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Sub-barrier fusion enhancement due to neutron transfer

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From the analysis of appropriate experimental data within a simple theoretical model, it is shown that the intermediate neutron transfer channels with positive Q values really enhance the fusion cross section at sub-barrier energies. The effect is found to be very large, especially for fusion of weakly bound nuclei. New experiments are proposed, which may shed additional light on the effect of neutron transfer in fusion processes.

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Neutron transfer cross sections are known to be rather large at near-barrier energies of heavy-ion collisions and there is a prevailing view that coupling with the transfer channels should play an important role in sub-barrier fusion of heavy nuclei (see, for example, Ref. [1] and numerous references therein). If, however, the sub-barrier fusion enhancement caused by the rotation of statically deformed nuclei and/or by the vibration of nuclear surfaces is well studied in many experiments and well understood theoretically, the role of neutron transfer is not so clear. There are two reasons for that. First, in the experimental study of the effect of the valence neutrons, we need to compare the fusion cross sections of different combinations of nuclei, which among other things have different collective properties, and it is not so easy to single out the role of neutron transfer from the whole effect of sub-barrier fusion enhancement. Second, it is very difficult, for many reasons, to take into account explicitly the transfer channels within the consistent channel coupling (CC) approach used successfully for the description of collective excitations in the near-barrier fusion processes. As a result, we are still far from good understanding of the subject. Moreover, there is no consensus on the extent to which the intermediate neutron transfer is important in fusion reactions.

Some years ago, Stelson *et al.* [2,3] proposed an empirical distribution of barriers technique and found that many experimental data may be well described by a flat distribution of barriers with the lower-energy cutoff, which corresponds to the energy at which the nuclei come sufficiently close together for neutrons to flow freely between the target and projectile (neck formation). There is no doubt that flows of neutron matter into or out of the region between the target and projectile regulate the fusion mechanism. However, in some cases the neutron excess itself does not lead to fusion enhancement (see below, ^{48}Ca+^{48}Ca and ^{40}Ca+^{48}Ca combinations). A simple phenomenological model for a CC calculation was proposed by Rowley *et al.* [4], in which the coupling with neutron transfer channels was simulated by a parametrized coupling matrix. It was found that sequential transfers with negative Q values can lead to a broad barrier distribution consistent with a neck formation. For positive Q values, however, the results revealed an ''antinecking'' configuration. Later, using the same scheme and assuming a dominance of neutron transfers with $Q=0$, Rowley fitted very well the fusion cross section for the ^{40}Ca+^{96}Zr reaction [5]. Nevertheless, the problem of developing a consistent microscopic approach with predictive power, which could clarify unambiguously the role of neutron transfer in sub-barrier fusion processes, remains open. It is especially important for forthcoming experiments with radioactive beams of accelerated neutron-rich fission fragments.

Recently, more and more experimental evidence has emerged for additional enhancement of the sub-barrier fusion cross section due to neutron transfer with positive Q values, both in reactions with stable nuclei and especially in reactions with weakly bound radioactive projectiles. A good example of this type is shown in Fig. 1, where the fusion cross sections for the ^{40}Ca+^{48}Ca and ^{48}Ca+^{48}Ca combinations [6] are plotted as a function of the center-of-mass energy divided by the Coulomb barrier. For the more neutron rich ^{48}Ca+^{48}Ca combination, one could expect higher sub-barrier fusion enhancement compared to the ^{40}Ca+^{48}Ca reaction. The experiment gives the opposite result. Moreover, while the cross sections for ^{48}Ca+^{48}Ca can be well reproduced by CC calculations including inelastic excitations to the 2^+ and 3^- states of both nuclei, the cross sections of ^{40}Ca+^{48}Ca at deep sub-barrier energies were found much larger than the calculated ones [6]. The authors assumed that just the coupling with neutron transfer channels with positive Q values gives this additional enhancement for the ^{40}Ca+^{48}Ca combination.

