DESCRIPTION OF LIGHT CHARGED PARTICLE EMISSION IN TERNARY FISSION

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Outline

◇ Model for binary and ternary fission based on the cluster model and statistical approach: short overview.

◇ New trajectory calculations for the spontaneous ternary fission of $^{252}\mathrm{Cf}$ accompanied by light charged particles

- He
- Be and C

Model for nuclear fission

We improved the scission-point model for binary fission and proposed a model for ternary fission. The model incorporates:

◇ Cluster approach (dinuclear system model) ⇒ scission configuration consists of several fragments (clusters). Parameters: masses, charges, and deformations of the fragments, and distances between the fragments.

◇ Statistical approach ⇒ analysis of relative probabilities by calculating potential energies of different scission configurations.

$$U = \sum U_i + V_{int}, \qquad U = U(Z_i, A_i, \beta_i, r_i)$$

where i is the number of the fragment.

Advantages and features of the model

◇ The use of a double folding nuclear interaction potential allows to calculate the distances between the fragments (they are not free parameters).

◇ Fragment deformations at the scission point are calculated by minimization of potential energy.

◇ Deformation dependent shell corrections are calculated by using the Strutinsky method.

◇ Excitation energy and temperature at scission are calculated (they are not free parameters):

$$E^* = E_0^* + Q - \sum E_i^{def} - V_{int}$$

In our model it is possible to analyse a wide range of scission configurations and obtain the relative probabilities of their formation. This allows us to calculate different fission characteristics and describe various experimental data.

Obtained results

With our model we have already described:

◇ Total kinetic energy of the fission fragments as a function of the light fragment mass in binary fission.

A. V. Andreev *et al.*, Eur. Phys. J. A **22** (2004) 51

◇ Bimodality effect in fission of actinides (two modes with different kinetic energies).

A. V. Andreev *et al.*, Eur. Phys. J. A **26** (2005) 327

◇ Charge distributions in ternary fission.

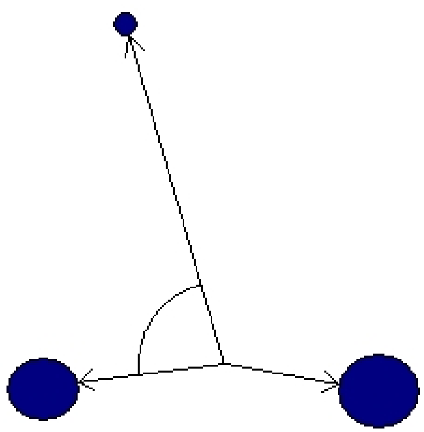
A. V. Andreev *et al.*, Eur. Phys. J. A **30** (2006) 579

◇ Neutron mutiplicity distributions from fission fragments as a function of fragment mass.

