The quest for Cooper pair transfer in heavy-ion reactions: the ^{206}Pb+^{118}Sn case

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(Dated: September 3, 2024)

In this letter we report on effects of nucleon-nucleon correlations probed in nucleon transfer reactions with heavy ions. We measured with high efficiency and resolution a complete set of observables for neutron transfer channels in the ^{206}Pb+^{118}Sn system employing a large solid angle magnetic spectrometer, which allowed to study a wide range of internuclear distances via a detailed excitation function. The coupled channel theory, based on an independent particle transfer mechanism, follows the experimental transfer probabilities for one- and two-neutron pick-up and stripping channels. The experimental two-neutron transfer cross sections indicate that in reactions between pair-vibrational (closed shell) and pair-rotational (open shell) nuclei, correlations manifest via pair-addition and pair-removal modes, which constitute one of the elementary modes of excitations in nuclei.

The pairing interaction is responsible for the formation of Cooper pairs, i.e. for the correlation of fermions moving in time reversed states, and plays a fundamental role for a variety of quantum mechanical systems [1–5]. In the nuclear case, pairing leads to the modification of the level densities near the ground states, the odd-even staggering of nuclear masses and the deviation of the moment of inertia from the rigid-body values [6–8]. These manifestations of pairing can be probed in transfer reactions [9–15]. Transfer reactions with heavy ions offer unique possibilities since a large number of nucleons may form pairs. Such reactions are governed by the dynamics of the nuclear surfaces, which strongly depends on the internuclear distance, and only those pairs close to the surfaces act in the transfer process. Within the very short interaction time ($\sim 10^{-21}$-10^{-22} seconds), few nucleons can be transferred, yet even one single pair can lead to remarkable effects, as observed in enhanced transfer cross sections due to the effect of correlations [9, 11].

The correlations involve the structure of both interacting partners and the reaction mechanism is dominated by the long range Coulomb interaction which acts very early in the scattering process and thus may strongly compete with the transfer channel. To take into account the competing reaction channels [16, 17] theories need to be compared with data in a wide range of internuclear distances, from above to below the Coulomb barrier. Experimentally one has to collect high resolution data [18, 19] well below the barrier, where nuclei interact at very large distances and where the distortion of the Coulomb elastic waves by the nuclear attraction may easily be accounted for. The low energy region is however also characterized by low transfer cross sections and to preserve both high resolution and detection efficiency is very difficult [20–24]. This is why data were taken mostly close to the Coulomb barrier [11]. A major breakthrough happened with the advent of large solid angle magnetic spectrometers [25–27] whose capabilities to fully identify the reaction products made these experiments feasible [28, 29]. This was due to the innovative way of developing and applying to low energy heavy-ion reactions the concepts of trajectory reconstruction.

In the ^{116}Sn+^{60}Ni system [30–32] the experimental transfer probabilities for one- and two-neutron transfer channels (P_{1n} and P_{2n}, respectively), measured via excitation functions and angular distributions, were compared with microscopic calculations [33], which provided a consistent description of the whole set of data. The experimental two-neutron transfer probabilities, in particular, were reproduced for the first time by incorporating neutron-neutron correlations. In few high resolution experiments carried out so far in reactions with ground-state Q values for neutron transfers close to the

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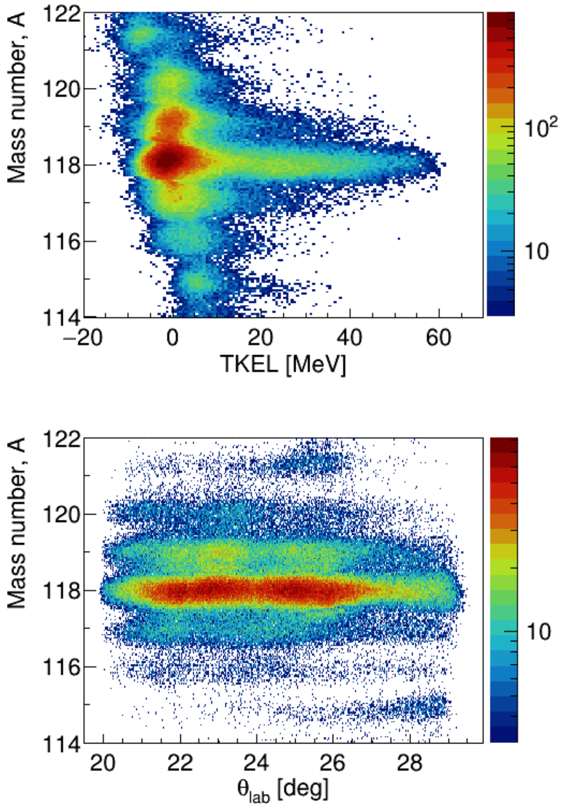

