Effects of nuclear induced breakup on the fusion of ^{6}Li+^{12}C system around barrier energies

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The availability of the energetic beams of loosely bound nuclei lying in the close proximity of drip lines has created a renewed interest in nuclear reaction studies. Among all the possible reaction channels the fusion of loosely bound radioactive ions with the stable targets is of immense importance in conjugation with the production of super heavy elements and the reactions of astrophysical interest. Recently, many efforts have already been made to study the static as well as dynamic effects arising because of large size and high probability of breakup of loosely bound nuclei on fusion cross section. However regarding the dynamic effects of breakup on fusion reaction cross section, very conflicting results have been reported [1]. Hence it needs further investigation.

Here we have used the dynamic polarisation potential (DPP) approach to study the nuclear induced breakup effect on fusion of weakly bound nuclei [2]. In order to derive an explicit expression of breakup DPP induced by strong nuclear interaction between the projectile and target, let us consider the collision of a weakly bound projectile consisting of fragments '*b*' and '*c*', with a light target. The nuclear coupling interaction after carrying out a multipole expansion, can be written as.

$$V^{N}(\mathbf{r},\mathbf{x}) = 4\pi U_{PT}^{N}(\mathbf{r})\left\{\sum_{l,m}(i)^{l}\,Y_{lm}^{*}(\hat{\mathbf{r}})Y_{lm}(\hat{\mathbf{x}})\right\}\left[exp\left(-\left[\frac{m_b\mathbf{x}}{m_P a}\right]^{2}\right)\right]j_l\left(i2\frac{m_b\mathbf{r}\,\mathbf{x}}{m_P a^{2}}\right)$$
$$+(-1)^{l}\,4\pi U_{PT}^{N}(\mathbf{r})\left\{\sum_{l,m}(i)^{l}\,Y_{lm}^{*}(\hat{\mathbf{r}})Y_{lm}(\hat{\mathbf{x}})\right\}\left[exp\left(-\left[\frac{m_c\mathbf{x}}{m_P a}\right]^{2}\right)\right]j_l\left(i2\frac{m_c\mathbf{r}\,\mathbf{x}}{m_P a^{2}}\right)$$
$$-4\pi U_{PT}^{N}(\mathbf{r}) \tag{1}$$

The nuclear polarization potential is given by

$$U_l^{Pol}(\mathbf{r},\mathbf{r}') = \left(\frac{F_1(\mathbf{r},\mathbf{r}') + 2F_2(\mathbf{r},\mathbf{r}')}{2}\right)$$
$$\times\left[\left\{-i\frac{2\mu}{\hbar^{2}k}\left|S_l^{opt}\right|Sin\left(k\mathbf{r}-\frac{l\pi}{2}+\delta_l^{N}\right)Sin\left(k\mathbf{r}'-\frac{l\pi}{2}+\delta_l^{N}\right)\right\}\right] \tag{2}$$

where

$$F_1(\mathbf{r},\mathbf{r}') = -(4\pi)^{2}U_{PT}^{N}(\mathbf{r})U_{PT}^{N}(\mathbf{r}')$$
$$\times\int|\phi_0(\mathbf{x})|^{2}\sum_{m,m'}V_{j,1}^{N}(\mathbf{r},\mathbf{x})\,V_{j,1}^{N}(\mathbf{r}',\mathbf{x})\,d\mathbf{x} \tag{3}$$

$$F_2(\mathbf{r},\mathbf{r}') = (4\pi)^{3}U_{PT}^{N}(\mathbf{r})U_{PT}^{N}(\mathbf{r}')\int|\phi_0(\mathbf{x})|^{2}\mathbf{x}^{2}d\mathbf{x} \tag{4}$$

(where the symbols are same as defined in Ref. [3]). The optical *S*- matrix is calculated in the same way as in Ref. [4]. The breakup polarization potential is obtained numerically by using Eq. (2) in the following relation

$$U_l^{bu}(\mathbf{r}) = \frac{1}{u_l(k\mathbf{r})}\int U_l^{Pol}(\mathbf{r},\mathbf{r}')u_l(k\mathbf{r}')d\mathbf{r}' \tag{5}$$

Owing to the small binding energy of the projectile its excitation leads to the breakup and Eq. (5) may be utilised to calculate the breakup transmission co-efficient T_l^{bu} via

$$T_l^{bu} = 1-\exp\left[-2\int_{\rho_0}^{\infty}\frac{\mathrm{Im}U_l^{bu}/E_{c.m.}}{\sqrt{1-2\eta/\rho-l(l+1)/\rho^{2}}}d\rho\right] \tag{6}$$

