ПОТРІЙНИЙ ПОДІЛ

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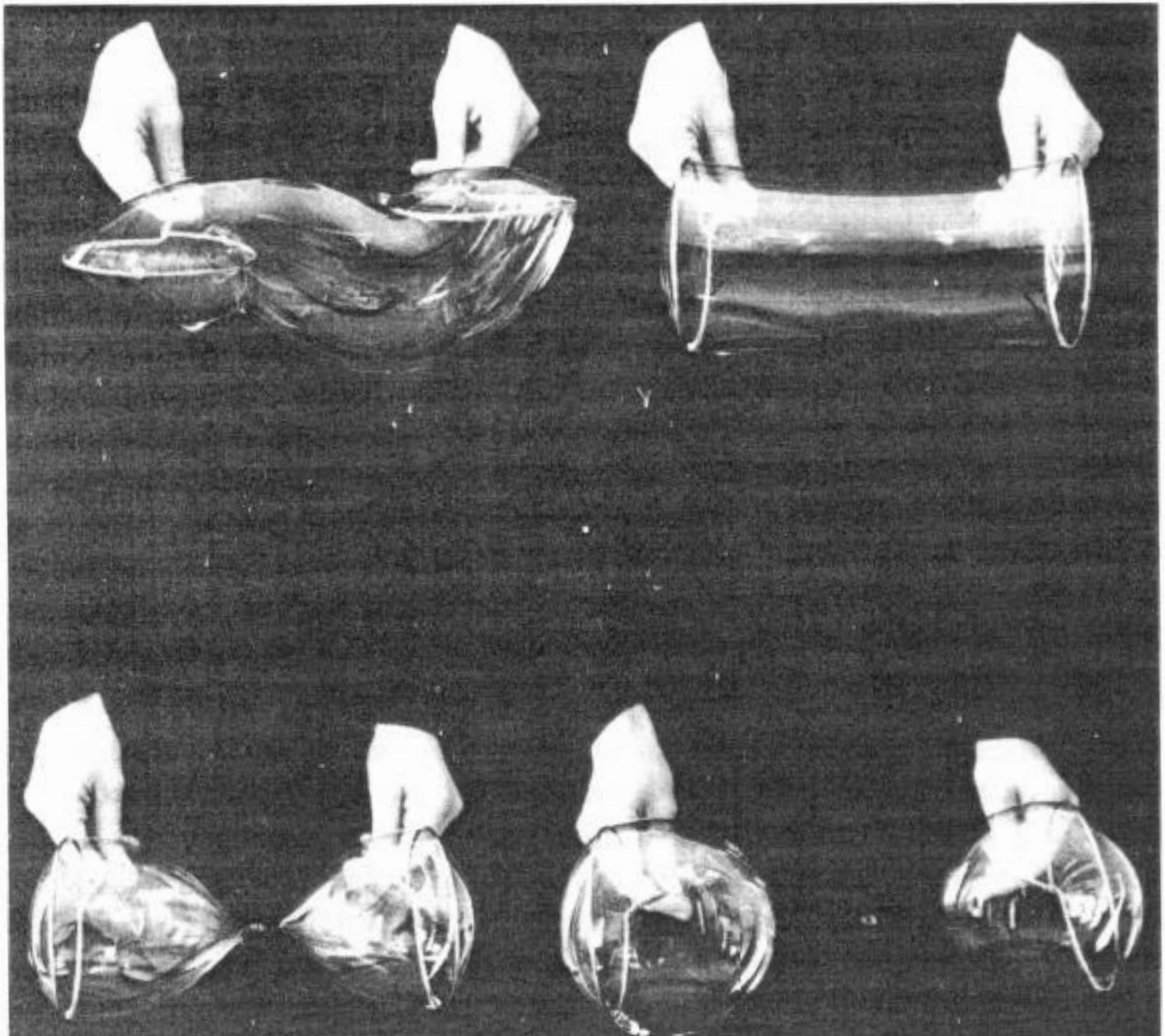


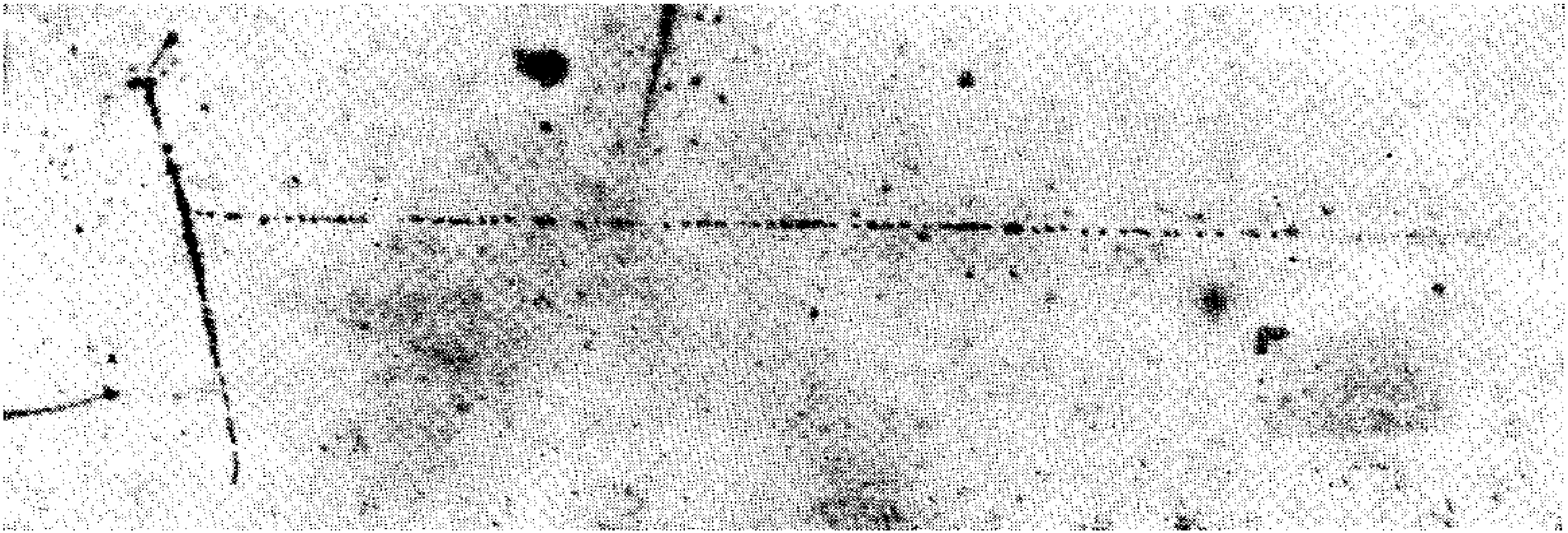
Відкриття потрійного поділу: 1946-1947

частиц. Об этом явлении стало известно в 1946—1947 гг. из работ нескольких групп исследователей, которые использовали как толстослойные фотопластинки (Перфилов [1], Цзен Сан-Цзян и др.[2], Воллан и др.[3], Демерс [4], Грин и Ливси [5]), так и специально сконструированные ионизационные камеры (Фарвелл и др.[6]).

1. Н. А. Перфилов, Диссертация, РИАН СССР (1947).
2. Tsien San-Tsiang, Ho Zah-Wei, R. Chastel, L. Vigneron, J. phys. et radium 8, 165 и 200 (1947); Tsien San-Tsiang, J. phys. et radium 9, 6 (1948).
3. E. O. Wollan, C. D. Moak, R. B. Sawyer, Phys. Rev. **72**, 447 (1947).
4. P. Demers, Phys. Rev. **70**, 974 (1946).
5. L. L. Green, D. L. Livesey, Nature **4036**, 332 (1947); L. L. Green, D. L. Livesey, Phylos. Trans. **241**, 323 (1948).
6. G. Farewell, E. Segre, C. Wiegand, Phys. Rev. **71**, 327 (1947).

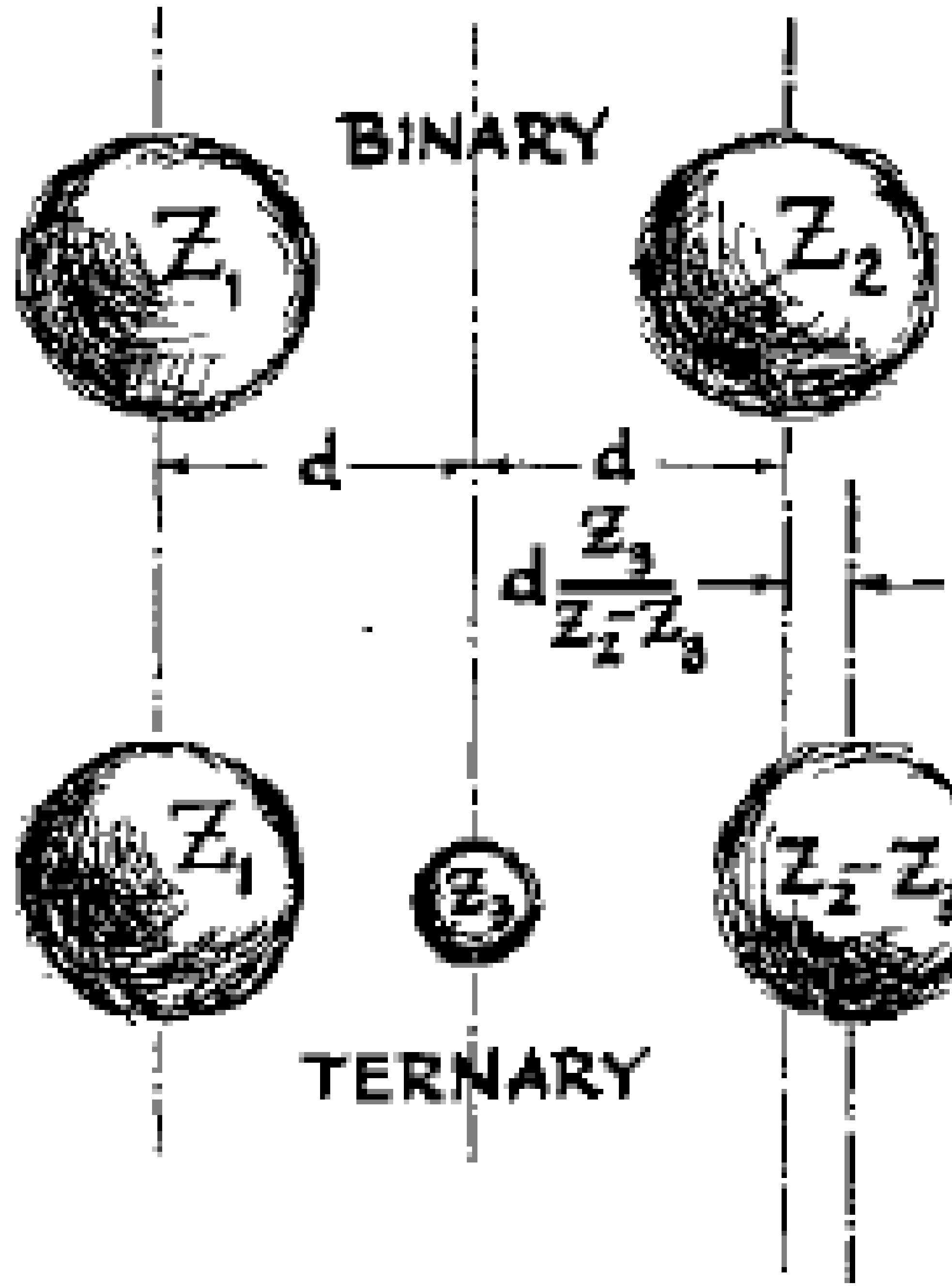
Подія потрійного поділу

α + 2 уламка поділу



ПОТРІЙНИЙ ПОДІЛ ЯДЕР - особливий вид поділу ядер, коли утворення 2 осколків супроводжується вильотом легкої зарядженої частинки.

У переважній більшості випадків це довгопробіжна альфа-частинка з середньою енергією приблизно в 3 рази більшою, ніж у випадку альфа-розпаду важких ядер.


BINARY
Z1
Z2
d
d
d Z3 / Z2-Z3
Z1
Z3
Z2-Z3
TERNARY

Подія потрійного поділу natTh + 40Ar => α + 2 уламка поділу

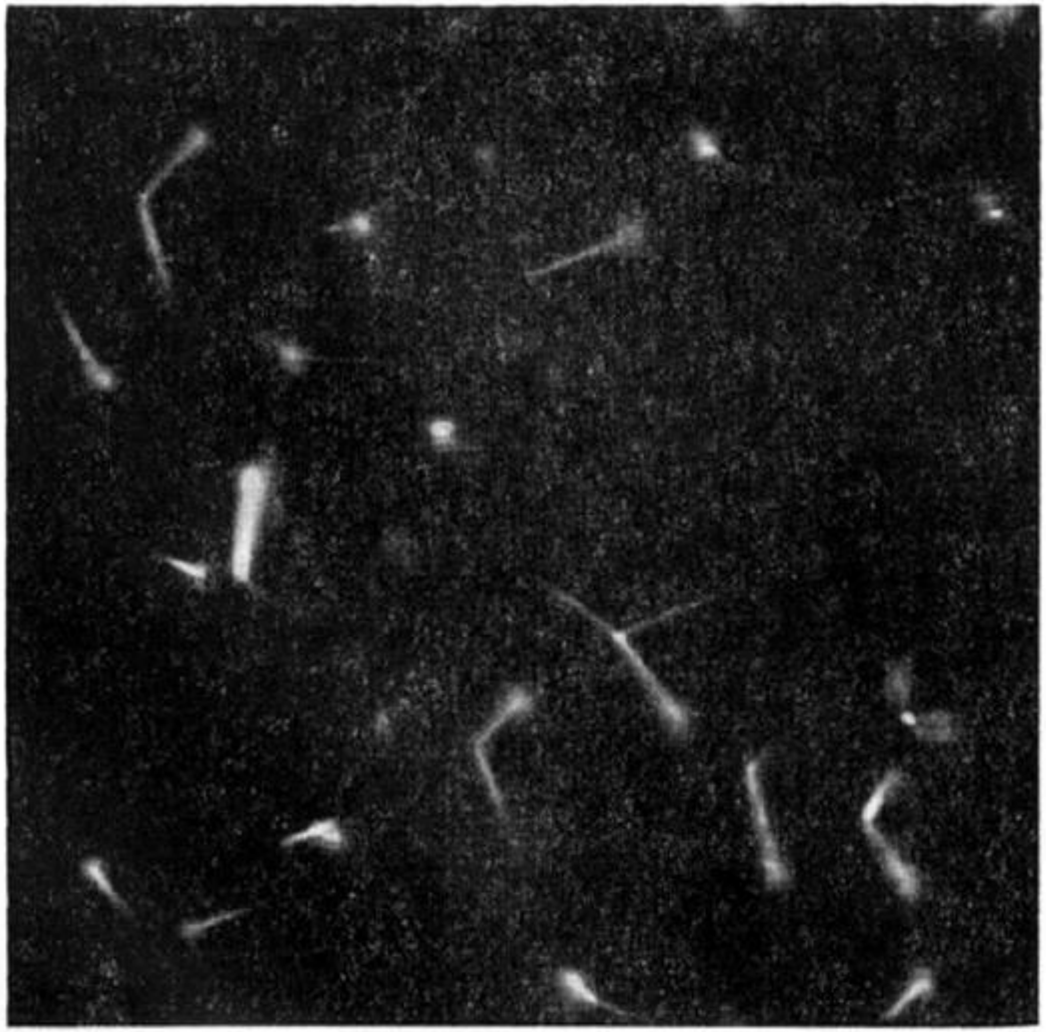
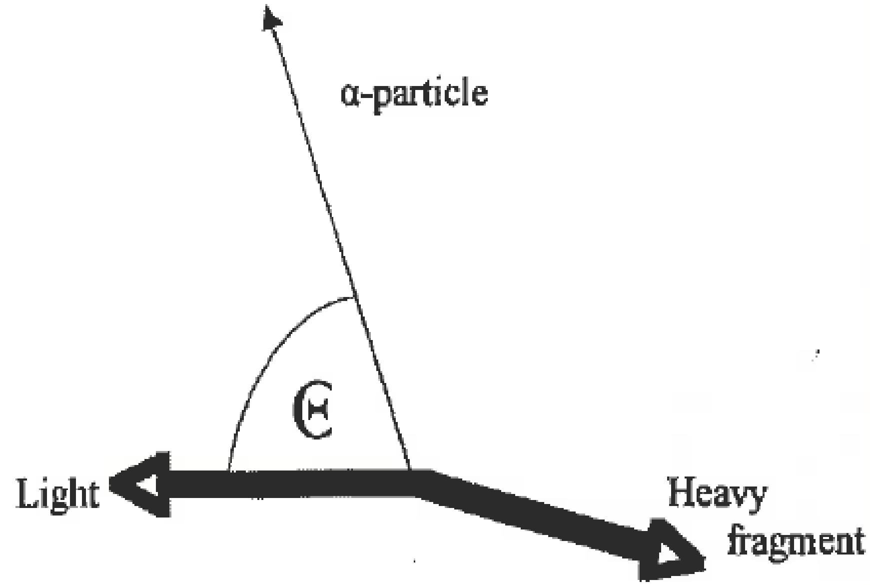
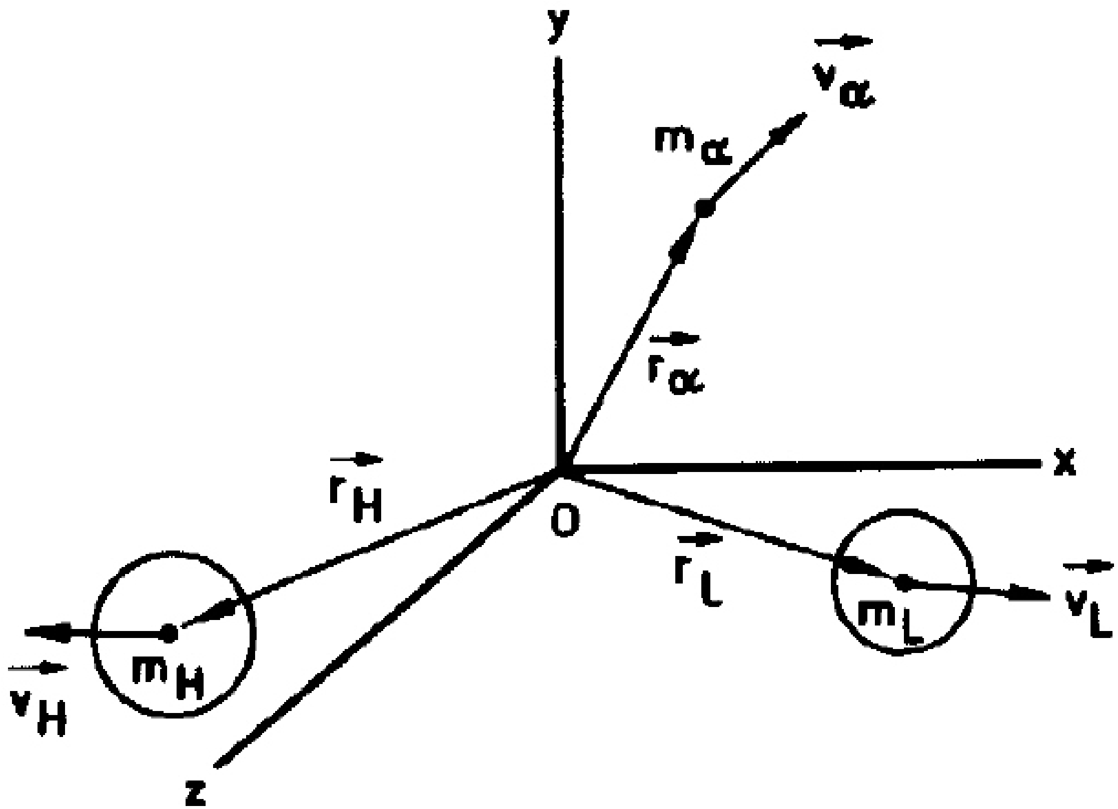