FIG. 1: (Color online): Mass vs TKEL (top panel) and mass vs scattering angle (bottom panel) for Sn isotopes detected in the ^{206}Pb+^{118}Sn reaction at $E_{\rm lab}$ = 1090 MeV and at $\theta_{\rm lab}$=25°. A repetitive pattern of the overwhelming elastic peak may generate some degree of overlap for near-by masses. We estimated that the possible over-counting of yields of the ($\pm 2n$) channels is at most ∼20%.

optimum ($Q_{\rm opt}$ ∼ 0), large enhancement was found for the (neutron) open shell ^{120}Sn+^{112}Sn [34], but almost no enhancement was needed for the (neutron) closed shell ^{144}Sm+^{208}Pb [35]. The presently studied ^{206}Pb+^{118}Sn system represents a key case since it involves nuclei with open and closed shells and thus may shed light on the effect of pair correlations. The optimum Q values [36] for this reaction are suitable for observing both neutron pick-up and stripping (the terms pick-up and stripping are conventionally referred to the lighter partner of the reaction), thus giving the compelling opportunity to measure at the same time the addition and removal of pairs of neutrons from lead and tin isotopes. These channels correspond to pair vibrations (closed-shell nuclei like Pb) and pair rotations (nuclei with many particles outside closed shells like Sn) [4, 5, 9], which, together with surface vibrations and single-particle excitations, constitute the elementary modes of excitations in nuclei [37].

Transfer channels have been measured in a wide range of bombarding energies, from close to far distant collisions. The experimental conditions needed to perform such a measurement with heavy systems required to get the highest mass, nuclear charge and energy resolutions achievable within the present detector technology. A ^{206}Pb beam was accelerated at E$_{\rm lab}$=1200, 1090 and 1035 MeV with an average current of ∼2 pnA employing the PIAVE-ALPI accelerator complex of LNL. A 200 μg/cm^2 ^{118}Sn target, with an isotopic purity of 99.6%, was used. We detected target-like fragments in PRISMA [29], placed at $\theta_{\rm lab}$=25°, with a further measurement at 35° for the highest energy only. Selected results for this highest measured energy have been reported in Ref. [38]. The nuclear charge was identified via energy-loss and total-energy provided by the ionization chamber at the focal plane. The large momentum acceptance of the spectrometer ($\Delta p/p = \pm 10\%$) allowed to accommodate most of the atomic charge states with a single setting of the magnetic fields. The mass identification was achieved via trajectory reconstruction of the ions inside the magnetic elements of the spectrometer [29], a quadrupole followed by a dipole. It was based on the position information at the entrance [39] and at the focal plane [40] together with the time-of-flight between them (see Refs. [38, 41–43] and references therein).

To show the achieved mass resolution, we plot in Fig. 1 examples of the mass versus Total Kinetic Energy Loss (TKEL) (top panel) and mass versus scattering angle (bottom panel) for Sn isotopes. The TKEL is reconstructed assuming a binary reaction and imposing the conservation of momentum. The quality of the mass distribution can be better appreciated in the bottom matrix, where the straight bands illustrate the correct trajectory reconstruction. One sees clearly the presence of the elastic+inelastic and both neutron pick-up and stripping channels. The TKEL distributions are very narrow, typical of scattering at sub-barrier energies, and with most of the events close to the ground-to-ground-state transitions. To illustrate these last features we display in Fig. 2 the TKEL spectra for the quasielastic, one- and two-neutron pick-up and stripping channels at the two lowest measured bombarding energies. The TKEL are shown together with calculations performed with the GRAZING code [44, 45]. The experimental energy resolution, taking into account trajectory reconstruction, detectors and target effects, was estimated to be ∼ 4-5 MeV. In the spectra one sees that the main transfer flux is near the optimum Q values for all neutron transfer channels, with the distributions much narrower than the ones measured at the highest energy [38]. Tails reflecting large energy loss components are still visible in the spectra, though they did not affect significantly the evaluation of the (by far dominant) quasielastic components. Cuts in TKEL have been made [38], to ensure that the extracted cross sections reflect quasielastic reaction processes. GRAZING well describes the experimental TKEL spectra, indicating the correct inclusion of the range of partial waves involved in the reaction. Possible slight shifts between experimental and calculated TKEL can be attributed to the fact that GRAZING uses an average level density and keeps only one average Q-value for neutron pick-up and

