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Short Note

Strong enhancement of two-neutron transfer in the system ^{206}Pb+^{118}Sn

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Abstract. One and two neutron transfer has been measured in the heaviest asymmetric nuclear system with semi magic nuclei showing superfluid properties, in ^{206}Pb+^{118}Sn collisions at an energy well below the Coulomb barrier with scattering orbits covering the largest angles. Particle-γ coincidence techniques using 5 Euroball-Cluster detectors (EB) combined in a set-up with the Heidelberg-Darmstadt NaI-Crystal Ball (CB) have been used. Transfer channels are identified with EB via their known γ-decays of the lowest excited states. Using the unique feature of the set-up with the CB, transfer to well defined final states with known quantum numbers (without feeding) are selected using the high efficiency multiplicity filter of the CB (*no* second γ-ray). The data are analysed using the semiclassical approach and transfer probabilities are obtained. The enhancement for the two-neutron transfer populating the low lying superfluid 2^+ state in ^{120}Sn (and ^{116}Sn), while the Pb-branch is in the groundstate is deduced by comparison with the strongest single neutron transfer transition. Large enhancements (EF$\simeq 10^3$) are observed. This is the first direct measurement of enhancement for a heavy nuclear binary system with experimentally separated levels suggesting a strong contribution from superfluid pair transfer.

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Single and multiple transfer of neutrons between heavy superfluid nuclei has been studied to observe the "collective" enhancement in the pair transfer expected if nuclei with open shells are brought into contact. These nuclei, e.g. isotopes in the Sn region (N = 50-82) and in the Pb-region for N < 126, show systematic properties of pairing "rotational" bands [1,7]. The collective transition associated with the pairing field, namely the two-neutron transfer probability is expected to be strongly enhanced in such cases [1–8]. Due to the experimental difficulties with very heavy ions which make particle identification rather difficult and the separation of final states populated in the reaction practically impossible, the definition of the experimental quantities and the enhancement connected with the two-neutron transfer have not been unique and a matter of varying arguments; some compilation of recent results is given in [1,2].

A rather simple *global definition* of the enhancement has been connected to experiments with no energy resolution but complete particle identification (for example work based on radiochemistry, or using magnetic separation techniques), where the whole strength in the single and two particle transition has been measured [1]. In these cases the single particle transfer strength appears to be governed by a sum-rule for states at the Fermi surface, and the two-particle transfer, as a sequential process, can attain an enhancement via interference terms acting constructively, connected with the phases of the states populated as intermediate steps in the first transfer process [4–6,8]. The enhancement is obtained by comparison of the two-neutron transfer with the expected product of the single steps and is then connected to the number of intermediate states. Experimentally, typically small values in the range of 2 - 5 are observed [1]. Larger enhancements would have to be attributed to additional effects like dynamic configuration mixing and/or to contributions of a one-step two-nucleon transfer, whose conceptual descrip-

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tion would be best given in terms of a macroscopic formulation of the pairing mode [5], which is related to the nuclear density at the surface.

A more stringent *microscopic* definition of enhancement has been defined in the earlier work based on the (t,p) or (p,t) reactions summarized in [7]. In these cases complete separation of final states is achieved. The comparison is made between *one typical* single nucleon transfer transition with the two neutron ground state to ground state ($0^+ \rightarrow 0^+$) transitions. However, due to the quantal properties of the light-ion reactions recourse to DWBA-calculations is necessary to extract enhancements. Here the heavy ion induced transfer is advantageous because it gives direct access to probabilities using the semi-classical properties of the reactions, just like in Coulomb excitation [3]. The present experiment for the first time opens the possibility to derive this microscopic enhancement in heavy ion reactions, because with the use of the high resolution Ge γ-detectors (5 Euroball-Cluster detectors, EB) in coincidence with particle-detection devices and a 4π NaI-Ball (the Heidelberg-Darmstadt Crystal Ball, CB), a uniquely defined transition can be picked out by removing the feeding in both fragments for the CB-multiplicity filter set to zero. A similar approach for reactions with deformed nuclei has been pursued by Härtlein et al. [11].

