Physics Letters B 834 (2022) 137477

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Evidence of proton-proton correlations in the $^{116}$Sn $+^{60}$ Ni transfer reactions

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ARTICLE INFO

*Article history:*
Received 10 May 2022
Received in revised form 23 August 2022
Accepted 28 September 2022
Available online 30 September 2022
Editor: B. Blank

*Keywords:*
Sub-barrier transfer reactions
Proton-proton correlations
Magnetic spectrometers

ABSTRACT

One and two proton transfer channels have been measured in $^{116}$Sn+$^{60}$Ni with the magnetic spectrometer PRISMA by making an excitation function at several bombarding energies, from above to well below the Coulomb barrier. The total kinetic energy loss distributions show the predominance of quasi-elastic processes in the sub-barrier regime. The data have been compared with calculations performed with the GRAZING program, based on semiclassical formalism, and in the Distorted Wave Born Approximation (DWBA), which provided a good theoretical description of the extracted transfer probabilities for the one proton transfers. The much larger values of the experimental two proton transfers compared with those evaluated within an independent particle transfer mechanism, indicate the presence of strong proton-proton correlations. The results complement the ones of the previously analyzed one- and two-neutron transfers, providing significant new information on the subject compared to past works.



The pairing interaction is fundamental in characterizing the properties of finite quantum many body systems in the vicinity of the ground state. A very specific probe of this pairing component in the nuclear interactions, which ties up nucleons in a highly correlated state with zero angular momentum, is the two-nucleon transfer reactions. These kind of reactions link different isotopes or isotones adding or removing quanta of excitations, of vibrational character when dealing with closed shell nuclei, or of rotational character when dealing with nuclei with many particles outside closed shells [1,2].

A large amount of works have been carried out on two nucleon transfer reactions since at least four decades, but it is a fact that studies on proton transfer channels have been generally much less extensive than on neutron transfer. Well known experimental difficulties exist with both light ions (see e.g. Refs. [3,4] for the ($^3$He, $n$) reaction) and heavy ions (see e.g. Refs. [5–7] and references therein). In the latter, besides energy resolution, one faces the problem to get sufficient resolution for full mass and nuclear charge identification, especially at energies close or below the Coulomb barrier. Calculations of absolute cross sections for two-proton transfer channels generally underpredicts the experimental data, even by large factors.

With heavy ions, one can follow, in the same reaction and thus on the same footing, the transfer of single nucleons and of pairs of nucleons, for both neutrons and protons. A recently studied case is the $^{116}$Sn+$^{60}$Ni system [8,9], with closed proton and open neutron shells. We measured an excitation function in inverse kinematics [8], and an angular distribution via $\gamma$-particle coincidences [9]. The experimental transfer probabilities for one- and two-neutron transfer channels as a function of the distance of closest approach for a Coulomb trajectory were compared with microscopic calculations, which provided a consistent description of the whole set of data. The experimental two-neutron transfer probabilities, in particular, were reproduced by incorporating neutron-neutron correlations. Very recently, this study has been characterized as the nuclear analogue to the (alternating-current) Josephson effect, thus allowing a sensible determination of the nuclear Cooper pair correlation length [10,11]. This was possible because one could inspect at the behavior of the transfer probabilities over a wide range of distances of closest approach, corresponding to energies from above to well below the Coulomb barrier.

According to nuclear structure theories, the pairing interaction should be equally important for protons and for neutrons. The

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https://doi.org/10.1016/j.physletb.2022.137477

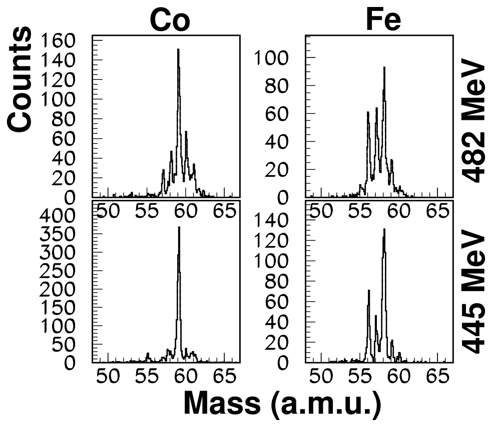


**Fig. 1.** Mass spectra of Co (one-proton stripping channels) and Fe (two-proton stripping channels) isotopes in the $^{116}Sn+^{60}Ni$ system at 482 MeV and 445 MeV.

