Probing the pairing interaction through two-neutron transfer reactions

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Cross sections for (p, t) two-neutron transfer reactions are calculated in the one-step zero-range distorted-wave Born approximation for the tin isotopes ^{124}Sn and ^{136}Sn and for incident proton energies from 15 to 35 MeV. Microscopic quasiparticle random-phase approximation form factors are provided for the reaction calculation and phenomenological optical potentials are used in both the entrance and the exit channels. Three different surface/volume mixings of a zero-range density-dependent pairing interaction are employed in the microscopic calculations and the sensitivity of the cross sections to the different mixings is analyzed. Since absolute cross sections cannot be obtained within our model, we compare the positions of the diffraction minima and the shapes of the angular distributions. No differences are found in the position of the diffraction minima for the reaction ^{124}Sn$(p, t)^{122}$Sn. On the other side, the angular distributions obtained for the reaction ^{136}Sn$(p, t)^{134}$Sn with surface and mixed interactions differ at large angles for some values of the incident proton energy. For this reaction, we compare the ratios of the cross sections associated to the ground state and the first excited state transitions. Differences among the three different theoretical predictions are found and they are more important at the incident proton energy of 15 MeV. As a conclusion, we indicate (p, t) two-neutron transfer reactions with very neutron-rich Sn isotopes and at proton energies around 15 MeV as good experimental cases where the surface/volume mixing of the pairing interaction may be probed.

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I. INTRODUCTION

Pairing correlations play an important role in determining the properties of a large number of open-shell superfluid nuclei. Many efforts have been devoted in the last years to investigate and better clarify the deep nature of the pairing interaction in several nuclear systems, from finite atomic nuclei to compact neutron stars, which may be regarded as the most exotic nuclear systems in nature. A detailed review of methods, analyses, and results concerning the pairing interaction and the study of pairing correlations has been published in 2003 by Dean and Hjorth-Jensen [1]. We mention in what follows some examples of more recent works which are devoted to the study of nuclear superfluidity: (i) the localization of Cooper pairs in the nuclear medium has been analyzed within different models and in different contexts [2–6]; (ii) polarization effects, i.e., the impact on pairing correlations of the coupling to collective phonons is discussed in the community (see, for example, Refs. [7,8]); (iii) a bridge between finite nuclei and infinite matter has been established and the pairing gaps in nuclei have been calculated by fitting the interaction on symmetric and neutron matter [9]; (iv) $T = 1$ and $T = 0$ (neutron-proton pairing in $N \sim Z$ nuclei) are being investigated and, in this respect, an interesting study of partial-wave contributions to pairing has been recently presented by Baroni *et al.* [10].

The derivation of the pairing interaction on a fully microscopic basis is being performed nowadays and pairing gaps have actually been obtained from low-momentum interactions $V_{\text{low-}k}$ [11]. However, in most of the available mean-field-based models, a more phenomenological attitude is still usually adopted also because the agreement between the theoretical $V_{\text{low-}k}$ gaps and the experimental values does not improve significantly with respect to what obtained with phenomenological interactions. It is worth mentioning that in phenomenological interactions not only the bare interaction but also higher-order terms are taken into account in an effective way. While in the Gogny case almost the same interaction is employed in both particle-hole and particle-particle channels, in Skyrme-mean-field-based models the pairing interaction which is used in the particle-particle channel is usually different from the interaction used in the mean-field channel [12]. This prevents the problems related to double counting in the particle-particle channel. One of the current choices for the pairing interaction is a zero-range interaction depending on the isoscalar density. Extensions of this form to include also a dependence on the isovector density have been recently proposed [13,14]. The parameters appearing in the expression of the pairing interaction are fitted on nuclear properties following different criteria. One of these criteria consists in using the experimental odd-even mass staggering as a constraint and this choice has been extensively analyzed [15–18].