Fig. 1. Etched charged-particle tracks in thorite which was irradiated with 400-MeV Ar ions. The two-pronged events are binary fissions, the three-pronged events are ternary fissions. Typical prongs are 5 to 10 μ long. For further examples of ternary fission in this experiment see Fig. 6 of R. L. Fleischer, P. B. Price, and R. M. Walker, Science 149, 383 (1965). The Ar beam is incident at 9° to the horizontal.

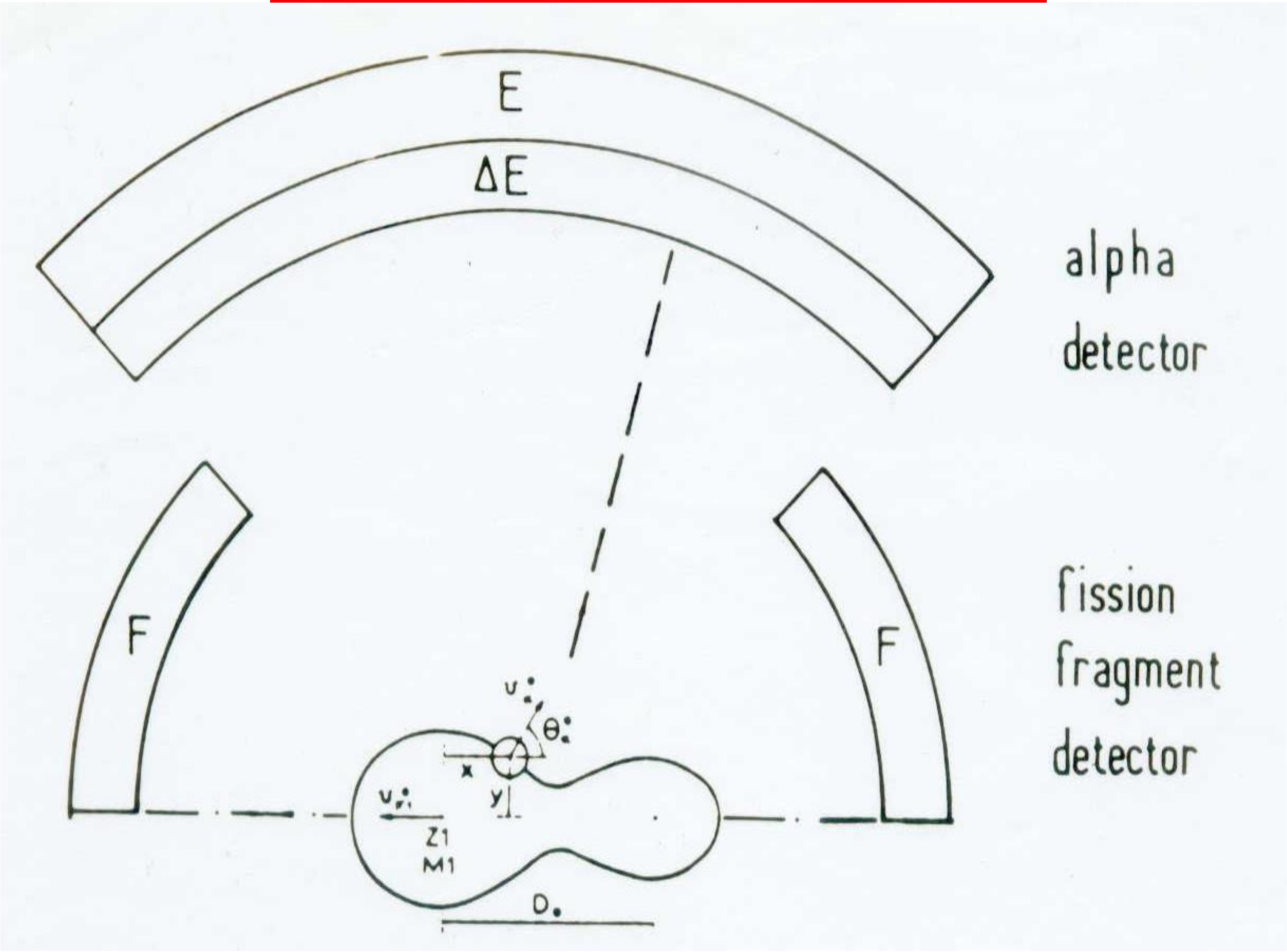
R.L. Feischer et al., Phys. Rev. 143, 943 (1966)

Kinematic of ternary fission

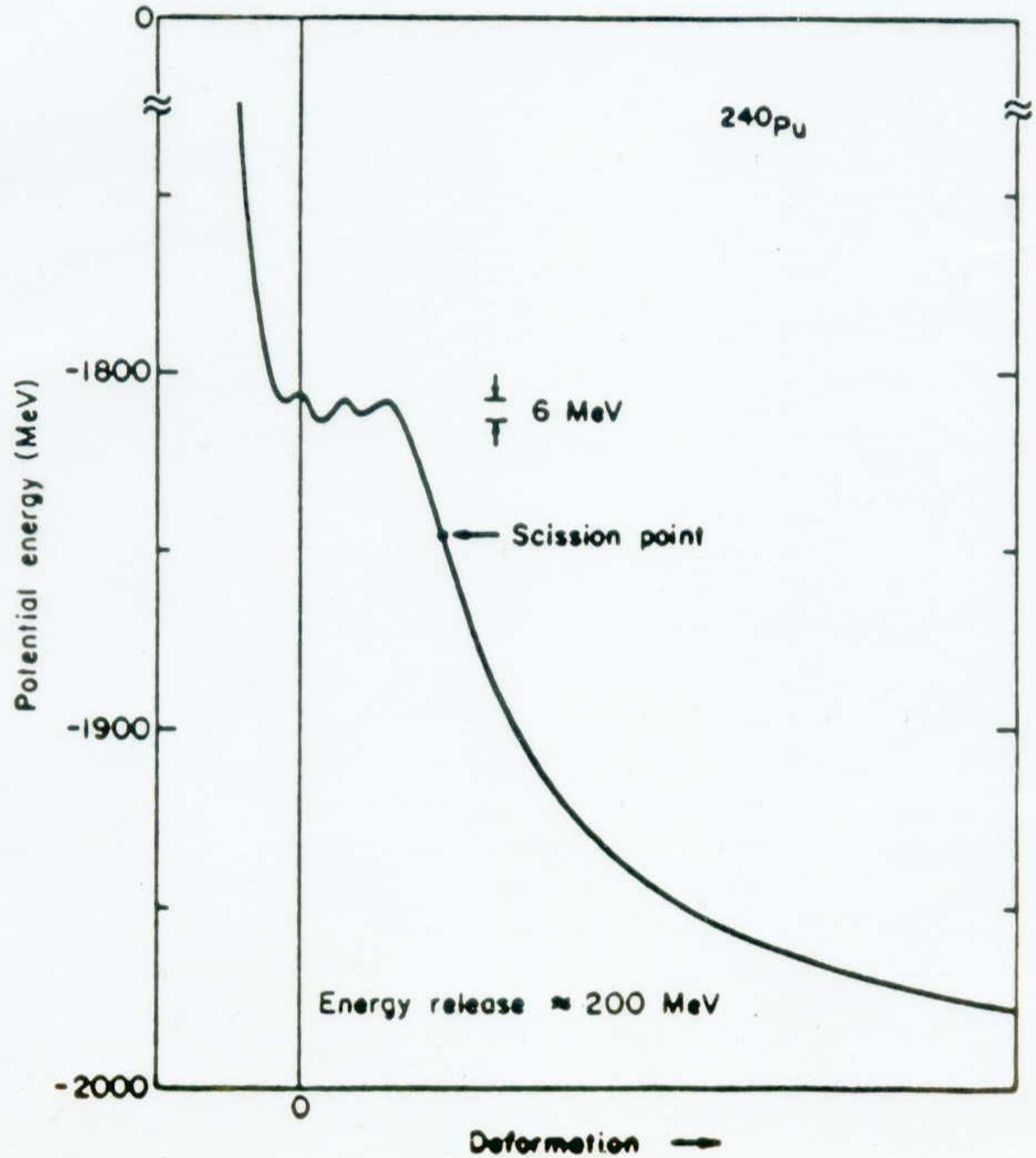




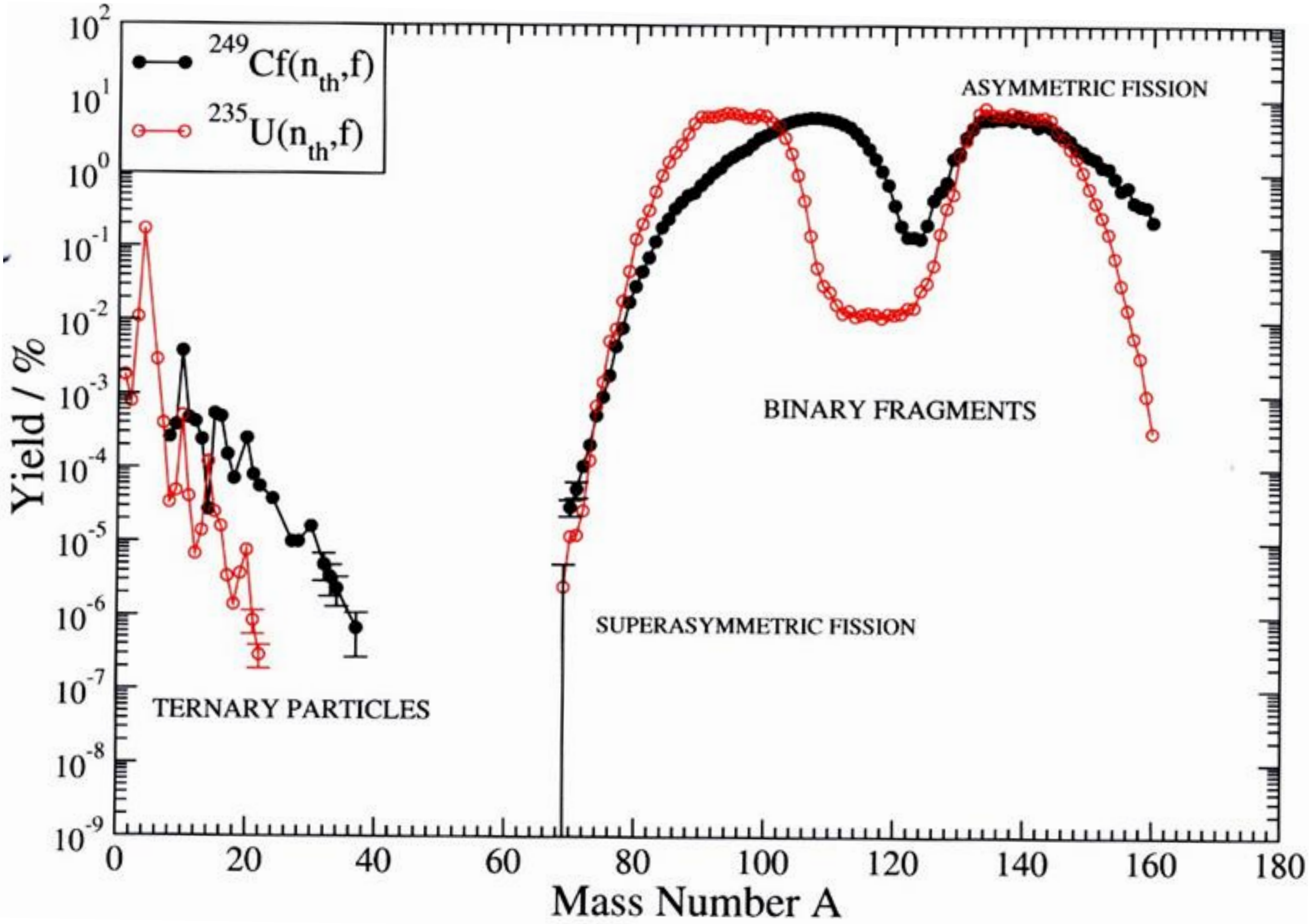
LongRangeAlpha-particles emission during fission



Schematic experimental setup

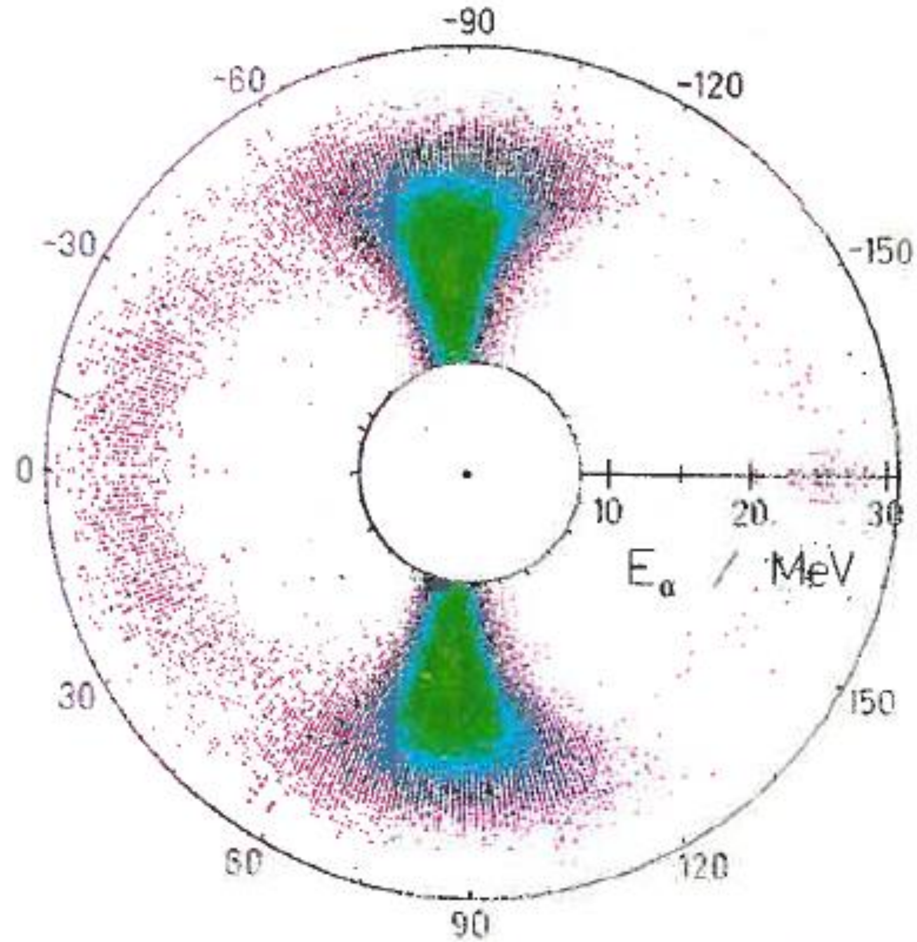


By study ternary fission we can better understand the fission dynamics around scission point.



