Decay of ^{118,122}Ba* compound nuclei formed in ^{78,82}Kr + ^{40}Ca reactions using the dynamical cluster-decay model of preformed clusters

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Application of the preformed clusters based dynamical cluster-decay model (DCM) is made to the recent data on decay of the compound systems ^{118,122}Ba* at a relatively low bombarding energy of 5.5 MeV/A. The same model has been applied earlier to the intermediate mass fragment (IMF) data of ^{116}Ba*, observed at medium and higher incident energies. For the heavier ^{118,122}Ba* systems, however, a complete mass fragmentation spectrum is observed experimentally. Except for a small narrow region of heavier mass fragments ($8 \leqslant Z_L \leqslant 15$), the DCM gives an overall reasonable description of the observed data on both the intermediate mass fragments and the fusion-fission cross-sections, whereas the statistical model calculations based on BUSCO and GEMINI codes describe the intermediate mass fragment data and the heavier mass fragment and fusion-fission data, respectively. Within the DCM (with preformation factor $P_0 = 1$), the possibility of non-compound-nucleus decay contributing to the region $8 \leqslant Z_L \leqslant 15$ of heavier mass fragments is also explored. All three models use the maximum angular momentum $\ell_{\max}$ as a fitting parameter, which in the DCM is fixed via a neck-length parameter for the penetrability $P \to 1$.

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I. INTRODUCTION

Barium nuclei have been of much interest from time to time. First, as an extension of the phenomenon of exotic cluster radioactivity to parents other than radioactive nuclei, the ^{12}C emission from various $^{112-120}$Ba nuclei (with ^{100}Sn and its heavier isotopes as daughter nuclei) has been the subject of several investigations, both theoretically [1–4] and experimentally [5,6]. The ground state decay of Ba has not yet been observed. Then, a new phenomenon of intermediate mass fragments (IMFs, with $3 \leqslant Z \leqslant 9$), also referred to as "clusters" or "complex fragments", emitted from excited compound systems, was observed in ^{58}Ni + ^{58}Ni → ^{116}Ba* reactions at both the high ($E_{\text{c.m.}} = 315$ MeV) [7,8] and medium ($E_{\text{c.m.}} =$ 174, 185.5, 187.5, and 197 MeV) energies [9,10]. The IMFs' cross section, σ_{IMF}, is known [11–13] to be small, of the order of 5–10% of the light particles' (LPs, $Z \leqslant 2$) cross section, referred to as the fusion-evaporation cross section. The fusion-evaporation cross section for the Ba* compound system has also not been measured as yet. The measured σ_{IMF} for the ^{116}Ba* decay at all the above-mentioned medium and high energies are so far understood only on the preformed cluster based dynamical cluster-decay model (DCM) of one of us (R.K.G.) and collaborators [14]. The DCM describes the ^{116}Ba* data on σ_{IMF} reasonably well and predicts an additional fusion-fission of ^{116}Ba* that consists of fragments at the heavy end of symmetric and near symmetric division ($14 \leqslant Z \leqslant 28$), very recently observed at GANIL [15] for the decays of ^{118,122}Ba* nuclei (see below).

With the availability of the neutron-rich ^{82}Kr beam, the GANIL experiment [15] was made at a still lower energy of 5.5 MeV/A for ^{78,82}Kr on ^{40}Ca target ($E_{\text{c.m.}} = 145.42$ and 147.87 MeV, respectively), and the cross sections, kinetic energies, and angular distributions of fragments were measured for charges $6 \leqslant Z \leqslant 28$ emitted from ^{118,122}Ba*. The measured characteristics are compatible with binary emission from a compound nucleus. An interesting result of these measurements is that the yields for symmetric division of ^{118}Ba* are higher by about 30%, compared to those for ^{122}Ba*. Also, for both the compound systems, a strong odd-even effect is observed for light fragments ($Z \leqslant 10$), which persists to some extent for higher-Z fragments with highly reduced amplitude. Furthermore, cross sections for even-Z fragments are higher for ^{118}Ba* but those for odd-Z are higher for ^{122}Ba*. Here it may be relevant to recall that this suppression of even-Z fragments with the addition of neutrons to the compound system was also observed in the very early experiments on the decay of ^{56,58,60}Ni* [16,17]. The α-nucleus spectrum, observed for $N = Z$ ^{56}Ni*, nearly disappeared for its $N > Z$ isotopes, which is rather well understood within the general framework of the fragmentation theory [18–21]. The same fragmentation theory provides a basis for the DCM used in the above-mentioned study for the decay of ^{116}Ba* [14] and is used here in this article for understanding the recent data for ^{118,122}Ba* decays.

