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# Sub-barrier transfer reactions and the nuclear Josephson effect

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**Abstract.**
Nucleon-nucleon correlation properties have been studied with the PRISMA spectrometer 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 (see e.g. [1–5] and Refs. therein). These effects 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. 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 [16–18], $^{92}$Mo+$^{54}$Fe [19], $^{197}$Au+$^{130}$Te [20] and $^{206}$Pb+$^{118}$Sn [21, 22], spanning up to four orders of magnitudes in cross sections. With the coupling of AGATA [23] to the PRISMA spectrometer we could probe 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) [24, 25], with Cooper-pair tunnelling between superfluid nuclei, whose manifestation has been recently proposed [26, 27] 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 [28, 29].

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 $\gamma$ array.

## 2 Recent results on nucleon-nucleon correlation studies with PRISMA

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 in-

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verse 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 [30–32]. 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 ~ 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.

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 [21, 22], 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 performed below the Coulomb barrier and their interpretation in terms of pairing vibrational structures in lead are reported in Ref. [22].

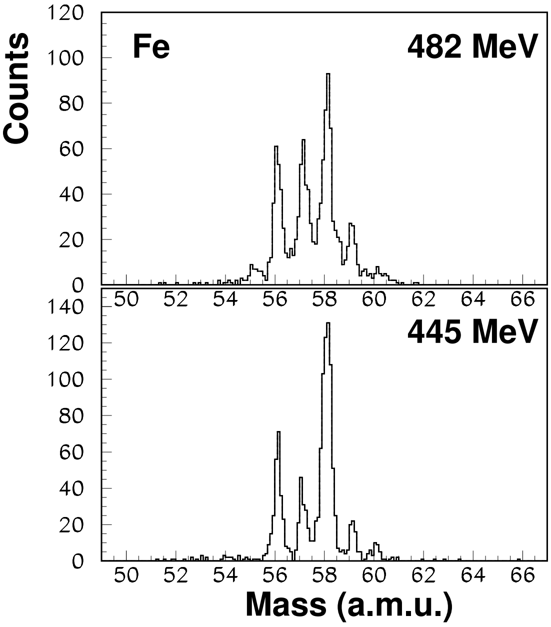

**Figure 1.** Mass spectra of Fe (two-proton stripping channels) isotopes in the $^{116}$Sn+$^{60}$Ni system at 482 MeV and 445 MeV.

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. In general, one has to remark 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 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 proton transfer data for the $^{116}$Sn+$^{60}$Ni system [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.

The transfer probabilities as a function of the distance of closest approach $D$ for a Coulomb trajectory are plotted in Fig. 2. 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) (see e.g. Refs. [30, 41] for a presentation of the general formalism of the DWBA approach) by using for the wave functions of relative motion their CWKB form as in Ref. [42]. The agreement with data indicates the correctness 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 [43, 44] 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. 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.

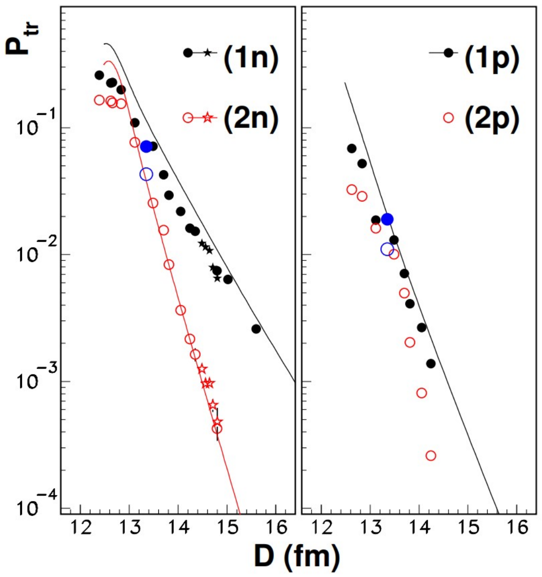

**Figure 2.** (Color online): Transfer probabilities ($P_{tr}$) as a function of the distance of closest approach ($D$) for the one- and two-neutron (Refs. [16, 18]), and one- and two-proton (Ref. [17]) transfer channels. Solid lines are calculated transfer probabilities (see text). The full stars near 14.5 fm are the data from Ref. [18] The blue full and empty points near 13.5 fm are the new data [52].

## 3 Search for a nuclear Josephson effect in the $^{60}$Ni+$^{116}$Sn system

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 $\xi$ 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 $2\pi$ 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).