The experiment has been performed at the UNILAC at GSI-Darmstadt with a beam of ^{118}Sn at two energies of 5.14MeV/u and 5.32MeV/u and a target of ^{206}Pb consisting of a 400μg/cm^2 Pb-layer and a carbon backing. The enrichment of the target material was 99.8%. The incident energies were chosen in such a way that the minimum distance reached for scattering angles towards 180° was large enough to have only small contributions from nuclear interactions. This distance of closest approach, R_{min}, is determined by the charge product Z_1Z_2, the incident energy E_{cm}, and the scattering angle Θ_{cm} (in the center of mass), by the relation, $R_{min} = Z_1Z_2/E_{cm}\ [1 + 1/\sin(\Theta_{cm}/2)]$. The parameter, d_0, used in calculations for the choice of the incident energy and later in the presentation of the transfer probabilities, is defined, removing the $A^{1/3}$ dependence from R_{min}, to be $d_0 = R_{min}/(A_1^{1/3} + A_2^{1/3})$ and indicates the amount of nuclear overlap encountered in the processes studied. For the presentation of the data in terms of transfer probabilities, P_{tr}, as a function of nuclear distances, the differential range Δd_0 per data point was chosen to be $\Delta d_0 \simeq 0.025$fm. The uncertainty due to the angular resolution of the particle detection device is considerably smaller and will be shown as horizontal bars. The minimum distances covered in the present experiment are in the range of d_0 = 1.38fm - 1.53fm. Absorption into neutron transfer channels starts typically at $d_0 \simeq 1.5$fm, more complicated nuclear processes set in at values of d_0 around 1.4fm [1].

The experimental set-up with 5 Euroball-Cluster detectors (EB) [9], arranged in a ring at about 150°, and the Crystal Ball (CB) [10], covering a large fraction of the remaining solid angle, has been used in a series of experiments; details are described elsewhere [12]. As important

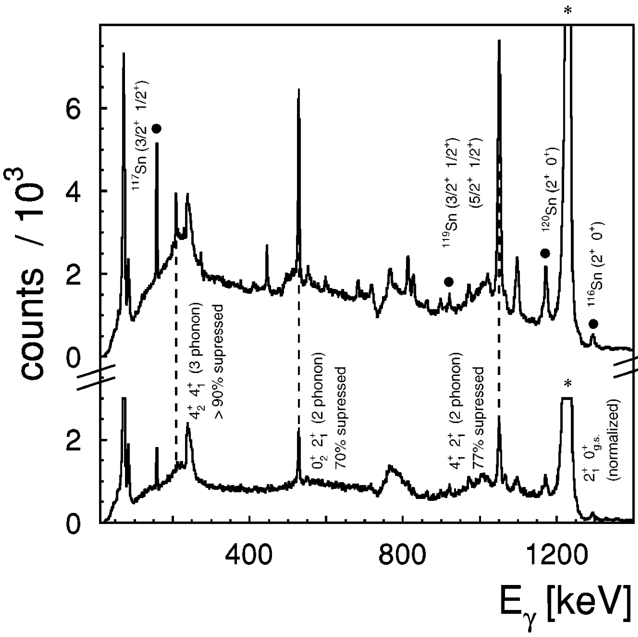

Fig. 1. γ-ray spectra from EB-Clusters, Doppler-corrected for Sn nuclei. The upper spectrum is obtained without any conditions set on the Crystal Ball (CB), the lower spectrum in anticoincidence (CB-multiplicity=0), normalized to the $2_1^+ \rightarrow 0_{g.s.}^+$ transition in ^{118}Sn at an energy of 1230keV. Lines from multiple Coulomb-excitation reactions of the ^{118}Sn projectile and their suppression due to the CB-filter can be seen. Transitions representing one and two neutron transfer channels are indicated by black dots

quantities the efficiencies of the two parts of the γ-ray detection are cited: For the EB the total photopeak efficiency for an energy of 1.33MeV is 2.2%; for the CB the total interaction efficiency is still 78%, although parts had been removed to accommodate the EB-Clusters.