The ^{118,122}Ba* data [15] are also analyzed by these authors using the statistical models, the BUSCO and GEMINI codes. In the BUSCO code [7], the Hauser-Feshbach formalism (for LPs) is extended to include also the observed IMFs up to $Z = 20$ ($0 \leqslant Z \leqslant 20$), and in the GEMINI code [22] for heavier compound systems ($A_{\text{CN}} > 100$), the IMFs ($Z \geqslant 3$) are considered as binary fission in the statistical fission model of Moretto [23] with Sierk's barriers [24], but the light particles ($Z \leqslant 2$) are still treated within the Hauser-Feshbach method. The maximum angular mometum $\ell_{\max}$, instead of being given by the measured fusion cross sections, was considered as a free parameter to be fitted to yields around the symmetric splitting and the level density parameter $a = A_{\text{CN}}/8$. However, the authors of Ref. [15] find that whereas GEMINI fails to reproduce the whole Z distribution of the measured cross sections, BUSCO fails to reproduce the Z dependence of the cross-section ratios as well. In view of our earlier work [14] on DCM for ^{116}Ba*, in the following we present our initial results on the application of the DCM to the GANIL data for ^{118,122}Ba* systems.

The article is organized as follows: A brief account of the DCM for a hot and rotating compound system is presented in Sec. II and its application to ^{118,122}Ba* data is made in Sec. III. The parameters of the model, the neck-length ΔR (and maximum angular momentum ℓ_{max}), are first taken to be the same as those for ^{116}Ba* in Ref. [14] and then are obtained for the best fit to the measured yields of different fragment mass regions. Finally, a summary and discussion of our results is given in Sec. IV.

II. THE DYNAMICAL CLUSTER-DECAY MODEL (DCM)

The dynamical cluster-decay model is well described in our earlier articles [14,25–33]. Based on the fragmentation theory (see, e.g., Ref. [34]), it is worked out in terms of the collective coordinates of the mass and charge asymmetries $\eta = (A_H - A_L)/(A_H + A_L)$ and $\eta_Z = (Z_H - Z_L)/(Z_H + Z_L)$, and the relative separation R, which in the DCM refer, respectively, to the nucleon division (or nucleon exchange) between the outgoing fragments and the transfer of the kinetic energy of the incident channel ($E_{c.m.}$) to the internal excitation (total excitation energy, TXE, or total kinetic energy, TKE) of the outgoing channel. H and L stand, respectively, for heavy and light fragments. In terms of these coordinates, using the partial waves, the compound nucleus (CN) decay, or the fragments production cross section,

$$\sigma_{\rm CN} = \sum_{\ell=0}^{\ell_{\max}} \sigma_{\rm CN}^{\ell} = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{\max}}(2\ell+1)P_0 P; \quad k = \sqrt{\frac{2\mu E_{\rm c.m.}}{\hbar^2}}. \tag{1}$$

Here, the preformation probability P_0 refers to η motion and the penetrability P to R motion. The reduced mass $\mu = [A_L A_H/(A_L + A_H)]m = \frac{1}{4}Am(1-\eta^2)$ and the maximum angular momentum ℓ_{max} is defined later. m is the nucleon mass. Apparently, in the DCM, both the light particles (LPs) and the complex intermediate mass fragments (IMFs) up to symmetric division ($Z = 28$ for Ba*) are treated as the dynamical collective mass motions of *preformed clusters or fragments* through the barrier. For the non-compound-nucleus (nCN) decays, like the preequilibrium fission, quasifission (qf) or deep inelastic collisions (DIC), the entrance channel keeps its identity, and hence the preformation factor $P_0 = 1$, referred to as DCM($P_0 = 1$) in the following.

