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BARRIER DISTRIBUTIONS AND SYSTEMATICS OF FUSION- AND CAPTURE CROSS SECTIONS

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Dedicated to Adam Sobiczewski in honour of his 70th birthday

Methods of predicting 'capture' cross sections, *i.e.*, cross sections for sticking of two colliding nuclei after overcoming the interaction barrier, are presented. Close links between the capture excitation functions and smearing of the interaction barrier are discussed. By using a new 'polynomial fit' method of determining $d^2(E\sigma)/dE^2$ values, the barrier distributions have been directly deduced for several precisely measured fusion excitation functions found in the literature, and compared with results of standard 'point difference' method. Existing data on near-barrier fusion- and capture excitation functions for about 50 medium and heavy nucleus–nucleus systems have been analyzed using a simple formula obtained assuming Gaussian shape of the barrier distribution. Systematics of the barrier distribution parameters, the mean barrier and width of the distribution, are presented and proposed to be used together with the closed-form 'error function formula' for predicting unknown capture cross sections in experiments on synthesis of super-heavy elements.

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1. Introduction

Since many years Adam Sobiczewski's name associates with spectacular series of discoveries of new super-heavy elements, the process that considerably extended limits of the periodic table in the transuranium region. Adam Sobiczewski predicted essential properties of these new exotic nuclei long time before experimentalists could present evidence of their formation. However, with the increasing atomic number of the new elements, experimentalists faced more and more difficulties caused by a dramatic decrease of the production cross-sections. In the latest experiments in which the heaviest elements of $Z = 112$–116 were observed, the production cross-sections diminished to a level of 1 picobarn. It became a real challenge for experimentalists to detect and identify a single atomic nucleus during weeks of measurements. Therefore it is crucial to be able to predict optimum conditions for these experiments, *i.e.*, to determine the best projectile-target combination and an exact value of the bombarding energy at which the narrow excitation function of the production cross-section has its maximum.

2. Distinction between fusion- and capture cross sections

Formation of a heavy nucleus in its ground state can be viewed (see Ref. [1] and references therein) as a process of successful outcome of three stages: *(i)* the overcoming of the interaction barrier in a collision of the projectile and target nuclei, and formation of a tightly connected composite system ('capture' process), *(ii)* evolution of the composite system from the capture configuration to a fully equilibrated compound nucleus (fusion), and *(iii)* deexcitation of the compound nucleus by emission of neutrons or other light particles and γ rays — thus avoiding prompt fission (survival). Therefore, the production cross section for the evaporation-residue nucleus, σ_{ER} is given by the sum of partial-wave contributions of the product of the partial capture cross section $\sigma_{\rm capt}(E,l)$ times the fusion probability $P_{\rm fus}(E,l)$ and times the survival probability $P_{\rm surv}(E,l)$:

$$\sigma_{ER}(E) = \pi\lambda\!\!\!^{-2} \sum_{l=0}^{\infty}(2l+1)\cdot T(E,l)\cdot P_{\rm fus}(E,l)\cdot P_{\rm surv}(E,l)\,, \qquad (1)$$

where $\lambda\!\!\!^{-}$ is the wavelength of the colliding system, $\lambda\!\!\!^{-2} = \hbar^2/(2\mu E)$, and $T(E,l)$ is the probability of overcoming the entrance-channel potential-energy barrier for a given angular momentum. In experiments aimed at production of superheavy nuclei, the energy range of fusion excitation functions is limited to the lowest near-barrier and sub-barrier energies, where only the lowest partial waves contribute. As the rotational energy of the composite system is negligible at so low bombarding energies, Eq. (1) can be factorized in l-integrated form:

$$\sigma_{ER}(E) = \sigma_{\rm capt}(E)\cdot P_{\rm fus}(E)\cdot P_{\rm surv}(E). \qquad (2)$$

In collisions of light and medium-mass systems, the factor $P_{\rm fus}=1$ because nearly in all events when the system overcomes the interaction barrier

