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Multi-neutron transfer in ^{62}Ni+^{206}Pb: A search for neutron pair transfer modes

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Pair correlation effects in the transfer processes have been investigated through an odd-even staggering in the measured yields of Q-value integrated multi-neutron transfer channels in the ^{62}Ni+^{206}Pb system at three bombarding energies close to the Coulomb barrier. The experimental results for these inclusive transfer data suggest a dominance of a sequential mechanism in the transfer process.

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In order to explain the specific features of the different nuclear species one has to enrich the independent particle description by incorporating residual interactions. Among the different features we mention the tendency of identical nucleons to couple in pair with total angular momentum zero. This special kind of correlation is attributed to the existence of short-range residual forces, pairing in particular, that are responsible for several nuclear effects. In the present work we are motivated by the enhanced transition rates in the transfer of two nucleons observed in light ion reactions [1], namely (p,t), (t,p), and in collisions between heavy ions [2–8].

Of particular interest in this study are the collisions between heavy ions in that they offer the possibility of observing multiple transfer of pairs and thus to measure, at least in principle, the pair-density in the nuclear medium [9,10]. Such an ideal picture is masked by several effects. The reaction mechanism increases in complexity with the increasing number of transferred particles, it is, for instance, not clear if the pairs transfer proceeds in a cluster- or sequential-like picture. The reaction is dominated by the Coulomb interaction that favors the excitation of inelastic states and thus pushes the transfer strength in a region of excitation energy where pair correlations are weaker. The experimental requirements for the detection of channels that imply the transfer of many pairs (in general many nucleons) are very demanding, one needs high detection efficiency, down to a few μb/sr, and a very good charge (Z), mass (A), and energy resolution. Since the effect of correlations should manifest itself in a narrow energy window close to the ground state of the reaction products, distinguishing the population of individual nuclear states would be the best, however this is presently extremely difficult. If one wants to preserve all the above requirements, only inclusive cross sections can be given. With the limitations of inclusive data many experiments have been performed and a considerable amount of discussions about reaction mechanism and enhancement factors for pair-transfer modes have been done (see, e.g., Refs. [2,8] and references therein). It is along this line that we performed the experiment we are going to discuss choosing a suitable projectile and target combination in order to favor the population of states close to the ground states of the reaction products.

In recent high resolution experiments performed at Argonne with a magnetic spectrograph [11,12] and at Legnaro with a time-of-flight spectrometer [13,14], the transfer of neutrons has been observed with sufficient statistics up to three nucleon pairs. The available data show that the total angle and Q-value integrated cross sections for pure neutron transfer channels drop by almost a constant factor ($\simeq$3.5–4) per each transferred neutron, this suggests that the process in question proceeds via a successive transfer of independent particles [15,16]. In the mass spectra of ^{58}Ni+^{124}Sn [12] and ^{40}Ca+^{124}Sn [13] systems, at specific angles an odd-even staggering has been seen. This may be attributed to a contribution from neutron pair modes. However, it is in general very difficult to disentangle possible pair effects from differences induced in the yields simply by large variations in the reaction Q values (cf. Table I).

In order to have an unmixed indication of possible effects of correlations in the multinucleon transfer reactions we investigated the system ^{62}Ni+^{206}Pb, where the ground-ground state Q values for pure neutrons are all close to the optimum Q value ($Q\simeq 0$) and equals within 1–2 MeV (cf. Table I). The even isotopes of lead form a beautiful system of pair vibration and the energies of the 2^+ levels are all very simi-

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TABLE I. Ground-ground state Q values (in MeV) for pure neutron pickup transfer channels for the systems studied in the present and previous works.