The role of the pairing vibration modes (associated to pair-transfer reactions) in providing a helpful insight into superfluidity in nuclei has been discussed since several years [19,20]. For recent reviews on the main advances achieved in multinucleon transfer reactions at energies close to the Coulomb barrier see Refs. [21,22]. The excitation modes related to the transfer of nucleonic pairs in superfluid nuclei are actually expected to be strongly sensitive to the specific features of the pairing interaction [20]. It has been recently suggested that the observables related to pairing vibrations could be considered as useful additional constraints in the fitting procedures of phenomenological interactions [23,24]. In particular, in the currently used zero-range density-dependent

interaction, the surface/volume mixing of the interaction can be tuned by modifying the parameter x in the expression

$$V(\vec{r}_1,\vec{r}_2)=\delta(\vec{r}_1-\vec{r}_2)V_0\left[1+x\left(\frac{\rho(\vec{R})}{\rho_0}\right)^{\alpha}\right], \qquad (1)$$

where $\vec{R}=(\vec{r}_1+\vec{r}_2)/2$; $x=0$ and $x=1$ represent the extreme cases of a pure volume and a pure surface interaction, respectively. Microscopic quasiparticle random-phase approximation (QRPA) calculations for the 0^+ [23] and the 2^+ [24] pair-transfer modes have been performed and it has been shown that the transition densities actually depend on the different choices of the pairing interaction in terms of surface/volume mixing. In particular, differences have been found between the two cases of a pure surface interaction and a mixed interaction.

To finally prove that the observables associated to pairing vibrations can indeed guide us toward a deeper comprehension of this specific aspect of the pairing interaction, cross sections have to be evaluated. The analysis is pursued here in this direction. The idea is to perform a calculation of cross sections where the form factor of the transition is evaluated microscopically. The self-consistent microscopic QRPA results are used as structure inputs for the reaction calculation. We consider two-neutron transfer (p,t) reactions where the Hartree-Fock-Bogoliubov (HFB) + QRPA approach is used to describe the microscopic nuclear structure and the one-step distorted-wave Born approximation (DWBA) is employed for the reaction dynamics. The cross sections in the DWBA are calculated using the Distorted Waves University of Colorado Kunz 4 (DWUCK4) code [25]. While the evaluation of the form factors is based on self-consistent and completely microscopic structure calculations, some limitations of the present reaction calculations have to be mentioned. A first limitation is the inability of such calculations to reproduce measured absolute cross sections [26]: we thus compare in this work only angular profiles and in particular the location of the diffraction minima. Furthermore, it has to be noticed that in one-step DWBA calculations inelastic excitations in the reaction channels and two-step processes corresponding to sequential particle transfers are missing [26]. The relative importance of these processes is still quite an open question. Owing to these limitations, we consider the results presented in this work as a first qualitative indication and not a precise prediction about the sensitivity of the cross sections to the surface/volume character of the pairing interaction.

The analysis presented in this work is done for the tin isotopes ^{124}Sn, which is stable, and ^{136}Sn, which is unstable and very neutron-rich.

The article is organized as follows. In Sec. II the microscopic QRPA form factors are shown. In Sec. III the cross sections are analyzed and a comparison with the experimental data is presented for the case $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$. Conclusions and perspectives are summarized in Sec. IV.

II. MICROSCOPIC FORM FACTORS

For the excitation modes associated to (p,t) reactions, the transition densities are calculated between the ground state of the nucleus with A nucleons and a state (the ground state or an excited state) of the nucleus with $A-2$ nucleons. The form factor is obtained by folding the transition density with the interaction between the transferred pair and the residual nucleus. In our model, this interaction is actually chosen of zero range and this means that the transition densities directly provide the form factors. It is clear that with a zero-range interaction the shapes of the angular distributions can be well defined but the absolute values of the cross sections cannot be evaluated [27].

The structure calculations to derive the transition densities are performed in this work within the HFB + QRPA framework [27,28]. In this model, the modes associated to the transfer of pairs are obtained by considering the particle-particle (hole-hole) components of the QRPA Green's function for the transition $A\rightarrow A+2$ ($A\rightarrow A-2$) [27]. The strength function describing an excitation in the particle-hole channel is given by the well-known expression

$$S(\omega)=-\frac{1}{\pi}\mathrm{Im}\int F^{11*}(r)G^{11}(r,r';\omega)F^{11}(r')drdr', \qquad (2)$$

where "1" denotes the particle-hole subspace. G^{11} and F^{11} are thus the particle-hole components of the QRPA Green's function and of the excitation operator, respectively.

