Pair neutron transfer in ^{60}Ni+^{116}Sn probed via γ-particle coincidences

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We performed a γ-particle coincidence experiment for the ^{60}Ni+^{116}Sn system to investigate whether the population of the two-neutron pick-up channel leading to ^{62}Ni is mainly concentrated in the ground-state transition, as has been found in a previous work [D. Montanari *et al.*, Phys. Rev. Lett. 113, 052501 (2014)]. The experiment has been performed by employing the PRISMA magnetic spectrometer coupled to the Advanced Gamma Tracking Array (AGATA) demonstrator. The strength distribution of excited states corresponding to the inelastic, one- and two-neutron transfer channels has been extracted. We found that in the two-neutron transfer channel the strength to excited states corresponds to a fraction (less than 24%) of the total, consistent with the previously obtained results that the $2n$ channel is dominated by the ground-state to ground-state transition.

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I. INTRODUCTION

Low-energy multinucleon transfer reactions are among the most important tools to probe nucleon-nucleon correlations in nuclear systems [1, 2]. These correlations are particularly relevant in the studies of neutron-rich nuclei [3–6] where they play an important role in stabilizing the system by increasing their binding energy. In reaction theory we have learned that the evolution of a heavy-ion collision is dominated by the structure properties of the reactants, in particular by their surface and single-particle degrees of freedom [7–9], but the role of nucleon-nucleon correlations, as expressed by the trans-

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fer of pairs, is still an open question [10].

To have a deeper understanding of particle-particle correlation and to see if this correlation may eventually lead to the introduction of a pair mode in the reaction mechanism, we recently measured the transfer probabilities for one- and two-neutron transfer channels in the ^{60}Ni+^{116}Sn system [11]. This system is very well Q-value matched for the ground-state to ground-states transition, this matching condition is quite relevant because particle-particle correlations are essential in defining the ground-state properties. The transfer probabilities, measured up to very large distances of closest approach [12], have been analyzed by employing a microscopic theory [13, 14], which, for the first time in a heavy-ion collision, provided a consistent description of one- and two-neutron transfer channels, in shape and magnitude. For the calculation of the two-neutron transfer channel the formalism of Ref. [13] has been used. This formalism incorporates the contribution from both the simultaneous and successive terms. The ground-state to ground-state transition has been calculated by describing the ground states of ^{62}Ni and ^{114}Sn in the BCS approximation with a standard state-independent pairing force.

The experimental energy distribution for the two-neutron transfer channel prevented us from excluding contributions from the excitation of low-lying states because this distribution is concentrated in an energy region with a width of ∼2 MeV. We felt, therefore, that it was important to corroborate the theoretical conclusions by estimating the fraction of the total cross section going into excited states. To this purpose we performed a γ-particle coincidence experiment for the same ^{60}Ni+^{116}Sn system, employing the PRISMA spectrometer [15, 16] coupled to the Advanced Gamma Tracking Array (AGATA) demonstrator [17–19]; this combination provides unique features for the selection of transfer products and the efficient detection of associated γ rays.

II. EXPERIMENT AND RESULTS

A ^{60}Ni beam was accelerated at E_{lab}=245 MeV with an average current of ∼2 pnA onto a 100 μg/cm^2 strip (2 mm) ^{116}Sn target, employing the XTU-Tandem accelerator of the Laboratori Nazionali di Legnaro (LNL). The target isotopic purity was 99.6%. We detected Ni-like fragments in PRISMA placed at θ_{lab}=70°. This angle, slightly more forward than the grazing, was chosen to have a sufficient transfer yield under the condition that the relative motion trajectories are weakly affected by the nuclear components of the interaction. Under this condition the transfer yields are coming from partial waves (impact parameters) leading to a large distance of closest approach (where the transfer form factors are of exponential character [20] with their tail governed by the binding energy of the involved single-particle states) and are not affected by the absorption.

To detect γ rays we employed the AGATA demonstrator, based on highly segmented germanium detectors. The demonstrator, which comprised four triple cluster modules, was placed at a distance of 16.5 cm from the target covering backward angles in the range 130° - 170° in the laboratory system. In this configuration, the simulated full-absorption efficiency is 2.64% for 1.3-MeV γ rays (see Refs. [17–19]). Pulse-shape analysis was applied to the digitized signals, and the energies of individual γ rays were reconstructed via a tracking algorithm.

