Nucleon-nucleon correlations probed in sub-barrier transfer reactions and the nuclear Josephson effect

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Abstract.
In recent years a series of near- and sub-barrier transfer experiments have been carried out at LNL, with reaction products detected in inverse kinematics and at forward angles with the large solid angle magnetic spectrometer PRISMA. Nucleon-nucleon correlation properties have been studied by measuring transfer cross sections far below the Coulomb barrier, making excitation functions down to very low energies and corresponding to very large distances of closest approach where the nuclear absorption is small. Such kind of studies are of general interest since one probes the tails of the density distributions. One subtle case is the possible manifestation of a nuclear Josephson effect. Predictions have been made of a specific gamma strength function associated with the dipole oscillations generated by the, mainly successive, two neutron transfer process. The coupling of PRISMA to the AGATA gamma array, recently installed at LNL, offered a unique opportunity to study such an effect. In a very recent experiment we directly tested for the first time the possible manifestation of Cooper pair oscillations, observed to date only in condensed matter physics.

1 Introduction

Two-particle transfer reactions are the specific tools to investigate in nuclei the effects of particle-particle correlations induced by the pairing interaction. These effects are observed, among other things, in the lowering of the level density near the ground state for even-even systems, and, far from closed shells, in the modification of the ground state, with the paired nucleons spread over several single particle states around the Fermi surface (see e.g. [1–5] and Refs. therein). These features can be investigated nowadays with instrumentation of unprecedented sensitivity. The coming into operation of large acceptance magnetic spectrometers made it possible to perform measurements on multinucleon transfer reactions [6, 7] with good ion identification also at very low bombarding energies, where one meets the most suitable conditions to study pair correlations with two-nucleon transfer processes. At energies below the Coulomb barrier nuclei interact at very large distances, so that the distortion of the elastic Coulomb waves by the nuclear attraction is very small and may easily be accounted for. The study of binary collisions at low bombarding energies and thus at far internuclear distances is of general interest since one probes the tails of the density distributions. This is particularly important for nuclei with extended neutron distributions [8] or for halo nuclei [9], where absorptive effects [10, 11] may be significant also at large distances.

We already successfully demonstrated the powerful method of using PRISMA [6, 7, 12–14] for such studies, exploiting its unique performance in terms of both resolution and efficiency. Making use of inverse kinematics, target recoils have been detected in multinucleon transfer reactions for the systems ^{96}Zr+^{40}Ca [15], ^{116}Sn+^{60}Ni [16, 17], ^{92}Mo+^{54}Fe [18], ^{197}Au+^{130}Te [19] and ^{206}Pb+^{118}Sn [20], spanning up to four orders of magnitudes in cross sections. The main results for the ^{116}Sn+^{60}Ni system are visible when comparing the experimental transfer probability (P_{tr}) for one- and two-neutron transfer channels with microscopic calculations. In this system (superfluid nuclei) [16] the ground-to-ground-state Q values for one- and two-neutron transfer are very close to optimum ($Q_{opt} \sim 0$), representing a beautiful Q-value matched case. One sees that the employed microscopic theory accurately reproduces the experimental data in the whole energy range, in particular the transfer probability for two neutrons, both in magnitude and slope, by solely considering the ground to ground state transition. The nice agreement between data and calculations indicates that the two-neutron transfer channel in this system essentially populates only the ground state, consistently with the particle-gamma coincidence measurements performed in a second experiment [21], using PRISMA coupled to the AGATA [22] Demonstrator.

With the coupling of AGATA to the PRISMA spectrometer we could gain almost two orders of magnitude in yields compared to the previous γ-particle measurement, thus probing in more detail the role pairing correlations play in the transfer process. This offers a unique opportunity to study a nuclear (alternating current (AC)) Josephson-like effect (JE) [23, 24], with Cooper-pair tunnelling between superfluid nuclei, whose manifestation

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has been recently proposed [25, 26] using our data as a stepping stone. Predictions have been made of specific gamma strength functions associated with the dipole oscillations generated by the, mainly successive, two neutron transfer process, and the possibility opens up to directly test in nuclear physics, one of the most important effects of Cooper pair behaviour, observed to date only in condensed matter physics [27, 28].

In the first part of this contribution I will review some of the main results obtained in our studies on neutron-neutron and proton-proton correlation performed in heavy ion reactions at sub-barrier energies. In the second part I will discuss the importance of the ^{60}Ni+^{116}Sn system in connection with the possible manifestation of a nuclear Josephson effect, and present very preliminary results of a related experiment using PRISMA coupled to the AGATA γ array.

