Neutron Pair Transfer in ^{60}Ni + ^{116}Sn Far below the Coulomb Barrier

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(Received 27 March 2014; published 29 July 2014)

An excitation function of one- and two-neutron transfer channels for the ^{60}Ni + ^{116}Sn system has been measured with the magnetic spectrometer PRISMA in a wide energy range, from the Coulomb barrier to far below it. The experimental transfer probabilities are well reproduced, for the first time with heavy ions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon pairing correlations.

DOI: 10.1103/PhysRevLett.113.052501 PACS numbers: 24.10.-i, 25.70.Hi, 29.30.Aj

The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighboring states. In nuclei, this is seen in the lowering of the level density near the ground state for even-even systems, in fact, to create excited states one has to break at least one pair of nucleons so that the states have an excitation energy of at least 2Δ, i.e., the binding energy of the pair (Δ being the pairing gap). For nuclei far from the closed shells the pairing interaction modifies the ground state population pattern by spreading the paired nucleons over several single particle states at around the nominal Fermi surface [1–3].

In this Letter we will investigate if these structure properties will influence in a significant way the evolution of the collision of two nuclei, in particular on how they exchange nucleons in "gentle" collisions [4,5].

It is still an open question whether pair correlations can be probed in heavy ion collisions. The search for their signatures has been mainly attempted via the measurement of two-particle transfer channels, in particular, via the extraction of enhancement coefficients [6], defined as the ratio of the actual cross section to the prediction of models using uncorrelated states. Such enhancement factors should provide a direct measurement of the correlation of the populated states. Unfortunately, the experimental evidence of these factors is marred by the fact that almost all existing studies involve inclusive cross sections at energies higher than the Coulomb barrier and at angles forward of the grazing [7,8] where the reaction mechanism is complicated by the interplay between nuclear and Coulomb trajectories.

Suitable conditions to avoid the above shortcomings are met at energies below the Coulomb barrier, where nuclei interact at very large distances, so that the distortion of the Coulomb elastic waves by the nuclear attraction is very small and may easily be accounted for. This energy regime is of course characterized by low transfer cross sections [9]. Only with the advent of large solid angle magnetic spectrometers [10] the detection efficiency and resolution to identify the fragments reached a sufficient level to make these experiments feasible. This is illustrated in the recently studied ^{40}Ca + ^{96}Zr system [11], where an excitation function for one- and two-neutron transfers has been measured at energies far below the Coulomb barrier with the PRISMA spectrometer [12] testing the transfer form factors up to a distance of 15.5 fm.

Transfer reactions populate, at energies around the Coulomb barrier, a narrow Q-value window close to the optimum Q value, the latter being derived by requiring that the trajectories of the entrance and exit channels match smoothly [10,13]. Following these properties, we choose to study the ^{60}Ni + ^{116}Sn system, characterized by ground state Q values very close to optimum ($Q_{\mathrm{opt}} \sim 0$) for the one- and two-neutron pickup transfer, leading to ^{61}Ni ($1n$) and ^{62}Ni ($2n$), respectively. In the ^{40}Ca + ^{96}Zr system, mentioned above, the ground state Q value for the two-neutron transfer channel is at $\sim$6 MeV and, thus, one populates reaction products with high excitation energy. We stressed that the missing strength reported in the analysis [11] was probably caused by states with large angular momentum populated in the reaction and that we had not been able to include in the theoretical calculation.