$^{249}Cf(n_{th},f)$
$^{235}U(n_{th},f)$
ASYMMETRIC FISSION
BINARY FRAGMENTS
SUPERASYMMETRIC FISSION
TERNARY PARTICLES
Yield / %
Mass Number A

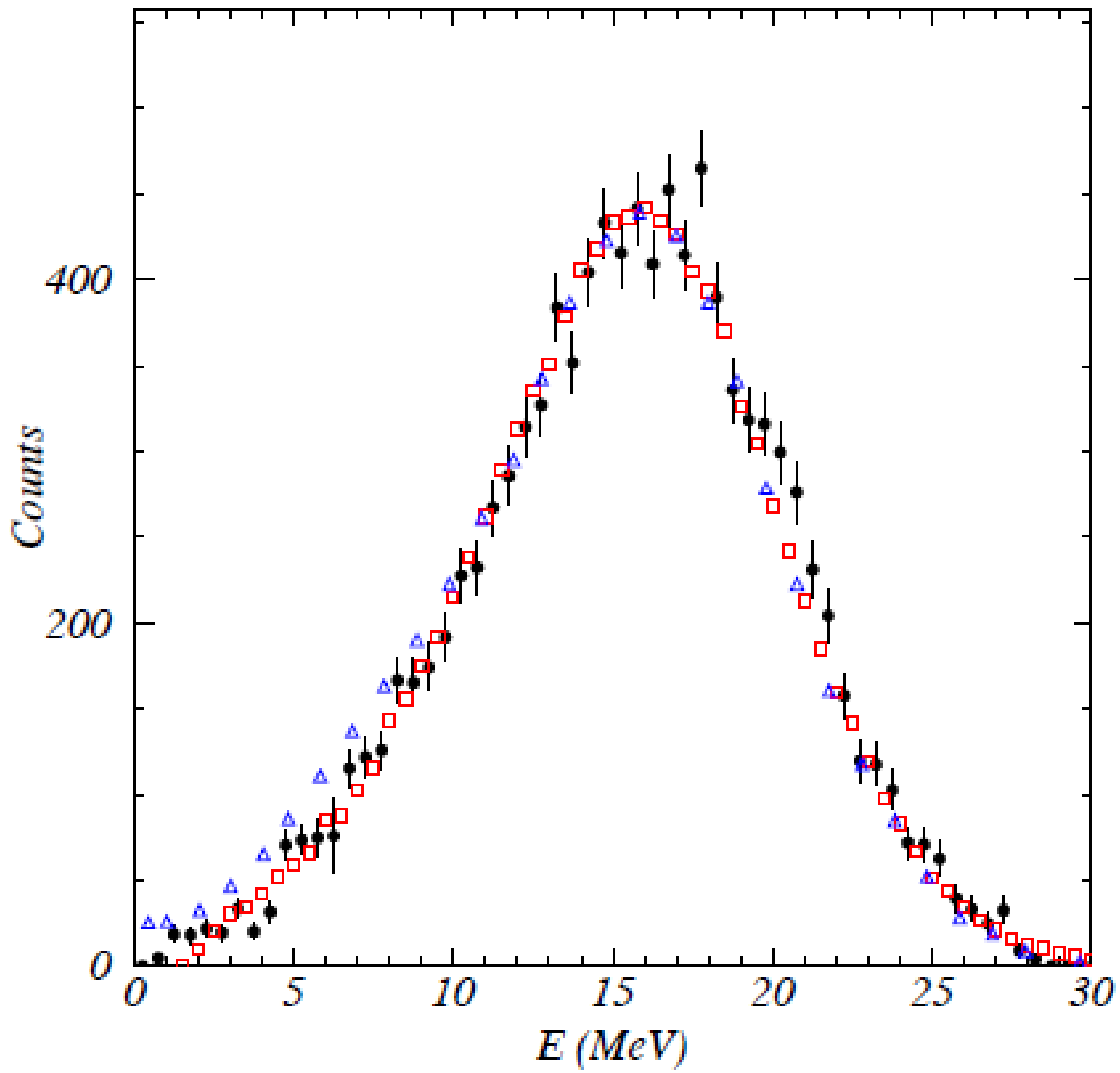
Angular and Energy distributions of alpha-particles



▲ Fig. 2: Scatter plot of ternary α-particle emission from ^{252}Cf(sf). In the polar diagram the fissioning nucleus is located at the centre with the light fragment moving to the left (Θ = 0°) and the heavy fragment to the right (Θ ≈ 180°). Each point in the plot corresponds to an α-particle from ternary fission. Energies of the ?-particles are represented as radii measured from the centre. Their angles of emission relative to light fragment momentum are given as the polar angles Θ of the radius vector, from ref. [5].

Mutterer, Theobald, in Nuclear Decay Mode, Ed. Poenaru (1996)

Energy distribution of ternary α particles from 252Cf spontaneous fission: Comparison of the present data (points with error bars) with results from Tishchenko *at al*. (squares) and Loveland (triangles).



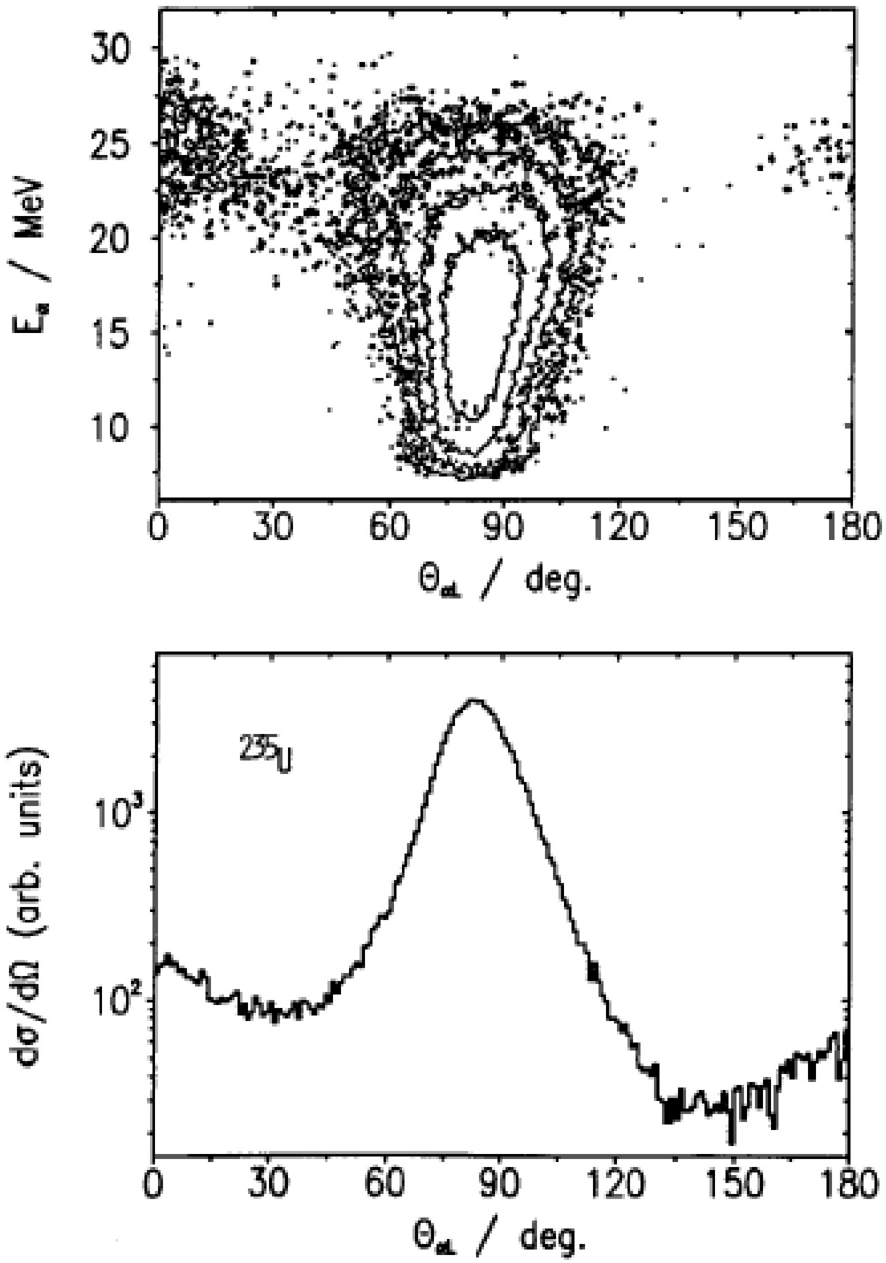
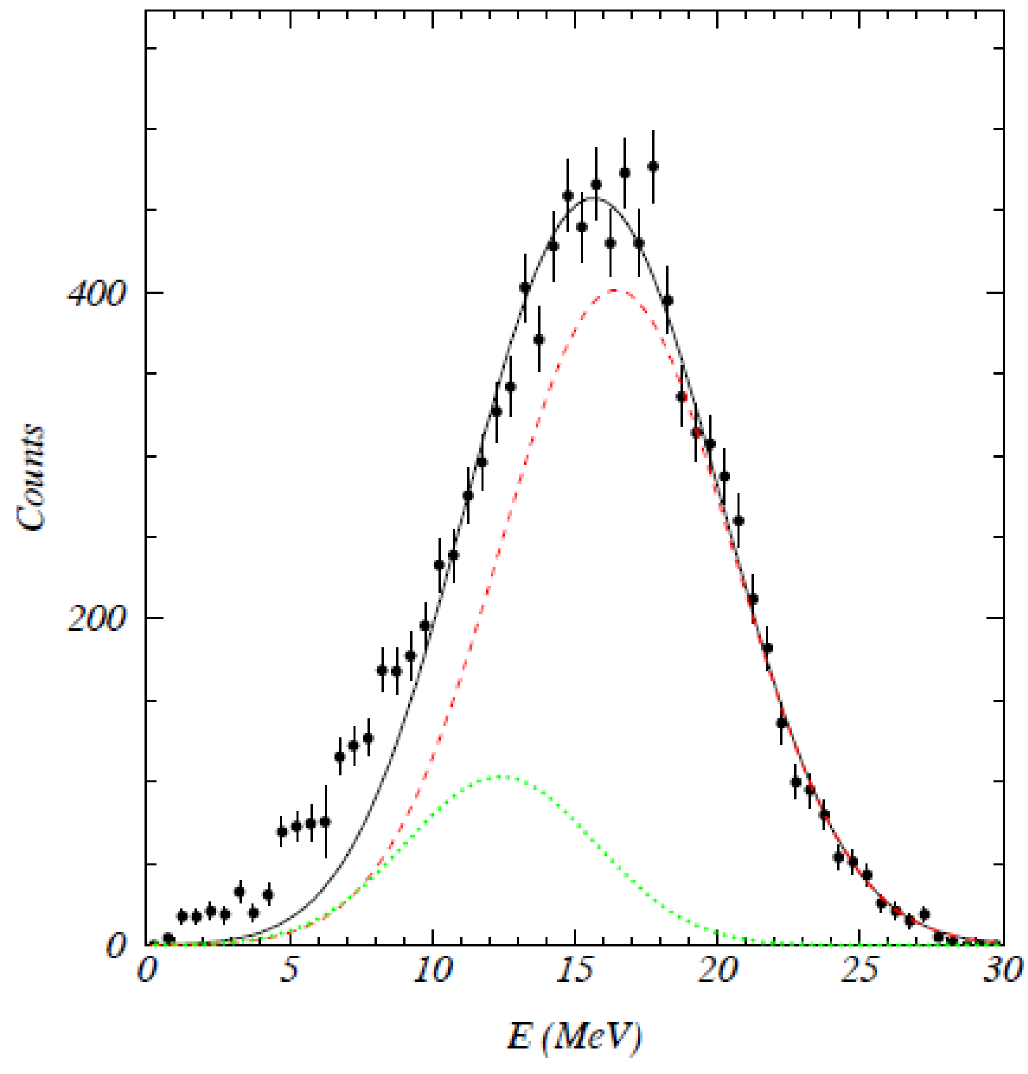


FIGURE 14. The lower part shows the ternary alpha particle yields as a function of the emission angle (with respect to the direction of the light fission fragment). The upper part shows the corresponding kinetic energies. (From Theobald J., in *Proc. Semin. on Fission*, *Pont d'Oye*, Wagemans, C., Ed., Rep. BLG, 586, SCK/CEN, Mol, Belgium, 1986, 63. With permission)

Розподіл енергії потрійних α-частинок при поділі 252Cf. Два Гауссіана, що відповідають даним вище 9 МеВ, враховують справжні потрійні α (домінуючий (екваторіальний) пік) і залишкові α від розпаду 5He.



235U+n_{therm} fragment mass distribution

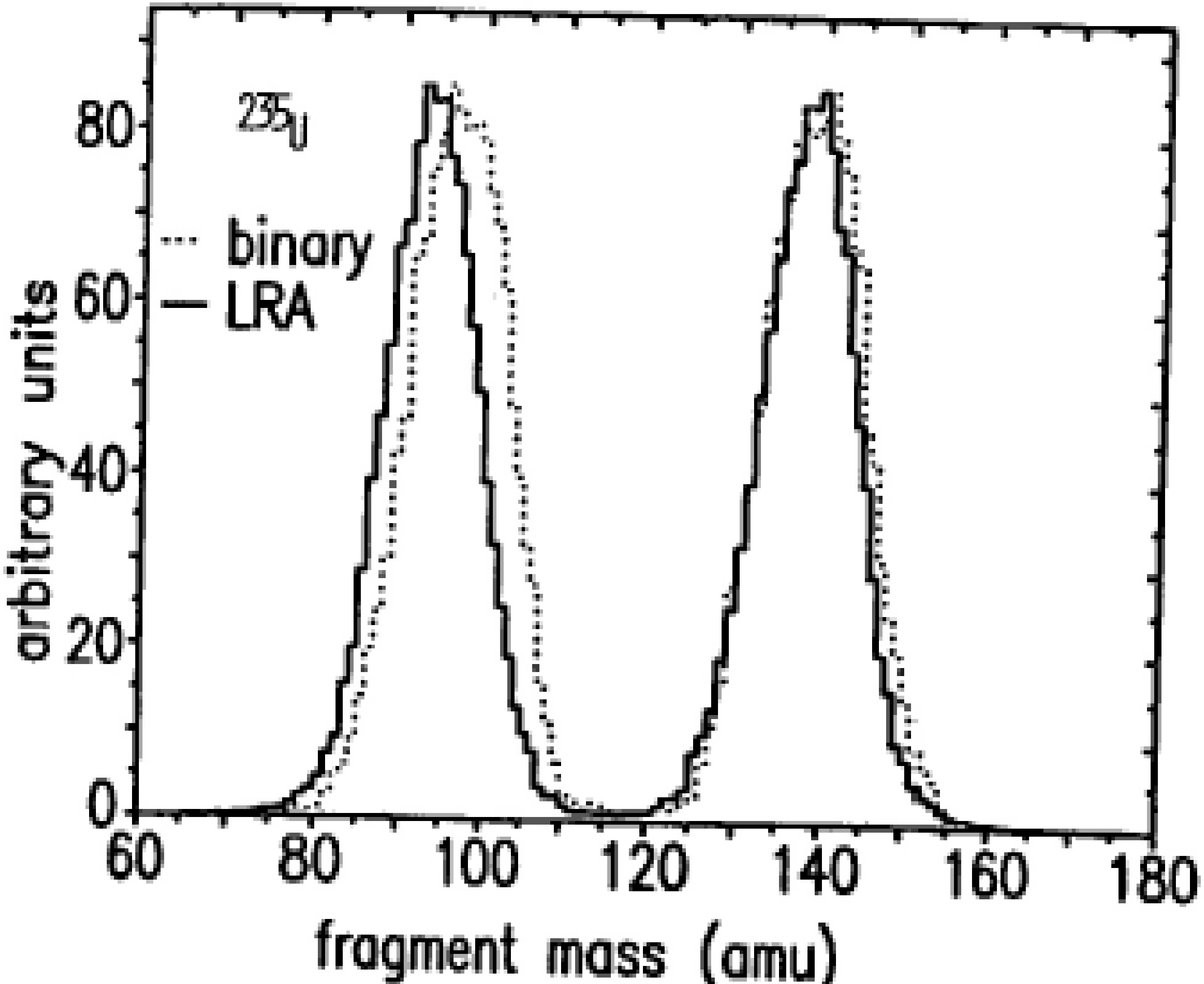


FIGURE 15. Fission fragment mass distribution in the binary and α-accompanied fission of $^{235}U + n_{th}$. (From Theobald, J., Report IKDA 85/22, Technische Hochschule, Darmstadt, West Germany, 1985.)

