CAN NUCLEAR ORBITING BE RESPONSIBLE FOR POLAR EMISSION IN FISSION?

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The hypothesis of a glory-like nature of polar emission of light charged particles in fission was investigated by means of the classical calculation of three-body trajectories. A model was studied according to which the light particle trajectories are bent towards the fission axis under the action of the Coulomb and nuclear potentials of the deformed fission fragments. The effect of the friction force was also studied. It appears that this hypothesis does not explain the considered phenomenon unless very dubious assumptions are made, concerning the diffuseness of fission fragment surface and the localisation of charged particle starting points.

1. *Introduction*

We have shown quantitatively in our previous work [1] that according to the conventional "three charged points" ternary fission model, light charged particles emitted from the region between two fission fragments should be so strongly deflected by Coulomb forces off the fission axis that very wide shadow cones (with half apex angles of about 45 deg for α particles and 55 deg for protons) should appear at the outer sides of the two-fragment system.

It was, however, experimentally found [2–8] that some of the charged particles, which accompany fission, can be registered in the vicinity of the fission axis. It was shown in Ref. [1] that this phenomenon (referred to as "polar emission") cannot be explained by conventional model of ternary fission even if considerable delay between the scission and the moment of the light particle emission is assumed. It is also difficult to explain it by evaporation of particles from the excited fission fragments [8]. The aim of the present work was to verify a hypothesis according to which nuclear orbiting can be responsible for this phenomenon.

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2. *The model*

According to the considered model, the particles are at first isotropically emitted from the neck area and their subsequent motion is governed by the Coulomb, nuclear and friction forces. The fate of a particle depends on the impact parameter: if it is small, the particle will be absorbed by one of the fragments, if it is large, the usual tripartition ("equatorial emission") occurs. We are looking for a range of impact parameter (depending of course on the kinematic and dynamic parameters of the model) for which the trajectories of the light charged particles can be bent into the "polar region" by the attractive nuclear force (Fig. 1).

The main feature of the conventional model [9–12] of tripartition, which remains unchanged in the present study, is its classical character. The motion of the three bodies is simulated by numerical integration of the two-dimensional Newton equations, and the initial spatial and momentum configuration is varied in attempt to reproduce the experi-

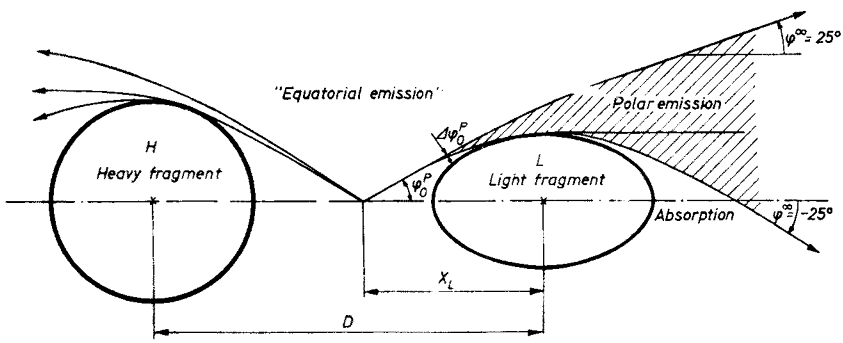


Fig. 1. Geometry of the model

mental distributions. In the considered problem the initial α particle energy has to be higher than 1 MeV if we want to obtain the final energy value in agreement with experiment (about 25 MeV). It means that for α particle the $R/\lambda\!\!\!^{-} > 2.5$, R being the fragment radius and $\lambda\!\!\!^{-}$ the wave length at the point of closest approach. Thus we could hope that we are on the safe side as regards the "classicity" of the problem. Anyway, we decided to apply first the classical approach before starting the much more difficult quantum diffraction calculations.

The main difference between our model and the one usually used consists in that our model accounts for the nuclear attractive forces. Specifically, in the term describing the alpha particle-fragment interaction we took account of the following factors: (*i*) sizes of all three bodies (usually they are treated as point-like objects), (*ii*) deformations of the fragments, (*iii*) nuclear attractive force as **-grad** (V_N), where V_N is the real part of the optical potential (usually only Coulomb forces are taken into account), (*iv*) the phenomenological friction term, which we assumed to be proportional to the relative velocity of the interacting bodies.