$^{116}Sn+^{60}Ni$ system offers an appealing opportunity to investigate how the two proton transfer channel, connecting nuclei that initiate from closed proton shells, compares with the two neutron transfer channel, involving open shells configurations. For proton transfer channels the Coulomb field is strongly modified due to the charge transfer during the collision process [12]. Such a modification in the trajectories of entrance and exit channels may lead to larger energy losses than for the pure neutron transfers. What was lacking so far was a study at far sub-barrier energies, where nuclei interact at large distances and where one meets the best conditions to remain in quasi-elastic regime [6]. However, this energy regime is characterized by low transfer cross sections and faces challenging experimental conditions [13–17]. This is why, with heavy ions, almost all studies of two-nucleon transfer channels were carried out at bombarding energies higher than the Coulomb barrier [5] and under these conditions the reaction mechanism and the full understanding of the process were impaired by the interplay between Coulomb and nuclear trajectories. Here we present a new body of data on proton transfer channels, measured with unprecedented efficiency and selectivity with the advanced generation magnetic spectrometer PRISMA [18–20], which allowed to clearly identify genuine quasi-elastic processes, in particular at sub-barrier energies.

The proton transfer data have been collected in the same experiment previously carried out for neutron transfers [8]. We briefly remind that the measurement was performed in inverse kinematics by using a $^{116}Sn$ beam (≈2 pnA) onto a $^{60}Ni$ target (100 $\mu$g/cm$^2$), employing the super-conducting PIAVE-ALPI accelerator complex of LNL. We measured, by detecting Ni-like recoils in PRISMA at $\theta_{lab}$=20°, an excitation function from above to well below the Coulomb barrier (the estimated entrance channel Coulomb barrier, with the value of 157.6 MeV, is located at 12.13 fm [12]). The main characteristics of the spectrometer are the large solid angle of $\simeq$ 80 msr (corresponding to ±6°, and ±11° for the in-plane and out-of-plane angular range, respectively) and a momentum acceptance $\Delta p/p = \pm 10\%$. 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 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. More details about the experimental conditions and trajectory reconstruction can be found in Ref. [8].

Examples of mass spectra for the Co and Fe isotopes are displayed in Fig. 1. The very good mass resolution $\Delta A/A \approx 1/210$ is guaranteed by the high kinetic energy of the recoils (≈ 5 - 6 MeV/A). One sees that pure proton stripping transfer channels (the terms stripping and pick-up are referred to the light partner of the reaction) have the largest yield. The comparable yields of the pure one and two proton stripping channels, for these nuclei below the Z=28 closed proton shell, suggest the importance of proton correlations. One sees that channels involving neutron pick-up and neutron stripping are also populated, with intensities that decrease more rapidly compared to the pure proton stripping ones in moving from above to below the barrier. The mass spectra display also a strong $^{56}Fe$ peak, corresponding to the stripping of two protons and two neutrons, which stands-out at the lower (sub-barrier) energy. This observation further suggests the key role played by correlations in the transfer process. A quantitative discussion must of course take into account optimum Q-value effects and nuclear structure properties. In the following we focus on pure one- and two-proton transfer channels.

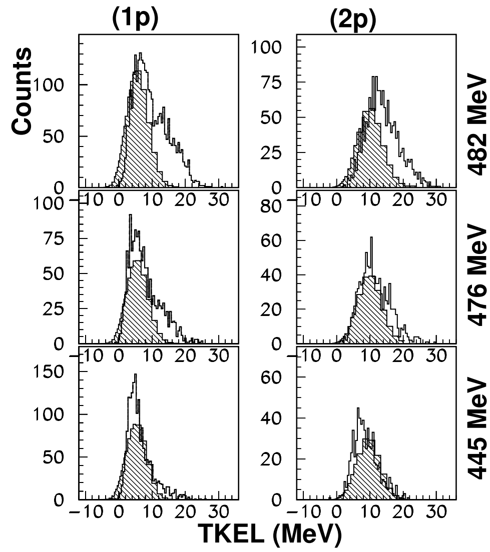


**Fig. 2.** TKEL spectra obtained for the pure one-proton stripping, $(1p)$, and pure two-proton stripping, $(2p)$, transfer channels at three representative bombarding energies, above (upper), near (middle), and below (lower) the Coulomb barrier ($E^B_{lab} = 462.2$ MeV). The results of the GRAZING code calculation are plotted as shaded histograms.

