Study of the neutron transfer effect in ^{11}Be + ^{238}U fusion reaction at near barrier energies

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The fusion reaction involving weakly bound nuclei, both stable and radioactive, has received a great attention during last two decades [1-3]. The early experiments carried out using Radioactive Ion Beams have confirmed the existence of an extended halo structure among some of these weakly bound nuclei. Owing to their exceptionally large size and very small binding energy of last nucleon(s) the fusion involving these nuclei differs fundamentally from those involving tightly bound nuclei. The nucleus ^{11}Be being a representative of well-established halo system has attracted a significant attention since from the beginning of the era of Radioactive Ion Beam facilities. Fekou-Youmbi et al [4] have studied the effect of halo structure on fusion cross section for ^{11}Be + ^{238}U system at near barrier energies and have found an enhancement in fusion cross section with respect to its stable isotope ^{9}Be. Subsequently Signorini [5] has studied the effect of low breakup threshold on fusion cross section for ^{11}Be + ^{238}U system and found an enhancement in fusion cross section at sub barrier energies. In the present work, we have studied the same system to understand the peculiar behavior of fusion cross section within the framework of quantum diffusion approach [6]. In this approach, various channel coupling effects are simulated through the dissipation and fluctuation effects. However, along with the channel coupling effects, the nuclear deformation and neutron transfer processes have also been identified as playing a key role in the analysis of fusion reactions. The partial wave capture cross-section, the cross-section for the formation of dinuclear system, is given by

$$\sigma_c(E_{c.m.}) = \pi\lambda\!\!\!^{-2}\sum_L (2L+1)P_{cap}(E_{c.m}, L) \qquad (1)$$

Within the framework of quantum diffusion model, the partial capture probability, P_{cap}, is obtained by integrating an appropriate propagator from initial state at t = 0 to the final state at time t and is given by

$$P_{cap} = \lim_{t\to\infty}\frac{1}{2}erfc\left[\frac{-r_{in}+\overline{R(t)}}{\sqrt{\Sigma_{RR}(t)}}\right] \qquad (2)$$

The first moment, $\overline{R(t)}$, and the variance, $\Sigma_{RR}(t)$, are given by

$$\overline{R(t)} = A_t R_0 + B_t P_0 \qquad (3)$$

$$\sum\nolimits_{RR}(t) = \frac{2\hbar^2\lambda\gamma^2}{\pi}\int_0^t d\tau' B_{\tau'}\int_0^t d\tau'' B_{\tau''} \times \int_0^\infty d\Omega \frac{\Omega}{\Omega^2+\gamma^2} \times coth\left[\frac{\hbar\Omega}{2T}\right] cos[\Omega(\tau'-\tau'')] \qquad (4)$$

with

$$B_t = \frac{1}{\mu}\sum_{i=1}^{3}\beta_i\,(s_i+\gamma)e^{s_i t}$$

$$A_t = \sum_{i=1}^{3}\beta_i[s_i(s_i+\gamma)+\hbar\lambda\gamma/\mu]e^{s_i t}$$

Above $\beta_i = [(s_i - s_j)(s_i - s_k)]^{-1}$, $i, j, k = 1,2,3$ and $i \neq j \neq k$ and s_i are the real roots of

$$(s+\gamma)(s^2-\omega_0^{\,2}) + \hbar\tilde{\lambda}\gamma s/\mu = 0 \qquad (5)$$

where γ, ω_0 and $\tilde{\lambda}$ are the internal excitation width, renormalized frequency and parameter related to the strength of linear coupling.

Combining Eqs. (3) and (4) one obtains

$$P_{cap} = \frac{1}{2}erfc\left[\left(\frac{s_1(\gamma-s_1)}{2\hbar\tilde{\lambda}\gamma}\right)^{1/2} \times \frac{\mu\omega_0^2 R_0/s_1 + P_0}{\left[\frac{s_1\gamma}{\pi(s_1+\gamma)}\left(\psi\left(1+\frac{\gamma}{2\pi T}\right)-\psi\left(\frac{s_1}{2\pi T}\right)\right)-T\right]^{1/2}}\right] \qquad (6)$$

Where $\psi(z)$ is the digamma function. By using Euler-Maclaurin integration formula, we get the simple expression for digamma function that is

$\psi(z+1) = \ln z$. For sub barrier fusion, in the limit of small temperature T→0, by using above expression for digamma function and substituting Eq. (5), we have

$$P_{cap} = \frac{1}{2} erfc\left[\left(\frac{\pi s_1(\gamma - s_1)}{2\mu\hbar(\omega_0^2 - s_1^2)}\right)^{1/2} \frac{\mu\omega_0^2 R_0 / s_1 + P_0}{[\gamma \ln(\gamma / s_1)]^{1/2}}\right]$$

As the choice of nucleus-nucleus potential plays an important role for the theoretical description of a nuclear reaction we have adopted here the proximity model [7] because of its simplicity and wider acceptability. The proximity potential model is used to calculate the values of barrier height (V_b) and barrier position (R_b) which comes out to be 43.01 MeV and 12.08fm before one neutron transfer and 42.89MeV and 12.17fm after one neutron transfer. Besides these, the values of R_0, which is very crucial and strongly depends on the separation of the region of pure Coulomb interaction and that of Coulomb nuclear interference and P_0 are determined through the procedure described in the Ref. [8].

In Fig 1, the fusion excitation functions of ^{11}Be + ^{238}U system are compared with the corresponding data taken from Ref. [5]. It is found that when neutron transfer effects are neglected a reasonable matching is found only at above barrier energies while data are significantly underestimated at below barrier energies. When one neutron transfer from ^{11}Be to ^{238}U is taken into account a significant enhancement in fusion cross section at around barrier energy is observed. Since the deformations of ^{238}U and ^{239}U are $\beta_2 = 0.215$ and $\beta_2 = 0.223$ respectively hence there is no change in shape after one neutron transfer. Thus the enhancement in fusion cross section in the vicinity of Coulomb barrier when the neutron transfer is taken into account is purely a transfer effect. As a consequence neutron transfer before fusion agreement between the data and predictions in the sub barrier energy region as well as at energies above the barrier improves significantly. The large enhancement at sub barrier energies shows that neutron transfer process plays a major role in this region.

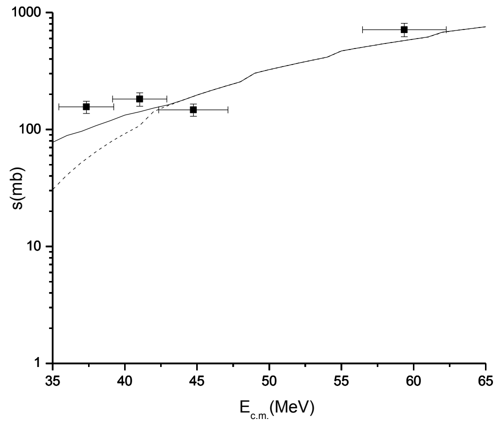

Fig.1. The fusion excitation function of ^{11}Be + ^{238}U system calculated by using quantum diffusion approach without neutron transfer (dotted line) and with neutron transfer (solid line) are compared with the experimental data (solid square) taken from Ref. [5].

In summary, the neutron transfer effects lead to sub barrier enhancement of fusion cross section for ^{11}Be + ^{238}U reaction. Further, the inclusion of these effects in the analysis improves the matching between data and predictions in the near barrier energy region.

References

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