Rather accurate description of sub-barrier fusion cross

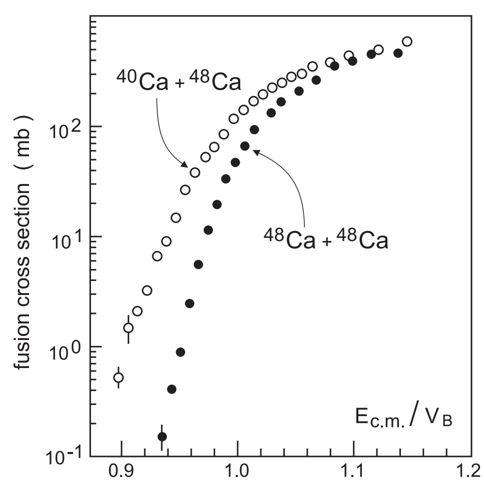

FIG. 1. Fusion cross sections for ^{40}Ca+^{48}Ca (open circles) and ^{48}Ca+^{48}Ca (filled circles) as a function of the reduced center-of-mass energy [6].

sections may be obtained within the semiempirical approach [7,8], in which the quantum penetrability of the Coulomb barrier is calculated using the concept of barrier distribution arising due to the multidimensional character of the real nucleus-nucleus interaction:

$$T(E,l)=\int f(B)P_{HW}(B;E,l)dB.$$

Here

$$P_{HW}=\frac{1}{1+\exp\left(\frac{2\pi}{\hbar\omega_B(l,E)}\left[B+\frac{\hbar^2}{2\mu R_B^2(l)}l(l+1)-E\right]\right)} \qquad (1)$$

is the usual Hill-Wheeler formula [9] for the estimation of the quantum penetration probability of the one-dimensional potential barrier with the barrier height modified to include a centrifugal term, $\hbar\omega_B(l,E)$ is defined by the width of the parabolic barrier, and R_B is the position of the barrier. The barrier distribution function $f(B)$, which satisfies the normalization condition $\int f(B)dB=1$, may be found from the multidimensional nucleus-nucleus interaction $V_{12}(r;\vec{\beta}_1,\theta_1,\vec{\beta}_2,\theta_2)$, where $\vec{\beta}=\{\beta_\lambda\}$ are the deformation parameters of the projectile and target ($\lambda=2,3,\ldots$) and $\theta_{i=1,2}$ are the orientations of statically deformed nuclei.

It is evident that the incoming flux may penetrate the multidimensional Coulomb barrier in the different neutron transfer channels. We denote by $\alpha_k(E,l,Q)$ the probability for the transfer of k neutrons at the center-of-mass energy E and relative motion angular momentum l in the entrance channel to the final state with $Q\leqslant Q_0(k)$, where $Q_0(k)$ is a Q value for the ground state to ground state transfer reaction. Then the total penetration probability may be written as

$$T(E,l)=\int f(B)\frac{1}{N_{tr}}\sum_k\int_{-E}^{Q_0(k)}\alpha_k(E,l,Q) \times P_{HW}(B;E+Q,l)dQdB, \qquad (2)$$

where $N_{tr}=[\Sigma_k\int\alpha_k(E,l,Q)dQ]$ is the normalization constant and $\alpha_0=\delta(Q)$.

In collisions of heavy nuclei for the transfer probability, one may use a semiclassical approximation (see, for example, Ref. [10]). Assuming predominance of the sequential neutron transfer mechanism, which means multiplication of transfer probabilities, one get $\alpha_k(E,l,Q)\sim e^{-2\kappa D(E,l)}$, where $D(E,l)$ is the distance of closest approach of the two nuclei and $\kappa=\kappa(\epsilon_1)+\kappa(\epsilon_2)+\cdots+\kappa(\epsilon_k)$ for sequential transfer of k neutrons, $\kappa(\epsilon_i)=\sqrt{2\mu_n\epsilon_i/\hbar^2}$ and ϵ_i is the separation energy of the ith transferred neutron. Experiments show that the transfer probability becomes very close to unity at a short distance between the two nuclei, when their surfaces are rather overlapped. We denote this distance by $D_0=d_0(A_1^{1/3}+A_2^{1/3})$ and will use for parameter d_0 the value of about 1.40 fm [10]. It is also well known that in heavy-ion few-nucleon transfer reactions the final states with $Q\approx Q_{opt}$ are populated with largest probability due to mismatch of incoming and outgoing waves. For neutron transfer Q_{opt} is close to zero.

