Properties of the ^{236m}U Fission Isomer

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Motivation & Outline

Past achievements

- double and triple humped fission barrier
    - fission resonances
    - conversion electrons
    - lifetimes (charge plunger technique)
    - γ and e^- spectroscopy

Recent advances

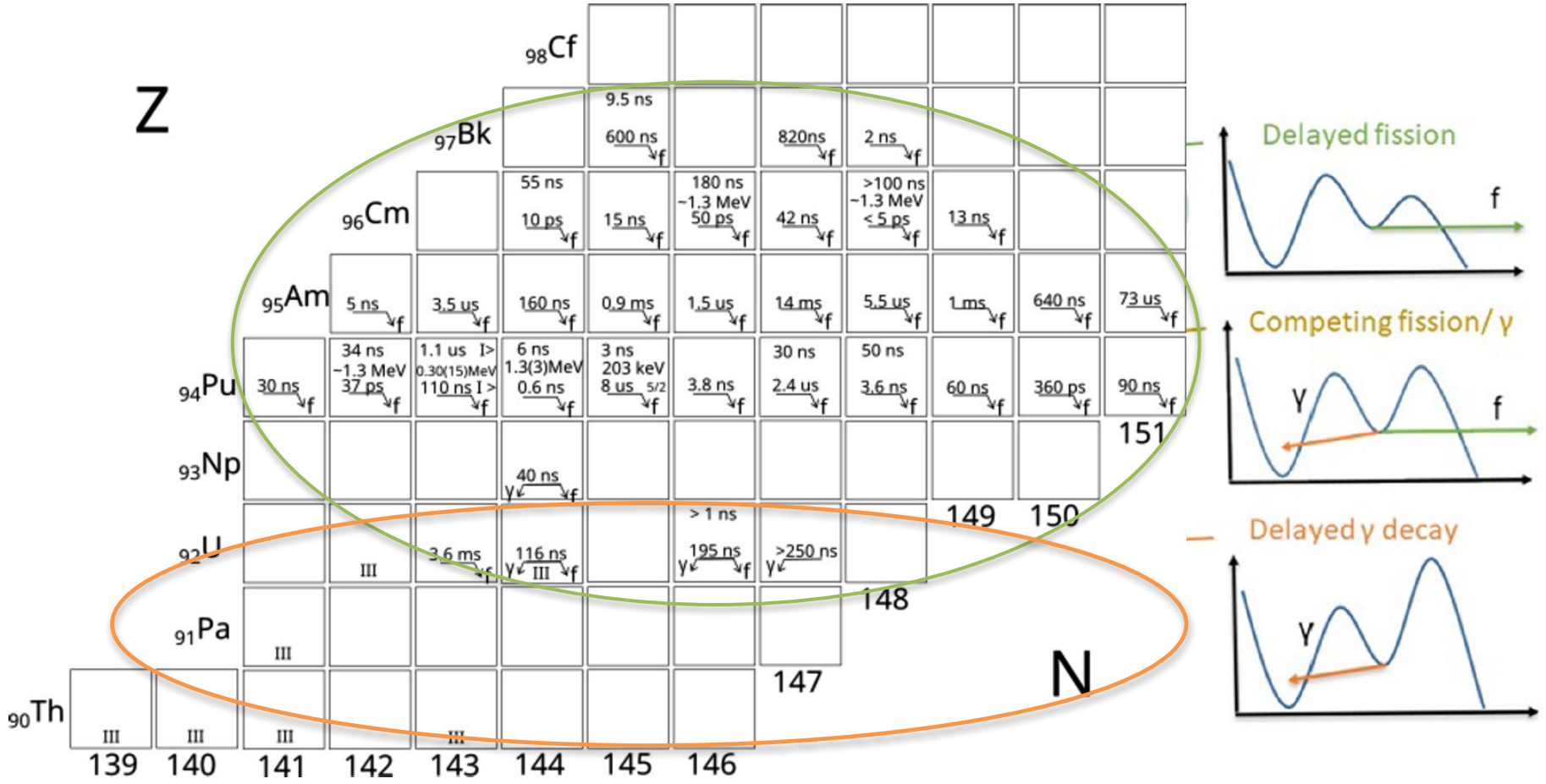
- shape isomerism in actinides is example of *extreme shape coexistence*
- highly deformed structures in the PES in deformation space, decay is substantially hindered.

Shape transition SD -> ND in ^{236}U (and ^{233}Th)

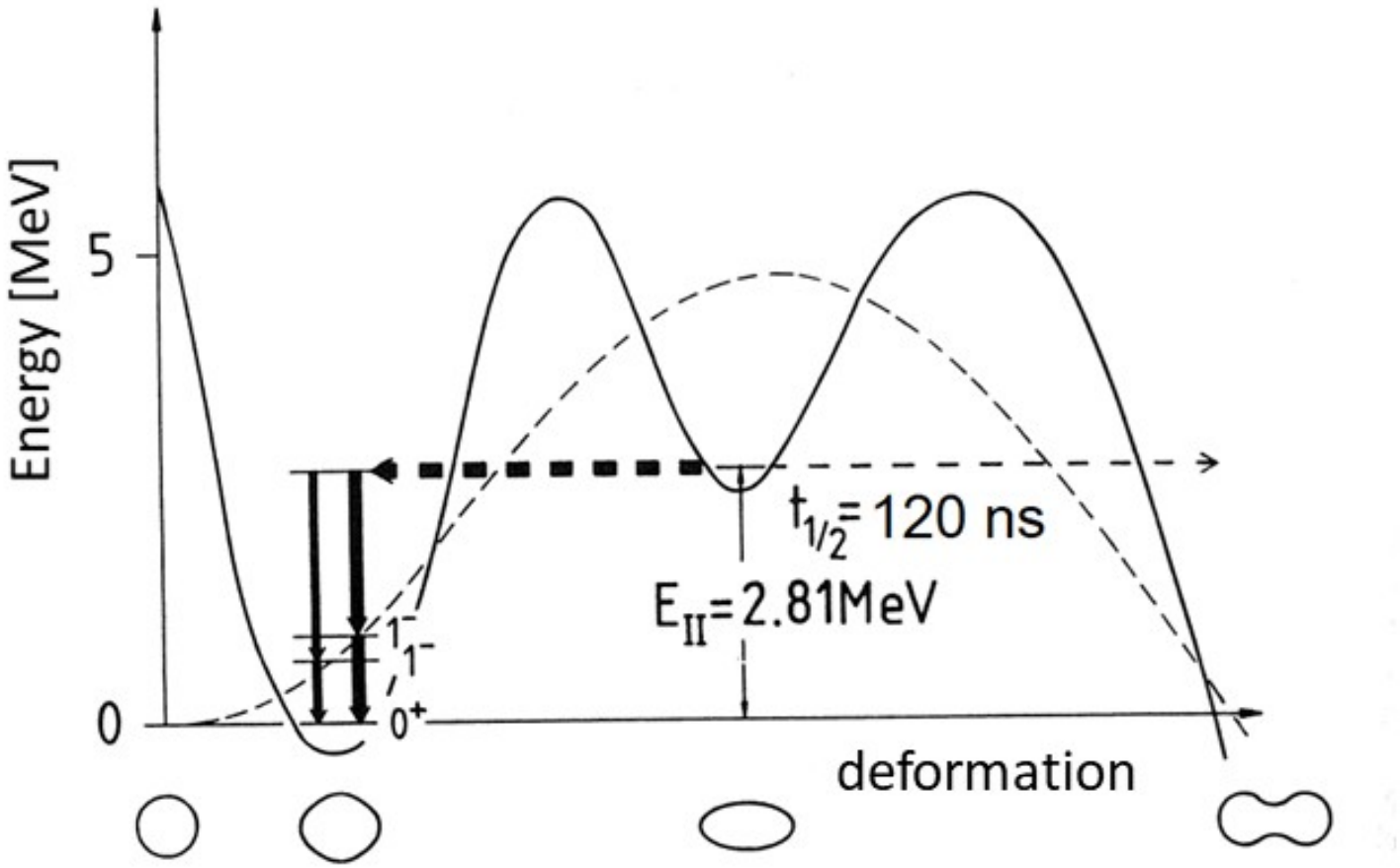
- new approaches:
    fragmentation reactions, IGISOL technique – T. Dickel
    improved spectroscopy – C. Hiver
    inverse kinematics – A. C. Zarzuelo

Multifaceted character of shape coexistence phenomena in atomic nuclei
S. Leoni , B. Fornal, A. Bracco, Y. Tsunoda, T. Otsuka Prog. Part. Nucl. Phys. 139 (2024) 104119

Shape isomers: status and perspectives across the nuclear chart
S. Leoni, B. Fornal, N. Marginean, J. N. Wilson Eur. Phys. J. Spec. Top. (2024) 233:1061



