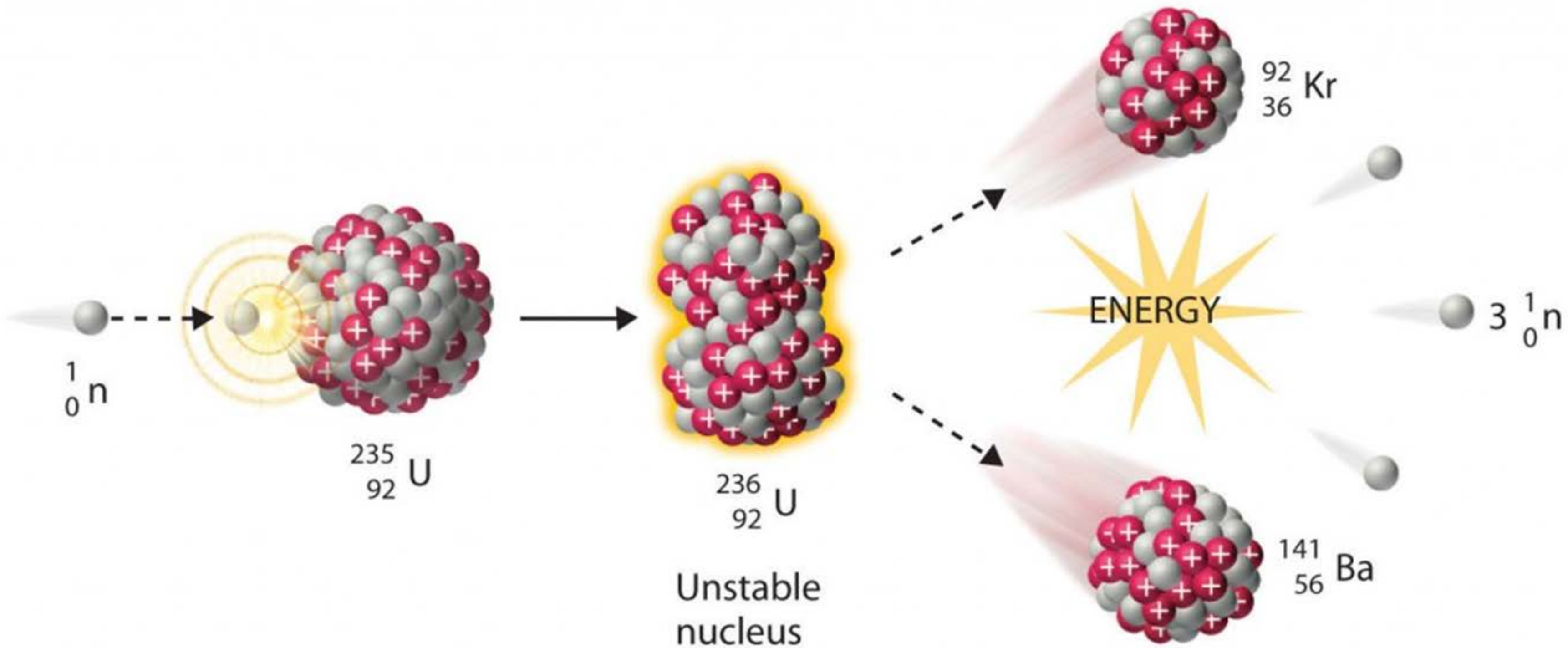
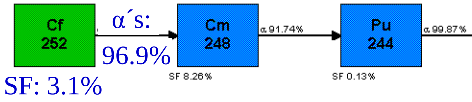
Nuclear Fission

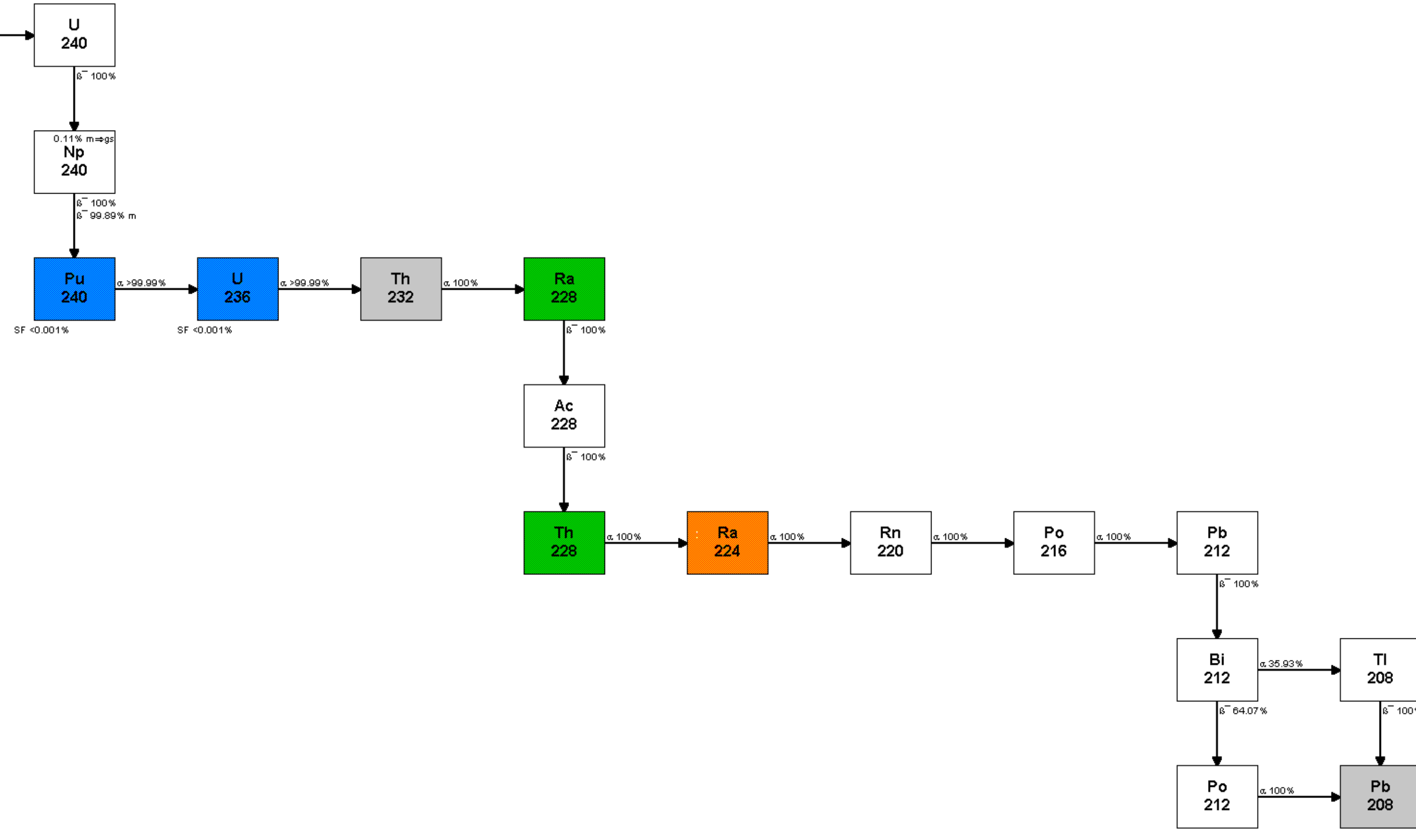
Hans-Jürgen Wollersheim



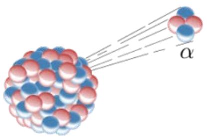
Lise Meitner, Otto Hahn

Details of the ^{252}Cf decay



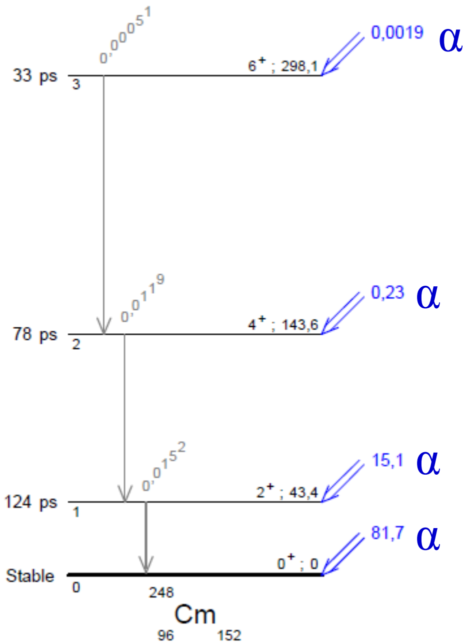


$T_{1/2}$ = 2.647 a



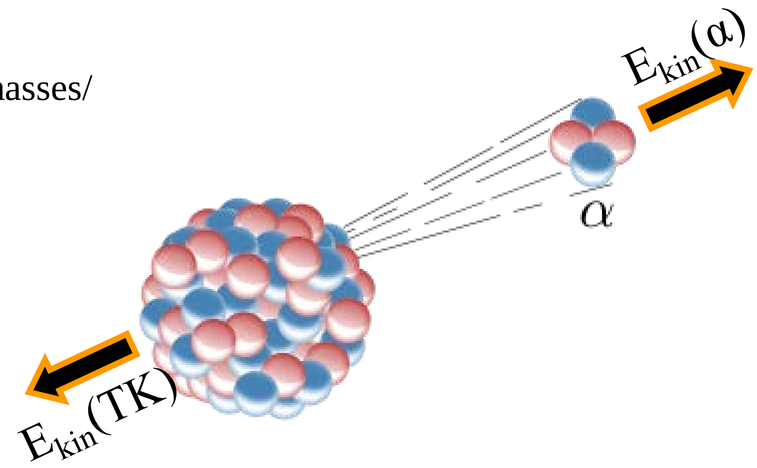
Q_α = 6.217 MeV

E_α = 6.118 MeV



α-decay of ^{252}Cf

Mass data: nucleardata.nuclear.lu.se/database/masses/



BE(^{252}Cf) = 1881.275 MeV
BE(^{248}Cm) = 1859.196 MeV
BE(^{4}He) = 28.296 MeV

$Q_\alpha = 6.217$ MeV

$$^{252}_{98}Cf_{154} \rightarrow {}^{248}_{96}Cm_{152} + \alpha$$

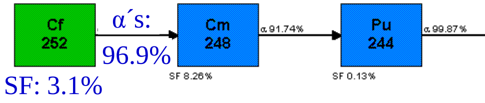
momentum conservation: $m_k \cdot v_k = m_\alpha \cdot v_\alpha \quad \rightarrow \quad v_k = \frac{m_\alpha}{m_k} \cdot v_\alpha$