System	Ref.	$+1n$	$+2n$	$+3n$	$+4n$	$+5n$	$+6n$
^{62}Ni+^{206}Pb	this work	−1.25	1.68	−0.62	1.43	−1.51	−0.80
^{40}Ca+^{124}Sn	[13]	−0.13	5.41	4.53	9.49	7.80	11.71
^{58}Ni+^{124}Sn	[12]	0.51	5.95	4.96	9.38	7.11	10.29
^{58}Ni+^{100}Mo	[11]	0.71	6.17	5.35	9.13	6.81	9.10
^{64}Ni+^{238}U	[14]	−0.06	3.80	3.04	5.55	3.75	6.09

lar, within 150 keV, and constitute also a nice example of quadrupole pairing states. These properties of lead nuclei favor the population of levels close to the ground states of the final products and therefore should enhance the effect of pair in the transfer process [17].

In the present Rapid Communication we report on the results of the search for pair transfer modes in the ^{62}Ni $+^{206}$Pb system focusing on the pure neutron transfer channels. The study has been done at three bombarding energies, from the Coulomb barrier up, to see if and how these pair modes persist as a function of the excitation energy. The experiment was performed at the Tandem + ALPI accelerator complex of the Laboratori Nazionali di Legnaro. A ^{62}Ni beam was delivered at the three energies of $E_{lab}=341.7$, 332.5, and 316.5 MeV (in the center of the target), with an average current of $\simeq$ 2 pnA. A 200 μg/cm^2 thick ^{206}Pb target with an isotopic enrichment of 99.98% sandwiched between two 15 μg/cm^2 C foils was used. Light reaction products have been detected with a time-of-flight (TOF) magnetic spectrometer [13] equipped with two microchannel-plate detectors (MCP) for TOF signals and a multiparametric ionization chamber of ΔE-E type for nuclear charge and energy determination. The energy resolution is $\simeq$1% for ions with $A\simeq$50–70 and energies 1–3 MeV/nucleon, taking into account the intrinsic resolution of the detector, target thickness, and kinematic energy shift. For optimum Z resolution, an energy loss of $\simeq$60% in the ΔE section of the ionization chamber has been maintained. Between the MCP's, two doublets of magnetic quadrupoles are placed with a resulting effective solid angle of $\simeq$3 msr. Angular distributions have been measured in the laboratory range 65°–140°, covering most of the total transfer flux at the three energies. In Fig. 1 an example is given of a mass-charge matrix at angles close to the grazing for two bombarding energies. The average mass and nuclear charge resolutions are $\Delta A/A\simeq 1/100$ and $\Delta Z/Z\simeq 1/60$, respectively. Even at the lowest bombarding energy and at backward angles resolutions were good enough to allow an unambiguous separation of the main channels. The transmission of the spectrometer has been determined, as normal practice [13,14], from the yield of quasielastic events as a function of the magnetic fields of the quadrupoles. The yields have been compared, at different angles, with the quadrupole fields switched on and off and the ratios, giving directly the effective solid angle of the instrument for a specific reaction, turn out to be $\simeq$13.7. It has been verified that for all pure neutron transfer channels and, in general, for most of the detected transfer channels, the $B\rho$ values corresponding to the measured Q values lie within the $\pm$10% acceptance window of the spectrometer. Absolute normalization of the cross sections and relative normalization between different runs were ensured by four silicon monitor detectors placed in the sliding-seal scattering chamber connected to the spectrometer.

