments. The presence of more complex degrees of freedom other than single-particle transfer modes, e.g., nucleon pairs or even α clusters cannot of course be ruled out. Disentangling these two effects is clearly important.

The signature that could identify the transfer of correlated pairs or α clusters could come, for instance, by the observation that a ‘‘drift’’ exists also in the proton pickup chain towards higher neutron numbers, since this would exclude nucleon evaporation as a main contribution. For this reason we suggested in the conclusions of [5] the study of the system ^{48}Ca+^{124}Sn, where one expects [11] a more symmetric population of nuclei along both the stripping and the pickup of neutrons and protons. This is the main motivation which led us to study this system. In the present work we focus on the discussion of the angle-integrated cross sections, for the relevant multinucleon transfer channels, and we show that cluster degrees of freedom are an essential ingredient for understanding the isotope yields. A preliminary report on the measurement has been presented in [12].

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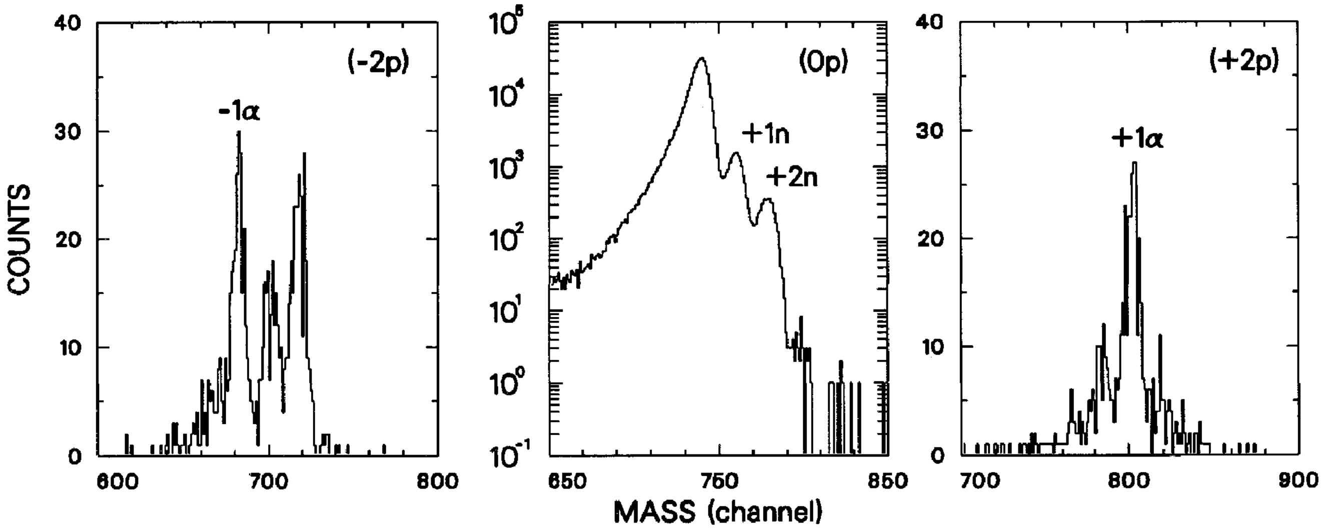

FIG. 1. Mass spectra for $Z=18$ $(-2p)$, 20 $(0p)$, and 22 $(+2p)$ at $\theta_{\rm lab}=75°$.

The experiment has been performed at the XTU-Tandem accelerator of the Laboratori Nazionali di Legnaro. A ^{48}Ca beam has been extracted as a ^{48}Ca-H$_3$ molecule from an ion sputter source and accelerated at $E_{\rm lab}=174$ MeV and with intensities of $\simeq 3$ pnA onto a ^{124}Sn target nucleus, with a thickness of 180 μg/cm^2 and an isotopic enrichment of 99.8%. The experimental setup is essentially the same as the one used in [5]. Briefly, light ejectiles have been detected with a 3.5 m long time-of-flight (TOF) magnetic spectrometer, equipped with two microchannelplate (MCP) detectors for TOF signals and a multiparametric ΔE-E ionization chamber, for nuclear charge and energy measurements. Between the MCP two doublets of magnetic quadrupoles are installed, allowing one to reach an effective solid angle of $\simeq 3$ msr and to detect consequently very weak transfer channels. The spectrometer was connected to a new large (1 m in diameter) scattering chamber of sliding-seal type, and angular distributions have been measured at seven angles in the range 50°–100°. Absolute normalization of the cross sections and relative normalization between different runs were ensured by four silicon detectors, placed at scattering angles $\theta_{\rm lab}=20°$ and on the corners of a square in a plane perpendicular to the beam. The mass and nuclear charge resolutions obtained in the experiment were $\Delta A/A \simeq 1/100$ and $\Delta Z/Z \simeq 1/60$, respectively, in the energy range 1.3–2.7 MeV/amu, hence a clear discrimination among transfer channels was possible without ambiguities in the whole measured angular range. Only for neutron stripping channels, a tail on the lower mass region of the overwhelming elastic peak did not allow one to extract reliable cross sections. No improvement was obtained by taking into account the position information of the ionization chamber. However, from the mass spectra obtained at the most backward angles, one can estimate a yield comparable to that of the neutron pickup channels. We stress the fact that, with the exception of the $+1n$ and $+2n$ transfer channels, the cross sections are generally very low (see Fig. 2) and a factor 3–30 smaller than those of ^{40}Ca+ ^{124}Sn [5]; therefore the experiment would have been unfeasible without an efficient setup. The spectrometer transmission was determined by experimentally varying the yield of all quasielastic events as a function of the magnetic fields of the quadrupoles, and by calculations performed with the code TRACE2D [13]. In addition, the total yield and the Q-value distributions of the elastic and of the one- and two-neutron pickup transfer channels were obtained with the quadrupoles switched off at three angles. The resulting intensity ratio of 15 ± 2 has been found to be almost independent on the angle and on the channel, and the value is consistent with the number previously obtained in the ^{40}Ca experiment [5] where the geometry was slightly different.

