CAN WE PREDICT CAPTURE AND FUSION EXCITATION FUNCTIONS?*

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Existing data on near-barrier fusion and capture excitation functions for about 50 medium and heavy nucleus–nucleus systems have been analysed using a phenomenological model, in which fusion barriers are assumed to have Gaussian distributions. Systematics of the barrier-distribution parameters, the mean barrier and its variance, are presented. Deduced values of the variance parameter show an important role of nuclear structure effects, which we propose to account for by relating values of the variance parameter with fusion energy thresholds calculated with the fusion adiabatic potential.

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1. Introduction

Accurate knowledge of "capture" excitation functions is very important for an optimum choice of projectile-target combination and bombarding energy in modern experiments aimed at production of new superheavy elements. We use the term "capture" to call the process of overcoming the interaction barrier in a nucleus–nucleus collision, followed by formation of a composite system. In general, the composite system undergoes fusion only in a fraction f of the capture events. For light and medium systems $f \approx 1$, but for very heavy systems, only a small portion ($f \ll 1$) of "capture" events lead to fusion. (For the remaining part of events, the system reseparates prior to equilibration in fast fission processes.) Clear distinction between fusion and capture cross section is then necessary.

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In the present work we analyse an ample set of near-barrier fusion excitation functions using a phenomenological model that assumes the Gaussian distribution of fusion barriers. For the chosen set of reactions, the fusion cross sections are practically identical with the capture cross sections. Therefore the established systematics, that also includes some capture data for super-heavy systems, enable one to predict capture cross sections for very heavy systems.

2. Analysis of fusion excitation functions

It is well known that fusion excitation functions cannot be satisfactorily explained assuming penetration through a single, well defined barrier in the total potential energy of a colliding nucleus–nucleus system. In order to reproduce shapes of the fusion excitation functions, especially at low near-threshold energies, it is necessary to assume coexistence of different barriers, a situation that is naturally accounted for in description of fusion reactions in terms of coupled channel calculations involving coupling to various collective states. As it was demonstrated by Rowley, Satchler and Stelson [1], an effective fusion-barrier distribution can be deduced from a precisely measured fusion excitation function by taking the double derivative of the product of the cross section multiplied by energy, $d^2(\sigma E)/dE^2$. Reversing the situation, we assume a certain shape of the barrier distribution in attempt to reproduce the measured fusion excitation functions and thus obtain their phenomenological parametrization.

We assume the Gaussian shape of the barrier distribution:

$$p(B) = \frac{1}{\sigma_B\sqrt{2\pi}} \exp\left[-\frac{(B-B_0)^2}{2\sigma_B^2}\right] \tag{1}$$

with the mean barrier B_0 and its variance σ_B being free parameters to be determined individually for each reaction by comparing predicted fusion excitation function with experimental data. By folding the barrier distribution, Eq. (1), with the classical expression for the fusion cross section,

$$\sigma_{\mathrm{fus}} = \pi R_B^2 \left(1 - \frac{B}{E}\right), \tag{2}$$

one obtains the following close formula for the energy dependence of the fusion cross section:

$$\sigma_{\mathrm{fus}} = \pi R_B^2 \frac{\sigma_B}{E\sqrt{2\pi}} \left\{X\sqrt{\pi}(1 + \mathrm{erf}X) + \mathrm{e}^{-X^2}\right\}, \tag{3}$$

where $X = (E - B_0)/(\sqrt{2}B_0)$, and $\mathrm{erf}X$ is the Gaussian error integral of the argument X. By R_B we denote the distance corresponding to location of the interaction barrier. Along with B_0 and σ_B, R_B is a parameter to be determined by fitting Eq. (3) to experimental data. In derivation of formula (3), the quantum mechanical tunneling is not accounted for. However, since the tunneling only slightly smears out the fusion excitation function around $E = B_0$, its effect is automatically included in an empirical value of the variance σ_B deduced for a given reaction.