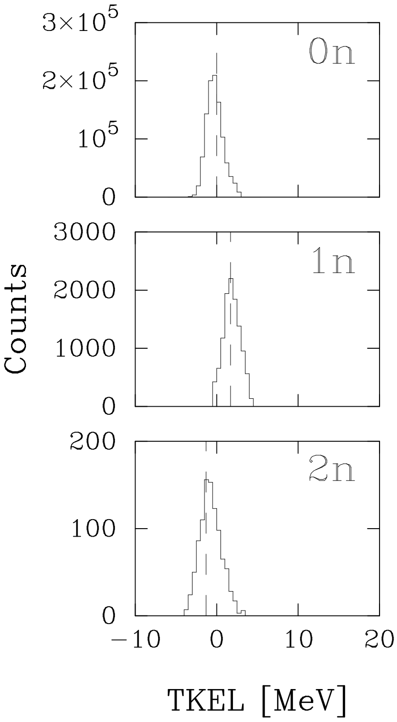

FIG. 1: TKEL spectra obtained for the elastic(+inelastic) ($0n$) and one-neutron ($1n$) and two-neutron ($2n$) pick-up channels in the ^{60}Ni+^{116}Sn reaction at E_{lab}=245 MeV and θ_{lab}=70°, corresponding to a distance of closest approach of 14.5 fm. The dashed lines correspond to the position of the ground-state Q values: $Q^{1n}_{\mathrm{gs}}= -\ 1.7$ MeV and $Q^{2n}_{\mathrm{gs}}= +\ 1.3$ MeV.

The identification of Ni isotopes in PRISMA has been done on an event-by-event basis through the reconstruction of the trajectories of the ions [15, 16] inside the magnetic elements, making use of the time-of-flight and position information at the entrance and at the focal plane of the spectrometer. For each fragment, the total kinetic energy loss (TKEL) distributions have been constructed by assuming a binary reaction and imposing the conserva-