Similarly, the strength function for the transition $(A\rightarrow A+2)$ is written as

$$S(\omega)=-\frac{1}{\pi}\mathrm{Im}\int F^{12*}(r)G^{22}(r,r';\omega)F^{12}(r')drdr', \qquad (3)$$

where "2" denotes the particle-particle subspace. The strength function describing the transition $(A\rightarrow A-2)$ is

$$S(\omega)=-\frac{1}{\pi}\mathrm{Im}\int F^{13*}(r)G^{33}(r,r';\omega)F^{13}(r')drdr', \qquad (4)$$

where "3" represents the hole-hole subspace. In the present QRPA calculations, the strength distributions have been evaluated using Eq. (4).

The first peak of the response functions given by Eqs. (3) and (4) describes the transition from the ground state of the A nucleus to the ground state of the $A\pm2$ nucleus.

The pair transition density is given by the following expression:

$$\delta\kappa^{\nu}(r\sigma)=\langle 0|c(r\tilde{\sigma})c(r\sigma)|\nu\rangle, \qquad (5)$$

where ν is the state under consideration (either the ground state or an excited state of the final nucleus).

As already done in Ref. [23], we use three different values of the parameter x in Eq. (1), $x=0.35$, 0.65, and 1. The first two cases are associated to a mixed pairing interaction while $x=1$ corresponds to a pure surface interaction. The other parameters of the pairing interaction are adjusted in the same way as in Ref. [23] (the fit is done on the two-neutron separation energies of Sn isotopes). The only difference between the present structure calculations and those shown in Ref. [23] is that the transition $A\rightarrow A-2$ transition is considered here whereas the transition $A\rightarrow A+2$ has been explored in Ref. [23].

In this work, we are interested in the transitions to the first 0^+_1 state, which is the ground state (g.s.) of the $A-2$ nucleus, and to the first 0^+ excited state (0^+_2) of the final $A-2$ nucleus. We thus consider the first two peaks of the QRPA

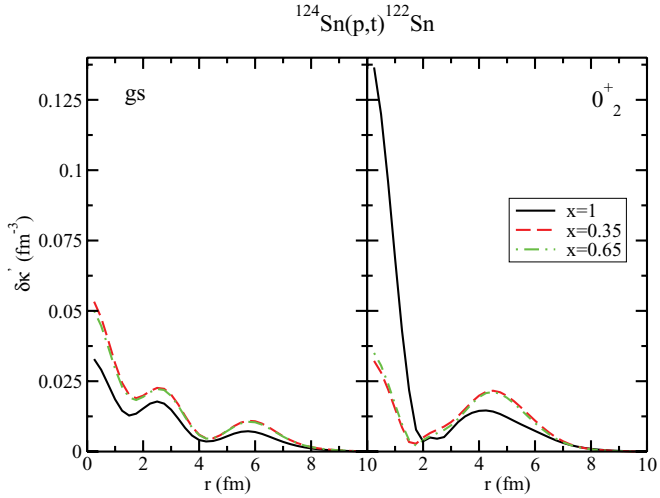

FIG. 1. (Color online) Form factors of the reaction $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ for the transition to the ground state (left) and to the first 0^+ excited state (right).

response functions and calculate the corresponding transition densities. The transition densities for the $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ and $^{136}\mathrm{Sn}(p,t)^{134}\mathrm{Sn}$ reactions are shown in Figs. 1 and 2: Left panels refer to the g.s. transition and right panels refer to the 0^+_2 transition. In general, one observes that the two form factors associated to the two mixed interactions are quite similar one to the other and different from the form factor corresponding to $x = 1$, especially in the right panels (0^+_2 transitions). Similar results have been already found in Ref. [23].

III. CROSS SECTIONS WITH DIFFERENT SURFACE/VOLUME MIXINGS

Optical potentials have to be provided together with the form factors for the reaction calculations. Phenomenological optical potentials are used here. The optical potential for the entrance channel (interaction between the proton and the

