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Selection of cold transfer and enhanced neutron-pair transfer in the ^{206}Pb + ^{118}Sn reaction

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Abstract. The neutron transfer in a very heavy asymmetric nuclear system, in ^{206}Pb + ^{118}Sn has been measured using particle-γ coincidence techniques with position-sensitive detectors, 5 EUROBALL-Cluster detectors (EB) and the Heidelberg-Darmstadt NaI-CRYSTAL BALL (CB). The fragments are identified via the known γ-decays of the lowest excited states using the high resolution of EB. Using the unique feature of the set-up with the CB, transfer to well-defined final channels with known quantum numbers is selected using the high-efficiency multiplicity filter of the CB with *no* second γ-ray, *i.e.* without feeding. The enhancement in the two-neutron transfer is deduced, for population of the low-lying super-fluid 2^+ states in ^{120}Sn and ^{116}Sn, while the 2n-transition remains in the ground state for the recoiling ^{20X}Pb-nuclei. Large enhancements up to EF $\simeq 10^3$ are observed. This is the first observation of neutron pair-transfer enhancement for a heavy nuclear binary system with superfluid properties with experimentally separated levels.

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1 Introduction

Two-neutron transfer between heavy superfluid nuclei has been studied to observe the "collective" enhancement in the pair transfer [1–5]. Such cases are obtained for nuclei with open shells, like in the Sn region ($N = 50$–82) and in the Pb-region for $N < 126$. Similar to the collective electromagnetic transitions in spatially deformed nuclei, the collective transitions associated with the pairing field, namely the two-neutron transfer is expected to be strongly enhanced [1–9]. In order to observe this effect, neutron pair transfer between heavy nuclei must be measured at energies below the Coulomb barrier in order to have cold reactions and the final reaction channel must be completely identified in order to have a microscopic interpretation of the reactions. The definition of the experimental quantities and the enhancement connected with the two-neutron transfer can be done on the basis of semi-classical concepts, the most recent compilation on this issue is given in refs. [3,4].

We present results of an experiment using *particle-γ-coincidence techniques*. Position-sensitive Parallel Plate Avalanche Counters (PPAC) are used to register the charged particles in coincidence with EUROBALL (EB) detectors and the CRYSTAL BALL (CB) from a binary reaction, such as Coulomb excitation or in a transfer processes, see also refs. [10–18]. These also give access to the velocity vectors needed for the Doppler-shift correction of the measured γ-rays from binary processes, where fragments reach velocities of $v/c > 0.1$. With the high resolution of Ge-detectors, unique identification of the reaction product is obtained by selecting a known γ-transition. A position-sensitive particle signal allows also the determination of the scattering angle, which is used for the determination of transfer probabilities as a function of reaction angle and minimum distance. Recently, results with this method for both spherical and deformed nuclei have been published [15,17–20].

In the present experiment another important feature [14,15] with the multiplicity trigger of the CB detector is used, to select among the cold reactions populating low-lying states, those transitions which correspond to the "supra-cold" transfer reactions leading to the lowest possible states. This experimental set-up opens the possibility for the first time to derive a *microscopic enhancement* for pair transfer in heavy-ion reactions. This is because a uniquely defined transition can be picked out

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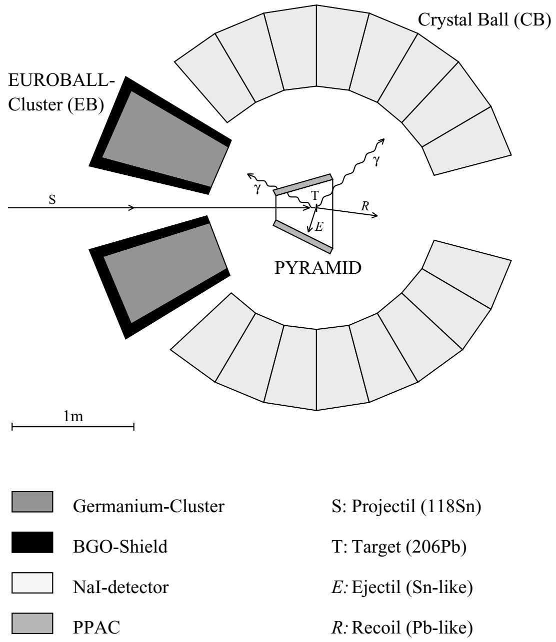

Fig. 1. Schematic view on the experimental set-up with EUROBALL detectors, the parallel-plate detectors (Pyramid) and the CRYSTAL BALL.

