ACCOMPANIED BY ALPHA-PARTICLES TERNARY FISSION OF ACTINIDES INDUCED BY THERMAL NEUTRONS

Larisa Titova, Stanislav Kadmensky, Elena Petrykina

Voronezh State University, Russia

titova_lv@phys.vsu.ru

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The main properties of the ternary fission of nuclei

Experimental facts:

•angular distribution of the third particles has maximal angle close to 90°

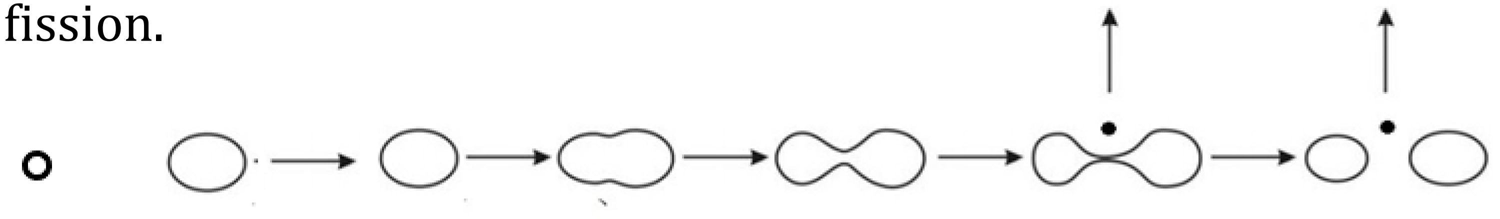
• energy distribution of the third particles has maximal energy T_{α} close to 16 MeV

Nucleus	T_{α}, MeV	Q_{α}, MeV	B_n, MeV
^{234}U	15,9	4,858	6,846
^{236}U	15,9	4,573	6,546

Ternary fission stages:

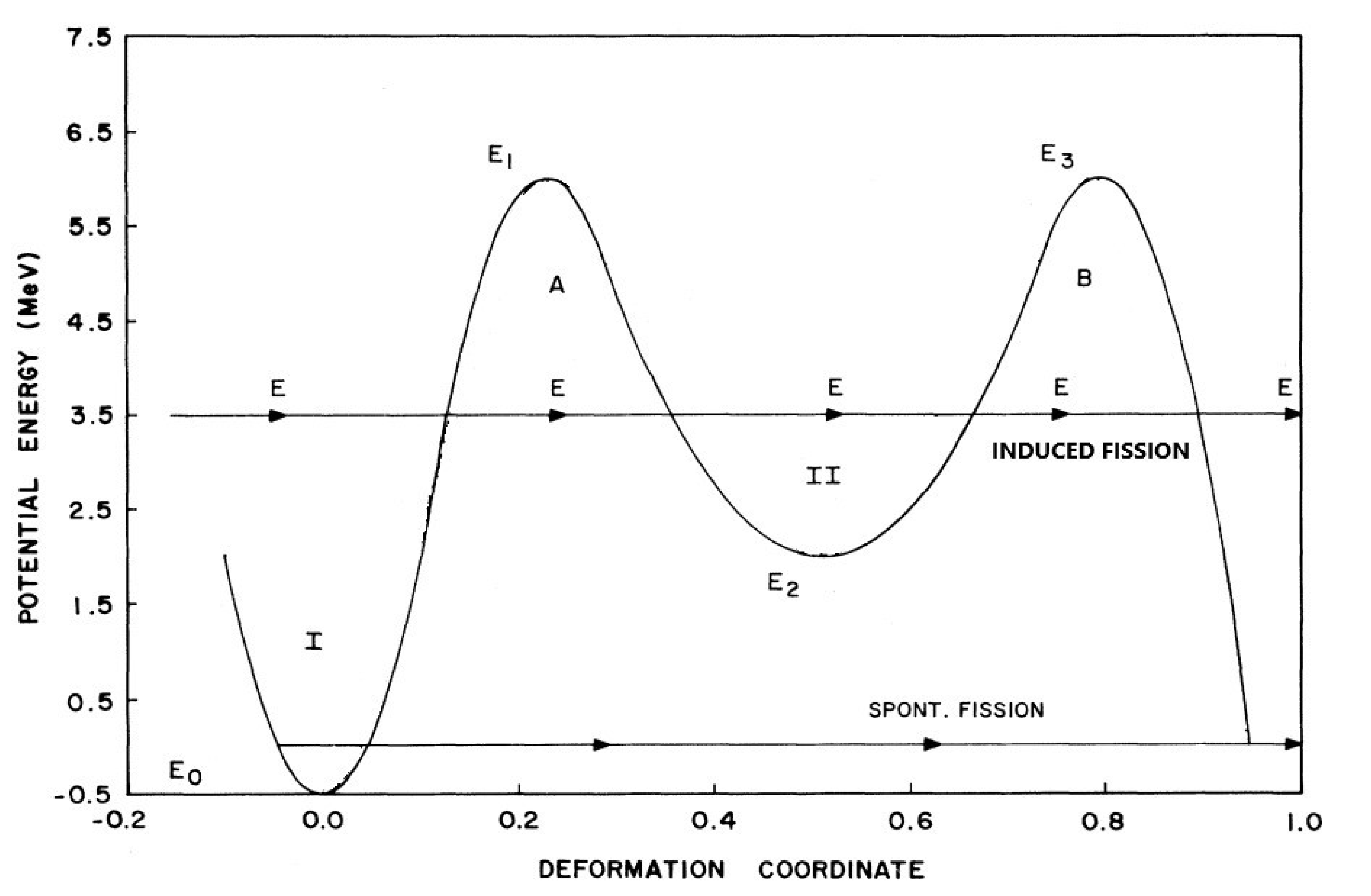
•from the fissile nucleus neck of the parent nucleus A the light particle A_3 is emitted, that fact is confirmed by the experimental angular distribution of the third particles,