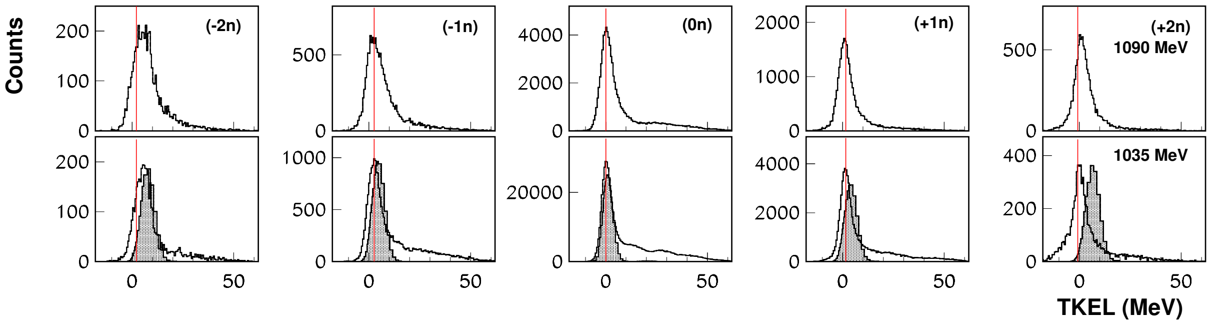

FIG. 2: (Color online): TKEL spectra obtained for the quasielastic and one- and two-neutron pick-up and stripping transfer channels at the two measured bombarding energies. The vertical lines correspond to the position of the ground state Q values: $Q_{gs}^{(-2n)}= -\ 2.17$ MeV, $Q_{gs}^{(-1n)}= -\ 2.59$ MeV, $Q_{gs}^{(+1n)}= -\ 1.60$ MeV, $Q_{gs}^{(+2n)}= +\ 0.77$ MeV. The results of the GRAZING code calculation are plotted as shaded histograms.

stripping channels. The results presented here are important as they probe large internuclear distances where data on heavy systems are extremely scarce.

In these low energy collisions (large internuclear distances) the transfer cross section is small compared to the elastic and can be treated as perturbation (like DWBA [46]). The representation of the transfer probability P_{tr}, defined as ratio of the transfer yield over the elastic+inelastic (entrance channel mass partition), as function of the distance of closest approach for a Coulomb trajectory D, is very convenient. This representation allows to merge results extracted from excitation functions at fixed angles and angular distributions at fixed bombarding energy, provided that one remains in the quasielastic regime. From the experimental point of view the construction of the transfer probabilities as ratios of yields, for channels having similar masses, nuclear charges and kinetic energies, minimizes the effect of the spectrometer transmission [41, 42]. In Fig. 3 we show the extracted transfer probabilities plotted as a function of distance of the closest approach. Since the form factor for transfer decays exponentially, the quasielastic transfer probabilities as a function of D follow, in a (semi-logarithmic) plot, straight lines with a slope related to the binding energy of the transferred nucleon [11, 18, 47]. The slope of the two-neutron transfer probability should then be twice that of the one-neutron one. As seen from the figure this is clearly the case both for the stripping and pick-up reactions.

We performed an analysis of the reaction with the GRAZING code [44, 45]. GRAZING is a semi-classical coupled-channel code that describes the evolution of the reaction by employing the well known form factors (matrix elements) for the inelastic excitation of the surface modes, of target and projectile, and the form factors for the single-particle exchange of neutron and protons. These single-particle form factors are constructed from the known single-particle levels of projectile and target. In this model the multinucleon transfer is calculated by assuming that the exchange proceeds via a successive mechanism. The results of such a calculation are shown, with straight lines, in Fig. 3. As it is apparent, the model well follows the transfer for both the pick-up and stripping channels in the whole measured D range.

