Heavy ion fusion at low energies

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Fusion of heavy ions is well studied over last three decades, however, new surprises open up with the availability of data of precision fusion measurements. Coupled reaction channels formalism has been very successful in explaining the heavy ion reaction in great detail for the energies around the one dimensional Coulomb barrier. It was shown that the CRC calculations can be understood in terms of simple macroscopic models such as energy dependent barrier penetration model, (EDBPM) [1] or based on distribution of barriers (DB) method [2]. In the coupled channels as well as in EDBPM model, fusion at deep sub-barrier energies should fall exponentially, depending on the barrier height at low energies (adiabatic barrier) and the barrier curvature $\hbar\omega$. The fusion slope function ($L(E)$) is defined as $L(E) = d(\log(E\sigma_f)/dE$, which is a measure of fall of the fusion excitation function at low energies. Recent precision measurements of fusion at deep sub-barrier energies [3] showed anomalously steeper decrease of cross sections with decreasing energy. Therefore, the L(E) showed anomalous steep increase at deep sub-barrier energies [3]. This is in contrast to the predictions of coupled channels calculations using parabolic barrier shape, where the $L(E)$ saturates to a constant equal to $2\pi/\hbar\omega$ at deep sub-barrier energies. Therefore, there exists a large discrepancy between experimental data and model predictions of this slope function. The anomalous decrease of fusion excitation function needs very large values for diffuseness parameter of the nuclear potential [5], implying smaller $\hbar\omega$ values. Further analysis showed that the energy independent smaller $\hbar\omega$ values used in any CC or other models, could not explain the anomalously large fusion $L(E)$. Therefore, the fits to deep sub-barrier cross sections require that the energy dependence of $\hbar\omega$ be incorporated. This feature is not present in any of the existing models and it may be suggesting that the nuclear potential shape through its diffuseness parameter depends on energy. In literature, inversion potentials were reported by making use of WKB transmission formula [9]. These potentials show anomalously thicker barrier at deep sub barrier energies as expected from steeper fall of excitation function. This anomalous shape is equivalent in description to energy dependent $\hbar\omega$ method. We estimated the equivalent $\hbar\omega$ of parabolic barrier transmission that reproduces the WKB transmission of the inversion potentials. The resulting $\hbar\omega$ as shown in Fig.1, decreases with decreasing energy. We model this as follows. Starting with a constant value at high energies called sudden limit $\hbar\omega_s$, (4.5 MeV), we varied the lower limit $\hbar\omega_{ad}$ as a free parameter to fit the fusion data using EDBPM. For this purpose, the variation of $\hbar\omega(E)$ is treated same as the effective barrier, therefore, $\hbar\omega$ varies between $\hbar\omega_s$ and $\hbar\omega_{ad}$, as in Eq.1. With this, the fusion slope function $L(E)$ saturates to $2\pi/\hbar\omega_{ad}$, as shown in Eq. 2, for details see [4].

$$\hbar\omega = \hbar\omega_{ad} + (\hbar\omega_s - \hbar\omega_{ad})\frac{E - E_1}{E_2 - E_1} \quad (1)$$

$$L(E) = \frac{d(\ln(E\sigma_f))}{dE} \approx \frac{2\pi}{\hbar\omega_{ad}} \quad (2)$$

We have analyzed fusion of several systems using this method. In Figs.2 we show the (a) fusion cross sections and the (b) fusion slope function for $^{16}O+^{208}Pb$, $^{6}Li+^{198}Pt$ systems.

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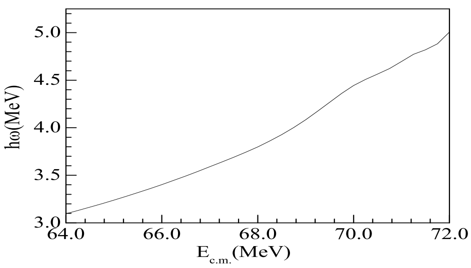
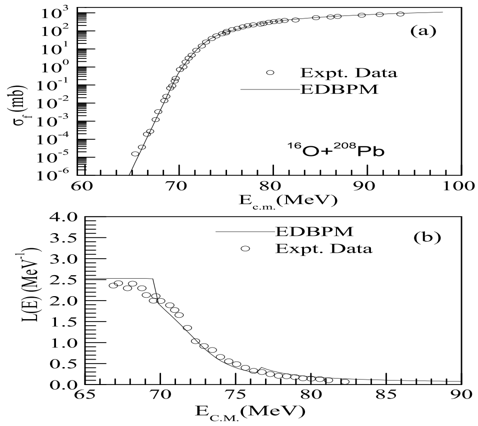


FIG. 1: $\hbar\omega$(E) required with parabolic barrier equivalent to WKB transmission through the inversion potential for ^{16}O+^{208}Pb system .

The experimental data is taken respectively from [10],[11]. These systems exhibit anomalous decrease of fusion cross section with decreasing energy at deep sub-barrier region. Thr resulting steep increase of $L(E)$ function at the lower energies could be reproduced in our model, signifying the quality of the fit by the model. The coupled channels method that fit these systems at high energy, fails to reproduce at lower energies. In the symposium, we will present the details and results for more systems.



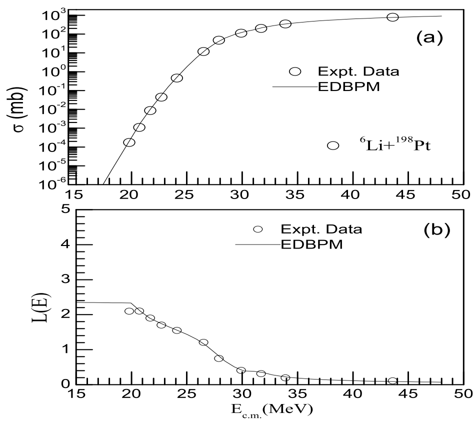


FIG. 2: (a) Symbols show the experimental cross sections for ^{16}O+^{208}Pb system [10], for ^{6}Li+^{198}Pt [11]. The curves are the EDBPM model fits with energy dependent $\hbar\omega$.
(b) Lower panel for each system shows fusion slope function derived from experimental data (symbols) and the model results are shown in curves.

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