Various particle emission at ternary fission

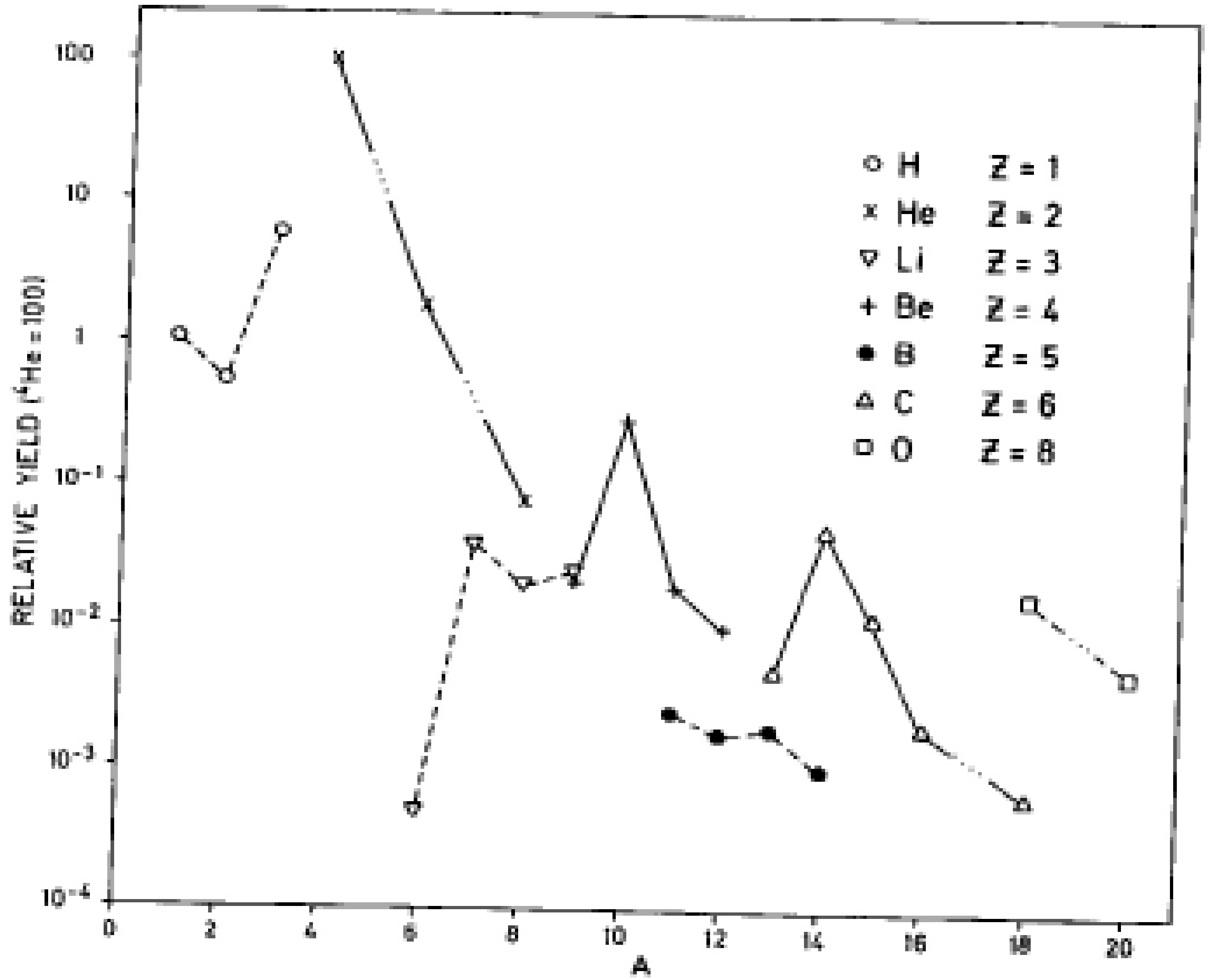
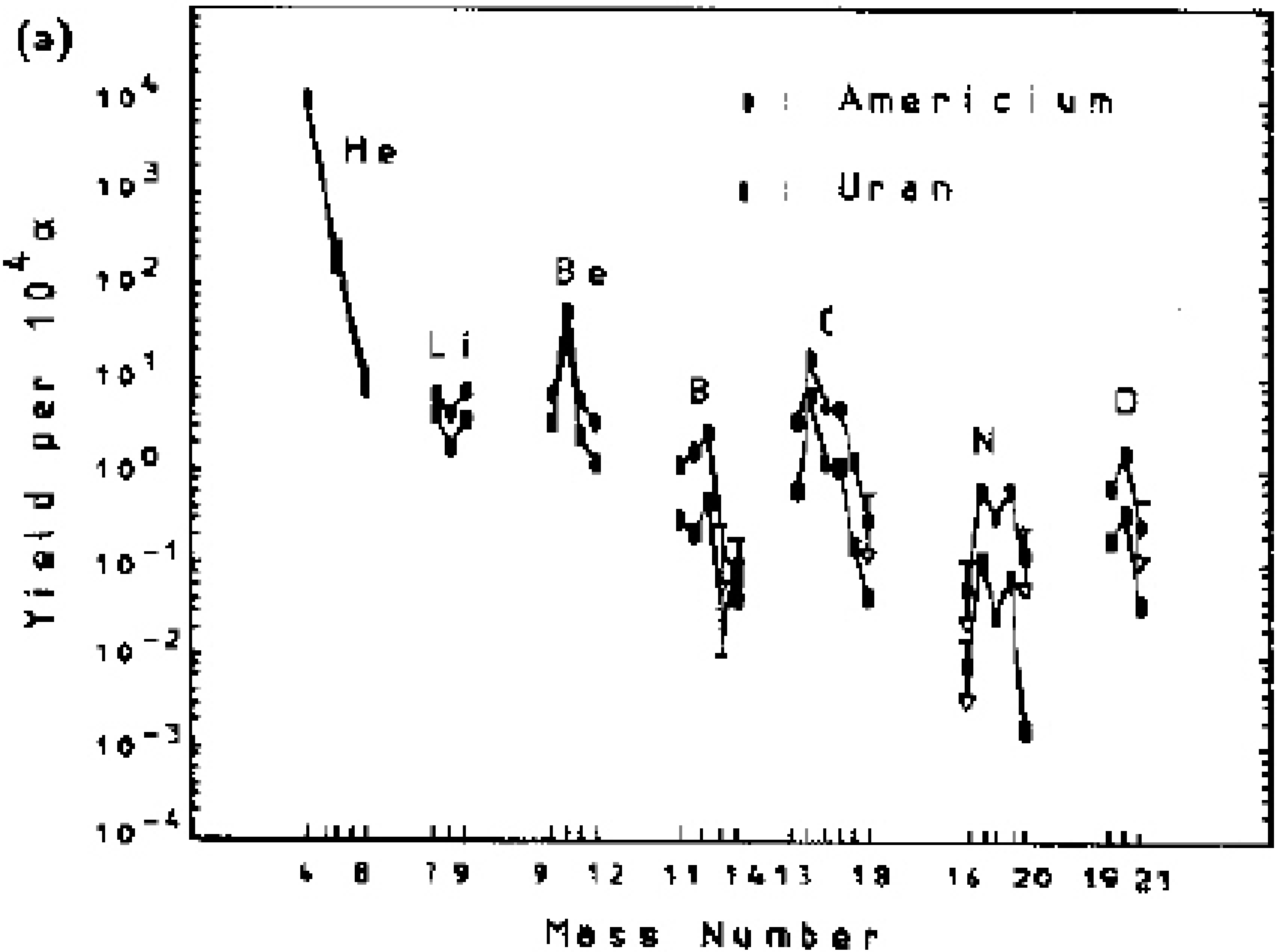
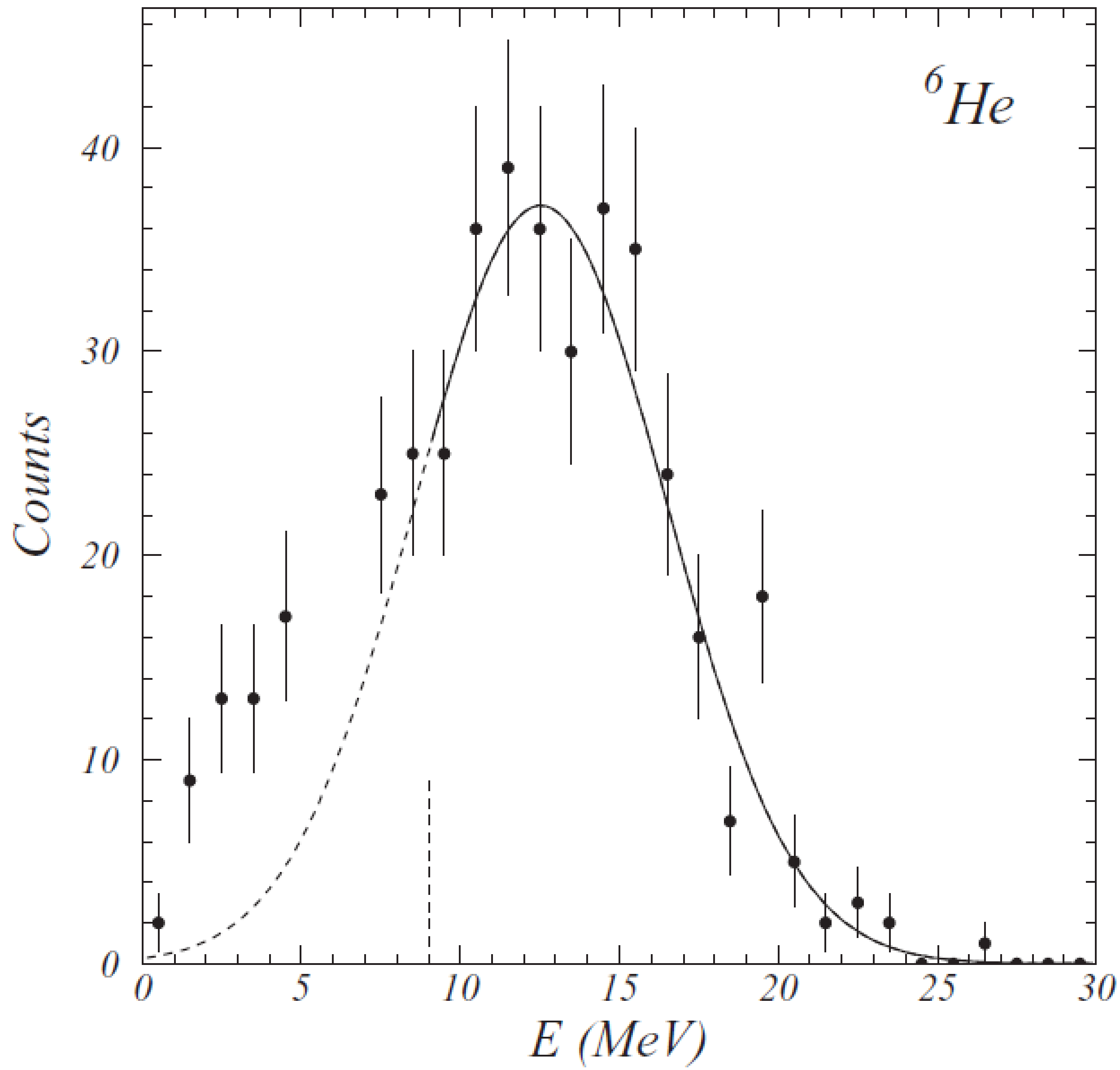


FIGURE 3. Relative yields of the charged light particles emitted in the thermal neutron-induced ternary fission of ^{235}U as a function of the particle mass (the "true" ^{4}He yield = 100).

Comparison of yields for various particle emission at ternary fission Am and U



Ternary spontaneous fission of 252Cf



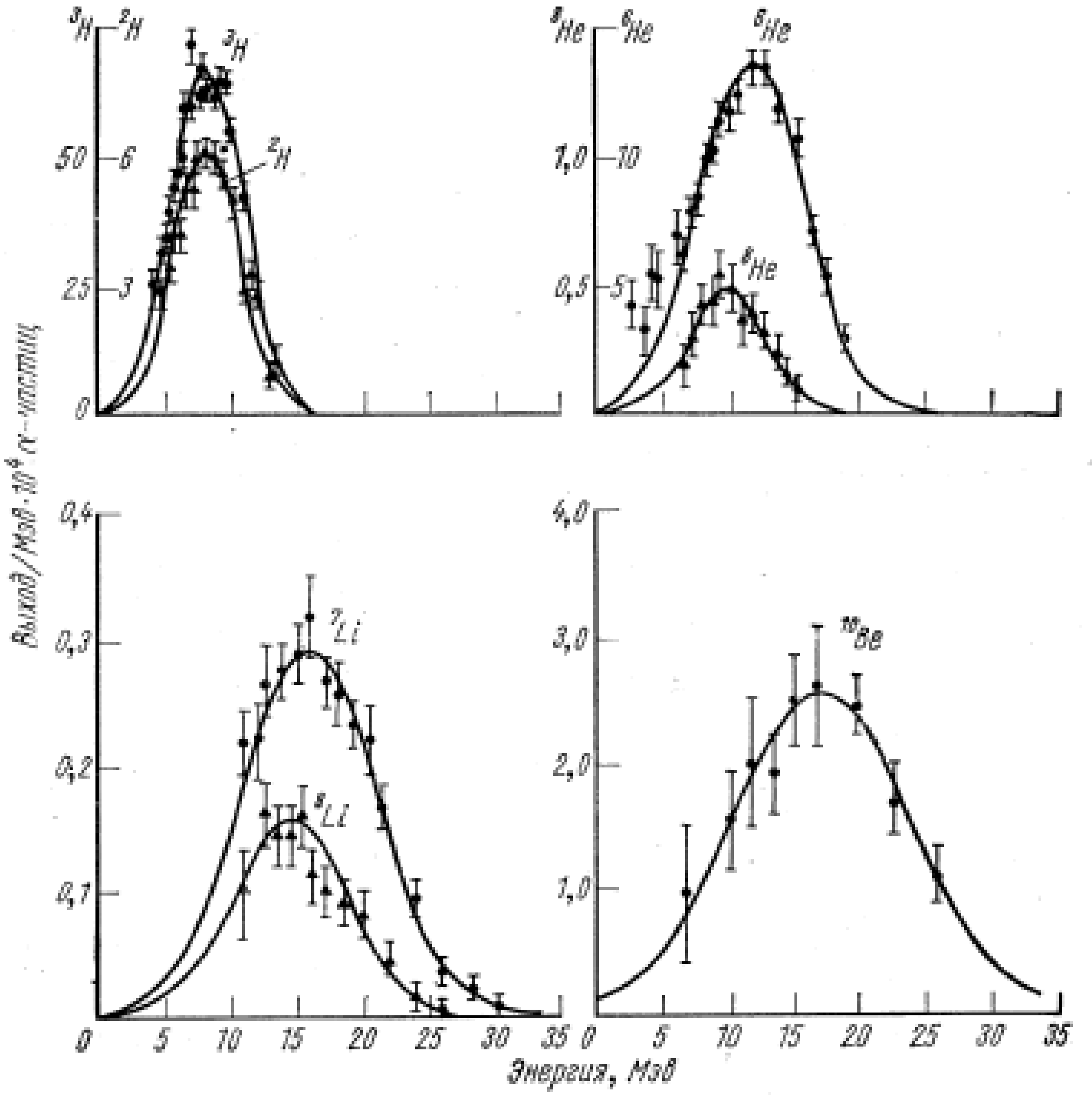


Рис. 12. Энергетические спектры изотопов водорода, гелия, лития и бериллия, образующиеся в делении ^{233}U нейтронами:

спектр ^{10}Be и часть спектра ^{8}He ниже 7 *Мэв* измерены с мишенью толщиной 0,09 *мГ/см*², закрытой Al фольгой 0,15 *мГ/см*². Остальные спектры получены мишенью толщиной 1,2 *мГ/см*², из U_3O_8 и Al фольгой толщиной 4,1 *мГ/см*². Спектры скорректированы на поглощение энергии частиц в мишени и Al фольге.