The preformation probability $P_0(A_i)$ $(\equiv \mid \psi(\eta(A_i)) \mid^2, i = H$ or $L)$ is the solution of the stationary Schrödinger equation in η, at a fixed $R = R_a$, the first turning point of the penetration path(s) shown in Fig. 1 of Ref. [14]. P_0 contains the structure information of the compound nucleus that enters via the fragmentation potential $V(\eta, T)$ or $V(A_i, T)$ in the Schrödinger equation. The $V(\eta)$ at each temperature (T) is calculated in Strutinsky macro-microscopic method, where the macroscopic term $V_{\rm LDM}$ is the T-dependent liquid drop energy of Davidson *et al.* [35], with its constants at $T = 0$ refitted [26,28] to give the recent experimental binding energies [36], and the microscopic shell corrections δU are the "empirical" estimates of Myers and Swiatecki [37], also taken as T dependent. The other terms in $V(\eta)$ are, respectively, the T-dependent Coulomb potential, the nuclear proximity potential [38], and the rotational energy term for spherical nuclei, with the moment of inertia taken in the complete sticking limit. For details, see Refs. [14] and [30]. The mass parameters $B_{\eta\eta}(\eta)$, entering the P_0 calculation via the kinetic energy term, are the smooth classical hydrodynamical masses [39], used here for simplicity. Note that the temperatures involved here are large ($T > 2.5$ MeV), such that the shell effects are almost completely washed out. Also, in the liquid drop model [35] used here, the pairing energy $\delta = 0$ for $T > 2$ MeV. Thus, the odd-even effects of the binding energies are expected to be small in the model at the energies of the experiments considered here. However, the role of taking $\delta > 0$ empirically, is also analyzed.

The penetrability P is the WKB integral between R_a and R_b, with R_b as the second turning point, satisfying

$$V(R_a, \ell) = V(R_b, \ell) = {\rm TKE}(T, \ell), \tag{2}$$

see Fig. 1 in Ref. [14]. The first turning point is defined as

$$R_a(T) = C_L(\eta, T) + C_H(\eta, T) + \Delta R(T), \tag{3}$$

which apparently depends on the TKE(T) via Eq. (2). C_i are the Süsmann central radii, $C_i = R_i - b^2/R_i$ with T-dependent radii $R_i(T) = 1.07(1 + 0.01T)A_i^{\frac{1}{3}}$ [35], and surface width $b(T) = 0.99(1 + 0.009T^2)$ [40]. This method of introducing a neck-length parameter ΔR, within the extended model of Gupta and collaborators [41–43], which simulates the two center nuclear shape parametrization, is similar to that used in both the scission-point [44] and saddle-point [12,13] statistical fission models. The parameter ΔR, taken to be the same for all ℓ values, is fixed for $P \to 1$ at $\ell = \ell_{max}$. Thus, ℓ_{max} and ΔR are interdependent quantities, as is evident from Fig. 1 in Ref. [14]. Also, ΔR are found to depend on temperature, because they represent the change in TKE(T) with respect to TKE($T = 0$) [14,30].

Finally, for the positive Q_{out} system under study, the compound nucleus excitation energy $E^*_{\rm CN}(= E_{c.m.} + Q_{in})$ gets distributed into TXE and TKE of the two outgoing fragments at each T, as

$$E^*_{\rm CN} + Q_{\rm out}(T) = {\rm TKE}(T) + {\rm TXE}(T). \tag{4}$$

Then, the exit channel fragments can be obtained in the ground state with TKE($T = 0$) $(= Q_{out}(T = 0))$ by allowing the emission of light particles and/or γ rays with an energy $E_x = {\rm TKE}(T) - Q_{\rm out}(T = 0) = {\rm TKE}(T) - {\rm TKE}(T = 0)$ such that, of the remaining excitation energy of the decaying system $[E^*_{\rm CN} + Q_{\rm out}(T)] - E_x = {\rm TKE}(T = 0) + {\rm TXE}(T)$, the TXE($T$) is used in the secondary emission of light particles from the primary fragments, which are on the average one α particle to two nucleons [7], but are not treated here as well as in most of the experiments. Instead, our calculations consider the primary, pre-secondary-evaporation fragments. Here, the compound nucleus temperature T (in MeV) is given by

$$E^*_{CN} = aT^2 - T, \tag{5}$$

with $a = A_{CN}/8$, taken in agreement with that used in the BUSCO and GEMINI codes by Bonnet *et al.* [15].