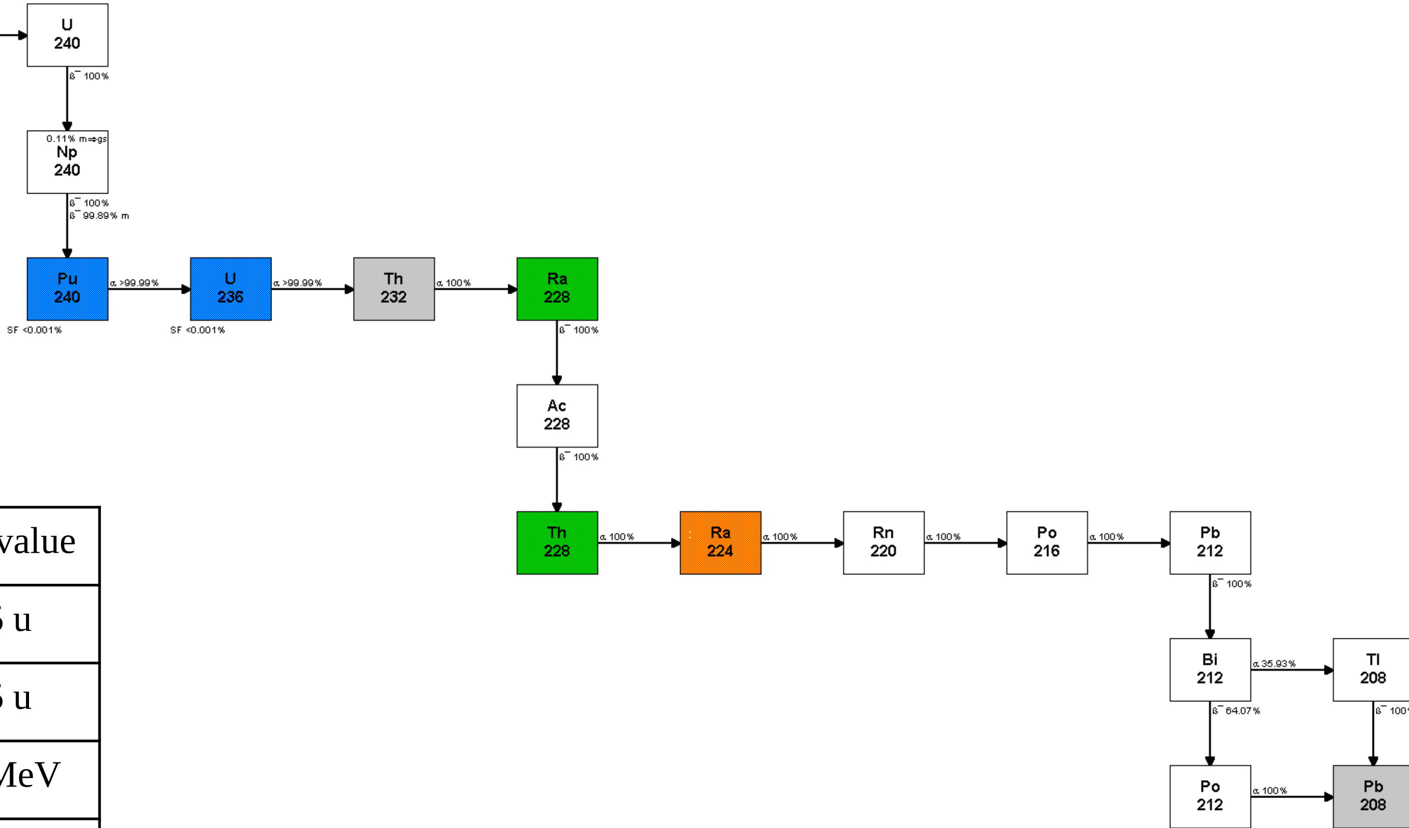
energy conservation:

$$\begin{aligned} Q_\alpha &= E_{kin}^{k} + E_{kin}^{\alpha} \\ &= \frac{m_k}{2} \cdot v_k^2 + E_{kin}^{\alpha} \\ &= \frac{m_k}{2} \cdot \frac{m_\alpha^2}{m_k^2} \cdot v_\alpha^2 + E_{kin}^{\alpha} \\ &= \frac{m_\alpha}{m_k} \cdot E_{kin}^{\alpha} + E_{kin}^{\alpha} \\ &= \frac{m_\alpha + m_k}{m_k} \cdot E_{kin}^{\alpha} \end{aligned}$$

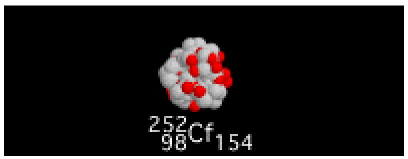
$$\rightarrow E_{kin}^{\alpha} = Q_\alpha \cdot \frac{m_k}{m_k + m_\alpha} = 6.217 MeV \cdot \frac{248}{252} = 6.118 MeV$$

Binary spontaneous fission of ^{252}Cf



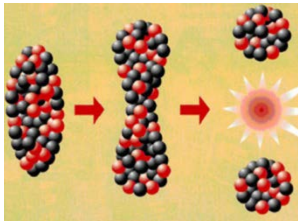


$T_{1/2} = 2.647$ a



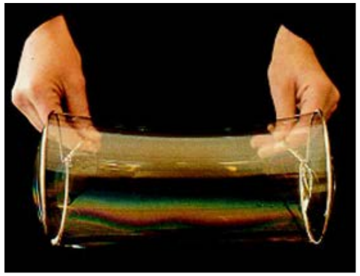
parameter	experimental value
$< A_L >$	108.9 ± 0.5 u
$<A_H >$	143.1 ± 0,5 u
$< E_L >$	103.5 ± 0.5 MeV
$< E_H >$	78.3 ± 0.5 MeV
< TKE >	181.8 ± 0.7 MeV
$< A/Z >_L$	2.50
$< A/Z >_H$	2.56

$$V_C(R_{int}) = \frac{1.44 \cdot 43 \cdot 55}{14} = 244\ MeV$$



$$TKE = 0.1071 \cdot Z_C^2/A_C^{1/3} + 22.3 = 185\ MeV$$

Ternary spontaneous fission of ^{252}Cf

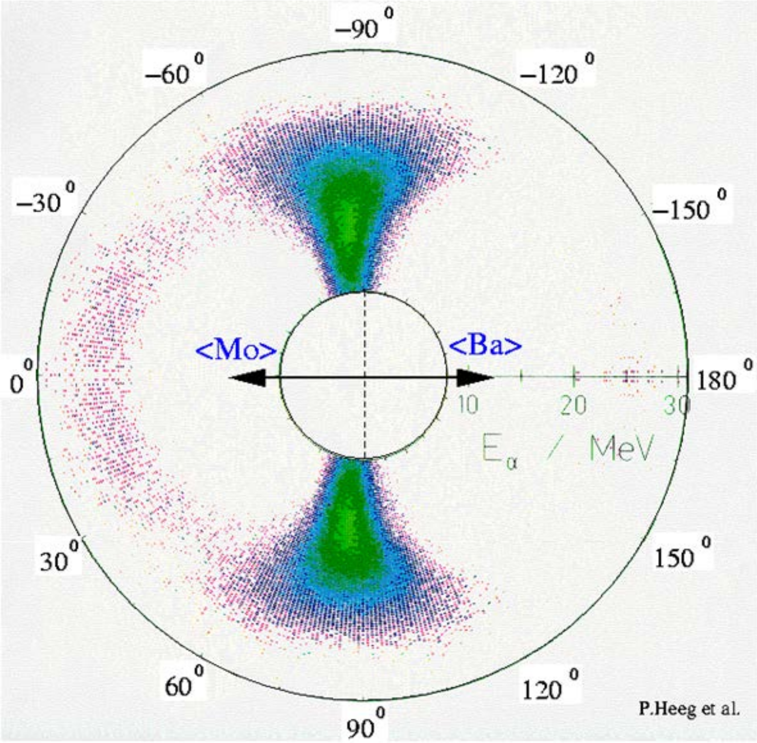




^{252}Cf source

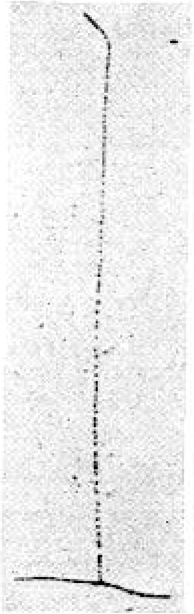
$T_{1/2} = 2.645$ y

bin. fission/α-decay = 1/31

ter. fission/α-decay = 1/8308



ternary LPCs yields	
^{3}H	950 ± 90
^{4}He+^{5}He	10^4
^{6}He+^{7}He	270 ± 30
^{8}He	25 ± 5
Li	60 ± 10
Be	175 ± 30
B	13.5 ± 4
C	80 ± 30



photographic emulsion

Tsien San-Tsiang, Phys. Rev. 71 (1947), 128

Quaternary spontaneous fission of ^{252}Cf

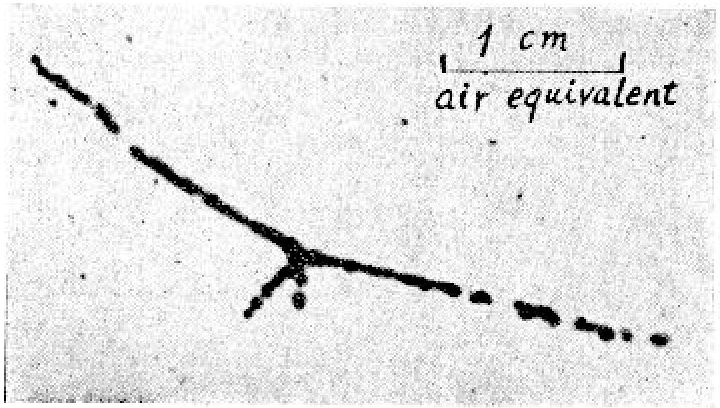


FIG. 4. Quaternary fission.