The specific feature of the present experiment was the use of a pyramidally shaped position sensitive parallel-plate avalanche counter (PPAC) [13], which had been rebuilt with a new and different timing readout structure [12]. With this PPAC the angles of the scattered Sn-isotopes in the laboratory have been measured from 80° up to 150°, the vectors of the emitted particles were reconstructed using kinematics and used for Doppler shift correction.

Data were selected if at least one PPAC and one EB-Cluster detector had given a signal. These particle-γ coincidences were sorted under the following conditions:

a) EB-Cluster singles in coincidence with the PPAC for Coulomb excitation and transfer processes.The lines will contain the feeding from levels above. The cross sections can be deduced by either selecting a Sn-isotope, and choosing the appropriate Dopplershift correction, or by selecting a Pb-isotope using the kinematics for the Dopplershift correction. The γ-ray spectrum for Sn-isotopes is shown in Fig. 1, lines representing transfer channels are marked by black dots. The spectrum is dominated by Coulomb excitation and very few transfer channels. The 158 keV transition in ^{117}Sn represents a state with the largest single particle strength (CFP-value close to unity). For ^{119}Sn the strongest γ-rays are found in two lines at approximately 900 keV (less visible than the 158 keV line due to smaller γ-efficiency). The energies represent in both cases two unseparated transitions, the one which we have chosen consists with 75% of a transition involving a single particle state and 25% of a core excited state. The strength for the single particle transfers thus has to be viewed with an uncertainty of 25%. More details on the selection of the transitions and the cross sections deduced from γ-ray spectra of Pb-isotopes will be discussed in a forthcoming paper [12].

b) Same as a) under the additional condition of multiplicity = 0 in the CB. Evidently lines which correspond to two- and higher- phonon excitations in Coulomb excitation are suppressed with respect to the $2^+_1 \rightarrow 0^+_{g.s.}$ transition. As shown in Fig. 1 the two lowest lying 2 phonon states are suppressed by 70% and 77% respectively, the observed three phonon state by more than 90%. Taking into account these values and the multiplicity distribution for the transfer channels, one can conclude that any feeding into the lowest lying states of the transfer channels is suppressed by about 85%. Thus in this case the transfer cross sections correspond mostly to transitions towards the selected state *and* the ground state to ground state transition in the partner "recoil nucleus".

The result of the present experiment will be presented in terms of *transfer probabilities*, $P_{tr}(d_0)$, which usually are directly derived from the cross sections. In the semiclassical approach the cross section for a process is given by the following expression where each factor represents a well defined quantity: $\sigma_{tr}(\Theta) = \sigma_{el}(\Theta)P_{tr}(\Theta)F(Q,L)$. The cross section $\sigma_{tr}(\Theta)$ for transfer (or Coulex) is given by the cross section $\sigma_{el}(\Theta)$ for the scattering leading to the scattering angle Θ, multiplied by the transfer- (excitation-) probability and a quantal correction factor F(Q,L), which accounts for the reduction due to the change of the classical scattering orbit by the dynamical parameters, Q-value and L-transfer [1,3]. For our reactions good matching with $Q_{opt} \simeq 0$MeV is ascertained for the transitions of interest (1n and 2n transfer), the Q-values ranging from -2.42MeV for ^{116}Sn to 1.01MeV for ^{120}Sn. The correction factor F(Q,L) can therefore be set to unity.

