Modeling Fission in the Cascade-Exciton Model

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Abstract

Recent developments of the Cascade-Exciton Model (CEM) of nuclear reactions to describe high energy particle induced fission are briefly described. The increased accuracy and predictive power of the CEM are shown by several examples. Further necessary work is outlined.

1. Introduction

A number of recent projects like accelerator transmutation of waste, accelerator-based conversion, accelerator-driven energy production, accelerator production of tritium, etc. have revived interest in reliable data from different types of nuclear reactions, including high energy fission (see, e.g., [1]).

Many efforts have been previously made to develop models of high energy fission and to implement them into codes used in applications. For example, the Fong statistical model of fission [2] has been incorporated into different Monte Carlo codes, e.g., at JINR [3, 4], ORNL [5], BNL [6], and PINP, Gatchina [7]. A similar approach based on the thermodynamical model of fission was developed in Moscow at ITEP by Stepanov [8] and was incorporated in the ITEP code INUCL. A more sophisticated and physically grounded, but at the same time, more complicated and time consuming approach is the dynamical “Diffusion Model of Fission” [9] implemented as a Monte Carlo code at INR, Moscow by Mebel et al. [10]. On the other hand, several much simpler approaches based on phenomenological distributions of fragments, such as Atchinson’s model [11], Nakahara’s model [12], and Rubchenya’s recent model [13] are also used in a number of codes. Finally, in a number of current works, high energy fission and fragmentation is calculated in a single statistical model of sequential binary decays, using the code GEMINI [14].

Fission is a slow process, which at intermediate and high incident energies is considered to take place after fast processes, described usually by intranuclear cascade models (INC), intermediate or preequilibrium processes, and evaporation from compound nuclei before fission. One of the models with a good predictive power for the first three stages of reactions preceding fission is the Cascade-Exciton Model (CEM) of nuclear reactions [15] in its currently improved modifications (see [16] and references therein). CEM, in its standard version [15], did not consider fission at all. Lately, the model has been extended by taking into account the competition between particle emission and fission at the compound nuclear stage and a more realistic calculation of nuclear level density [17]. A version of the CEM with these modifications, as realized in the code CEM92, was used successfully by Konshin [18] to calculate nucleon-induced fission cross sections for actinides in the energy region from 100 MeV to 1 GeV. Nevertheless, both CEM92 and a later version of the code, CEM95 [19], run into problems when used for preactinides [20]. In addition, CEM95 only allows us to calculate nuclear fissilities and fission cross sections but not the process of fission itself, and does not provide fission fragments and a further possible evaporation of particles from them. When, during the Monte Carlo simulation of the compound stage of a reaction with CEM95, we encounter a fission, we simply remember this event (that permits us to calculate fission cross section
and fissility) and finish the calculation of this event without a subsequent calculation of fission fragments and a further possible evaporation of particles from them.

This means that CEM95 is suitable for calculating yields of produced nuclides only in the spallation region. To extend the range of its applicability into the fission and fragmentation regions, it should be developed further. Our so far modest progress in modeling fission with the CEM is described in this paper.

2. Modeling Fission Cross Sections

Because we consider in detail only the third, compound-decay stage of nucleon-induced fission reactions, we will not discuss here the details of the modeling of the cascade and preequilibrium stages of the reactions [15, 16, 19]. We give below a brief summary of the models used in calculating fission and particle decay widths, and define the parameters whose variation is discussed in Section 3.