— it fuses forming a compound nucleus. However, in case of very heavy nuclear systems, the fact of overcoming the interaction barrier is not sufficient to guarantee fusion. It was found that often such a heavy composite system may eventually reseparate after a deep inelastic process called 'quasi-fission'. It was suggested in Refs. [2, 3] that heavy systems need an 'extra-push' energy to pass the way from the capture configuration to much more compact shape at the saddle point. In realistic dynamical models with inclusion of fluctuations, the extra push effect will translate into a considerable decrease of fusion probability, the *fusion hindrance* factor $P_{\rm fus} < 1$. A theory of the hindrance phenomenon, based on the Smoluchowski equation, and estimates of the hindrance factor for reactions used for production of superheavy elements, have been given in Ref. [1]. Similar interpretation of the hindrance factor in terms of the Langevin dynamics has recently been presented in Ref. [4]. Several phenomenological models were also proposed, see *e.g.*, [5, 6].

3. Capture cross sections

In this article we concentrate on analysis of existing very precise data on fusion reactions for medium-weight systems. Since for these reactions $P_{\rm fus} = 1$, the fusion data *automatically* provide information on the capture cross sections $\sigma_{\rm capt}$. By extrapolation, this information will then be used for estimating the capture cross sections in collisions of the heaviest systems used to produce superheavy nuclei.

It is well known that fusion excitation functions cannot be satisfactorily explained assuming penetration through a well defined barrier in one-dimensional potential 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, the effect that results from the coupling to other-than-relative-distance degrees of freedom. For example, the coupled channels calculations, involving coupling to various collective states, naturally predict noticeable fusion-barrier distributions.

3.1. Fusion barrier distributions

In 1991 Rowley, Satchler and Stelson [7] demonstrated that the fusion barrier distribution can be deduced from a precisely measured fusion excitation function by taking the second derivative of the product of the cross section multiplied by energy,

$$P(E) = \frac{d^2(\sigma E)}{dE^2}. \tag{3}$$

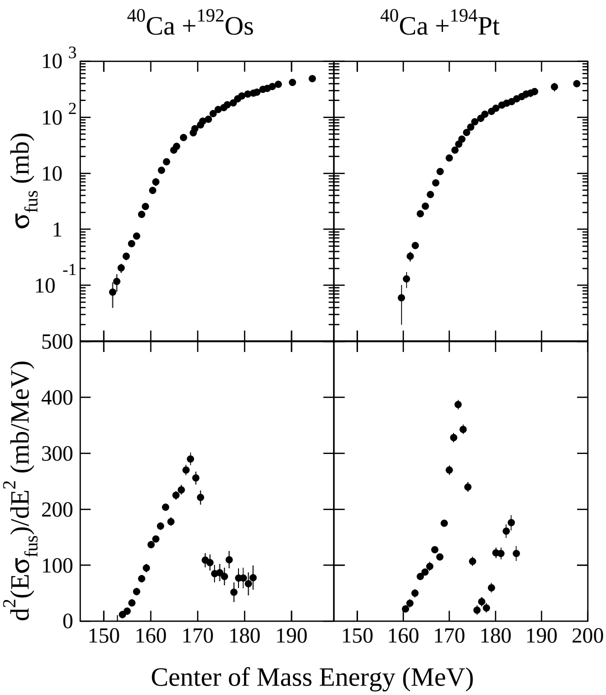

Fig. 1. Modern, precise measurements [8] of fusion excitation functions (top) enable determination of the 'fusion-barrier distributions' (bottom), by calculating the derivative $d^2(E\sigma_{\rm fus})/dE^2$, as proposed in Ref. [7]. Adapted from Ref. [8].

Fig. 1 shows two examples of the measured excitation functions and deduced fusion barrier distributions, taken from a work of Bierman *et al.* [8]. In the present article we do not discuss specific structural effects relevant for accounting for the coupling to various collective excited states. These effects are very sensitive to the smallest details of the measured excitation functions and their interpretation is often ambiguous. We will concentrate on some average characteristics of the fusion-barrier distributions that might be used for *predicting* fusion- or capture cross sections in the sub-barrier region.