A. V. Andreev *et al.*, Eur. Phys. J. A **30** (2006) 579

Experimental information

Spontaneous LCP-accompanied ternary fission of $^{252}\mathrm{Cf}$



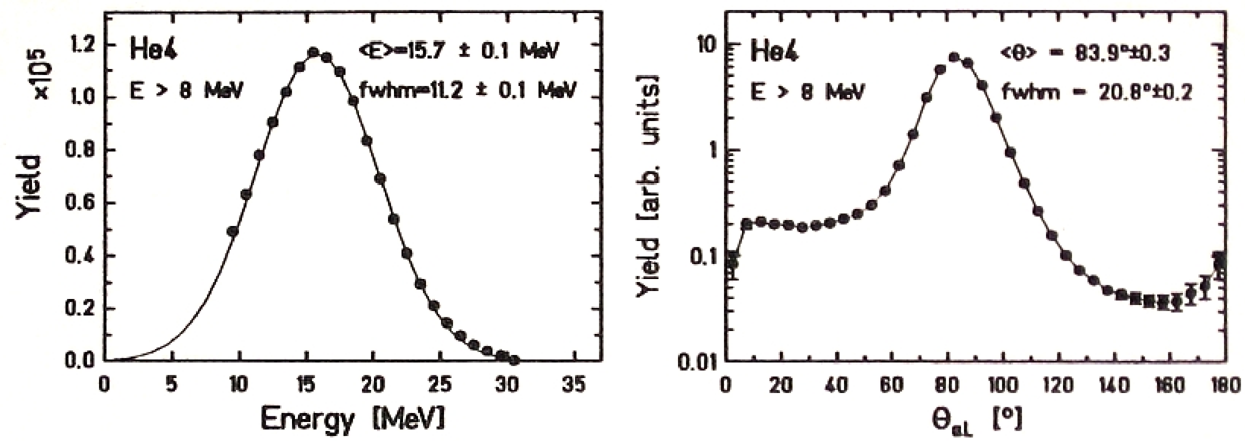


Figure 4: a (left): Measured energy distribution of ternary α-particles. The lower cut-off energy is 8 MeV.
b (right): Distribution of angles between α particles and light fission fragments (logarithmic scale), corrected for solid angle and geometrical efficiency.

$$\langle E \rangle_{\mathrm{He}} = 15.7 \text{ MeV}$$

$$\langle E \rangle_{\mathrm{Be}} = 17.5 \text{ MeV}$$

$$\langle E \rangle_{\mathrm{C}} = 26 \text{ MeV}$$

Exp.: M. Mutterer *et al.* (1996)

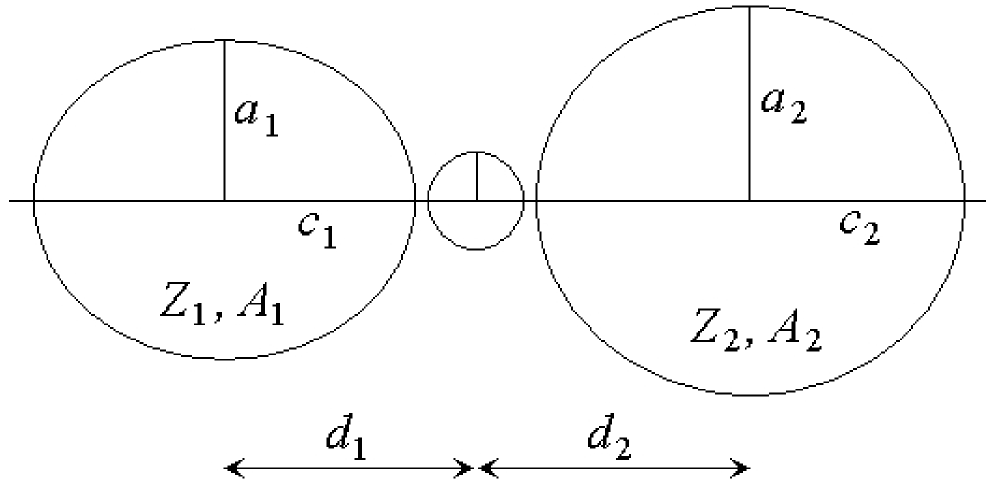
We describe ternary fission accompanied by emission of a light charged particle using the calculation of trajectories of three fragments.

The main difficulty of trajectory calculations is the definition of the initial conditions: initial coordinates and velocities of the three fragments.

The trajectory calculations starts from the scission point.

Our model allows to define the initial parameters at scission.

Potential energy of ternary system



$$\beta_i = c_i / a_i$$

$$\begin{aligned} U &= U_1(\beta_1) \ + \ U_2(\beta_2) \ + \ U_3 \\ &+ \ V_{12}^{int}(\beta_1, \beta_2, d_1 + d_2) + V_{13}^{int}(\beta_1, \beta_2, d_1) + V_{23}^{int}(\beta_1, \beta_2, d_2) \end{aligned}$$

$$\beta_3 = \beta^{gs}(A_3, Z_3) = \text{Const}$$

Double-folding potential

$$V^N(d) = \int \rho_1(\mathbf{r}_1)\rho_2(\mathbf{d}-\mathbf{r}_2)F(\mathbf{r}_1-\mathbf{r}_2)\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