We approximate the partial widths $\Gamma_j$ for the emission of a particle $j$ (j ≡ n, p, d, t, $^3$He, $^4$He) and $\Gamma_f$ for fission by the expressions:

$$\Gamma_j = \frac{(2s_j + 1)m_j}{\pi^2 \rho_c(U_c)} \int_{U_j - B_j}^{U_j} \sigma_{inv}^j(E) \rho_j(U_j - B_j - E) EdE ,$$

$$\Gamma_f = \frac{1}{2\pi \rho_c(U_c)} \int_0^{U_f - B_f} \rho_f(U_f - B_f - E) dE ;$$

where $\rho_c$, $\rho_j$, and $\rho_f$ are the level densities of the compound nucleus, the residual nucleus produced after the emission of the $j$-th particle, and of the fissioning nucleus at the fission saddle point, respectively; $m_j$, $s_j$ and $B_j$ are the mass, spin and the binding energy of the $j$-th particle, respectively, and $B_f$ is the fission-barrier height. $\sigma_{inv}^j(E)$ is the inverse cross-section for absorption of the $j$-th particle with kinetic energy $E$ by the residual nucleus. The “thermal” energies $U_k$ are defined by

$$U_c = E^* - E_{R}^c - \Delta_c ; U_j = E^* - E_{R}^j - \Delta_j ; U_f = E^* - E_{R}^{sp} - \Delta_f ,$$

where $E^*$ is the total excitation energy of the compound nucleus, and $E_{R}^c$ and $E_{R}^j$ are the rotational energies of the compound and residual nuclei at their ground state deformations

$$E_{R}^{gs} = \frac{L(L + 1)\hbar^2}{2J_{rb}} ,$$

where the rigid-body moment of inertia is approximated as

$$J_{rb} = 0.4m_N r_0^2 A^{5/3} .$$

For the fission saddle point,

$$E_{R}^{sp} = \frac{L(L + 1)\hbar^2}{2J_{sp}} ,$$

and $J_{sp}$, the moment of inertia of the saddle-point shape, is taken from Ref. [21] or [22].
Following Ref. [23], the pairing energies of the compound nucleus $\Delta_c$, of the residual nucleus $\Delta_j$, and of the fission saddle point $\Delta_f$ are estimated as:

$$\Delta_c = \chi_c \cdot 12/\sqrt{A_c} \; ; \; \Delta_j = \chi_j \cdot 12/\sqrt{A_j} \; ; \; \text{and} \; \Delta_f = \chi_e \cdot 14/\sqrt{A_c} \; (\text{in MeV}). \quad (3)$$

$A_j = A_c - A_j$, where $A_c$ and $A_j$ are the mass numbers of the compound nucleus and of the $j$-th particle, and $\chi_k = 0$, 1, or 2 for odd-odd, odd-even, or even-even nuclei, respectively. For the inverse cross sections, the approximations proposed by Dostrovsky et al. [24] are used,

$$\sigma_{inv}^j(E) = \sigma_{geom}^j \alpha_j \left(1 + \frac{\beta_j}{E}\right), \quad (4)$$

where

$$\sigma_{geom}^j = \pi R_j^2 ; \; R_j = \tilde{r}_0 A_j^{1/3} ; \; \tilde{r}_0 = 1.5 \; \text{fm} ; \quad (5)$$

$$\alpha_n = 0.76 + 2.2 A_j^{-1/3} ; \quad (5')$$

$$\beta_n = (2.12 A_j^{-2/3} - 0.05)/\alpha_n . \quad (5'')$$

For charged particles $\beta_j = -V_j$, where $V_j$ is the effective Coulomb barrier and the constants $\alpha_j$ are calculated for a given nucleus by interpolating the values of Ref. [24].

For the level density, we use the simple form

$$\rho(U_{eff}) \simeq \text{Const} \cdot \exp\{2\sqrt{a U_{eff}}\} ,$$

where $U_{eff}$ is the argument of $\rho$ in Eqs. (1) and (2). For the level density parameter $a_j$, we consider either a constant, one empirical determination of $a_j(Z, N)$ [25], or eight different sets of parameters of the form $a_j(Z, N, E^*)$, each with three empirically determined parameters[23], [26]–[28].