In spite of very high precision of modern measurements of the near-barrier fusion excitation functions, reliable determination of the barrier distribution by using Eq. (3) is not easy. A typical approach used in most of published papers consists in using 'three-points formula' or 'point difference formula' (see *e.g.* a review article by Dasgupta *et al.* [9]):

$$\frac{d^2(E\sigma)}{dE^2} = 2\left(\frac{(E\sigma)_3-(E\sigma)_2}{E_3-E_2} - \frac{(E\sigma)_2-(E\sigma)_1}{E_2-E_1}\right)\left(\frac{1}{E_3-E_1}\right), \qquad (4)$$

where $(E\sigma)_i$ are evaluated at energies E_i, and the value of $d^2(E\sigma)/dE^2$

is assigned to an energy $(E_1 + 2E_2 + E_3)/4$. Results of this procedure depend very much on the energy distance between points 1 and 3. As the barrier distribution is naturally smeared out due to quantum tunneling by its finite width of FWHM = 2–3 MeV [7], the experimentally deduced barrier distribution should be smoothed over a similar energy range, and therefore the energy distance $\Delta E = E_3 - E_1 \approx 2(E_2 - E_1)$ is usually chosen to be 4–6 MeV.

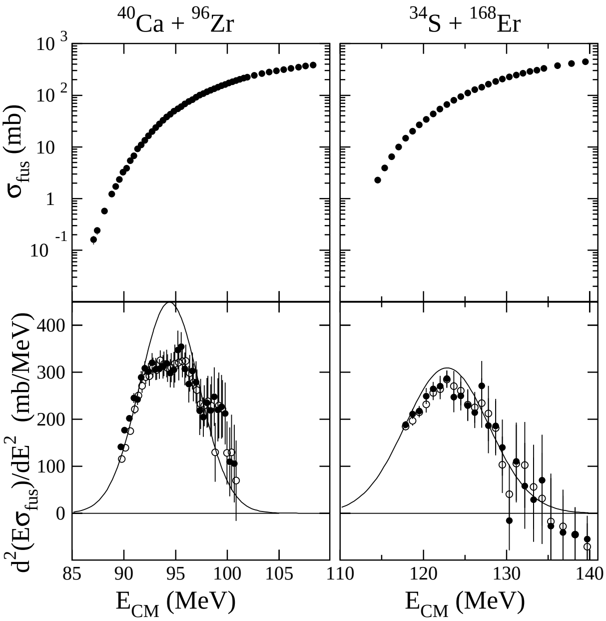

Fig. 2. Fusion excitation functions (top) and the deduced barrier distributions (bottom) for the ^{40}Ca + ^{96}Zr [10] and ^{34}S + ^{168}Er [24] reactions. The barrier distributions determined with the standard 'point difference method' and the 'polynomial fit method' are shown with full and open circles, respectively. The Gaussian barrier distributions obtained by fitting the 'error function formula', Eq. (8), to the fusion excitation functions are shown by solid lines (see text).

Figure 2 shows two examples of measured fusion excitation functions and deduced barrier distributions. In addition, Fig. 3 presents the deduced barrier distributions for four more reactions induced by ^{16}O projectiles on different targets. For comparison, we show the same barrier distributions obtained in an alternative way: Experimental values of $E\sigma$ were locally fitted to a second order polynomial by using the least square method,

$$E\sigma = a + bE + cE^2, \tag{5}$$

and thus a value of the coefficient in the quadratic term was used to deter-

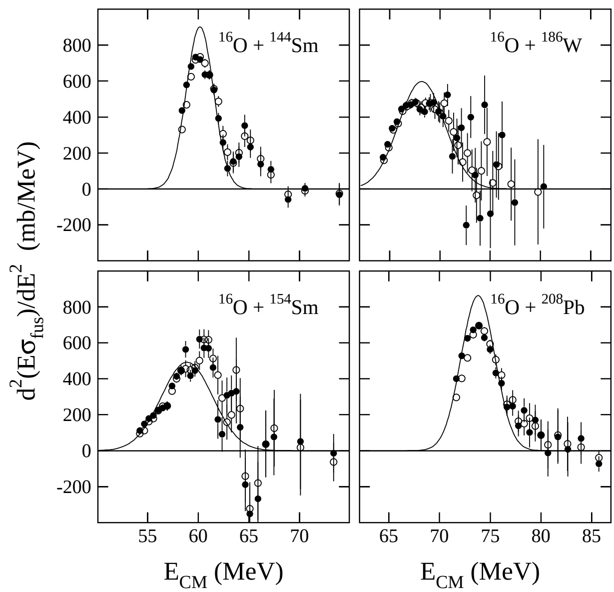

Fig. 3. The barrier distributions, $d^2(E\sigma_{\rm fus})/dE^2$, determined with the standard 'point difference method' (full circles) and the 'polynomial fit method' (open circles) for fusion reactions of ^{16}O ions with ^{144}Sm, ^{154}Sm, ^{184}W and ^{208}Pb target nuclei. The Gaussian-barrier distributions obtained by fitting the 'error function formula', Eq. (8), are shown by solid lines. Data taken from Refs. [19] and [17].