Total kinetic energy loss (TKEL) spectra were reconstructed assuming a binary reaction and imposing the conservation of momentum. The experimental energy resolution turned out to be ≈ 2 MeV and was evaluated from the entrance channel mass partition below the barrier (see Ref. [8] for details). The TKEL for the pure one- and two-proton stripping channels, i.e. $(1p)$ and $(2p)$, are displayed in Fig. 2 at selected energies. For the $(1p)$ channel one sees at the highest energy two main components. One component peaks close to the position of the ground-to-ground state $Q$-value (TKEL ≈ 5.13 MeV) and represents mainly the direct transfer. A second component, peaking at large TKEL, includes significant deep inelastic contributions. The two components overlap in the $(2p)$ channel, leading to a single broad distribution (the ground-to-ground state $Q$-value of this $(2p)$ channel corresponds to TKEL ≈ 6.13 MeV). What is very relevant for our discussion is the behavior of the distributions in going from above to below the barrier. One sees that for both channels they become more narrow, and larger energy losses tails strongly diminish.

From these findings one expects that the behavior of the transfer probabilities ($P_{tr}$) at sub barrier energies also reflects genuine quasi-elastic processes. Transfer probabilities have been then constructed, as ratio of differential cross sections of the transfer channels over the elastic. Below the barrier the angular distributions of the reaction products have almost the same shape and

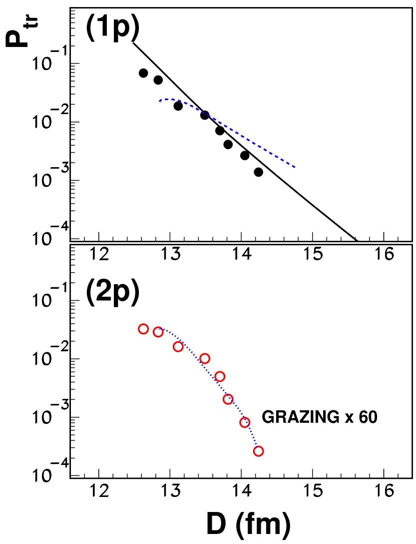


**Fig. 3.** Transfer probabilities ($P_{tr}$) as a function of the distance of closest approach ($D$) for the pure proton stripping channels. Points are the experimental data: ($1p$) (full black circles), and ($2p$) (red empty circles). The energies, in the center of the target, are 482.23, 475.53, 465.32, 452.49, 445.46, 441.81, 434.36, 428.51 MeV, corresponding to the distances of closest approach 12.657, 12.835, 13.116, 13.488, 13.701, 13.814, 14.051, and 14.243 fm. Solid lines are calculated transfer probability (see text). (Top): The blue dashed line is the result of the GRAZING code calculation, while the full black line is the DWBA calculation. (Bottom): The blue dotted line corresponds to the GRAZING calculation for the ($2p$) channel, scaled × 60.

are smoothly varying within the angular acceptance of the spectrometer. On this basis, we integrated the yield obtained in the full angular range and assigned the corresponding cross section to the one of the central angle $\theta_{\rm lab}$ = 20°. The transfer probabilities as a function of the distance of closest approach $D$ for a Coulomb trajectory are plotted in Fig. 3. It is visible that close to $D$ values around 13 fm the probabilities for the ($2p$) channel undergo a change of slope. We showed before that while for small $D$ the TKEL are affected by complex processes, for large $D$ the TKEL have a predominant character of direct transfer. This behavior of the transfer probabilities and their connection with the TKEL distributions, although apparently easy to guess a priori, could only be observed in performing a detailed excitation function.

A comparison with the experimental $P_{tr}$ has been performed by employing the GRAZING code [21,22]. In GRAZING, two ions interact via a Coulomb plus nuclear interaction and may exchange nucleons. The two nuclei are described as an ensemble of independent nucleons, the basic degrees of freedom being surface vibrations and single particle degrees of freedom. For the excitation of the surface modes the model employs the macroscopic approximation whose form factors are proportional to the $r$-derivative of the ion-ion potential and whose strength are given by the experimental $B(E\lambda)$. The model, for each transfer mode, stripping and pick-up of neutrons and protons, uses a representative form factor that is parameterized in accordance with [23], taking into account the single-particle properties of the two colliding ions. The different single-particle states that are participating to the transfer process are described by introducing average single particle level densities. The exchange of nucleons is treated independently and in the successive approximation.