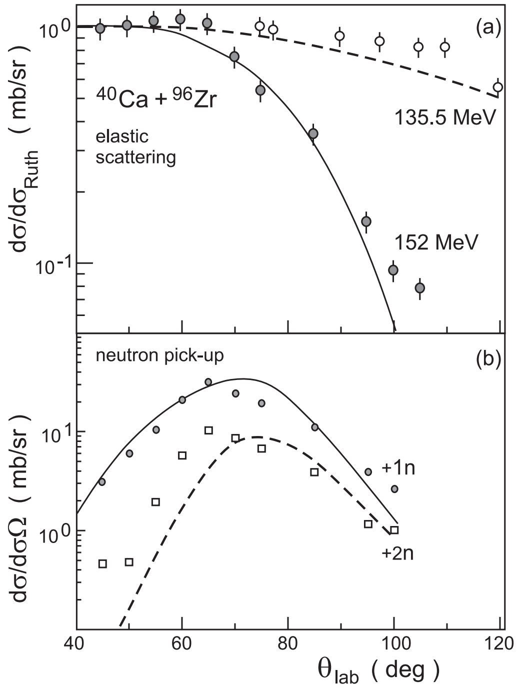

FIG. 2. Elastic scattering and neutron transfer angular distributions for $^{40}Ca+^{96}Zr$ [12]. (a) Elastic scattering cross sections at laboratory energies of 152 MeV (filled circles and solid curve) and 135.5 MeV (open circles and dashed curve). (b) Inclusive one-neutron (circles and solid line) and two-neutron (squares and dashed line) transfer cross sections at $E_{lab}=152$ MeV.

The Q window may be approximated by the Gaussian $\exp(-C[Q-Q_{opt}]^2)$ with the constant $C=R_B\mu_{12}/\kappa\hbar^2(2E-B)$ [11], where μ_{12} is the reduced mass of the two nuclei in the entrance channel. Finally, the transfer probability may be estimated in the following way:

$$\alpha_k(E,l,Q)=N_k e^{-C[Q-Q_{opt}]^2}e^{-2\kappa[D(E,l)-D_0]}, \qquad (3)$$

where $N_k=\{[\int_{-E}^{Q_0(k)}\exp(-C[Q-Q_{opt}]^2)dQ\}^{-1}$ and the second exponent has to be replaced by 1 at $D(E,l)<D_0$.

Of course, this formula is very simplified. For multineutron transfer an additional enhancement factor was found [10] (probably caused by simultaneous transfer of neutron pairs), which may increase the transfer probability compared to formula (3). It is not so well defined and is ignored here. At positive Q values there are neutron transfers to the discrete single particle states. However, in heavy nuclei the single particle strength functions, which are products of spectroscopic factors and level density (quantities needed for a proper description of neutron transfer to specific states), are usually spread over some energy regions with typical widths of several MeV and overlap with each other. As a result, in spite of all the simplifications, expression (3) gives a reasonable agreement with experimental data on inclusive near-barrier neutron transfer cross sections, which may be estimated as $\sigma_{tr}^{kn}(E,\theta)=\sigma_{el}(E,\theta)\int\alpha_k(E,l,Q)dQ$ with $l=l_{Ruth}(\theta)$ assuming Coulomb trajectories. This cross section implies summation over the all final states of residual nucleus. An experiment of such kind was performed for the

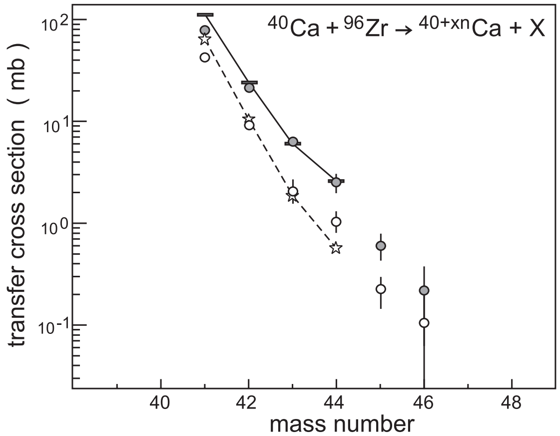

FIG. 3. Total neutron transfer cross sections for ^{40}Ca+^{96}Zr [12] at $E_{lab}=152$ MeV (filled circles) and $E_{lab}=135.5$ MeV (open circles). The strips and stars show the calculated cross sections.