2 Recent results on nucleon-nucleon correlation studies with PRISMA

2.1 Neutron-neutron correlations

In recent years neutron-neutron correlations were investigated in the closed-shell ^{40}Ca+^{96}Zr [15] and superfluid ^{60}Ni+^{116}Sn [16] systems from above to below the Coulomb barrier. The data were represented via the transfer probability (P_{tr}), defined as the ratio of the transfer yield over the quasi-elastic one, plotted as a function of the distance of closest approach (D). This representation is very convenient since it allows to merge results extracted from excitation functions at fixed angles and angular distributions at fixed bombarding energy, provided that one remains in the quasi-elastic regime. The use of the large-acceptance spectrometer PRISMA, combined with the inverse kinematics condition, allowed one to measure P_{tr} down to very large values of D, sufficiently far from the nuclear absorption region.

In both cases data have been compared with a microscopic theory [29–31]. For the inclusive one-neutron transfer cross section one calculated the transfer probability for a given single particle transition and one obtained the total transfer probability by summing over all possible transitions that can be constructed from the single particle states in projectile and target. For the two-particle transfer I just mention that one diagonalized the total Hamiltonian with a model space containing only two-particle configuration coupled to 0^+ (i.e. transfer of a J=0^+ pair). Calculations well reproduce the experimental slope as well as the absolute values of the transfer probabilities for the one neutron channel. For the two-neutron channel the data of ^{40}Ca+^{96}Zr were largely underpredicted, indicating the need to take into account states with higher multipolarities and/or more complex two-particle correlations. As seen in Table 1 the ground-to-ground-state Q values ($Q_{g.s.}$) for the two-neutron transfer strongly differs from the optimum Q-value (close to $\sim$ 0 MeV) and therefore the ground state transition does not contribute to the total transfer strength in agreement with what was experimentally observed in the Q values spectra [15].

Table 1. Ground to ground state Q values (in MeV) for up to four neutron pick-up transfer channel for the systems discussed in the present report.

Channel	1n	2n	3n	4n
^{40}Ca+^{96}Zr	+0.51	+5.53	+5.24	+9.64
^{60}Ni+^{116}Sn	-1.74	+1.31	-2.15	-0.24
^{118}Sn+^{206}Pb	-1.60	+0.77	-1.45	+0.44

A different situation occurs in the well Q-value matched system ^{60}Ni+^{116}Sn, with the $Q_{g.s.}$ for one- and two-neutron transfers very close to the optimum. Here the microscopically calculated transfer probabilities could well reproduce the experimental ones in absolute value and slope for both the (1n) and (2n) channels (we refer to Ref. [16] for details). I wish to emphasize that to calculate the (2n) channel one has to solve the well-known system of semiclassical coupled equations up to second-order Born approximation, whose amplitude consists of the simultaneous transfer of the pair of nucleons, which cancels out with the nonorthogonality term, and the term which represents the successive process via an intermediate channel. The ground states have been described in the BCS approximation with a standard state-independent pairing force. The nice agreement between data and calculations indicates that the two-neutron transfer channel in this system is populating essentially only the ground state, in agreement with the experimental total kinetic-energy loss distributions and consistently with particle-γ measurements [21] which provided an upper limit of 24 % for the possible excited state population.

An interesting and almost unexplored issue is whether and to what extent the effect of nucleon-nucleon correlations in the evolution of the reaction is modified in collisions amongst very heavy ions. In fact in these cases the population of final states with high excitation and angular momenta and/or multistep processes may significantly change the transfer strength of the ground-to-ground-state transitions. We recently studied the ^{118}Sn+^{206}Pb system [20], which is the heaviest (asymmetric) semi-magic combination with closed proton shells and open neutron shells, where the $Q_{g.s.}$ for neutron transfer are very close to the optimum, as seen in Table 1. Measurements have been performed in a wide range of internuclear distances and first results have been reported in a contribution to this proceedings [32], which I refer for details.

2.2 Proton-proton correlations

It is a fact that studies on proton transfer channels have been much less extensive than on neutron transfer. Calculations of absolute cross sections for two-proton transfer channels generally underpredicts the experimental data, even by large factors [33–35]. For proton transfer channels the Coulomb field is strongly modified due to the charge transfer during the collision process [2]. 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