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 to be difficult, 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 $\xi$). 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 $\gamma$ rays emitted through the transfer of Cooper pair [26, 27, 51]. To that effect, namely the determination of $\xi$, 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. 2) that $P_2$ is quite close to $P_1$ for distances of closest approach near 13.5 fm (nuclear correlation length $\xi$), 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. [26] indeed predict emission of $\gamma$-rays associated with the dipole oscillation generated by the two neutron transfer process. Such an electromagnetic emission is in the $\gamma$-ray energy region, and corresponds to the analog of the AC JE emission observed in superconductors in the microwave energy region in both absorption [29] 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 leading to $^{62}$Ni nuclei.

## 4 The PRISMA+AGATA experiment

To detect the predicted $\gamma$ emission associated with the two neutron transfer process, particle-$\gamma$ 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 $\gamma$ 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 $\gamma$ array is best suited for our purpose. We thus undertook a very challenging experiment [52] using the $^{116}$Sn+$^{60}$Ni reaction with PRISMA coupled to AGATA. In order to reproduce the same experimental conditions of Ref. [16] PRISMA has been set at $\theta_{lab}$=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. The target has been mounted on a movable frame located inside a properly designed spherical scattering chamber, inside which it was placed a beam stopper and an SSBD (Silicon Surface Barrier Detector) monitor detector to detect Rutherford scattered Ni-like ions.

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 predicted 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 to accomodate a reasonable energy resolution and a suffient gamma-particle coincidence rate.

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 [13] and at the focal plane [14] together with the time-of-flight between them. 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. I stress that to achieve high 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.

Figure 3 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. In the figure one clearly sees the main band of the Z=28 ions and the pro-

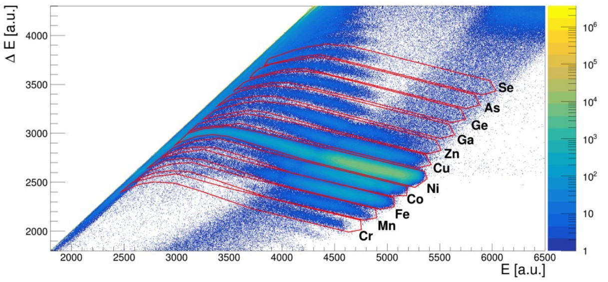

**Figure 3.** Example of a ΔE-E matrix obtained in the $^{116}$Sn+$^{60}$Ni reaction with the $^{116}$Sn beam at the bombarding energy $E_{lab}$=460 MeV and with the magnetic spectrometer PRISMA set at $\theta_{lab}$=20°. The most intense band corresponds to Ni ions, with proton stripping and proton 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.

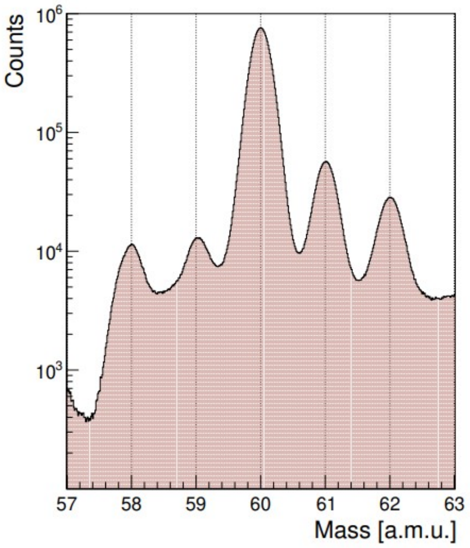

**Figure 4.** Mass spectrum for Ni isotopes obtained after full trajectory reconstruction of ions through the spectrometer and by gating on Z=28 in the ΔE-E matrix. One observes the main peaks corresponding to the (+1$n$) (mass 61) and (+2$n$) (mass 62) transfer channels, as well as the less intense neutron stripping channels.

ton 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]). Figure 4 displays the reconstructed 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 (+1$n$) and (+2$n$) transfer probabilities. The obtained values are displayed as full and empty blue points in Fig. 2, toghether with the data previously published for the same system [16–18], showing an excellent overlap. A similar agreement is visible for the one (−1$p$) and two proton (−2$p$) 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 $\xi$).

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 can then proceed with the $\gamma$ part, whose analysis is in progress. We are presently optimizing the Doppler correction (taking into account the geometry of the detectors and the velocity and trajectories of the ions through the spectrometer) and getting rid of the random coincidences, by selecting the time peaks between PRISMA and AGATA and by properly subtracting the background events. Full simulations are also being carried out. Simulations constitute an essential piece of information to jugde the origin of the event distributions, especially in the high energy region of the $\gamma$ spectra, where one also has to disentangle the possible contamination due to the discrete $\gamma$ 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.

## 5 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 spectrometer coupled to the AGATA gamma array. Such a combined set-up 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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