$$\rho_i(\mathbf{r}) = \frac{\rho_{00}}{1+\exp\left(\frac{s(\mathbf{r})}{a_{0i}}\right)}, \quad \rho_{00} = 0.17\ \mathrm{fm}^{-3}$$

$$F(\mathbf{r}_1-\mathbf{r}_2) = C_0\left(F_{in}\frac{\rho_0(\mathbf{r}_1)}{\rho_{00}} + F_{ex}\left(1-\frac{\rho_0(\mathbf{r}_1)}{\rho_{00}}\right)\right)\delta(\mathbf{r}_1-\mathbf{r}_2)$$

$$\rho_0(\mathbf{r}) = \rho_1(\mathbf{r}) + \rho_2(\mathbf{d}-\mathbf{r})$$

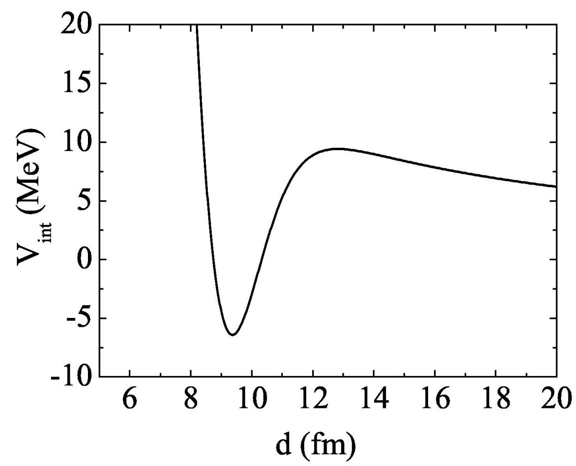
$$F_{in,ex} = f_{in,ex} + f'_{in,ex}\frac{N_1-Z_1}{A_1}\,\frac{N_2-Z_2}{A_2}$$

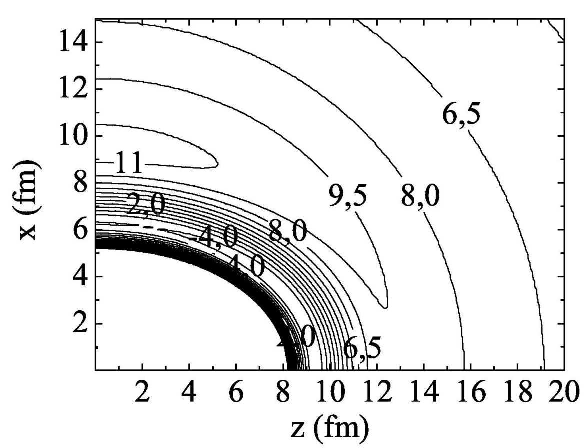
$$C_0 = 300\ \mathrm{MeV\ fm}^3,\ f_{in} = 0.09,\ f_{ex} = -2.59,\ f'_{in} = 0.42,\ f'_{ex} = 0.54$$

$$V^N(d) = C_0 \left\{ \frac{F_{in} - F_{ex}}{\rho_{00}} \left(\int \rho_1^2(\mathbf{r})\rho_2(\mathbf{r}-\mathbf{d})\mathrm{d}\mathbf{r} + \int \rho_1(\mathbf{r})\rho_2^2(\mathbf{r}-\mathbf{d})\mathrm{d}\mathbf{r} \right) + F_{ex} \int \rho_1(\mathbf{r})\rho_2(\mathbf{r}-\mathbf{d})\mathrm{d}\mathbf{r} \right\}$$