To keep the number of parameters at a reasonable level we neglected the time dependence of fragment deformation as well as the fragment rotation. As can be judged from the results of calculations these approximations do not influence our conclusions substantially.

3. *Method of calculation*

To calculate the trajectories and the asymptotic kinetic energies of three bodies we used the modified program of Krogulski and Błocki (Refs. [10, 13]). The modifications regarded not only the above mentioned changes in the force term of the Newton equation, but also included an automatic search routine of the initial angle of emission φ_0^{P} resulting in the final asymptotic angle φ^∞ close to zero. In addition, the program calculated (see Appendix) the intensity ratio P/E of the "polar"/"equatorial" emission, where the latter term [14] denotes the usual ternary fission with light charged particles emitted more or less perpendicular to the fission axis (see Fig. 1).

The nuclear absorption was simulated by discarding the trajectories penetrating the nuclear interior deeper than to the distance of the strong nuclear interaction radius.

4. *Parameters of the model*

The calculations were made for alpha particles scattered on the light fission fragment, the mass of which ($A_{\mathrm{L}} = 96$ amu) is equal to the experimental value of the mean light fragment mass in polar emission during ^{236}U fission [8].

To describe the Coulomb interaction between alpha particle and the spheroidal fragment we used the slightly corrected [15] formula of Świątecki [16]. The nuclear potential V_{N} was of the Woods-Saxon type, with the depth parameter $V_0 = 50$ MeV. Because of the fragment deformation the nuclear and Coulomb interactions depended on the relative orientation of the alpha particle and fission fragment, namely

$$V_{\mathrm{N}}(\theta) = V_0 \Big/ \left[1+\exp\left(\frac{r-R(\theta)}{a}\right)\right].$$

The radius parameter of the usual W–S potential was replaced by $R(\theta) = R_\alpha + 1.2\, A^{1/3} f_\beta(\theta)$. The function $f_\beta(\theta)$ takes account of the fragment spheroidal deformation which is defined by the quadrupole deformation parameter β through the semiaxes ratio $b/a = (1+\beta)/(1-\beta/2)$ and the volume conservation condition $a^2 b = r_0 A^{1/3}$. Three sets of deformation parameters β for light and heavy fragments were used: $(\beta_{\mathrm{L}}, \beta_{\mathrm{H}}) = (0, 0)$, $(0.3, 0)$ and $(0.7, 0.18)$. The second set relates to the ground state fragment deformations, while the third approximates the deformations at the scission moment [17].

The diffuseness parameter a was varied in the range 0.4–1 fm, the initial interfragment distance D in the range 22–30 fm, while the starting point of light particle was varied over the fission axis between two fragment surfaces. In addition some calculations were made for starting points lying 4 fm off the axis.

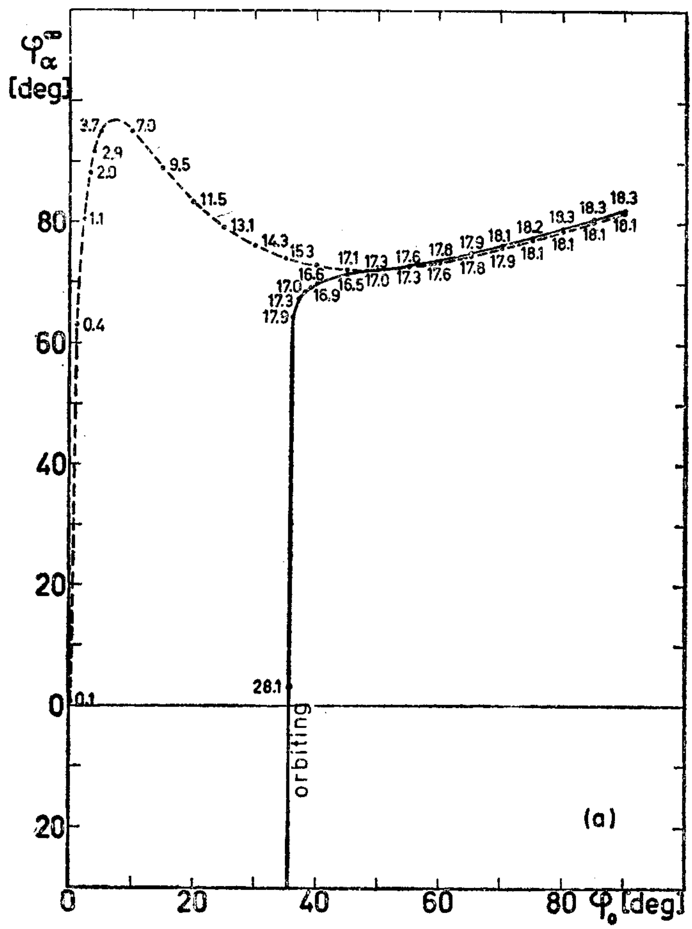
The initial kinetic energy E_α^0 of the alpha particle was varied from 1 to 15 MeV what corresponds to the range of E_α^0 usually used in ternary fission calculations, while the initial kinetic energy of the fragments was determined for every initial configuration in such a way as to ensure agreement of the final total kinetic energy $E_{\mathrm{tot}}^\infty = E_{2\mathrm{f}}^\infty + E_\alpha^\infty = 174.5$ MeV with the experimental mean [8].