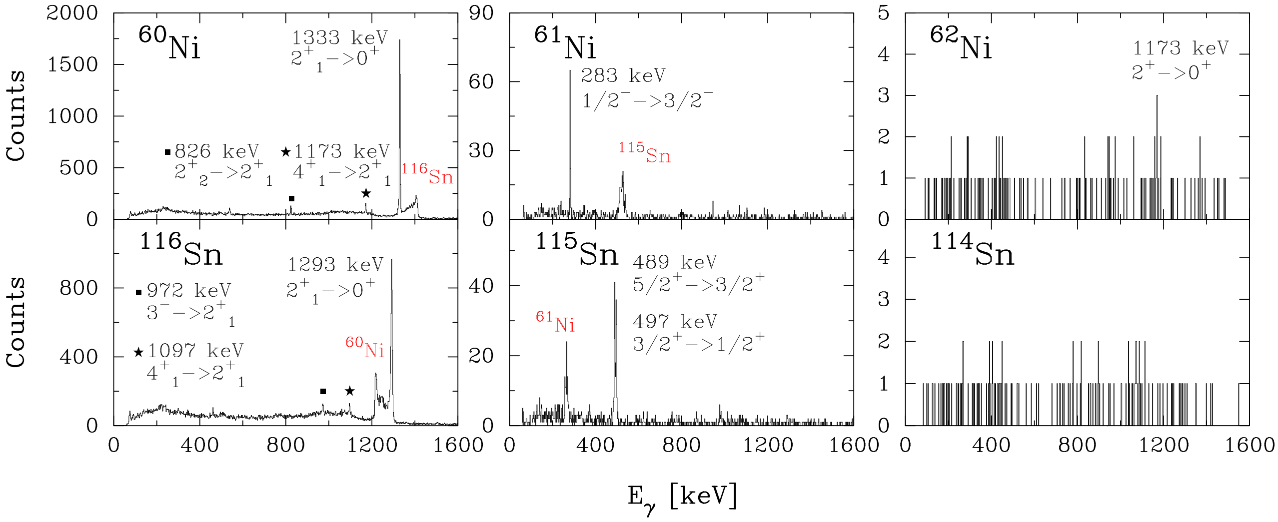

FIG. 2: (Color online): Top panels: Doppler-corrected γ spectra for ^{60}Ni, ^{61}Ni, and ^{62}Ni detected in PRISMA. Bottom panels: Doppler-corrected spectra for the heavy binary partners ^{116}Sn, ^{115}Sn, and ^{114}Sn (the bin is 2 keV wide). The strongest transitions are labeled with the γ-ray energy and spin and parity of the initial and final states. The broader peaks, corresponding to the wrongly Doppler-corrected reaction partner, are also labelled (red color) in each frame.

tion of momentum. The TKEL for the quasi elastic, one- and two-neutron pickup channels are reported in Fig. 1. The spectra display narrow distributions centered at the ground-state to ground-state Q values, with a width of $\sim$2.3 MeV. The spectra do not present any appreciable long energy tail; thus one may rule out contributions from small impact parameters that would lead to larger energy losses. Similar distributions were obtained in the previous measurement [11] when the bombarding energies were well below the Coulomb barrier. To examine the details of the populated states we show in Fig. 2 the γ spectra, taken with the demonstrator, in coincidence with ^{60}Ni, ^{61}Ni, and ^{62}Ni as identified by PRISMA and the ones associated with their binary partner, i.e., ^{116}Sn, ^{115}Sn, and ^{114}Sn. The Ni-like spectra have been Doppler corrected on an event-by-event basis by using the information of the ion velocity vector provided by the spectrometer and taking into account the geometry of the γ detectors. The spectra of the Sn-like fragments have undergone similar corrections but with velocity parameters obtained for the heavy binary partner.

For the inelastic channel (entrance channel mass partition) the spectra are dominated by the transitions from the first 2^+ excited states to the ground states of the projectile and the target. The other γ lines seen in the spectra are coming from the decay of higher lying states to the first 2^+ states. Because the intensity of these feedings is very small, we can conclude that most of the strength of the 2^+ is of direct character.

In the spectra of the one-neutron pick-up channel we observe essentially the population of the $1/2^-$ state in ^{61}Ni, decaying to the $3/2^-$ ground state, and of the $5/2^+$ state in ^{115}Sn, decaying to the $3/2^+$ state at 497 keV followed by the decay to the $1/2^+$ ground state with a similar strength. The decay of the $5/2^+$ state to the ground state can also be observed. In ^{61}Ni, the absence of the 67-keV transition, from the $5/2^-$ (5.3 ns lifetime) state to the ground state, is due to the presence of a 600-μm-thick Sn x-ray absorber put in front of the Ge detectors. In ^{115}Sn, the decays from the $7/2^+$ (613 keV) state and the $11/2^-$ (714 keV) state to the ground states are missing because of their long life times, 3 and 159 μs, respectively. For the two-neutron pickup channels the only recognizable γ-line corresponds to the transition from the 2^+ state to the 0^+ ground state of ^{62}Ni (see below).

In Table I we have summarized the results on the γ analysis by listing the strengths of the most important transitions, corrected for the contributions of the feeding and for their relative detection efficiencies in the AGATA array. These strengths have been normalized to the yield of the $2^+ \rightarrow 0^+$ transition in ^{60}Ni.

We remind the reader that from Ref. [11] we have indications that the total transfer cross section for the $2n$

TABLE I: Experimental yields and theoretical cross sections (taken at $\theta_{\rm lab}$=70°) for inelastic and neutron transfer channels, normalized to the 2^+ strength in ^{60}Ni. For the inelastic channels the calculations were done in the coupled-channels approximation while for the one-neutron pickup channels they were done in the distorted-wave Born approximation (DWBA). Both kinds of calculations were performed with the code PTOLEMY [21]. Experimental errors include systematic and statistical contributions.