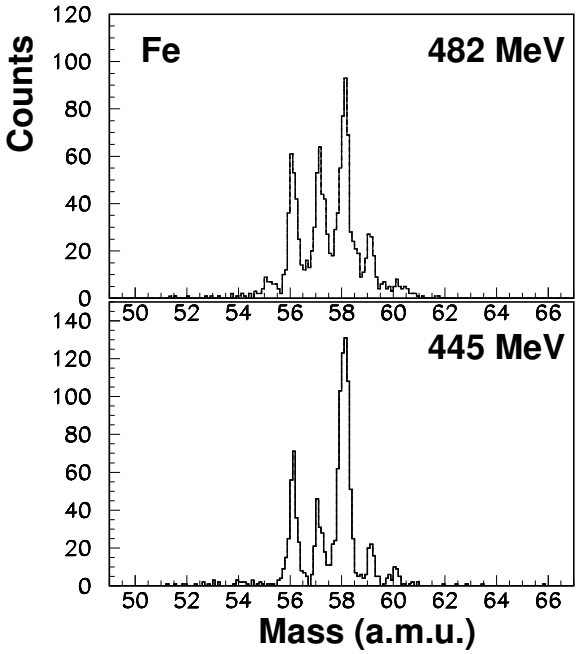

Figure 1. Mass spectra of Fe (two-proton stripping channels) isotopes in the ^{116}Sn+^{60}Ni system at 482 MeV and 445 MeV.

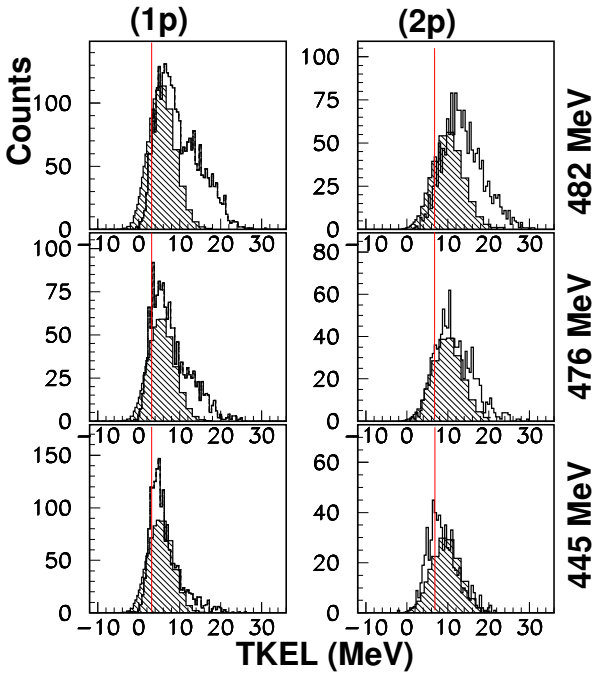

Figure 2. TKEL spectra obtained for the pure one-proton stripping, $(1p)$, and pure two-proton stripping, $(2p)$, transfer channels at three representative bombarding energies, above (upper), near (middle), and below (lower) the Coulomb barrier ($E^B_{\rm lab}$ = 462.2 MeV). The results of the GRAZING code calculation are plotted as shaded histograms. The vertical red lines represent the ground-to-ground-state Q-values.

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 [36–39]. 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 [40].

The ^{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. The proton transfer data [17] have been collected in the same experiment previously carried out for neutron transfers [16]. We observed 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. Examples of mass spectra for the Fe isotopes are displayed in Fig. 1. The mass spectra display, in particular, 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.

Total kinetic energy loss (TKEL) spectra were reconstructed assuming a binary reaction and imposing the conservation of momentum. 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 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 $\approx$ 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. The transfer probabilities as a function of the distance of closest approach D for a Coulomb trajectory are plotted in Fig. 3. The experimental and calculated transfer probabilities are reported for both neutrons and protons. For one- and two-neutron and one-proton transfer, the energy dependence of the probabilities are well reproduced by calculations, following the trend predicted by the binding energies. Calculations for the $(1p)$ channel have been carried out in the distorted wave Born approximation (DWBA) by using for the wave functions of relative motion their CWKB form as in Ref. [41]. The agreement with data indicates the cor-

rectness of the chosen set of single particle levels and the employed one-particle matrix elements.

Calculations of the transfer probabilities for the $(2p)$ channel were performed with the GRAZING [42, 43] code, where the exchange of nucleons is treated independently and in the successive approximation. 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.

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, 2, 40]. For the calculations of the two-neutron transfer channel we treated the ground-to-ground-state transition in the successive approximation [16]. For Ni we used the reported spectroscopic factors [44] while for Sn we calculated the ground states via a BCS approximation.