Formula (3) represents a very convenient parametrization for fusion and capture excitation functions, suitable for near-barrier energies. (At higher energies, the entrance-channel angular-momentum limitations, not accounted for by Eq. (3), may reduce the fusion cross section.) In Fig. 1, one can see four examples of measured [11,13] fusion excitation functions fitted with formula (3), using the least χ^2 method. We have analysed in such a way an ample set of published experimental data [2–18]. All the chosen excitation functions have been precisely measured in the near-barrier range of energies

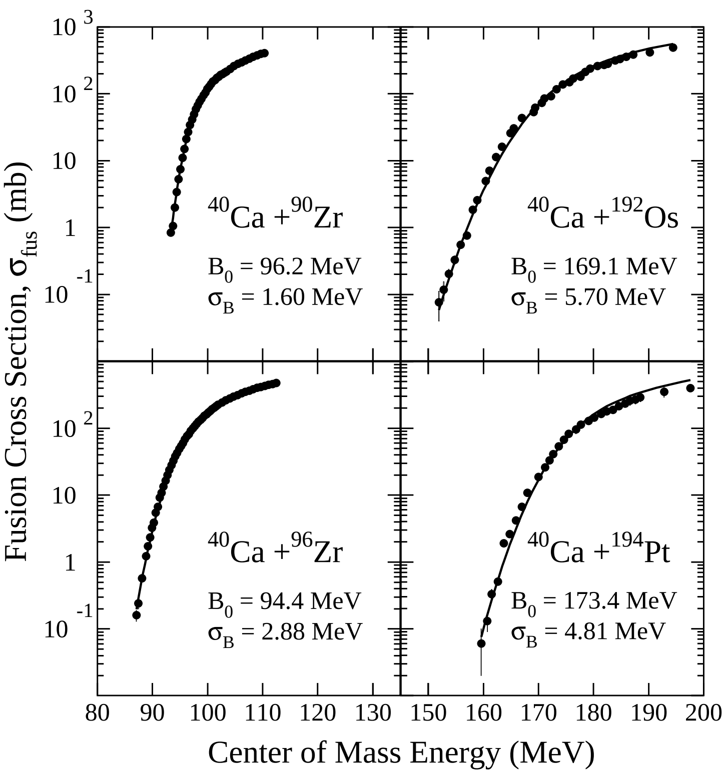

Fig. 1. Examples of fusion excitation functions calculated with Eq. (3), assuming Gaussian distribution of the fusion barrier. Experimental data are taken from Refs. [11,13].

where cross sections are most sensitive to the fusion-barrier distribution. Our analysis has revealed that the calculated excitation functions only very weakly depend on the variation of the radius parameter r_0. Therefore we fixed a value of $r_0 = R_B/(A_1^{1/3} + A_2^{1/3}) = 1.27$ fm (that seemed to fit best all the data), and carried out a systematic analysis of the whole set of data by varying only two parameters, B_0 and σ_B.

In Fig. 2 we present a compilation of the deduced values of the mean barrier B_0 plotted as a function of the parameter $z = Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$. This dependence is very regular and can be approximated by a second order polynomial function,

$$B_0 = 0.00136z^2 + 0.78z + 4.2 \text{ MeV} . \qquad (4)$$

We would like to emphasize the fact that the parametrization established for fusion reactions (full circles in Fig. 2) holds also for capture data [18] for very heavy systems (squares). Consequently, one can use Eq. (9) for reasonable predictions of the mean barrier heights for capture processes in not yet studied reactions.