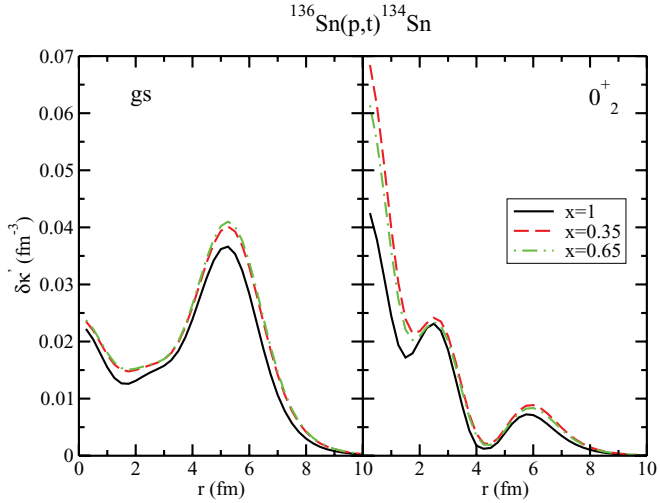

FIG. 2. (Color online) Form factors of the reaction $^{136}\mathrm{Sn}(p,t)^{134}\mathrm{Sn}$ for the transition to the ground state (left) and to the first 0^+ excited state (right).

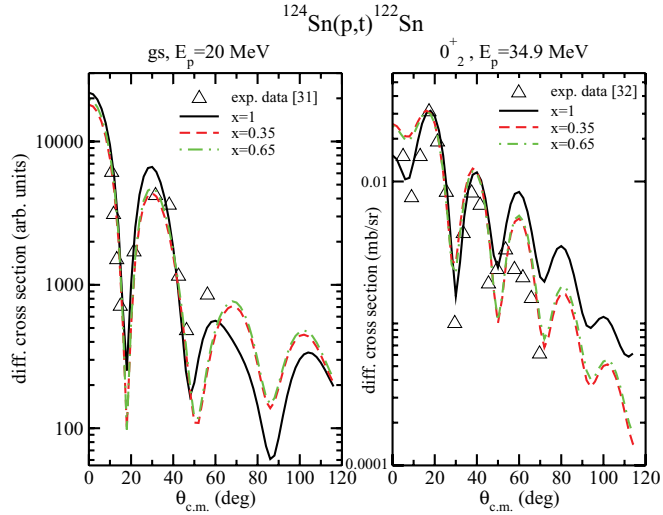

FIG. 3. (Color online) Left: Comparison between the calculated and the experimental cross sections for the transition to the ground state of the final nucleus. The reaction is $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ and the incident proton energy is equal 20 MeV. Right: Comparison between the calculated and the experimental cross sections for the transition to the first excited 0^+ state of the final nucleus. The reaction is $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ and the incident proton energy is equal 35 MeV.

nucleus) is constructed with the parameters of Ref. [29] which have been fitted on elastic scattering of protons by nuclei with $A > 40$ and with a proton laboratory energy $E_p < 50$ MeV. For the exit channel, the optical potential parameters have been fitted on the elastic scattering of the triton [30].

In the DWBA calculations performed with the DWUCK4 code, a neutron pair of zero angular momentum is transferred from one nucleus to the other. The g.s. $\rightarrow$ g.s. and the g.s. $\rightarrow$ 0^+_2 transitions are calculated for different incident proton energies E_p and with the three different pairing interactions. Incident proton energies range from 15 to 35 MeV.

Some experimental data for the reaction $^{124}\mathrm{Sn}(p,t)^{122}\mathrm{Sn}$ are available [31,32]. We have compared the theoretical angular distributions with the experimental points (Fig. 3) for the g.s. transition at $E_p = 20$ MeV (left) and for the 0^+_2 transition at $E_p = 35$ MeV (right). Data exist also at 20 MeV for the 0^+_2 [33]. However, at 20 MeV and for the 0^+_2, the Q value becomes very negative (-8 MeV) so that the calculated cross section exhibits an abnormal behavior and cannot be compared with the experimental one.

Since the calculated cross sections are not absolute, we have normalized them at the experimental amplitudes. The three curves are normalized to reproduce the highest experimental maximum in the two panels. Owing to this normalization procedure, we cannot compare the absolute values but only the angular profiles, i.e., the position of the diffraction minima. It turns out that for the three used pairing interactions the minima are located in all cases at the same values of the angle $\Theta_{\mathrm{c.m.}}$ (in agreement with the experimental data). One cannot thus deduce in this case any helpful hint about the surface/volume mixing of the pairing interaction.