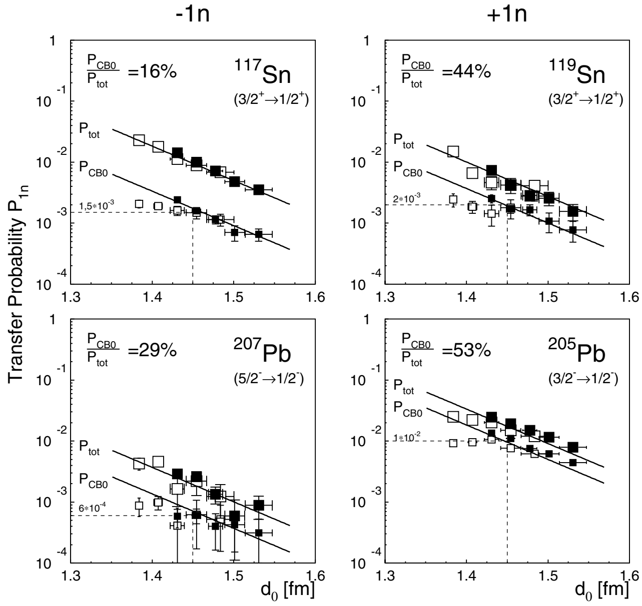

Fig. 2. Measured one-neutron transfer-probabilities for the channels selected via the indicated γ-transitions as a function of the overlap parameter d_0 without any condition (P_{tot}) and with the CRYSTAL BALL in anticoincidence (P_{CB0}). The percentage of the supra-cold component is indicated.

by *removing the feeding in both fragments* defined by the *CB-multiplicity filter set to zero*, here named CB0. The low-lying 2^+ states of these semi-magic nuclei are used, they are almost degenerate in excitation energy for different isotopes, and form also a "superfluid rotational band" as a function of pair-number [2,21,22].

The experiment has been performed at the UNILAC at GSI-Darmstadt with a beam of ^{118}Sn at two energies below the Coulomb barrier at 5.14 MeV/u and 5.32 MeV/u and a target of ^{206}Pb consisting of a 400 μg/cm^2 Pb layer and a carbon backing. The two energies have been chosen in order to have an independent variation of the dynamic parameters. The experimental set-up is shown in fig. 1. It consisted of a pyramidal reaction chamber with the PPACS, the 5 EUROBALL-Cluster detectors (EB) [11], and the CRYSTAL BALL (CB) [10] for measuring γ-rays. Preliminary results have been published in ref. [17].

2 Experimental results and interpretation

The system $^{206}\text{Pb} + {}^{118}\text{Sn}$ is the heaviest asymmetric semi-magic system with closed proton shells and open neutron shells which can be studied. From previous work [1] it is known that the ground states and also the low-lying 2^+ states of such nuclei show strong configuration mixing. In the following the low-lying 2^+ states of the spherical nuclei ^{116}Sn and ^{120}Sn as well as of ^{204}Pb are used to select the 2n-transfer reaction. The reactions were observed at large scattering angles from 80° to 150°.

To overcome efficiency variations in the PPACs, *e.g.* due to target shadowing, the γ-yields of the transfer lines were normalised to the Coulomb excitation transition of the lowest 2^+ state (1230 keV) to the 0^+ ground state in ^{118}Sn, and the lowest 2^+ state in ^{206}Pb (803 keV), respectively. The cross-sections for these transitions can be obtained with high accuracy from Coulomb excitation calculations with matrix elements known from previous work, the *Coulex cross-sections define the absolute scale*, and we obtain access to the absolute elastic and transfer cross-sections.

2.1 Results on transfer reactions

In this work the enhancement for the 2n-transfer has been determined by using the measured 1n- and 2n-transfer probabilities. The semi-classical properties of the present reactions and the use of transfer probabilities give direct access to the enhancement [4]. The definition of the *enhancement factor EF* can be made for selected (separated) two-nucleon (for example, the 0^+ to 0^+) transitions [1,4], relative to *one single-nucleon* transition; this is the *microscopic* definition. One- and two-neutron transfer probabilities for cold reactions have been identified in both directions via the characteristic γ-transitions in the EB spectra (see figs. 2 and 3) These probabilities can be considered to represent the macroscopic values for cold transfer, which are typically obtained in experiments with magnetic spectrometers [4,8,23].