We assumed the isotropic distribution of the initial directions of emission as defined by angles φ_0.

The friction force was assumed to be proportional to the relative velocity of the interacting bodies. Two variants of the friction tensor were considered: one isotropic, proportional to the real part of the optical potential V_N (see e.g. Ref. [18]) and the second, of the form proposed by Gross et al. [19]: $F_r = K_r(r)\dot{r}$, $F_\varphi = K_\varphi(r)r\dot{\varphi}$ with $K_r(r) = c_r g(r)$, $K_\varphi(r) = c_\varphi g(r)$, where the form-factor $g(r) = [\mathbf{grad}\ V_N(r)]^2$. The friction forces were varied from zero up to the value at which the "polar" trajectories could no more be realised.

5. *Results*

It appeared that is should be possible to find the interval of initial angles $\Delta\varphi_0^P$, for which α particles are scattered into the polar region. This interval, however, is so small (see Fig. 2) that the resulting intensity ratio of the polar /equatorial emissions P/E is usually many orders of magnitude smaller than that experimentally observed.



Since the main pieces of experimental information now available are the intensity and kinetic energy of the polar particles, it is convenient to compare the results of calculations with experimental data on the diagram, where the axes are: the intensity ratio P/E and the asymptotic kinetic energy of polar particle.

For the zero friction case the results of calculations made with various parameter sets are shown in Fig. 3. The following observations can be made. Firstly, we could not obtain deflection into the shadow cone ("polar" angles) with $E_\alpha^0 < 3$ MeV. Secondly, we found it remarkable that when varying the interfragment distance D, the starting point, the fragment deformations and the initial alpha particle energy E_α^0, we are moving only along the narrow strip in the plane [log (P/E), E_α^∞], being all the time at a large distance from the experimental point. This is due to that the calculated energy E_α^∞ is several MeV too large or the intensity ratio P/E is by several orders of magnitude too small, or both.

The P/E ratio depends on the values of parameters used in the calculations. The influence of some of the parameters is easy to predict. The polar trajectory is governed by a delicate balance between the Coulomb and nuclear forces and it is obvious that the higher is the kinetic energy of the projectile the easier it is to preserve this balance, i.e. the larger