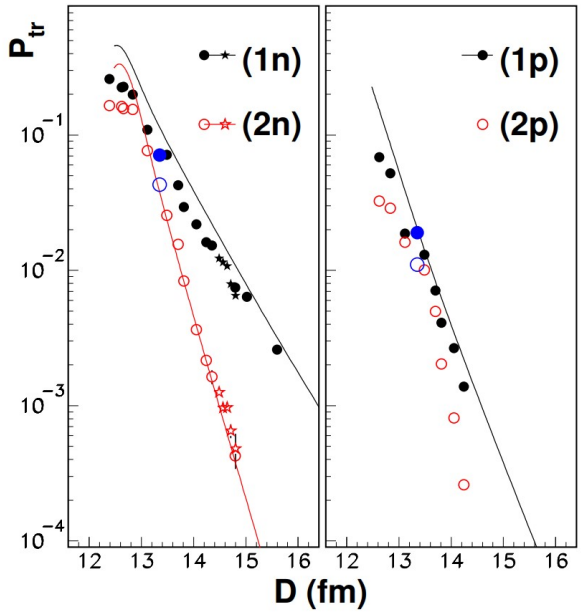

Figure 3. (Color online): Transfer probabilities (P_{tr}) as a function of the distance of closest approach (D) for the one- and two-neutron (Refs. [16, 21]), and one- and two-proton (Ref. [17]) transfer channels. Solid lines are calculated transfer probabilities (see text). The full stars near 14.5 fm are the data from Ref. [21] The blue full and empty points near 13.5 fm are the new data [53].

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.

3 The ^{60}Ni+^{116}Sn system as candidate to probe a nuclear Josephson effect

3.1 The Josephson effect: a brief recall of basic concepts

Let us consider a system made out of two superconductors weakly linked through a thin layer of an insulating material (Josephson junction). The Cooper pairs of each superconductor, described by a coherent (BCS) wavefunction, behave as quasi-bosons made out of two correlated fermions. This correlation takes place over an average distance ξ between the electron pairs, which is much larger than the thickness of the barrier (insulator). Consequently, the two electron partners of a Cooper pair continue to be correlated even if each of them is moving in a different of the two, weakly linked, superconductors. This phenomenon allows for the definition of a relative gauge phase across the Josephson junction and for the fact that in the calculation of the tunneling probability of electron pairs across the link, denoted P_2, one has to sum the phased amplitudes of each electron before taking modulus squared, the outcome being $P_2 \approx P_1$ within a proportionality factor of the order of unity. Thus, a Cooper pair direct current (DC), whose magnitude depends on the phase difference, flows from one superconductor to the other, wihout a biasing potential, known as the DC JE. Applying a constant voltage to the junction leads instead to an alternating current (AC), because the voltage causes the phase difference across the junction to increase over time. Since phases which differ in 2π are equivalent, a linear phase growth produces an alternating current and thus the emission of photons (known as AC JE) [45]. When the biasing potential achieves a value of the order of twice the pairing gap parameter, the (quasi-bosons) Cooper pairs become broken and the system moves away from the superconductor-superconductor regime. Thus, the current is carried by single electrons and one gets back to the Ohmic behaviour of the junction (see ref. [5] for details).

3.2 The nuclear Josephson effect

Attempts to find the analogue of the JE in nuclear physics [40, 46–50] have not provided clear cut results. The interpretation of the data turned out difficult to be carried out, due to finite size effects, the need to take into account many open reaction channels, and the time dependent nature of the transfer process. Phenomenological analysis in terms of enhanced cross sections generated by Cooper pair transfer in properly chosen heavy ion systems [40] was also not conclusive.

It was only recently that, in connection with the data collected by the PRISMA group for the ^{116}Sn+^{60}Ni system, one could extract precise information concerning

the transfer nuclear Cooper pair dimensions (correlation length, denoted ξ). Relating this quantity to the dipole moment of the, mainly successive transferred neutrons, predictions were made concerning the possibility to study a nuclear-like JE in terms of γ rays emitted by the transferred Cooper pair [25, 26, 51]. To that effect, namely the determination of ξ, it was central that one could follow, for the first time, the behaviour of the transfer probabilities over a wide range of bombarding energies down to well below the Coulomb barrier, where absorptive effects are minimized.

To make a connection with the JE found in condensed matter physics, and following the picture proposed by R.Broglia and coworkers, one can associate the dielectric layer to the surface-surface distance between the two nuclei at about the distance of closest approach D, while the applied voltage difference can be represented by the reaction Q-value divided by the effective charge of the tunneling Cooper pair. Within this change of representations, one observes (see Fig. 3) that P_2 is quite close to P_1 for distances of closest approach near 13.5 fm (nuclear correlation length ξ), becoming an order of magnitude smaller already at 1.3 fm beyond this distance. Using the language adopted above from superconductivity, the quasi-boson nature of the Cooper pairs evolves into a pair of quasi-particles, this transition being, in nuclei, not sharp due to finite size effects. Since for the (2n) transfer channel the Q_{gs} = +1.3 MeV (small but not zero), one is in the biased regime below twice the pairing gap parameter, in which case one expects an AC JE with associated photon emission. The authors of Ref. [25] indeed predict emission of γ-rays associated with the dipole oscillation generated by the two neutron transfer process. Such an electromagnetic emission is in the γ-ray energy region, and corresponds to the analog of the AC JE emission observed in superconductors in the microwave energy region in both absorption [28] and emission (see e.g. [45]). Calculations have been performed consistently with the values of the measured transfer probabilities for the two-neutron pick-up channel (+2n) leading to ^{62}Ni nuclei.

