Fusion enhancement with loosely bound nuclei on different targets

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Introduction

In low-energy nuclear reactions, one of the fields where structure and dynamics are more directly connected is sub-barrier heavy-ion fusion processes. The dynamical coupling to the internal degrees of freedom of the two fusing partners drives the behavior of these reactions at energies below the barrier. The proper description of a fusion process, therefore, is essentially demanding to single out the relevant coupled channels involved and to determine the associated diagonal and coupling potentials. This makes the situation with weakly bound nuclei more complex, due to the non trivial inclusion of the strongly coupled continuum break-up channels and the consequent opening of final three-body (or four, in the case of two-particle halo nuclei) channels. This had led from a theoretical point of view of diverging results on the enhancement/suppression of the fusion probabilities, and to extremely difficult experimental measurements to determine (and separate) different fusion and reaction channels. In a fully treated coupled-channel description, it is not easy to single out the role of specific issues. One of these is the possible role of the charged break-up channels in proton-halo nuclei with respect to the more common neutron break-up channels in neutron-halo nuclei. For this reason, recently we introduced a very simplified two-channel model [1], the first being the entrance channel and the second representing the full set of continuum break-up channels. In this channel we neglect the ejected particle (neutron or proton) and properly rescale energies and ion-ion potential. Our model was applied, as representative cases of neutron or proton halos, to the fusion with ^{58}Ni of either ^{11}Be and ^{8}B. In the present work, calculation are shown for the fusion cross-section for beams of ^{11}Be and ^{8}B on ^{28}Si. Comparison is also made with the case of ^{58}Ni as target in reference to below barrier fusion enhancement.

The Model

Fusion probabilities are calculated by solving the corresponding coupled-channel equations under incoming-wave boundary conditions (IWBC). The coupled-channel formalism for direct reaction processes given by Austern [2] expands the total wave function in terms of the wave function for the internal state of the projectile ϕ_β and the radial wave functions χ_β that accounts for the relative motion between projectile and target:

$$\Psi^{(+)} = \Sigma_\beta \frac{\chi_\beta(R)}{R}\phi_\beta. \qquad (1)$$

This leads to a set of coupled equations for the radial wave functions:

$$\frac{d^2\chi_\beta}{dR^2}+\frac{2\mu_\beta}{\hbar^2}[E_\beta - V_\beta^{eff}(R)]\chi_\beta = \frac{2\mu_\beta}{\hbar^2}\Sigma_{\alpha\neq\beta}V_{\beta\alpha}^{coup}(R)\chi_\alpha \qquad (2)$$

In these expression V is the interaction potential while, for a given channel β, μ_β is the reduced mass, and E_β is the relative energy. The coupling potential V_{coup} is given as a derivative Woods Saxon form with same radius and diffuseness of the proximity potential for the incoming channel. The strength is set to a 10% of the strength of the same proximity potential.

The total transmission probability is then given by,

$$T = \sum_\beta \mid T_\beta^2 \mid = |t_1|^2 + \frac{v_2}{v_1}|t_2|^2 \qquad (3)$$

where v_1 and v_2 are the velocities corresponding to channel 1 and 2.

The fusion cross-section, in terms of partial waves, is given by

$$\sigma = \sum_{\ell=0}^{\ell_{max}} \sigma_\ell = \frac{\pi\hbar^2}{2\mu_1 E}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)T_\ell(E). \quad (4)$$

The probability of transmission for the partial wave can also be calculated simply by a shift of energy,

$$T_\ell \cong T_0\left[E - \frac{\ell(\ell+1)\hbar^2}{2\mu_1 r_0^2}\right], \quad (5)$$

where r_0 is the position of the barrier for the s-wave. For further details see Ref. [1].

Calculations and Discussion

The cross section of the fusion reactions involving ^{8}B and ^{11}Be beams and target of ^{28}Si are calculated. For each reaction, we compare the situation without break-up, where there is no coupling to the second channel, with the possibility of coupling to the break-up channel. In both cases, and as a result of this coupling, a certain enhancement is found. In order to compare the reactions with both cases appropriately, we show in Fig. 1, a reduced fusion cross sections in terms of the collision radius of each reaction versus the energy divided by the estimated Coulomb barrier. This is also compared with that of ^{58}Ni case taken from Ref. [1]. As expected, the two no-coupling cross sections coincide approximately, whereas the coupling cases show different results. Here, it is clearly seen that for the case of ^{58}Ni as target the proton break-up case has a larger cross section at low energies. However for the case of ^{28}Si as target, it is observed that there is no prominent enhancement for the proton break-up.

For below barrier energies, a clear difference between the proton and neutron induced effects on fusion is found for both targets, ^{58}Ni and ^{28}Si. In the proton case, the secondary barrier is below the barrier in the incoming channel and so it allows a larger enhancement at low energies. It is concluded that proton enhancement is proportional to the Coulomb barrier and therefore is more clear in heavy targets like Ni. Thus the enhancement due to proton or neutron breakup also depends on the target used. It would be of interest to find the range of mass number for which there is prominent enhancement due to proton breakup as compare to neutron case.

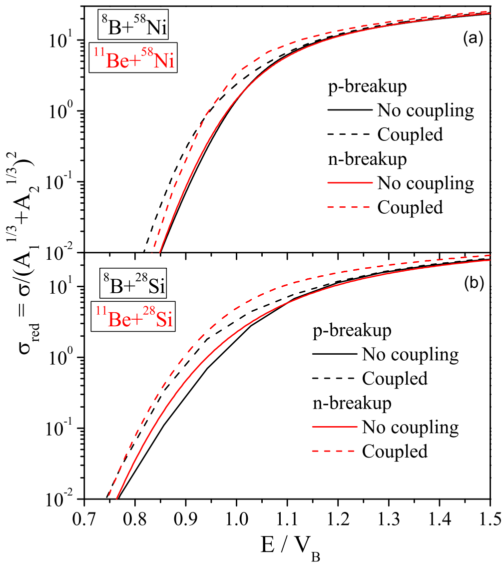

FIG. 1: (a) Cross section divided by the square of the interaction radius versus the energy divided by the estimation of the Coulomb barrier in the incoming channel (V_B) for ^{8}B+^{58}Ni and ^{11}Be+^{58}Ni fusion reactions. We compare the no coupling cases for both reactions (solid line) with the proton (dotted line) and neutron (dashed line) break-up cases. (b) same as part (a) but for ^{28}Si as target.

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References

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[2] N. Austern *et. al*, Phys. Rep. **154**, 125 (1987).