^{40}Ca+^{96}Zr reaction [12]. In Fig. 2 experimental [12] and calculated elastic scattering and neutron transfer angular distributions are shown for ^{40}Ca+^{96}Zr. The elastic scattering cross section was calculated with the same ion-ion potential used below for the analysis of fusion process in this combination. An absorptive potential was added (with $W_0=-10$ MeV, $r_0=1.22$ fm, and $a_W=0.85$ fm) to reproduce the decrease of elastic scattering cross section at large angles at above-barrier energies. In Fig. 3 the total neutron transfer cross sections are shown, demonstrating a qualitative agreement of the simplified expression (3) with the experimental data.

From Eq. (2), one can see that in the reactions with negative values of all $Q_0(k)$ there is no *additional* enhancement of the total penetration probability of the Coulomb barrier $T(E,l)$ due to the neutron transfer in the entrance channel, because the "partial" penetration probability $P_{HW}(B;E+Q,l)$ becomes smaller for negative Q values. It means that neutron transfers with zero and/or negative Q values (most probable processes) play their role and lead to some regular fusion probability. If, however, $Q_0(k)$ are positive for some channels, in spite of the lower transfer probability to the states with positive Q values compared to $Q=0$, the penetration probability may significantly increase due to a gain in the relative motion energy for $Q>0$. In other words, an intermediate neutron transfer to the states with $Q>0$ is, in a certain sense, an "energy lift" for the two interacting nuclei. This looks quite different from the well-known fusion enhancement due to surface vibrations or rotation of nuclei leading to decrease of potential barrier in some channels. However, having in mind the driving potential of dinuclear system depending in addition on neutron transfer (or mass asymmetry), the above mentioned gain in the relative motion energy may be interpreted in the usual way as a decrease of the driving potential in some neutron transfer channels.

Using for the 2^+ and 3^- excited states of ^{40,48}Ca and for the ion-ion potentials the same parameters as in Ref. [6], we repeated the CC calculations for the ^{48}Ca+^{48}Ca and ^{40}Ca+^{48}Ca fusion reactions. As in Ref. [6], the calculated cross section was found to be lower compared to the experimental data for ^{40}Ca+^{48}Ca at deep sub-barrier energies, whereas quite satisfactory agreement was obtained for ^{48}Ca+^{48}Ca. The semiempirical calculation of the fusion cross section [7,8] gives the same result (see Fig. 4). Contrary to the ^{48}Ca+^{48}Ca combination, where the values of $Q_0(k)$ are negative in all the neutron transfer channels, for the ^{40}Ca+^{48}Ca reaction $Q_0(2n)=+2.6$ MeV and $Q_0(4n)=+3.9$ MeV. It means that in its intermediate channels (^{42}Ca+^{46}Ca) and (^{44}Ca+^{44}Ca) the system has a gain in energy, which may increase the penetration probability of the Coulomb barrier. Indeed, as can be seen from Fig. 4, the neutron transfer leads to a noticeable increase in the fusion cross section at sub-barrier energies and gives much better agreement with the experiment. Looking at the barrier distribution functions (bottom panel of Fig. 4), we may see that the neutron transfer does not simply smooth this function but makes it very asymmetric with a long high-energy tail.