III. CALCULATIONS

First of all, we use the constants of the model $\Delta R = 1.16$ fm (and $\ell_{max} = 91\hbar$), obtained for $^{58}Ni + ^{58}Ni \rightarrow ^{116}Ba^*$ [14], and calculate the fragmentation potentials $V(A_i)$ and hence the preformation probability $P_0(A_i)$ for both the $^{118,122}Ba^*$ systems formed in $^{78,82}Kr + ^{40}Ca$ reactions at 5.5 MeV/A of bombarding energy. Figure 1 illustrates our result for $^{118}Ba^*$, where P_0 is plotted as a function of fragment mass A_L for different ℓ values. An interesting result from this figure is that the LPs ($A_L = 1$–4), the light mass fragments ($A_L = 5$–14) denoted IMFs, the heavy mass fragments ($A_L = 15$–27 and $A_L = 28$–41) denoted HMFs, and the near symmetric fission (nSF) and symmetric fission (SF) fragments ($A_L = 42$–48 and $A_L = 49$–59) show different characteristic behaviors. Such an interesting structure (sudden changes) with respect to the mass of fragments suggests that we should treat the different mass regions differently, implemented by using different ΔR (and hence different ℓ_{max}) values for different mass regions. The use of different ΔR and/or ℓ_{max} values for different fragment mass regions is also made in our earlier calculations for the $^{56}Ni^*$ compound system [30]. Note, in the DCM we fix ΔR for $P \rightarrow 1$ at $\ell = \ell_{max}$, which for any fixed mass region means $\ell = \ell_{max} \pm 1$ at the most.

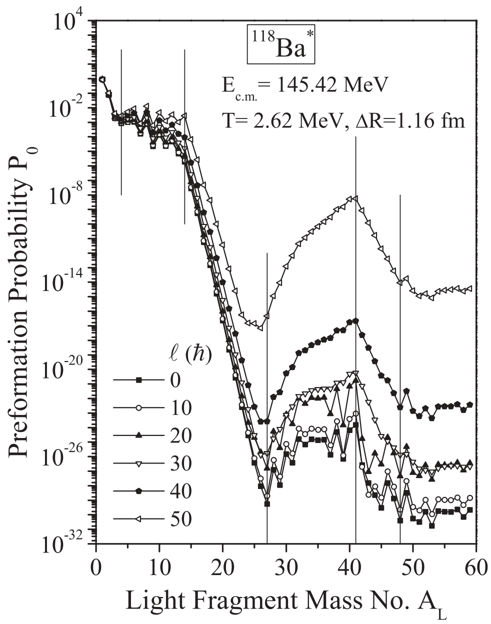

FIG. 1. Preformation probability P_0 as a function of fragment mass A_L, and for different ℓ values, calculated by using the DCM for the compound system $^{118}Ba^*$ at $E_{c.m.} = 145.42$ MeV (equivalently $T = 2.62$ MeV), using the fragmentation potentials V(A_i) calculated at $R = R_a = C_L + C_H + \Delta R$, $\Delta R = 1.16$ fm.