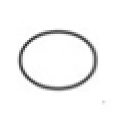
•at the next stage, this daughter nucleus is broken into two primary fragments $A_{\rm LF}$ and $A_{\rm HF}$ of ternary fission.



In induced ternary fission of actinide compound nucleus (A, Z) the emission of the long-ranged third light particle occurs, for example α-particle, its energy T_{α} at the emission moments sufficiently succeeds the heat Q_{α} for the traditional α-decay of the nucleus (A, Z) and is close to Coulomb barrier height B_{α}

Deformation potential





- Since the fissile nucleus does not pass in the vicinity of the rupture point in the equilibrium thermal state with a sufficiently high temperature T, a noticeable **influence of the superfluid nucleon-nucleon correlations** on the probability of formation of the ternary fission products remains. Due to the influence of these correlations, the greatest probabilities of the third particle formation from the nucleon groups of the neck of the fissile nucleus are associated with such shell states of these groups, **when the total orbital moments are zero.**

Models, describing the properties of ternary fission

Double rupture of the neck between prefragments, the emergence of the third particle [*Halpern Proc. Symp. Physics and Chemistry. Vienna, IAEA, p. 369, 1969*]; Double rupture of a fissile nucleus in ternary fission, when two fission fragments occur at the first stage, and then the third particle emitted from the lighter of the fragments– **used temperatures T ~ 1 MeV.**

Fissile system remains "cold" and on the stages of the ternary fission, from the beginning with the descent of fissile nuclei with the external saddle points and ending his rupture into fragments, despite of the strong nonadiabatic collective deformation motion of the nucleus.

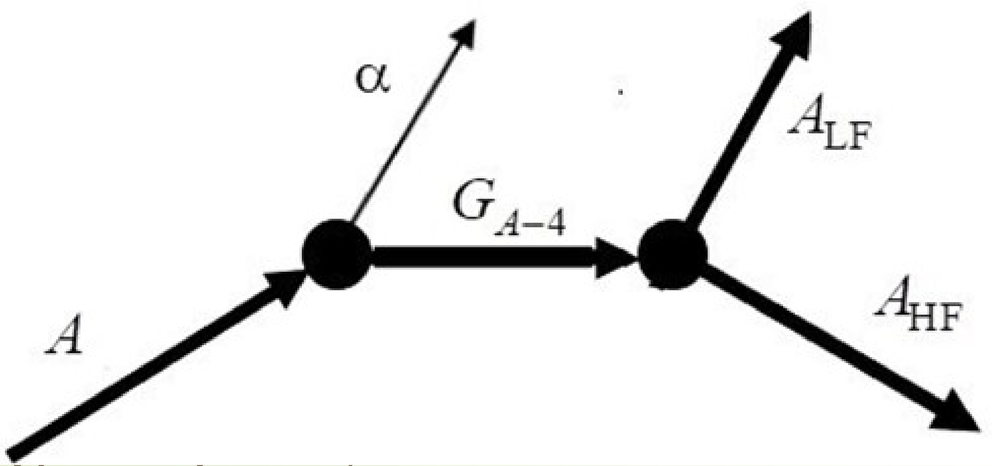
- **The model of non-evaporational pre-equilibrium mechanism** of the light particles emission in ternary fission – the impact caused by nonadiabatic collective deformation motion of the fissile nucleus relative to the nucleon and cluster degrees of freedom of this nucleus “shake-up” effects [*N. Carjan, J. Phys. (Paris)* ***37****, 1279 (1976), O. Tanimura, T. Fliessbach, Phys. Rev.* ***A 328****, 475 (1987)*] considers ternary fission as two-step process, at the first stage of which, under the action of the time-dependent non-adiabatic potential of the nucleus, long-range α-particles with energies Eα≈Bα are released from the parent nucleus, and the residual nucleus is formed, at the second stage this nucleus decays onto two fragments.