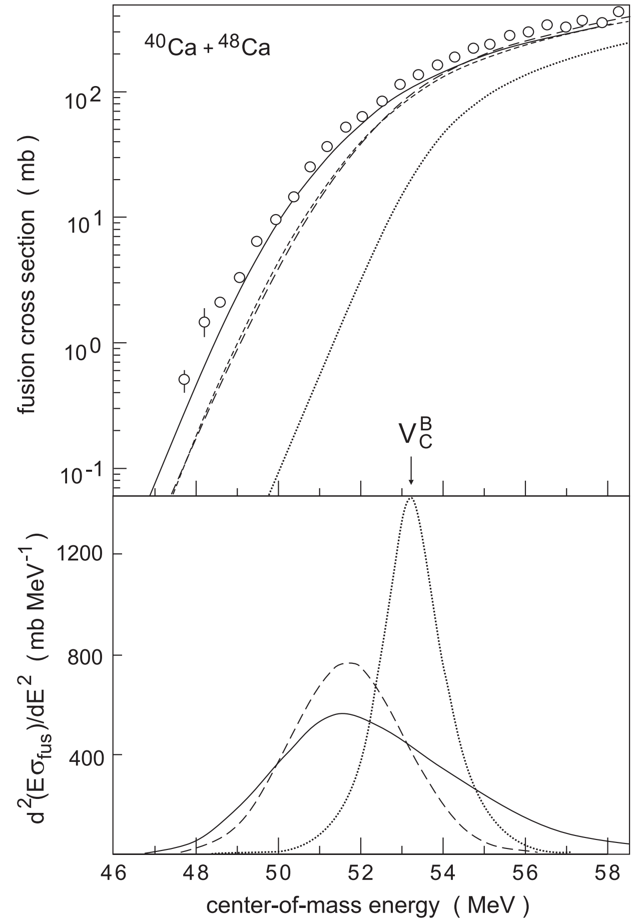

FIG. 4. Fusion cross section [6] (top panel) and barrier distribution functions (bottom panel) for ^{40}Ca+^{48}Ca. The short and long dashed curves correspond to CC [13] and semiempirical [7,8] calculations without neutron transfer. The solid line shows the effect of $2n$ ($Q_0=+2.6$ MeV) and $4n$ ($Q_0=+3.88$ MeV) transfer in the entrance channel. No-coupling limit is shown by dotted curve.

Even higher neutron transfer Q_0 values (+0.51 Mev, +5.53 Mev, +5.24 Mev, and +9.64 Mev for one, two, three, and four neutron transfer channels, respectively) are in the ^{40}Ca+^{96}Zr reaction. The near-barrier fusion cross sec-

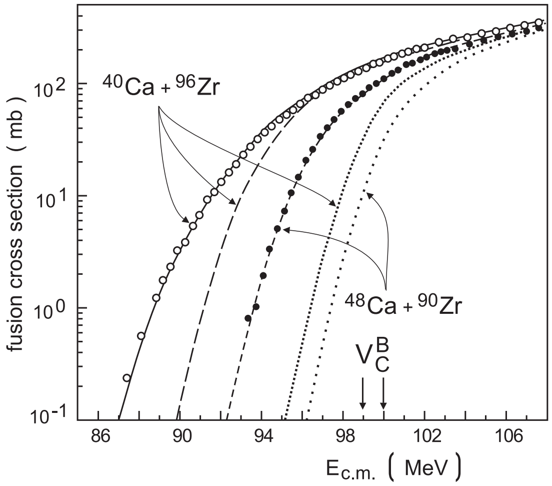

FIG. 5. Fusion excitation functions for ^{40}Ca+^{96}Zr (open circles) and ^{40}Ca+^{90}Zr (filled circles) [14]. The no-coupling limits are shown by the dotted curves. The dashed curves show the semi-empirical calculations without neutron transfer, whereas the solid line was obtained taking into account neutron transfer in the entrance channel of the ^{40}Ca+^{96}Zr reaction.