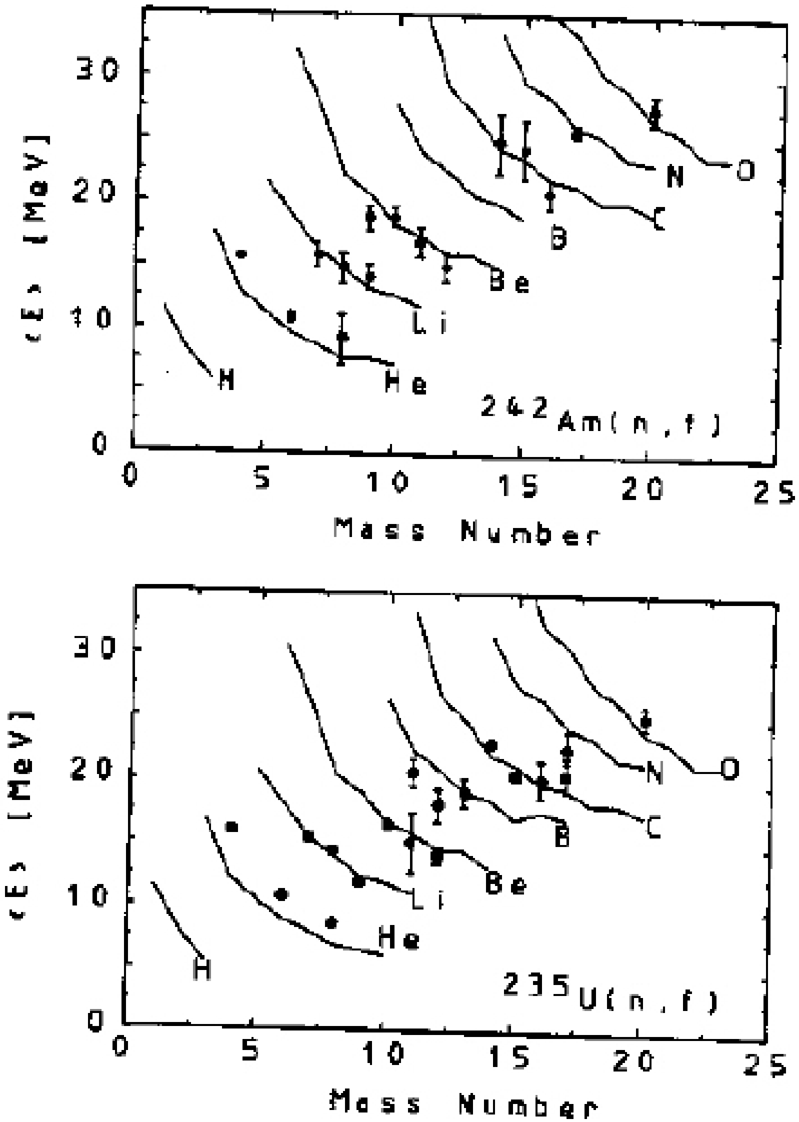
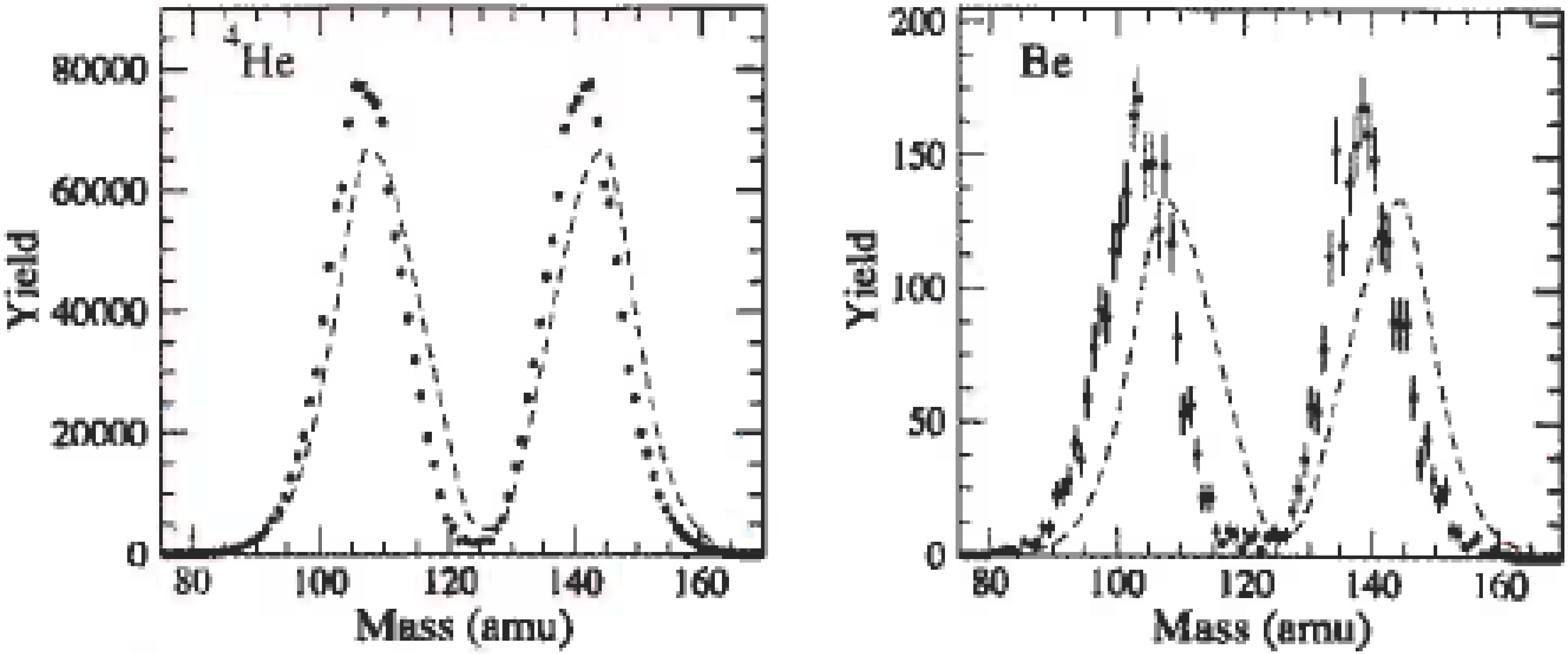


Figure 12.8. Mean energies of light charged particles in ^{235}U(n_{th}, f) and ^{242}Am(n_{th}, f), compared to a trajectory calculation. (From Baum W *et al* 1991 *Proc. Seminar on Fission Pont D'Oye II (Pont D'Oye, 1991)* ed C Wagemans *Internal Report* p 78. With permission.)



▲ Fig. 4: Fragment mass distributions in ternary fission of ^{252}Cf(sf) with ^{4}He and Be as the light charged particles (black points with error bars in the left and right panel, respectively). Yields are given as the number of events measured. Binary mass distributions are shown for comparison as red dashed curves. For each reaction the binary distributions are normalised to the total number of counts in the ternary distribution, from ref. [8].

Dependence of ternary particles yields on energy of initial nucleus

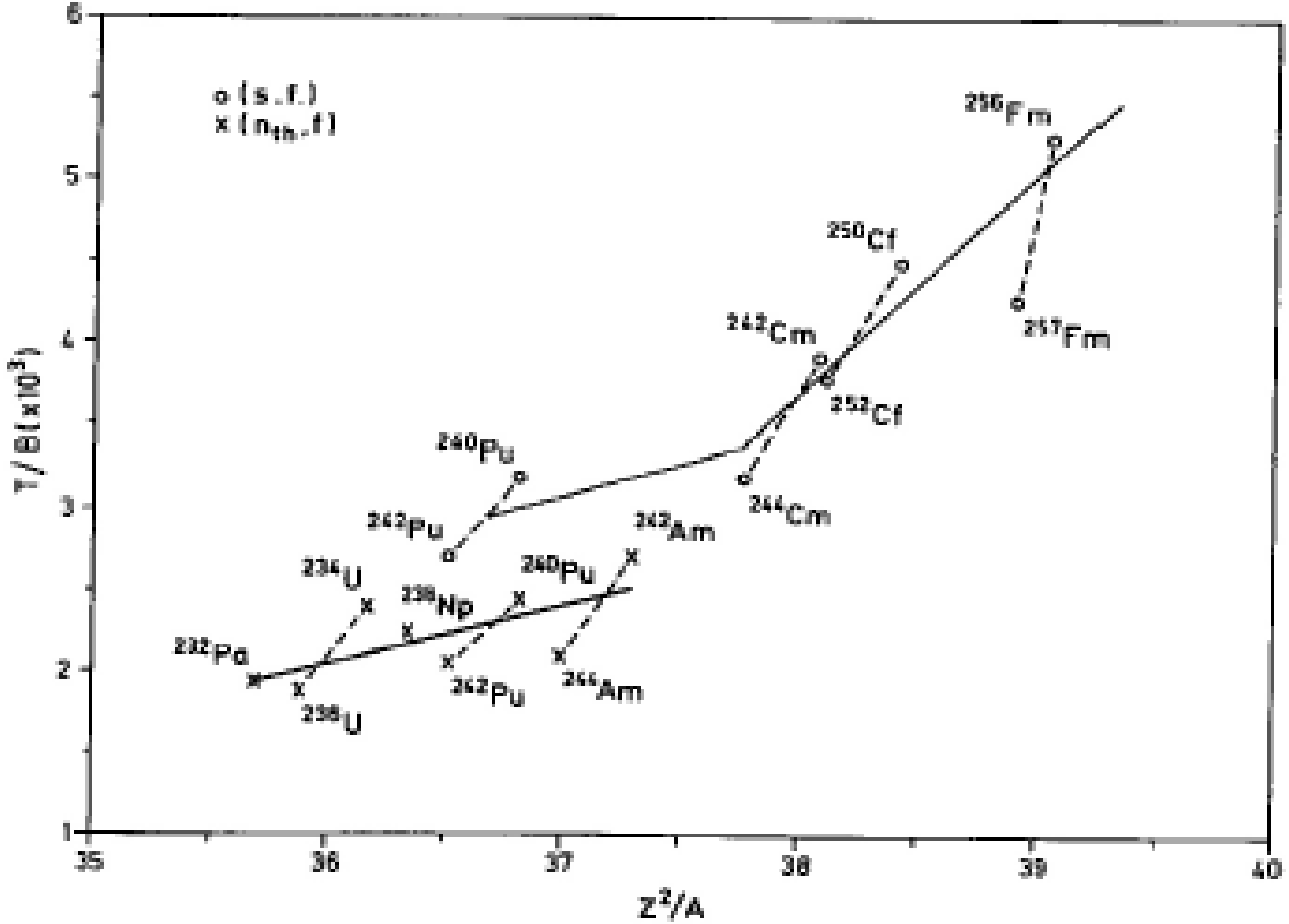


FIGURE 7. Total number of ternary particles emitted per fission (T/B) as a function of Z^2/A of the fissioning system. (From Wagemans, C., Schillebeeckx, P., D'hondt, P., Bocquet, J. P., and D'Eer, A. in *Proc. Semin. on Fission, Pont d'Oye*, Wagemans, C., Ed., Rep. BLG 586, SCK/CEN, Mol, Belgium, 1986, 78. With permission.)

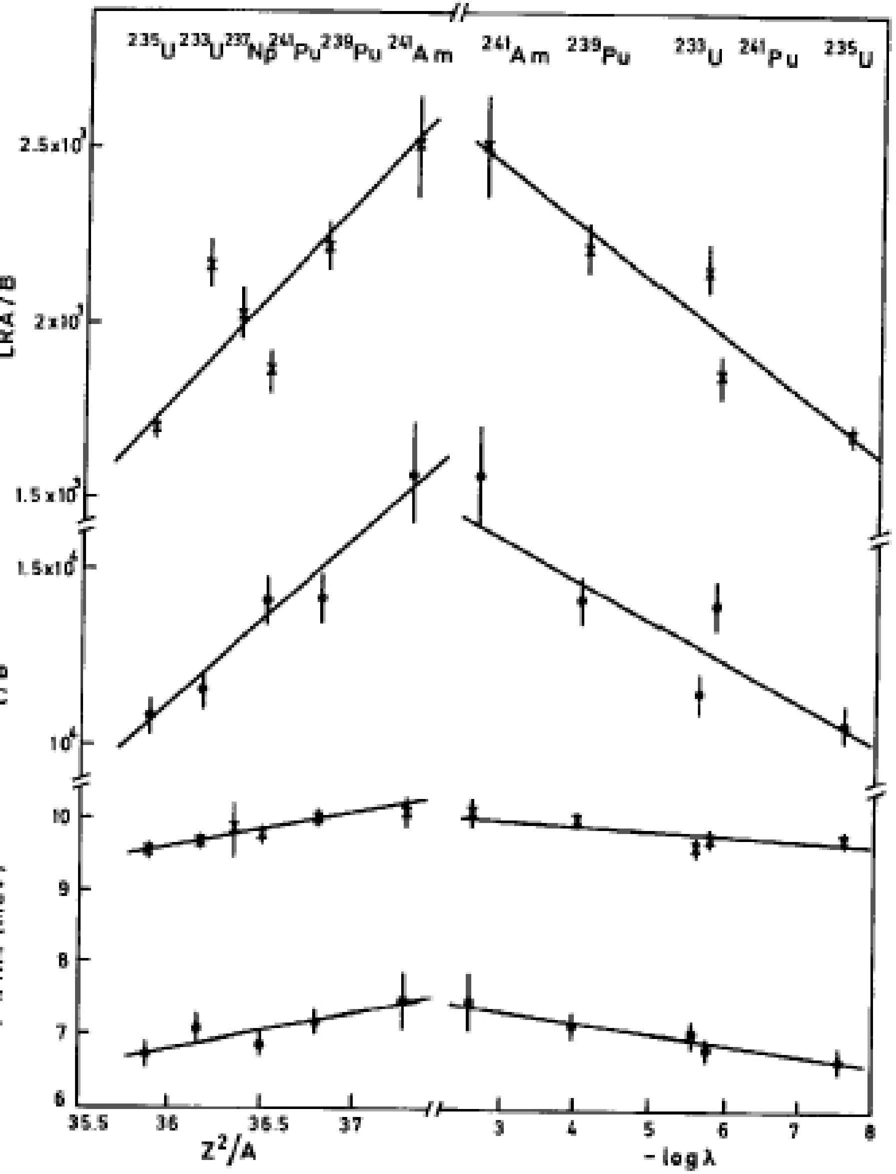
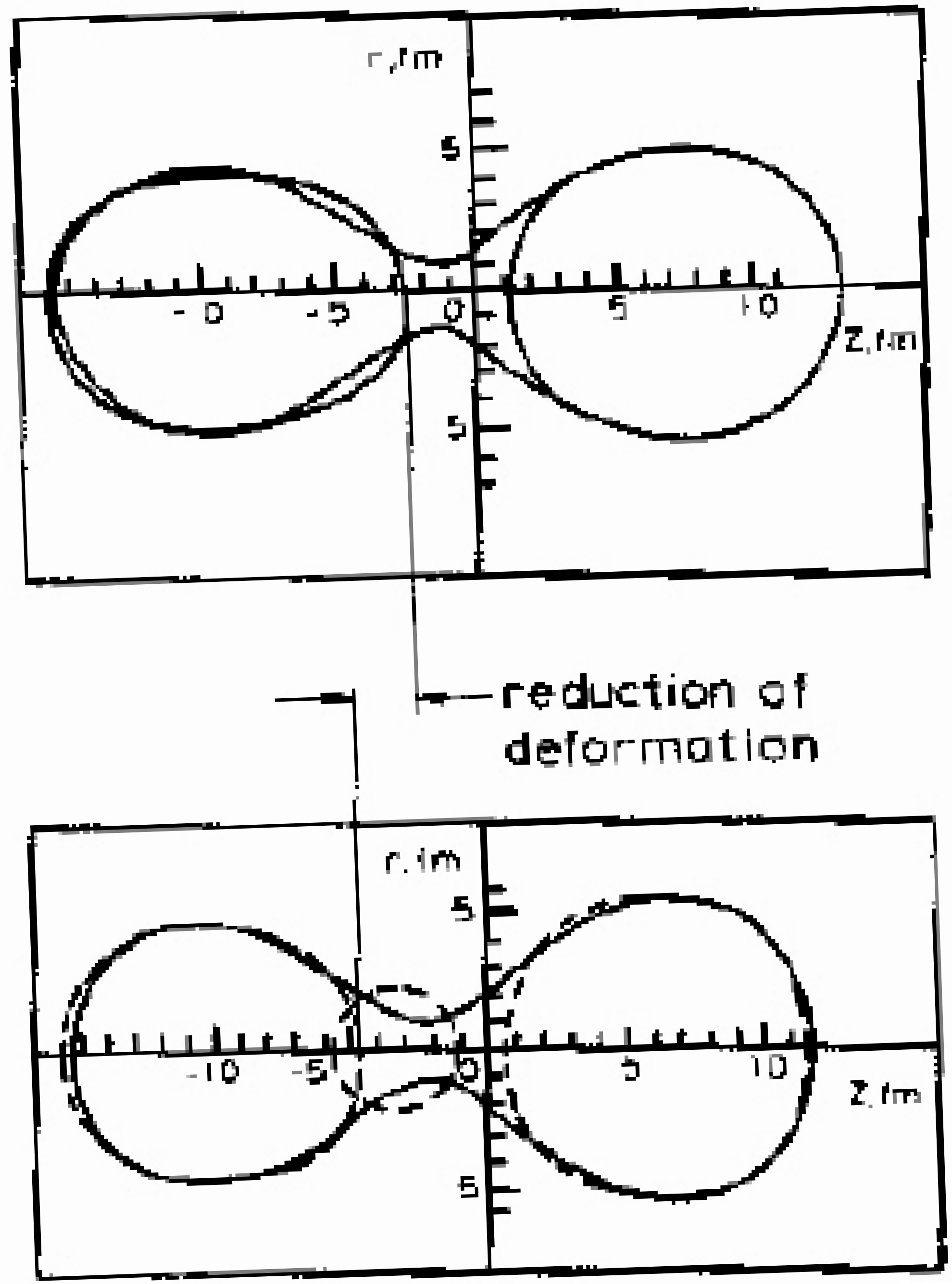
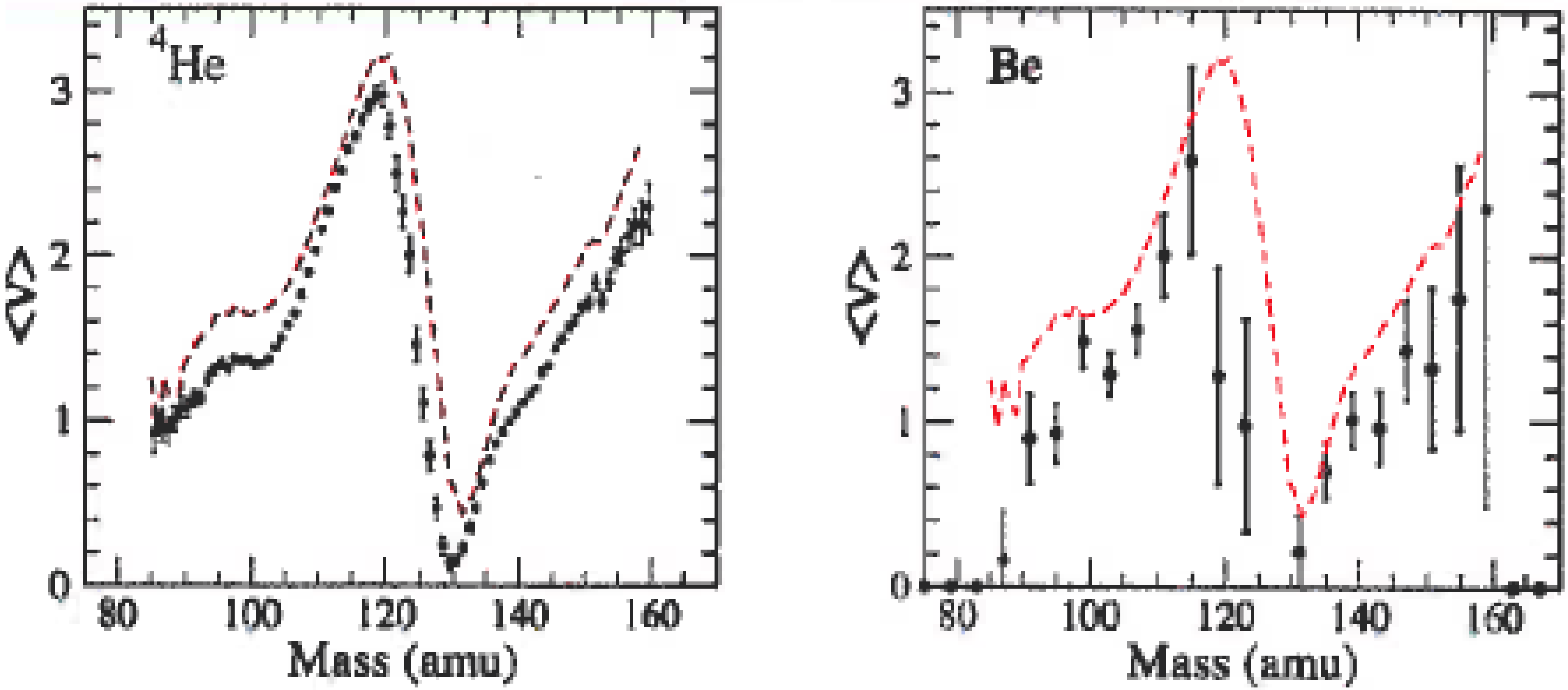


FIGURE 5. Absolute ternary α and triton yields and FWHM of the α (×) and triton (•) energy distributions for the thermal neutron-induced fission of ^{233}U, ^{235}U, ^{237}Np, ^{239}Pu, ^{241}Pu, and ^{241}Am as a function of Z^2/A and of $-\log\lambda$ of the fissioning system. Here λ is given in a^{-1}. Note that the Np data have not been displayed as a function of $-\log\lambda$, no λ-value being available for ^{238}Np. A solution for this and similar cases could be to calculate λ from the Q_α-value using the Geiger-Nutall law. (From Wagemans, C., Schillebeeckx, P., D'hondt, P., Bocquet, J. P., and D'Eer, A., in *Proc. Semin. on Fission, Pont d'Oye*, Wagemans, C., Ed., Rep. BLG 586 SCK/CEN, Mol, Belgium, 1986, 78. With permission.)