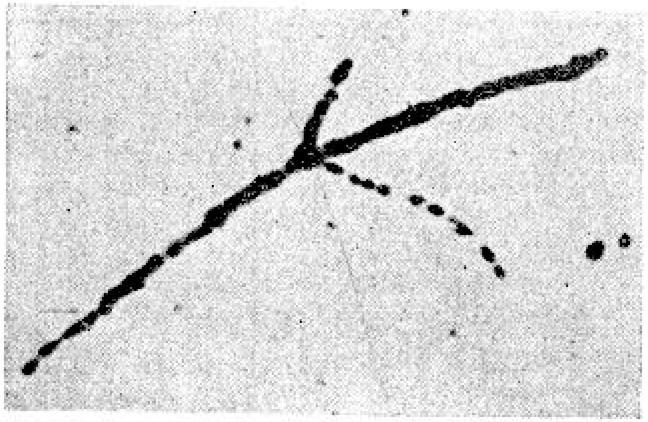
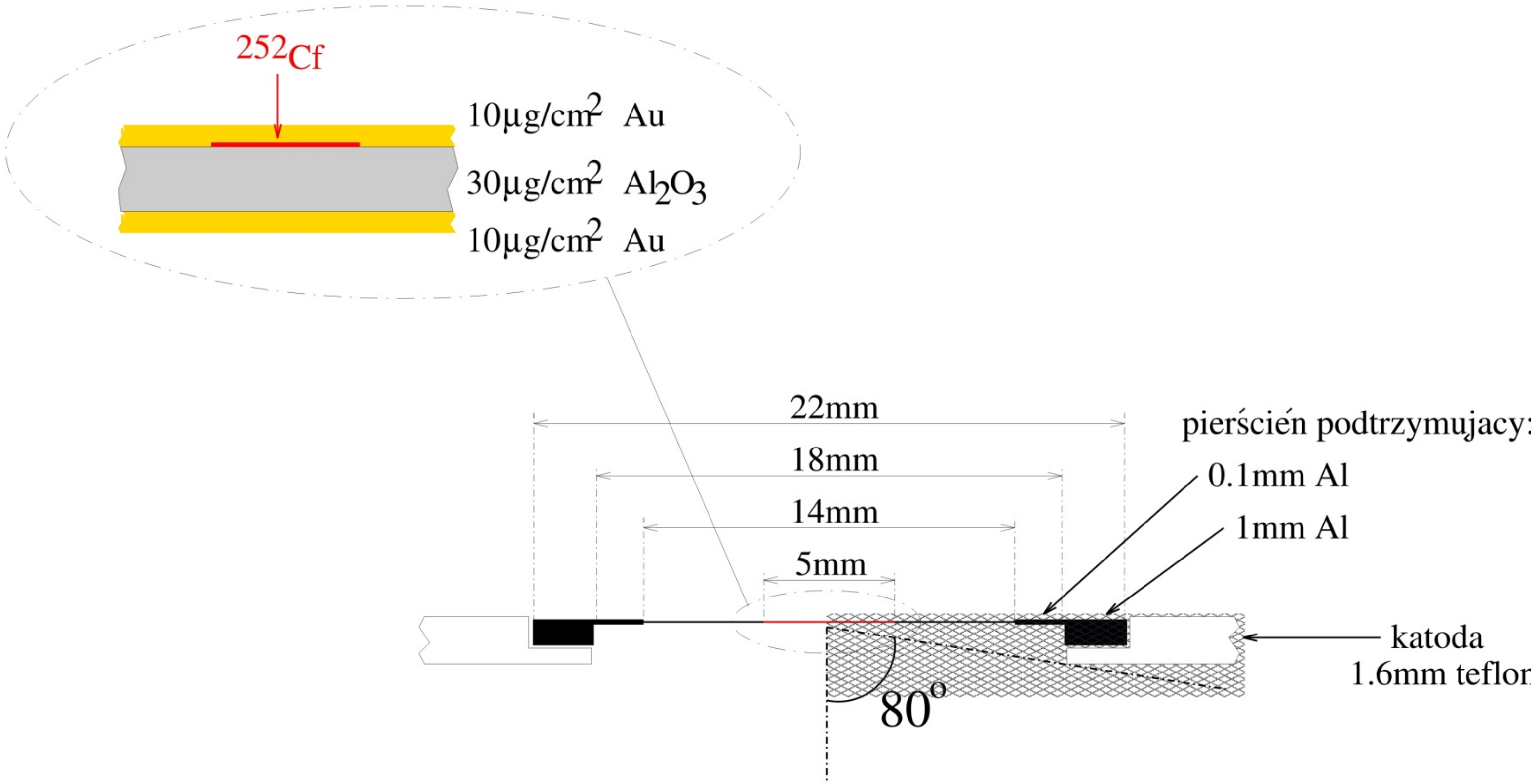


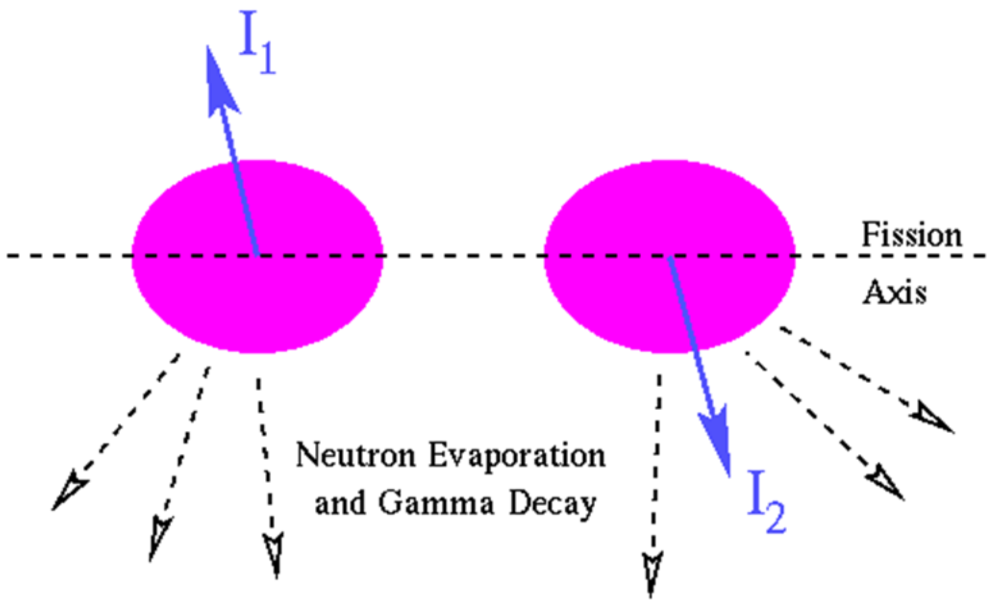
FIG. 5. Quaternary fission. (In same scale as Fig. 4.)

Tsien San-Tsiang, Phys. Rev. 71 (1947), 128

Details of the ^{252}Cf source



Spontaneous fission of ^{252}Cf



^{252}Cf spin J = 0
fragment spin J = < 7-8 >

$\langle N_\gamma \rangle = 9.35$

The origin of fragment spins and their alignment:

Collective vibrational modes like bending or wriggling at the saddle-to-scission stage and subsequent Coulomb excitation.

Experimental method:

fragment – γ-ray angular correlation measurement

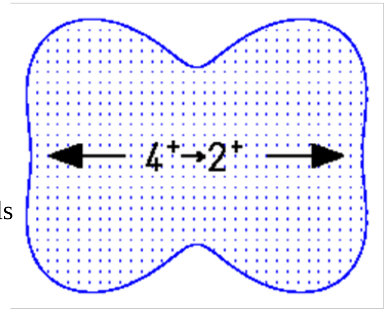
K. Skarsvag Phys.Rev. C22 (1980) 638

γ-ray emission from aligned nuclei

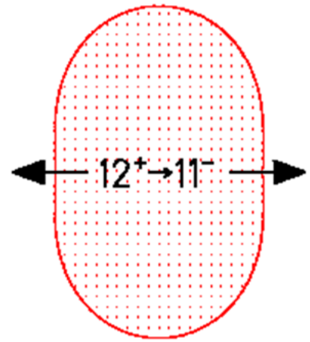
$$\frac{dW}{d\Omega_{rest}} = \sum_{Q=0,2,4} \frac{\sqrt{2Q+1}}{4\pi} \cdot \tau_{Q0}(J_i) \cdot F_Q(J_f, L, L, J_i) \cdot P_Q(cos\theta_{\gamma p})$$

Legendre polynomials

γ-γ correlation coefficients



E2



E1

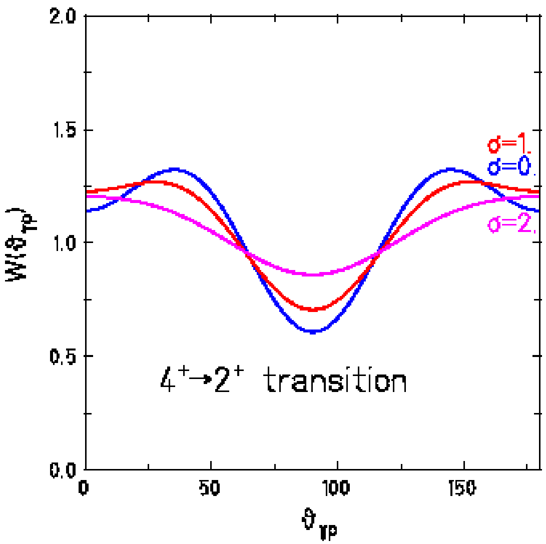
example:

$$\tau_{20}(J) = \left(\frac{J(J+1)}{(2J-1)\cdot(2J+3)}\right)^{1/2} \cdot \left(3\frac{\langle K^2\rangle}{J(J+1)} - 1\right)$$

$$\tau_{40}(J) = \left[\frac{J^3(J+1)^3}{(2J-3)(2J-2)(2J-1)(2J+3)(2J+4)(2J+5)}\right]^{1/2} \cdot \left[35\frac{\langle K^4\rangle}{J^2(J+1)^2} - 30\frac{\langle K^2\rangle}{J(J+1)}\left(1 - \frac{5}{6J(J+1)}\right) + 3\left(1 - \frac{2}{J(J+1)}\right)\right]$$

$$\langle K^n\rangle = \sum_K K^n \gamma_K \quad with \quad \gamma_K = exp\left(-\frac{K^2}{2\sigma^2}\right) \Big/ \sum_{K'} exp\left(-\frac{K'^2}{2\sigma^2}\right)$$

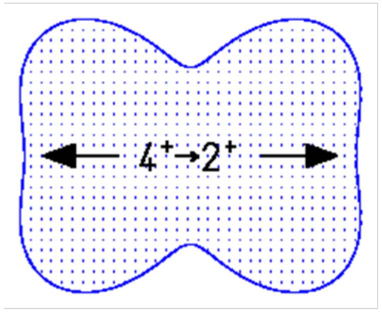
Gaussian distribution



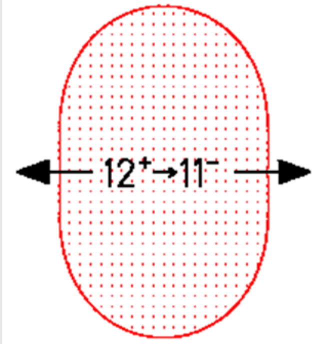
A.L.Barabanov IAE-5670/2 (93) S.R. de Groot & H.A. Tolhoek, Beta and gamma-ray spectroscopy, ed. K. Siegbahn, p 613 (1955)

γ-ray emission from aligned nuclei

$$W(\theta) = \sum_{Q=0,2,4} \frac{\sqrt{2Q+1}}{4\pi} \cdot \tau_{Q0}(J_i) \cdot F_Q(J_f, L, L, J_i) \cdot P_Q(cos\theta)$$