$$a(Z, N, E^*) = \tilde{a}(A) \left\{1 + \delta W_{gs}(Z, N) \frac{f(E^* - \Delta)}{E^* - \Delta}\right\} , \quad (6)$$

where

$$\tilde{a}(A) = \alpha A + \beta A^{2/3} B_s \quad (7)$$

is the asymptotic Fermi-gas value of the level density parameter at high excitation energies. Here, $B_s$ is the ratio of the surface area of the nucleus to the surface area of a sphere of the same volume (for the ground state of a nucleus, $B_s \approx 1$), and

$$f(E) = 1 - \exp(-\gamma E) . \quad (8)$$

The shell and pairing corrections $\delta W_{gs}(Z, N)$ (which also enter the calculation of the binding energies $B_j$) may be approximated using the systematics due to Cameron [29], Truran, Cameron and Hilf [30], or Myers and Swiatecki [31]. The fission barriers $B_f$ are calculated by one of several macroscopic models [32]–[37], with the addition of $\delta W_{gs}(Z, N)$. In addition, we may use a temperature-dependent barrier [38, 39] or one independent of temperature. The level density parameter at the saddle point, $a_f$, used in Eq. (2), is assumed to be a constant times the value of $a_n$.

As the fission cross sections for preactinides constitute a small part of the total reaction cross section, the statistical weight method [38] is used to calculate fission cross sections instead of the straightforward Monte-Carlo technique. It allows us to obtain statistical uncertainties of the calculated fission cross sections generally of not more than 5–10% with only 3000 inelastic events in each calculation. Following
Ref. [38] we use the statistical functions \( W_n = \prod_{i=1}^{N} w_{ni} \) and \( W_f = 1 - W_n \). Here, \( W_n \) is the probability of the nucleus to “drop” the excitation energy \( E^* \) by a chain of \( N \) successive evaporations of particles; \( W_f \) is the probability for the nucleus to fission at any of the chain stages; \( w_{ni} = 1 - w_{fi} \) is the probability of particle emission at the \( i \)-th stage of the evaporative process; \( w_{fi} \) is the corresponding fission probability which is easy to determine using the formulae (1,2) for the widths \( \Gamma_f \) and \( \Gamma_f \). After the subsequent averaging of \( W_f \) over the total number \( N_{in} \) of the cascades followed, and after multiplication of the result by the corresponding total inelastic cross section \( \sigma_{in} \), we obtain the following expression for the fission cross section:

\[
\sigma_f = \frac{\sigma_{in}}{N_{in}} \sum_{i=1}^{N_{in}} (W_f)_i .
\]  

(9)

This approach is used in a version of the CEM as realized in the code CEM95 [19]. It allows us to calculate quite reliable fission cross sections for actinides in a large range of incident energies, provided the level density parameter at the saddle point \( a_f \), or more exactly, the ratio \( a_f/a_n \) can be varied to reproduce data. As an example, the incident energy dependence of experimental [40, 41] and calculated fission cross section for interaction of neutrons with \(^{238}\text{U}\) is shown in Fig. 1.

![Fig. 1. Energy dependence of the neutron-induced fission cross section of \(^{238}\text{U}\). Calculations are performed with Krappe, Nix, and Sierk fission barriers [34], Cameron shell and pairing corrections [29], the third Iljinov et al. systematics for the level density parameters [23], with a dependence \( B_f(L) \) estimated by a phenomenological approach (formulas 28–30 from Ref. [17]) with the value for the moment of inertia of a nucleus at the saddle-point \( J_{sp} \) from Ref. [22], without taking into account the dependence of \( B_f \) on excitation energy \( E^* \), and with the value for the ratio \( a_f/a_n = 1.02 \). The experimental points are from Refs. [40, 41]. For comparison, two values of \( \sigma_f \) calculated at \( T_n = 100 \) and 160 MeV in Ref. [42] with the code LAHET [43] are shown by open triangles.](image-url)
We performed these calculations with Krappe, Nix, and Sierk fission barriers [35], Cameron shell and pairing corrections [29], the third Iljinov et al. systematics for the level density parameters [23], with a dependence $B_f(L)$ estimated by a phenomenological approach (formulas (28–30) from Ref. [17]) with the value of the moment of inertia of a nucleus at the saddle-point $J_{sp}$ from Ref. [21], without taking into account the dependence of $B_f$ on excitation energy $E^*$, and with the value for the ratio $a_f/a_n = 1.02$. For comparison, two values of fission cross sections calculated in Ref. [43] with the well known code LAHET [43] are shown for $T_n = 100$ and 160 MeV. One can see that CEM95 describes correctly (and as well as LAHET) the shape and the absolute value of the fission cross section at these intermediate incident energies with this choice for $a_f/a_n$.