Isomeric γ decay vs delayed fission

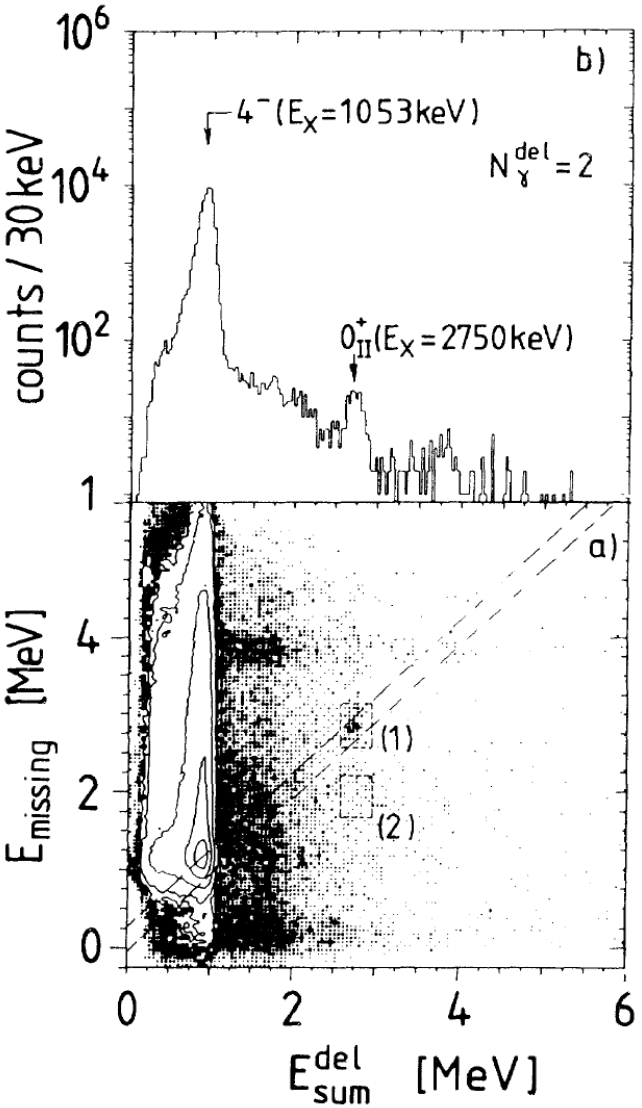


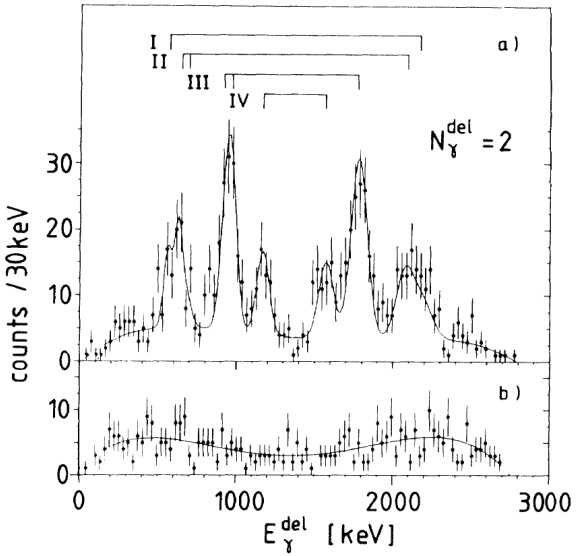
Isomeric γ decay should dominate for light actinide nuclei like ^{236,238}U

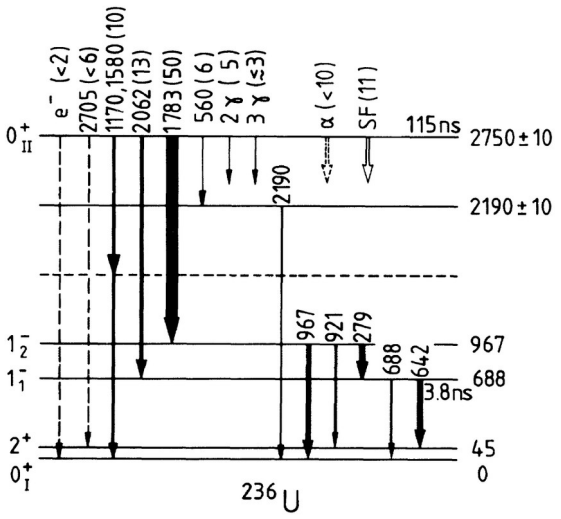
^{238}U P.A. Russo, J. Pedersen, R. Vandenbosch, Nucl. Phys. A 240 (1975) 13

^{236}U J. Schirmer, J. Gerl, D. Habs, D. Schwalm, Phys. Rev. Lett. 63, 2196 (1989)

Isomeric γ decay of ^{236m}U







J. Schirmer, J. Gerl, D. Habs, D. Schwalm, Phys. Rev. Lett. 63, 2196 (1989)

Experimental setup

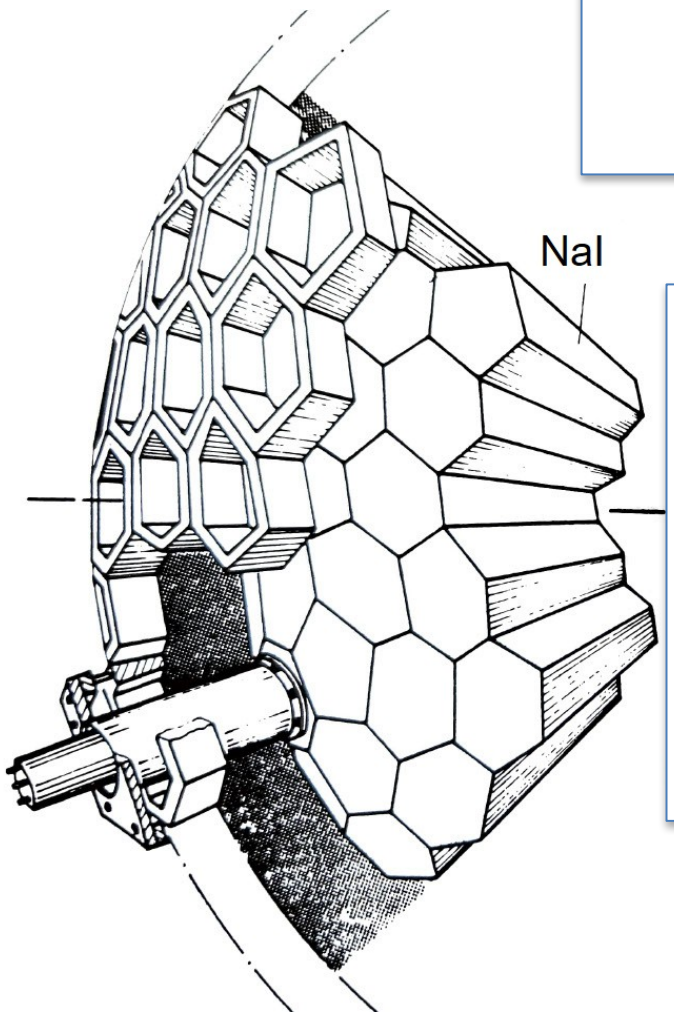
Gamma detection:
Crystal Ball spectrometer CB
162-3= 159 NaI crystals
4π coverage
Crystal length: 20 cm
Inner diameter: 50 cm

Particle detection
Si detector, annular
1 mm thickness
Backward angles: 119-159 deg

Beam: ^{2}H, deuteron
Energy: 11 MeV
Pulsed beam: 298 ns

Target: ^{235}U
(metallic, 93%, 3.5 mg/cm^2)

Beam time: 16 days



J. Schirmer, et al Phys. Rev. Lett. 63, 2196 (1989)

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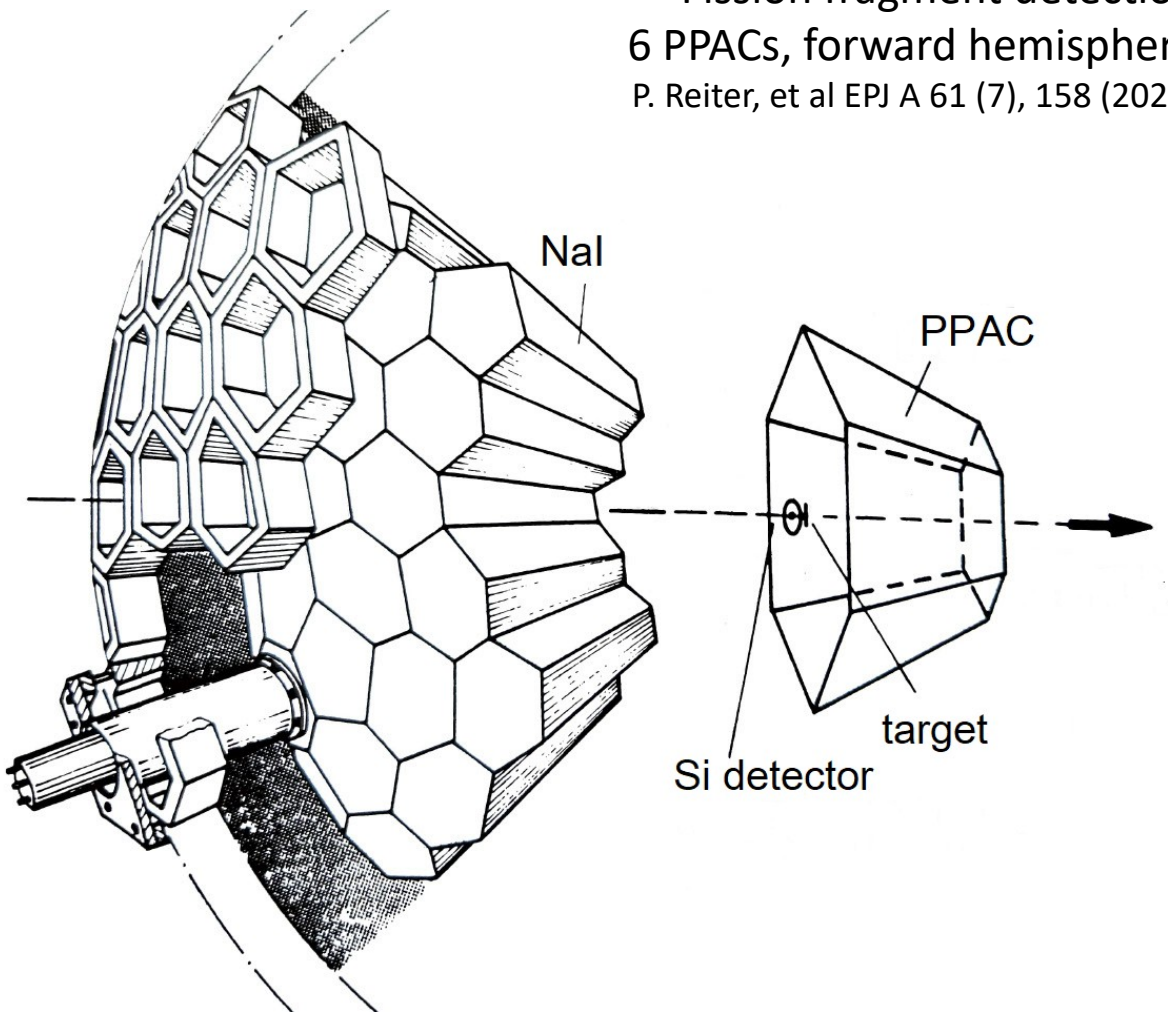
Fission fragment detection
6 PPACs, forward hemisphere
P. Reiter, et al EPJ A 61 (7), 158 (2025)