But in the mechanism *[O. Tanimura, and T. Fliessbach/ Z. Phys A 328. — 475. — 1987]* there is a problem of describing the kinetic energies of the primary fission fragments, which should be reduced by increasing the energy of the emitted particle E_α from Q_α to B_α .

2) Using the results of paper *[S.G. Kadmensky, Yu.V. Ivankov, Phys. At. Nucl. 77, 1075; (2014)]* for two-proton radioactivity the new **virtual mechanism for spontaneous ternary fission** of nucleus (A, Z), is suggested, where the ternary fission is described as two-step process, when at the first stage the α-particle is emitted from parent nucleus with energy of the motion $T_\alpha \approx B_\alpha$ with the formation of the **virtual state of the intermediate nucleus (A– 4, Z– 2)**, which in the second stage divides into two fragments. The emitted α-particle energy ($T\alpha$-$Q\alpha$) is taken by reducing the heat of the intermediate nucleus fission Q_f by the value ($T\alpha$-$Q\alpha$) in comparison with the binary fission energy Q_{0f} of parent nucleus (A, Z).

The ternary fission

$$\Gamma_{\alpha f}^{A} = \frac{1}{2\pi} \int_{Q_\alpha^A + \Delta}^{Q_f^A} \frac{\Gamma_\alpha^A(T_\alpha)\left(\Gamma_f^{A-4}\right)^0}{\left(Q_\alpha^A + \cancel{|\ldots_\alpha|} - T_\alpha\right)^2} dT_\alpha$$



$\left(\Gamma_f^{A-4}\right)^0$ is fission width from the state of the daughter nucleus (A-4,Z-2) from the configuration (0)

$\Gamma_\alpha^A(T_\alpha)$ is α -decay width from the ground state of the parent nucleus (A,Z) with the α-particle emission from the nucleus neck

$$\Gamma_\alpha^A(T_\alpha) = \omega^0 \cdot \left(\Gamma_\alpha^A(T_\alpha)\right)^0 ,$$

ω^0 is the probability of the parent nucleus transition from the first well of deformation potential to the configuration (0) of this nucleus with neck between two prefragments

$$Q_{\alpha f}^A = E(A,Z) - E(A_1,Z_1) - E(A_2,Z_2) = Q_\alpha^A + Q_f^{A-4} ,$$

Energy distributions of the alpha-particles in ternary fission (experimental data)

Nucleus	(s,f)			(n,f)				a - decay
	N, 10^{-3}	<T>, MeV	FWHM, MeV	N, 10^{-3}	<T>, MeV	FWHM, MeV	B_n, MeV	Q, MeV
^{250}Cf	2.93±0.10	15.95±0.13	10.49±0.16	2.77±0.11	16.09±0.18	10.64±0.27	6,625	6.128
^{252}Cf	2.56±0.07	15.96±0.09	10.22±0.18	2.41±0.14	15.89±0.12	10.60±0.18	6,134	6.216
^{244}Cm	3.16±0.09	15.99±0.08	9.99±0.29	2.43±0.08	16.14±0.06	10.32±0.11	6,802	5.901
^{246}Cm	2.49±0.12	16.41±0.20	9.73±0.28	2.15±0.12	16.35±0.15	10.10±0.20	6,458	5.475
^{248}Cm	2.30±0.10	15.97±0.12	10.03±0.14	1.85±0.10	16.01±0.13	10.37±0.24	6,214	5.162
^{240}Pu	2.51±0.14	16.55±0.27	9.54±0.41	2.22±0.07	15.9±0.2	10.1±0.2	6,544	5.256
^{242}Pu	2.17±0.07	15.79±0.21	9.25±0.24	1.86±0.05	15.9±0.1	9.8±0.1	6,309	4.985