mine a value of $d^2(E\sigma)/dE^2 = 2c$. In order to compare the two methods in identical conditions, we used in the polynomial fit the same range of experimental points ΔE as in the 3-points method, $\Delta E = E_3 - E_1$, and moreover, a value of $d^2(E\sigma)/dE^2$, determined for a given set of points within the range ΔE, was assigned to the same position $E = E_2$ as in the equivalent calculation with the 3-points method.

It is seen from Figs. 2 and 3 that both methods yield comparable distributions, although for the same range ΔE, the polynomial fit method gives somewhat less scattered results. As it was emphasized by many authors in the past (see *e.g.*, Ref. [9]), the deduced barrier distributions depend strongly on the choice of the energy step between selected consecutive points, E_1, E_2, and E_3. Similar dependence is observed when the energy range ΔE is varied in the polynomial fit method. Additional uncertainty is connected with very large errors on the right-hand side of the barrier distribution, an effect due to flattening of fusion excitation functions at over-the-barrier energies. Therefore, only the low-energy side of the barrier distribution can be determined with satisfactory precision.

3.2. Fusion and/or capture excitation function formula

Discussed above difficulties in precise determination of the barrier distribution and also quite a limited collection of precisely measured fusion excitation functions, suitable for direct determination of the barrier distribution, led us to a different approach that can be used for a systematic overview of existing data and possibility to *predict* fusion excitation functions.

Neglecting structure effects in the barrier distributions, such as the double-peak shapes observed *e.g.* in ^{16}O induced reactions, we *assume* a Gaussian shape of the barrier distribution:

$$p(B) = \frac{1}{w\sqrt{2\pi}} \exp\left(-\frac{(B-B_0)^2}{2w^2}\right), \tag{6}$$

with the mean barrier B_0 and its width w 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. (6), with the classical expression for the fusion cross section,

$$\sigma_{\rm fus} = \pi R_{\rm B}^2 \left(1 - \frac{B}{E}\right), \tag{7}$$

we obtain [1] the following formula for the energy dependence of the fusion cross section:

$$\sigma_{\rm fus} = \pi R_{\rm B}^2 \frac{w}{E\sqrt{2\pi}} \left[X\sqrt{\pi}(1 + {\rm erf}X) + \exp(-X^2)\right], \tag{8}$$

where

$$X = \frac{E - B_0}{\sqrt{2}\,w}, \tag{9}$$

and erf$X$ is the Gaussian error integral of the argument X. By $R_{\rm B}$ we denote the relative distance corresponding to location of the interaction barrier. Along with B_0 and w, $R_{\rm B}$ is a parameter to be determined by fitting Eq. (8) to experimental data.

In derivation of formula (8), the quantum effect of sub-barrier tunnelling is not accounted for. However, since the tunnelling only slightly smears out the fusion excitation function around $E = B_0$, its effect is simulated and accounted for in an *effective* value of the width w deduced for a given reaction.

The 'error function formula', Eq. (8), represents a very convenient parametrization for fusion- and capture excitation functions, especially in the range of near-barrier energies. In case of capture reactions its validity extends even to higher energies. However fusion cross sections, determined in many experiments by measuring the evaporation-residue cross section, should not be compared with predictions of Eq. (8) at higher energies because entrance-channel angular-momentum limitations, not accounted for by Eq. (8), may reduce the fusion cross section at well-above-the-barrier energies.

4. Analysis of fusion excitation functions

In Fig. 4 we show four examples of measured [8, 10] fusion excitation functions fitted with formula (8) by using the least χ^2 method. It is seen that the fusion excitation functions can be reproduced very accurately over the entire near-barrier energy range where the measured cross sections vary by four orders of magnitude. The fitting procedure constrains the parameters B_0 and w sufficiently to determine the overall shape of the barrier distribution for a given reaction.