Using different ΔR (fm) [and ℓ_{max} ($\hbar$)] values for different mass regions, namely, 1.6 [52], 1.35 [66], 1.34 [74], and 1.27 [81] for $A_L = 1$–14 (LPs + IMFs), 15–41 (HMFs), 42–48 (nSF), and 44–61 (SF) in $^{118}Ba^*$, and 1.65 [59], 1.17 [69], 1.15 [78], and 1.07 [86] for $A_L = 1$–14, 15–36, 37–43, and 44–61, respectively, in $^{122}Ba^*$, the mass fragmentation potentials $V(A_i)$ are calculated, whose energetics are found to be similar to those for $^{116}Ba^*$ (see Fig. 2 in Ref. [14]). So also is the case for the ℓ-summed P and P_0 (see Fig. 3 in Ref. [14]). Based on such a potential $V(A_i)$, the compound nucleus cross sections are calculated and given in Fig. 2 for both the compound systems $^{118,122}Ba^*$ and compared with the experimental data [15]. Because $T > 2$ MeV for both the data, the pairing strength $\delta = 0$ in the liquid drop model used here in the DCM calculations. Also shown in Fig. 2(a) are the statistical model calculations of Bonnet *et al.* [15] for $^{122}Ba^*$, based on BUSCO and GEMINI codes, respectively, for $\ell_{max} = 45$ and $66\hbar$. We notice in Fig. 2(a) that whereas the BUSCO code fits only the light IMFs data, and the GEMINI code fits the HMFs, nSF, and SF data, the DCM fits are reasonable for both the lower end of light IMFs and the upper end of heavy HMFs, the nSF and SF data. Perhaps, the interesting result is that both the BUSCO and the DCM agree in predicting a sudden decrease of yield at $Z \geqslant 8$, the BUSCO predicting continuously decreasing yields and the DCM a kind of valley (underestimating the data) for fragment charge region $8 \leqslant Z_L \leqslant 15$. The GEMINI code overestimates the data in the $6 \leqslant Z_L \leqslant 13$ region. In other words, none of the three models describe the region in the neighborhood of $8 \leqslant Z_L \leqslant 15$. As one of the possible solutions to this problem, within the DCM($P_0 = 1$), we have estimated the non-compound-nucleus decay contribution σ_{nCN} for this region of $Z_L = 8$–15 fragments alone, by defining $\sigma_{nCN} = \sigma^{Expt}_{CN} - \sigma^{Cal}_{CN}$ for each fragment. For the best-fitted ΔR (and ℓ_{max}) values, interestingly the valley gets filled, and the DCM calculated $\sigma_{CN} + \sigma_{nCN}$ for this region gives a much better agreement with the data. The ΔR (and ℓ_{max}) values for the chosen $8 \leqslant Z_L \leqslant 11$ and $12 \leqslant Z_L \leqslant 15$ regions are, respectively, 1.88 fm ($0\hbar$) and 1.86 fm ($1\hbar$) for the DCM($P_0 = 1$) calculations of σ_{nCN}.

The effect of nonzero pairing ($\delta > 0$) in V_{LDM} is also illustrated in Fig. 2(b) for $^{118}Ba^*$, taking $\delta(T)$ in V_{LDM} as a fitting parameter, say, to ^{12}C data. Here both the data and the calculations are plotted separately for odd- and even-Z fragments. For $\delta = 16.65$ MeV, in agreement with experiments [15], we notice a stronger preference for even-Z over the odd-Z fragments.

Figure 3 shows a comparison of our calculated ratio of cross sections for $^{118}Ba^*$ and $^{122}Ba^*$, i.e., $\sigma_{^{118}Ba}/\sigma_{^{122}Ba}$ (for both cases of $\delta = 0$ and $\delta > 0$) as a function of Z_L, compared with its measured values and the GEMINI code predictions. Evidently, though the ratios in two models (GEMINI and DCM) are an order of magnitude different, the DCM also shows an enhancement of the cross section for the neutron-deficient compound system $^{118}Ba^*$ (ratio is larger than the one for most of the fragments), as is the case for the data and the GEMINI code. The GEMINI predictions are rather impressive, though the DCM predictions are also improved for the case of nonzero pairing.