The measurement was performed in inverse kinematics by using a ^{116}Sn beam with average currents of $\sim$2 pnA onto a 100 μg/cm^2 strip ^{60}Ni target, employing the superconducting PIAVE-ALPI accelerator complex of LNL. The

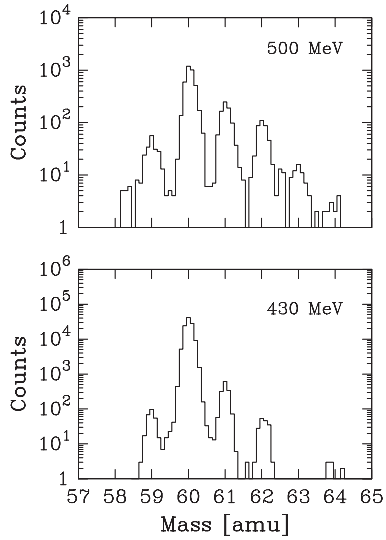

FIG. 1. Mass spectra of Ni isotopes in the ^{60}Ni + ^{116}Sn system at two representative energies, above and below the Coulomb barrier.

target isotopic purity was 99.81%. We measured, by detecting Ni-like recoils in PRISMA at $\theta_{\mathrm{lab}} = 20°$, an excitation function from above to well below the Coulomb barrier varying the beam energy from 500 to 395 MeV in steps of ~10 MeV and further intermediate steps using a C-foil as degrader. For normalization, two monitor silicon detectors have been used at $\theta_{\mathrm{lab}} = 55°$ and 60° to get pure Rutherford scattered ^{60}Ni ions.

The identification of fragments has been done on an event-by-event basis by using, for the atomic number, the range of the ions as a function of the total energy released in the ionization chamber and, for the mass, by reconstructing the trajectories of the ions [14] inside the magnetic elements of PRISMA, making use of time of flight and position information at the entrance and at the focal plane of the spectrometer. Mass spectra for Ni isotopes are displayed in Fig. 1 for two bombarding energies. The very good mass resolution $\Delta A/A \sim 1/240$ is guaranteed by the high kinetic energy of the recoils (~6 MeV/A). The high efficiency of PRISMA allowed us to detect transfer products down to $\sim 10^{-4}$ with respect to the elastic yield. To illustrate the channel separation and the almost background-free conditions, we display in Fig. 2 a two-dimensional matrix of mass vs total kinetic energy loss (TKEL) for the lowest energy point where both (1n) and (2n) have been measured.

In these low energy collisions the cross sections for the transfer products are proportional to the elastic one; thus, it is convenient to represent them in terms of transfer probability P_{tr} defined, for the measured angle, as the ratio of the transfer yield over the quasielastic one. It is customary to present the P_{tr} so defined as a function of the distance of closest approach for a Coulomb trajectory D. For the (1n) and (2n) channels, the measured transfer

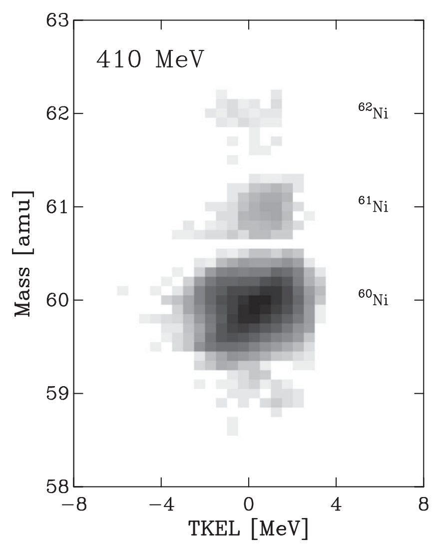

FIG. 2. Matrix of mass vs total kinetic energy loss (TKEL) for Ni isotopes at $E_{\mathrm{lab}} = 410$ MeV. One sees the clear separation between quasielastic and (1n) and (2n) transfer channels and the concentration of the TKEL distributions in a narrow range close to ~0 MeV.