E2



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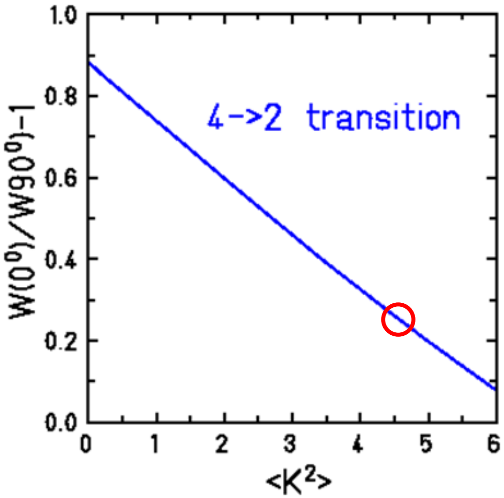
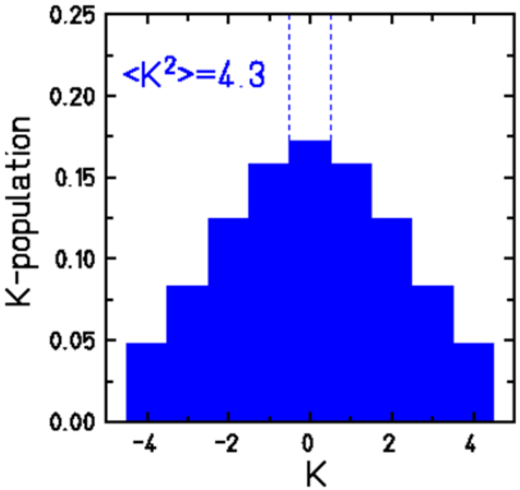
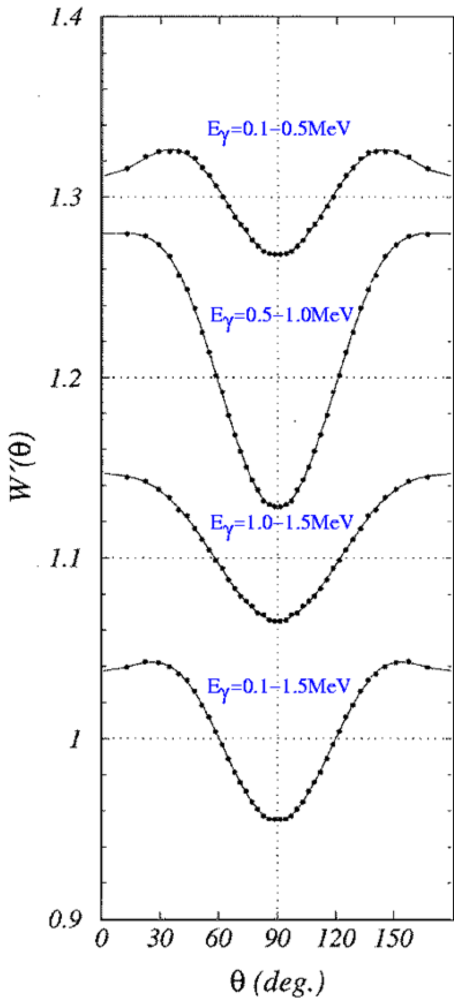
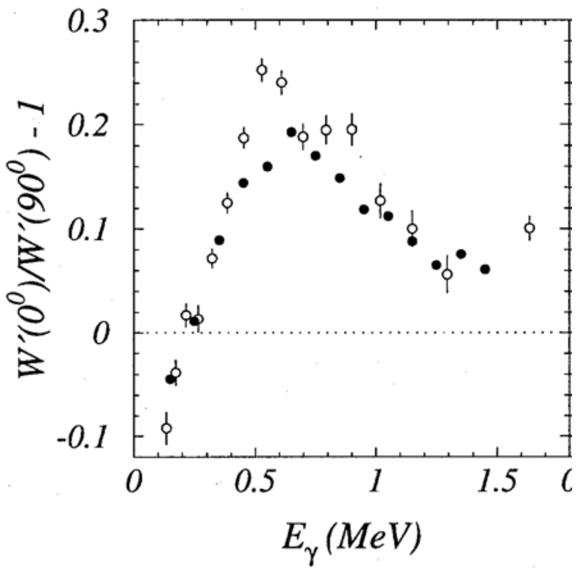


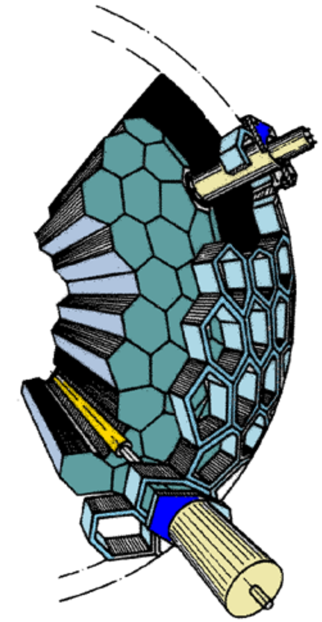
K-distribution at saddle point



Anisotropy of γ-ray in binary fission of ^{252}Cf







Darmstadt Heidelberg
Crystal Ball

ΔE_γ = 90 keV

fragment – γ-ray angular
correlation measurement

(no discrimination between different multipole transitions)

Yu.N.Kopatch et al. PRL 82(99),303 K.Skarsvag, PR C22(80),638

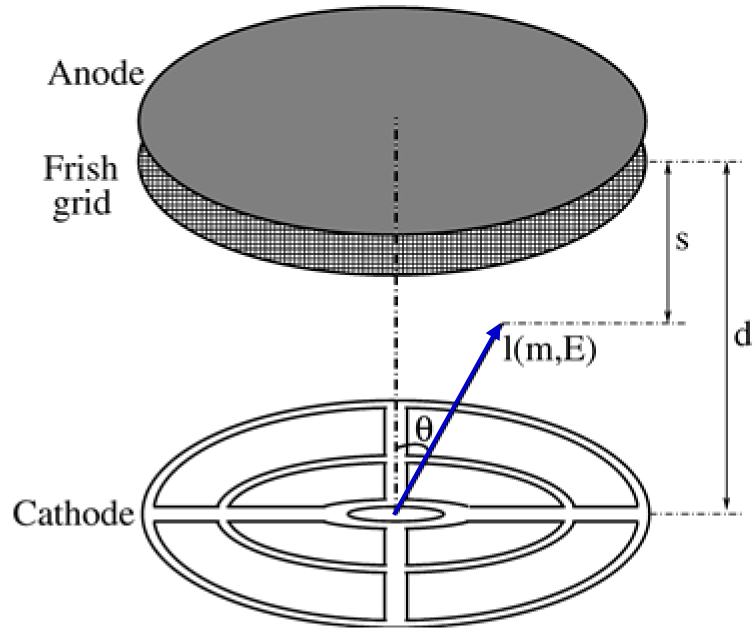
4π twin ionization chamber for fission fragments

measured quantities:

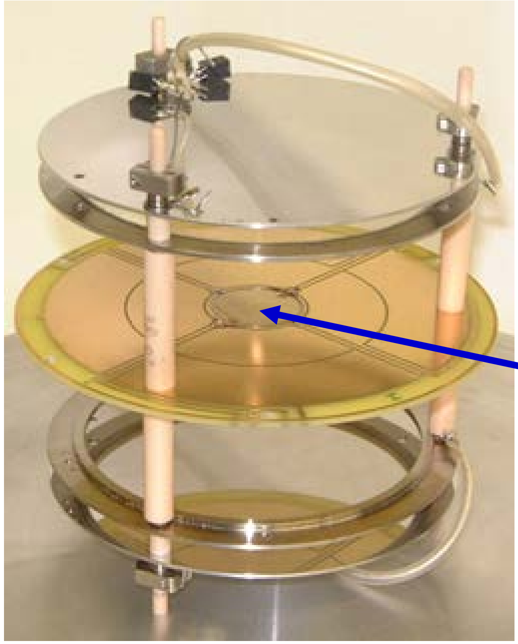
E_H, E_L → A_H, A_L

e^- drift-time → ϑ

segmented cathode → φ



methane at 570 torr
cathode diameter 15cm



^{252}Cf source (25k f/s)

$T_{1/2}$ = 2.645 y
E_α = 6.118 and 6.076 MeV
bin. fission/α-decay = 1/31
ter. fission/α-decay = 1/8308

4π twin ionization chamber for fission fragments

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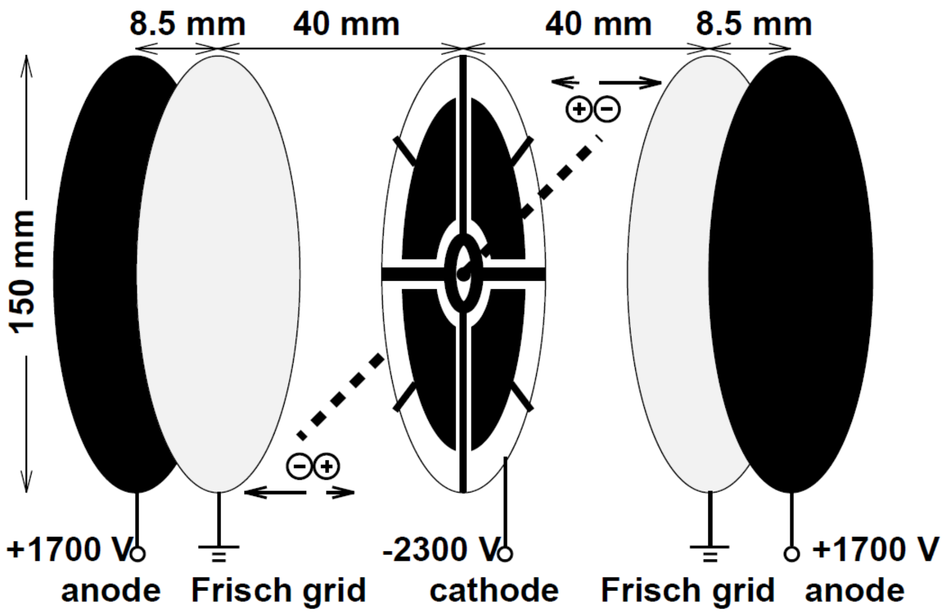