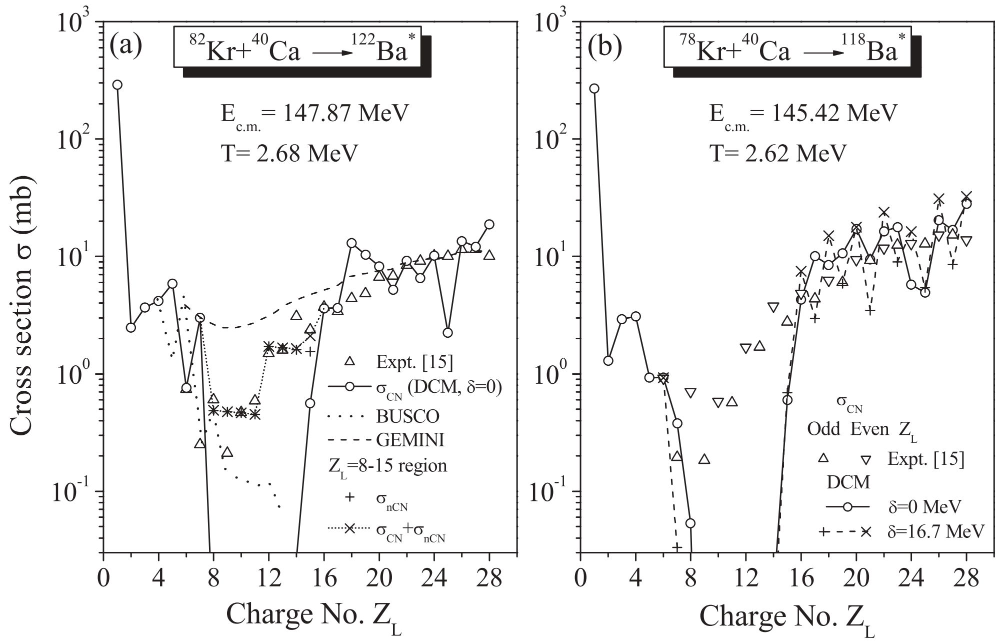

FIG. 2. The calculated cross sections $\sigma_{\rm CN}$ are compared with the measured ones [15] as a function of the charge Z_L of the light fragment for the ^{118,122}Ba* decays at incident laboratory energy of 5.5 MeV/A. Because only the charges of fragments are measured in experiments, the calculated yields for each charge are summed over the energetically favored masses of fragments. In panel (a) we further make the comparison with the statistical model calculations of Bonnet *et al.* [15] for ^{122}Ba*, based on BUSCO and GEMINI codes, and also add the non-compound-nucleus contribution $\sigma_{\rm nCN}$, calculated on DCM($P_0 = 1$) for $Z_L = 8$–15 fragments only. Note that at the T values of experiments ($T > 2$ MeV) the pairing strength $\delta = 0$ in the liquid drop model used here in the DCM calculations. The role of nonzero pairing strength ($\delta > 0$) is illustrated in panel (b) for ^{118}Ba*, using $\delta = 16.65$ MeV, fitted to ^{12}C data.

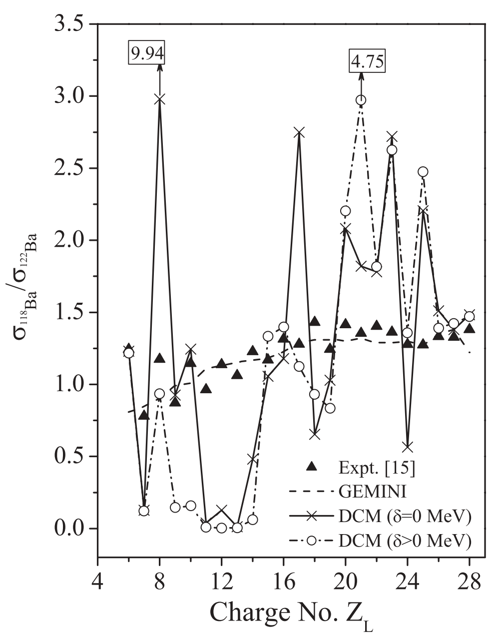

FIG. 3. The ratio $\sigma_{^{118}\rm Ba}/\sigma_{^{122}\rm Ba}$ as a function of Z_L for experiments [15], compared with the predictions of the GEMINI code and the DCM calculations (for two different pairing strengths $\delta = 0$ and $\delta > 0$). $\delta = 16.65$ and 16.15 MeV, respectively, for ^{118}Ba* and ^{122}Ba*, for a similar best fit to the ^{12}C data. Note that a similar DCM calculation for the $\delta = 0$ case is published in Ref. [33], which is preliminary and hence differs somewhat from the present final results.

IV. SUMMARY AND DISCUSSION

Summarizing, in this article we have extended the application of the preformed clusters based dynamical cluster-decay model (DCM) to the new Z cross-section (and ratio) data on the decay of ^{118,122}Ba* formed in ^{78,82}Kr + ^{40}Ca reactions at a relatively low laboratory energy of 5.5 MeV/A [15]. Comparison is also made with the available [15] statistical model calculations based on BUSCO and GEMINI codes. The three models show varied successes; it is not possible to conclude which one is definitely better than the other two. The BUSCO code is best suited for light IMFs (not worrying about the fission phase space) and the predictions of the GEMINI code could be improved for use of different barriers like that of the generalized liquid drop model [40], in particular the very asymmetric fission barriers, because the Sierk model [24] is very good only for symmetric fission barriers. Also, in contrast to the statistical HF and/or fission models, the DCM has shortcomings with respect to the fission space, as both the level densities and the angular momenta of the fission fragments are not at all taken into account.

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