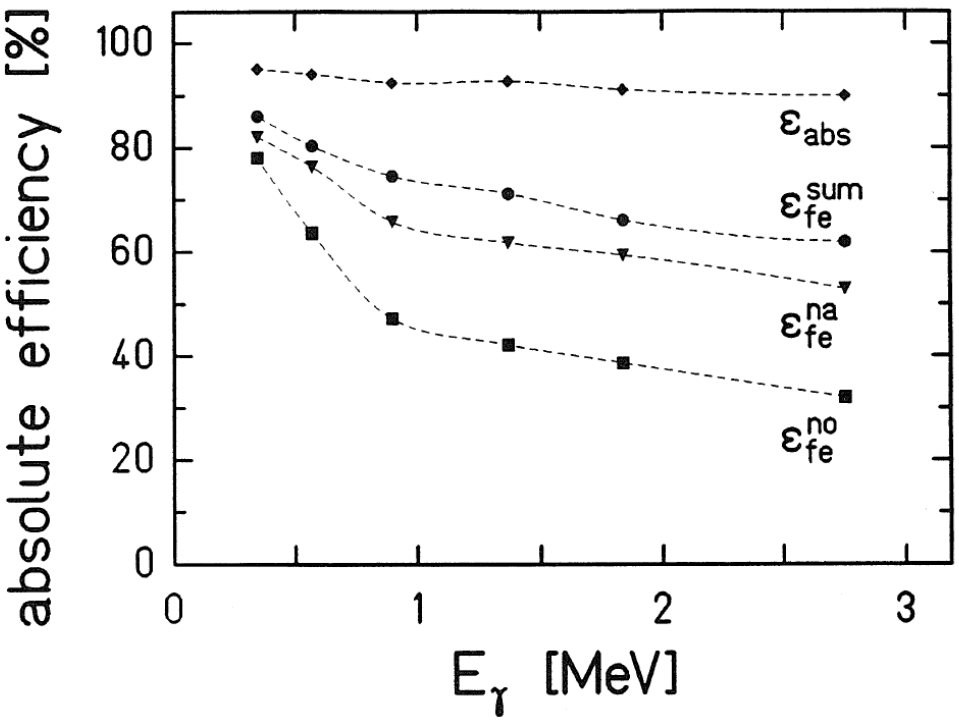


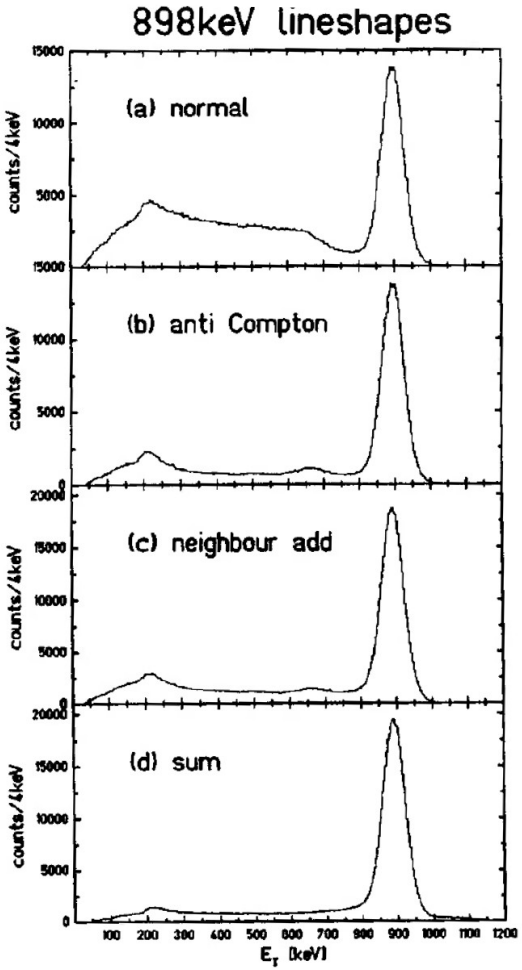
First experiment was performed without PPAC
J. Schirmer, et al Phys. Rev. Lett. 63, 2196 (1989)