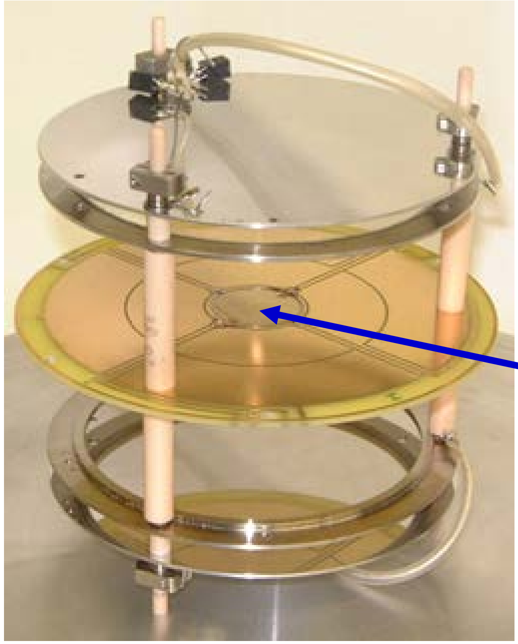

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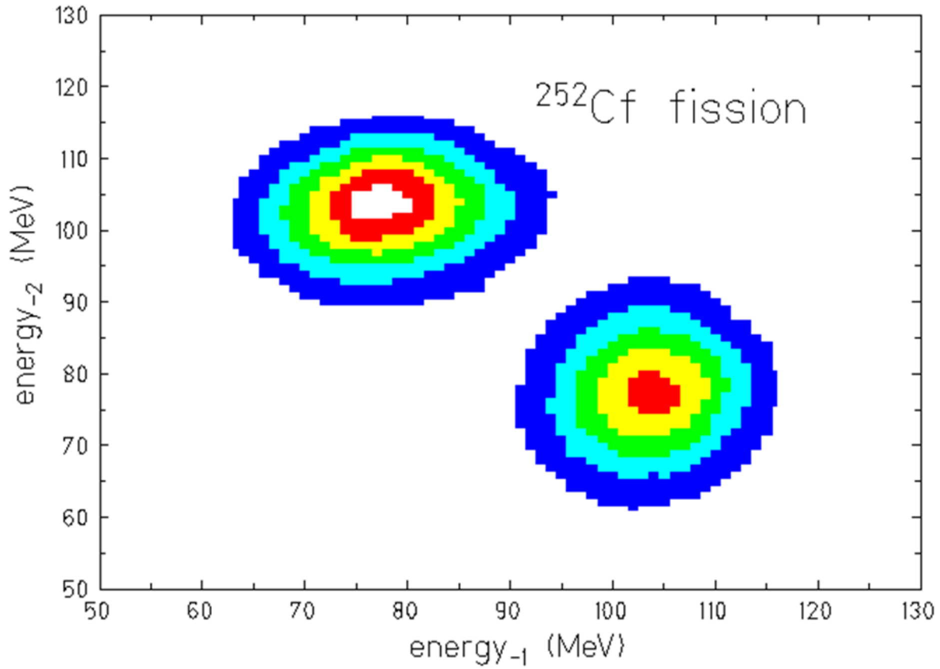
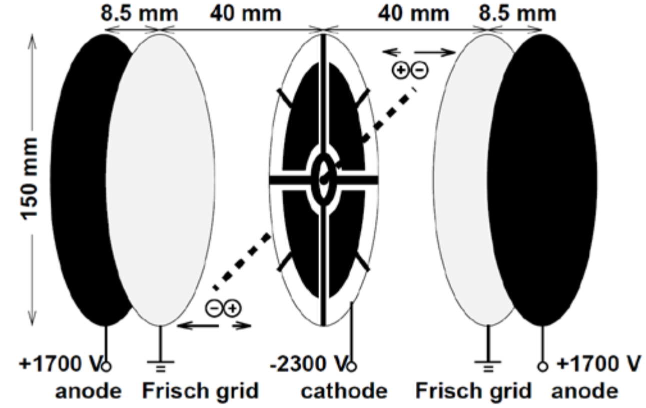
M.Mutterer et al. Sanibel (97)

Fission fragment mass measurement





The kinetic energies of the fragments are converted into ionization energy, and the fragments stop before reaching the Frisch grids.

$$m_1 v_1 + m_2 v_2 = 0 \quad \rightarrow \quad m_1 E_1 = m_2 E_2$$

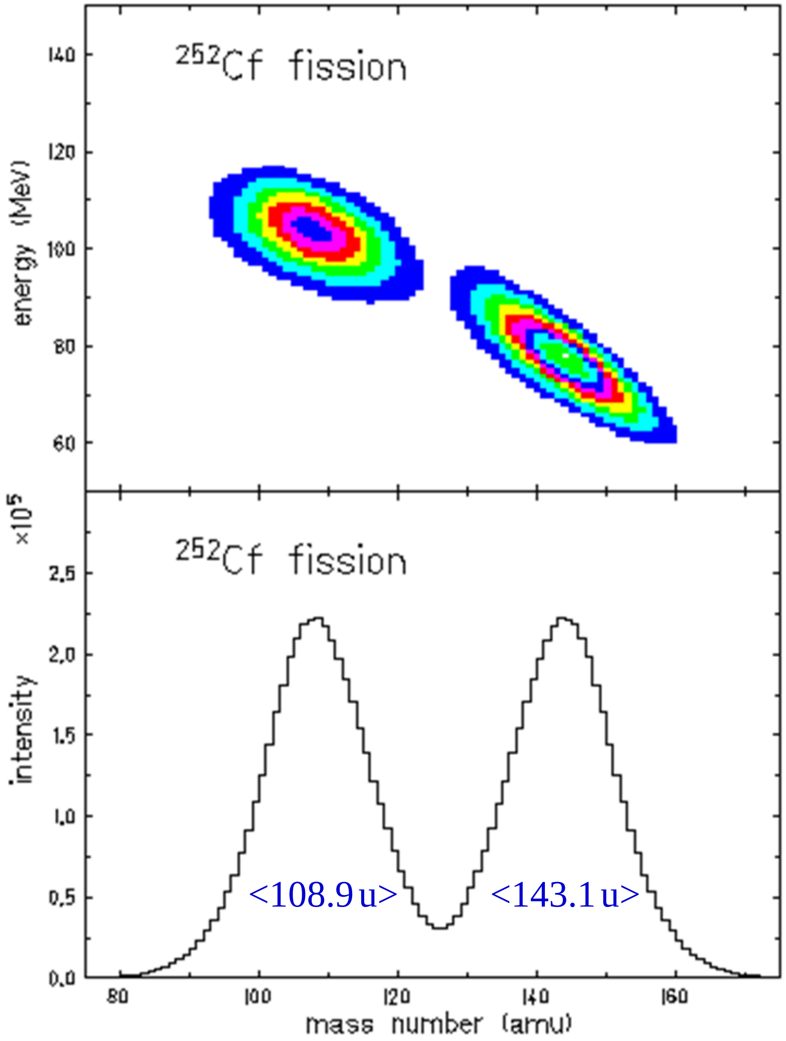
$$m_1 = (m_1 + m_2)\frac{E_2}{E_1 + E_2}$$

$$\langle E_L \rangle = 103.5 \pm 0.5\ MeV \quad \rightarrow \quad \langle A_L \rangle = 108.9 \pm 0.5$$

$$\langle E_H \rangle = 78.3 \pm 0.5\ MeV \quad \rightarrow \quad \langle A_H \rangle = 143.1 \pm 0.5$$

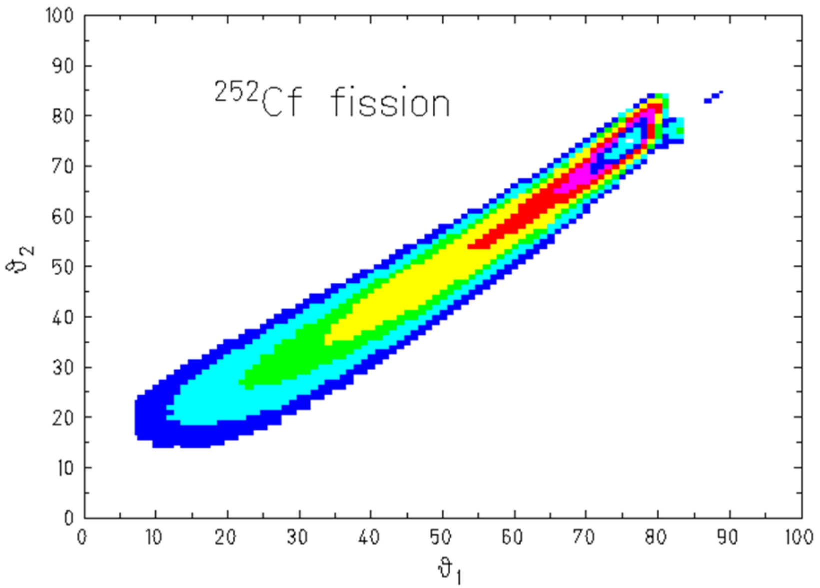
$m_1 + m_2 = 252$

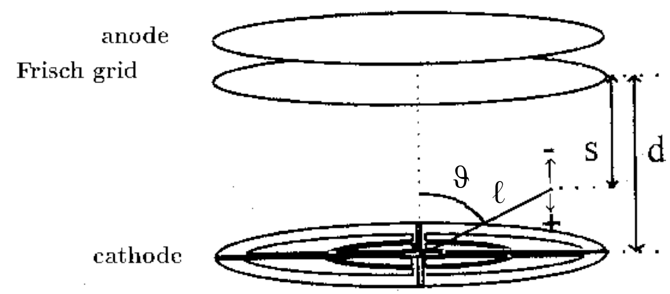
Fission fragment mass measurement



mass resolution σ = 3 u

Determination of the polar angles





The anode time signals are caused by the first electrons which pass the Frisch grids and are thus linear dependent on bot the lengths of the fragment tracks and the cosine of the polar angle θ.

$$drift - time: \quad T = {}^{s}/_{v_{drift}}$$

$$s = d - \ell(E,A) \cdot cos(\vartheta)$$

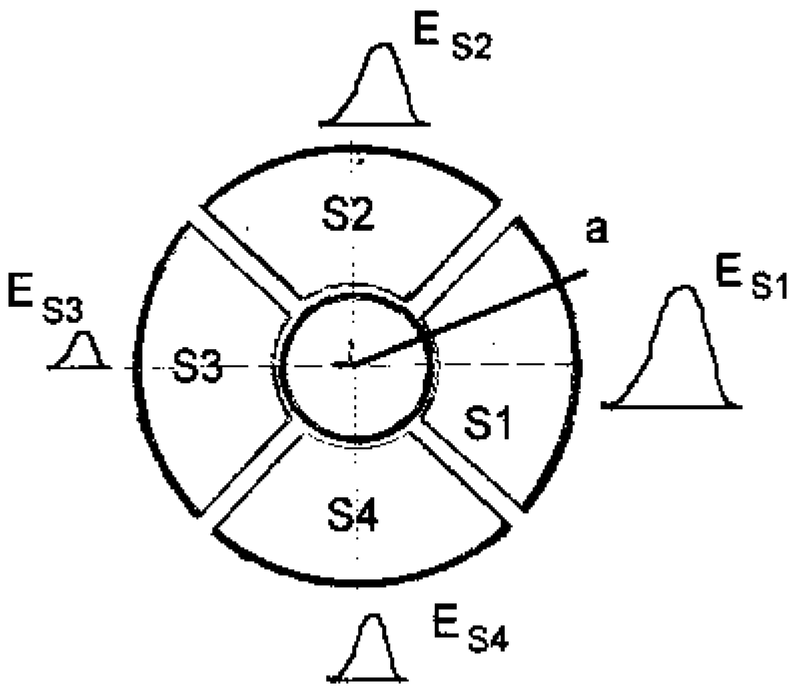
$$cos(\vartheta) = \frac{d - T \cdot v_{drift}}{\ell(E,A)}$$

drift velocity: v_{drift} = 10 cm/μs
range of fragments in methan gas: ℓ(E,A)
distance cathode-anode: d = 3.8 cm