3. Further Development of the Model

Our analysis [17, 20] shows that fission cross sections calculated with CEM95 both for actinides and preactinides are the most sensitive to the ratio of the level density parameters in the fission and neutron emission channels, $a_f/a_n$. The variation of the $a_f/a_n$ value by only a few percent from the optimal value makes the cross sections vary by a factor of 1.5–2, although the shape of the excitation function does not change appreciably. The sensitivity of calculated fission cross sections to other CEM95 input parameters, i.e., to the choice for the level density parameter systematics, nuclear masses, shell and pairing corrections, saddle-point moments of inertia, and for the macroscopic and microscopic fission barriers is lower. The majority of these choices give nearly the same shape to the fission excitation function. The absolute scale of the excitation function varies from one model to another. For any model it is possible to improve the agreement with experiment by adjusting the $a_f/a_n$ parameter. However, it is not possible to alter the shape of the calculated excitation functions, which for preactinides are typically too steep above 100 MeV [20].

Since CEM95 allows us to describe well the characteristics of nuclear reactions that do not involve fission, like double differential spectra of secondary particles as well as spallation product yields (see [16] and references therein), it is natural to search for the reasons for the discrepancies in the modeling of fission cross sections for preactinides observed in [20].

Two different possibilities are:

1) taking into account dynamical effects in fission, which reflect the connection between single-particle and collective nuclear degrees of freedom (see, for example, [44]). The diffusive character of nuclear motion towards and over the saddle point due to nuclear viscosity leads to a decrease of the value of the fission width. This effect may rise with the excitation energy, i.e., in just the direction needed for a better description of the experimental fission cross sections [20];

2) modification of the calculation of the level density at the saddle point. This possibility [20] is discussed below.

As mentioned above, CEM95 incorporates several different level density parameter systematics. Most of them utilize formula (6) for the excitation energy dependence of the level density parameter, which was suggested first by Ignatyuk et al. [27]. It reflects the effect of the strong correlation between the single-particle state density and the shell correction magnitude for low excitation energies, and the fade out of the shell effects on the level density for high excitations [26, 27].

In the original version of CEM95, the level density parameter systematics based on formulae (6) and (7) are applied for all decay channels of an excited nucleus except for the fission channel. In the latter case, the level density parameter at the saddle point $a_f$ is calculated using an analogous parameter for the neutron emission channel, $a_n$, and a constant ratio, $a_f/a_n$, which serves as a fitting parameter of the model. Thus the shell-effect influence on the level density in the neutron emission channel is automatically conveyed to the level density at the saddle point. On the other hand, we expect that shell corrections at the saddle point should bear no relation to those at the ground state, due to the large saddle-point deformation, and
the consequent different microscopic level structure near the Fermi surface. In fact, the shell corrections at the saddle point should be of much smaller magnitude than those at the ground state for nuclei with a spherical ground-state shape, due to the greatly reduced symmetry of the saddle-point shape compared to the ground state (see also Refs. [45, 46]).