γ Efficiency Calorimeter & Spectrometer

Crystal Ball spectrometer

4π coverage NaI crystal length: 20 cm





Calorimetric efficiency at 2 -3 MeV ε > 60 %

Single energy efficiency at 1 MeV ε > 65 %
neighbour add mode

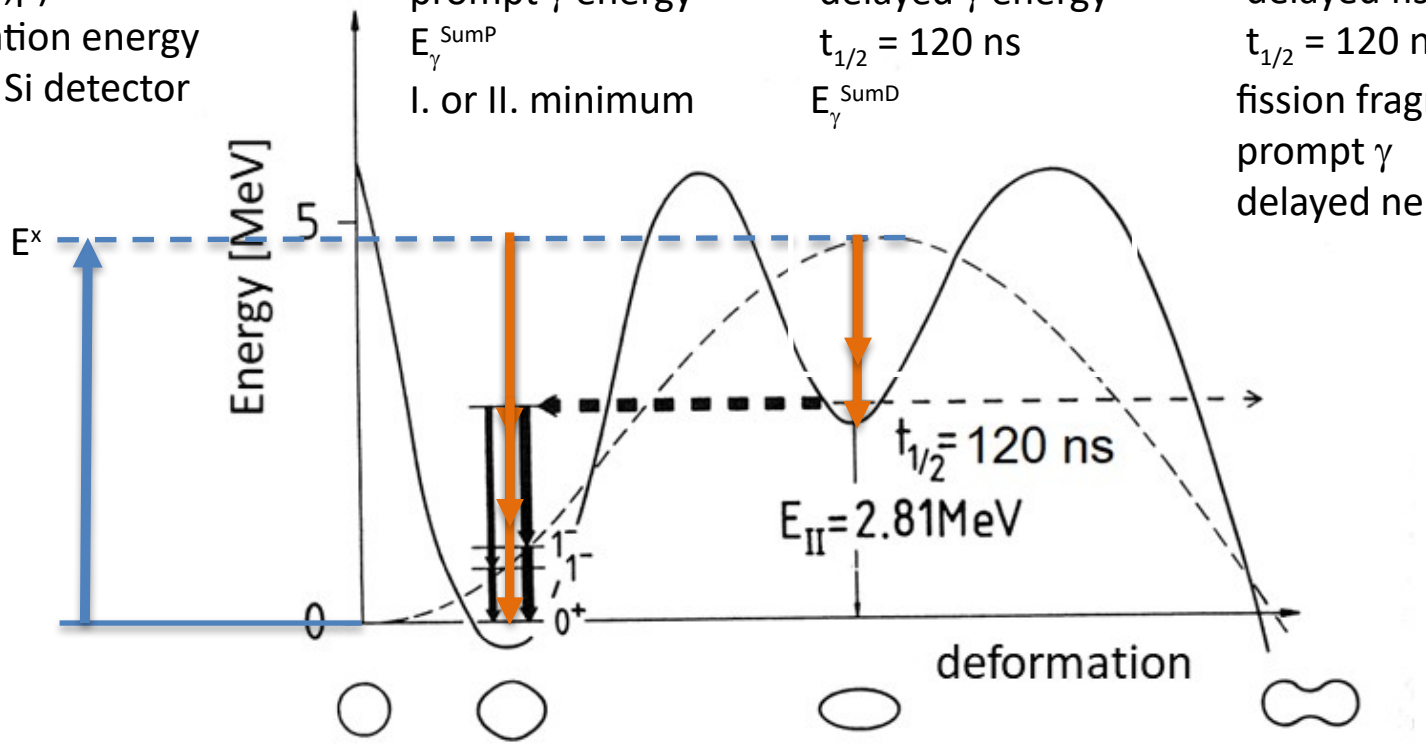
Detection of Isomeric Decay of ^{236m}U

$^{235}U(d,p)\,^{236}U$
excitation energy
E^x via Si detector

prompt γ energy
E_γ^{SumP}
I. or II. minimum

delayed γ energy
$t_{1/2}$ = 120 ns
E_γ^{SumD}

delayed fission
$t_{1/2}$ = 120 ns
fission fragment
prompt γ
delayed neutrons



prompt de-excitations: $E^x = E_\gamma^{SumP}$

missing energy: $E_{Miss} = E_{Isomer} = E^x - E_\gamma^{SumP}$

isomeric γ decay: $E_{Isomer} = E_\gamma^{SumD} = E_{Miss}$

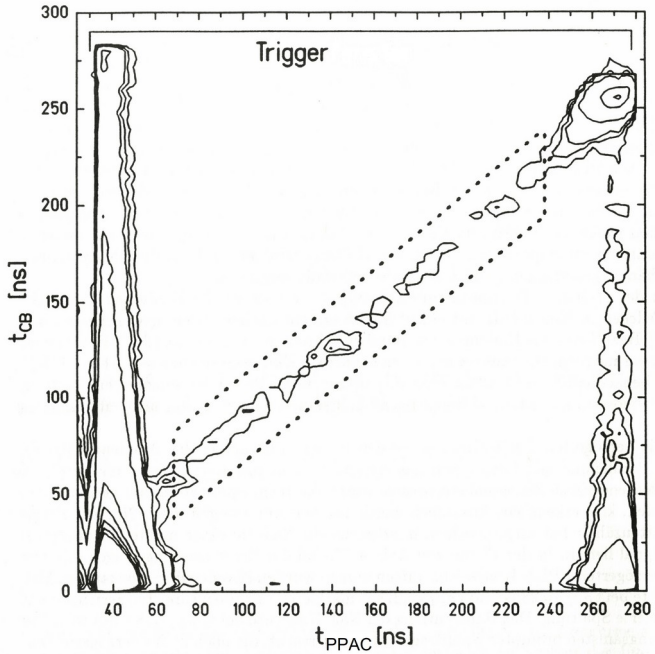
analysis requires energy balance

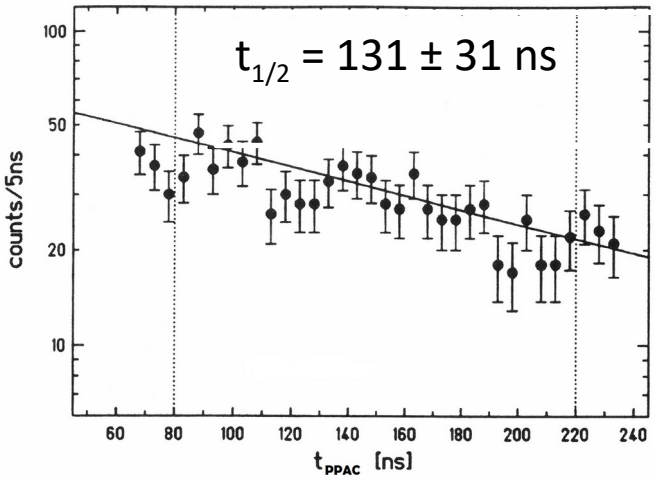
- $E^x = E_\gamma^{SumP} + E_\gamma^{SumD}$
- $E_{Miss} = E_\gamma^{SumD}$

two conditions based on calorimetry

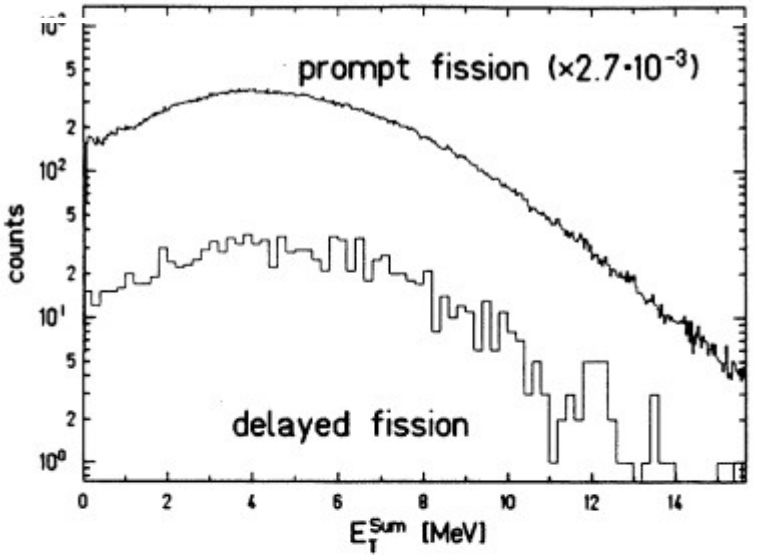
Decay of ^{236m}U via Delayed fission

PPAC vs CB time

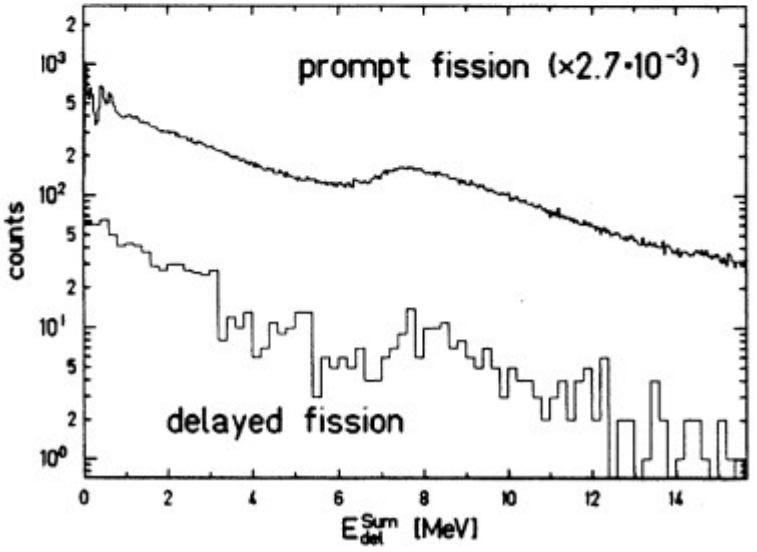




γ sum energy from fission fragments



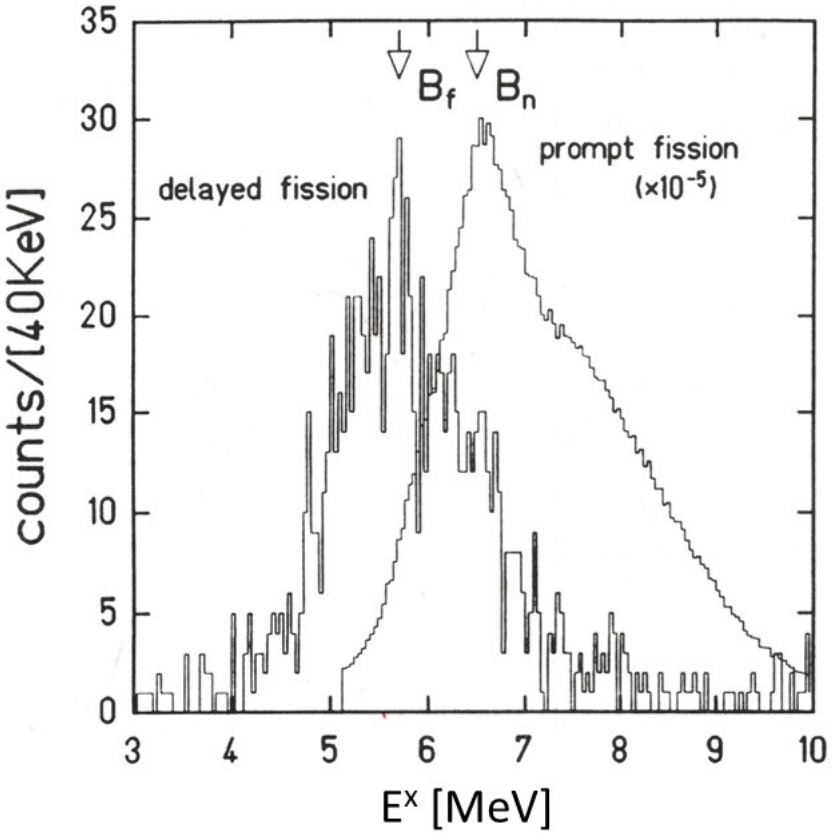
neutron detection

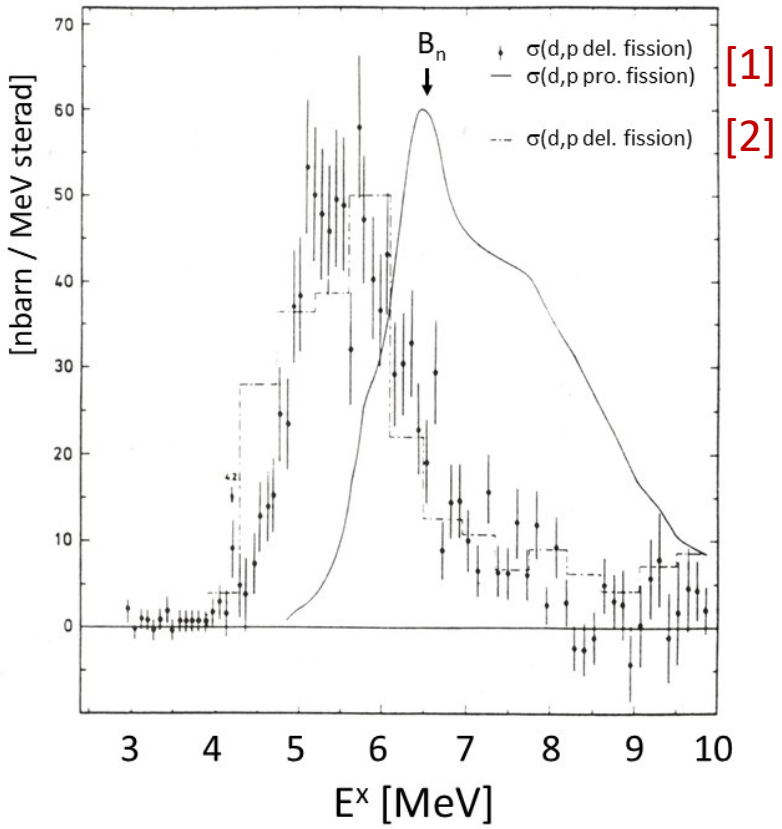


Decay of ^{236m}U via Delayed fission

Excitation function

Comparison between prompt and delayed fission





[1]

