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# Signatures of multiphonon and neutron transfer couplings in the fusion of $^{36,32}S+^{110}Pd$

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Fusion-evaporation cross sections have been measured for $^{32,36}S+^{110}Pd$ to high accuracy in the energy range around the Coulomb barrier. The two extracted fusion barrier distributions display very similar structures with two well-resolved peaks below the nominal barrier, which are consistent with a model calculation including the coupling of the one-, two-, and three-phonon collective vibrations of $^{110}Pd$. A third lower-energy barrier, together with a strong relative cross section enhancement, is observed for $^{32}S+^{110}Pd$, and is reproduced by coupling the two-neutron pickup channel which has a large and positive ground state $Q$ value (+5.1 MeV). For $^{36}S+^{110}Pd$, the calculated effect of the corresponding transfer channel (with negative $Q$ value) is much smaller.

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Many years of experimental and theoretical studies have supplied a lot of information about the dynamics of subbarrier heavy-ion fusion (see [1,2] for recent reviews), but various basic questions about the quantum-mechanical barrier penetration process, in the presence of internal degrees of freedom of the colliding system, still remain unanswered. Essentially, in spite of the good or even excellent results obtained by coupled-channels (CC) calculations in many systems (see, e.g., [3,4]) both for cross section enhancements and for angular momentum distributions [5], a clear-cut identification of the relevant degrees of freedom involved in the fusion mechanism is often missing.

Recently, it has been proposed [6] that the distributions produced by the splitting of the nominal barrier into a manifold of barriers, due to the coupling of channels, can be obtained by accurate measurements of the cross sections by simply differentiating twice the fusion excitation functions. These distributions allow a much deeper insight into the fusion dynamics than the cross sections alone, being more directly linked to the coupled channels.

This has triggered a renewed interest for subbarrier fusion studies, and representations of barrier distributions were actually extracted for various systems involving the collision of a spherical nucleus ($^{16}O$) with a deformed target ($^{154}Sm$, $^{186}W$) [7–9]. The barrier distributions were found to be very sensitive to the nuclear deformation parameters, and the extracted values are in good agreement with those obtained, e.g., by Coulomb excitation. Such data were also successfully analyzed in terms of CC calculations employing the interacting boson model to describe the structure of the colliding nuclei [10]. Characteristic distributions are also predicted [11] for coupling to nucleon transfer channels with positive and negative $Q$ values.

More recently, nuclei without stable ground-state deformations were considered and our group performed a high-precision study of $^{58}Ni+^{60}Ni$ [12]; in this case, a barrier distribution with three clear peaks was observed, which could be explained by double-phonon couplings in both nuclei. This was surprising, since they do not have a typical vibrational structure.

It seemed to us very interesting that subbarrier fusion may preserve clear signatures of complex nuclear vibrations. Thus we decided to undertake a complete measurement of the two systems $^{32,36}S+^{110}Pd$, where the vibrational nature of the target $^{110}Pd$ is well established [13]; its lowest $2^+$ excitation lies at only 374 keV with a large $B(E2)=58$ W.u. to the ground state, and the two-quadrupole-phonon triplet is well identified, with transition strengths to the $2_1^+$ state reasonably close to the vibrational limit. Even most of the levels of the three-phonon multiplet are possibly known. The nucleus $^{36}S$ is expected to be relatively inert in the fusion process, since its $2_1^+$ level is at rather high excitation energy (3.29 MeV) with a weak transition rate to the ground state (2.7 W.u.). A relatively stronger effect is expected to come from $^{32}S$, due to the larger collectivity of its lowest $2_1^+$ state. We utilized $^{32}S$ in addition to $^{36}S$ for two reasons: (1) if the two barrier distributions turn out to be very similar, this is a further strong argument to attribute to the (common) $^{110}Pd$ degrees of freedom the main influence on fusion; (2) for $^{36}S+^{110}Pd$ all neutron transfer channels have rather large negative $Q$ values, but for $^{32}S+^{110}Pd$ the two-neutron pickup channel has $Q_{g.s.}=+5.1$ MeV and this is predicted [11] to produce a characteristic additional low-energy peak in the barrier distribution (and larger subbarrier cross sections as well). So far, the only experimental evidence of a low-energy structure associated with a positive $Q$-value transfer channel has been obtained in the study of the two systems $^{16,17}O+^{144}Sm$ [14], but no clear-cut demonstration exists of the influence of any nucleon transfer channel on fusion barrier distributions.