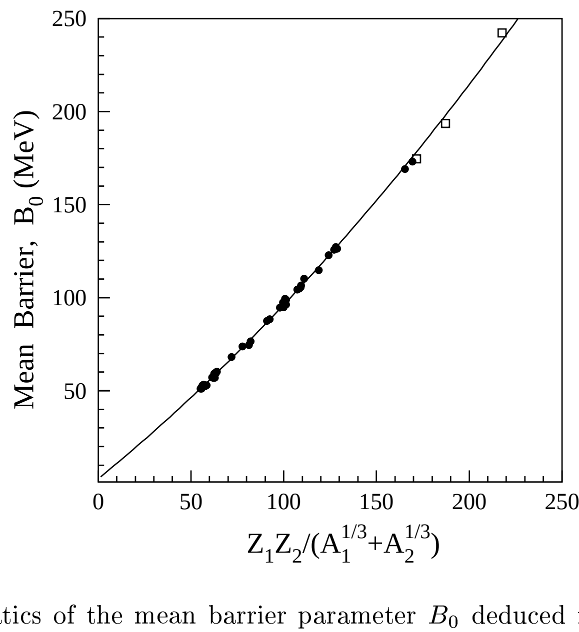

Fig. 2. Systematics of the mean barrier parameter B_0 deduced from analysis of about 50 published fusion and capture excitation functions. Results for capture reactions [18] are indicated by different symbols (squares). Solid line represents parametrization given by Eq. (4).

Contrary to B_0, the dispersion parameter σ_B does not behave so regularly. This is not surprising, regarding possible coupling to rotational and vibrational states in the fusing nuclei, the mechanism that strongly influences effective barrier distributions in the coupled-channels approach. Regarding this, σ_B must depend not only on the "global" parameters, such as Z and A of the fusing nuclei, but also on their structural characteristics. In Fig. 3 (left) we present all the deduced values of σ_B plotted as function of the mean barrier B_0. Undoubtedly, there is a correlation between these two quantities: σ_B systematically increases with increasing B_0. However, points in Fig. 3 (left panel) are considerably scattered suggesting significant influence of nuclear structure effects. Much better correlation is obtained in

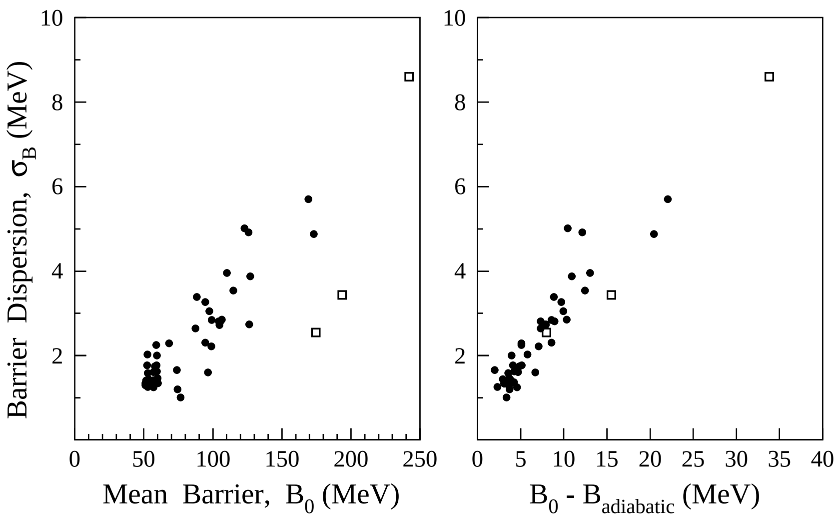

Fig. 3. Systematics of the barrier dispersion parameter σ_B deduced from analysis of about 50 published fusion and capture excitation functions. Results for capture reactions [18] are indicated by different symbols (squares). See text.

the right panel of Fig. 3 where σ_B is plotted as a function of the excess of B_0 above the adiabatic fusion barrier $B_{\text{adiabatic}}$, calculated as in Ref. [19]. The adiabatic barriers depend on the fusion Q-value and show close correlation with fusion energy thresholds [19] in measured excitation functions. By using the correlation between σ_B and $(B_0 - B_{\text{adiabatic}})$, we can account, to some extent, for nuclear structure effects in individual values of σ_B. From Fig. 3 (right panel) we read the following relation:

$$\sigma_B = 0.22(B_0 - B_{\text{adiabatic}}) + 0.7 \text{ MeV} \tag{5}$$

that well approximates the observed correlation.

To summarize, we carried out an extensive analysis of fusion excitation functions using the formula (3) obtained assuming the Gaussian shape of fusion-barrier distributions. From this analysis we have determined phenomenological expressions that describe systematics of the mean barrier B_0 and variance σ_B (Eqs. (4) and (5), respectively), and enable one to predict fusion and/or capture cross sections, an important but not well known factor necessary to predict production cross sections of super-heavy elements.

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