angular resolution	
ϑ	σ
30^0	4.2^0
50^0	2.5^0
70^0	2.3^0

Determination of the azimuthal angle

The energy signal of cathode sections → azimuthal angle φ



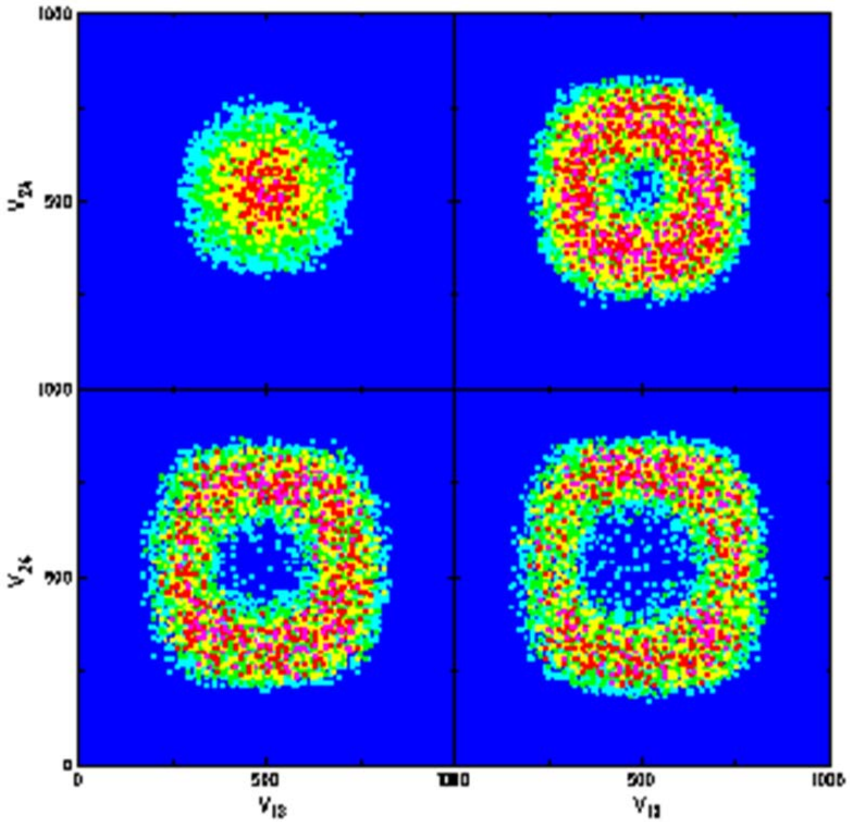
energy signals of the four sectors depend on the orientation of the fission axis

$$V_{13} = \frac{E_{S1}}{E_{S1} + E_{S3}} \qquad V_{24} = \frac{E_{S2}}{E_{S2} + E_{S4}}$$

$$tan\varphi = \frac{V_{24} - 0.5}{V_{13} - 0.5}$$

Determination of the azimuthal angle

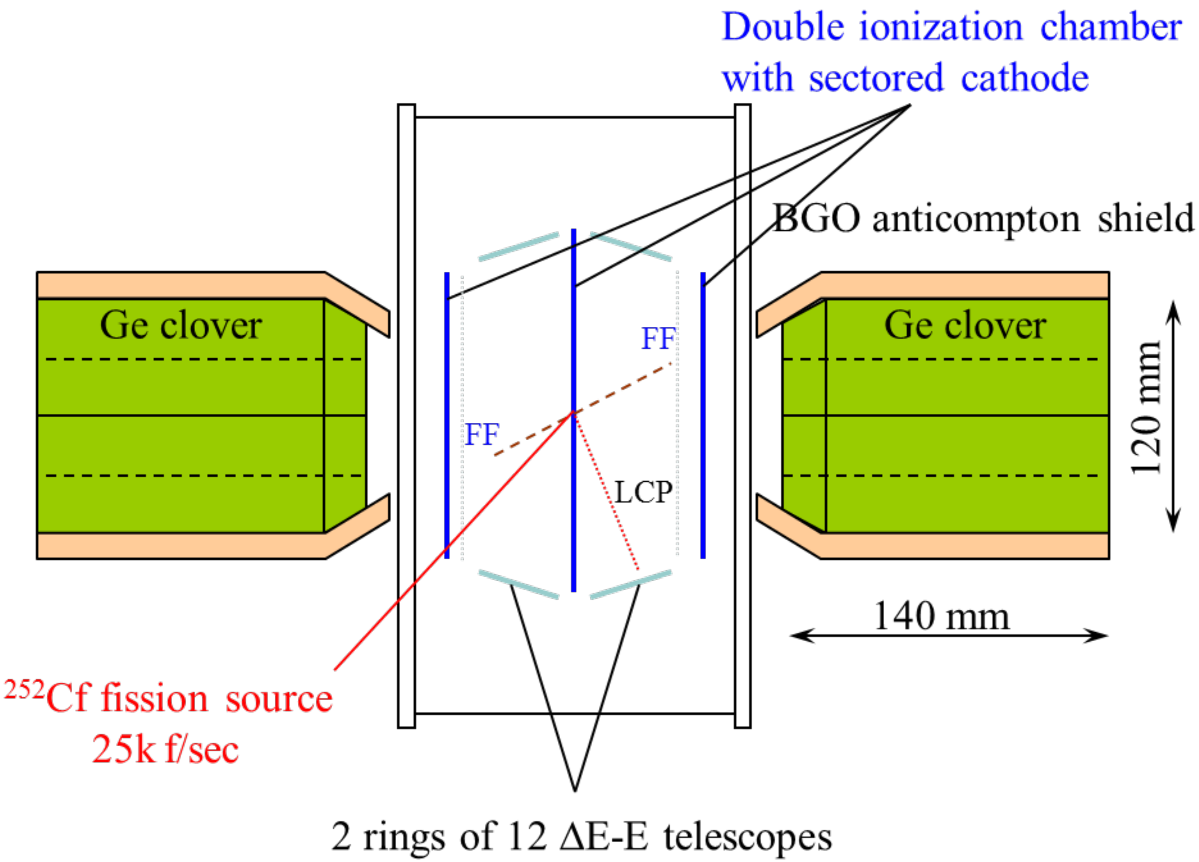
The energy ratios for different emission angles ϑ

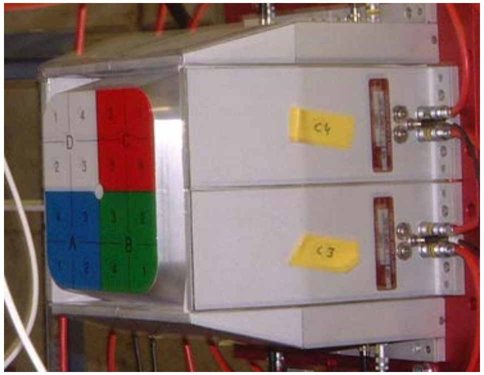


$$V_{13} = \frac{E_{S1}}{E_{S1} + E_{S3}} \qquad V_{24} = \frac{E_{S2}}{E_{S2} + E_{S4}}$$

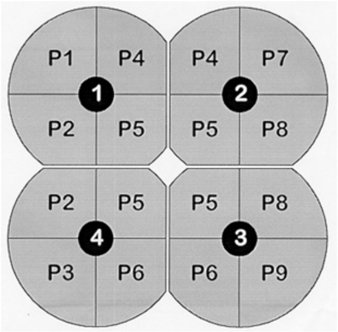
$$tan\varphi = \frac{V_{24} - 0.5}{V_{13} - 0.5}$$