In selecting the CB-Filter condition (CB0), the direct population of the state whose γ-decay is chosen in EB is obtained. This result we call the supra-cold reactions. The predicted slopes are indicated and they are in good agreement with the experimental data. In addition they are independent of the incident energy and also identical to those of the data without the CB filter. This gives

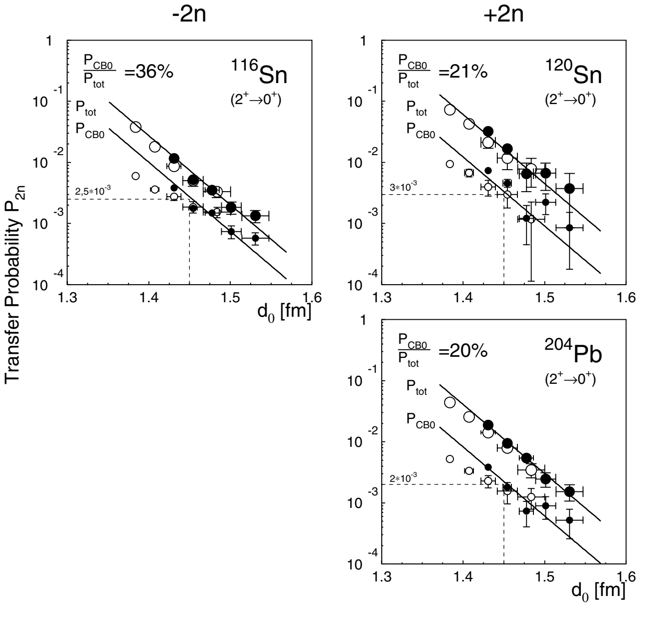

Fig. 3. Measured two-neutron transfer probabilities for the transitions selected with the $0^+ \to 2^+$ γ-decay as a function of the overlap parameter d_0 without any condition ($P_{\rm tot}$) and with the CRYSTAL BALL in anticoincidence ($P_{\rm CB0}$). The percentage of the supra-cold component is indicated.

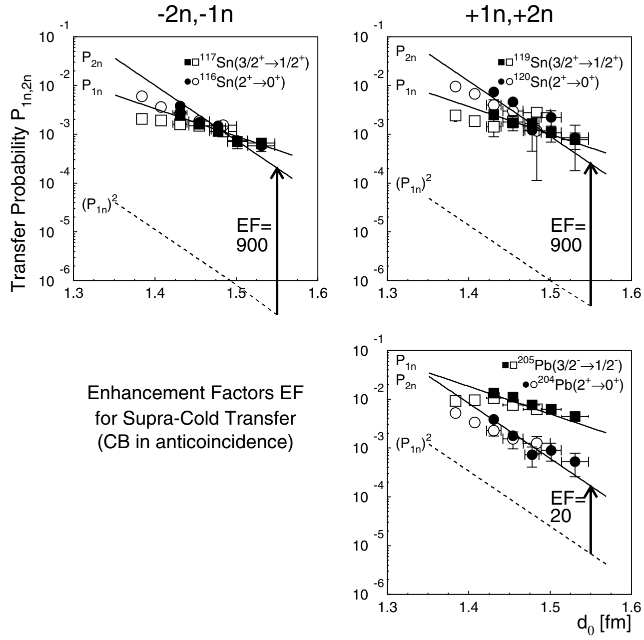

Fig. 4. One-neutron ($P_{\rm 1n}$) and two-neutron ($P_{\rm 2n}$) transfer probabilities as a function of the overlap parameter d_0 with the CRYSTAL BALL in anticoincidence (CB0). The left column shows the neutron transfer from Sn to Pb, the right column vice versa. Filled symbols refer to a bombarding energy of 5.14 MeV/u, open symbols to 5.32 MeV/u. The nuclei are identified by the characteristic γ-transitions. The continuous lines show the theoretically predicted slopes, the dashed lines represent the calculated square of the 1n-transfer probabilities. The shift observed between the square of the 1n-transfer probability and the corresponding 2n-transfer probability defines the enhancement factor EF.

strong support to the claim that in the experiment proper conditions for cold reactions have been chosen. We show with the data horizontal error bars, which appear due to the angular width chosen; the statistical error bars are indicated if larger than the data points.

From the data (fig. 4) the enhancement factors EF can be derived by determining the parallel shift of the 2n-transfer probability compared to the square of the 1n-transfer probability. The anticoincidence with the CB also defines the quantum states of the partner nucleus, which must be the ground state for the no feeding case. This is not strictly true for ^{119}Sn and ^{205}Pb because both nuclei have a first-excited state at a very low excitation energy of very long lifetimes, which cannot be measured with the CB.

For our purpose to determine the enhancement, we find an ideal and clean case for 1n-transfer with the γ-transition $3/2^+ \to 1/2^+$ in ^{117}Sn with the partner ^{207}Pb and for the 2n-transfer with the $2^+ \to 0^+$ gamma-decay in ^{116}Sn with the partner ^{208}Pb. For more details, see ref. [18]. In this case the CB0-filter can determine exactly the quantum numbers of both partner nuclei and for this case we obtain from the data of the supra-cold reaction a microscopically defined enhancement factor of EF = 900, as shown in fig. 4.