Уламки менш деформовані при потрійному розподілі





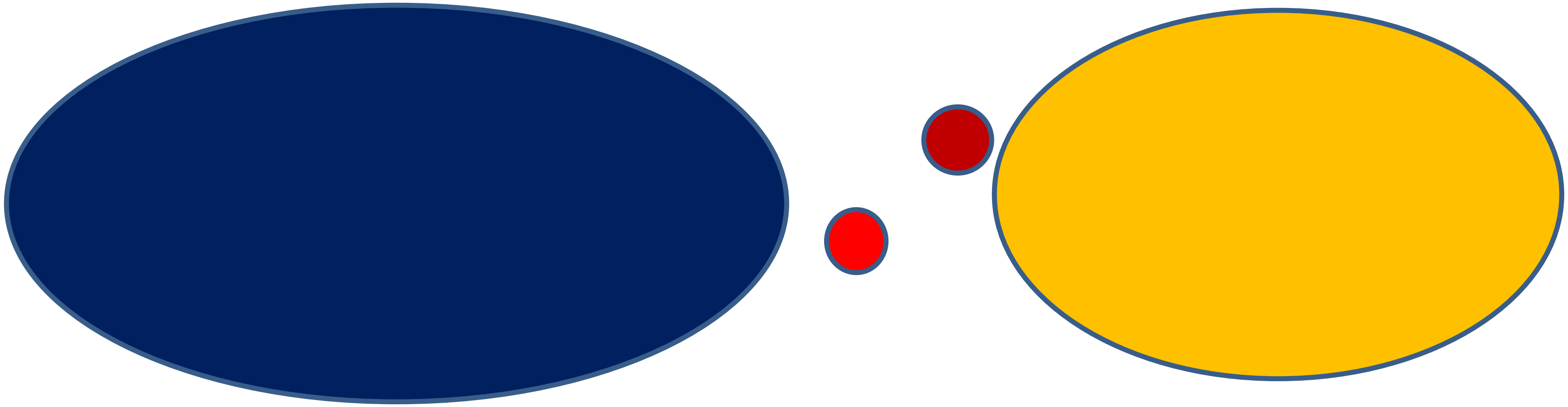
▲ **Fig. 5:** Neutron multiplicities as a function of fragment mass in ternary fission of $^{252}Cf(sf)$ with ^{4}He and Be as the light charged particles (black points with error bars in the left and right panel, respectively). Neutron multiplicity data from the corresponding binary fission reaction are given as dashed red curves, from ref. [8].

Четвертинний поділ:

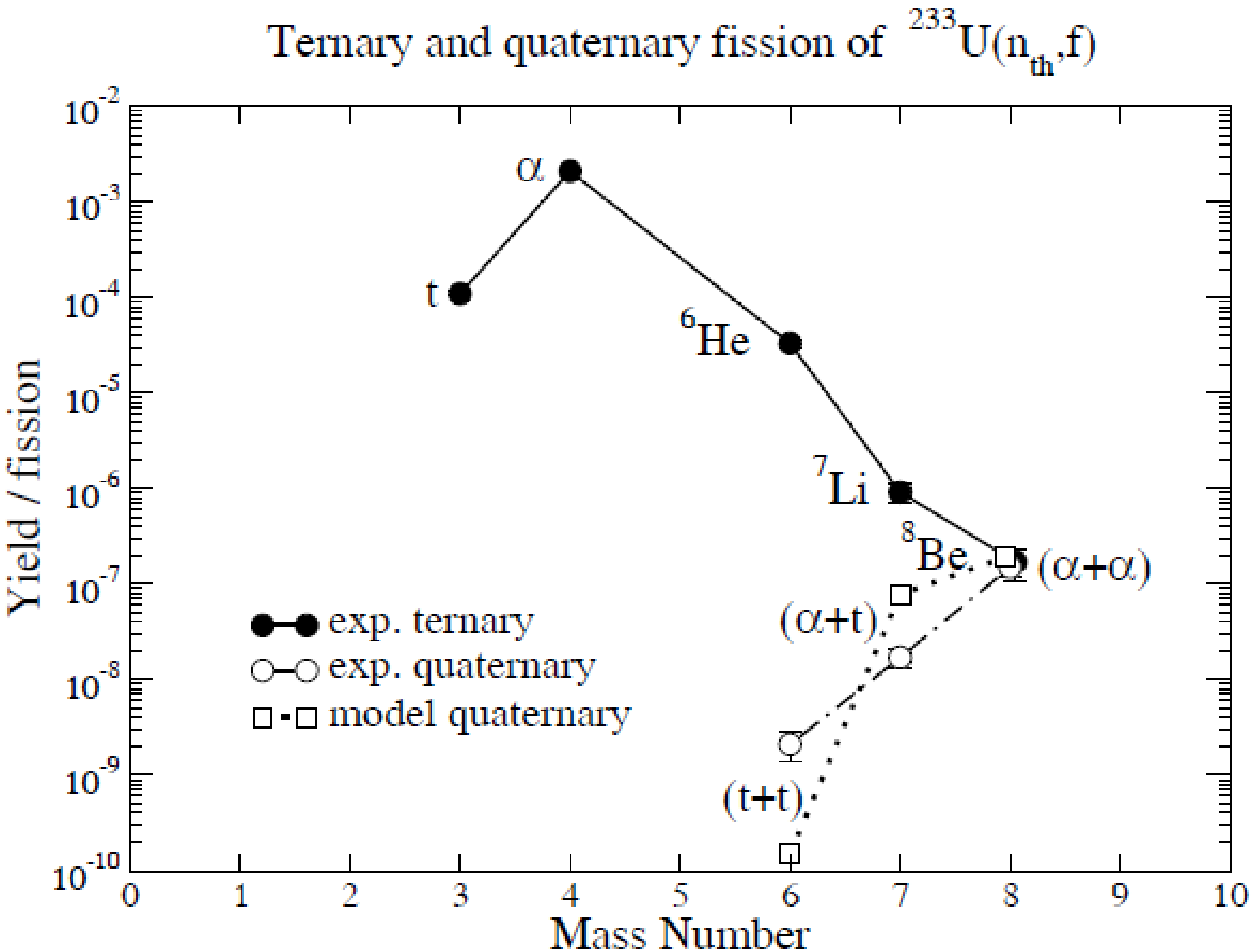
2 alpha-particles

+

2 fission fragments

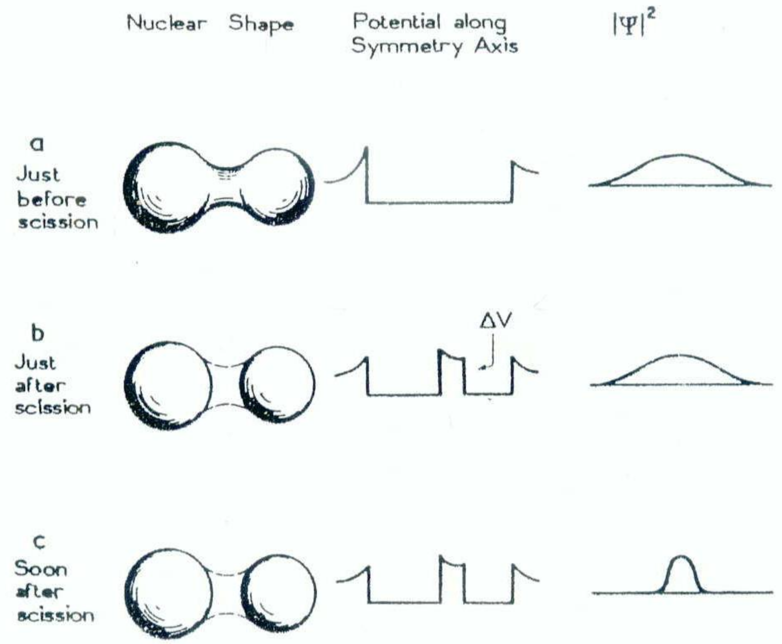


Виходи четвертинного поділу в 233U (nth,f) щодо відповідних виходів складових потрійних частинок.



Механізми потрійного поділу

Halpern's sudden approximation



How a sudden absorption of the neck between two fission fragments can lead to the release of an alpha particle between them. The sudden disappearance of the neck results in the potential change for an alpha particle (row b). If the change is fast enough, there is no change in the wave function. But subsequently the alpha-particle wave function can be reduced in regions occupied by nuclear matter due to absorption (row c). The surviving part of the wave function represents a free alpha particle in the region between fragments.

Double Random Two Independent Neck-Rupture

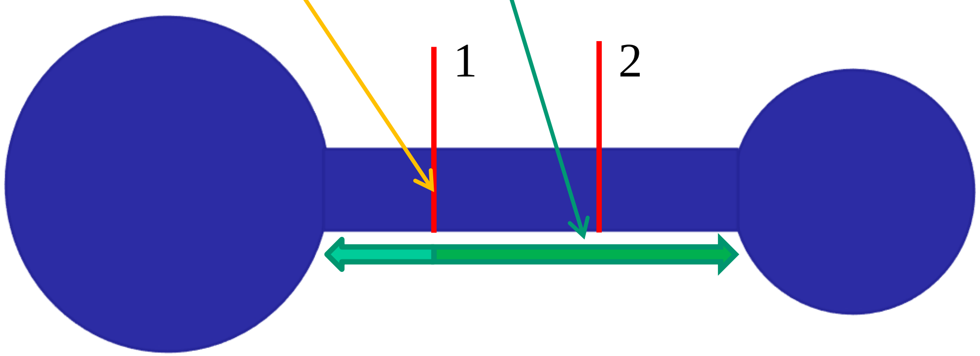
Hypothesis: during the lifetime of the neck 't_n', two independent ruptures occur with equal probabilities. These probabilities are uniformly distributed in space and time: they are the same at each point along the neck and at each moment of time during t_n.

In addition to t_n there are two other times that are important:

t_r (of the neck rupture) and

t_{abs} (of the neck absorption by the fragments)

Consequence: if the 2nd ruptures arrives in the interval [t_r , t_{abs} - t_r] after the 1st rupture the fission is ternary.