When drip lines are approached, neutron skins become thicker: surface effects and low-density pairing features are

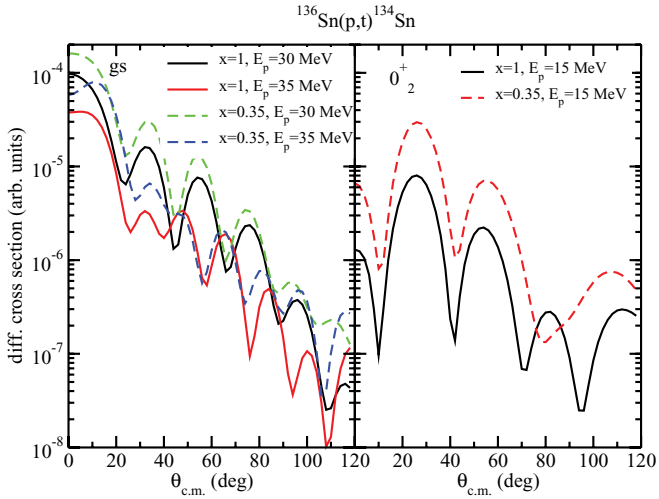

FIG. 4. (Color online) Left: Cross sections for the reaction ^{136}Sn$(p,t)^{134}$Sn obtained in the cases of a pure surface interaction ($x = 1$) and a mixed interaction ($x = 0.35$). The transition to the ground state of the final nucleus is considered and two values of the incident proton energy are selected, $E_p = 30$ and 35 MeV. Right: Cross sections for the reaction ^{136}Sn$(p,t)^{134}$Sn obtained in the cases of a pure surface interaction ($x = 1$) and a mixed interaction ($x = 0.35$). The transition to the first excited 0^+ state of the final nucleus is considered and the value of 15 MeV is selected for the incident proton energy.

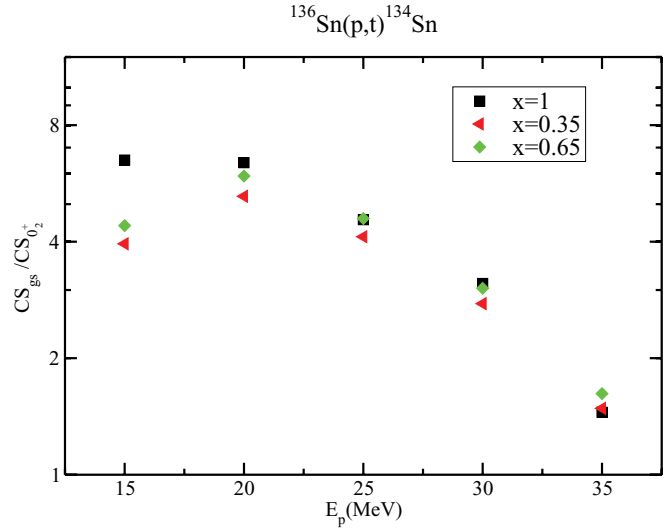

FIG. 5. (Color online) Ratios of the cross sections associated to the g.s. and to the 0_2^+ transitions at different proton energies for the reaction ^{136}Sn$(p,t)^{134}$Sn.

thus expected to be typically more important. Owing to this, we have considered also the pair-transfer reaction ^{136}Sn$(p,t)^{134}$Sn where a more neutron-rich nucleus is involved. With the next-generation facilities, it is expected that beams of very neutron-rich tin isotopes such as ^{134,136}Sn will be produced with sufficiently high intensity for performing two-nucleon transfer experiments. We have performed the same kind of calculations as for the case ^{124}Sn$(p,t)^{122}$Sn (E_p ranging from 15 to 35 MeV). In this case, we have checked the sensitivity of the calculations with respect to the choice of the optical potential in the entrance channel. We have found similar results using the optical potential of Ref. [34].