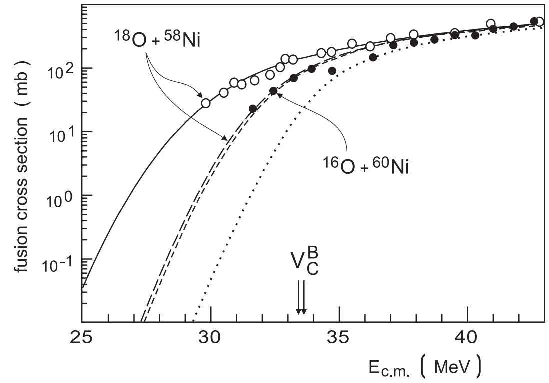

FIG. 6. Fusion excitation functions for ^{18}O+^{58}Ni (open circles) and ^{16}O+^{60}Ni (filled circles) [15]. The no-coupling limit is shown by the dotted curve (it is practically the same for both cases). The dashed curves show the calculations without neutron transfer. The solid line was obtained with formulas (2) and (3).

tions for this reaction have been measured in Ref. [14] in comparison with the ^{40}Ca+^{90}Zr combination and a great difference between the two combinations has been found (see Fig. 5). Using the "proximity" ion-ion potential (which gives the corresponding Coulomb barriers $B_0 = 99$ MeV and $B_0 = 100$ MeV for ^{40}Ca+^{90}Zr and ^{40}Ca+^{96}Zr spherical nuclei), the quadrupole and octupole vibration properties of ^{40}Ca and ^{90,96}Zr (see, for example, Ref. [14]), one can reproduce quite well the experimental fusion cross sections for ^{40}Ca+^{90}Zr without any coupling with transfer channels. We failed to do the same in the case of ^{40}Ca+^{96}Zr. However, if the neutron transfer is taken into account by means of formulas (2) and (3), the calculated cross sections agree quite well with the experiment (see Fig. 5). The effect here arises mainly from one- and two-neutron transfer channels and it is much larger than in the case of ^{40}Ca+^{48}Ca, because the transfer probability at sub-barrier energies sharply decreases with increasing the number of transferred neutrons.

While trying to find experimentally the neutron transfer effect in fusion processes, one should be careful in the choice of the two combinations to be compared in order to avoid additional changes in the fusion cross sections, which may originate from some other effects. In this connection, such combinations as ^{18}O+^{58}Ni and ^{16}O+^{60}Ni leading to the same compound nucleus are very interesting because the vibration properties of ^{58}Ni (2^+, 1.45 MeV, $\beta_2 = 0.183$) and of ^{60}Ni (2^+, 1.33 MeV, $\beta_2 = 0.207$) are very close and the ion-ion interaction potentials have to be also very close. In contrast with ^{16}O+^{60}Ni, the neutron transfer Q_0 values are positive and rather large in the ^{18}O+^{58}Ni reaction: $Q_0(1n) = +0.96$ MeV and $Q_0(2n) = +8.20$ MeV. Unfortunately, the fusion cross sections for these two combinations have been measured only at near-barrier energies [15]. Nevertheless, the effect of one- and two-neutron transfer in the entrance channel of the ^{18}O+^{58}Ni fusion reaction is large and well visible (see Fig. 6).

One may expect a stronger effect from the neutron transfer with positive Q values in fusion reactions of radioactive weakly bound projectiles with stable target nuclei. Inspiring experiments of such kind have already been performed using the ^{6}He beam [16–18], demonstrating in general terms an enhancement of the fusion probability for ^{6}He compared to ^{4}He. However, again it is rather difficult to interpret unambiguously the results of these experiments. In the fusion-fission reactions (such as ^{6}He+^{238}U [18]), one has to distinguish the processes of complete and incomplete fusion of the projectile. Comparing the evaporation residue (ER) cross sections in the ^{6}He+^{209}Bi and ^{4}He+^{209}Bi fusion reactions [17], one has to take into account that different compound nuclei are obtained in these reactions with different excitation energies and different decay properties. To avoid additional ambiguities, one may propose to measure the ER cross sections in reactions, in which the same compound nucleus is formed, such as $^6\mathrm{He}+A \rightarrow C$ and $^4\mathrm{He}+(A-2) \rightarrow C$, for example. In that case any difference in the ER cross sections may originate only from the difference in the entrance channels of the two reactions.