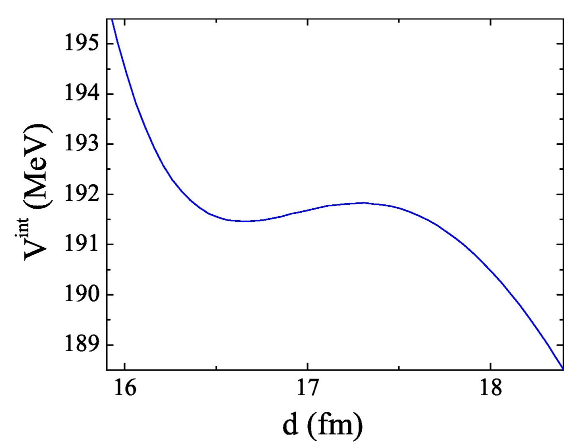
Interaction of two nuclei

$^{106}\mathrm{Mo} + ^4\mathrm{He}$



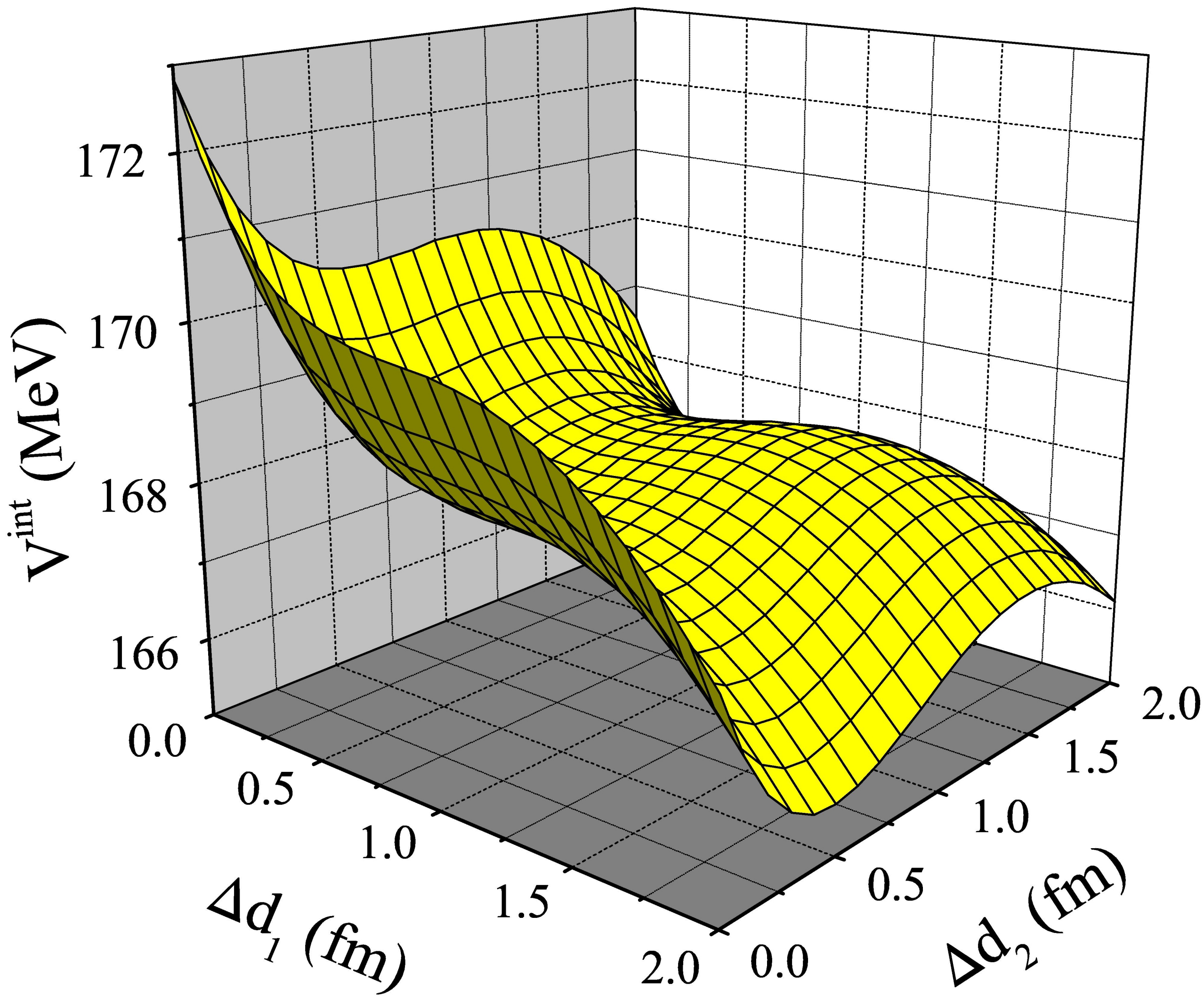


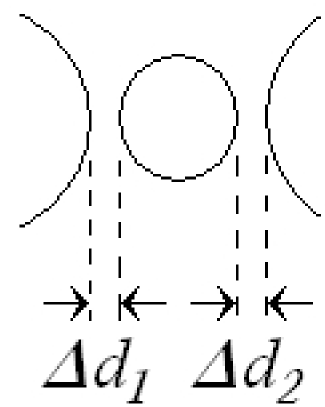
$^{106}\mathrm{Mo} + ^{146}\mathrm{Ba}$