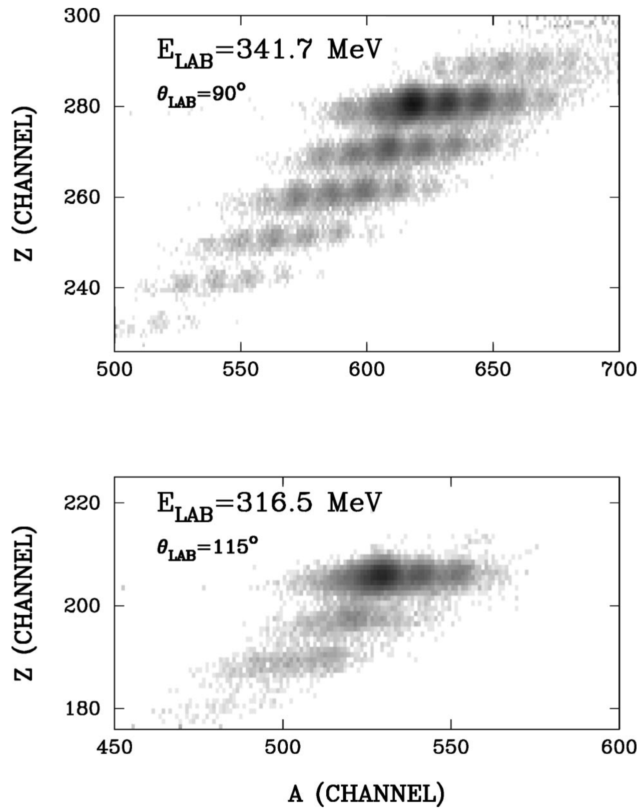

FIG. 1. A-Z matrix at the indicated energies and angles. The most intense spot in both matrices corresponds to $Z=28, A=62$.

In Fig. 2 we show the experimental (dots) Q-value integrated angular distributions for the neutron pickup and proton stripping channels, their bell-shapes indicate the grazing character of the reaction. In Fig. 3 we show the experimental (histogram) total kinetic energy loss (TKEL) distributions. At the three bombarding energies one observes that only the $+1n$ and $+2n$ channels have the main population close to the ground-ground state Q value (it is indicated by the down arrows in each frame) while the more massive transfer channels display a population towards more negative Q values with the tail increasing with the number of transferred neutrons. A similar behavior is observed for pure proton transfer channels that have been included in this analysis for completeness. The observation of these long tails in the Q value spectra, even for the present projectile and target combination, constitute our main point, i.e., any contribution from ''cold'' pair transfers, associated with low excitation energy, is likely hidden by the dominant ''warm'' sequential transfer processes. Unfortunately the low statistics for the $+4n$, $+5n$, $+6n$ transfer channels prevents us from attempting any further analysis of these TKEL spectra in terms of Q-value bins.