In order to estimate the importance of taking into account this effect, we perform calculations for neutron- and proton-induced reactions on $^{208}$Pb and $^{209}$Bi with the parameter $a_f$ being energy-independent, which is equivalent to the disappearance of the shell-effect influence on the level density at the saddle point. The magnitude of the parameter $a_f$ is calculated using formula (7) with the same values of the coefficients $\alpha$ and $\beta$ that are utilized for the other decay channels. The parameter $B_s$ is adjusted to provide the best agreement with the experimental fission cross section approximations. All the other model parameters are fixed and the same as for the calculations described in Ref. [20]. The optimal values of the parameter $B_s$ are 1.18 and 1.15 for interactions of protons with $^{209}$Bi and $^{208}$Pb, and 1.12 for neutron-induced reactions for both $^{209}$Bi and $^{208}$Pb, respectively.

The values for the parameter $B_s$ are physically reasonable because they are larger than 1, which reflects the larger deformation of the fissioning nucleus at the saddle point in comparison with the equilibrium state and they are not far from the value $B_s \approx 2^{1/3}$, which is expected for the saddle-point configuration of the preactinides [47]. However, we do not yet understand why different values are needed for proton- and neutron-induced fission, and why the values of $B_s$ for incident neutrons are significantly smaller than those corresponding to the known deformation of saddle-point shapes in this mass region.

The ratio $a_f/\tilde{a}_n$, where $\tilde{a}_n$ is the asymptotic (large $E^*$) level density parameter for neutron emission, is fixed by the fitting of $B_s$, and is not independently fitted as has to be done in the standard CEM95. $\tilde{a}_n$ is calculated using Eq. (7) and the values $\alpha = 0.072$ and $\beta = 0.257$, which correspond to the 3rd Iljinov et al. systematics [23]. The ratios appear to depend only weakly on the nuclear mass. For the reactions under study their values (given in Fig. 2) are in the range 1.045–1.070.

The results of calculations with the modified CEM95 are shown in Fig. 2. We see a much better description of the experimental fission cross sections in comparison with the original version for nucleon energies of 100–500 MeV. On the other hand, the calculation systematically overestimates to a slight extent the fission cross sections below 100 MeV. We emphasize that other related improvements need to be made before a final assessment of the model’s value and predictive capability can be made. For example, an expected excitation-energy dependence of the ground-state shell correction would change the average height of the calculated fission barriers as the incident energy is increased.

To test these modifications to CEM95 for other types of nuclear reactions, we performed calculations for a number of photon- and pion-induced reactions as well. One example is shown in Fig. 3. We see that the modified version of CEM95 allow us to get a much better agreement with the experimental data also for photofission reactions. Similar improvements were obtained for fission cross sections induced by intermediate energy $\pi^-$ on Sn, on Bi, as well as on the actinide $^{238}$U nucleus [57].

Although these results are only preliminary and questions still remain, e.g., about the optimal value of the parameter $B_s$; the current modifications [21] do indicate the crucial importance of properly incorporating appropriate level densities and motivate the search for a consistent model of barriers, ground-state masses, and level densities which may improve the predictive power of the CEM. Besides this modification of the CEM95 code introduced especially for a better description of fission cross sections, we have been working on further improvement to the CEM [16], striving for a model capable of predicting different characteristics of nuclear reactions for arbitrary targets in a wide range of incident energies. Many of the modifications made for a better description of the preequilibrium, evaporative, and even for the cascade stages of reactions will affect as well the fission channel. So, we have incorporated into the CEM the
Fig. 2. Comparison between the experimental data and calculations of the cross sections for the reactions $^{209}\text{Bi}(p,f)$, $^{209}\text{Bi}(n,f)$, $^{208}\text{Pb}(p,f)$, and $^{208}\text{Pb}(n,f)$ using the original and modified versions of CEM95. The solid lines represent the approximation of the experimental data according to [20]. The short-dashed lines show the original CEM95 results and the long-dashed lines, the results after the modification of the fission channel in CEM95.
Fig. 3. Comparison between the experimental data [48]–[56] and the calculations on fission probability and fission cross section for photofission of $^{197}$Au using the original and modified (noted in this figure as CEM98) versions of the CEM95 code.