Interaction in ternary system

Definition of the distances between the fragments

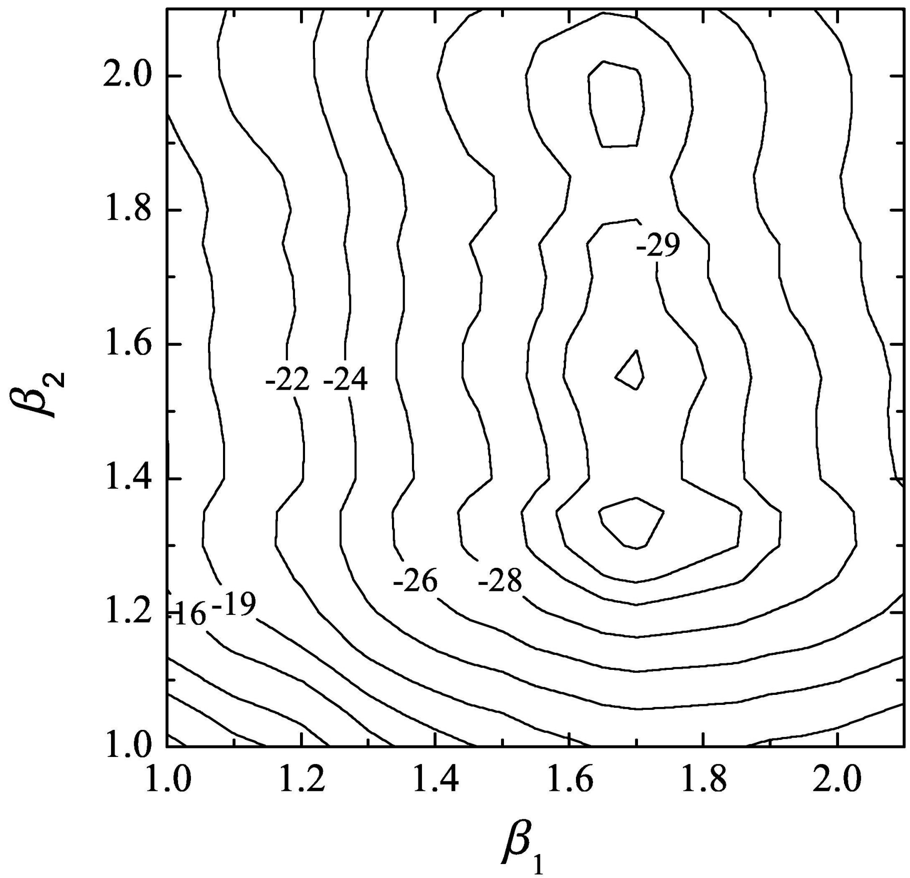




Potential energy surfaces

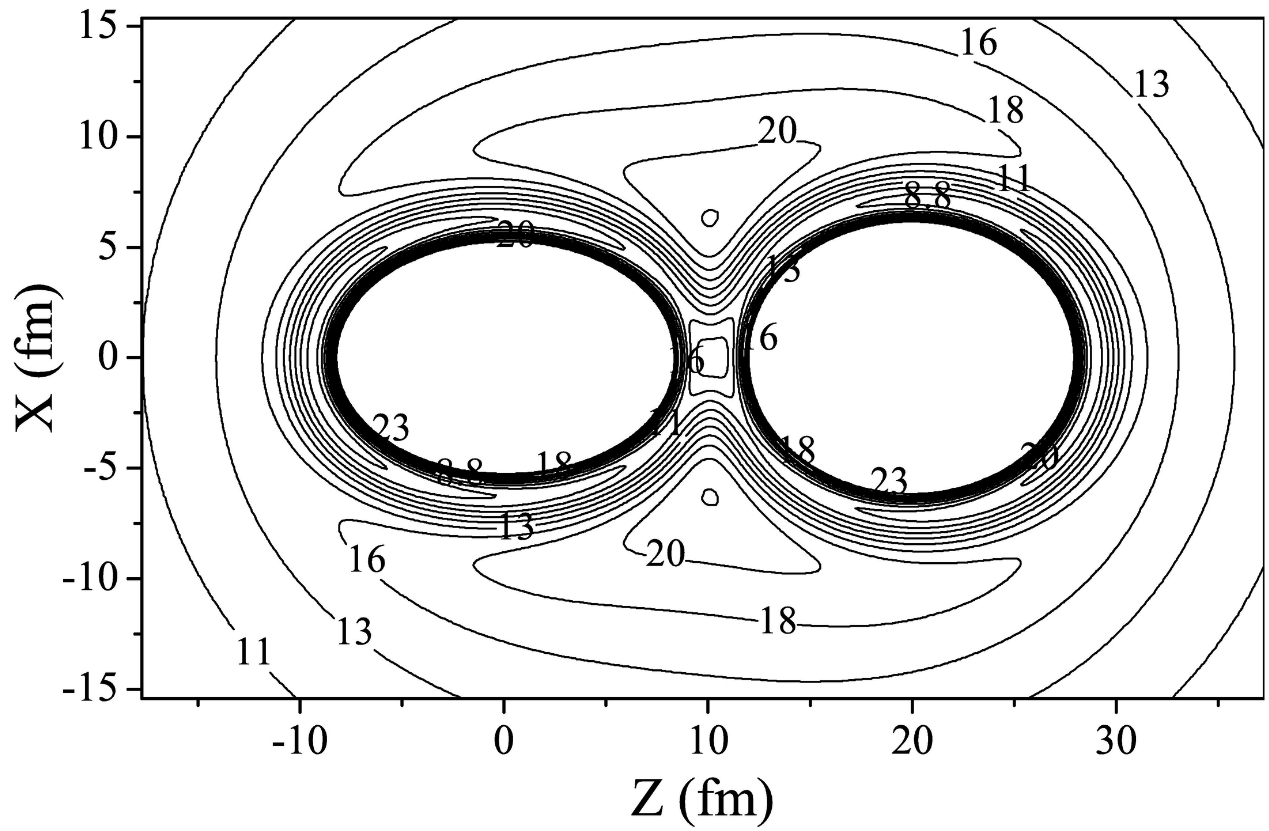
Definition of the deformations

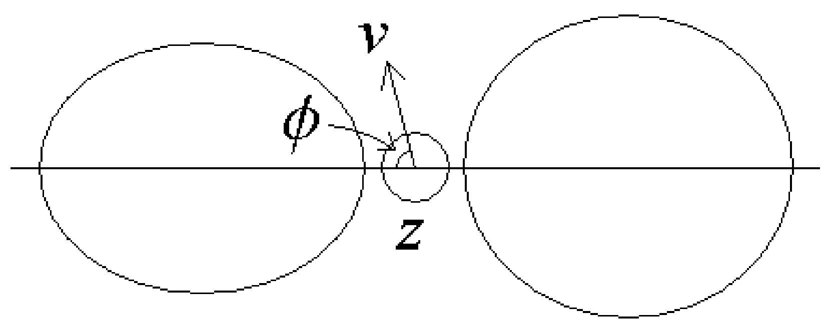
$$^{252}\mathrm{Cf} \rightarrow {}^{106}\mathrm{Mo} + {}^{4}\mathrm{He} + {}^{142}\mathrm{Xe}$$



The potential energy is given in MeV relative to the energy of compound fissioning nucleus.