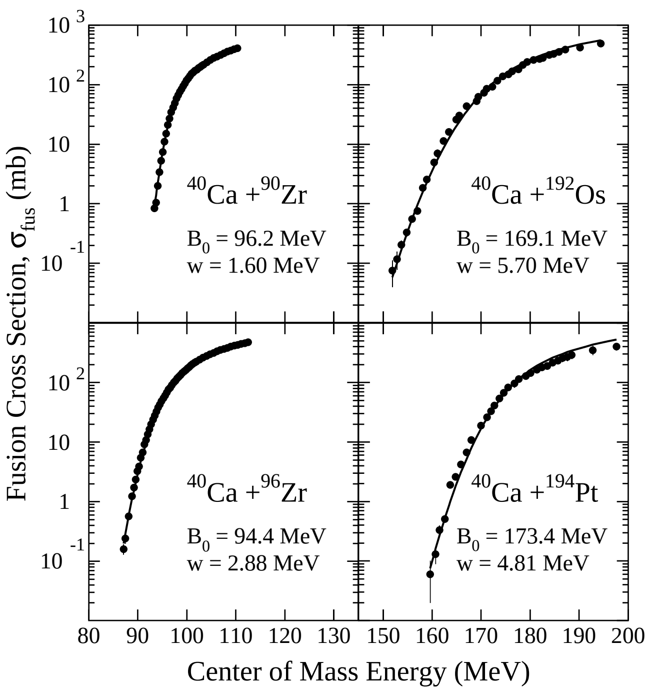

Fig. 4. Precisely measured fusion cross sections (full circles) in the ^{40}Ca + ^{90,96}Zr [10] and ^{40}Ca + ^{192}Os,^{194}Pt [8] reactions. Solid curves have been calculated with the 'error function formula', Eq. (8), for shown values of B_0 and w parameters (the mean barrier and width of the barrier distribution, respectively), obtained by minimizing χ^2.

We have compared the Gaussian distributions, obtained from fitting formula (8) to experimental data, with the barrier distributions that could be determined directly either with the point-difference method or the polynomial fit method, see figures 2 and 3. Quite good agreement with directly determined distributions is observed regarding the overall features, *i.e.*, the mean barrier energy, distribution width, and absolute values. A great advantage of the proposed method of fitting the excitation functions with Eq. (8) is that the overall characteristics of the barrier distributions (B_0, w) can be obtained even from less precise experimental data that exclude possibility of reliable determination of the second derivative $d^2(E\sigma)/dE^2$.

By using Eq. (8), we have analysed an ample set of published experimental data for about 50 medium and heavy nucleus–nucleus systems [8, 10–25]. All the chosen excitation functions have been measured in the near-barrier range of energies 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 $R_{\rm B}$ in Eq. (8). Therefore we fixed a value of $r_0 = R_{\rm B}/(A_1^{1/3} + A_2^{1/3}) = 1.27$ 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 w.

5. Systematics of the barrier-distribution parameters

In order to use Eq. (8) for *predicting* fusion and capture cross sections for not yet studied reactions, we attempted to systematize values of the parameters B_0 and w.

In Fig. 5 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,

$$B_0 = 0.00136z^2 + 0.78z + 4.2 \text{ MeV}. \tag{10}$$

In addition to B_0 values obtained from the analysis of fusion reactions, Fig. 5 includes also the mean barriers deduced from capture data for very heavy systems, ^{48}Ca + ^{208}Pb, ^{58}Fe+^{208}Pb and ^{48}Ca+^{238}U, studied by Itkis et al. [25]. (For these heavy systems, capture cross sections have been determined by measuring the quasi-fission cross sections.) It is important to note that following our expectations, the parametrization established for near-barrier fusion of medium mass systems (full circles in Fig. 5) holds also for description of capture cross sections in reactions of very heavy systems (open squares). Consequently, one can use Eq. (10) for reasonable predictions of the mean barrier heights for capture processes in collisions of the heaviest systems.

