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Fission characteristics of ^{216}Ra formed in heavy-ion induced reactions

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Abstract. A Kramers-modified statistical model is used to calculate the cross-section of the evaporation residue, fission cross-section, average pre-fission multiplicities of protons and α-particles for ^{216}Ra formed in ^{19}F+^{197}Au reactions and results are compared with the experimental data. To calculate these quantities, the effects of temperature and spin K about the symmetry axis have been considered in the calculations of the potential energy surfaces and the fission widths. It is shown that the results of the calculations using values of the temperature coefficient of the effective potential $k = 0.008 \pm 0.003$ MeV^{-2} and scaling factor of the fission-barrier height $r_s = 1.004 \pm 0.002$ are in good agreement with the experimental data.

Keywords. Statistical model; fission; pre-scission particle multiplicity.

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1. Introduction

The fission process was first described by Bohr and Wheeler [1]. This description was based on a statistical model according to which fission is governed by the available phase space above the fission barrier. Then, Kramers introduced fission as a diffusion process across the fission barrier [2]. This description, later refined by Grangè *et al* [3], introduced a friction constant governing the coupling between the equilibrated intrinsic nuclear degrees of freedom and the nuclear deformation.

The theoretical estimate of the transition-state fission decay width according to Bohr and Wheeler can be given as

$$\Gamma_f = \frac{1}{2\pi}\frac{1}{\rho_{CN}(E^*)}\int_0^{E^*-B_f}\rho_{sad}(E^* - B_f - \varepsilon)d\varepsilon, \tag{1}$$

where ρ_{CN} and ρ_{sad} are the level density of the compound nucleus at the ground and saddle points, respectively, B_f is the fission barrier height, and ε represents the kinetic energy associated with the fission distortion. The density of states can be approximately written as

$$\rho \propto \exp(2\sqrt{a(q)E_{\text{int}}}) \tag{2}$$

and by making several simplifying assumptions, eq. (1) can be changed to [4]

$$\Gamma_{\text{f}} = \frac{T}{2\pi}\text{e}^{-B_{\text{f}}/T}, \tag{3}$$

where T and E_{int} are the temperature and intrinsic energy, respectively. The intrinsic energy can be given by

$$E_{\text{int}} = E^* - V(q),$$

where E^* is the total excitation energy of the system and $V(q)$ is the potential energy.

Dynamical calculations of the fission rate using the Langevin equation [5] or the Fokker–Planck equation [6] give an asymptotic fission decay width for a system with fixed spin K about the symmetry axis

$$\Gamma_{\text{f}}(k) = (\sqrt{1+\gamma^2} - \gamma)\frac{\hbar\omega_{\text{eq}}}{2\pi}\exp\left(-\frac{B_{\text{f}}}{T}\right), \tag{4}$$

where γ is the dimensionless nuclear viscosity given by $\gamma = \beta/2\omega_{\text{sp}}$, β is the reduced nuclear dissipation coefficient, and ω_{eq}, ω_{sp} are the curvatures of the potential energy surface at the equilibrium position and the fission saddle point, respectively. B_{f}, ω_{eq}, and ω_{sp} are all assumed functions of K.

It should be mentioned that eq. (4) is the fission width for a system with fixed spin K about the symmetry axis. Therefore, by assuming axially symmetric shapes, the full fission decay width can be obtained by summing over all possible K [7]

$$\Gamma_{\text{f}} = \frac{\sum_{K=-J}^{J} P(K)\Gamma_{\text{f}}(K)}{\sum_{K=-J}^{J} P(K)}, \tag{5}$$

where $P(K)$ is the probability that the system is in a given K

$$P(K) = \frac{T}{\hbar\omega_{\text{eq}}}\exp\left(-\frac{V_{\text{eq}}}{T}\right), \tag{6}$$

where V_{eq} is the sum of the Coulomb, nuclear, and the rotational energies at the equilibrium position. It should be noted that the above equation is obtained by assuming that the excitation energy is high enough that the temperature is the same at all the saddle points and at all the equilibrium positions. At lower excitation energies it is necessary to replace the temperature in eq. (4) with the average of the nuclear temperatures at the corresponding equilibrium and saddle points and to replace the temperature in eq. (6) by the temperature at the corresponding equilibrium position.