[2]

[1] U. Goerlach, et al., Phys. Rev. Lett. **48**, 1160–1163 (1982)

[2] J. Pedersen, B. Rasmussen, Nucl. Phys. A **178**(2), 449–457 (1972)

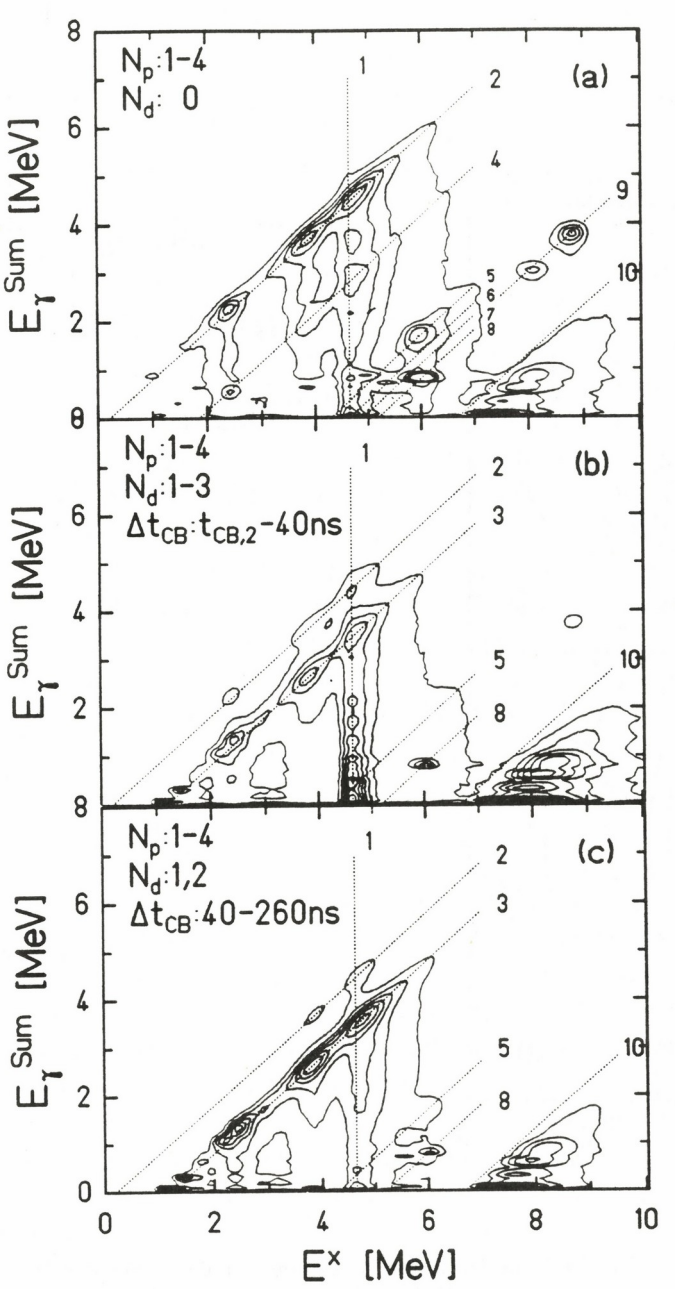
γ Decay of ^{236m}U

reaction channel selection via energy conservation: $E^x = E_\gamma^{Sum}$

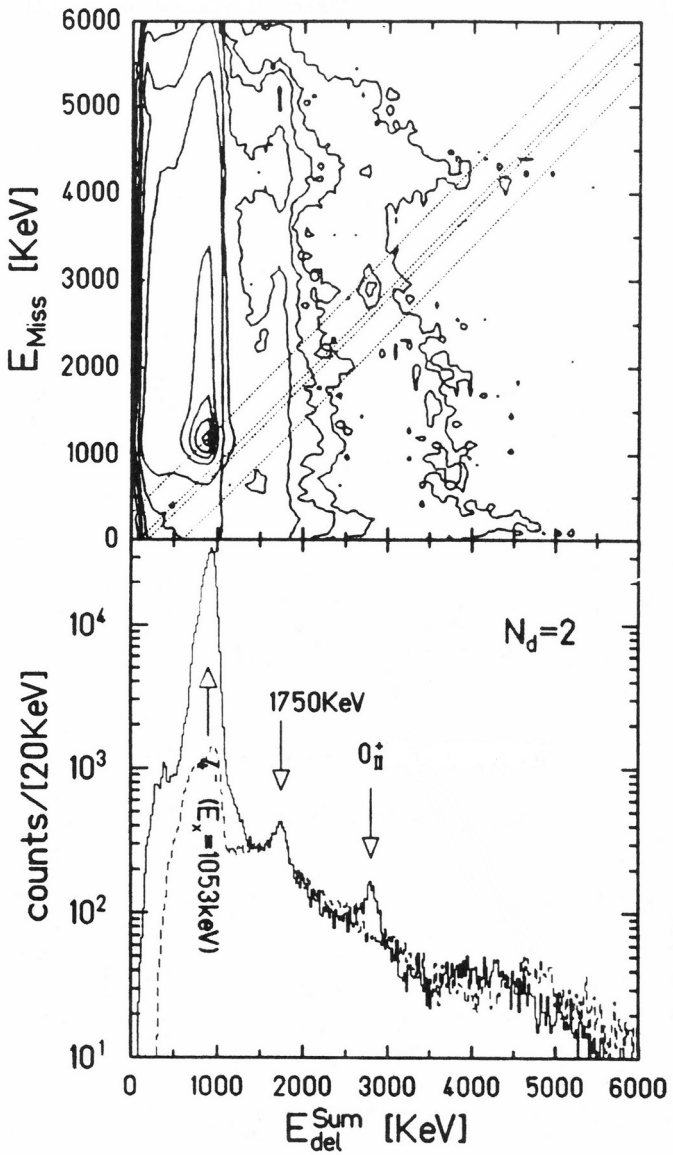
CB analysis conditions

- prompt multiplicity
- delayed multiplicity
- delayed time window

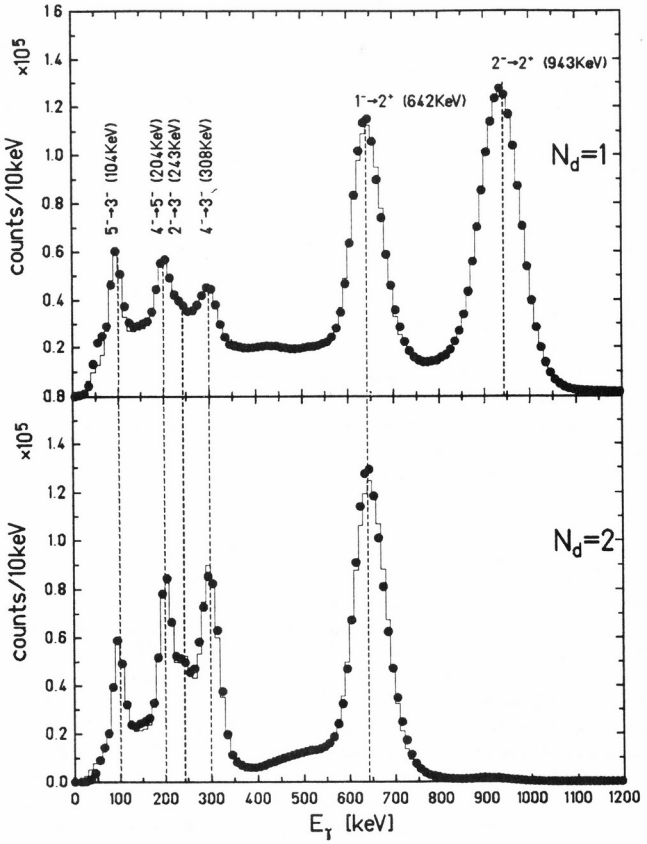
1: ^{235}U(d,d')
2: ^{235}U(d,pγ)^{236}U
3: ^{235}U(d,pγ)^{236}U (K-Isomer)
4: ^{238}U(d,pγ)^{239}U
5: ^{235}U(d,tγ)^{234}U
6: ^{235}U(d,d'γ)
7: ^{238}U(d,tγ)^{237}U
8: ^{16}O(d,pγ)^{17}O
9: ^{12}C(d,pγ)^{13}C
10: ^{235}U(d,pnγ)^{235}U