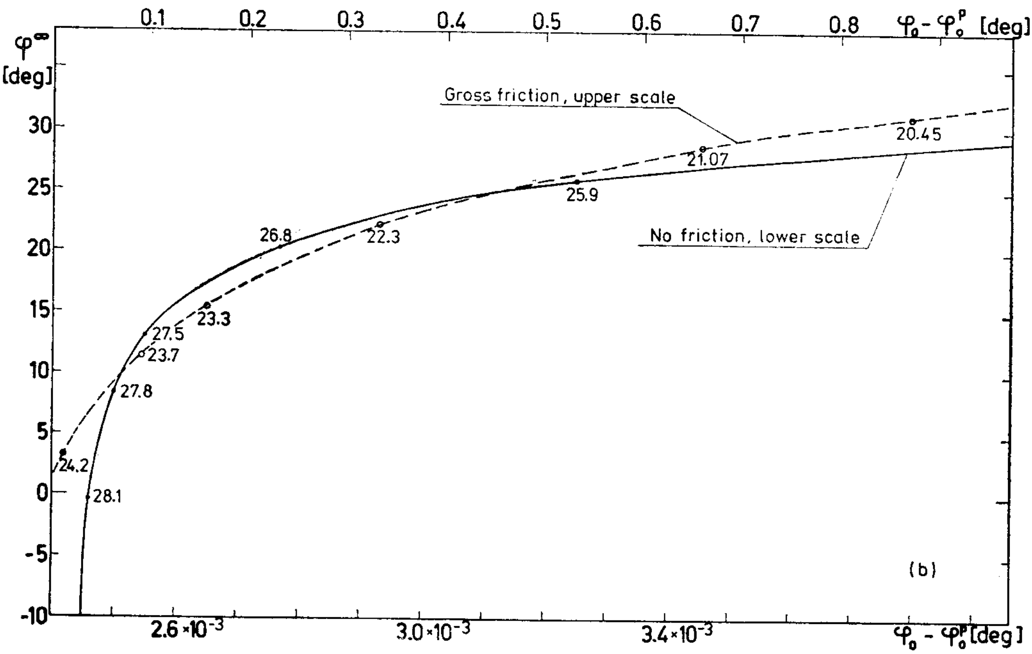


Fig. 2. (a) Dependence of the asymptotic angle φ_α^∞ on the initial emission angle φ_0 for exemplary values of model parameters: $D = 26$ fm, $x_L = 14$ fm, $E_\alpha^0 = 5$ MeV, $\beta_L = 0.3$, $\beta_H = 0$, $a = 0.6$ fm, no friction. The results of the conventional "three charged points" model are shown by a dashed line for comparison. The numbers denote asymptotic kinetic energies of the α particle. (b) The same dependence is shown here in greater detail in the vicinity of the glory angles. The dashed curve (and upper scale) refer to the parameter values for which best agreement with experiment was obtained: the Gross friction, $D = 26$ fm, $x_L = 12$ fm, $a = 1$ fm, $E_\alpha^0 = 3$ MeV. For the "no-friction" case the glory angle φ_0^P was 35°, when the Gross friction was assumed, $\varphi_0^P = 82°$