V. Rubchenya, Sov. J. Nucl. Phys. 35 (1982) 334; V. Rubchenya and S. Yavshits, Z. Phys. A329 (1988) 217

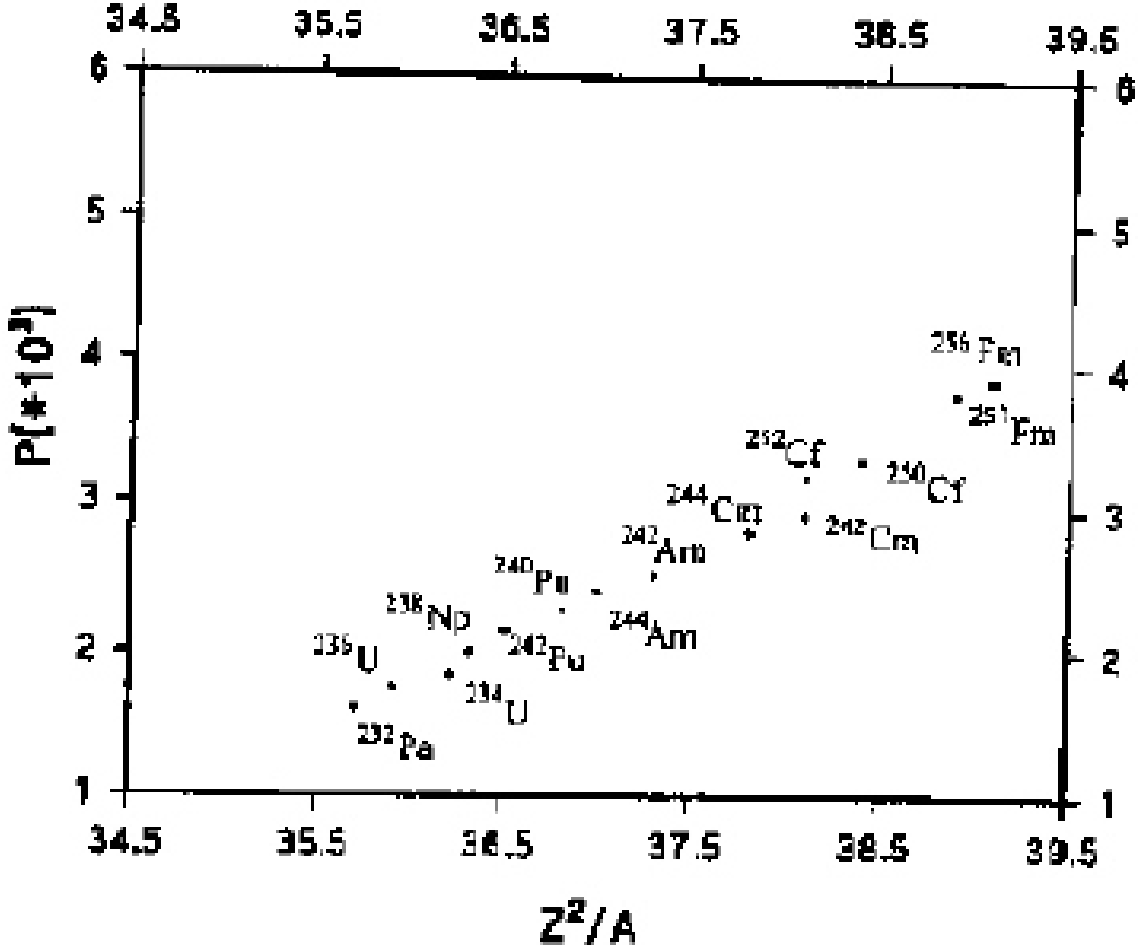


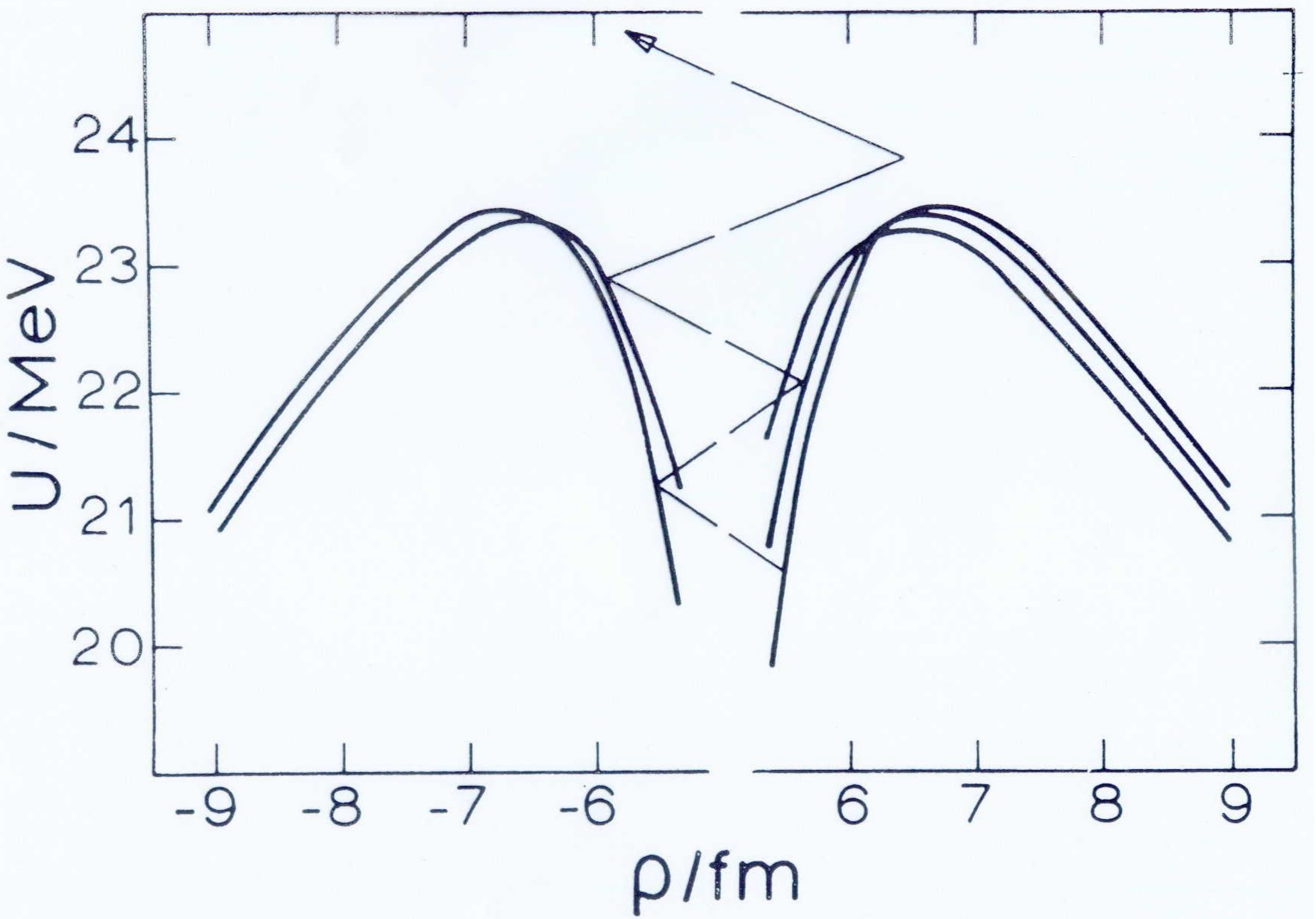
Figure 12.4. Probability $P = T/B$ for ternary fission, calculated from the double-neck-rupture theory of Rubchenya and Yavshits [13] for various fissioning systems, versus fissility Z^2/A. Values are normalized to the experimental value for $^{235}U(n_{th}, f)$.

α-decay between saddle and scission

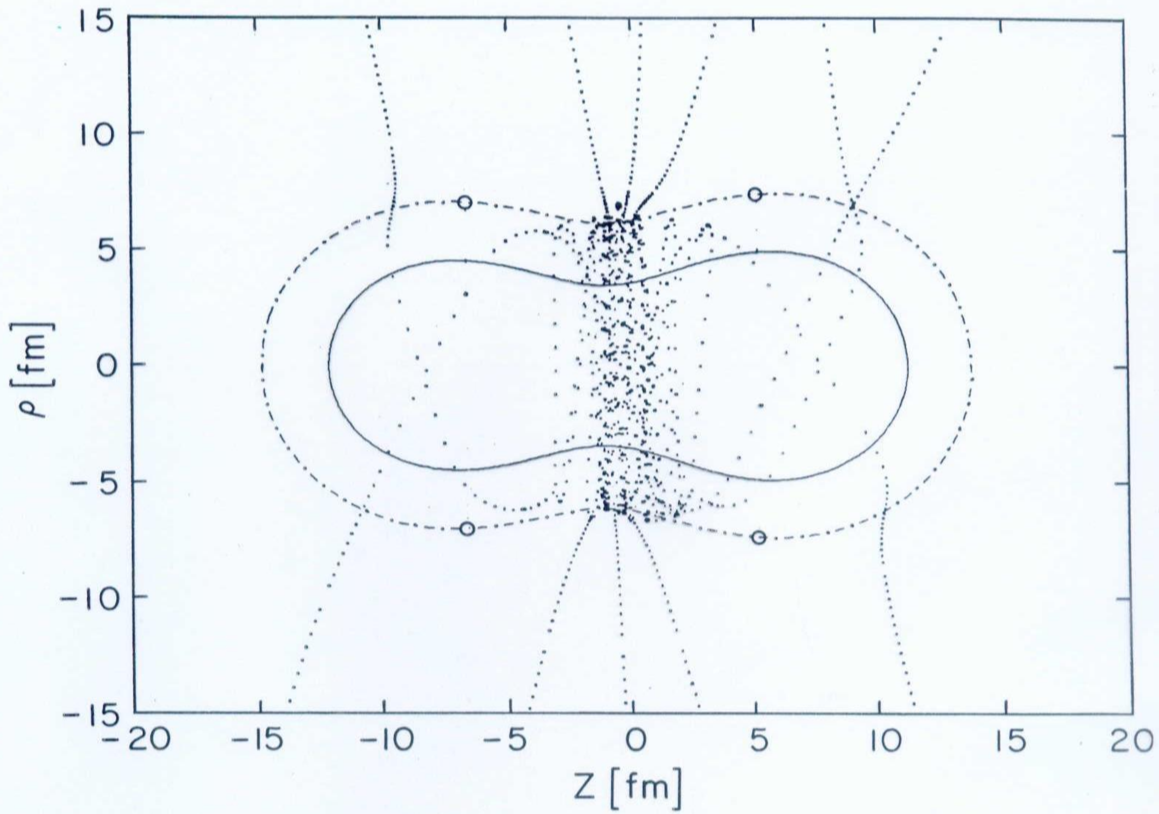
Hypothesis: all fissile nuclei are α emitters in their ground state. This property (of being an α emitter) is continuously influenced by the new shapes and the new energy balances that the nucleus goes through on its way to scission. A possible source for the scission α's would therefore be the α decay from the last stage of the fission process.

One-body mechanism: the simplest mechanism through which an α cluster in a fissioning nucleus can gain enough energy to escape is the collision with the moving wall of the α-nucleus potential.

N. Carjan:
J. Physique **37** (1976) 1279
and
Ph.D. Thesis, TH Darmstadt,
Difo-Druck, Bamberg, 1977.

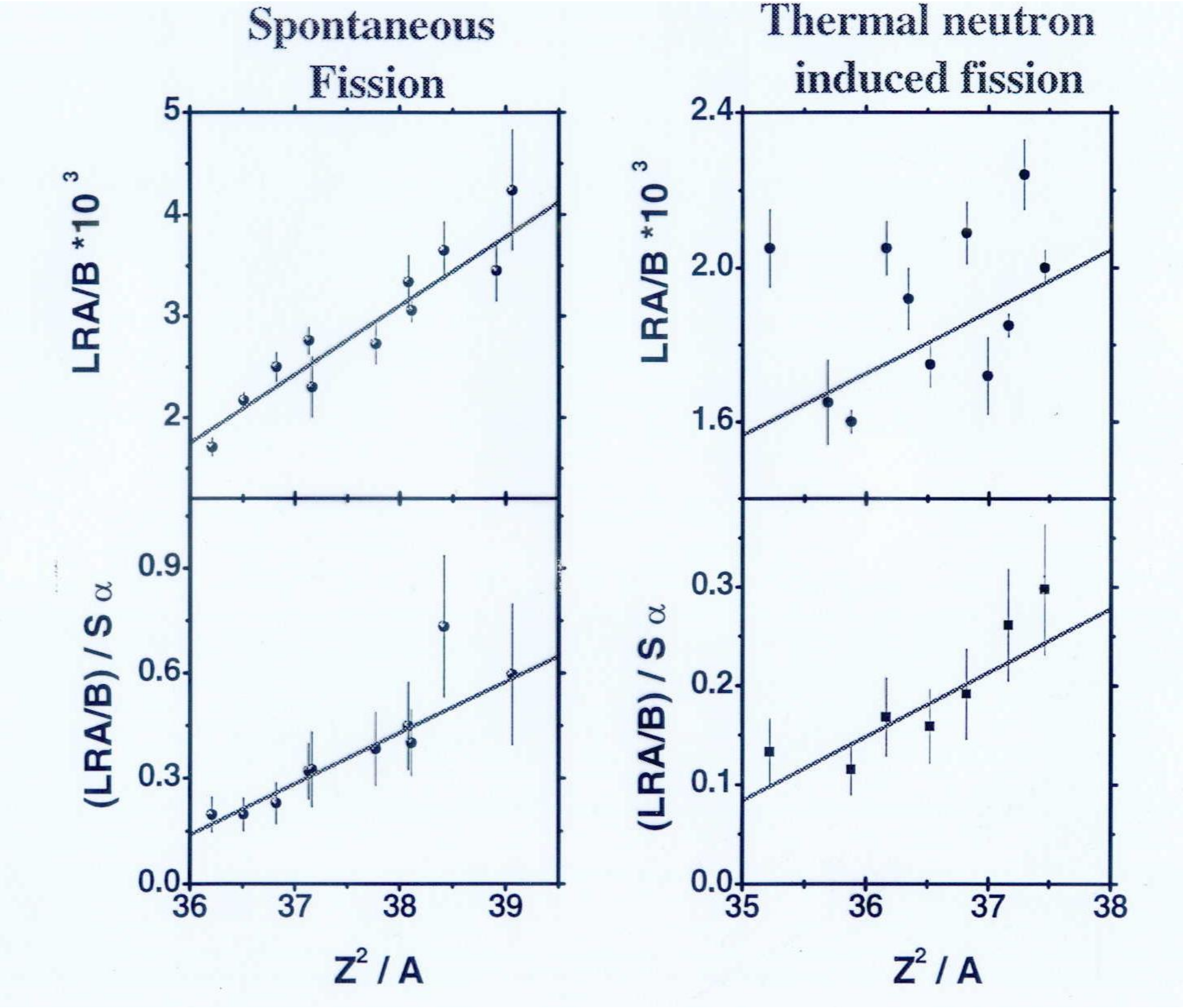


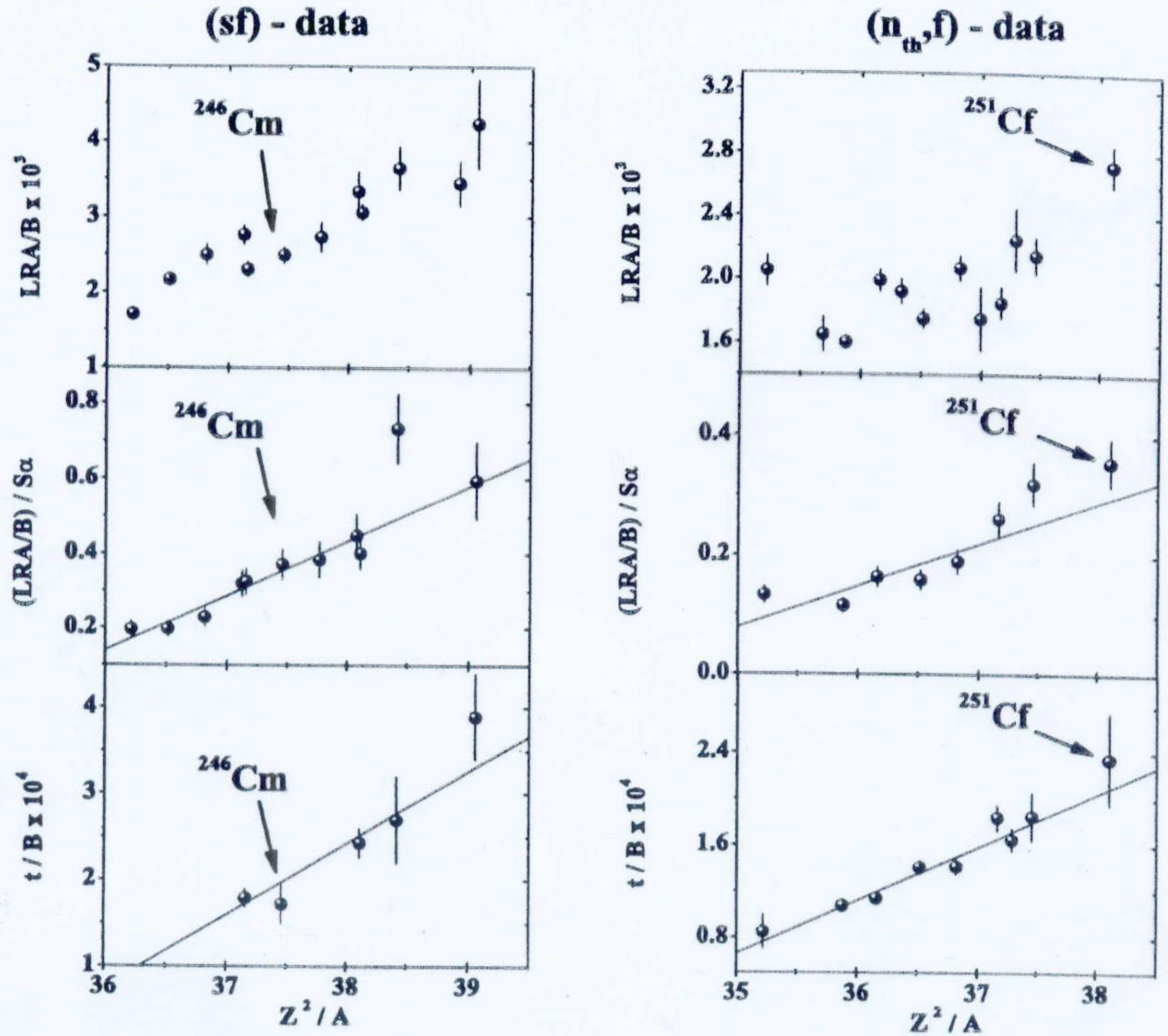
Barriers as seen by the α-particle in ^{236}U and α-energies during the last reflections



Trajectories leading to α emission. The four circles on the ridge separate the regions of ,ositive (in the center) and negative (at the extremities) interactions. The dash-dot curve represents the ridge of the α-nucleus potential at $t = 2 \times 10^{-21}$ sec (the average emission time).

Important role of the spectroscopic factor (alpha clustering)

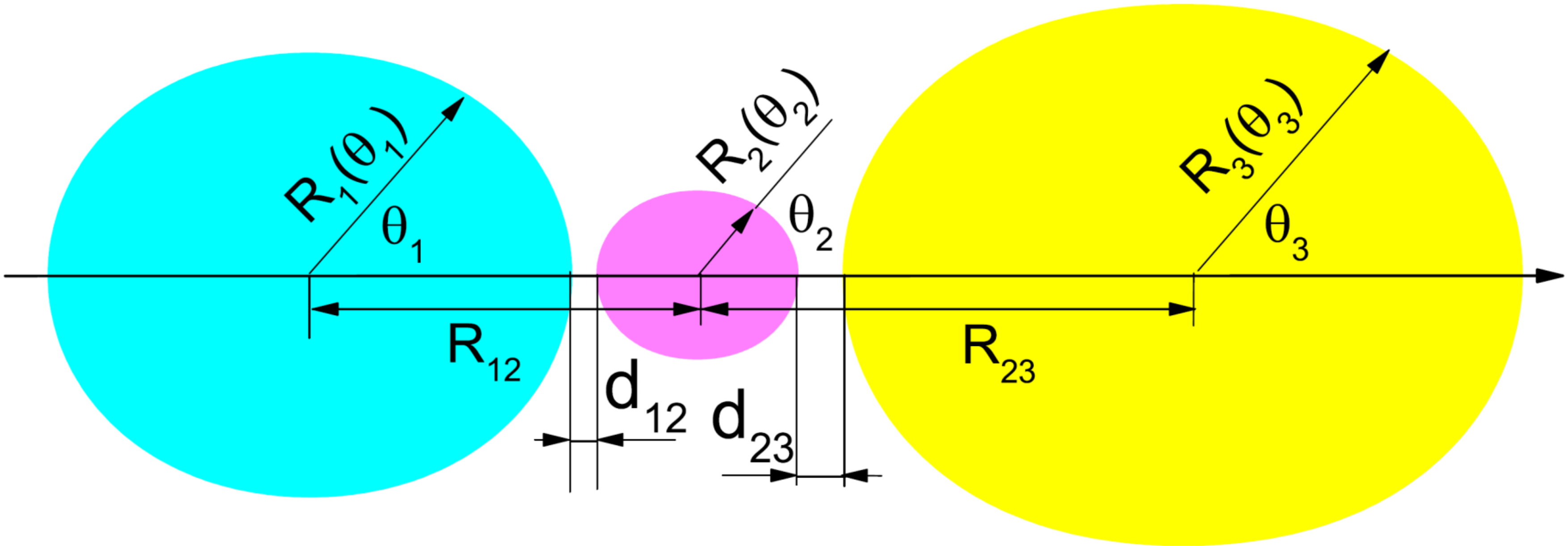




O. Serot, C. Wagemans et al., in 'Seminar on Fission', Pont d'Oye V (2003)

Figure 5. Ternary alpha (top) and triton (bottom) emission probabilities from (sf)-data (left) and (n_{th},f)-data (right) as a function of the fissility parameter of the fissioning nucleus. The LRA/B data corrected for the α-cluster preformation probability are plotted in the middle. Data obtained from the present work are indicated.