[1] S.Vermote // Nucl.Phys. A837 (2010) 176;
[2] S. Vermote // Nucl. Phys. A 806 (2008) 1
[3]O. Serot, C. Wagemans // Nucl. Phys. A 641 (1998) 34

Binary fission width

$$\Gamma_f^A = \omega^0 \left(\Gamma_f^A\right)^0$$

The alpha-particle energy distribution, normalized by the yield N_α of the alpha-particles in ternary fission

$$W_{\alpha f} = \frac{\Gamma_{\alpha f}^A(T_\alpha)}{\Gamma_f^A} = \frac{1}{2\pi} \frac{\left(\Gamma_\alpha^A(T_\alpha)\right)^0 \left(\Gamma_f^{A-4}\right)^0}{(Q_\alpha^A - T_\alpha)^2 \left(\Gamma_f^A\right)^0}$$

If consider, that $\frac{\left(\Gamma_f^{A-4}\right)^0}{\left(\Gamma_f^A\right)^0} \approx 1$, α-decay width of the nucleus in configuration (0):

$$(\Gamma_\alpha^A(T_\alpha))^0 = \omega_\alpha \frac{\hbar c\sqrt{2T_\alpha}}{2R_{neck}\sqrt{\mu_\alpha c^2}} P(T_\alpha),$$

where $P(T_\alpha)$ is penetrability factor for Coulomb barrier, ω_α is probability of α-particle if the parent nucleus, R_{neck} – is intermediate nucleus neck radius.

$$P(T_\alpha) = exp\left\{-\frac{2}{\hbar}\int_{z_1}^{z_2} \sqrt{2\mu(V(z) - T_\alpha)}\, dz\right\}$$

In [Kadmensky S.G., Titova L.V., Lyubashevsky D.E. Physics of Atomic Nuclei. 2020. V. 83. № 4. C. 581-590.] the estimations of the R_{neck} were derived:

$$R_{neck} = \omega_\alpha \frac{\hbar c \sqrt{2T_{\alpha\,max}}}{2\Gamma_{\alpha\,max}\sqrt{M_\alpha c^2}} P(T_{\alpha\,max}),$$

where $W_{\alpha f}(T_\alpha)$ is α - particle energy distribution.

Nucleus	Rneck(n,f)/Rneck (s,f)	ω_α, 10^{-2} (s,f) Rneck=2,5 fm [1]	ω_α, 10^{-2} (n,f) Rneck=2,5 fm [1]
^{250}Cf	0.92	2.36	2.57
^{252}Cf	1.08	2.37	2.19
^{244}Cm	1.21	3.13	2.57
^{246}Cm	1.40	2.84	2.37
^{248}Cm	1.27	2.55	2.01
^{240}Pu	1.28	3.06	2.39
^{242}Pu	1.19	2.56	2.13
^{234}U	-	-	2.92
^{236}U	-	-	2.10

Davies K.T.R et al. // Phys. Rev. C 16 (1977) 1890
O.Serot et al. Eur. Phys. J. A 8 (2000) 187

Preliminary results for tritons

Nucleus	Rneck(n,f)/Rneck (s,f)	ω_t, 10^{-3} (s,f)	ω_t, 10^{-3} (n,f)
^{250}Cf	0.87	6.95	7.95
^{252}Cf	1.04	7.67	7.98
^{244}Cm	1.02	8.90	8.67
^{246}Cm	0.91	8.94	9,67
^{248}Cm	0.99	7.96	9.77

Summary

- The formulae for the widths for the ternary fission induced by thermal neutrons on the base of the virtual mechanism were constructed.
- Using the experimental energy distributions of α –particles in ternary fission of compound nuclei ^{240}Pu, ^{242}Pu, ^{242}Cm, ^{244}Cm ^{246}Cm, ^{250}Cf, ^{252}Cf and obtained formulae it was demonstrated that the alpha-particle is emitted from the close to each other configurations of the fissile nucleus in (s,f) and (n,f) reactions.
- The calculated probabilities of the alpha-particle formation in the fissile nucleus neck for ^{242}Cm, ^{244}Cm ^{246}Cm, ^{250}Cf, ^{252}Cf are larger than tritons formation probabilities in about one order of magnitude.
- **Outlook:** consider the ternary fission with p,t,He-isotopes and clusters emission;
- clarify the interaction potentials of the third particle and the fission fragments, as well as to take into account all possible combinations of fragments arising in ternary fission in order to get Coulomb barrier penetrability.

Thank you for your attention!