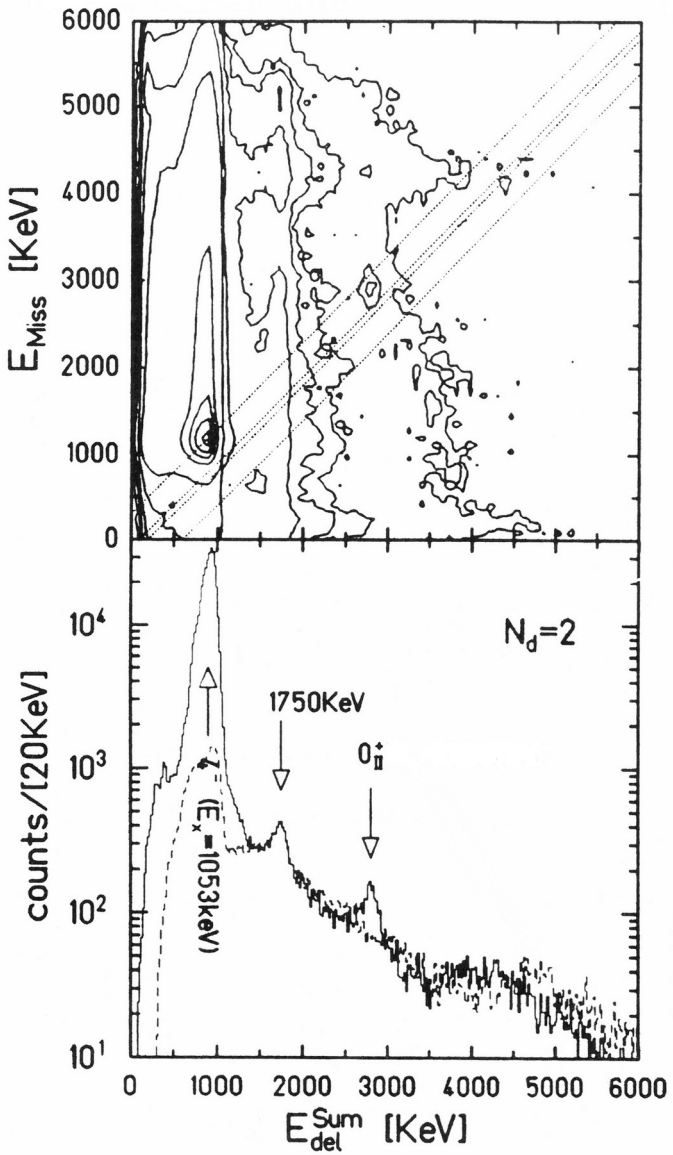
γ Decay of ^{236m}U E_{Miss} vs E_{del}^{Sum}



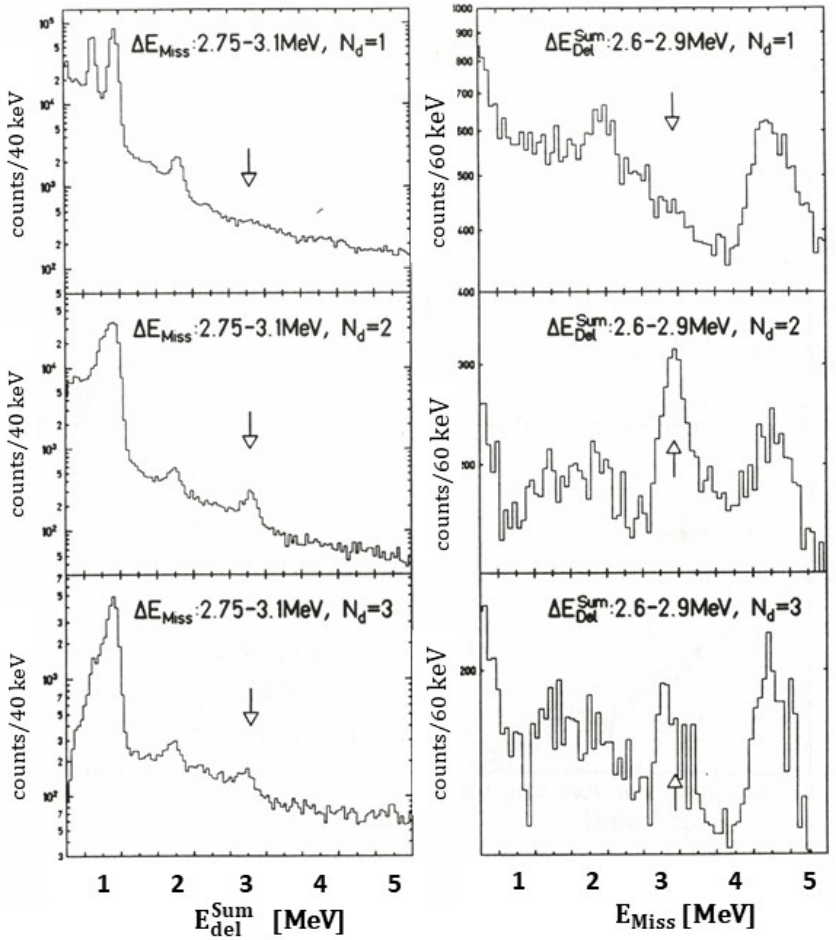
K-Isomer at E^x =1053keV



γ Decay of ^{236m}U E_{Miss} vs E_{del}^{Sum}



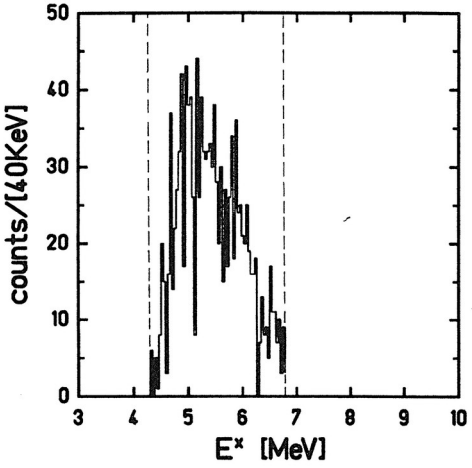
isomer at E^x =2.8 MeV



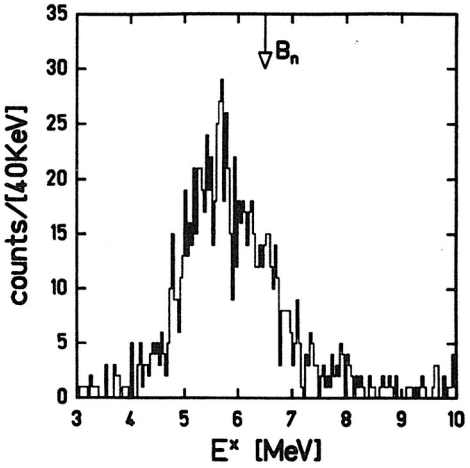
γ Decay from E_{Miss} - E_{del}^{Sum} vs delayed fission of ^{236m}U