	Experiment	Theory
^{116}Sn(2^+)	0.792 ± 0.160	0.720
^{116}Sn(4^+_1)	0.042 ± 0.011	0.056
^{60}Ni(4^+_1)	0.060 ± 0.013	0.11
^{115}Sn($5/2^+$)	0.018 ± 0.003	0.037
^{61}Ni($1/2^-$)	0.014 ± 0.003	0.033
^{62}Ni(2^+)	< 0.00145	-

channel is well described by including only the ground-state to ground-state transition; so what is shown in Table I would be a confirmation of these results if the transition to the 2^+ state in ^{62}Ni were a small fraction of the total transfer strength. To arrive at this conclusion we start by calculating the above ratios in a way that is consistent with Ref. [11]. Because the ratios in Table I, in good approximation, represent the direct population of states in the reaction, they could be compared with results obtained with any reaction code. Of particular relevance are the calculations for the one-neutron pickup because they provide a direct check on the one-particle form factors that have been used in the successive approximation for the two-neutron transfer.

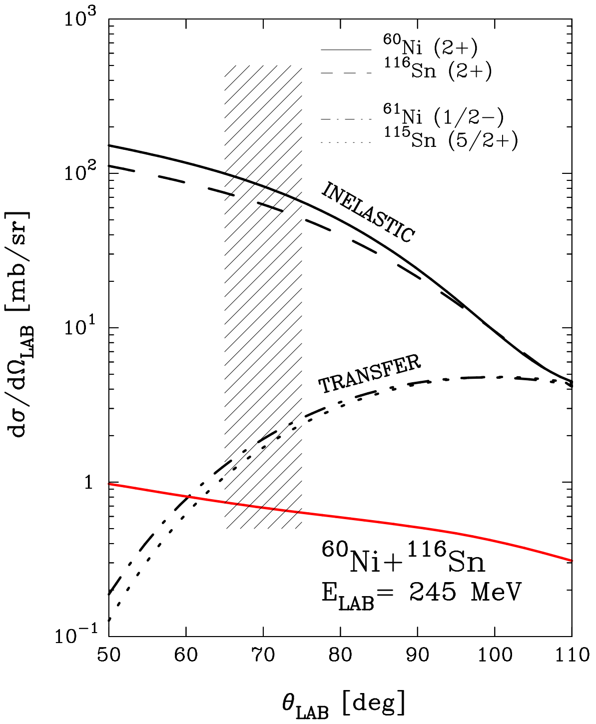

FIG. 3: (Color online) Differential cross sections, from coupled-channels or DWBA calculations (see text), for the indicated states in ^{60,61}Ni and ^{116,115}Sn in the ^{60}Ni+^{116}Sn reaction at $E_{\rm lab}$=245 MeV. The red (gray) line is the elastic over Rutherford ratio. The hatched area corresponds to the PRISMA angular acceptance.

For the inelastic and one-neutron transfer channels the calculations have been performed by employing the same optical potential of Ref. [11]. Because of the collectivity of the low-lying states of the target and the projectile and because of the strong Coulomb field, we have decided, for the inelastic channel, to perform a coupled-channels calculation [21] by including the 2^+ and 4^+ states, in the vibrational approximation, and with the tabulated values for the deformation parameters. For the one-neutron pickup channel the calculations, for the indicated single-particle transitions, have been performed in the DWBA approximation [21]. For the form factors and the associated spectroscopic factors we have used the ones of Ref. [11]. The calculated angular distributions are reported in Fig. 3 and the corresponding ratios of the cross sections (for the relevant PRISMA angle) are reported in Table I. We would like to emphasize the reasonable agreement between the experiment and the theory that has been obtained not via best-fits analysis but by using the optical potential and spectroscopic factors as in Ref. [11] and by using the tabulated values for the deformation parameters.