The theoretical $P_{tr}$ are shown in Fig. 3. For the calculations we slightly increased (by 10%) the level density and adjusted the overall strength of the transfer form factors (via correction factors, 0.7, both for protons and neutrons). This can be justified by the fact that the GRAZING code takes into account the single-particle properties through average single particle level densities, and uses representative transfer form factors. The sensitivity of the calculated probabilities to these ingredients may be significant, especially for the proton channels and for nuclei near the closed proton shells. One has anyway to keep in mind that certain prescriptions in theory have been checked many times in the case of neutron transfers, and they have to be revisited in the case of proton transfers.

**Table 1**
Proton single particle levels and corresponding energies for $^{116}$Sn and $^{60}$Ni. Spectroscopic factors (reported in the table as SF) of a single particle level are extracted from the experimental spectroscopic factors [29] 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 2-4 MeV).

| | $nlj$ | $\epsilon_j$ [MeV] | SF |
|---|---|---|---|
| $^{116}$Sn | $1g_{7/2}$ | -3.903 | 0.8125 |
| | $2d_{5/2}$ | -3.721 | 0.7 |
| | $2d_{3/2}$ | -1.784 | 0.65 |
| | $3s_{1/2}$ | -1.606 | 0.6 |
| | $1h_{11/2}$ | -1.367 | 0.52 |
| $^{60}$Ni | $1d_{3/2}$ | -14.222 | 0.75 |
| | $2s_{1/2}$ | -14.186 | 0.83 |
| | $1f_{7/2}$ | -9.018 | 0.825 |

Calculations for the ($1p$) channel have been also carried out in the distorted wave Born approximation (DWBA) by using for the wave functions of relative motion their CWKB form as in Ref. [24]. We employed for the real part of the potential, the Woods Saxon parameterization of Ref. [12] ($V_0$ = − 82.6 MeV, $R_0$ = 1.18 fm, a = 0.687 fm). For the imaginary part we calculated it microscopically [25–27] in order to be compatible with the form factors used for the one-particle transfer. The inclusive cross section was obtained by summing up all the contributions coming from the single particle transitions. In Table 1, 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 $^{59}$Co. 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 Ref. [28] and by weighting each transition with the corresponding experimental spectroscopic factor (see Table 1 and Ref. [29]). The computed transfer probabilities are shown in Fig. 3 (full black line in top panel). The good description of the one-proton channel, indicates the correctness of the chosen set of single particle levels and the employed one-particle matrix elements.

The understanding of the behavior of the one proton transfers authorizes us to approach the much more complex two proton transfer process. Calculations of the transfer probabilities for the ($2p$) channel were performed with GRAZING. The results are shown in the bottom panel of Fig. 3. One sees how theory follows the energy dependence of the experimental $P_{tr}$. On the other hand, the theoretical probabilities had to be scaled up by almost two orders of magnitude to match the absolute values of the data.

It is important to assess the kind of agreement reached between the experimental and GRAZING calculated TKEL. We remind that these TKEL distributions are governed by the reaction dynamics, the masses and charges of colliding nuclei, mass and charge of the transferred particle, the bombarding energy and the transferred momentum and all these observables have to be included in any reaction code. The use of the semiclassical theory is well suited for this purpose and is well justified for our heavy-ion system since the wave length associated with the relative motion is much smaller than the interaction region. The requirement that the trajectory of entrance and exit channels matches smoothly defines the optimum $Q$-value ($Q_{\rm opt}$), where the transition probability has a maximum. The results are shown in Fig. 2. One sees how the

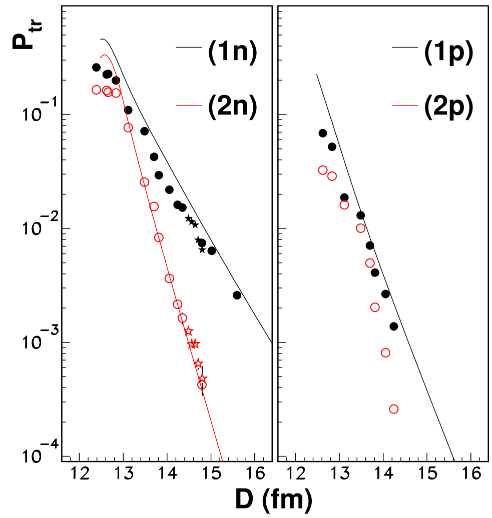


**Fig. 4.** Transfer probabilities ($P_{tr}$) as a function of the distance of closest approach ($D$) for the one- and two-neutron (as published in Refs. [8,9]), and one- and two-proton transfer channels. Solid lines are calculated transfer probabilities (see text).

experimental TKEL are well reproduced, especially at the lowest energy, implying that the transfer process is correctly treated as a direct one.