Excitation energy E^x

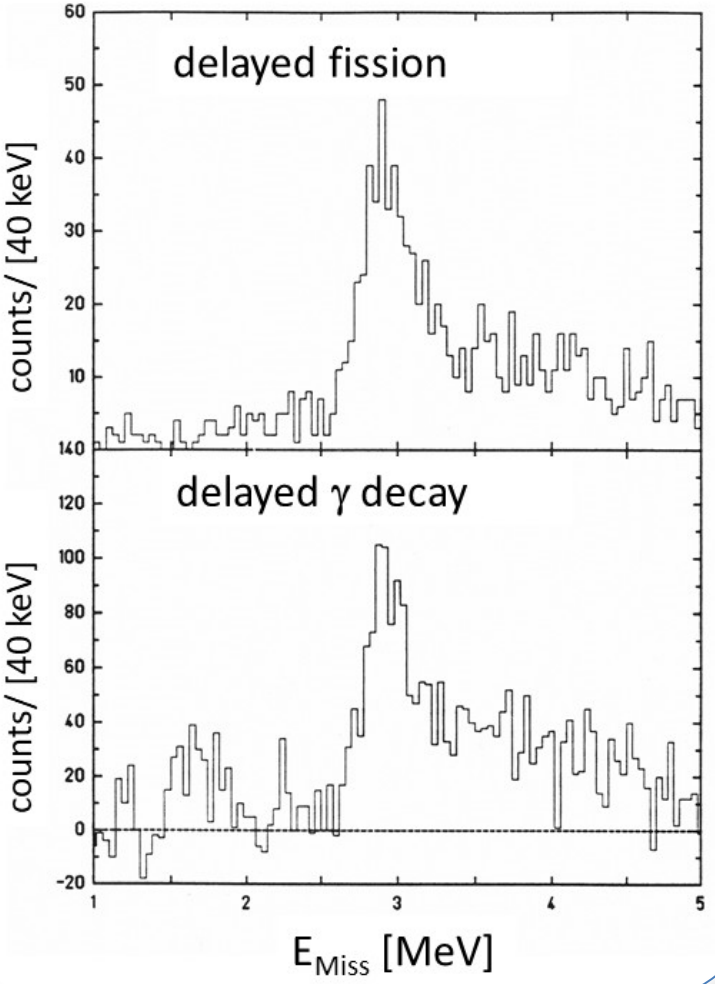
isomeric γ decay



delayed fission



Missing prompt energy E_{Miss}



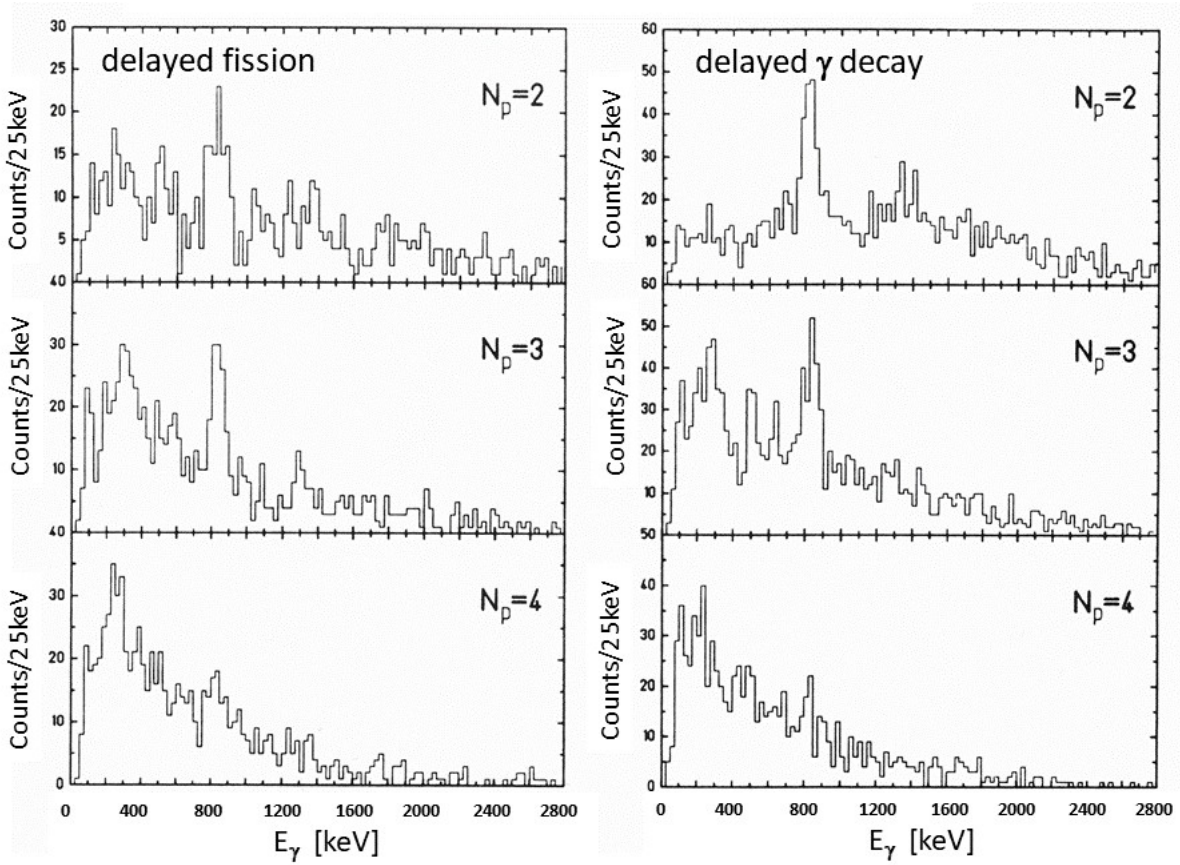
Comparison of half life:

delayed fission $t_{1/2}$ = 131 ± 31 ns

isomeric γ decay $t_{1/2}$ = 123 ± 30 ns

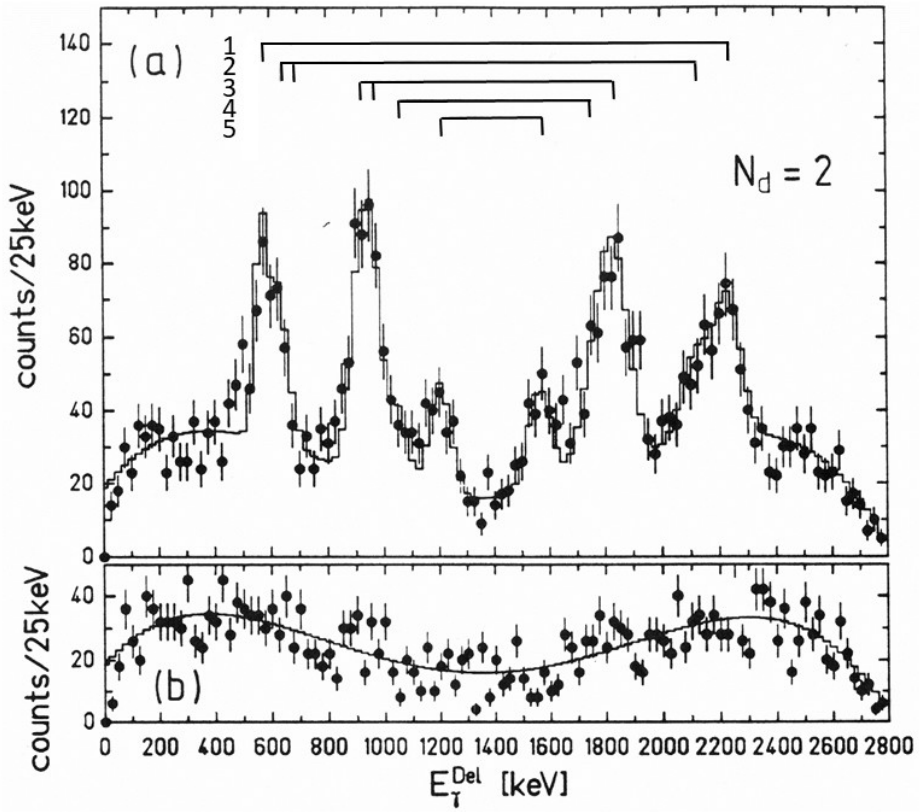
γ Decay from E_{Miss} - E_{del}^{Sum} vs delayed fission of ^{236m}U

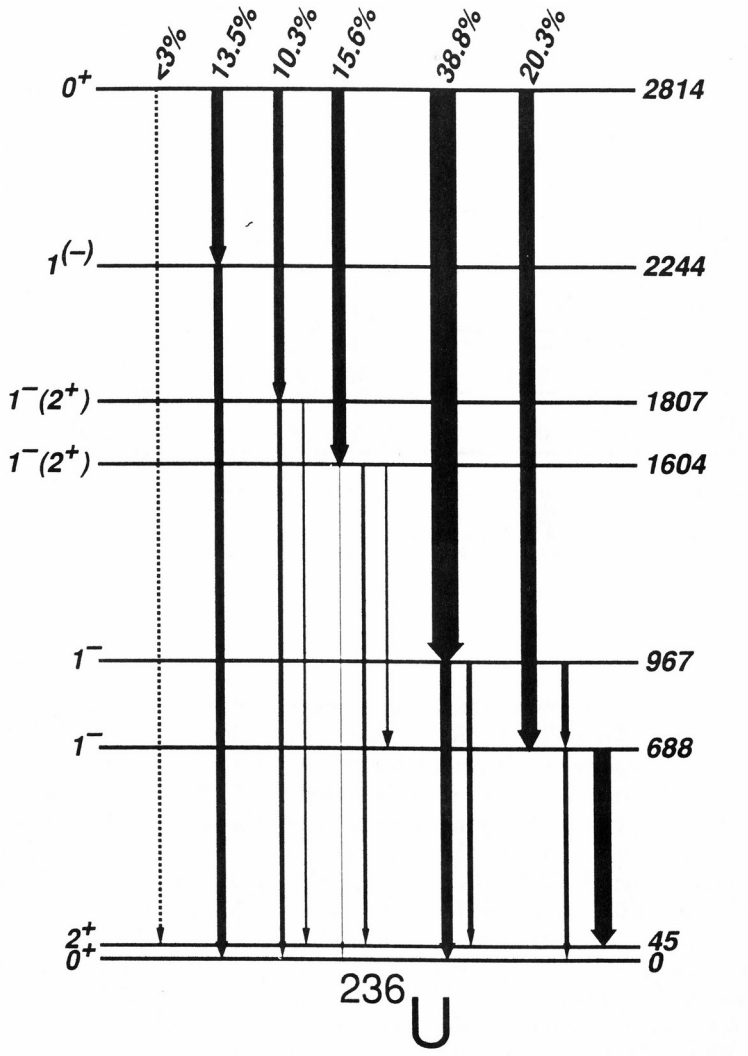
Prompt γ-ray energies feeding second of ^{236m}U



Difference in analysis: E_γ spectrum for delayed fission events does not require $E_{Miss} = E_{Del}^{Sum}$

Isomeric γ Decay of ^{236m}U





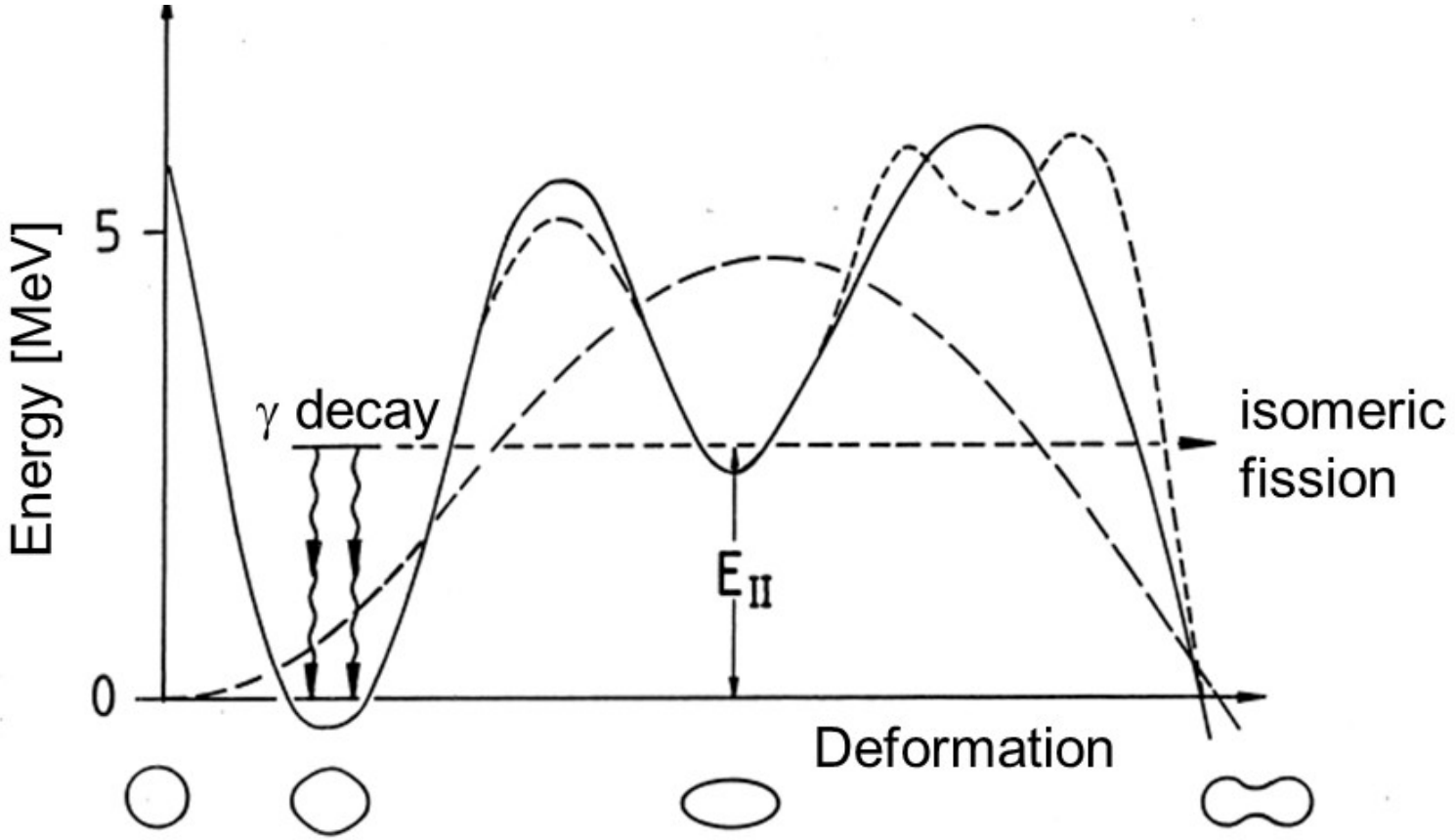
- Five E1 transitions $0^+ \rightarrow 1^-$
  - $E(1^-)$@688 keV $B(E1, 0^+ \rightarrow 1^-) = 6.58 \times 10^{-11}\ e^2fm^2$
  - $E(1^-)$@967 keV $B(E1, 0^+ \rightarrow 1^-) = 1.71 \times 10^{-10}\ e^2fm^2$