To understand if the population of the 2^+ state in the two-neutron pickup channel is a small fraction of its total strength we have to provide an estimation of the ratio, as in Table I, also for the full strength of the $2n$ channel. In an approximate way we can arrive at this result by using the values in Table I and Figs. 3 and 4. For the measured angle ($\theta_{\rm lab}$ = 70°), we can write in good approximation:

$$\sigma_R - \sigma_{el} = \sigma(2^+,^{60}\text{Ni}) + \sigma(2^+,^{116}\text{Sn}) \qquad (1)$$

which can be reassembled in the form:

$$\sigma_R \left(1 - \frac{\sigma_{el}}{\sigma_R}\right) = \sigma(2^+,^{60}\text{Ni}) \left(1 + \frac{\sigma(2^+,^{116}\text{Sn})}{\sigma(2^+,^{60}\text{Ni})}\right) \qquad (2)$$

which provides an estimation of the inelastic cross section for the 2^+ state in ^{60}Ni. From Fig. 4, the transfer probability for the $2n$ channel at the distance of closest approach corresponding to 70° is P_{2n}=0.0012. By remembering that $\sigma_{2n} = \sigma_R\ P_{2n}$ and by using the above formula (with σ_{el}/σ_R=0.64, extracted from Fig. 3, and

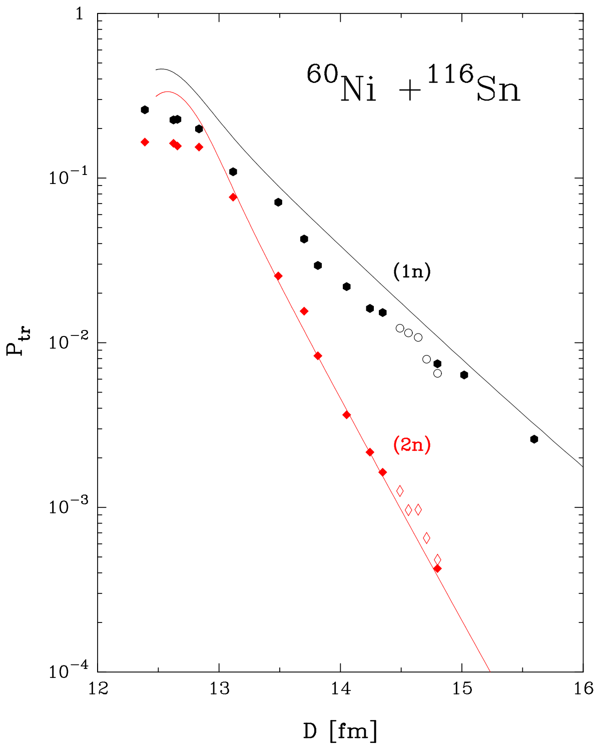

FIG. 4: (Color online) Experimental (symbols) and microscopically calculated (lines) transfer probabilities for the one- and two-neutron pickup channels plotted as a function of the distance of closest approach D. Open symbols correspond to the presently obtained angular distribution in direct kinematics while solid symbols refer to the excitation function previously performed in inverse kinematics [11].

with the other ratio taken from the Table I), one gets

$$\frac{\sigma_{2n}}{\sigma(2^+,^{60}\mathrm{Ni})} = 0.006 \ . \qquad (3)$$

So from the last line in Table I, we can conclude that the transitions to the excited states contribute less than 24% to the total strength.

To support this estimation, we made a simple multi-Gaussian fit of the TKEL spectra of Fig. 5. This fit is feasible for this channel because very few transitions may contribute, the ground-state to ground-state transition and the one that may lead to the excitation of the 2^+ state (at 1.17 MeV) in ^{62}Ni. The excitation of the 2^+ state (at 1.3 MeV) in ^{114}Sn may be ignored because the γ spectra do not show any evidence for this transition. To have a better description of the high-energy tail of the spectra we added also the transition at a higher excitation energy that we fixed at 2.34 MeV. The width of the Gaussians have been fixed from the low-energy side of the spectrum. This width (2σ) turns out to be of 2 MeV and represents the energy resolution of the experiment. The TKEL spectrum is well described with three Gaussians, one that corresponds to the ground-state to ground-state transition with a weight of 0.6, one that corresponds to the excitation of the 2^+ states with a weight of 0.29, and one tahta corresponds to the higher excitation energy with a weight of 0.11. From these numbers it follows that the 2^+ states contribute 29% to the total transfer strength, a number in reasonably good agreement with the previous estimation.