The promising reactions of such type are ^{6}He+^{206}Pb and ^{4}He+^{208}Pb with the formation of α-decayed ^{212}Po compound nucleus. In the first combination there are intermediate neutron transfer channels with very large positive Q values: $^6\mathrm{He}+{}^{206}\mathrm{Pb} \rightarrow {}^5\mathrm{He}+{}^{207}\mathrm{Pb}$ ($Q_0 = 4.9$ MeV)$\rightarrow {}^4$He $+{}^{208}$Pb ($Q_0 = 13.1$ MeV)$\rightarrow {}^{212}$Po. Of course, as mentioned above, the probability for neutron transfer to the ground states is rather small, but the total possible gain in energy is very high as compared with the height of the Coulomb barrier (which is about 20 MeV) and has to reveal itself in the fusion probability of ^{6}He compared to ^{4}He.

To calculate the ER cross sections for these combinations, we used the Woods-Saxon type potentials for ^{4}He+^{208}Pb ($V_0 = -96.44$ MeV, $R_V = 8.15$ fm, $a_V = 0.625$ fm [19]) and for ^{6}He+^{206}Pb ($V_0 = -109.5$ MeV, $R_V = 7.83$ fm, $a_V = 0.811$ fm, proposed in Ref. [20] for low-energy ^{6}Li scattering), which give the corresponding fusion barriers $B_0 = 20.6$ MeV (at $R_B = 10.8$ fm) and $B_0 = 19.4$ MeV (at $R_B = 11.2$ fm). The vibration properties of ^{208}Pb

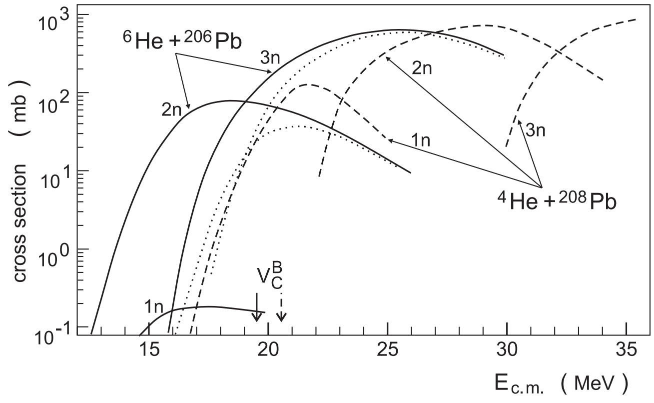

FIG. 7. Excitation functions for the production of evaporation residues in the ^{6}He+^{206}Pb (solid curves) and ^{4}He+^{208}Pb (dashed curves) reactions. Dotted curves show the $2n$ and $3n$ evaporation channels in the ^{6}He+^{206}Pb fusion reaction calculated ignoring the neutron transfer channels.

(3^-,2.61 MeV, $\beta_3=0.16$) and ^{206}Pb (2^+,0.80 MeV, $\beta_2=0.04$) were also taken into account to find the barrier distribution function $f(B)$, though it plays a minor role here. The calculated ER cross sections for both reactions are shown in Fig. 7. As can be seen, the effect of the intermediate neutron transfer channels in the ^{6}He+^{206}Pb fusion reaction is very large and may enhance the fusion cross section by several orders of magnitude at deep sub-barrier energies. We ignored here the influence of the breakup channel on the fusion of ^{6}He. However, at sub-barrier energies the breakup channels seem to play not such an important role as the neutron transfers [21].

Many other combinations of stable and unstable nuclei should reveal a noticeable enhancement of the sub-barrier fusion cross sections due to intermediate neutron transfer with positive Q values. They are ^{40,48}Ca+^{124,116}Sn, ^{16,18}O+^{42,40}Ca, ^{9,11}Li+^{208,206}Pb, and many others, which have positive Q_0 values of the $1n$ and/or $2n$ transfer channels for one combination and negative or zero Q_0 values for another one. A direct comparison of the corresponding experimental fusion cross sections has to display immediately such an enhancement.

Note, in conclusion, that the method proposed is rather simplified. However, it takes into account approximately the main effect of neutron transfer with positive Q values, agrees reasonably with experiment, and has a predictive power. There is no doubt that a more sophisticated consideration of neutron transfer in sub-barrier fusion processes is needed. However, for many reasons, it is rather difficult to perform with a high accuracy. Three-body time-dependent Schrödinger equation and/or transport theories could be used for that.

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