updated experimental atomic mass table by Audi and Wapstra [58], the nuclear ground-state masses, deformations, and shell corrections by Möller et al. [59], and the pairing energy shifts from Möller, Nix, and Kratz [60] into the level density formula. In addition, we have derived a corrected systematics for the level
density parameters using the Ignatyuk expression Eqs. (6,7), with coefficients fitted to the data analyzed by Iljinov et al. [23] (we discovered that Iljinov et al. used $11/\sqrt{A}$ for the pairing energies $\Delta$ (see Eq. (3)) in deriving their level density systematics instead of the value of $12/\sqrt{A}$ stated in Ref. [23] and found several misprints in nuclear level density data shown in their Tabs. 1 and 2 used in fitting). We derived also additional semiempirical level density parameter systematics using the Möller et al. [59] ground state microscopic corrections, both with and without the Möller, Nix, and Kratz [60] pairing gaps. We also introduced in the CEM a new empirical relation to take into account the excitation-energy dependence of the ground-state shell correction $\delta W_{gs}$ in the calculation of fission barriers:

$$B_f(A, Z, L, E^*) = B^0_f(A, Z, L) - \delta W_{gs} \times \exp \left( -0.3 \sqrt{E^*} \right), \quad (10)$$

where $B^0_f(A, Z, L)$ is the macroscopic fission barrier of a nucleus with $(A, Z)$ and an angular momentum $L$ calculated with the BARFIT routine [57], $\delta W_{gs}$ is the ground state shell correction by Möller, Nix, Myers, and Swiatecki [59], and $E^*$ is the excitation energy with the rotational energy removed. The excitation energy dependence, $\exp \left( -0.3 \sqrt{E^*} \right)$, was derived here empirically for a better description of fission cross sections. We incorporate also calculation of the pairing gap at the saddle point according to Möller, Nix, Myers, and Swiatecki [59]:

$$\Delta_{fiss} = 4.8 B_s \times [1/(Z^{1/3}) \text{ (if } Z \text{ even}) + 1/(N^{1/3}) \text{ (if } N \text{ even})]. \quad (11)$$

After incorporation of all these improvements into CEM95 we find a much better description for a number of nucleon-induced fission cross sections. As an example, Fig. 4 shows neutron-induced fission cross section of gold recently measured by Staples [61] compared with standard CEM95 calculations and with the improved version described above, for which $a_f/a_n$ and the value of the coefficient of $\sqrt{E^*}$ were the parameters varied. The former results were obtained without taking into account shell corrections in the calculation of the level density at the saddle point, i.e., using Eq. (7) as discussed in the beginning of this section but without an adjustment of the value for $B_s$ as we used for the results shown in Figs. 2 and 3; instead we used the CEM95 default value of $B_s = 1.0$. One can see that the improved model reproduces the data very well, while the standard CEM95 has big problems for this reaction.

Our work is not finished. For instance, we are not satisfied with the situation that in the improved versions of the CEM we still have an additional input parameter to describe fission cross sections: either $B_s$, in the approach [20] illustrated in Figs. 2 and 3, or $a_f/a_n$, in our later version shown in Fig. 4. Of course, it is possible to fit these input parameters to available fission cross sections, then to incorporate the fit into the code, as was done, e.g., in Atchinson’s model [11] used in LAHET [43] or Stepanov’s model [8] used in the INUCL code at ITEP and in a number of other similar codes. But such an approach seems to be lacking in predictive power for unmeasured reactions, and we hope to find a better solution to the problem.