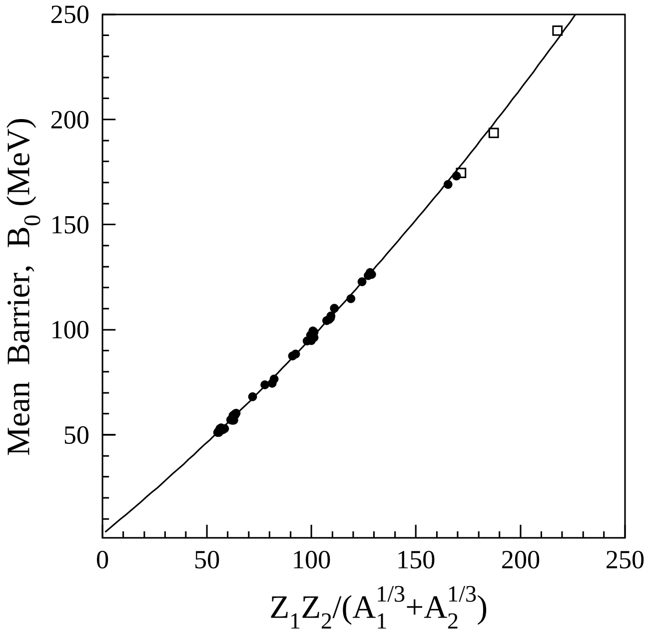

Fig. 5. Systematics of the mean barrier B_0, determined from analysis of fusion- and capture excitation functions for about 50 nuclear systems, found in the literature (Refs. [8, 10–25]). Results for capture reactions [25] are indicated by different symbols (squares). Solid line represents parametrization given by Eq. (10).

Contrary to B_0, the width parameter w 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. Therefore it is natural that w depends not only on the 'global' parameters, such as Z and A of the fusing nuclei, but also on their structural characteristics. Having in mind a simplistic picture of two touching nuclei with vibrating surfaces causing the smearing of the barrier height, we expect that magnitude of the smearing depends on the depth of the nuclear potential V_0. (The vibration of nuclear surfaces in the touching configuration can be represented as vibration of the radius parameter R_0 of an effective Saxon–Woods-shaped nuclear potential relative to a steady Coulomb potential.) The depth V_0 of the nuclear part of the nucleus–nucleus *fusion* potential can be calculated in a model-independent way as:

$$V_0 = Q_{\rm fus} + C_{\rm cn} - C_1 - C_2, \tag{11}$$

where $Q_{\rm fus} = (M_1 + M_2 - M_{\rm cn})c^2$ is the fusion Q-value determined by the ground-state masses of the colliding nuclei, M_1 and M_2, and the compound nucleus, $M_{\rm cn}$, and C_1, C_2 and $C_{\rm cn}$ are the Coulomb energies of these nuclei. In a parametrization of the standard liquid-drop-model [26], this difference of the Coulomb energies can be expressed [27] as:

$$C_{\rm cn} - C_1 - C_2 = C_0 = 0.7054 \left[\frac{(Z_1+Z_2)^2}{(A_1+A_2)^{1/3}} - \frac{Z_1^2}{A_1^{1/3}} - \frac{Z_2^2}{A_2^{1/3}} \right] \text{MeV}. \quad (12)$$

Fig. 6 displays the deduced values of the width parameter w plotted as a function of the depth V_0 of the nuclear part of the fusion potential. Evidently, there is a close correlation between these two quantities. One can use this fact as argument in support of the mentioned above idea of the vibrational nature of the barrier smearing. Nevertheless, significant dispersion of points displayed in Fig. 6 shows that not all relevant structural effects are accounted for in this way.