Experimental set-up

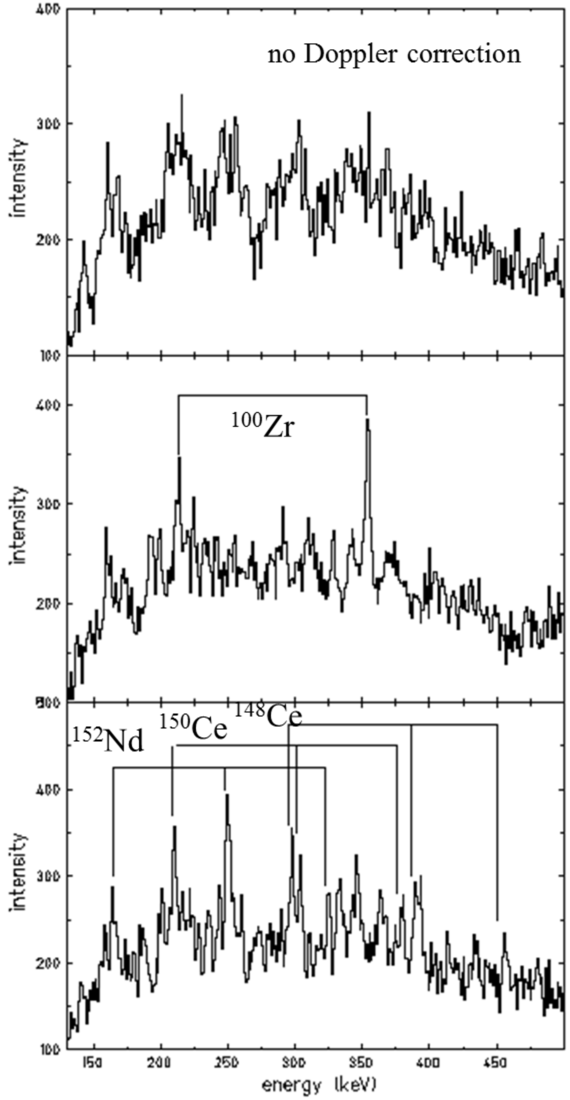




4 segmented Clover detector



Spectroscopy of binary fission fragments



$$\frac{v}{c} = 3.4 - 4.5\ \%$$

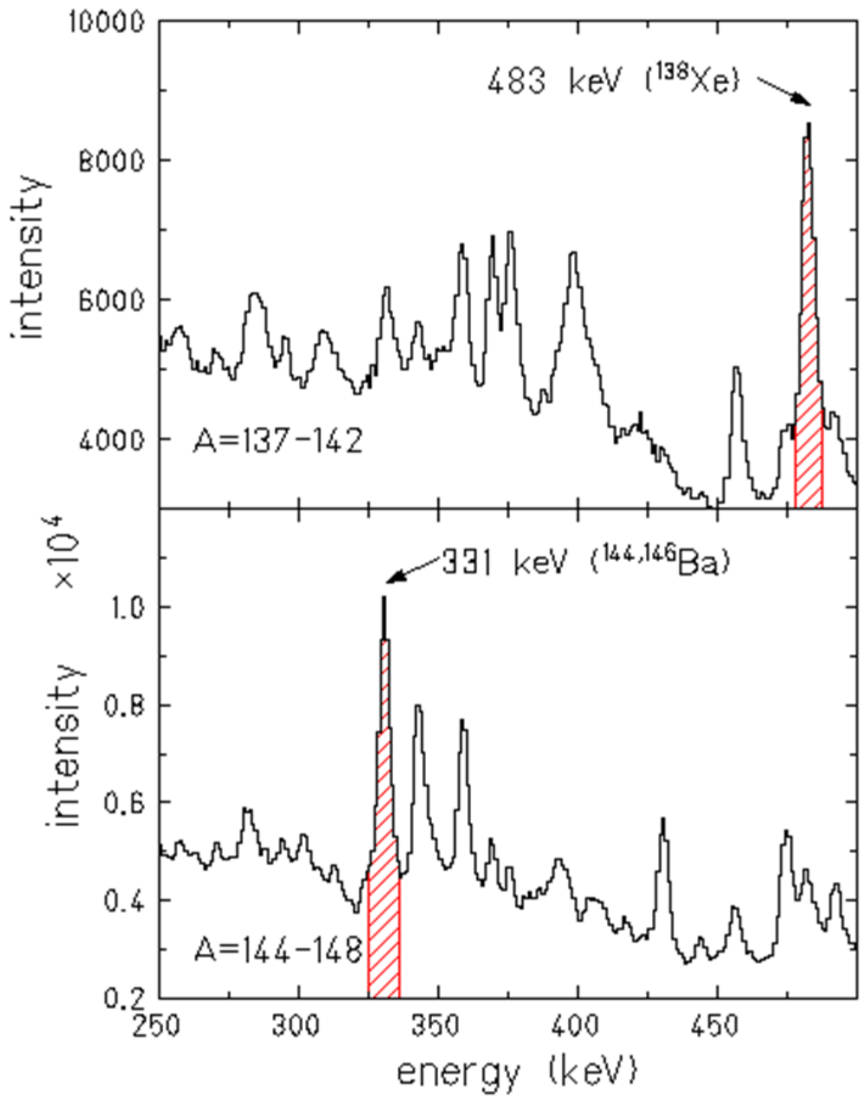
$$\Delta\vartheta_{\gamma} = 18^{0}$$

$$\frac{\Delta E_{\gamma}}{E_{\gamma}} = 1\%$$

$$\varepsilon_{ph} = 2.5\%$$

$$\frac{\Delta E_{\gamma}}{E_{\gamma}} = 1\%$$

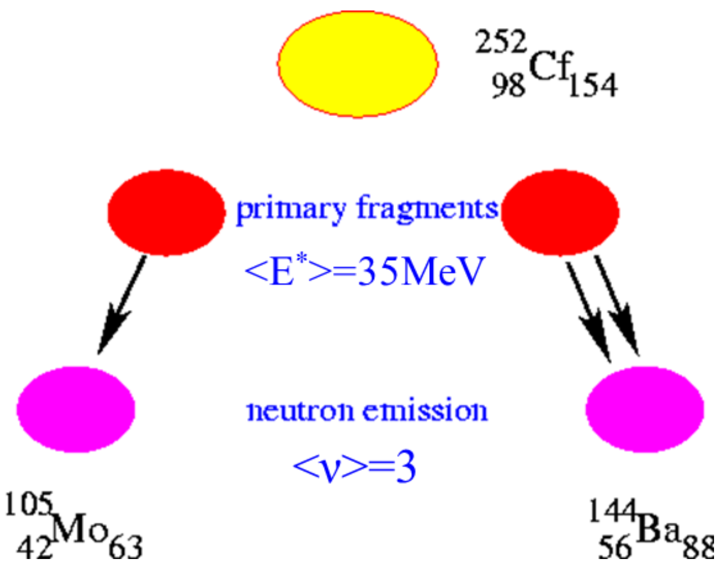
Analysis of the particle-γ angular correlation

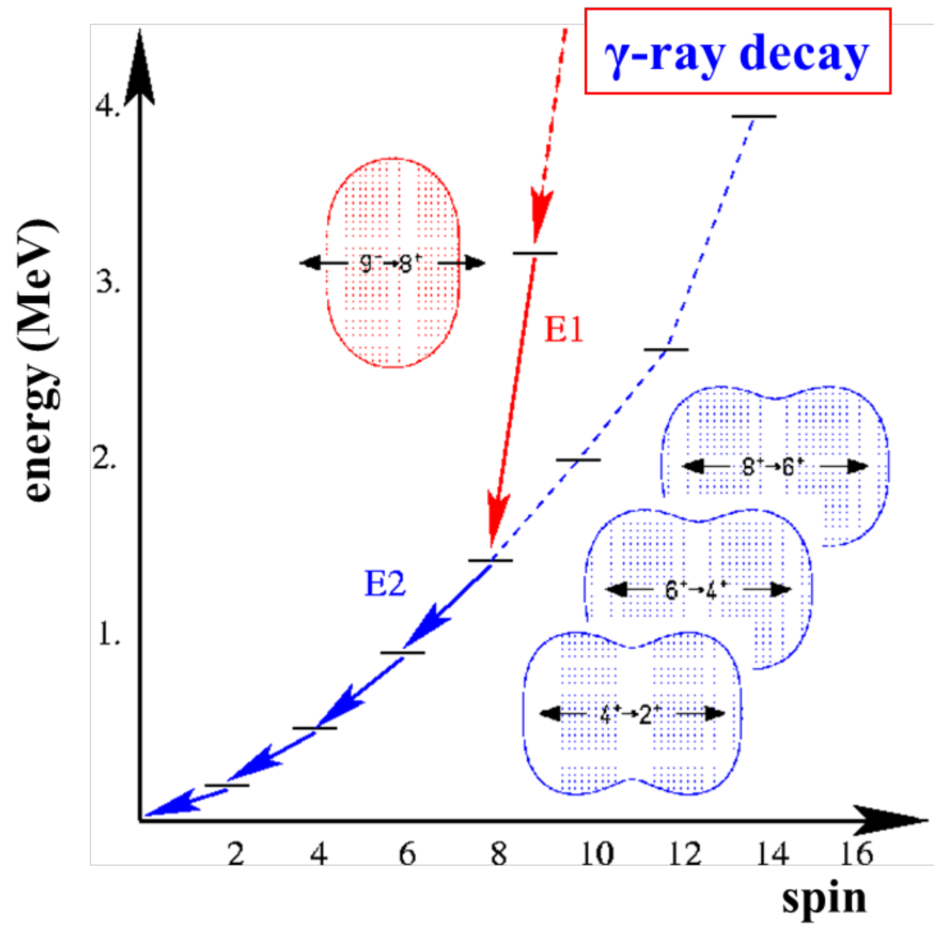


$$10^0 \leq \vartheta_p \leq 80^0$$

$$-34^0 \leq \vartheta_\gamma \leq 34^0$$

Spontaneous fission process of ^{252}Cf



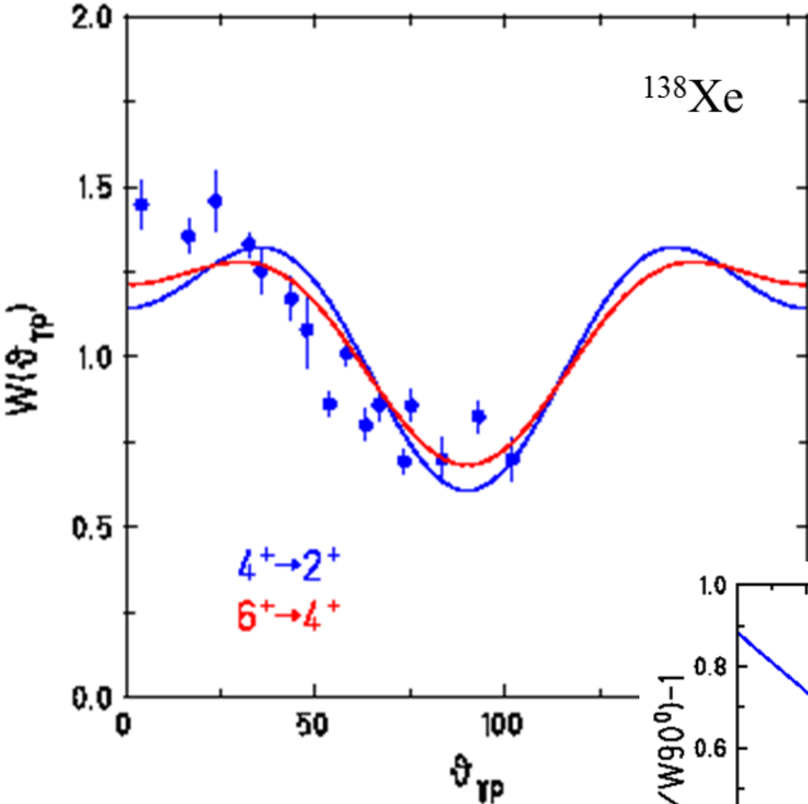


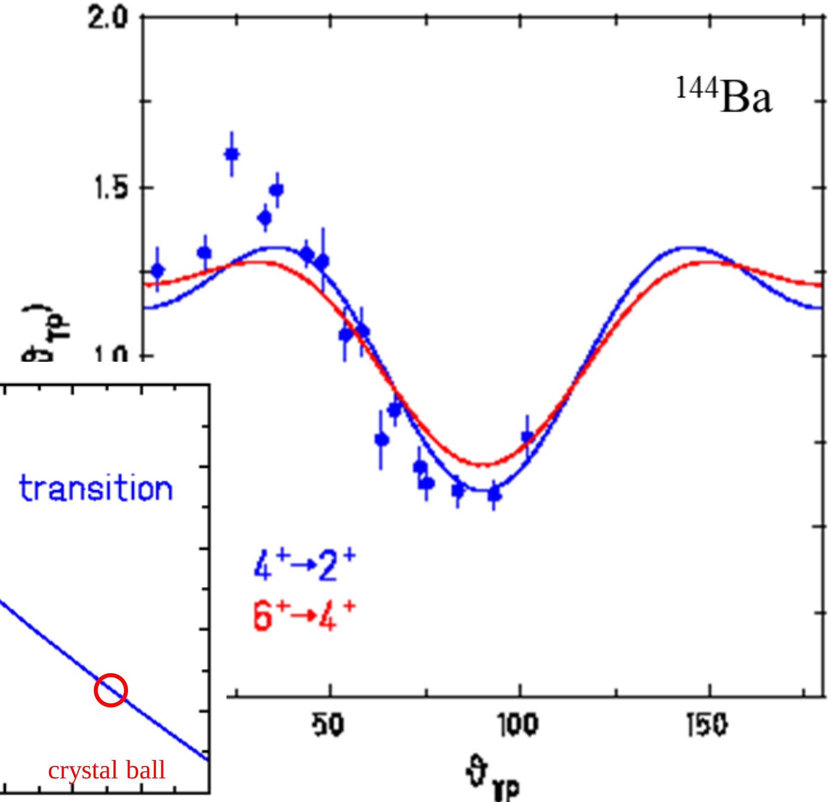
excitation energy of fission fragments **35 MeV**

