Sequential Fusion: Sub-barrier Fusion Enhancement Due to Neutron Transfer

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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. If, however, the sub-barrier fusion enhancement caused by rotation of statically deformed nuclei and/or by vibration of the 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 with each other 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.

Recently more and more experimental evidence appears 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. Example of this type is shown in Fig. 1, where the fusion cross sections for the \(^{40}\text{Ca}+^{48}\text{Ca}\) and \(^{48}\text{Ca}+^{48}\text{Ca}\) combinations [1] are plotted as a function of the reduced center-of-mass energy.

In [2-4] a new approach was proposed for description of the near-barrier fusion of nuclei with intermediate neutron transfer. Let the projectile \(a=(b+n)\) has a valence neutron, which moves much faster than the relative motion of colliding nuclei \(a+A\). This neutron can be transferred from the projectile \(a\) to the target \(A\) before the nuclei overcome the Coulomb barrier and come in contact. If the neutron is transferred with a negative \(Q\)-value, the relative motion of the nuclei \(b\) and \(B=(A+n)\) becomes slower and at initial sub-barrier energy these nuclei will re-separate giving a contribution to the cross section of normal transfer process, which dominates at sub-barrier energies. If, however, the valence neutron is transferred to the states with positive \(Q\)-values (if they are), then the nuclei \(b\) and \(B\) get a gain in kinetic energy and may overcome the Coulomb barrier with larger probability giving a contribution to the fusion cross section. This process can be called sequential fusion.

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 \(Q \leq Q_0(k)\), 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

\[
T(E,l) = \int f(B) \frac{1}{N_p} \sum \int \alpha_k(E,l,Q) \times P_{\text{H}}(B;E+Q,l)dQdB
\]

Where \( f(B) \) is the barrier distribution function (calculated without neutron transfer effect), \( N_p = \sum \int \alpha_k(E,l,Q)dQ \) is the normalization constant, \( P_{\text{H}} \) is the usual Hill-Wheeler penetration probability, and \( \alpha_0 = \delta(Q) \). In collision of heavy nuclei for the transfer probability one may use a semiclassical approximation

\[
\alpha_k(E,l,Q) = N_k e^{-CQ-\delta_{\text{sep}}} e^{-2\kappa[D(E,l)-D_b]},
\]

where \( \kappa \) is defined by the neutron separation energy, and \( D(E,l) \) is the distance of closest approach.

From Eq.(1), 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 \( P_{\text{H}}(B;E+Q,Q,l) \) 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 (see schematic Fig. 3). 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.

Rather high neutron transfer \( Q_0 \)-values (+0.51 MeV, +5.53 MeV, +5.24 MeV, and +9.64 MeV for 1, 2, 3, and 4 neutron transfer channels, respectively) are in the \( ^{40}\text{Ca}+^{96}\text{Zr} \) reaction. The near-barrier fusion cross sections for this reaction have been measured in [5] in comparison with the \( ^{40}\text{Ca}+^{99}\text{Zr} \) combination and a great difference between the two combinations has been found (Fig. 2). Using the “proximity” ion-ion potential (which gives the corresponding Coulomb barriers \( B_0=99 \) MeV and \( B_0=100 \) MeV for \( ^{40}\text{Ca}+^{96}\text{Zr} \) and \( ^{40}\text{Ca}+^{99}\text{Zr} \) spherical nuclei), the quadrupole and octupole vibration properties of \( ^{40}\text{Ca} \) and \( ^{90,96}\text{Zr} \) (see, for example, [5]), one can reproduce quite well the experimental fusion cross sections for \( ^{40}\text{Ca}+^{90}\text{Zr} \) without any coupling with transfer channels. We failed to do the same in the case of \( ^{40}\text{Ca}+^{96}\text{Zr} \). However, if the neutron transfer is taken into account, the calculated cross sections agree quite well with the experiment (Fig. 2). The effect comes mainly from one and two-neutron transfer channels and it is much larger than in the case of \( ^{40}\text{Ca}+^{48}\text{Ca} \) because the transfer probability at sub-barrier energies sharply decreases with increasing the number on transferred neutrons.