The experiment was performed at the XTU Tandem accelerator facility of the Laboratori Nazionali di Legnaro. Beams of $^{36(32)}S$ with energies in the range 106.5–137.1

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(102.9–129.3) MeV bombarded an 80 $\mu$g/cm$^2$ metallic layer of $^{110}$Pd, evaporated onto a thin (20 $\mu$g/cm$^2$) carbon foil. The target isotopic enrichment was 98.79% in mass 110 and beam intensities were typically 5–20 pnA. The forward recoiling evaporation residues (ER) were separated from the transmitted beam and beamlike particles by an electrostatic deflector. The ER were then identified by a time-of-flight energy telescope consisting of a microchannel plate detector and (40 cm downstream) of a Silicon surface-barrier detector. The large mass asymmetry of the two S+Pd systems allowed a beam rejection factor at 0° routinely better than $10^8$.

Four monitor detectors, placed at $\theta \simeq 30°$ symmetrically around the beam direction, were used for normalization purposes. Moreover, for each run the counts in the four monitors allowed us to establish the beam direction very accurately (to within 0.1°) and (small) deviations from the nominal 0° were taken into account in the data reduction. Also the position of the beam spot (usually 1.5 mm in diameter) on the target affects the relative counts of the monitors and the corresponding correction is possible; anyway that position (very stable) was checked at the beginning and at the end of each run by a quartz viewer, allowing to appreciate beam shifts of 0.2 mm.

The errors introduced by such maximum uncertainties on the cross section measurements are significantly smaller than the statistical ones. This overall reliability of the method is "demonstrated" by the fact that the peak structure observed in the second derivatives of the excitation functions is essentially unaffected by the small corrections for beam direction and/or beam spot position. The experimental setup is described in more detail in Ref. [15].

The ER were detected at 0° at energies increasing in $\Delta E_{\rm lab} = 0.5$ MeV steps from well below the Coulomb barrier up to $\simeq 5$ MeV above, and in larger steps at higher energies. The beam quality was given a particular care; the uncertainty in the beam energy in a Tandem accelerator is given by various contributions, among which the following: (1) the finite aperture of the entrance and exit (energy-defining) slits of the analyzing magnet, (2) changes in the ion source and focusing conditions before the analyzing magnet, which may produce small variations of the trajectories inside that magnet, and (3) possible hysteresis effects of the magnet. As reported in [16], the overall maximum uncertainty of the *absolute* beam energy of the LNL Tandem was established to be 0.13%; in the present experiment the *relative* accuracy of the sequence of measured energies was much better, since (1) the aperture of the energy-defining slits was kept as small as possible (2 mm), (2) in order to minimize the hysteresis effects, both 0° excitation functions were measured in a single sequence of runs, where the magnetic field was always decreasing, and (3) the ion source had very stable working conditions during the whole experiment. The beam energy loss in the $^{110}$Pd target was $\approx$600–650 keV, depending on the energy. Therefore the measured cross sections are anyway averaged over such an energy range which is substantially larger even than the maximum uncertainty in the absolute beam energy (130 keV at 100 MeV).

For the $^{36}$S+$^{110}$Pd system, ER angular distributions were measured in the range −9° to +4° at $E_{\rm lab}$= 112.5, 120.3, and 132.3 MeV. As found in previous cases [12,17,18], the change in width and shape of the angular distributions with beam energy can be neglected. The ER cross sections at 9° are $\simeq$1/700 of the values at 0°. For $^{32}$S+$^{110}$Pd only one angular distribution was measured at $E_{\rm lab}$= 123.3 MeV in the range −6° to +4°.