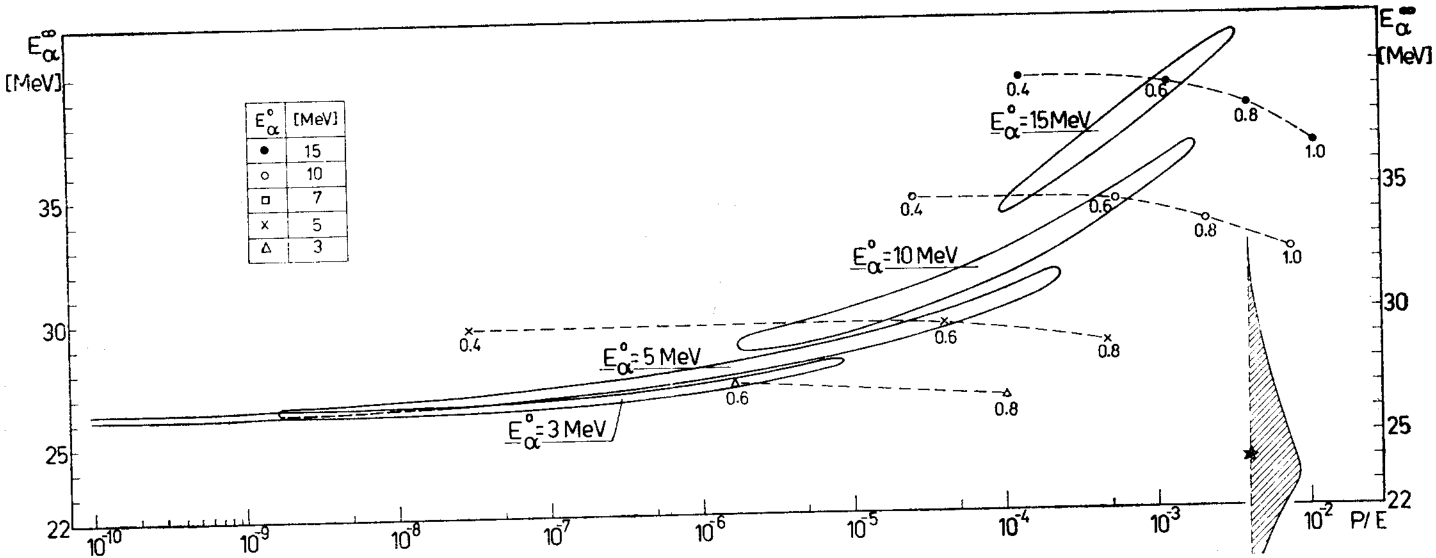


Fig. 3. The calculated asymptotic kinetic energy of polar α particles versus the calculated intensity ratio of "polar"/"equatorial" emission. By varying all the parameters of the model except the diffuseness parameter a and friction, we can reach only the area marked by contours for different values of E_α^0, being at a large distance from the experimental point, denoted by the asterisk. Only by increasing the diffuseness parameter a we can decrease the disagreement to some extent (this trend is shown by dashed lines connecting the results obtained for $a = 0.4$–1.0 fm with other parameters constant). The results refer to the "no friction" case. A shadowed distribution gives the shape of experimental spectrum of polar α particles

is $\Delta\varphi_0^P$. The region of this nearly equilibrium is also wider when the nuclear potential is not very steep ($\Delta\varphi_0^P$ increases with a), while the potential depth has no influence on the results.

Increasing the diffuseness parameter a we can decrease to some extent the disagreement between experimental and calculated results; further improvement can be obtained by providing for the friction force.

Within the considered model, the experimental value[1] of the P/E intensity ratio and the value 24.5 MeV of polar α particles kinetic energy (it is the mean experimental value for emission along the light fragment trajectory) can be reproduced only if the following assumptions are simultaneously made:

(*i*) the friction force has the form proposed by Gross et al. and their friction coefficient values are used,

(*ii*) the interaction radius is very large: $R(\theta) = R_\alpha + 1.2\,A^{1/3}f_\beta(\theta)$,

(*iii*) the diffuseness parameter is very large: $a = 1$ fm,

(*iv*) the starting point is strongly localised, e.g. for the interfragment distance $D = 26$ fm the emission has to take place at a distance of 12.0 ± 0.3 from the light fragment center,

(*v*) the initial alpha particle energy is of about 3 MeV.

6. *Discussion*

It is difficult to assess the validity of these assumptions. The form-factor used works very well even for relatively light nuclei $^{12}C + ^{27}Al$, Ref. [19], we are not aware, however, about the similar investigations for alpha particles. Our results are very sensitive to both the form-factor and the friction coefficients used. With the form-factor proportional to the real optical potential, the calculated and experimental results differ by a factor of 10 as regards intensity and by 2 MeV as regards kinetic energy, at the best. For the Gross form-factor, a change in the radial friction coefficient by a 50 per cent changes the P/E ratio also by a factor of 10. The tangential friction coefficient is not critical but it has to be much smaller than the radial one.

When decreasing the interaction radius from $R_\alpha + 1.2A^{1/3} \approx 1.6\,A^{1/3}$ to $1.2A^{1/3}$ the polar emission intensity is reduced by at least two orders of magnitude.

The value $a = 1$ seems to be very unrealistic; one has to remember, however, that diffuseness of the fission fragment surface shortly after scission may be quite different from that of the usual nuclei. In any case decreasing the a value from 1 to 0.8 (or 0.6) fm gives rise to a discrepancy of at least 2(4) MeV in alpha particle kinetic energy and reduces the P/E ratio by a factor of 5(10).

The strong localisation of the emission point does not seem physically plausible because of the Heisenberg principle. In any case such a localisation is not necessary for "equatorial" emission and this fact can contribute to that the P/E intensity ratio will be further reduced.

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[1] The intensity given in Ref. [3] relates to the value integrated over all angles, assuming the evaporation type of the angular distribution in the fragment reference system. The value used here refers to the range of angles in the interval of 0–25 degrees.

As regards the initial alpha particle kinetic energy one can say that this parameter is very inaccurately known for "equatorial" emission and the value $E_\alpha^0 = 3$ MeV cannot be completely rejected.