Even stronger effect from the intermediate neutron transfer with positive \( Q \)-values one may expect in fusion reactions of radioactive weakly bound projectiles with stable target nuclei. Inspiring experiments of such kind have been already performed using the \( ^6\text{He} \) beam demonstrating in general terms an enhancement of the fusion probability for \( ^6\text{He} \) compared to \( ^4\text{He} \). However, again it is rather difficult to interpret unambiguously the results of these experiments. In the fusion-fission reactions (like \( ^6\text{He}+^{238}\text{U} \) one has to distinguish the processes of complete and incomplete fusion of the projectile. Comparing the evaporation residue
(ER) cross sections in the $^{6}\text{He}+^{209}\text{Bi}$ and $^{4}\text{He}+^{206}\text{Bi}$ fusion reactions, 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 $^{6}\text{He}+\text{A} \rightarrow \alpha \text{C}$ and $^{4}\text{He}+(\text{A}-2) \rightarrow \alpha \text{C}$, 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 $^{6}\text{He}+^{206}\text{Pb}$ (see schematic Fig. 3) and $^{4}\text{He}+^{208}\text{Pb}$ with formation of the same $\alpha$-decayed $^{212}\text{Po}$ compound nucleus, which were proposed to be studied in [2-4]. In the first combination there are intermediate neutron transfer channels with very large positive $Q$-values: $^{6}\text{He} + ^{206}\text{Pb} \rightarrow ^{5}\text{He} + ^{207}\text{Pb} (Q_0 = 4.9 \text{ MeV}) \rightarrow ^{4}\text{He} + ^{208}\text{Pb}(Q_0 = 13.1 \text{ MeV}) \rightarrow ^{212}\text{Po}$. As mentioned above, the probability for neutron transfer to the ground states are 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 $^{6}\text{He}$ compared to $^{4}\text{He}$.

The predicted cross sections for both reactions are shown in Fig. 4. As can be seen the effect of the intermediate neutron transfer channels in the $^{6}\text{He}+^{206}\text{Pb}$ fusion reaction is very large and may enhance the fusion cross section by several orders of magnitude at deep sub-barrier energies.

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 $^{12,14}\text{C}+^{42,40}\text{Ca}$, $^{16,18}\text{O}+^{42,40}\text{Ca}$, $^{40,48}\text{Ca}+^{124,116}\text{Sn}$, $^{9,11}\text{Li}+^{208,206}\text{Pb}$, 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. Direct comparison of the corresponding experimental fusion cross sections has to display immediately such an enhancement.

Additional enhancement in sub-barrier fusion of weakly bound neutron rich nuclei can be used, in principle, for synthesis of new super-heavy nuclei in reactions with radioactive beams. There are, for example, $^{26}\text{F}+^{248}\text{Cm} \rightarrow ^{271}\text{Db}+3\text{n} (Q_{1n-4n} = 3.7 / 5.2 / 5.7 / 3.8 \text{ MeV})$, $^{30}\text{Na}+^{248}\text{Cm} \rightarrow ^{275}\text{Hs}+3\text{n} (Q_{1n-4n} = 2.6 / 4.0 / 4.9 / 3.8 \text{ MeV})$, $^{34}\text{Mg}+^{248}\text{Cm} \rightarrow ^{279}\text{Hs}+3\text{n} (Q_{1n-4n} = -0.1 / 3.7 / 2.5 / 5.7 \text{ MeV})$, $^{37}\text{Si}+^{248}\text{Cm} \rightarrow ^{282}\text{Hs}+3\text{n} (Q_{1n-4n} = 2.5 / 2.2 / 4.2 / 2.4 \text{ MeV})$. However, the corresponding cross sections for ER production are rather small here due to a low survival probability of easily fissionable heavy compound nuclei, and beam intensity has to be higher than $10^8$ pps in all these reactions.

**REFERENCES**