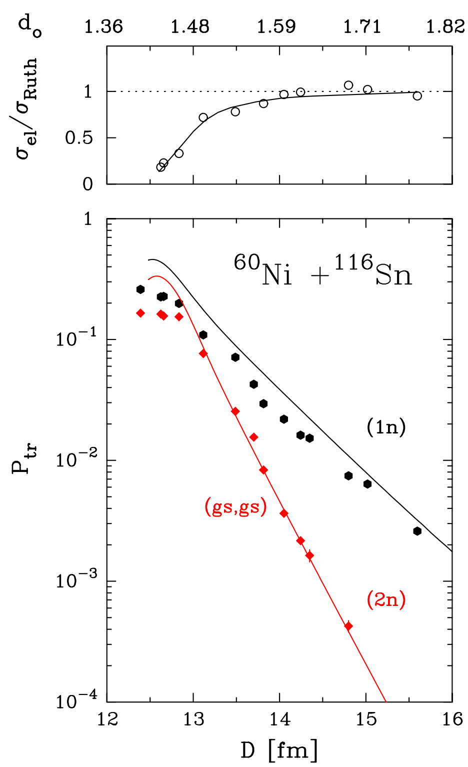

FIG. 3 (color online). Top: Ratio between the quasielastic and the Rutherford cross section. Symbols represent the experimental values, solid line is the theoretical calculation with the GRAZING code. Bottom: Experimental (points) and microscopically calculated (lines) transfer probabilities for the one- (^{61}Ni) and two-neutron (^{62}Ni) pickup plotted as a function of the distance of closest approach D (the entrance channel Coulomb barrier is estimated to be at 12.13 fm [4]). We also report (top) the reduced distance $d_0 = D/(A_1^{1/3} + A_2^{1/3})$. The shown errors are only statistical and in most cases are smaller than the size of the symbol.

probabilities are plotted in the lower panel of Fig. 3. The transfer probability is directly related to the square of the matrix element governing the transfer process and this, due to the very large internuclear distance, is proportional to the tail of the single particle wave functions of the connected states [13,15]. This is manifested by the exponential behavior of the $(1n)$ channel. The extracted slope is indeed compatible with the binding energies (in projectile and target) of the transferred neutron. In the simple approximation that the two-neutron transfer is a successive process one obtains that its corresponding slope is just the square of the one of the $(1n)$ channel. Indeed this is what is seen from the data. The relative normalization between the one- and two-neutron transfer channels can be obtained from the simple description $P_2 = \mathrm{EF} \cdot P_1^2$, EF being the enhancement factor. We obtain for EF a value of 5.5. One has to be aware that this enhancement factor cannot be ascribed solely to the presence of correlations, in fact the oversimplified model is lacking phase-space and statistical considerations. In what follows, the data will be analyzed with models that take explicitly into account the structure of the two nuclei.

The flattening of both probabilities at small internuclear distances (large bombarding energies) is related to the increase of the absorption. In connection with this, in the same figure (top panel) the ratio of the ^{60}Ni experimental yield over the Rutherford cross section is reported. The ratio has been normalized to unity for large D (i.e., below the barrier) where the quasielastic scattering coincides with the Rutherford one. This quasielastic distribution will be later used to construct from the theoretical cross section the transfer probability in a way consistent with the experimental definition.

The calculations are performed in a distorted wave Born approximation (DWBA) by using for the wave functions of relative motion their CWKB form as in Ref. [16]. For the one-neutron transfer channel, the inclusive cross section is simply obtained by summing up all the contributions coming from the single particle transitions. For the two-neutron transfer channel, we included only the ground to ground state transition in the successive approximation (we remind the reader that the simultaneous component is canceled out by the nonorthogonality correction). We stress that the shown results are not coming from a best fit procedure, indeed, calculations have been performed by employing the experimental spectroscopic factors for the one particle transfer and B coefficients for the two particle transfer.

