A new phenomenon, the hindrance of heavy-ion fusion reactions, has recently been found in many medium-heavy systems [1]. 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, $\sigma$, in terms of the logarithmic derivative, $L(E) = \frac{d\ln(\sigma/E)}{dE}$ and the $S$-factor, $S(E) = \sigma E \exp 2\pi\eta$, where $\eta = Z_1 Z_2 e^2 / (\hbar v)$ is the Sommerfeld parameter and $E$ is the center-of-mass energy. In many systems, the $S$-factor shows an evident maximum at extreme sub-barrier energies. The energy location, $E_s$, of the $S$-factor maximum is just at the crossing point of the experimental $L(E)$ curve and the constant $S$-factor expression ($L_s = \pi \eta / E$), whose logarithmic derivative value is $E_s$. 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 $L_s$ vs. $E$ plots, for systems ranging from $^{10}$B-$^{10}$B to $^{90}$Zr-$^{92}$Zr. Even for light systems there is a crossing point of $L(E)$ with the constant $S$-factor prediction. The systematics of the sub-barrier hindrance is illustrated in the figure. 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 a and b, respectively. Aside from local deviations of $L_s$ from the value of 2.33 MeV$^{-1}$ in medium-heavy systems (of the order of ~10%, arising from nuclear structure), the purely empirical expressions

$$L_{s,\text{emp}} = 2.33 + 500 / (Z_1 Z_2 \sqrt{\mu}) \text{ (MeV$^{-1}$)}; \quad E_{s,\text{emp}} = (0.495 Z_1 Z_2 \sqrt{\mu} / L_{s,\text{emp}})^{2/3} \text{ (MeV)}, \quad (1)$$

are seen to reproduce the experimental values in the figure (solid curves). These two equations thus represent the overall systematics for the onset of the sub-barrier fusion hindrance. The behavior seen in the figure 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.

Figure 1: Plots of $E_s$ and $L_s$ vs. $Z_1 Z_2 \sqrt{\mu}$. Here $\mu$ is the reduced mass of the colliding system.

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References