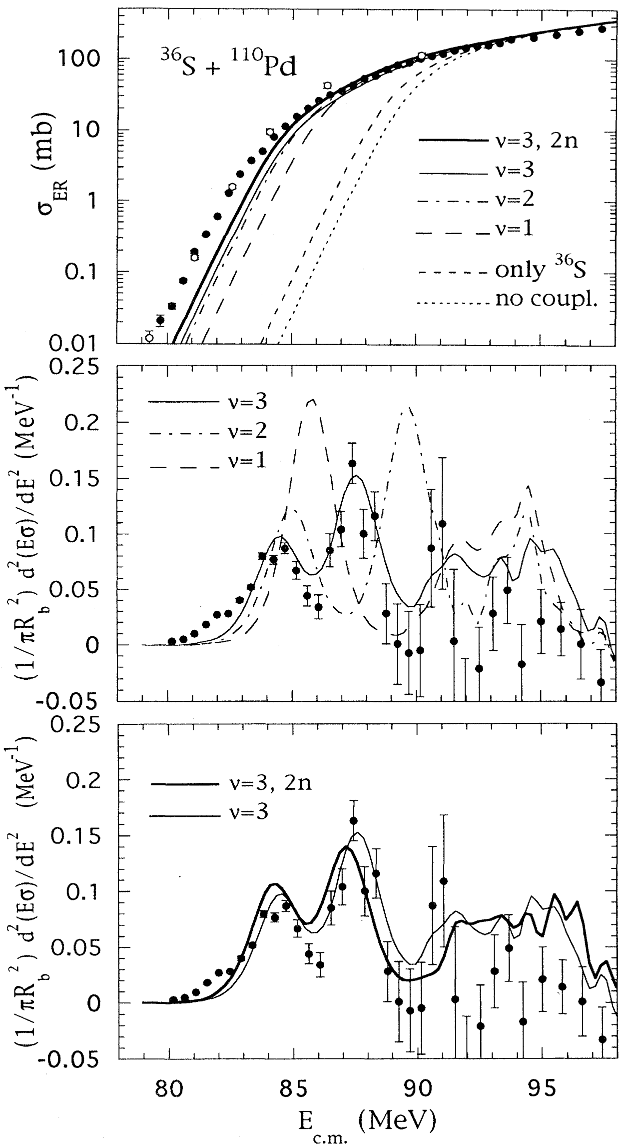


FIG. 1. Fusion excitation function (upper panel) and barrier distribution (central and lower panel) of $^{36}$S+$^{110}$Pd. The CC calculations (see text) show the effect of coupling to $\nu$= 1, 2, and 3 phonons of $^{110}$Pd, to the $2_1^+$ and $3_1^-$ states of $^{36}$S, and, in addition, to the two-neutron transfer channel (thick solid lines).

The absolute cross section normalization relies in addition on the relevant geometric solid angles ($\simeq$0.1 msr for the TOF-E telescope) and on the transmission efficiency of the electrostatic filter, which was determined to be $T$=0.45 ±0.04 (see Refs. [15,12] for details). As we are going to show, all the cross sections we obtain this way are in good agreement with previous measurements.

The two fusion excitation functions are shown in Figs. 1 and 2 (upper panels). Here the beam energy loss in the target

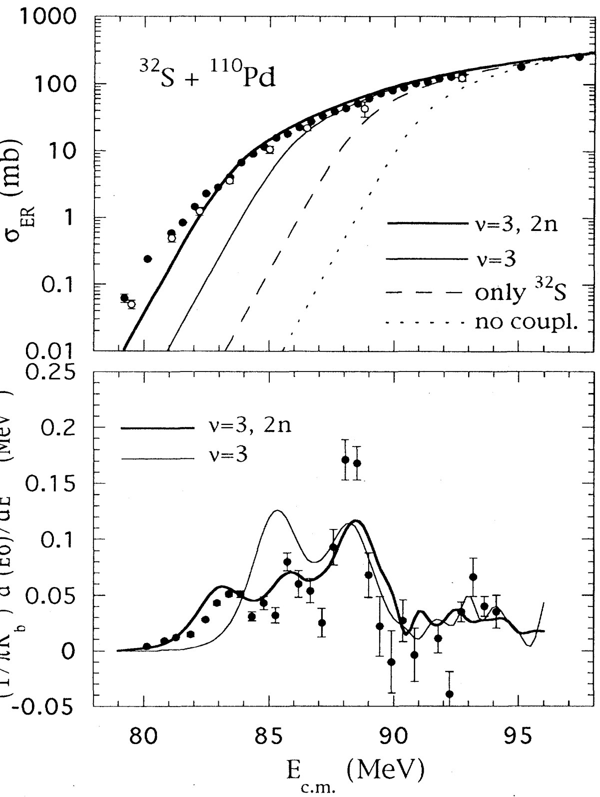


FIG. 2. Fusion excitation function and barrier distribution of $^{32}S+^{110}Pd$, compared with the results of CC calculations. See caption of Fig. 1 for more details.