4 The ^{60}Ni+^{116}Sn experiment with the AGATA demonstrator : a reanalysis

There is an essential difference between a system of two weakly coupled superconductors, with an amount of Cooper pairs of the order of the Avogadro number, and two weakly coupled superfluid nuclei, where only few Cooper pairs are active. In the former case the phase transition from the superconducting to the non-superconducting phase is sharp while in the latter case the transition is more smooth. This implies that it is not unlikely that (dynamical) pairing coherence is operative also at bombarding energies significantly below the Coulomb barrier. Indeed, theory predicts that, by lowering the bombarding energy below the Coulomb barrier, the strength distribution generated by the dipole oscillations maintains its shape, the energy integrated one reflecting the decrease of the cross section for the two-neutron transfer channel. We thus felt relevant to perform a reanalysis of the γ spectra obtained in Ref. [21], considering also the energy range higher than that of the discrete γ lines. The results, presented below, allowed also to address and configure on a more quantitative basis the new experiment.

The γ-spectra, shown in Fig. 4, were obtained for the ^{60}Ni+^{116}Sn reaction [21] in a direct kinematic experiment at E_{lab}=245 MeV, with the PRISMA spectrometer [6, 7] at θ_{lab}=70° coupled to the AGATA Demonstrator γ-array. That experiment had as purpose to determine the transfer strength to the known excited states, to be compared with the inclusive data obtained in Ref. [16]. It was shown that the main flux in the two-neutron transfer channel is in the ground-to-ground-state transition, in agreement with microscopic calculations. The emitted γ rays correspond to the known discrete lines of the Ni and Sn isotopes, Doppler corrected taking into account the geometry of particle and γ detectors and the velocity of both the light and heavy reaction products. In the experiments performed so far with PRISMA one measured directly the velocity vector for the (detected) light partner while the one for the heavy partner was derived assuming binary kinematics. For the ^{62}Ni and ^{114}Sn nuclei, associated with the two-neutron transfer channel, the only recognizable γ-line within the limited statistics, corresponds to the transition from the 2^+ state to the 0^+ ground state of ^{62}Ni.

The spectra of Fig. 4 are shown in the energy range up to ≈ 4 MeV, much larger than the one displayed in Ref. [21], and cover the suitable region near the maximum of the predicted strength function. The bombarding energy and angular setting of the original experiment correspond to an average distance of closest approach D_0 ≈14.5 fm (see Ref. [21]), where the transfer probabilities of the one- and two-neutron transfer channels differ by about one order of magnitude. From the calculations [52], performed at the corresponding distance of closest approach as in the inverse kinematic experiment of Ref. [16], one estimates to observe just few γ events per day in coincidence with ^{62}Ni ions.

In Fig. 4 one observes a distribution of events with energies larger than those of the visible discrete γ lines (all lying within the 1-2 MeV range). The poor statistics does not allow to quantitatively discuss and eventually identify the origin of the structure of the event distributions, which may be due, for instance, to random coincidences or to high energy γ rays. The group of few events near 3-4 MeV in the ^{62}Ni spectrum is located, on average, at a higher energy as compared to that of the corresponding group in ^{114}Sn, the difference between the centroids of the two groups being a few hundreds of keV, a consequence of the Doppler corrections applied for the discrete γ lines. In the case in which one considers a γ ray of e.g. ≈4 MeV, produced by the dipole oscillation associated with the two-neutron transfer channel, one should take into account the fact that it would be emitted from a moving source corresponding to the center of mass of the binary system. With the geometry of the detectors used in [21], the computed Doppler shift of the ≈4 MeV γ ray amounts to tenths of keV, a value too small compared with the predicted width of the γ ray distribution of few MeV.