2.2 CRC calculations for two-neutron transfer and enhancement

We have used the coupled reaction code FRESCO [24] to calculate absolute cross-sections for 1n- and 2n-transfers by using known spectroscopic factors as compiled in the Nuclear Data sheets [25]. The calculation proceeds in the usual way for heavy-ion reactions [4], namely that for the 1n-transfer the product of the spectroscopic amplitudes of the neutron in the two states in the two fragments has to be given for the chosen transition. The relevant information has been compiled in ref. [18].

For the two-neutron transfer in the microscopic basis the number of configurations has been chosen with typically six or seven values of (n, l, j), in both nuclei (Sn and Pb). For the configurations from two major shells with opposite parity the sign of the 2n-amplitudes are chosen with opposite sign. The final values for the amplitudes A_i chosen for the 2n-form factors are obtained from products of single neutron wave functions (using information from ref. [25]), and are cited in ref. [18]. In order to calculate transfer probabilities, the elastic-scattering cross-section is calculated with parameters taken from [8]; their values have little influence on the transfer probabilities calculated in first or second order (the absorption cancels out when the probabilities are calculated). The transfer amplitude is a sum of a direct process and a sequential one. In addition to the direct population of the Sn(2^+)-states in 2n-transfer with angular momentum transfer $l = 2$, the route via the inelastic vibrational excitation in the incident channel and a subsequent $l = 0$ transfer, also called the *indirect route*, can be of importance.

The results of the calculations can be summarised as follows: in our case the *sequential process* is strongly suppressed relative to the one-step process for the 0^+ states, whereas for the 2^+ states a contribution of 30% is obtained. The *indirect route* is also found to be usually considerably smaller than the direct route. The interference of the direct and indirect routes turns out to be different for stripping and pick-up processes, as already noted before [4]; the result for the sum is sometimes smaller than the direct route alone.

For the experimental transfer probabilities, which are representative for the average 1n-transfer process, and the determination of the enhancement, the calculations agree satisfactorily with the experimental result. We cite some values of the transfer probabilities (including the ground states, for which no data have been obtained) at a distance parameter $d_0 = 1.45$ fm, and compare to the data given in the figures and in the tables:

^{120}Sn(2^+): exp $6.0 \cdot 10^{-3}$, calc $4.0 \cdot 10^{-3}$;

^{117}Sn: exp $2.0 \cdot 10^{-3}$, calc $2.3 \cdot 10^{-3}$;

^{116}Sn(0^+): exp — , calc $4.7 \cdot 10^{-2}$;

^{116}Sn(2^+): exp $2.3 \cdot 10^{-3}$, calc $4.0 \cdot 10^{-3}$;

^{119}Sn: exp $3.0 \cdot 10^{-3}$, calc $7.0 \cdot 10^{-3}$;

^{120}Sn(0^+): exp — , calc $6.5 \cdot 10^{-3}$;

^{120}Sn(2^+): exp $6.0 \cdot 10^{-3}$, calc $4.0 \cdot 10^{-3}$.

From these results the calculated enhancements factors of 1000 are obtained, in agreement with experiment. This is a very satisfactory result considering the uncertainties, which enter into the calculations and in the data.

3 Conclusions

In this work we were able to measure with a unique set-up consisting of the EUROBALL-Clusters and the Heidelberg-GSI-CRYSTAL BALL for γ-ray detection and position-sensitive charged-particle detectors for the first time neutron transfer transitions between well-defined states for a very heavy system consisting of spherical nuclei with superfluid neutron configurations. With this experimental technique it was possible to obtain the microscopic enhancement related to the comparison of the square of the single-neutron transfer for a typical single-particle state to the 2n-transfer for a separated superfluid state. The values of the *microscopic enhancement* observed are EF $\simeq$ 1000 for two cases as predicted in ref. [6] for pure ground-state to ground-state transitions. It turns out that the cases described here, with the observation of 2^+ states, give a similar enhancement as for the 0^+ to 0^+ transitions. This observation is quantitatively reproduced in CRC calculations.

In conclusion, we can say that the experimental method described is a powerful approach to study reaction mechanisms in reactions with very heavy ions, where charged-particle spectroscopy is far away from the possibility to determine the quantum states of reaction fragments. The future use of such set-ups with large gamma-detector arrays like AGATA appears rather promising for nuclear-reaction studies.

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