In our system, with closed proton and open neutron shells, the two-nucleon transfer reactions connect $0^+$ states organized in vibrational/rotational bands, and a selective population of such $0^+$ states is expected [1,5,12]. For the calculations of the two-neutron transfer channel we treated the ground to ground state transition in the successive approximation [8]. For $^{62}$Ni we used the reported spectroscopic factors while for $^{116}$Sn we calculated the ground states via a BCS approximation. In Fig. 4 we report the experimental and calculated transfer probabilities for both neutrons and protons. For one- and two-neutron and one-proton transfer, the energy dependence of the probabilities is well reproduced by calculations, following the trend predicted by the binding energies. For the two-proton transfer, we have to consider the effect of the $Q$-value window. This window is very different for neutrons and protons, for neutrons it is centered at $Q = 0$ and it is quite narrow (ground states transitions are favored), for protons it is centered at larger $Q$ and is wider (let's remind that the optimum $Q$-value is, for protons, dominated by the Coulomb interaction, this is very different between entrance and exit channel). The optimum $Q$-value window for protons, implies that excited $0^+$ states or states with larger angular momentum generated by higher order correlations may play a significant role. The effect of correlations in the wave function of the transferred nucleons includes not only the one induced by the pairing interaction (in the $0^+$ states) but also the one induced by a generic residual interaction that correlate states of larger angular momentum.

For the neutron transfer, the knowledge about the underlying structure of the $0^+$ states was mostly acquired through two-nucleon transfer reactions, with many systematic studies carried out via $(p, t)$ and $(t, p)$ reactions [2,30]. Such systematic studies for two-proton transfer reactions are rather limited. In particular, for $^{58}$Fe and $^{118}$Te, which correspond to two-proton removal from $^{60}$Ni and two-proton addition to $^{116}$Sn, respectively, the cross sections and spectroscopic information of such $0^+$ states are not well established [2,29,31]. For the closed $Z = 50$ proton shell, a first excited $0^+$ state at 1.7 MeV has been recognized as proton pairing vibrational excitations. While for $Z = 28$ isotones, the $0^+$ excited states at 2.3 and 3.3 MeV may be possible candidates. We have to keep in mind that while in the case of open neutron shells the collective aspects are important, for closed proton shells the underlying structure of single-particle levels contributes more significantly to the absolute cross sections. The experimental TKEL spectra of the $(2p)$ channel (see Fig. 2), with only the quasi-elastic component at sub-barrier energies, few MeV wide, are compatible with the population of the excited $0^+$ states, as well as states with larger angular momentum, and their mutual excitation. To inquire about the character of the pertinent states, considerable more information is needed on the components of proton configuration.

The here presented proton-transfer data, measured over a wide range of distances of closest approach, from above to well below the Coulomb barrier, represent a significant step forward compared to past works, where studies were limited to close barrier energies only. Our findings could only be achieved by inspecting at the behavior of the TKEL and transfer probabilities on the same footing. The good agreement between the measured and calculated TKEL, in particular at large distances, indicates that the transfer is correctly treated as a direct process. On the other hand, the calculated absolute value of the two-proton transfer probability, obtained by considering solely an independent nucleon transfer, strongly underpredicts the experimental data, evidencing the presence of strong proton-proton correlations. How these correlations can account for the missing cross sections is an issue.

In general, the microscopic treatment of two proton transfers in heavy ion reactions is still a challenge. The proton single-particle level density and the corresponding single-particle form factors are much less known than the ones for neutrons. Much more quality data on proton transfer on different systems need to be collected, most of all at sub-barrier energies. These kind of studies will become soon feasible by the coupling of the PRISMA spectrometer to the large gamma array AGATA [32].

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

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 (https://cordis.europa.eu/project/id/262010). This work has been supported in part by the Croatian Science Foundation under Project no. 7194 and in part under Project no. IP-2018-01-1257.

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