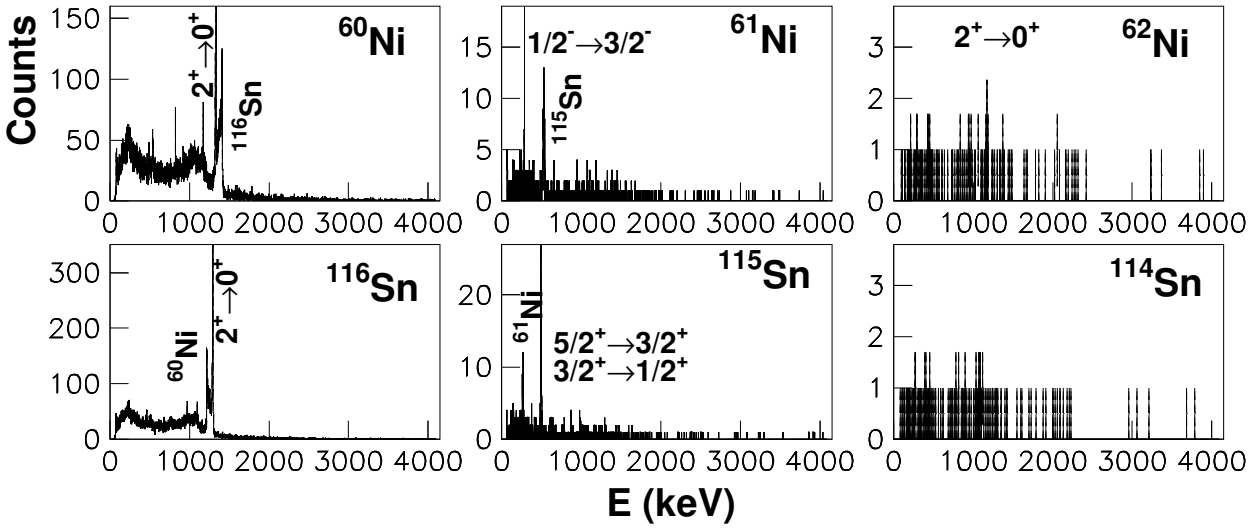

Figure 4. Top panels: Doppler corrected γ spectra for ^{60}Ni, ^{61}Ni and ^{62}Ni detected in PRISMA in coincidence with the AGATA Demonstrator, displayed in the full energy range up to 4 MeV. Bottom panels: spectra Doppler corrected for the heavy binary partners ^{116}Sn, ^{115}Sn and ^{114}Sn (the bin is 1 keV wide). The strongest transitions are labelled with the γ-ray energy, and spin and parity of initial and final states. The broader peaks correspond to the wrongly Doppler corrected reaction partner. Details of this measurement, performed in direct kinematics, are in Ref. [21].

The experiment reported in [21] was performed with the AGATA Demonstrator, an array which at the time of the measurement included four triple clusters and therefore covered only a limited fraction ($\approx$ 7-8%) of the full solid angle. Thus, the reconstruction of the γ-ray energy via tracking procedure was significantly affected by the details of the detector geometry, in particular by those events hitting the outer crystals and eventually leaking out from them. Moreover, one also had to take into account the fact that the detection efficiency depends on the γ-ray energy, which distorts the final event distribution. A simulation of the spectra incorporating the above mentioned features has been carried out by reconstructing the γ-ray energy via a tracking procedure. It considers the γ-array characteristics and the kinematics of the binary reaction, with the γ rays emitted by the light and heavy reaction partners, the former detected in PRISMA, the latter moving at the correlated kinematic angle. The program has as input the gamma energies and strengths of the discrete lines experimentally observed. The event distribution, also at energies higher than the last observed discrete gamma lines, has been generated by implementing an exponential function which takes into account the (measured) efficiency dependence on the γ-ray energy. The simulation has been carried out using as input the predicted gamma-strength function. It was assumed for simplicity that the γ-ray angular distribution is isotropic. It was also assumed that the γ rays are emitted by a non-moving source, which is justified by the fact that, as said before, the Doppler shift is very small compared with the predicted width of the distribution (few tenths of keV as compared to few MeV). Within the limitation of the poor statistics (just few events) and the consequent large fluctuations in the final number of counts and their location in the spectrum, the results did not allow to make definite conclusions. At the same time it appeared obvious that to have any chance to observe the predicted events would have required a jump of two orders of magnitude in statistics. This became possible with the availability of the new PRISMA+AGATA configuration.

5 The PRISMA+AGATA experiment

To detect the predicted γ emission associated with the two neutron transfer process, particle-γ coincidences need to be performed. The width of the distribution is $\sim$ 3 MeV so for these transitions efficiency is a very important parameter. On the other hand, other known discrete γ lines associated with the transfer products will be visible and since one has to control them with great accuracy all over the measurement it is mandatory to have also high energy resolution, thus the AGATA γ array is best suited for our purpose. We thus undertook a very challenging experiment [53], whose very preliminary results are described below.