Here ρ_0 represents the product of the distance of closest approach and the wave number k_l, and is obtained from

$$1-2\eta/\rho_0-l(l+1)/\rho_0^{\,2}=0\cdot \tag{7}$$

The effect of breakup channel coupling on the fusion cross section is incorporated by multiplying the partial fusion probability T_l^{f} with the breakup survival probability $\sqrt{1-T_l^{bu}}$. Thus the fusion cross section becomes

$$\sigma_f^{coup} = \frac{1}{2}\frac{\pi}{k^2}\left(\sum_{l=0}^{\infty}(2l+1)\sqrt{1-T_l^{bu}}\,T_l^{f}(+F)\right) + \frac{1}{2}\frac{\pi}{k^2}\left(\sum_{l=0}^{\infty}(2l+1)\sqrt{1-T_l^{bu}}\,T_l^{f}(-F)\right) \qquad (8)$$

The variation with respect to inter nuclear separation ‘ r ’of dipole approximated nuclear coupling potential is shown in Fig. 1 for the ^{6}Li + ^{12}C system for a fixed value of x=2.0 *fm*. As usual, the potential is highly attractive at very small inter nuclear separations and reduces significantly at very large distances. In Fig. 2 the variation of nuclear potential with respect to separation between fragments of projectile ‘ x’ for a fixed value of r = 6.1 *fm*, which is surface touching distance, is shown for the same nuclear system. It is clearly observed in this figure that there is a minimum in potential at x =5.0 *fm*. It means that the equilibrium separation of two valence neutrons from the centre of mass of the core is about 5.0 *fm* when the projectile and target are at touching distance. This large equilibrium separation may be ascribed to the weak binding energy of the projectile.

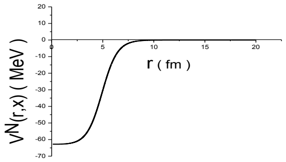

Fig. 1The nuclear coupling potential as a function of inter nuclear separation for the ^{6}Li + ^{12}C system.

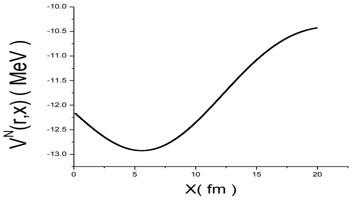

Fig. 2The nuclear coupling potential as a function of distance from core to the valence nucleons for the ^{6}Li + ^{12}C system.

In Fig. 3 the fusion cross section for ^{6}Li+^{12}C system calculated by including the breakup channel coupling effect arising because of the strong and short range nuclear forces of a light target is compared with the standard one dimensional barrier penetration model. In the sub-barrier energy regime it has been found that there is significant enhancement due to the breakup channel coupling as compared with the predictions of simple one dimensional barrier penetration model. It may be ascribed to the fact that coupling to other reaction channels at sub-barrier energies would lead to an enhancement of the transmitted flux and thus of the fusion cross-section. It is equivalent, at the nuclear level, to the enhancement of the tunnelling probability due to the presence of additional degrees of freedom, as observed in coupled channel analysis, for a given system. On the other hand, at energies greater than the barrier height there is a strong suppression of the fusion cross section with respect to one dimensional barrier penetration model. This suppression may be attributed to the flux lost to the breakup channel resulting in the decrease of nuclei available for fusion.

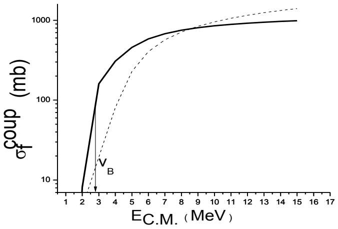

Fig. 3 The effects of the nuclear breakup channel on the fusion excitation function for ^{6}Li+^{12}C system. Dashed line corresponds to the calculations of 1DBPM whereas solid line represents the calculation performed by including nuclear induced dynamic polarisation potential.

In conclusion we have studied the effect of nuclear induced breakup on the fusion cross section for ^{6}Li + ^{12}C system around the barrier energy regime using the dynamic polarisation potential (DPP) approach. It has been found that there is enhancement in fusion cross section due to the nuclear induced breakup channel coupling in the sub-barrier energy regime while suppression is observed well above the barrier as compared to standard barrier penetration model.

References

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