A new phenomenon - heavy-ion fusion hindrance at extreme sub-barrier energies

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A new phenomenon, the hindrance of heavy-ion fusion reactions, has recently been found in many medium-heavy systems [1-4]. This hindrance occurs only at extreme sub-barrier energies and there is no satisfactory explanation in present model calculations, whereas the fusion cross sections at near or above barrier energies agree well with standard coupled-channels calculations. A sensitive method for identifying this sub-barrier hindrance is provided by expressing the cross section, σ, in terms of the logarithmic derivative, $L(E)$ and the S-factor

$$L(E) = \frac{d(ln(\sigma E))}{dE}; \qquad S(E) = \sigma E \exp 2\pi\eta, \qquad (1)$$

where $\eta = Z_1 Z_2 e^2/(\hbar v)$ is the Sommerfeld parameter and E is the center-of-mass energy [2]. In many systems, the S-factor shows an evident maximum at extreme sub-barrier energies. The energy location, E_s, of the $S(E)$ maximum is just at the crossing point of the experimental $L(E)$ curve and the constant S-factor expression ($L_{cs} = \pi\eta/E$ [2]), whose logarithmic derivative value is L_s.

This phenomenon was first observed for medium mass systems, where the fusion reaction Q-values are very negative. The systematic dependence of the hindrance on the total mass and Q-value has now been investigated from the $L(E)$ vs. E plots [5], for systems ranging from $^{10}B+^{10}B$ to $^{90}Zr+^{92}Zr$, Fig. 1. Even for light systems there is a crossing point of $L(E)$ with the constant S-factor prediction.

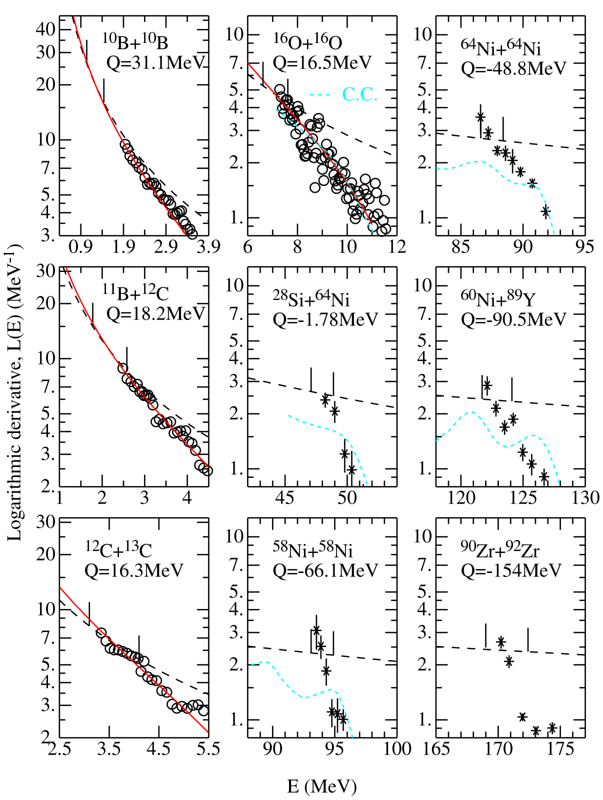

FIG. 1: Plot of $L(E)$ vs. E for several colliding systems. The dashed, blue dotted and red curves correspond to a constant S factor prediction, a C.C. calculation, and a fit of the form $a_0 + b_0/E^{3/2}$, respectively.

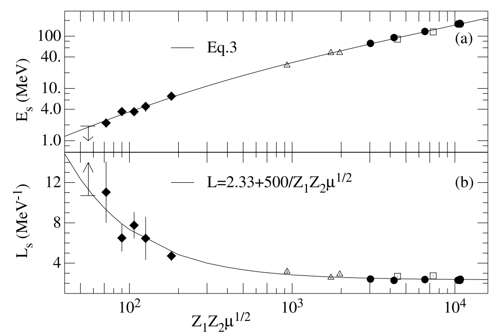

FIG. 2: Plots of E_s and L_s vs. $Z_1 Z_2 \sqrt{\mu}$. Here μ is the reduced mass of the colliding system.

The systematics of the sub-barrier hindrance is illustrated in Fig. 2. Here, the derived values of E_s and $L_s = L(E_s)$ are plotted as functions of the parameter $Z_1 Z_2 \sqrt{\mu}$ in panels 2a and 2b, respectively. Aside from local deviations of L_s from the value of 2.33 MeV^{-1} in medium-heavy systems (of the order of $\sim$ 10%, arising from nuclear structure), the purely empirical expressions

$$L_s^{emp} = 2.33 + 500/(Z_1 Z_2 \sqrt{\mu}) \ \ (\text{MeV}^{-1}), \qquad (2)$$

and correspondingly

$$E_s^{emp} = (0.495 Z_1 Z_2 \sqrt{\mu}/L_s^{emp})^{2/3} \ \ (\text{MeV}), \qquad (3)$$

are seen to reproduce the experimental values in Fig. 2 (solid curves). These two equations thus represent the overall systematics for the onset of the sub-barrier fusion hindrance. The behavior seen in Fig. 2 provides indications that the hindrance phenomenon is closely related to the entrance channel through the parameter $Z_1 Z_2 \sqrt{\mu}$, though an explanation of the phenomenon is still unclear. The systematics has important implications for both the reaction mechanism and nucleo-synthesis in astrophysical sites.

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