5.1 Experimental conditions

In this recent experiment we used the same ^{116}Sn+^{60}Ni reaction as in the previous work [16]. PRISMA has been

coupled to the AGATA gamma array equipped with 13 cluster detectors, located in the hemisphere at backward angles with respect to PRISMA. For a 4 MeV gamma ray, the photopeak efficiency of AGATA was 2.8% when used in a tracking mode. Some additional La_2Br_3 detectors have been also employed. In order to reproduce the same experimental conditions of Ref. [16] PRISMA has been set at θ_{lab}=20°, a well suited forward angle to detect with high efficiency and resolution target-like ions scattered in inverse kinematic reactions at sub-barrier energies. The ^{116}Sn beam was accelerated by the PIAVE-ALPI complex of LNL at the energy E_{lab}=460 MeV and with an average current of 1.5 pnA onto a 200 $\mu g/cm^2$ ^{60}Ni target (supported by a 20 $\mu g/cm^2$ C-foil) with an isotopic purity of 99.97%. The target has been mounted on a movable frame located inside a properly designed spherical scattering chamber, inside which it was mounted a beam stopper and an SSBD (Silicon Surface Barrier Detector) monitor detector, placed at 55° on the opposite side with respect to PRISMA, to detect Rutherford scattered Ni-like ions and to control the quality of the beam and for relative normalization between different runs.

The bombarding energy has been chosen taking into account the beam energy loss in the Ni target so to have in its center an effective energy E_{lab}=452 MeV, corresponding to a distance of closest approach D=13.5 fm, close to the theoretically calculated value of the correlation length. This energy, about 5% below the Coulomb barrier, is a compromise between measuring at small D, with higher transfer yields but probing a region where absorption due to other competing reaction channels would take place (thus possibly precluding the qualification of a Josephson-like junction), and measuring at large D, where absorption is minimized but on the other hand the transfer yields drop off and the effect may quickly disappear. The thickness of the target was chosen on the basis of an optimum compromise between conflicting requirements. On one side one had to preserve a resolution not larger than 3-4 MeV in the Q-value spectra to be able to distinguish the quasi-elastic region near the ground-to-ground-state transitions from the tail due to larger energy loss, which is also fundamental in the analysis of the gamma ray spectra. On the other side the very small expected gamma-particle coincidence rate required a minimum thickness for the experiment to be feasible.

5.2 PRISMA data analysis

The nuclear charge was identified via energy-loss and total-energy provided by the ionization chamber of the PRISMA focal plane. The mass identification was achieved via trajectory reconstruction of the ions inside the magnetic elements of the spectrometer, a quadrupole followed by a dipole. It is based on the position information at the entrance and at the focal plane together with the time-of-flight between them. The large momentum acceptance of the spectrometer ($\Delta p/p$ = ±10%) allowed to accommodate most of the atomic charge states with a single setting of the magnetic fields. I stress that to achieve high

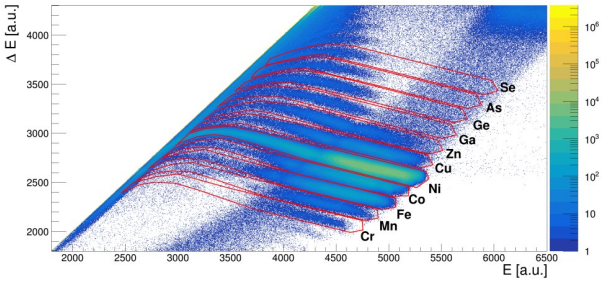

Figure 5. Example of a ΔE-E matrix obtained in the ^{116}Sn+^{60}Ni reaction with the ^{116}Sn beam at the bombarding energy E_{lab}=460 MeV and with the magnetic spectrometer PRISMA set at θ_{lab}=20°. The most intense band corresponds to Ni ions, with proton stripping and proton pick-up channels located below and above the Ni band, respectively. The events along the left diagonal are coming from low energy Sn-like ions entering into the spectrometer and located in the (unshown) upper part of the matrix. Part of the transfer channels along the proton pick-up direction likely overlap with a convolution of strongly damped and quasi-fission processes. The quasi diagonal band appearing on the right side of the matrix is due to pile-up events (consider that the ratio of these pile-up to true transfer events is of the order of 10^{-4}).

mass and nuclear charge resolutions are a necessary requirement at these low bombarding energies since the elastic yield overwhelms up to even more than two orders of magnitudes the transfer one. To detect ions at sub-barrier energies not only with good resolution but also with the highest efficiency, the use of inverse kinematics is also essential since it provides ion high kinetic energy and forward focusing.

Fig. 5 shows an example of ΔE-E matrix, obtained by integrating for the ΔE part the first two subsections of the ionization chamber [14], a choice that optimizes the Z separation of the Ni-like events. I just mention that the integration of the first subsection only, allows instead to better display the band of the Sn-like ions which have a shorter range into the gas of the IC. In the figure one clearly sees the main band of the Z=28 ions and the proton transfer channels along both the stripping and pick-up directions. The high efficiency of the PRISMA detectors allowed to observe an extended event distributions of Z much higher than 28, where the transfer channels likely overlap with a convolution of strongly damped and quasi-fission processes. These kind of events may be present with significant yield also at these sub-barrier energies (see e.g. Ref. [6]).