There exist at least two strong arguments against the considered hypothesis. First, independently of the parameter values used one cannot obtain the alpha particle kinetic energy lower than 22.5 MeV, while in fact the experimental spectrum spreads down to 19 MeV (see Fig. 3). Secondly, similar calculations made for protons gave the intensity

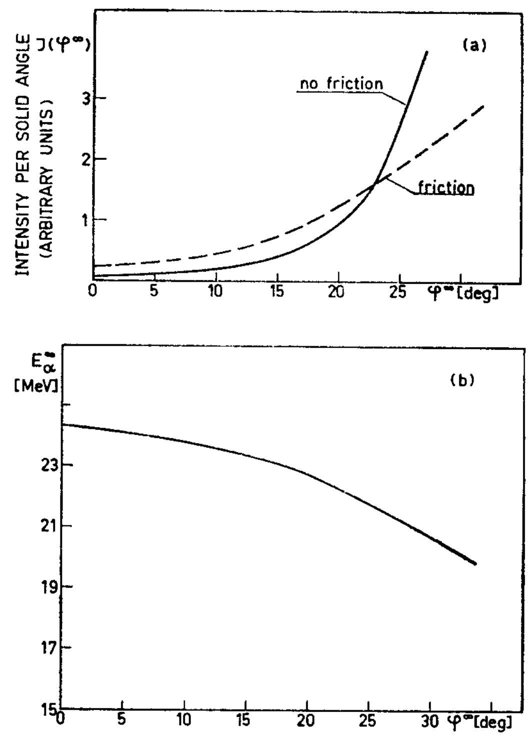

Fig. 4. (a) The angular distributions calculated for both cases given in Fig. 3b, and (b): the predicted dependence of the polar particle kinetic energy on the asymptotic angle of emission (for the case with Gross friction)

ratio P/E at least by 2 orders of magnitude smaller than that experimentally determined, the difficulties in reproducing the low energy part of energy spectrum being similar as in the alpha particle case.

Before finally rejecting the considered hypothesis we should make the following reservation: our calculations showed that the results are sensitive to the poorly known friction form-factor and to the fragment shapes shortly (10^{-21}s) after scission. It seems that the detailed measurements of the polar emission angular distribution would be very valuable in this respect, since it is not so sensitive to the parameter values used. In our model the angular distribution of polar emission is given by $(d\varphi_\alpha^\infty/d\varphi_0)^{-1}$. It is seen in Fig. 4

that according to the considered model we should observe a smooth decrease of the intensity of polar particles when approaching the fission axis. Observation of any structure of this distribution or rise of intensity near the fission axis will suggest another, e.g. diffractive, mechanism of polar emission.

7. *Conclusion*

It appears that the nuclear attraction of particles emitted from the region between the fission fragments cannot be responsible for the phenomenon of polar emission, unless very dubious and/or ad hoc assumptions are made.

APPENDIX

Calculation of the "polar"/"equatorial" emission ratio P/E

According to the considered model, trajectories of particles emitted in angle interval $[\varphi_0^P, \varphi_0^P+\Delta\varphi_0^P]$ will be bent into the polar region, which by convention is defined as the region of asymptotic angles $0 \leqslant \varphi_\alpha^\infty \leqslant 25°$. The events with $\varphi_\alpha^\infty < 0$ can be discarded, since due to the steepness of the deflection function $\varphi_\alpha^\infty(\varphi_0)$ in the region of $\varphi_\alpha^\infty < 0$ their contribution is negligible (cf. Fig. 2). The events with $\varphi_0 > \varphi_0^P+\Delta\varphi_0^P$ give rise to the usual ternary fission ("equatorial emission") while the particles with $\varphi_0 < \varphi_0^P$ are absorbed.

The solid angle contained within the cone of half apex angle φ_0^P is

$$\Omega(\varphi_0^P) = 2\pi(1-\cos\varphi_0^P),$$

thus the solid angle between two cones of half apex angles φ_0^P and $\varphi_0^P+\Delta\varphi_0^P$ is

$$\Omega(\Delta\varphi_0^P) \approx 2\pi\Delta\varphi_0^P \sin\varphi_0^P.$$

Assuming the isotropic distribution of the initial angle φ_0 we obtain for the "polar"/"equatorial" intensity ratio

$$\frac{\mathrm{P}}{\mathrm{E}} \approx \frac{\Omega(\Delta\varphi_0^P)}{4\pi-2\Omega(\varphi_0^P)} \approx 0.5\Delta\varphi_0^P \operatorname{tg}\varphi_0^P,$$

where the approximate equality of φ_0^P for scattering on the light and heavy fragments has been assumed additionally.

It deserves adding that although our formula for P/E is not directly applicable for the off-axis starting points, we verified that for such cases the $\Delta\varphi_0^P$ interval is similar to that obtained when starting from the fission axis, whence we cannot significantly improve the agreement with experiment by taking into account the off-axis starting points.

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