In this paper we use a modified statistical model similar to ref. [8], to reproduce the experimental data on the cross-section of the evaporation residue, fission cross-section, average pre-fission multiplicities of protons, and α-particles for ^{216}Ra formed in ^{19}F+^{197}Au reactions. To reproduce these quantities, we consider the effects of temperature and spin K about the symmetry axis on the calculations of the potential energy surfaces and the fission widths as in ref. [8].

It should be mentioned that many authors, for studying different features of fission process, used dynamical models based on Langevin or Fokker–Planck equations [9–17].

The present paper is organized as follows: In §2 the model and basic equations are described. The results of the calculations are presented in §3. Finally, concluding remarks are given in §4.

2. Description of the statistical model and basic equations

In the present study, we use a modified statistical model similar to ref. [8] to simulate the fission process of ^{216}Ra formed in ^{19}F+^{197}Au reactions. This procedure allows for multiple emissions of light particles and higher chance of fission. After each emission, we recalculate the intrinsic energy and the angular momentum and continue the cascade procedure until the intrinsic energy becomes smaller than either the fission barrier or the binding energy of a neutron. The loss of angular momentum is taken into account by assuming that each neutron, proton, or a γ quantum carries away $1\hbar$ while the α-particle carries away $2\hbar$.

The particle emission width of a particle of kind ν can be calculated as in ref. [18]

$$\Gamma_\nu = (2s_\nu + 1)\frac{m_\nu}{\pi^2\hbar^2\rho_{\rm c}(E_{\rm int})}\int_0^{E_{\rm int}-B_\nu} {\rm d}\varepsilon_\nu \rho_{\rm R}(E_{\rm int} - B_\nu - \varepsilon_\nu)\varepsilon_\nu\sigma_{\rm inv}(\varepsilon_\nu), \quad (7)$$

where s_ν is the spin of the emitted particle ν and m_ν is its reduced mass with respect to the residual nucleus. $\rho_{\rm c}(E_{\rm int})$ and $\rho_{\rm R}(E_{\rm int} - B_\nu - \varepsilon_\nu)$ are the level densities of the compound and residual nuclei. The variable ε_ν is the kinetic energy of the evaporated particle ν. The intrinsic energy and the separation energy of the particle ν are denoted by $E_{\rm int}$ and B_ν. The inverse cross-sections can be written as [18]

$$\sigma_{\rm inv}(\varepsilon_\nu) = \begin{cases} \pi R_\nu^2(1 - V_\nu/\varepsilon_\nu), & \text{for } \varepsilon_\nu > V_\nu \\ 0, & \text{for } \varepsilon_\nu < V_\nu \end{cases}, \quad (8)$$

with

$$R_\nu = 1.21[(A - A_\nu)^{1/3} + A_\nu^{1/3}] + \left(3.4/\varepsilon_\nu^{1/2}\right)\delta_{\nu,n}, \quad (9)$$

where A_ν is the mass number of the emitted particle $\nu = n, p, \alpha$. The barriers for the charged particles are

$$V_\nu = \frac{[(Z - Z_\nu)Z_\nu K_\nu]}{(R_\nu + 1.6)}, \quad (10)$$

where $K_\nu = 1.32$ for α and 1.15 for proton.

The width of the gamma emission is calculated as in ref. [19]. The potential energy V is obtained from the modified liquid-drop model (MLDM). In the MLDM, the potential energy of a nucleus can be written as [7,20]

$$\begin{aligned} V(q, A, Z, J, K) = {} & B_{\rm s}(q)E_{\rm s}^0(Z, A) + B_{\rm c}(q)E_{\rm c}^0(Z, A) \\ & + \frac{(J(J+1) - K^2)\hbar^2}{I_\perp(q)(4/5)MR_0^2 + 8Ma^2} \\ & + \frac{K^2\hbar^2}{I_\parallel(q)(4/5)MR_0^2 + 8Ma^2}, \end{aligned} \quad (11)$$

where $B_c(q)$ and $B_s(q)$ are the Coulomb and surface energy terms, respectively. E_s^0 and E_c^0 are, respectively, the surface and Coulomb energies of the corresponding spherical system as determined by Myers [21,22], M is the mass of the system, $R_0 = 1.2249$ $A^{1/3}$ fm and $a = 0.6$ fm. $I_\perp$ and $I_{||}$ are the momenta of inertia with respect to the axes perpendicular and parallel to the symmetry axis of the fissioning nucleus.