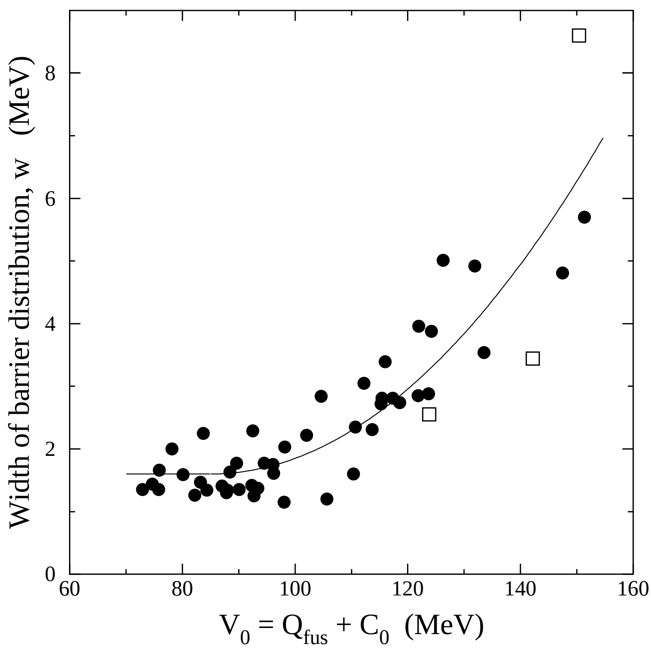

Fig. 6. Systematics of the width w of the barrier distribution, determined from analysis of fusion- and capture excitation functions for about 50 nuclear systems, found in the literature (Refs. [8, 10–25]). Results for capture reactions [25] are indicated by different symbols (squares). Solid line represents parametrization given by Eq. (13). For definition of the depth of the fusion potential V_0, see text.

Another possible dependence, namely a correlation between the width parameter w and the height of the 'adiabatic fusion barrier' [27] was examined in Ref. [28] and used then for systematizing w-values. We stay however with the correlation between w and V_0 because V_0-values can be easier evaluated (in comparison with the adiabatic barriers).

The observed correlation between the width of the barrier distribution, w and the depth V_0 of the nuclear part of the fusion potential can be parametrized as a constant value for relatively light systems, and a quadratic dependence for heavier systems:

$$w = 1.6 \text{ MeV} \quad \text{for} \quad V_0 < 85\,\text{MeV}, \tag{13a}$$
$$w = 1.6 + 0.0011\,(V_0 - 85)^2\,\text{MeV} \quad \text{for} \quad V_0 \geq 85\,\text{MeV}. \tag{13b}$$

This dependence is shown in Fig. 6 by solid line.

6. Summary and conclusions

We have studied possible ways of predicting capture cross sections in nucleus–nucleus collisions at near-barrier and sub-barrier energies, a vital question for experiments aimed at production of new super-heavy elements. The capture cross section reflects the probability of overcoming the interaction barrier and therefore is sensitive to the barrier height and its distribution. We have demonstrated a new computational tool for direct determination of the barrier distribution by calculating the Rowley's [7] derivative $d^2(E\sigma)/dE^2$ from a local fit of a quadratic function to $E\sigma$ values ('polynomial fit method'). Results obtained with this method look similar to those obtained with traditional 'point difference' method.

From the point of view of predictions of the capture cross section in sub-barrier region, relevant for experiments on super-heavy elements, deciding role is played by *low-energy* tail of the barrier distribution. Therefore we applied, very successfully, a simple formula for the capture cross section, derived under assumption of a Gaussian shape of the barrier distribution. We deduced the barrier distribution parameters, the mean barrier B_0 and the distribution width w, for an ample set of existing data on near-barrier fusion- and capture excitation functions for about 50 medium and heavy systems. A meaningful information on B_0 and w was obtained even for not very precisely measured excitation functions, for which direct determination of $d^2(E\sigma)/dE^2$ was not possible. The *low-energy* tails of so determined barrier distributions perfectly agree with profiles of the distributions determined directly (for those precisely measured systems for which the direct method could be applied). Of course, the 'error function formula', Eq. (8), ignores the nuclear structure effects usually appearing (with very large error bars) at energies *above* the mean barrier.

We have presented systematics of the barrier-distribution parameters B_0 and w obtained by fitting fusion- and capture excitation functions with the 'error function formula'. The mean barrier B_0 turned out to be a smooth function of the Coulomb interaction parameter $z = Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$, but the width parameter w clearly depends on nuclear structure effects. We have observed a correlation between w and depth of nuclear part of the nucleus–nucleus fusion potential, V_0, that may account for some nuclear structure effects via the ground-state masses of the projectile and target nuclei. However deviations from smooth relation between w and V_0 are large, that means that not all relevant structural effects are accounted for in this way.

We propose to use the 'error function formula', Eq. (8), with B_0 and w parameters taken from the established systematics, Eqs. (10) and (13), for calculating and predicting unknown capture cross sections in planning new experiments on production of super-heavy elements.

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