Concerning modeling of the fission processes themselves, i.e., description of the Z, A, angle and energy distributions of fragments with a possible further evaporation from (or even fission of) fragments, we are just at the very beginning of the work. As a “zeroth-order approach” to the problem, we attempted so far only to use in CEM95 after the evaporation stage of a reaction, when we have to simulate a fission, the well-known code GEMINI [14] and Stepanov’s model [8] in their original versions. Our first results are inadequate. This is not surprising, as the distributions of residual nuclei after the evaporation stages of reactions, before fissioning, with respect to the mass $A$, charge $Z$, excitation energy $E^*$, momentum $P$, and angular momentum $L$ calculated with the CEM will not be the same as those calculated with INUCL which successfully uses Stepanov’s fission model [8], or with those from the Liége INC by Cugnon et
Fig. 4. The energy dependence of the neutron-induced fission cross section of gold. Experimental data (filled circles) are by Staples [61]. CEM95 calculations (opened circles) are performed with fission barriers from [36], shell and pairing corrections from [30], level-density-parameter systematics from [23], no dependence of $B_f$ on $E^*$, and $a_f/a_n = 1.10$. The new calculations (open squares, noted in this figure as CEM97) are made with ground-state masses and shell corrections from [59], pairing energy shifts in the level density formula from [60], level density systematics corrected as described in the text in the Ignatyuk form with coefficients fitted to the data compiled by Iljinov et al. [23], macroscopic fission barriers from the BARFIT routine [37], the microscopic parts of fission barriers with thermally damped ground-state shell corrections according Eq. (10), the level density at the saddle point without shell corrections, and the pairing gap at the saddle point from [59], cf. Eq. (11).
Fig. 5. The energy dependence of neutron- and $\pi^-$-induced fission probabilities and fission cross sections of Bi and average values of $Z$, $A$, $E^*$, and $L$ for compound nuclei formed after the preequilibrium stage of reactions and for the nuclei which actually do fission, all calculated in CEM95. Experimental data for $\pi^-$-induced reactions are from Peterson [57] and for neutron-induced fission cross sections of Bi from the compilation by Prokofiev [20].
which has some success using GEMINI. In addition, as we see from Fig. 5, even the distributions of the compound nuclei remaining after the preequilibrium stage of reactions and of those nuclei which actually fission, both calculated with the CEM, are similar only in a restricted range of energy while for a good fraction of the incident energies from 10 MeV to 5 GeV, these distributions differ significantly.

This means that it is not justified to take just an excited compound nucleus and to try to adjust all parameters for the fission, as compound nuclei remaining after the preequilibrium stage of reactions in CEM95 and real fissioning nuclei often have quite different characteristics, and all calculations needed to fix fission parameters have to be done from the very beginning, making this work very time-consuming.

4. Summary

We have performed a number of improvements to the Cascade-Exciton model of nuclear reactions for a better modeling of fission. These developments include a modified calculation of the level density parameter of nuclei at the saddle point, incorporation into the model of the updated atomic mass tables by Audi and Wapstra [58], incorporation of calculated nuclear ground-state masses, deformations, and shell corrections by Möller et al. [59], and pairing energy shifts from Möller, Nix, and Kratz [60] in level density calculations, derivation of a corrected systematics for level density parameters of the Ignatyuk form using the compilation of experimental nuclear level density data by Iljinov et al. [23] and the Möller et al. ground-state microscopic corrections, both with and without the Möller, Nix, and Kratz pairing gaps, development of a new empirical relation to take account the thermal damping of ground-state shell corrections, and a number of other refinements to improve the description of the cascade, preequilibrium, and evaporative stages of reactions, which also affect calculation of the fission channel.

As we have shown by a number of examples the improvements to the CEM made so far clearly have increased its predictive power for fission probabilities and cross sections. Our work is not finished. We hope to find a solution for predicting fission cross sections for arbitrary targets in a wide range of incident energies without introduction of an additional input parameter and we are only beginning to develop a model appropriate for the CEM to describe mass, charge, energy and angular distributions of fission fragments with a possible further evaporation of particles from fragments (or even sequential fission).

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