We feel important to show how the GRAZING model describes other aspects of the reaction. In Fig. 4 we show the elastic+inelastic over Rutherford cross section ratio plotted as a function of distance of the closest approach. The model reproduces quite well this ratio over several orders of magnitude, in particular the drop well beyond the quarter point [46]. This is very important, as GRAZING calculates the evolution of the reaction without the use of any imaginary potential. The depopulation of the entrance channel is created by the reactions that exchange nucleons between projectile and target and is indeed well followed by the model. We here recall that the model describes the relative motion of the two ions by employing a nuclear plus Coulomb potential, with the empirical potential of Ref. [12] as nuclear part, which well reproduces the elastic scattering of many target and projectile combinations.

Looking into more detail at Fig. 3, one sees how the experimental probabilities for the one-neutron transfers are well reproduced by the theory. Although noteworthy, the achieved agreement may not be so surprising, since these channels constitute the building blocks of the model, i.e. the model is constructed to describe these channels correctly. On the other hand the experimental probabilities for the two neutron transfers are slightly underpredicted (by a factor ≤ 2). Since GRAZING incorporates an independent particle transfer mechanism only, this difference provides a measure of the effect of two-particle correlations in the presence of nuclei that are closed shells. While keeping in mind the inclusive character of our reaction, we remind that the pairing interaction allowed to correlate spectra of neighboring even-even nuclei [37]. Of key relevance was the determination of the matrix elements connecting pair addition and pair removal. Tin

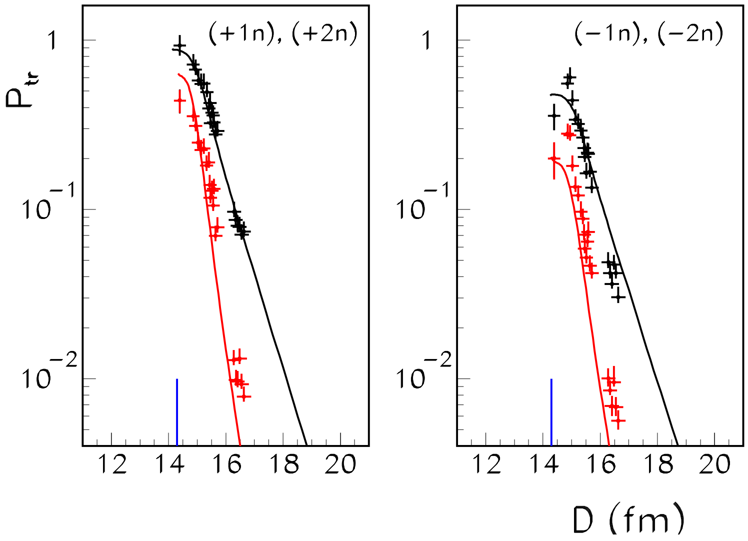

FIG. 3: (Color online): Experimental (points) and calculated (lines) transfer probabilities for the one- and two-neutron pick-up (left) and stripping (right) plotted as a function of the distance of closest approach D. The probabilities have been obtained by dividing the transfer cross sections by the elastic(+inelastic) (entrance channel mass partition) cross sections. The points have been obtained by binning, for each measured energy, the PRISMA angular acceptance in steps of $\Delta\theta \sim 1°$. At the smallest measured D, corresponding to the highest measured energy and angles forward than the grazing, we plotted the value corresponding to the central angle only. Experimental errors incorporate the indetermination of the beam energy (horizontal bars) and the contribution of the detector resolution, trajectory reconstruction and tail in the mass spectra due to the overwhelming elastic channel (vertical bars). Calculations have been performed with the GRAZING code. The vertical blue line corresponds to the calculated radius of the Coulomb barrier (14.3 fm) [12].

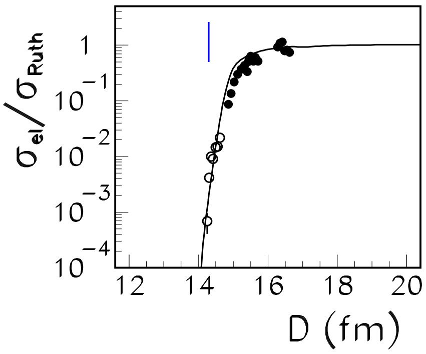

FIG. 4: (Color online): Experimental (points) and calculated (line) elastic(+inelastic) ($\sigma_{\rm el}$) over Rutherford ($\sigma_{\rm Ruth}$) cross sections. At the smallest measured D, corresponding to the highest measured energy and angles forward than the grazing, we plotted the full angular distribution (empty circles). Data include statistical errors only. Calculations have been performed with the GRAZING code at $E_{\rm cm}$ = 430.5 MeV. The vertical blue line, as in Fig. 3, corresponds to 14.3 fm.