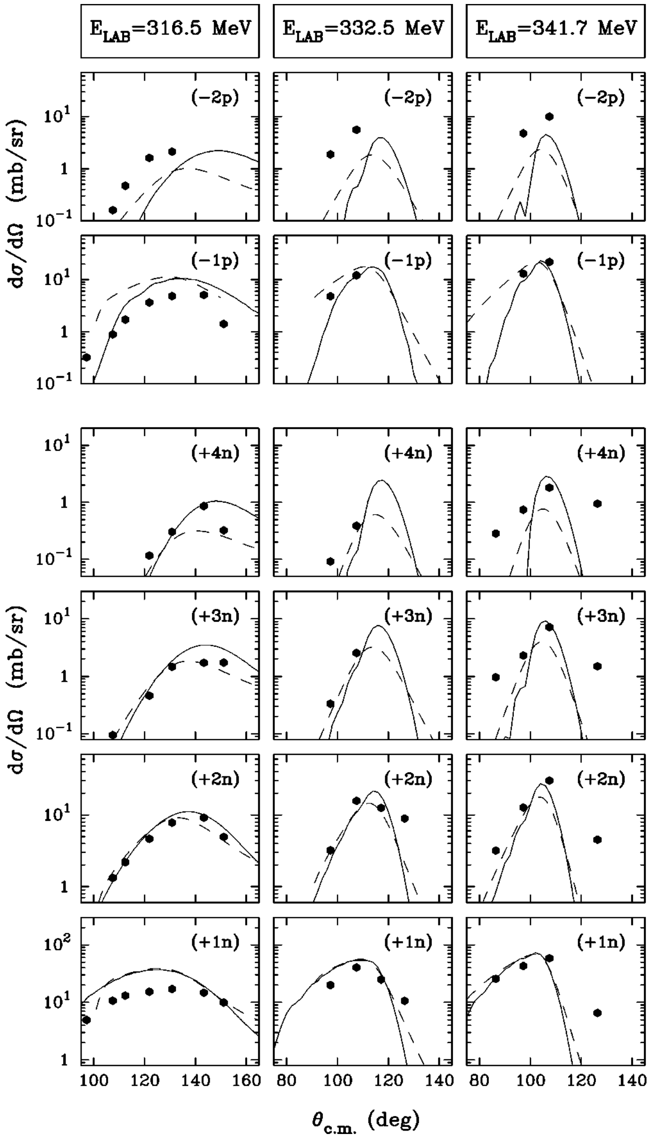

FIG. 2. Experimental (dots) and theoretical (lines) Q-value integrated angular distributions for the neutron pickup and proton stripping channels. The full line corresponds to the calculations done with the complex WKB theory while the dashed one to the calculations using the GRAZING program (see text). Experimental errors are within the size of the symbols and correspond to the statistical ones only. Systematic errors are estimated to be $\simeq 15\%$ on average.

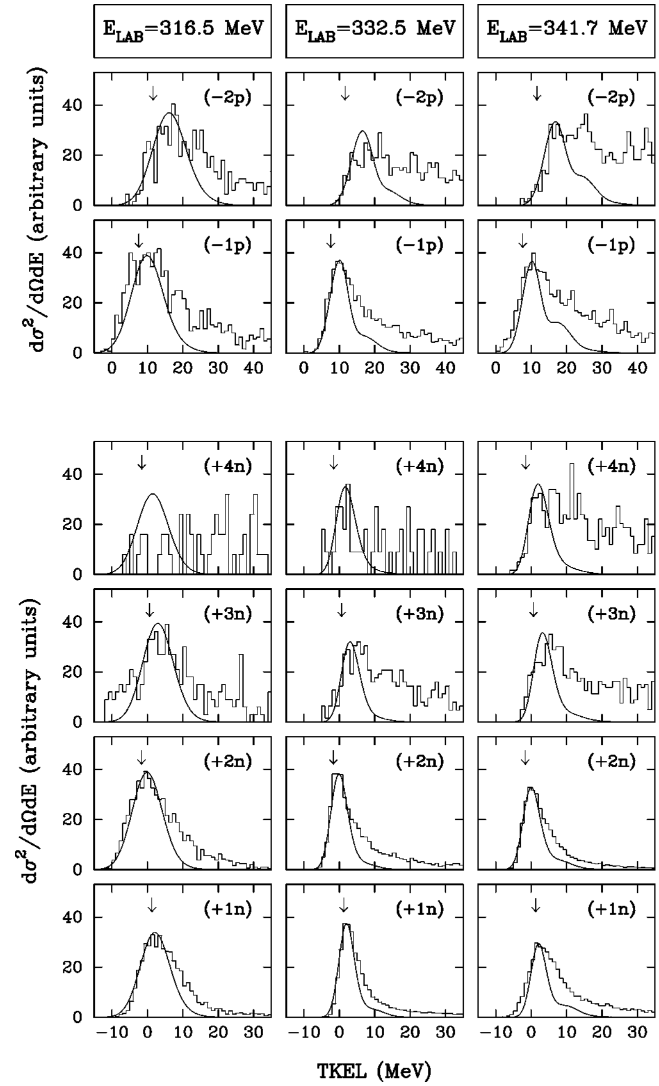

FIG. 3. Experimental (histograms) and theoretical (lines) total kinetic energy loss (TKEL) distributions for the pure neutron pickup and proton stripping channels. The down-arrows indicate the ground-ground state Q values. At the lowest bombarding energy the width of the spectra is significantly larger due to the unavoidable loss of energy resolution of the detector and to the target thickness.

In Fig. 4 we show for the three bombarding energies the experimental Q-value integrated differential cross sections obtained at an angle close to the grazing (where the spectrometer has been placed to obtain the highest statistics) as a function of the number of transferred neutrons. To show any possible odd-even staggering the data points have been connected with lines, one for the odd-transferred channels the other for the even. The trend of the data is almost energy independent and, at least within the experimental accuracy, displays a constant drop of the cross sections as a function of the transferred number of neutrons without any clear odd-even staggering, the one-neutron pickup channel seems, at all energies, to have a somewhat lower cross section than the one suggested by the common trend. The results obtained in these inclusive measurements indicate that the multinucleon transfer channels are dominated by a sequential mechanism, and therefore we feel that the observation of the eventual contribution of direct pair-transfer modes lies in the possibility of distinguishing the population of individual states.