It should be mentioned that the Bohr–Wheeler fission decay width given by eq. (3) was obtained by assuming that the level density parameter is independent of the nuclear shape. This equation, by using a deformation dependence of the level density of the form

$$a(q) = a_\nu A + a_s A^{2/3} B_s(q) \tag{12}$$

can be written as

$$\Gamma_f \approx \frac{T}{2\pi} \exp\left(\frac{-B_{\text{eff}}}{T}\right). \tag{13}$$

In eq. (12) A is the mass number of the compound nucleus and B_s is the surface energy in the liquid drop model. The values of the parameters $a_\nu = 0.073$ MeV^{-1} and $a_s = 0.095$ MeV^{-1} in eq. (12) are taken from the work of Ignatyuk *et al* [23]. In eq. (13) the effective potential barrier height can be given by

$$B_{\text{eff}} = B_f - \Delta a T^2, \tag{14}$$

where Δa is the difference in the level density parameter at the saddle point and the equilibrium position. It should be noted that at high exaction energy, if the level density parameter at the saddle point is larger than the level density parameter at the equilibrium position, then we obtain the unphysical result, because the effective barrier height becomes negative. The reason that eq. (13) becomes invalid at high excitation energy is that, at finite temperature, the generalization of the potential energy function that determines the driving force is the free energy [24]

$$F = E_{\text{tot}} - TS(q, E), \tag{15}$$

where S is the entropy. If the level density parameter is a function of nuclear deformation, then the locations of equilibrium points will be a function of excitation energy and can be defined by the equilibrium points in the entropy or level density parameter as a function of deformation

$$\left(\frac{\partial S(q)}{\partial q}\right)_E \approx \left(\frac{\partial(2\sqrt{a(q)E_{\text{int}}})}{\partial q}\right)_E = 0, \tag{16}$$

and not by the equilibrium points in the potential energy, $V(q)$. Searching for the equilibrium points in the entropy is the same as searching for the equilibrium points in a temperature-dependent effective potential energy [25]

$$V_{\text{eff}}(q, A, Z, J, K, T) = V(q, A, Z, J, K) - \Delta a(q)T^2, \tag{17}$$

where $\Delta a(q)$ is the difference between $a(q)$ and the corresponding value for the spherical system.

If the level-density parameter is assumed to be eq. (12), then the effective potential can be obtained using a $(1 - kT^2)$ dependence of the surface energy

$$V_{\mathrm{eff}}(q, A, Z, J, K, T) = B_{\mathrm{s}}(q)E_{\mathrm{s}}^0(Z, A)(1 - kT^2) + B_{\mathrm{c}}(q)E_{\mathrm{c}}^0(Z, A) + \frac{(J(J+1) - K^2)\hbar^2}{I_{\perp}(q)(4/5)MR_0^2 + 8Ma^2} + \frac{K^2\hbar^2}{I_{\parallel}(q)(4/5)MR_0^2 + 8Ma^2}, \quad (18)$$

where $k = c_{\mathrm{s}}A^{2/3}/E_{\mathrm{s}}^0$. Töke and Swiatecki [26] obtained $c_{\mathrm{s}} \approx 0.27$ and other estimates of c_{s} gave values of k between 0.007 and 0.022 MeV^{-2} [23,27–30]. It should be stressed that c_{s} is very sensitive to the assumed properties of nuclear matter and to other approximations [30].

The total fusion cross-section is usually calculated from

$$\sigma_{\mathrm{Fus}} = \sum_J \frac{\mathrm{d}\sigma_{\mathrm{Fus}}(J)}{\mathrm{d}J}, \quad (19)$$

where the angular momentum distribution of the compound nucleus can be described by the formula

$$\frac{\mathrm{d}\sigma_{\mathrm{Fus}}(J)}{\mathrm{d}J} = \frac{2\pi}{k^2}\frac{2J+1}{1 + \exp((J - J_{\mathrm{c}})/\delta J)}, \quad (20)$$

where J_{c} is the critical angular momentum and δJ is the diffuseness. The parameters J_{c} and δJ can be approximated by the following relations [31]:

$$\delta J = \begin{cases} (A_{\mathrm{P}}A_{\mathrm{T}})^{3/2} \times 10^{-5}\,[1.5 + 0.02(E_{\mathrm{c.m.}} - V_{\mathrm{c}} - 10)], & \text{for } E_{\mathrm{c.m.}} > V_{\mathrm{c}} + 10, \\ (A_{\mathrm{P}}A_{\mathrm{T}})^{3/2} \times 10^{-5}\,[1.5 - 0.04(E_{\mathrm{c.m.}} - V_{\mathrm{c}} - 10)], & \text{for } E_{\mathrm{c.m.}} < V_{\mathrm{c}} + 10, \end{cases} \quad (21)$$

and

$$J_{\mathrm{c}} = \sqrt{A_{\mathrm{P}}A_{\mathrm{T}}/A_{\mathrm{CN}}}(A_{\mathrm{P}}^{1/3} + A_{\mathrm{T}}^{1/3})(0.33 + 0.205\sqrt{E_{\mathrm{c.m.}} - V_{\mathrm{c}}}). \quad (22)$$