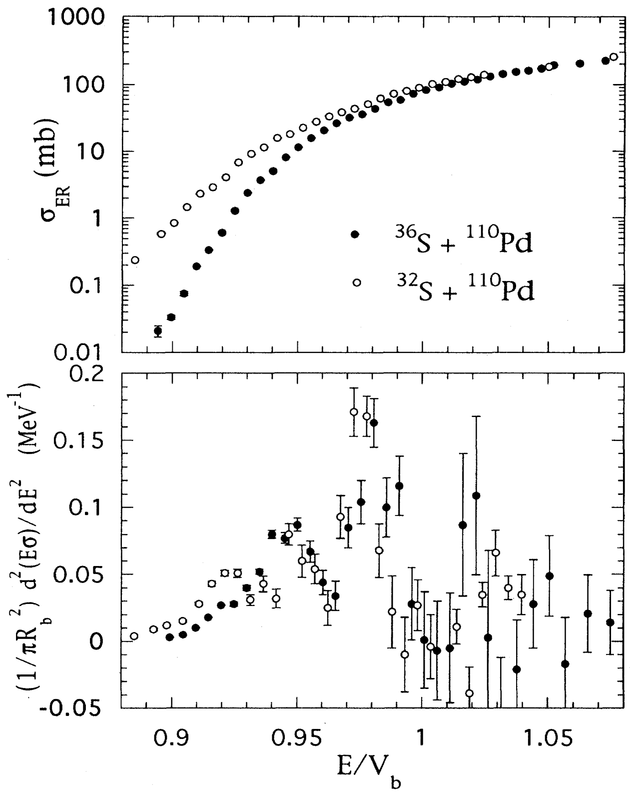


FIG. 3. Comparison of the two fusion excitation functions and barrier distributions in a reduced energy scale.

has been taken into account, as well as the target isotopic impurities. Only statistical errors are shown, which do not exceed the symbol size for most experimental points; they are $\simeq 10\%$ below the $\simeq 0.5-1$ mb level and 3–1 % at higher energies. The absolute cross section scale is estimated to be accurate to within $\pm 15\%$; the various contributions to the systematic errors come from the geometrical solid angle uncertainties, from the angular distribution integrations, and from the transmission measurements. The cross sections measured at a few energies by Pengo *et al.* [19] are shown as open symbols, and one notices a good agreement with the present data.

The second derivatives of the excitation functions are reported in the lower panels of Figs. 1 and 2; the "data" have been obtained using a point-difference formula [7], by taking every fourth experimental point of the excitation function ($\Delta E_{\mathrm{c.m.}} \simeq 1.5$ MeV). In the high energy region the beam energy step was larger (2 or 4 MeV); this is the reason why the experimental errors do not increase any more, but on the other hand possible structures of the barrier distributions are smoothed out. The second derivatives are normalized to $\pi R_b^2$, i.e., to 3871 (3746) mb for $^{36(32)}S$, $+^{110}Pd$, respectively. The unperturbed barrier parameters have been derived by using the Akyüz-Winther potential [20] [$V_b = 89.15$ (90.53) MeV, $r_b = 11.10$ (10.92) fm and $\hbar\omega = 3.73$ (3.96) MeV for $^{36(32)}S+^{110}Pd$, respectively].

A few qualitative observations need be done before considering the results of CC calculations, and our task is facilitated by a comparison of the two excitation functions and barrier distributions shown in Fig. 3. The plots are done vs the energy relative to the nominal Coulomb barrier. The fusion below the barrier is greatly enhanced for the $^{32}S$ case; this evidence was already interpreted [19,21] as due to the two-neutron transfer channel.

At variance with the apparently featureless excitation functions, the two fusion barrier distributions show an interesting shape with clearly separated peaks. Both distributions display a minimum around $E/V_b = 1.0$. For $^{32}S$ a higher barrier is probably seen at $E/V_b \approx 1.03$; the errors are too large for $^{36}S$ to establish the presence of any peak in that energy region, where at least one barrier "must" exist anyway (at least one barrier is pushed upwards in energy by the coupling mechanism). Overall, a distribution with more than three peaks [including the unobserved high-energy barrier(s)] has to be associated to the fusion process of $^{36}S+^{110}Pd$: hence two or more coupled channels contribute mainly to the reaction and, given the negligible effect of the $2^+$ level of the projectile and the largely negative $Q$ values of all transfer channels, we are naturally led to consider multiple-phonon surface vibrations of $^{110}Pd$.

