Effects of Projectile Breakup on Fusion Reactions around Barrier Energies

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The fusion of loosely bound radioactive ions with the stable targets is of immense importance in conjugation with the reactions of astrophysical interest and has attracted considerable attention over past few decades [1]. So it is quite tempting to investigate static effects of extraordinary spatial extension and the dynamic effects arising because of the very low threshold for breakup on the fusion cross section involving loosely bound nuclei. As a result many efforts have already been made in this direction and have found that there is an enhancement in sub barrier fusion cross section due to large size of the projectile. However, as far as dynamic effects are concerned, so far very conflicting results have been reported in the literature about whether the fusion is enhanced or hindered at above and below barrier energies and needs further investigation.

Theoretically, the role of breakup channel in the fusion of halo nuclei can be studied either by a coupled channel (CC) approach or by an approach based on the dynamic polarization potential (DPP). However, the CC method becomes extremely complicated when more and more numbers of channels are to be included in the calculations. On the other hand in the dynamic polarization potential approach the coupling between different excited states does not pose any problem as it can be considered as additive, so that the polarization potential induced by the coupling to two states is approximately the sum of the potentials corresponding to the coupling to each one independently. Thus the polarization potential approach becomes more useful to include the coupling to large sets of states, like the continuum of breakup states, for which standard coupled channels calculations become very difficult.[9] In the present work, we have studied the effects of coupling to breakup channel for ^{6}He+^{238}U system on fusion cross section in near barrier energy regime within the framework of DPP approach. We have taken into account the DPP induced by long range Coulomb interaction as well as that induced by strong nuclear interaction.

The l –dependent Coulomb dipole induced dynamic polarization potential is obtained by considering [2, 3]

$$V^{C}(\mathbf{r},\mathbf{x})=\frac{4\pi\ m_c Z_P Z_T e^2}{3m_{b+c}}\frac{\mathrm{x}}{r^2}\sum_m Y_{1m}^{*}(\hat{\mathbf{x}})Y_{1m}(\hat{\mathbf{r}})$$

and is expressed as

$$U_l^{\mathrm{Pol,C}}(\mathrm{r},\mathrm{r}')=\frac{{\alpha_p}^2}{8\pi}\frac{3}{4\pi}\left[\frac{4\pi}{3}\frac{m_c Z_P Z_T e^2}{m_{b+c}}\right]^2$$
$$\left\{\frac{l+1}{2l+1}G_{l+1}^{(+)}(\mathrm{r},\mathrm{r}')+\frac{l}{2l+1}G_{l-1}^{(+)}(\mathrm{r},\mathrm{r}')\right\}\frac{1}{\mathrm{r}^2\mathrm{r}'^2}$$

Similarly the nuclear induced DPP is obtained by considering[4]

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

and is expressed as [5]

$$U_l^{Pol,N}(\mathsf{r},\mathsf{r}')=F_1(\mathsf{r},\mathsf{r}')\left\{\frac{l+1}{2l+1}G_{l+1}^{(+)}(\mathrm{r},\mathrm{r}')+\frac{l}{2l+1}G_{l-1}^{(+)}(\mathrm{r},\mathrm{r}')\right\}$$
$$+F_2(\mathbf{r},\mathbf{r}')G_l(\mathrm{r},\mathrm{r}')$$

with

$$F_1(\mathsf{r},\mathsf{r}')=\boldsymbol{F}_1(\boldsymbol{r},\boldsymbol{r}')=-(4\boldsymbol{\pi})^2\boldsymbol{U}_{\boldsymbol{PT}}^{\boldsymbol{N}}(\mathsf{r})\boldsymbol{U}_{\boldsymbol{PT}}^{\boldsymbol{N}}(\mathsf{r}')$$
$$\int|\boldsymbol{\phi}_0(\mathsf{x})|^2\sum_{\boldsymbol{m},\boldsymbol{m}'}\boldsymbol{V}_{\boldsymbol{j},1}^{\boldsymbol{N}}(\mathsf{r},\mathsf{x})\,\boldsymbol{V}_{\boldsymbol{j},1}^{\boldsymbol{N}}(\mathsf{r}',\mathsf{x})\boldsymbol{dx}$$