When $0 < E_{\mathrm{c.m.}} - V_{\mathrm{c}} < 120$ MeV; and when $E_{\mathrm{c.m.}} - V_{\mathrm{c}} > 120$ MeV the term in the last brackets is put equal to 2.5.

The fission cross-section can be written in terms of the fusion cross-section as follows:

$$\sigma_{\mathrm{Fiss}} = \sum_J \sigma_{\mathrm{Fus}}(J)\frac{\Gamma_{\mathrm{f}}}{\Gamma_{\mathrm{tot}}}. \quad (23)$$

At a given beam energy E, the total evaporation residue cross-section can be obtained by summing of the cross-sections from each J, these being the products of the capture cross-sections and the probabilities of surviving fission $(1 - P_{\mathrm{f}}(J, E^*))$

$$\sigma_{\mathrm{Er}}(E^*) = \pi\lambda\!\!\!^{-2}\sum_{J=0}(2J+1)T_{\mathrm{J}}(1 - P_{\mathrm{f}}(J, E^*)). \quad (24)$$

It should be mentioned that in many statistical model codes [32–37], authors have used the ratio of the level density, a_f/a_n, and a scaling of the FRLDM barrier heights, f_B, which can be adjusted to reproduce experimental data at low and intermediate excitation energies. But fission in heavy-ion reactions cannot be accurately modelled as a function of the excitation energy, using the J dependence of the $T = 0$ fission barriers, and a fixed value of a_f/a_n. In the present paper, we want to consider other free parameters which perform similar roles as a_f/a_n and f_B [8]. We consider the temperature coefficient in the effective potential formula, k, and a scaling of the MLDM radii from their default values used to calculate the surface and Coulomb energies with the parameter r_s. The surface energy is proportional to the square of r_s, while the Coulomb energy is inversely proportional to r_s. A value $r_s = 1$ is the standard MLDM with fission-barrier heights in agreement with the FRLDM. Raising r_s above 1 decreases the Coulomb energy and increases the surface energy. This causes the fission barriers to increase. It should be stressed that the advantage of using r_s instead of f_B is that the curvature at the ground states and the fission transition points, the barrier locations, and heights are all being determined in a self-consistent manner as a function of J, K, and T.

3. Results of the calculations and discussion

In this paper we carried out calculations of the cross-section of the evaporation residue, fission cross-section, average pre-fission multiplicities of protons and α-particles for ^{216}Ra formed in ^{19}F+^{197}Au reactions.

In the calculations, the magnitude of the reduced nuclear dissipation coefficient is taken as 3×10^{21} s^{-1}. Moreover, due to the small amount of charged particle multiplicities we

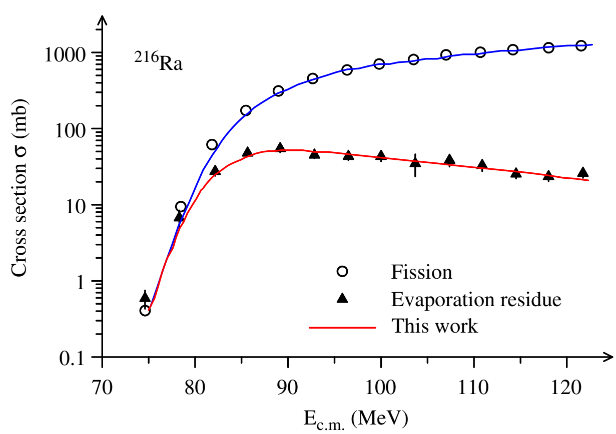

Figure 1. The results of the cross-section of the evaporation residue and the fission cross-section (solid lines) for ^{19}F + ^{197}Au reaction, calculated by considering $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$. The experimental data for fission cross-section (open circles) and evaporation cross-section (closed triangles) are taken from ref. [38].