In Table I, we report the sets of single particle levels for the projectile and target that are used for the construction of all the single particle transitions that populate ^{61}Ni. The one particle matrix elements (form factors) are calculated, in the prior representation, by using the single particle wave functions constructed with the shell model potentials of Refs. [17,18] and by weighting each transition with the corresponding spectroscopic factor (reported in the table as

TABLE I. Neutron single particle levels for ^{116}Sn and ^{60}Ni. The occupation/vacancy (V_j^2/U_j^2) of a single particle level correspond to the BCS calculation for the ^{116}Sn and to the ones extracted from the experimental spectroscopic factors of Ref. [18] for the ^{60}Ni where for a given j state we have summed the spectroscopic factors of all states with the same j lying in a reasonable energy range (of 2–3 MeV). The BCS calculations (for the tin) are performed by using for the pairing interaction $G = 20.5/A$ ($\lambda = -9.75$ MeV and $\Delta = 1.56$ MeV). Also shown are the energies (E_j) of the corresponding quasiparticle states. The last column reports the spectroscopic factors (B coefficients) for the two particle states, they are related to the occupation probability amplitude U_j and V_j via the relation $B_j = \sqrt{j+1/2} \cdot U_j V_j$.

	nlj	ϵ_j [MeV]	E_j [MeV]	V_j^2/U_j^2	B_j
^{116}Sn	$1g_{9/2}$	−16.58	7.01	0.9874	0.272
	$2d_{5/2}$	−11.51	2.35	0.8740	0.658
	$1g_{7/2}$	−10.86	1.92	0.7900	0.910
	$3s_{1/2}$	−9.70	1.56	0.4870	0.483
	$2d_{3/2}$	−9.51	1.58	0.4280	0.661
	$1h_{11/2}$	−8.12	2.25	0.1402	−0.770
	$2f_{7/2}$	−3.11	6.81	0.0134	−0.224
	$3p_{3/2}$	−1.77	8.12	0.0094	−0.134
^{60}Ni	$2p_{3/2}$	−11.33	1.56	0.33	−0.524
	$2p_{1/2}$	−9.66	1.83	0.65	−0.5
	$1f_{5/2}$	−9.33	2.05	0.4	−0.34
	$1g_{9/2}$	−5.16	5.80	0.5	0.1

occupation probability V_j^2 for tin and vacancy U_j^2 for nickel). For nickel, the reported spectroscopic factors are the ones of Ref. [18] while for tin they are not well known experimentally and, therefore we calculated them via a BCS transformation by using a state-independent pairing interaction with $G = 20.5/A$ that lead to a Fermi energy $\lambda = -9.75$ MeV and a pairing gap $\Delta = 1.56$ MeV. Dividing the obtained cross section by the corresponding quasielastic cross section, one gets for the $(1n)$ channel the transfer probability, shown in Fig. 3 with a full line. We can conclude that the experimental data are reasonably described in the whole range of D indicating the correctness of the chosen set of single particle levels even if we overestimate the experimental transfer probability by ~30%.

For the calculation of the $(2n)$ channel we used the formalism of Ref. [5] that describes the ground to ground state transition. In this formalism we employ the same single particle form factors used for the $(1n)$ channel. The ground states of ^{62}Ni and ^{114}Sn have been described in the BCS approximation and the B coefficients are reported in Table I. The results, divided by the quasielastic, are displayed in Fig. 3 with a solid line. The experimental points are very well described both in magnitude and in slope indicating that the two-neutron transfer channel in this system is populating essentially only the ground state.

Representing the outcome of a transfer reaction in terms of transfer probabilities plotted as a function of the distance

D is quite appealing since the angular distributions at different bombarding energies all coalesce in a single line at large distances. Thanks to this, the calculation can be performed at a single bombarding energy by transforming the angular distribution from the scattering angle θ to the distance of closest approach D. We checked this procedure by performing calculations at several bombarding energies and by employing the same conditions as in the experiment. The calculations have been performed by using, for the real part of the potential, the Woods Saxon parametrization of Ref. [4] ($V_0 = -82.6$ MeV, $R_0 = 1.18$ fm, $a = 0.687$ fm). For the imaginary part we decided to calculate it microscopically [19,20] in order to be compatible with the form factors used both for the one- and two-particle transfer channels. At the bombarding energy of 475 MeV we have been able to fit this microscopic potential with a Woods Saxon shape having the same geometry of the real part and $W_0 = -20$ MeV. To demonstrate that the empirical potential is suitable for this system, we show in Fig. 3 (top), with a full line, a calculation of the quasielastic cross section performed with the code GRAZING [21,22].