Variation of initial conditions

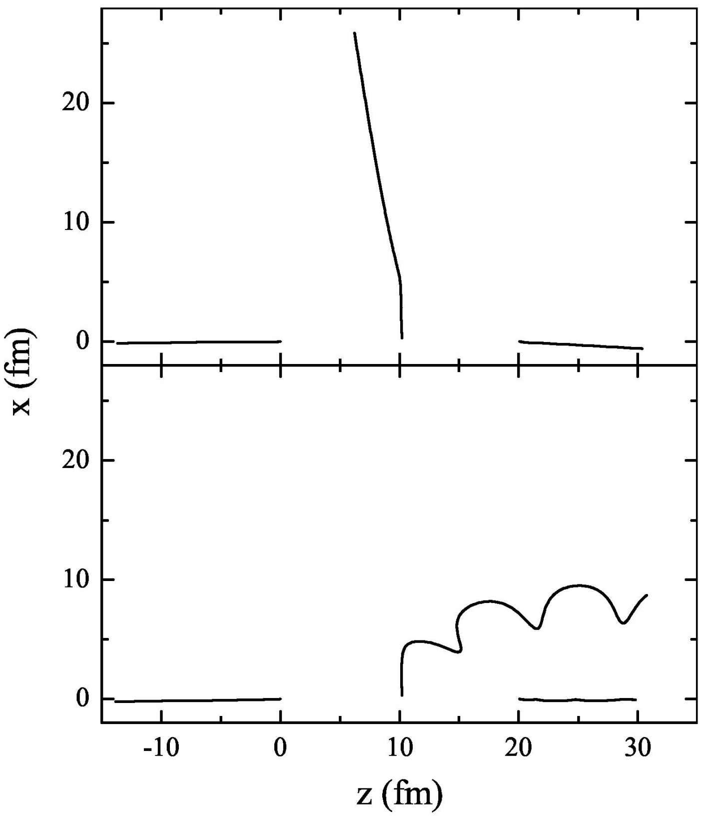




Results of trajectory calculations

$$^{252}\mathrm{Cf} \to {}^{106}\mathrm{Mo} + {}^{4}\mathrm{He} + {}^{142}\mathrm{Xe}, \qquad \beta_{\mathrm{Mo}} = 1.7,\ \beta_{\mathrm{Xe}} = 1.35$$

$$E_{k,0}^{\alpha} = 17\ \mathrm{MeV}$$



$$E_k^{\mathrm{heavy}} = 173\ \mathrm{MeV}$$

θ_0 - initial direction of the velocity of the alpha-particle

θ_{13} - angle between the trajectories of lighter fragment and alpha-particle

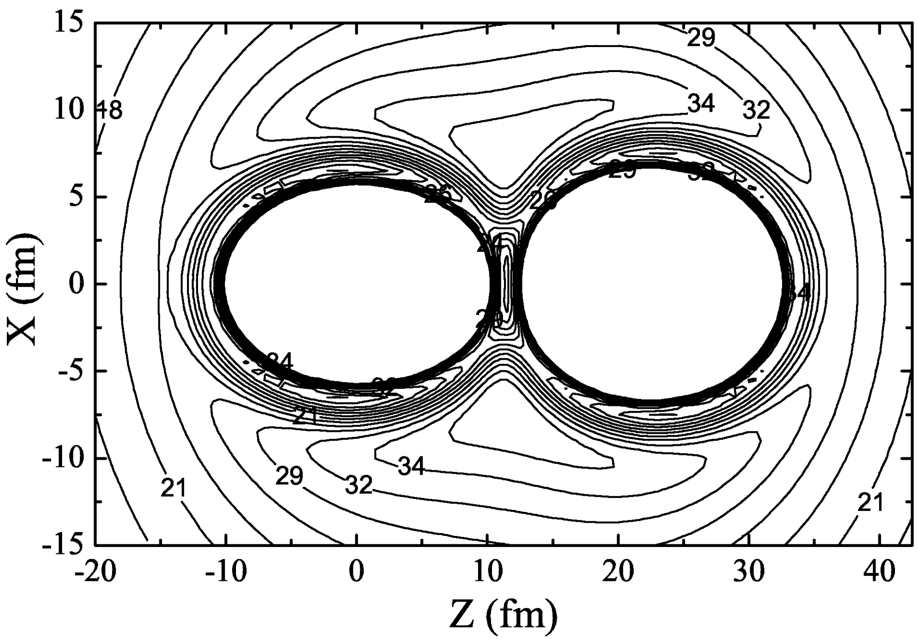
θ_0(rad.)	θ_{13}(deg.)	E_k^{α}(MeV)
1.538	75.8	16
1.539	79.1	16
1.540	81.3	16
1.541	83.2	16
1.542	85.0	16
1.543	87.0	16
1.544	89.2	16
1.545	92.3	16