and lead nuclei have been previously studied via (t,p) or (p,t) reactions [9, 10] in order to elucidate the role of the pairing correlations. In the vicinity of the shell closure, the pairing correlations manifest via vibrational structure, here one talks about pair vibrations, in contrast to the pair rotations encountered in the middle of the shell. The pairing vibration model predicts that the ratio of the cross sections for the population of the different ground states is proper of an harmonic situation, with the strengths proportional to the number of phonons in the final state. For the present reaction, where both neutron pick-up ($+2n$) and stripping ($-2n$) channels are available, the ratio of the strength for the addition and removal of two neutrons has been extracted by linear fits of the transfer probabilities as function of D. The slopes of the fitted lines (defined by the neutron binding energies) are almost the same for the two channels, so this procedure ensured that the obtained values are independent on D. The ratio turns out to mirror the one of the (p,t) and (t,p) reactions leading to ^{204}Pb and ^{208}Pb ground states, respectively (see Fig. 6-62 in Ref. [5] with the ratio of 1.7). We can argue that, since ^{118}Sn is a member of the pair rotational band [9], with the transfer strength of the addition and removal of two neutrons being quite isotope independent, its effect on the ratio of cross sections may elide to a large extent. The obtained value indicates that in our reaction most of the two-neutron transfer cross sections are concentrated in ground states (see also the narrow peaks in the TKEL spectra shown in Fig. 2). These facts illustrates how the Pb partner, which governs the size of the cross sections, manifests its vibrational structure and pair vibration character [37].

The obtained results evidence the fundamental role played by the nuclear surfaces in the transfer mechanism. The study at different internuclear distances probes the behaviour of the main observables, the transfer probabilities and total kinetic energy loss (see Ref. [48] and references therein). This is particularly important for heavy systems, which, due to the high Coulomb field, do not develop a barrier and consequently a pocket, which defines the region where strong absorption takes place. The measurement in a wide D range allowed to follow and thus to control the transition from the large to the small D regions, dominated by quasielastic and absorptive processes, respectively. The intermediate D region, where the possible effects due to correlations and absorption mix up, is also where a concept has been developed to link neutron transfer reactions with Cooper pair tunneling [49, 50] and the formation of a Josephson junction [51, 52]. Our results indicate that, to approach these studies, a proper selection of the bombarding energies and consequently the internuclear distances is mandatory. Absorptive effects may start to be significant also at large D, where nuclei with extended neutron distributions [53–56] may be exploited to measure the density dependence of the pairing interaction [57].

We measured multinucleon transfer reactions for the ^{206}Pb+^{118}Sn system in a wide range of bombarding energies by employing the large solid angle magnetic spectrometer PRISMA. The experimental transfer probabilities for elastic+inelastic, one- and two-neutron pick-up and stripping channels have been extracted and compared with the GRAZING code. It is remarkable that theory is able to describe at the same time all relevant channels. A slight underprediction of the experimental two neutron transfer probabilities can accommodate the contribution of the transfer of correlated neutrons. This is also seen in the ratio of the two-neutron stripping and pick-up cross sections, which mirrors the one extracted in light-ion induced reactions, manifesting, even in heavy-ion reactions, the pair vibration character of Pb.

Acknowledgements

We are grateful to the whole Legnaro National Laboratories accelerator group for providing the high-quality ^{206}Pb beam exploiting the highest performance of the PIAVE - ALPI accelerator complex. We are also grateful to the Legnaro National Laboratories target laboratory for making high-quality targets. This work was partly supported by the ENSAR2 Grant Agreement nb. 654002, and by the Croatian Science Foundation project no. IP-2018-01-1257, and in part by the Center of Excellence for Advanced Materials and Sensing Devices (Grant No. KK.01.1.1.01.0001). M. Siciliano is supported by U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under the Contract No. DE-AC02-06CH11357. This work was also partly supported by the National Science Centre, Poland (NCN) (grant no. 2020/39/D/ST2/00466).

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