Orientation and position of deformed fragments



The collinear orientation of axial-symmetric deformed fragments.

The total interaction potential energy of these fission fragments is

$$\begin{aligned} V(R_{12}, R_{23}, \beta_1, \beta_2, \beta_3) = V_{13}^{\mathrm{C}}(R_{13}, \beta_1, \beta_3) \\ +V_{12}^{\mathrm{n}}(R_{12}, \beta_1, \beta_2) + V_{12}^{\mathrm{C}}(R_{12}, \beta_1, \beta_2) \\ +V_{23}^{\mathrm{n}}(R_{23}, \beta_2, \beta_3) + V_{23}^{\mathrm{C}}(R_{23}, \beta_2, \beta_3) \\ +E_1^{\mathrm{def}}(\beta_1) + E_2^{\mathrm{def}}(\beta_2) + E_3^{\mathrm{def}}(\beta_3). \end{aligned} \tag{1}$$

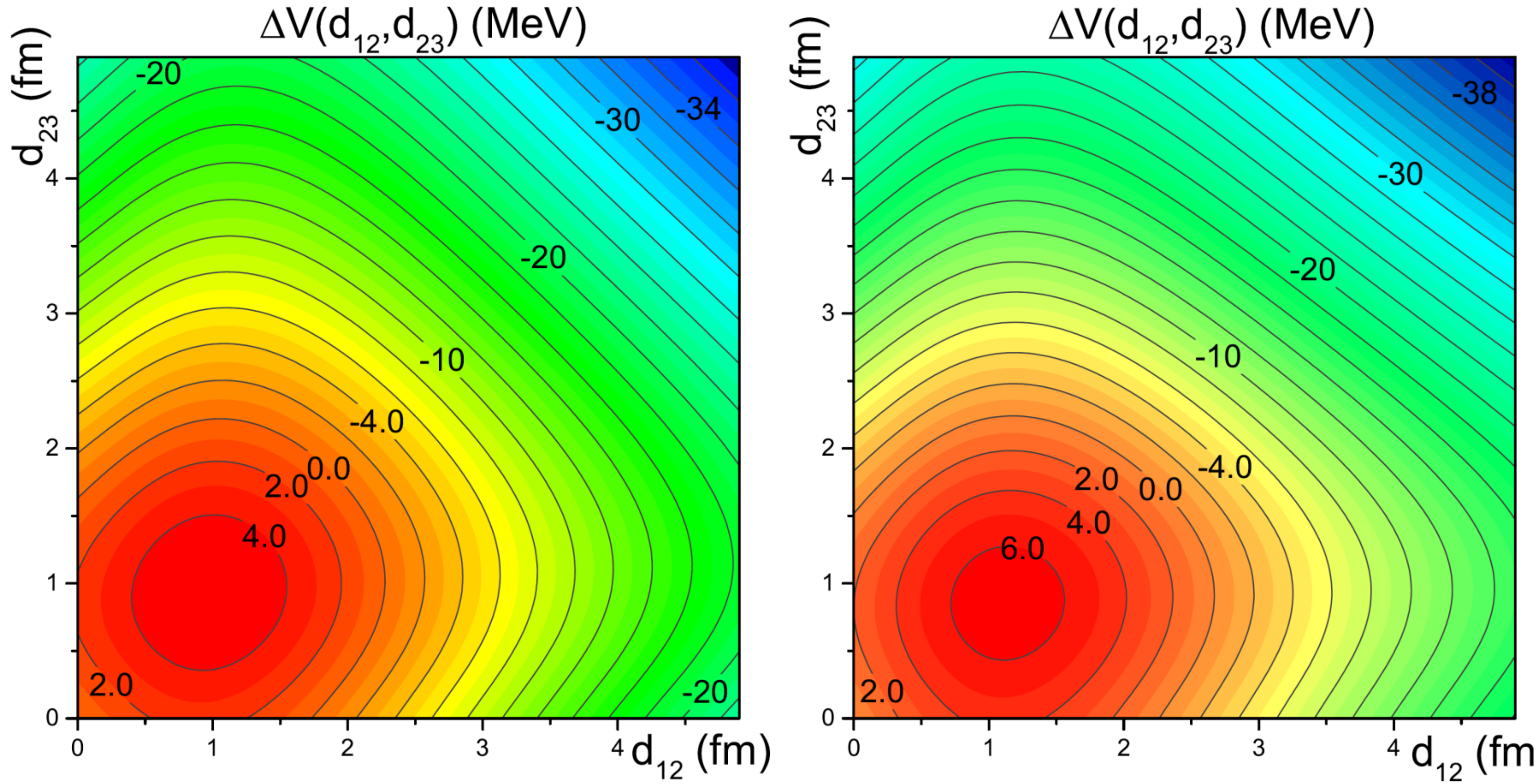
Here $V_{ij}^{\mathrm{n}}(R_{ij}, \beta_i, \beta_j)$ and $V_{ij}^{\mathrm{C}}(R_{ij}, \beta_i, \beta_j)$ are, respectively, the nuclear and Coulomb interactions between fragments i and j, $E_i^{\mathrm{def}}(\beta_i)$ is the deformation energy of fragment i, β_i is the surface quadrupole deformation parameter of fragment i. The deformation parameter β_i relates to the surface radius of deformed nucleus $R_i(\theta_i) = R_{0i}\left[1 + \beta_i Y_{20}(\theta_i)\right]$.

$$E^*_{A_1,Z_1,A_2,Z_2} = \varepsilon^* + Q - B_{A_1,Z_1,A_2,Z_2} \tag{2}$$

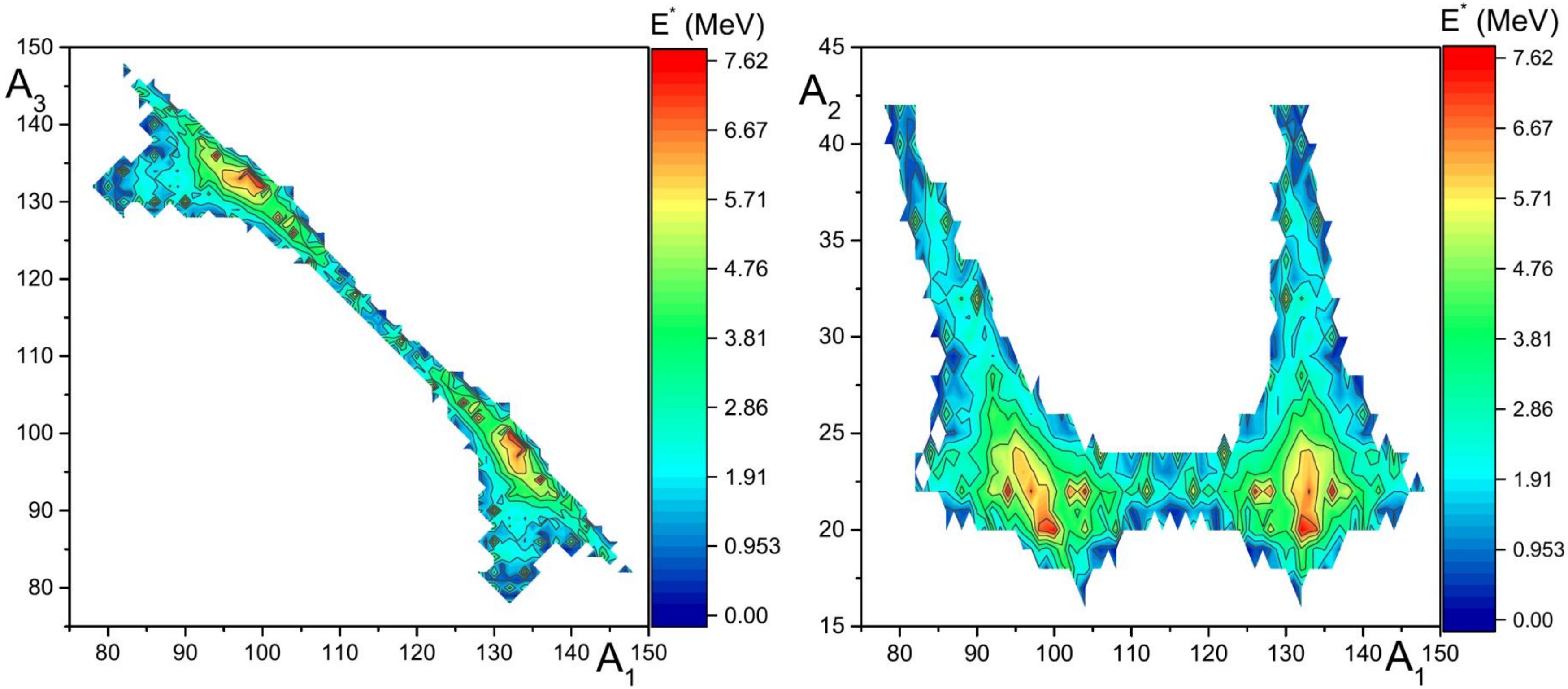
is the total excitation energy of fragments at the lowest barrier point. The yield is proportional to

$$YIELD \propto rho_{A_1,Z_1}(\frac{A_1}{A}E^*_{A_1,Z_1,A_2,Z_2}) \cdot rho_{A_2,Z_2}(\frac{A_2}{A}E^*_{A_1,Z_1,A_2,Z_2}) \cdot rho_{A_3,Z_3}(\frac{A_3}{A}E^*_{A_1,Z_1,A_2,Z_2}). \tag{3}$$

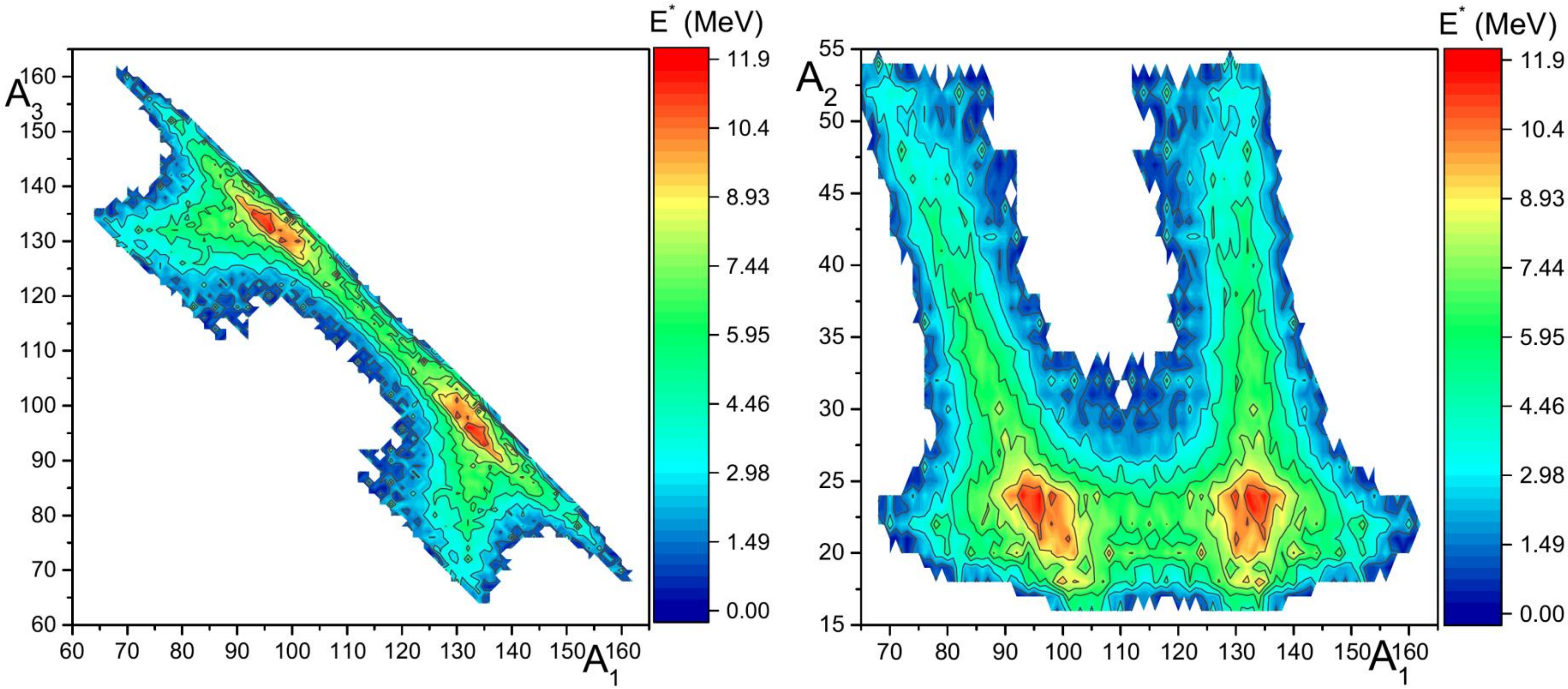
$$\Delta V(d_{12}, d_{23}) = V(R_{12}^t + d_{12}, R_{23}^t + d_{23}, \beta_1^l, \beta_2^l, \beta_3^l) - V(R_{12}^t, R_{23}^t, \beta_1^l, \beta_2^l, \beta_3^l). \tag{4}$$



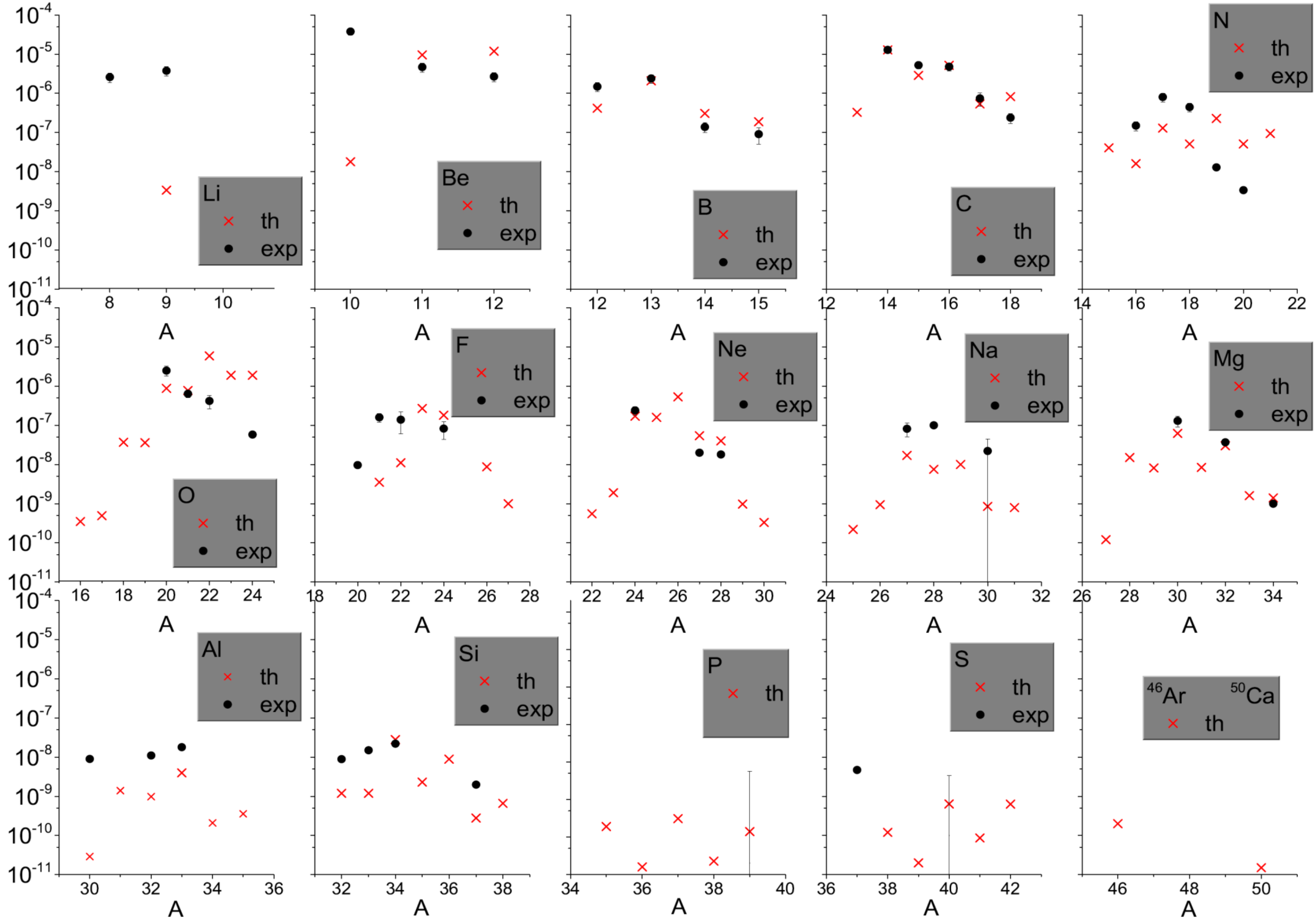
The differences of the potentials $\Delta V(d_{12}^t, d_{23}^t)$ at the values of deformation parameters at the lowest barrier point for the fission of ^{252}Cf into fragments ^{98}Zr+^{22}O+^{132}Sn (left) and ^{72}Ni+^{48}Ca+^{132}Sn (right).



The dependence of the total excitation energy of fragments E^* for the triple spontaneous fission of ^{252}Cf on masses the fragments.



The dependence of the total excitation energy of fragments E^* for the triple fission of ^{252}Cf at excitation energy $\varepsilon^* = 10$ MeV on masses of the fragments.



Yield (probability per binary fission event) of ternary particles from ^{250}Cf.

Thanks for attention!!!