The data are compared with a model that treats multinucleon transfer channels as a sequential transfer of independent single particles. This model is based on the complex WKB theory for one-particle transfer reactions developed in Refs. [18,19] and generalized to incorporate multinucleon transfer channels in Ref. [20]. We refer to the mentioned references for details, here we simply remind the reader that the formalism involves the same approximations which were exploited to calculate the absorptive [21] and polarization [22] component of the optical potential and the off-diagonal

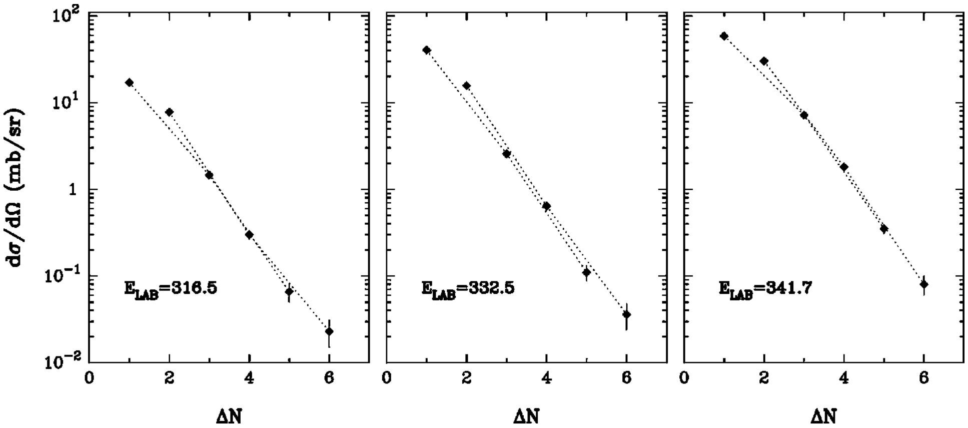

FIG. 4. Experimental differential cross sections at $\theta_{lab}=115°$, 90°, 80° for $E_L=316.5$, 332.5, 341.7 MeV, respectively, as a function of the number of transferred neutrons (ΔN). The indicated errors are only statistical. The dotted lines are a guide for the eye and connect the even and odd ΔN (see text).

inelastic couplings. To calculate the single-particle form factors governing the exchange of nucleons (they constitute the main ingredient of our calculations) we employ the single-particle levels shown in Fig. 5. While these are well defined both for protons and neutrons in the case of lead, for nickel we can talk about single-particle levels only for protons. For neutrons it is, in fact, more appropriate to talk about quasiparticle and quasihole states, this is the reason why the states $2p_{1/2}$, $1f_{5/2}$, and $2p_{3/2}$ appear twice with different energies corresponding to the quasiparticle states in ^{63}Ni and to the quasihole states in ^{61}Ni. The occupancies/vacancies of the above levels are indicated by the length of the line representing them (see also Ref. [23]).

Using for the real part of the optical potential the empirical potential of Ref. [24], with an imaginary part of the same geometry and a strength of -40 MeV, we obtain for the angular distribution the results shown in Fig. 2. The imaginary potential has been kept constant for all three bombarding energies. In order to check if our model space for the quasiparticle and single particle levels is adequate we compare in Fig. 3 our calculated energy spectra for a given partial wave (we choose an l close to the grazing) with the experimental ones obtained at an angle close to the maximum of the angular distribution. As is apparent from the figure the theory describes reasonably the spectra for one and two particle transfer channels. For the more massive transfer channels we seem to miss strength at high TKEL but we remind the reader that the theoretical spectra are calculated for a specific partial wave and not at a specific angle, here the contributions from several partial waves are important. Keeping in mind that no attempt has been made to fit the experimental data but only known information on single (quasiparticle) states and optical potential parameters are used, we can conclude that the theory reproduces reasonably well the overall evolution of the transfer data both with energy and the number of transferred nucleons, even so the theory is overpredicting the cross section for the $+1n$ channel at the lowest energy. These results indicate that the multinucleon transfer channels are dominated by a sequential mechanism and stress that the observation of contributions from direct pair-transfer modes lies in the possibility of distinguishing the population of individual states.