For some values of the proton incident energy, the location of the diffraction minima is not the same when different pairing interactions are used. We show in Fig. 4 only the relevant cases, i.e., those corresponding to the incident energies for which some discrepancies have been found in the angular profiles associated to different pairing interactions. The two cases of mixed interactions ($x = 0.35$ and $x = 0.65$) do not actually significantly differ one from the other while discrepancies are found between the pure surface case and the mixed cases. As an illustration, we show for the mixed interaction only the case $x = 0.35$. We compare in Fig. 4 the results obtained for $x = 1$ and $x = 0.35$. In the left panel, the *gs* transition is described for the two values of incident energy $E_p = 30$ and 35 MeV. For $E_p = 30$ MeV, the curves to compare are the solid black ($x = 1$) and the dashed green ($x = 0.35$). For $E_p = 35$ MeV, the curves to compare are the solid red ($x = 1$) and the dashed blue ($x = 0.35$). In the right panel, the 0_2^+ transition is described for $E_p = 15$ MeV. One observes in both panels that the profiles of the cross sections corresponding to $x = 1$ and $x = 0.35$ differ at large angles ($\Theta_{\text{c.m.}} > 70$ degrees). We are aware that measurements are more difficult at large angles because the corresponding cross sections are very low. Nevertheless, this result indicates that very neutron-rich Sn isotopes may be interesting cases to analyze. On the basis of this first indication, we continue our investigation for ^{136}Sn and we show in Fig. 5 the ratios of the cross sections associated to the g.s. and to the 0_2^+ transitions at different proton energies. Even if absolute cross sections cannot be calculated within the present reaction model, the ratios of the cross sections related to the g.s. and the 0_2^+ transitions are meaningful quantities to analyze. These ratios are proportional to the ratios of the transition probabilities associated to the two transitions and that the proportionality factor is the same independently of the pairing interaction. The comparison of the ratios obtained with different pairing interactions can thus provide interesting predictions about the sensibility of the cross sections to the choice of the pairing interaction. It can be seen that differences exist among the three sets of results and they are more important at the lowest energy of 15 MeV, that represents the case where the reaction takes place mostly in the surface region of the nucleus. Hence, we suggest very neutron-rich Sn isotopes and proton energies around 15 MeV as favorable cases for future (p,t) or (t,p) pair-transfer experiments that can provide a deeper insight into the surface/volume character of the pairing interaction. Performing (t,p) reaction measurements in inverse kinematics is quite more challenging than (p,t), but such reactions would allow one to populate different states of Sn isotopes that may also represent very favorable cases for pairing studies.

IV. SUMMARY AND PERSPECTIVES

We have evaluated (p,t) two-neutron transfer-reaction cross sections in the zero-range DWBA approximation for

the two cases ^{124}Sn$(p,t)^{122}$Sn and ^{136}Sn$(p,t)^{134}$Sn. The limitations of these reaction calculations have been discussed. Microscopic form factors have been provided for the reaction calculation where the transition densities are calculated within the HFB+QRPA approach. A phenomenological zero-range density-dependent pairing interaction is used in the particle-particle channel of this model and three different surface/volume mixings have been considered for the pairing interaction: a pure surface interaction and two mixed surface/volume interactions. The sensitivity of the cross sections to these different choices has been investigated for the two reactions. Our reaction calculation does not provide absolute cross sections. We thus compare only the angular profiles and in particular the location of the diffraction minima. We consider several values of the incident proton energy, from 15 to 35 MeV.

For ^{124}Sn$(p,t)^{122}$Sn, negligible discrepancies are found in the location of the minima and in the shape of the angular distributions among the different pairing cases for all the considered incident proton energies. For this reaction, experimental data exist at $E_p = 20$ and 35 MeV and the comparison with the experimental points is satisfactory in all cases, independently of the the pairing interaction.

A more interesting case seems to be the reaction ^{136}Sn$(p,t)^{134}$Sn where a very neutron-rich nucleus is involved. For some values of the energy of the proton, discrepancies at large angles ($\Theta_{\text{c.m.}} > 70$ degrees) are found in the position of the minima between the pure-surface case and the mixed-interaction case (the two mixed interactions lead to very similar results). This is a first qualitative indication that suggests that this case can be interesting to be explored experimentally. We have compared the ratios of the cross sections associated to the g.s. and to the 0_2^+ transitions at different proton energies. Sizeable differences among the three theoretical predictions are found especially at the lowest proton energy of 15 MeV. New-generation accelerators should allow soon to produce ^{134,136}Sn beams with sufficiently high intensity. The conclusion of this work is that pair-transfer reactions for a very neutron-rich Sn isotope and at proton energies around 15 MeV (reactions in the surface region of the nucleus) may be good experimental cases where the surface/volume nature of the pairing interaction can be elucidated. This is a first indication. More precise reaction calculations should certainly be performed to get absolute cross sections; more accurate predictions could be obtained by taking into account more complex processes like two-step excitations which are so far neglected in the present calculations whereas they are included in more sophisticated reaction codes [8].

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