The fact that in this reaction the transfer strength is concentrated around the ground state is illustrated in Fig. 4 which displays the experimental total kinetic energy loss for the quasielastic, one- and two-neutron pickup channels at three representative bombarding energies. The TKEL is reconstructed assuming a binary reaction and imposing the conservation of momentum. The experimental energy resolution, taking into account detector resolution, trajectory reconstruction, beam position, and angle indetermination on target and target straggling effects, was estimated to be ~2 MeV. This is visible in the TKEL distribution for the entrance channel mass partition ($0n$) below the barrier, which turns out to be similar for the transfer channels. The TKEL spectra are clearly peaked around the ground state Q value, depicted by dashed lines in the figure.

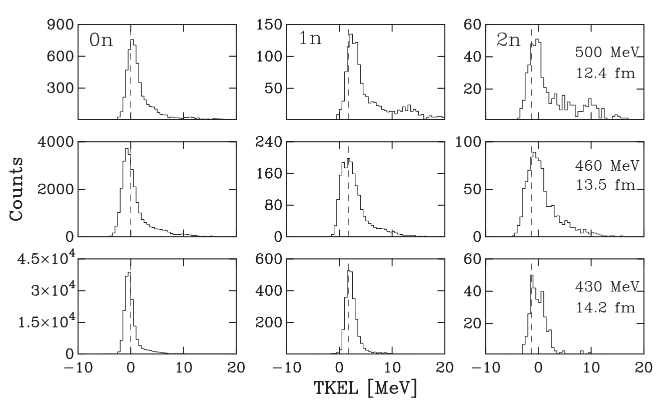

FIG. 4. TKEL spectra obtained for the quasielastic and one- and two-neutron transfer channels at three representative bombarding energies, above (upper), near (middle), and below (lower) the Coulomb barrier. The corresponding distances of closest approach (in fm) are indicated. The dashed lines correspond to the position of the ground state Q values: $Q_{gs}^{(1n)} = -1.7$ MeV and $Q_{gs}^{(2n)} = +1.3$ MeV.

We measured transfer probabilities for one- and two-neutron transfer channels from the Coulomb barrier energy to energies corresponding to very large distances of closest approach where the nuclear absorption is negligible. The employed microscopic theory, that incorporates nucleon-nucleon correlations, essential for the population pattern of the single particle levels around the Fermi energy, very well reproduces the experimental data in the whole energy range, in particular, the transfer probability for two neutrons is very well reproduced, in magnitude and slope, by considering solely the ground-ground state transition. We would like to emphasize that, for the first time in a heavy ion collision, we have been able to provide a consistent description of one- and two-neutron transfer reactions by incorporating, in the reaction mechanism, all known structure information of entrance and exit channel nuclei. In particular, there is no need to introduce any enhancement factor for the description of two-neutron transfer, of course very important are the correlations induced by the pairing interaction. This has to be considered a significant step forward in the understanding of two-neutron transfer processes. This achievement has been possible only because the chosen system is very well Q-value matched so that the reaction is dominated by the ground-ground state transition. Whether these results will be useful to define a new mode, the two-particle transfer channel, to be added to the well known surface modes and one-particle transfer in the reaction model, is still an open question, in particular in connection with the definition of the matrix element for the excitation of this new mode like the macroscopic form factor of Ref. [23].

Such studies of two-nucleon transfer reactions are presently at the focus of a renewal of interest [24,25], and pave the road for future investigations at sub-Coulomb energies with radioactive beams [26–28] to investigate new predicted phenomena, like those related to the density dependent pairing interactions and extended neutron distributions in neutron rich nuclei [29].

The authors are grateful to the LNL Tandem-ALPI staff for the good quality beams and the target laboratory for the excellent target. This work was partly supported by the EC FP6—Contract ENSAR No. 262010. A. G. was partially supported by the P2IO Excellence Laboratory.

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