The data show the pickup and stripping of both protons and neutrons [11]. Figure 1 reports the mass spectra for $Z=18$, 20, and 22 obtained at $\theta_{\rm lab}=75°$ with full statistics. Here, the most important results are already visible. Pure one- and two-neutron pickup channels $(0p)$ have a sizable intensity but then a dramatic drop of about two orders of magnitude appears for the transfer of three and four neutrons. This drop does not follow the smooth trend observed in the experiments of [4,5], where one deduced an average decrease of a factor $\simeq 3.5$ per transferred neutron. This may be due (see also later) to neutron evaporation from the primary fragments as one can argue from the low neutron binding energies of ^{51}Ca and ^{52}Ca (4.4 and 4.7 MeV, respectively). The other striking feature is the presence of a strong α-transfer channel both on the pickup $(+2p)$ and on the stripping $(-2p)$ side. The $+1\alpha$ channel is the highest one in the $+2p$ distribution, with a yield similar to the $+1p$ channel (see also Fig. 2).

The angular distributions are bell shaped and peak at 75° with an average width of $\simeq$30°. By fitting them with near Gaussian curves, total cross sections have been obtained. In Fig. 2 we show these experimental total cross sections for the isotope distributions together with two sets of theoretical calculations. For the channels $+4n$, $+2p-3n$, and $-2p+1n$, due to their very small cross sections, data have been taken only at few angles and the integrated cross sections have larger errors.

We discuss first the top part of Fig. 2. The calculations showed here have been performed within the model of [9,10] which, to our knowledge, is the only one able to treat the full