Be- and C-accompanied fission

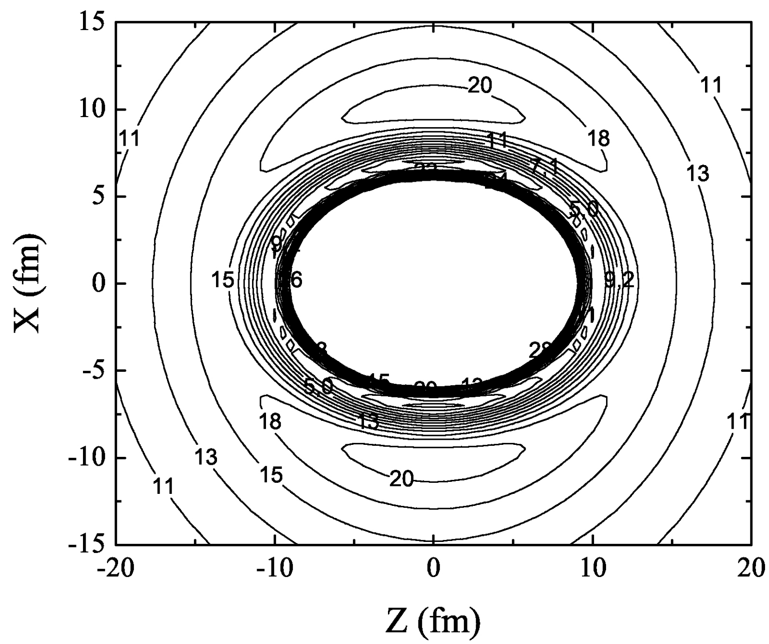
Exp.: $\langle E\rangle_{\mathrm{He}} = 15.7$ MeV, $\langle E\rangle_{\mathrm{Be}} = 17.5$ MeV, $\langle E\rangle_{\mathrm{C}} = 26$ MeV.

The Coulomb barriers for Be and C are higher than for $\mathrm{He} \Longrightarrow$ The energies of Be and C calculated in the same manner as for He are larger than in the experiment.

$^{252}\mathrm{Cf} \to {}^{102}\mathrm{Zr} + {}^{10}\mathrm{Be} + {}^{140}\mathrm{Xe}$



$^{102}\mathrm{Zr} + {}^{10}\mathrm{Be}$



Be- and C-accompanied fission

After split of the ternary system LCP can fly with one of the heavy fragments. Then the LCP can be emitted from such a pair during the separation of the heavy fragments while the distance is smaller than about $100\ \mathrm{fm}$.

Due to the separation of the heavy fragments the Coulomb barrier decreases enough. Still, these distances are small enough to produce the "focusing" effect: the LCP moves near to the perpendicular to the direction of the heavy fragments.

Summary

For alpha-accompanied ternary fission we proposed a method for definition of initial conditions for trajectory calculations based on our model of fission. The experimental data on alpha-accompanied ternary fission of $^{252}\mathrm{Cf}$ are well reproduced.

We proposed a different mechanism of ternary fission accompanied by emission of heavier LCP in which the LCP is emitted after some separation of heavy fragments.