To overcome efficiency variations in the PPAC's, e.g. due to target shadowing, the γ-yields of transfer lines were normalized to the Coulomb excitation transition of the lowest 2^+ state in ^{118}Sn (1230keV). For the determination of absolute cross sections and transfer probabilities the excitation probabilities (yields) as a function of scattering angle of the 2^+ state in ^{118}Sn are compared with calculations based on multiple Coulomb excitation which contain up to three phonons and several parallel feeding routes. Thus the Coulex cross sections which define an absolute scale, because the B(E2)-values entering the calculation are known from previous work, give access to the absolute elastic and transfer cross sections. For the extraction of the transfer probabilities the absorption being equally present in both the Coulex yields and the transfer yields is cancelled in the experimental ratios of transfer/Coulex which are used as primary data. This procedure of determining transfer probabilities as function of d_0 with values of d_0 reaching well into the region of absorption has been shown to give good results in many cases [2,4], provided that sufficiently small energies are used.

In Fig. 2 we show the results for the probabilities deduced for the one-neutron and two-neutron transfer, according to the selection of the CB-multiplicity = 0, i.e. no second γ-ray, populating levels, as indicated in Fig. 1, in the lighter and heavier Sn isotopes, with the corresponding Pb-isotopes being in their ground states. These results can be used to compare the 1n- and 2n- transfer strengths and to obtain a value of the *pairing enhancement* in the microscopic definition, related to well separated transtions.

An important feature of the semiclassical method is that the slope of the transfer probabilities as a function of d_0 can be predicted from simple considerations, namely the decay constants, α, of the tails of the bound state wavefunctions which are given by the reduced mass and the binding energies. Thus the observed slopes give a hint if the proper conditions in the experiment have been chosen, and in the ideal case the 2n-transfer will appear as the square of the 1n transfer probabilities, with twice the value of the decay constant ($\alpha_{2n} = 2\alpha_{1n}$). The predicted curves are shown in Fig. 2, together with the experimental values. The shift between the experimental 2n probabilities and the predictions is defined as the *pairing enhancement*, EF, by the definition: EF = $P_{tr}(2n)/(P_{tr}(1n))^2$.

In the microscopic definition with separated states, which has been employed in earlier studies of pairing in the 2n transfer by (t,p) reactions, one typical (or the strongest) single particle transition with the quantum numbers (nlj) has been compared to the $0^+ \rightarrow 0^+$ transitions, the latter consisting of a mixture of configurations $\Sigma(\mathrm{nlj})^2$, among which the chosen single particle (nlj)-transition is one part. The coherent mixture of the different shell model orbits contributing to the two-neutron state was observed to give an enhancement of typically EF=20 for Sn-isotopes [7]. For transfer reactions between two superfluid nuclei values of approximately $(20)^2$ must be exspected. Previous studies of heavy ion 2n-transfer reactions with less resolution, and using indirect methods have produced similar values for EF [4,15–17,19].

The approach of the present study goes also beyond the previously obtained results on particle-γ-coincidence studies on neutron transfer [14–19], because the anticoincidence gating (CB-multiplicity = 0) gives access to transfer transitions leading to uniquely defined states in *both* fragments. Therefore in the present case we will be able to use the microscopic definition with the only difference that in one branch, here in the projectile (Sn) vertex, the transition to the 2^+ state is observed. The 2^+ states are actually known to carry almost the same pairing properties as the groundstates [20]. Calculations for $0^+ \rightarrow 0^+$ transitions between Sn-isotopes in a microscopic basis by Broglia et al. have predicted enhancements of EF $\simeq 10^2 - 10^3$ [6].