The events along the left diagonal are coming from low energy Sn-like ions entering into the spectrometer and located in the (unshown) upper part of the matrix. For the sake of completness I can mention that the Sn to Ni yield ratio roughly reflects the ratio of Rutherford cross sections, taking also into account that the dipole and quadrupole magnetic fields of the spectrometer, set to collect with maximum yield the Ni ions, were almost the same as the ones needed for Sn ions. Fig. 6 displays the reconstructed

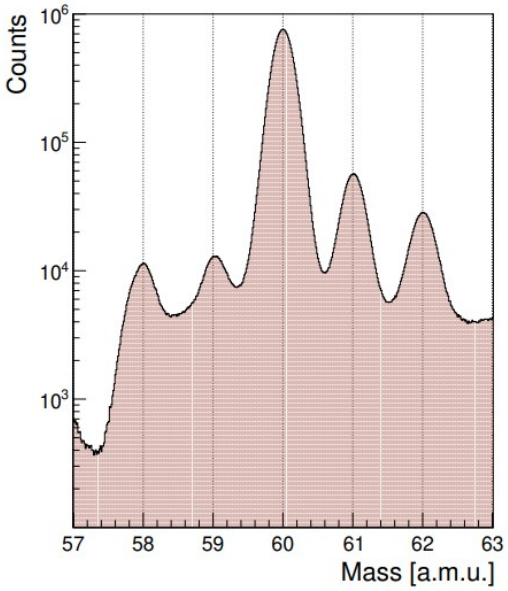

Figure 6. Mass spectrum for Ni isotopes obtained after full trajectory reconstruction of ions through the spectrometer and by gating on Z=28 in the ΔE-E matrix. One observes the main peaks corresponding to the $(+1n)$ (mass 61) and $(+2n)$ (mass 62) transfer channels, as well as the less intense neutron stripping channels.

mass distributions for Ni isotopes, demonstrating the good achieved resolution. By the ratio of the (Z=28) yields for A=61 and A=62 over the elastic A=60, one could get the $(+1n)$ and $(+2n)$ transfer probabilities. The obtained values are displayed as full and empty blue points in Fig. 3, toghether with the data previously published for the same system [16, 17, 21], showing an excellent overlap. A similar agreement is visible for the one $(-1p)$ and two proton $(-2p)$ stripping channels. The figure illustrates the consistent overlap of three meausurements, carried out in different conditions and in different times, demonstrating the correct behaviour of the extracted transfer cross sections. The achieved statistics will allow to construct an angular distribution by dividing the measured angular range into bins of one to two degrees, thus covering a range of distances of closest approach around 13.5 fm (correlation length ξ).

5.3 Analysis of coincident γ-rays

With the discussed optimum experimental conditions, the achieved mass and nuclear charge resolutions and the obtained consistent values of the transfer probabilities, well encompassing the region near D=13.5 fm and thus the correlation length, one will then proceed with the γ part. One of the first steps will be to optimize the Doppler correction taking into account the geometry of the detectors and the velocity and trajectories of the ions through the spectrometer. One then has to get rid as much as possible of the random coincidences, by selecting the time peaks defining the time coincidence between PRISMA and AGATA detectors and properly subtracting the background events, both playing with the timing and energy spectra . Full simulations will constitute an essential piece of information to jugde the origin of the event distributions, especially in the high energy region of the γ spectra, where one also has to disentangle the possible contamination due to the discrete γ rays. In this procedure, the Q-value information from PRISMA will be probably a key element to try to recognize possible true events deriving from the predicted dipole oscillations.

6 Conclusions

Nucleon-nucleon correlation properties have been studied for a variety of systems, from closed shell to superfluid nuclei, making excitation functions down to very low energies and corresponding to very large distances of closest approach where the nuclear absorption is small. The large solid angle magnetic spectrometer PRISMA has been shown to be an outstanding device for such studies, which are of general relevance since one can probe the tail of the nuclear surfaces.

In this context, it has been shown how the recently measured ^{116}Sn+^{60}Ni can be considered as a very suitable candidate to find possible manifestations of a nuclear Josephson effect. Following the theoretical predictions of a specific gamma strength function associated with the dipole oscillations generated by the, mainly successive, two neutron transfer process, an experiment has been very recently performed employing the PRISMA spertrometer coupled to the AGATA gamma array. Such a combined set-up, installed at LNL, offered in fact unique opportunities to directly test the possible manifestation of Cooper pair oscillations, observed to date only in condensed matter physics.

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