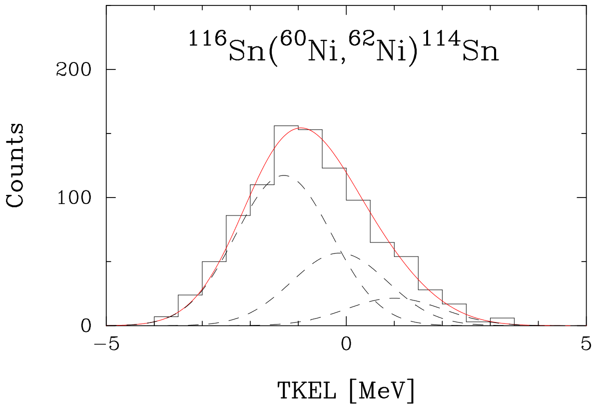

FIG. 5: (Color online) Experimental TKEL spectrum (histogram) for the $2n$ channel, together with the Gaussian fits (lines). The three Gaussians (dashed lines) have the same standard deviation of 1 MeV and are centered, respectively, at -1.3, -0.14, and 1 MeV, corresponding to the transitions to the ground state, to the 2^+ state and the higher-energy states in ^{62}Ni.

Probably it is not correct to ascribe the ~24% of the total strength of the $2n$ channel to a direct transfer process that populates the 2^+ state in ^{62}Ni because higher-order transitions can populate the same state. Due to the collectivity of the low-lying 2^+ states in ^{60}Ni and ^{62}Ni and because of the strong Coulomb field (PRISMA is placed at a forward angle and the trajectories that correspond to those angles are predominantly Coulomb trajectories), a possible mechanism for the excitation of those states is a Coulomb excitation of the 2^+ state in the entrance channel followed by the transfer or the process where the transfer takes place before the Coulomb excitation. If this is the case, part of this strength should be ascribed to the ground-state to ground-state transition.

As mentioned above to have a reasonable fit of the TKEL spectra we included a high-energy transition at 2.34 MeV; this value corresponds to the 4^+ state in ^{62}Ni but from the spectra itself and from the detected γ transitions we do not have evidence for this assignment. We like to quote this 4^+ state solely from the fact that the transfer reaction mechanism tends to favor the excitation of states with large angular momentum transfer. This excitation is also favored by the more complicated mechanism quoted above due to the collectivity of the 2^+ state of the two nickel partners of the reaction.

In the present measurement we obtained an angular distribution in the range $\theta_{\rm lab} = 65°$-$75°$; thus following the usual procedure we could extract from this angular distribution the transfer probabilities P_{tr} for the $1n$ and $2n$ channels. These are shown (open symbols) in Fig. 4 in comparison with the data of Ref. [11], which reveals a consistent matching of the two experiments.

Our results on the population of the 2^+ state in ^{62}Ni are supported also by other experiments; in fact the population of the different states in the same nucleus was studied via two-neutron transfer by employing (t,p) and (p,t) reactions [22–24]. Here it was found that the population of the low-lying 2^+ state is much smaller than the one of the ground state (the ratio being of a factor of 10 to 3). Also the light-ion $(^{14}C,^{12}C)$ reaction was used [25] to study the same nucleus; here the population of the 2^+ state with respect to the ground state is only a factor of 2 smaller, probably indicating that with heavier projectiles the multistep mechanism (inelastic followed by transfer and vice versa) and the transfer of angular momentum play important roles in the transfer mechanism. It is worth noting that in Ref. [25] the analysis of the two-neutron transfer reactions incorporated both successive and simultaneous contributions and showed that the successive one greatly dominated the reaction.

III. CONCLUSIONS

As a follow-up of a previous study on one- and two-neutron transfer reactions at sub-barrier energies in ^{60}Ni+^{116}Sn, we performed (for the same system) a γ-particle coincidence experiment, with PRISMA coupled to the AGATA demonstrator, to estimate the fraction of total cross section going into excited states. From the experimental intensities of the γ lines we extracted, for the two-neutron transfer channel, the strength going to excited states. This turned out to be less than 24% and is compatible with the theoretical description of the transfer process that predicted a dominance of the ground-state to ground-state transition.

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