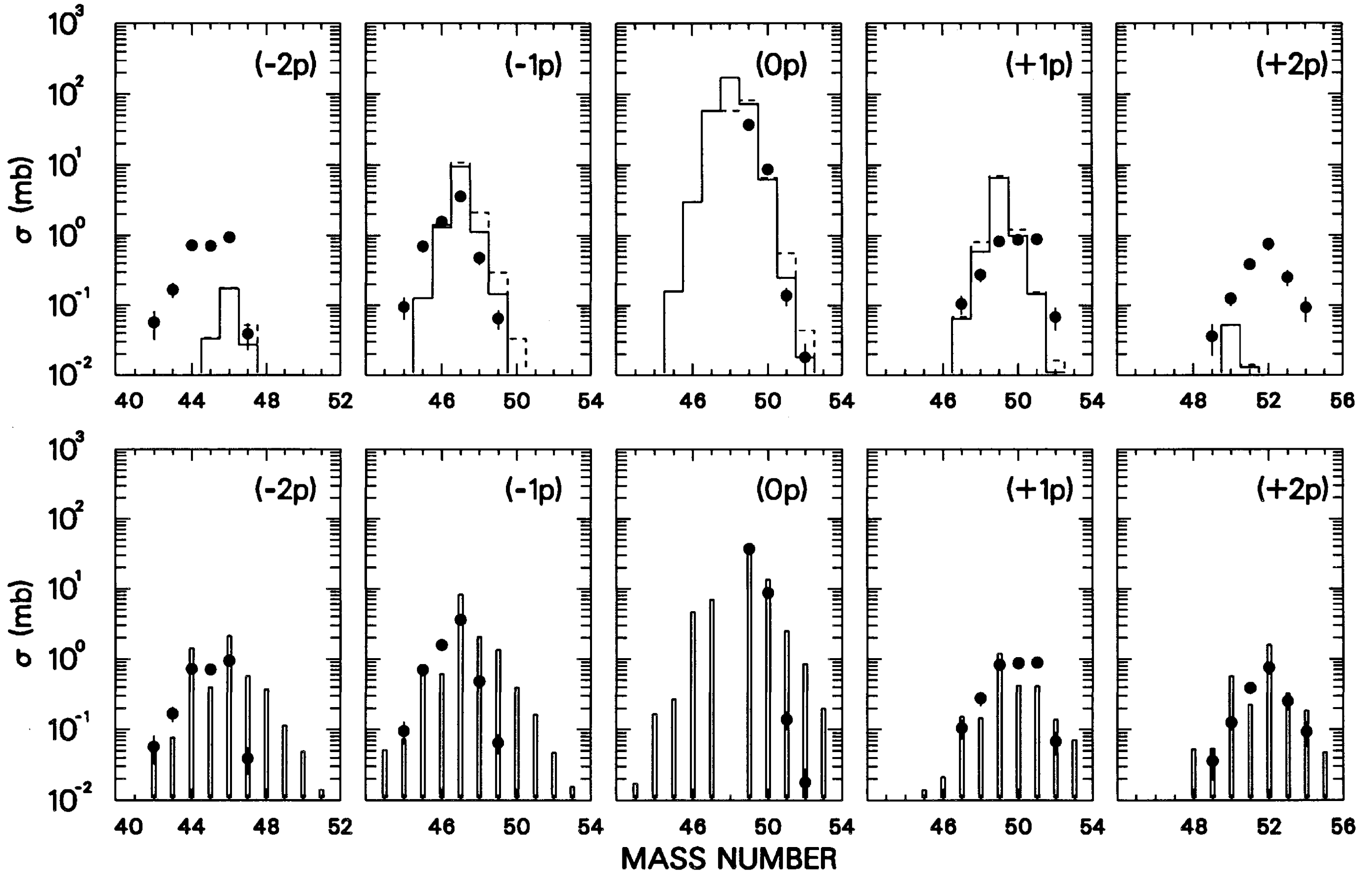

FIG. 2. Experimental (points) and calculated (histograms) angle-integrated cross sections for the transfer products (see text). Experimental errors take into account statistics and systematic errors coming from monitor and spectrometer solid angle determination, beam focusing, integration of the mass and charge spectra, and integration of the angular distributions.

body of our data. The model includes independent single-particle transfer modes and inelastic excitation to few collective states and takes into account the effects of neutron evaporation from the primary fragments. We refer to the cited references for details both for the formalism and for the discussion of the different parameters entering the calculation. The solid line (dashed line) in Fig. 2 (top) represents the calculated yield after (before) neutron evaporation. Looking first at pure neutron transfer channels ($0p$) we notice how theory correctly reproduces the data. In particular, the big drop in the cross section for the $+3n$ and $+4n$ channels is nicely reproduced (solid lines). Neutron evaporation contributes significantly to the final yield, lowering the cross sections by a factor 2–4. A similar agreement for the neutron channels was also found in the ^{40}Ca experiment [5]. For the $-1p$ and $+1p$ isotope distributions we still have quite a good global agreement between data and theory. A new feature shows up for the $-2p$ and $+2p$ channels, where one observes a large drift of the data on the neutron stripping side for the $-2p$ case and on the neutron pickup side for the $+2p$ case. Calculations clearly underestimate the corresponding cross sections, and suggest that more complex degrees of freedom have to be taken into account for a description of the reaction mechanism.

The above formalism, unfortunately, is not apt to incorporate correlated pair and/or α-cluster transfer modes. In order to see if these transfer channels can account for our data, at least in a qualitative way, we performed a second calculation using the CWKB (complex WKB) formalism, which has been previously used for the analysis of the reaction ^{32}S+^{208}Pb [14]. To perform this second analysis we incorporated the one-particle transfer channels to all the known single-particle states of the projectile and target with the corresponding spectroscopic factors. To these we added six more channels: those pertinent to the transfer of pairs of nucleons ($\pm 2n$ and $\pm 2p$) and two additional ones for the α clusters ($\pm\alpha$). The form factors for pair transfer have been taken from the macroscopic model [15] to be proportional to the r derivative of the optical potential; for the $\pm\alpha$ channels we have adopted a cluster form factor constructed in accordance to [16,17]. The normalization of these macroscopic formfactors has been chosen to reproduce the experimental total cross section for the $\pm 2n$, $\pm 2p$, and $\pm\alpha$ channels.

For the real nuclear component we have used the empirical potential of [18] ($V_0 = -76$ MeV, $r_0 = 1.18$ fm, and $a = 0.68$ fm) while for the imaginary part we have performed a microscopic calculation [19,20] using the same set of single-particle states of the present calculation. The resulting potential has been fitted with a Woods-Saxon shape ($W_0 = -30$ MeV, $r_0 = 1.18$ fm, and $a = 0.62$ fm).

In the lower part of Fig. 2 we show the results of the calculated primary reaction yields (histograms) together with the experimental data. One notices immediately that the theoretical yields overestimate the data on the neutron-rich side of the different isotope distributions for each charge partition. The neutron evaporation strongly modifies these cross sections, but by including the transfer of clusters into the formalism, we are not in a condition to determine the excitation energies of the reaction products and therefore to estimate the evaporation. However, it is clear that the redistribution of cross sections due to this process will not alter in a significant way the largest cross sections.

We believe that these data and the calculations support the idea that cluster degrees of freedom, at least for certain nuclei, have to be included in any microscopic model aiming at the description of the reaction mechanism between heavy ions. Of course much more refined calculations are needed both for structure and reaction models.

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