For $^{32}S+^{110}Pd$ the barrier distribution is strikingly similar to the other one (thus reinforcing our speculations about the dominance of $^{110}Pd$ excitations), at least down to $E/V_b \simeq 0.93$. But a very important fact shows up at lower energies: a further barrier with non-negligible weight is clearly seen. This justifies the relative cross section enhancement (Fig. 3, upper panel), and it is tempting to associate that peculiar low-energy structure with the effect of the $2n$-transfer channel of $^{32}S+^{110}Pd$.

Simplified CC calculations have been performed using the constant coupling approximation, but considering explicitly the finite $Q$ value of the coupling channels. We have not used the CCFUS computer code, where multiphonon excitations cannot be taken into account. Rather, we diagonalize the coupling matrix at $r=r_b$ (see also Kruppa *et al.* [22]), and the resulting eigenvalues and eigenvectors are used to calculate the fusion cross section as a weighted sum of eigenchannel contributions, as, e.g., in [23]. Hill-Wheeler transmission coefficients are used, assuming that the barrier positions and curvatures are the same for all partial waves and are not changed by the coupling interactions. The nuclear potential used is the same producing the unperturbed barriers mentioned above, with parameters $V_0=71.71$ (71.41) MeV, $r_0=1.177$ (1.178) fm, and $a=0.669$ (0.672) fm for $^{32(36)}S+^{110}Pd$.

Only first-order coupling terms have been considered (the only experimental evidence of a direct connection between the two-phonon states and the ground state of $^{110}Pd$ is a very weak $2_2^+ \rightarrow 0_{g.s.}^+$ $E2$ transition of 0.82 W.u. [13]), and the form factors for inelastic excitations have been derived from the usual collective model expression [23], where the deformation lengths are simply related to the experimental $B(E\lambda)$ transition strengths. These are known both for the lowest $2^+$ and $3^-$ excitations of $^{32,36}S$ and for the one- and two-phonon vibrations of $^{110}Pd$; recently, also the $6_1^+ \rightarrow 4_1^+$ $B(E2)$ value has been measured [24] resulting not too far from the spherical harmonic-vibrator limit [25]. As our aim here, also in view of the above-mentioned approximations, is only to understand the main features of the data, we have chosen to simply represent the one-, two-, and three-phonon surface vibrations of $^{110}Pd$ in the coupling matrix by the $6_1^+ \rightarrow 4_1^+ \rightarrow 2_1^+ \rightarrow 0_{g.s.}^+$ sequence (three excitation energies and three coupling strengths); considering explicitly the full two-phonon $4_1^+$-$2_2^+$-$0_2^+$ triplet does not change qualitatively our conclusions. All coupling strengths were "experimental" ones, except the $2_1^+ \rightarrow 0_{g.s.}^+$ transition of $^{110}Pd$, for which we decided to use a larger deformation length ($\approx 33\%$ larger) to better reproduce the energy difference between the two major peaks of the barrier distribution of $^{36}S+^{110}Pd$; the modified strength was used also in the subsequent calculations for $^{32}S+^{110}Pd$. In previous analyses of low-energy fusion and scattering data [12,26,4], the authors pointed out the need of using deformation parameters larger than tabulated values.

Moreover, we have considered for both systems a two-neutron transfer channel whose form factor has been calculated according to the macroscopic formulation [27,28]

$$F_{2n}=\frac{\beta_{2n}R}{3A}\frac{dU(r)}{dr}, \qquad (1)$$

where the pair deformation parameter $\beta_{2n}$ has been adjusted to fit the data (see below).

We consider first the results of phonon couplings and in particular for $^{36}S+^{110}Pd$: the cross section enhancement over the no-coupling case (Fig. 1) is very large, and a small effect is calculated to come from the low-lying excitation of $^{36}S$, as expected. On the contrary, large enhancements are produced by the phonon couplings in $^{110}Pd$. We notice that (1) the third phonon brings a smaller effect compared to the two-phonon calculation as far as cross sections are concerned, and (2) the complete calculation still underpredicts the subbarrier data, even though a large part of the enhancement is explained. But let us now turn to the fusion barrier distributions: here the difference between the two- and three-phonon case is spectacular, and it is clear that one needs to go to the three-phonon level in order to reproduce the experimental distribution. A small bump in the data around 82 MeV explains the failure of the calculations to reproduce the low-energy cross sections. Our approximate model is not able to "produce" a barrier in that energy region, whose nature remains therefore unknown; considering four-phonon vibrations is not justified by any spectroscopic information on $^{110}Pd$, but is a possibility which deserves further (and more rigorous) investigations.