We take this opportunity to compare the angular distributions with the ones obtained with the semiclassical coupled

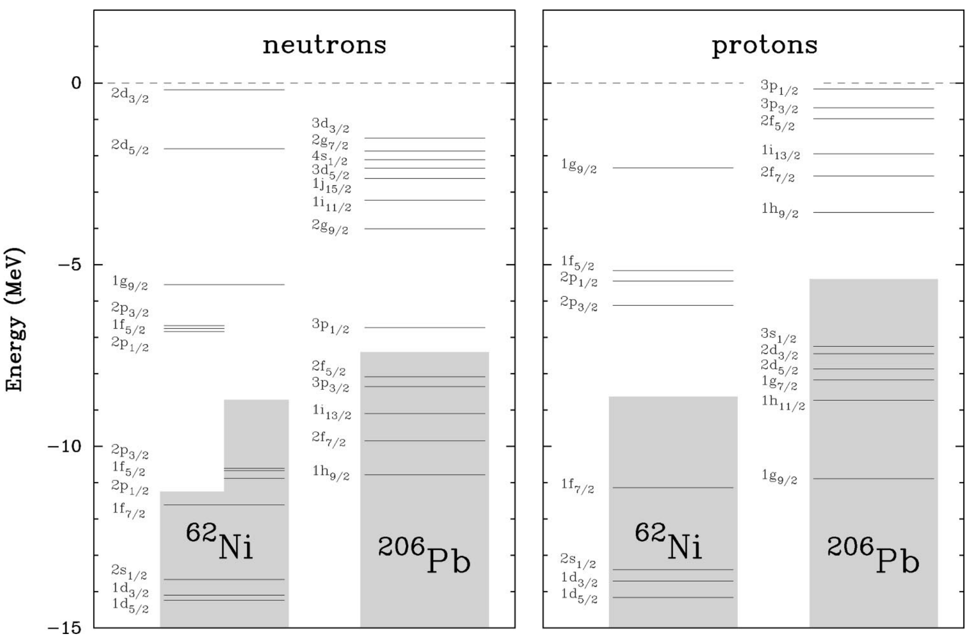

FIG. 5. Single-particle levels for projectile and target used in the calculations. The shaded areas indicate the occupied levels. Notice that in the case of nickel the neutrons do not have a sharp Fermi energy reflecting the quasiparticle quasihole nature of its spectrum (see text).

channels program GRAZING [25], developed from the theory of Ref. [15], that has been successfully used for the description of fusion excitation functions and barrier distributions [26] and has been used to analyze the data of Refs. [13,14]. Such a model describes the redistribution of mass, charge, energy, and angular momentum in a nuclear collision in terms of independent single nucleon transfer modes and the inelastic excitations of collective states. The results of such calculations are shown in Fig. 2 with a dashed line. Also in this case no attempt has been made to fit the data, noting that the model uses average form factors and average single-particle level densities, the description of the data is adequate and the comparison with the complex WKB calculations, where the actual single particle (quasiparticle) levels are used, is quite remarkable.

In conclusion, multinucleon transfer reactions, at least within the accuracy of the present inclusive data, do not show any significant contribution from pair-transfer modes. Coupled channels calculations adequately describe the experimental results and support the dominance of a sequential mechanism in the transfer process. Pair-transfer modes may eventually be identified if the population to individual nuclear levels can be achieved, for instance with high energy resolution spectrometers and a significant increase in the detection efficiency.

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