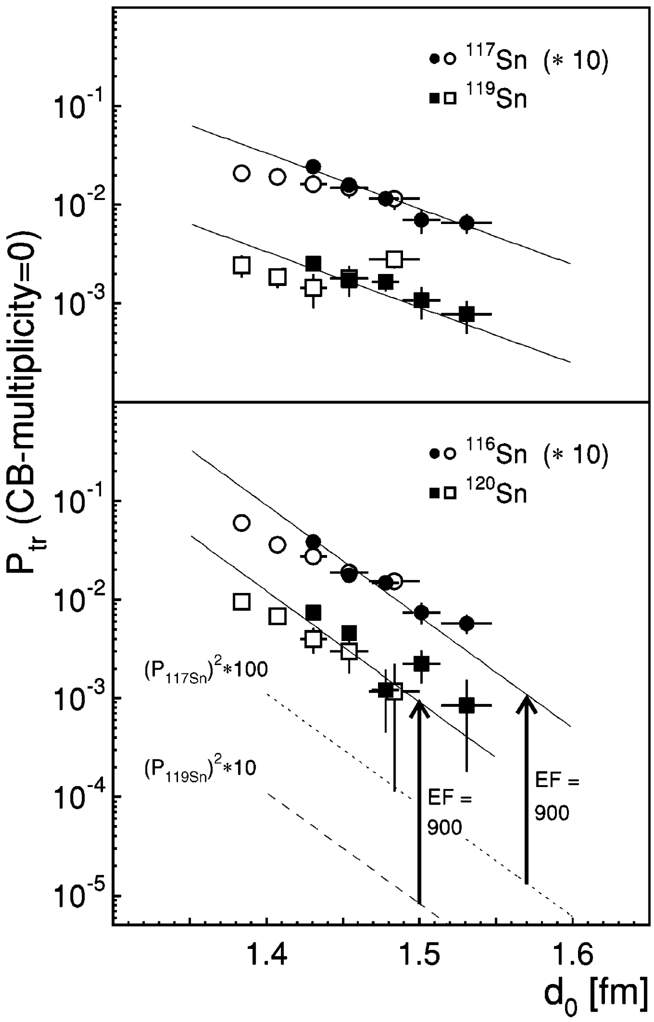

Fig. 2. One neutron (above) and two neutron (lower part) transfer-probabilities in $^{206}Pb+^{118}Sn$ collisions as a function of the overlap parameter d_0 with the Crystal Ball in anticoincidence. Filled symbols refer to a bombarding energy of 5.14 MeV/u, open symbols to 5.32 MeV/u. The nuclei are identified by the characteristic γ-transitions indicated in Fig. 1. The calculated square of the 1n-transfer probabilities are drawn as dashed lines in the lower part. The shift between the square of the 1n-transfer probability and the corresponding 2n transfer probability defines the enhancement factor EF

Previous studies with less resolution using indirect methods have produced similar values for EF for heavy ion 2n-transfer reactions [4,15–17].

Inspecting the results for the measured 1n and 2n transfer probabilities shown in Fig. 2 we observe that the slopes of the probabilities are fairly reproduced by decay constants assuming the known binding energies for values of d_0 >1.42fm where the absorption is still less than about 95%. The enhancement can thus be deduced: The value is EF $\simeq$ 900 for both, the ^{119,120}Sn branch and the ^{117,116}Sn branch. These observed enhancements of the order of 10^3 are dependent on the choice of the single neutron transfer transition which may vary by a factor of 2-3, however, the experimentally observed states are the strongest single particle states, which occurred in the spectrum; in ^{119}Sn actually two transitions are not separated at 920 keV [12]. The observed enhancement is still strong for the 2^+ states which are part of the superfluid properties in heavy nuclei [20]. The large pairing enhancement must also be seen in the perspective of the more complex reaction mechanism which we must anticipate in these heavy systems: the Coulomb excitation in Sn attains large probabilities (for the case of a heavy partner like ^{206}Pb), the 2n transfer will contain large contributions from a two step process in which, after Coulex to the 2^+ state, the transfer of a spin zero pair between the 2^+ states ("in the first floor") will occur, the latter carrying a similar enhancement as the pair transfer between the groundstates. Included in the total result is the other vertex ($0^+ \rightarrow 0^+$ from ^{206}Pb to ^{204}Pb or to ^{208}Pb respectively), which carries the maximum enhancement. Theoretical considerations show that the observed enhanced two neutron transfer is mainly due to the coherent interference of a large number of transfer amplitudes acting in the intermediate single particle states populated in the odd-mass nuclei (^{119}Sn,^{205}Pb and ^{117}Sn,^{207}Pb). The observed result shows for the first time the direct measurement of the enhanced flow of neutron pairs between heavy nuclei in a microscopic definition.

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