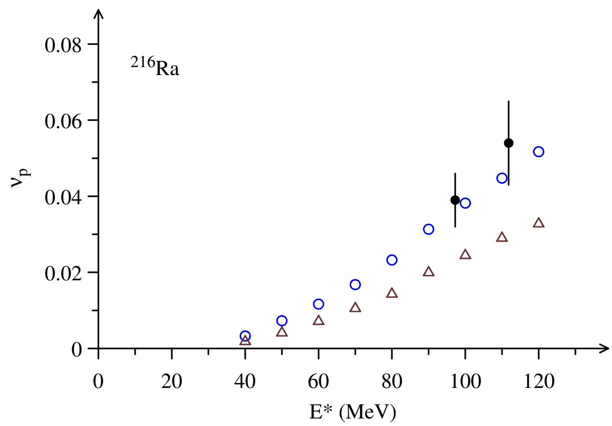

Figure 2. The results of the pre-fission multiplicities of protons (open circles) as a function of excitation energy for ^{216}Ra calculated by considering $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$. The open triangles show the results of pre-fission multiplicities of protons calculated by considering $k = 0$ and $r_s = 1$. The experimental data for pre-fission multiplicities of protons (closed circles) are taken from ref. [39].

use 10^7 event sets in the calculations. Figure 1 shows the results of the residue and fission cross-sections for ^{216}Ra. It can be seen from figure 1 that the results of the calculations are in good agreement with the experimental data by using $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$.

Figures 2 and 3 show the calculation results for the average pre-fission multiplicities of protons and α-particles for ^{216}Ra.

It is important to remember that in calculations, the parameters k and r_s are adjusted to reproduce a single fission cross-section and a single α-multiplicity at a single beam energy

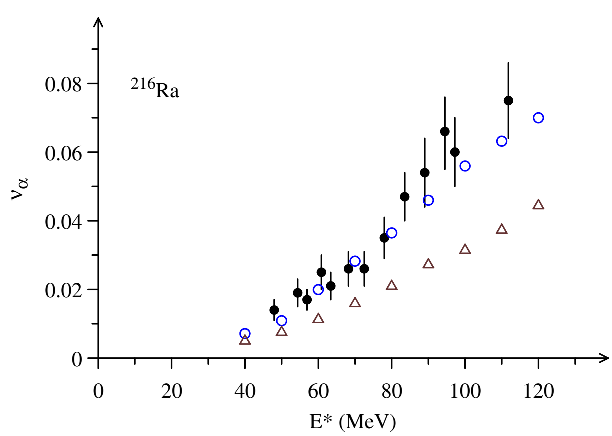

Figure 3. Same as figure 2, but for the pre-scission α-multiplicities. The experimental data (closed circles) are taken from ref. [39].

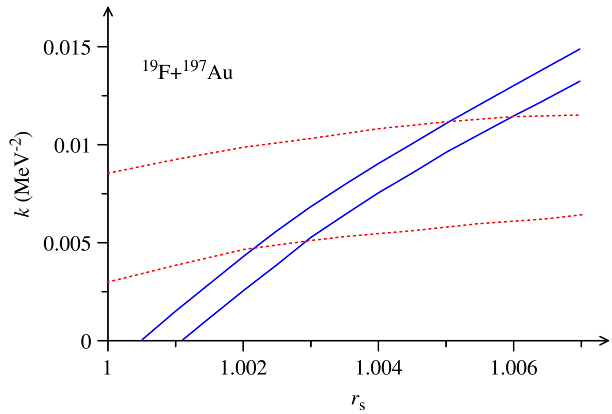

Figure 4. The plot showing how $E_{c.m.} \approx 80$ MeV α-multiplicity constrains the parameter k and r_s to the regions between the dotted curves, while the fission cross-section constrains these parameters to the regions between the solid curves.

and no adjustment is made to fit the energy dependencies of data shown in figures 1 and 3. Figure 4 shows how the $E_{c.m.} \approx 80$ MeV $^{19}F + {}^{197}Au$ data constrain the adjustable parameters to $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$. The fission cross-section at $E_{c.m.} \approx 80$ MeV constrains k and r_s to lie in the region between the solid curves and α-multiplicity constrains k and r_s to lie in the region between the dotted curves.

In the present study, we also check the magnitude of $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$ by reproducing experimental data on the residue cross-section and proton multiplicities for ^{216}Ra. Figures 1 and 2 show the results of calculations for the residue cross-section and the proton multiplicities for ^{216}Ra. It can be seen from figures 1 and 2 that the results of calculations are in good agreement with the experimental data.