The case of $^{32}S+^{110}Pd$ is very interesting: by taking into account only the inelastic excitations of both projectile and target, we obtain predictions that are much further below the experimental subbarrier cross sections than in the case of $^{36}S$ (see Fig. 2). One notices also that the corresponding barrier distribution (thin solid line) is completely different from the experiment; it obviously resembles the corresponding calculation for $^{36}S+^{110}Pd$ (Fig. 1, lower panels), and the different weight distribution between the two main peaks is the consequence of the stronger effect of $^{32}S$ excitation.

The additional effects of two-neutron transfer couplings have been investigated for both systems. For $^{32}S+^{110}Pd$, by adding in the coupling matrix the transfer of a neutron pair from $^{110}Pd$ to the ground state and to the $2_1^+$ state of $^{32}S$ with comparable strengths, we get the curves shown as thick solid lines in the two panels of Fig. 2. Apart from the very low-energy part, the fusion excitation function is well reproduced, and the barrier distribution has three main peaks between 80 and 92 MeV with positions and strengths in rather good agreement with the data. $F_{2n}=2$ MeV was chosen, corresponding to $\beta_{2n}\simeq 7$ which is slightly smaller than the value $\beta_{2n}=9$ [28] used to reproduce the $^{58}Ni+^{64}Ni$ subbarier fusion and the $^{64}Ni(^{18}O,^{16}O)^{66}Ni$ reaction [27]. Since we consider transfer to the g.s. *and* to the $2_1^+$ state, it does not seem unreasonable that the strength is shared between the two channels to some extent. By considering $2n$ transfer to the g.s. only (besides the surface vibrations) yields a barrier distribution where the two lower energy bumps have significantly different positions and weights.

For $^{36}S+^{110}Pd$ both two-neutron pickup and stripping channels have $Q_{g.s.}\approx -2.7$ MeV. In analogy with $^{32}S$, we have considered the stripping channel $^{110}Pd(^{36}S,^{34}S)$ $^{112}Pd$ leading to the ground state and to the lowest $2^+$ state of $^{34}S$. The calculated effect on cross sections (Fig. 1) is not negligible (up to a factor 2 at low energies), but the barrier distribution does not change much; one may argue that its agreement with the data is better "without" the transfer channel.

We have neglected in the present analysis the possible role of one-nucleon transfer channels. Including them in our simplified coupling scheme is not straightforward, but we are aware of the fact that they should be anyway considered in more refined CC calculations, and could change our conclusions to some extent. A non-negligible effect may be expected from the one-neutron pickup channel in $^{32}S+^{110}Pd$, which has $Q_{g.s.}=-0.16$ MeV (see for comparison the effect of the one-neutron stripping channel in $^{17}O+^{144}Sm$, with $Q=+2.6$ MeV [14]). All other one-neutron pickup and stripping channels in both systems have large negative $Q$ values. It is quite possible that our parametrization of the two-neutron transfer form factors with adjusted strengths actually includes some contribution from the one-nucleon transfer channels.

In conclusion, we have reported here on detailed fusion cross section measurements for the two systems $^{36,32}S+^{110}Pd$. By differentiating twice the excitation functions we have extracted the fusion barrier distributions which show interesting shapes with well separated peaks. A simple analysis of the data in terms of approximate CC calculations has been performed, which indicates the dominance of $^{110}Pd$ surface vibrations up to the three-phonon level. There is a significant difference in the two barrier distributions at very low energies; this evidence is well reproduced by taking into account for $^{32}S+^{110}Pd$ the positive $Q$-value two-neutron pickup channel which also explains the relative cross section enhancement with respect to the other system. In $^{36}S+^{110}Pd$ the two-neutron transfer channel is much less important. Of course we cannot conclude that our simplified CC analysis is a unique fit to the data; the strong similarity of the barrier distributions for the two systems is an indication that the relevant degrees of freedom belong to $^{110}Pd$, but the approximate character of our CC calculations does not allow us to prove that three-phonon couplings are necessary. Moreover, the possible role of one-nucleon transfer channels, besides two-neutron transfer, should be investigated.

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