where

$$V_{j,1}^{N}(\mathsf{r},\mathsf{x})=\sum_{j=b,c}(-1)^{L_j}\exp\left[-\left(\frac{\mathrm{m_j}\mathsf{x}}{\mathrm{m_p}a}\right)^2\right]j_1\left(i2\frac{\mathrm{m_j}\mathsf{r}\,\mathsf{x}}{\mathrm{m_p}a^2}\right)$$

with $L_j=1$ for $j=c$ and $L_j=0$ for $j=b$

and

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

The subscripts ‘*b*’ and ‘c’ represents the fragments of the projectile. The derivational details of these expressions are given in Ref.[5]. The corresponding breakup polarization potential is obtained by using the following expression

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

Now, the effect of breakup channel coupling on the fusion cross section is incorporated by multiplying the fusion transmission coefficient $T_l^{\,f}$ with the breakup survival probability $\sqrt{1-T_l^{bu}}$ so that the fusion cross section becomes

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

Here F is the channel coupling strength parameter and B is valence nucleons separation energy.

The breakup transmission co-efficient T_l^{bu}, is related to breakup polarization potential and is given by

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

Because of the small binding energy of last two neutrons, the ^{6}He nucleus easily dissociates into ^{4}He and dineutron clusters. As mentioned above the breakup occurs through the long range Coulomb interaction and the short range strong nuclear interaction. We have investigated the effects of Coulomb and nuclear induced breakup on fusion of ^{6}He+^{238}U system and the results are presented in Fig. 1. A large sub barrier enhancement and a slight reduction very well above the barrier in fusion cross section after coupling the breakup channel as compared with the BPM is clearly noticed from this figure. The agreement between the data and predictions made by incorporating the coupling of breakup channel to the fusion improves significantly.

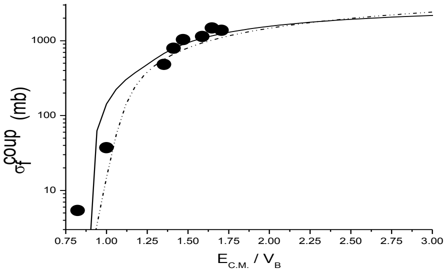

Fig. 1 The fusion excitation function for ^{6}He+^{238}U system corresponding to the calculation performed by simple BPM (dashed dot dot) by simultaneously including Nuclear and Coulomb induced breakup channels (solid line). Data points are taken from Ref.[6].

It is well known that the binding energy of the projectile strongly affects its breakup into constituent fragments and hence the breakup channel coupling effects on the fusion involving loosely bound projectiles. The dependence of breakup channel coupling effects on the valence nucleons separation energy for ^{6}He+^{238}U system is shown in Fig. 2. As per expectation the breakup cross section increases with the decrease in binding energy and hence the breakup is highly probable channel for a loosely bound nucleus. Owing to high probability of dissociation, a loosely bound nucleus considerably affects the fusion as is evident from Fig. 2.

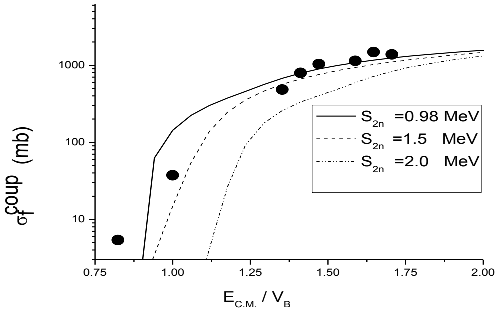

Fig. 2. Same as Fig. 1 but for different values of two neutrons separation energy.

In conclusion, we have investigated the effects of breakup of weakly bound nuclei on the fusion reactions using the dynamic polarization potential approach for ^{6}He+^{238}U system. It has been found that in the sub-barrier energy regime there is an enhancement in the fusion cross section while at very well above the barrier a suppression of the fusion cross section with respect to one dimensional barrier penetration model is there. The agreement between the data and predictions for the system considered here improves significantly due to the inclusion of breakup effects in the analysis.

References

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