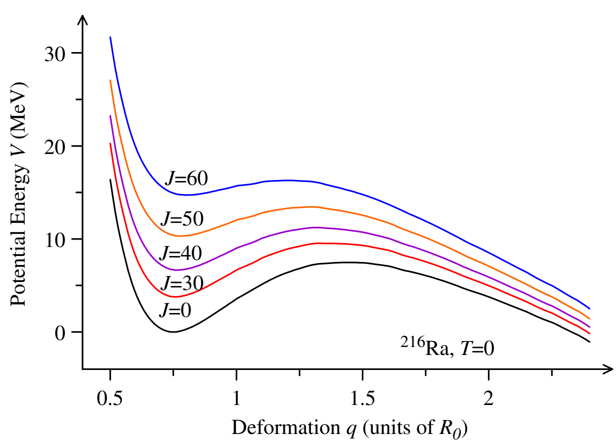

Figure 5. Potential energy surfaces at $J = 0, 30, 40, 50, 60\ \hbar$ and $T = 0$. R_0 is the radius of the spherical nucleus.

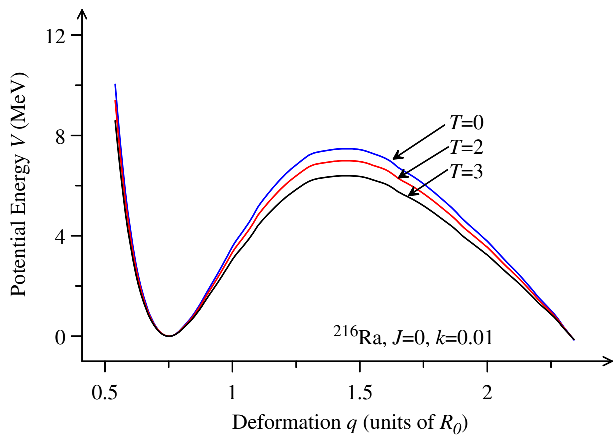

Figure 6. Potential energy surfaces at $T = 0, 2, 3$ MeV, $J = 0$, and $k = 0.01$ MeV^{-2}. R_0 is the radius of the spherical nucleus.

It can be seen from figures 2 and 3 that at lower and intermediate excitation energies the values of the average pre-fission multiplicities of protons and α-particles calculated using $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$ are close to the experimental data, but at higher excitation energies the calculated data are slightly lower than the experimental data. It can be explained as follows: at lower excitation energy a compound nucleus is formed with a lower value of spin and a lower value of temperature and then the height of the fission barrier is large (see figures 5 and 6), and so the protons and α-particle widths are larger than the fission width. Consequently, the protons and α-particles have enough time to be emitted before fission. Furthermore, a compound nucleus at higher excitation energy is formed with a larger value of spin and with a larger value of temperature. Thus, the fission barrier height will be reduced and therefore the proton and α-particles widths are comparable to the fission width, and consequently the calculation data for the pre-scission multiplicities are slightly lower than the experimental data.

4. Conclusions

A Kramers-modified statistical model was used to calculate the average pre-fission multiplicities of protons, α-particles, evaporation residue cross-section, and the fission cross-section for ^{216}Ra formed in ^{19}F + ^{197}Au reactions and results were compared with the experimental data. To calculate these quantities, the effects of temperature and spin K about the symmetry axis have been considered in the calculations of the potential energy surfaces and the fission widths.

In many statistical model codes, authors have used a scaling of the FRLDM barrier heights, f_B, and the ratio of the level density, a_f/a_n, as free parameters to reproduce experimental data at low and intermediate excitation energies. But fission in heavy-ion reactions cannot be accurately modelled as a function of the excitation energy, using the J dependence of the $T = 0$ fission barriers, and a fixed value of a_f/a_n. But in the present study, we considered other parameters as free parameters which perform similar roles as a_f/a_n and f_B. We considered the temperature coefficient in the effective potential formula, k, and a scaling factor of the fission barrier height r_s.

In calculations, the parameters k and r_s were adjusted to reproduce a single fission cross-section and a single α-multiplicity at single beam energy for ^{216}Ra. It was shown that the results of the above-mentioned experimental data are in good agreement with the experimental data using $k = 0.008 \pm 0.003$ MeV^{-2} and $r_s = 1.004 \pm 0.002$. It should be stressed that our result for k is consistent with the other researches [23,26–30]. The authors in these references have given values of k in the range of 0.007–0.022 MeV^{-2}.

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