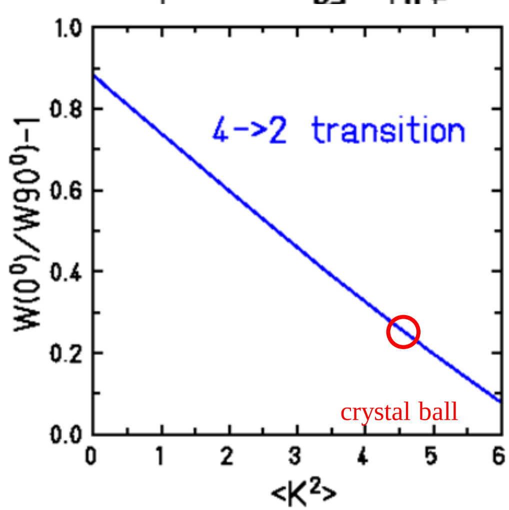
evaporation of 3 neutrons

Fission fragment γ-ray angular correlation

$4^+ \rightarrow 2^+$ *transition*

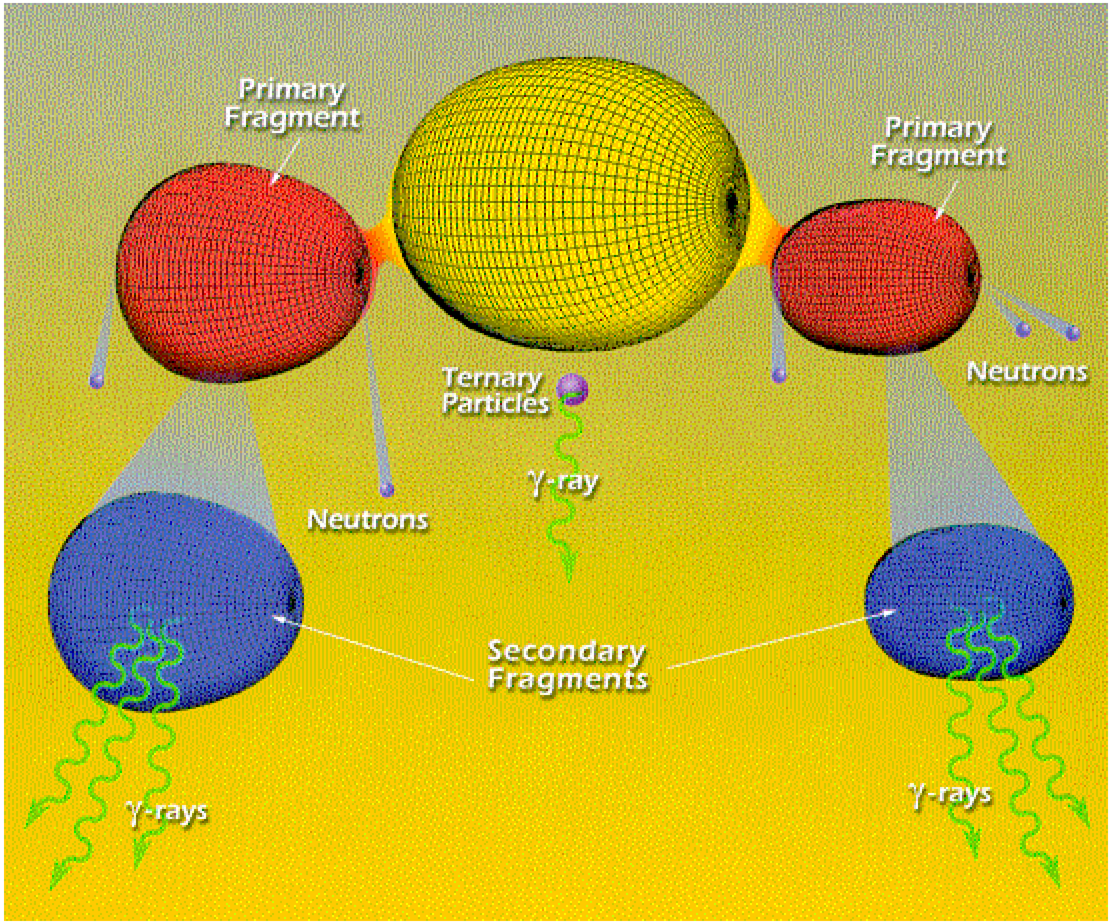




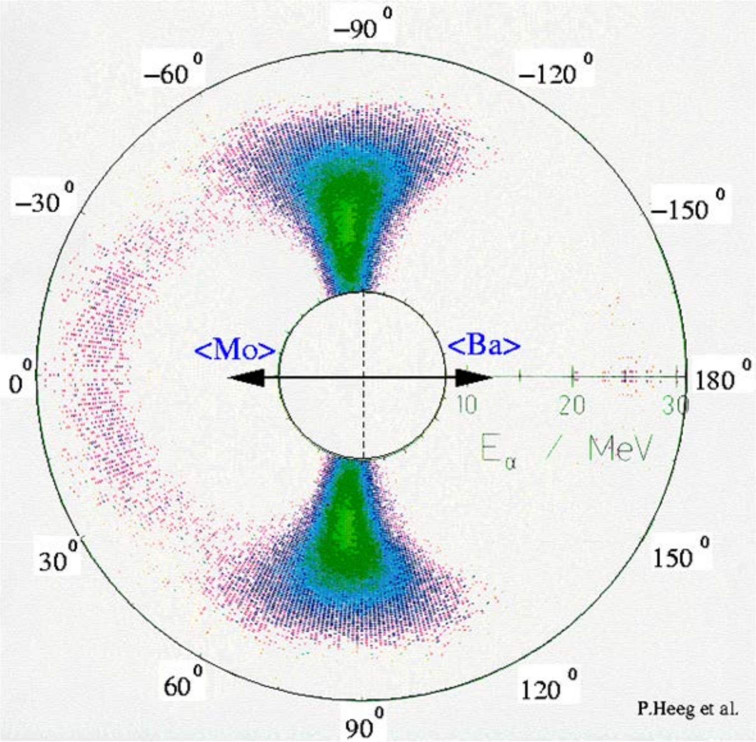


no loss of alignment!

Ternary spontaneous fission of ^{252}Cf



Ternary spontaneous fission of ^{252}Cf



ternary LPCs yields	
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Li	60 ± 10
Be	175 ± 30
B	13.5 ± 4
C	80 ± 30

Fragments → E_H, E_L, ϑ, φ

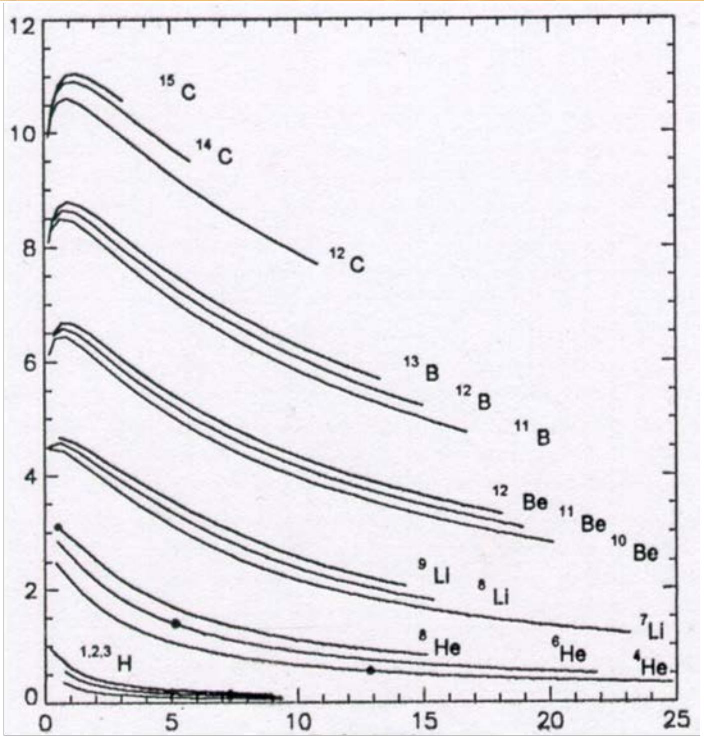
LCPs → E, ΔE, ϑ, φ

γ-rays → E, ϑ, φ

2 rings of ΔE-E telescopes

Separation of light charged particles

dE (MeV)

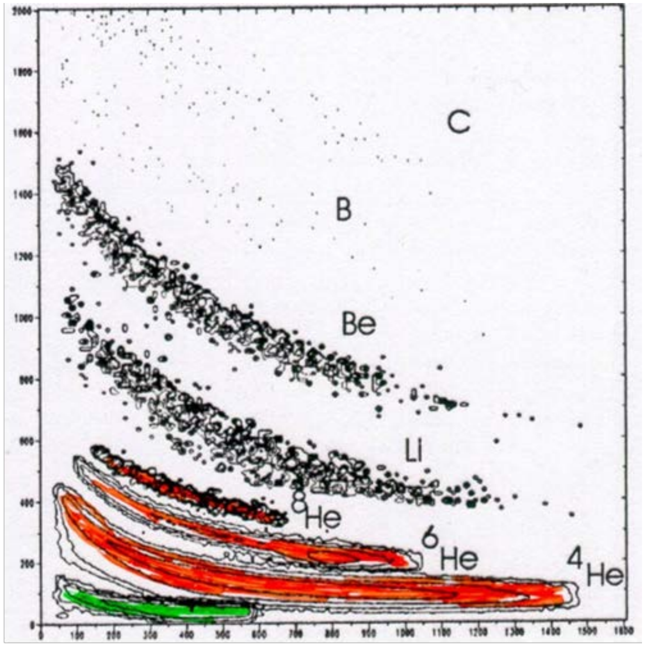


E_{res}(MeV)

simulation

data

energy loss



residual energy

Summary

❖ **γ-ray spectroscopy of fission fragments**

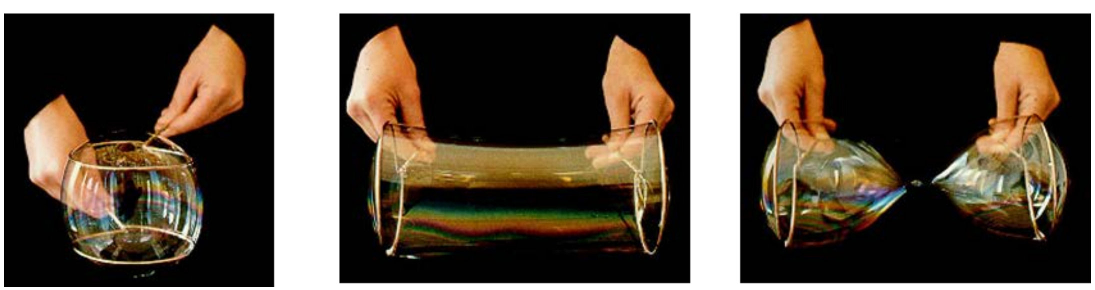
open fission source, Doppler-shift correction
access to short-lived γ-ray transitions

❖ **angular anisotropy of γ-rays**

angular anisotropy of individual γ-ray transitions
- spin orientation
- changes in the spin population between binary and ternary fission

❖ **fragment – LCP correlations**

- isotope yields of heavier LCPs
- formation of LCPs in excited states
- quaternary fission (emission of 2 LCPs)



Soap Bubble Experiments (M. Schuyt, Seifenblasen, die Kugeln der Götter, 1988, Köln, Du Mont)