- no single-step γ decay into first excited 2^+ state at E=45keV
  - lower limit: $E(2^+)$@45 keV $B(E2, 0^+ \rightarrow 2^+) < 6.76 \times 10^{-7}\ e^2fm^4$

Consistent results
J. Schirmer, et al.; Phys. Rev. Lett. 63, 2196 (1989)
P. Reiter, et al.;Eur. Phys. J. A **61**(7), 158 (2025)

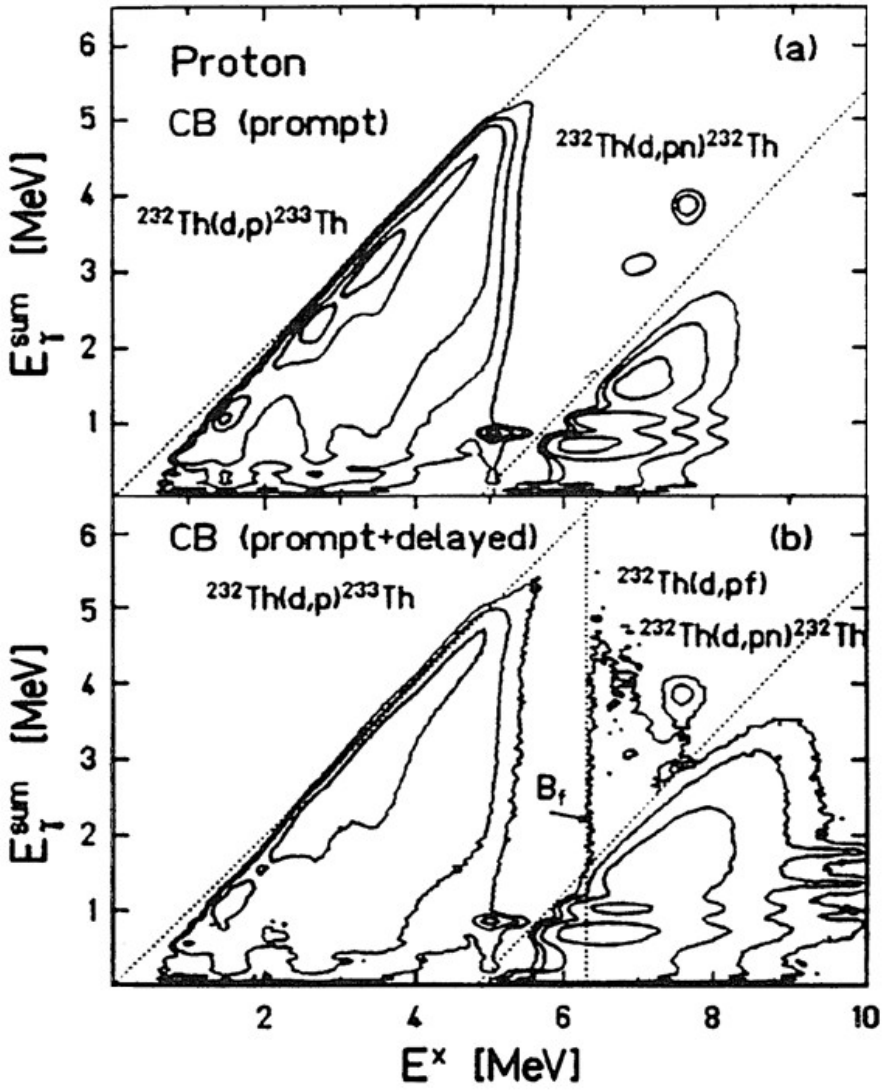
Search for a shape isomer in ^{233}Th

Triple humped fission barrier

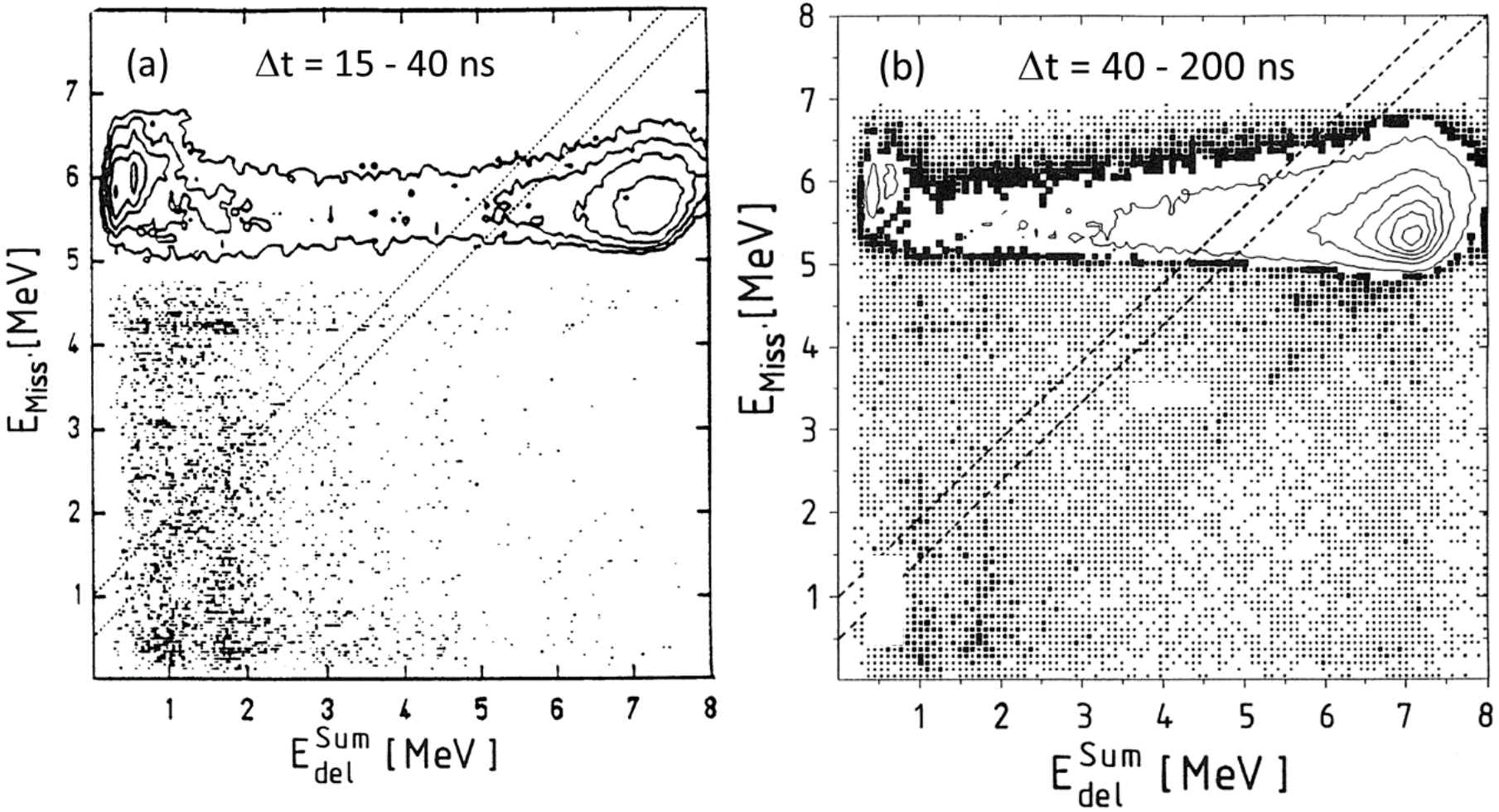


J. Blons, et al.; Nucl. Phys. 615 A **414**(1), 1–41 (1984), J. Blons, et al.; Nucl. Phys. A **477**(2), 231–255 (1988)
neutron-capture on ^{232}Th, *s*-wave resonances, isomeric γ-decay S. Oberstedt et al.; Nucl. Phys. A **578**(1), 31 (1994)

Search for a shape isomer in ^{233}Th



Search for a shape isomer in ^{233}Th



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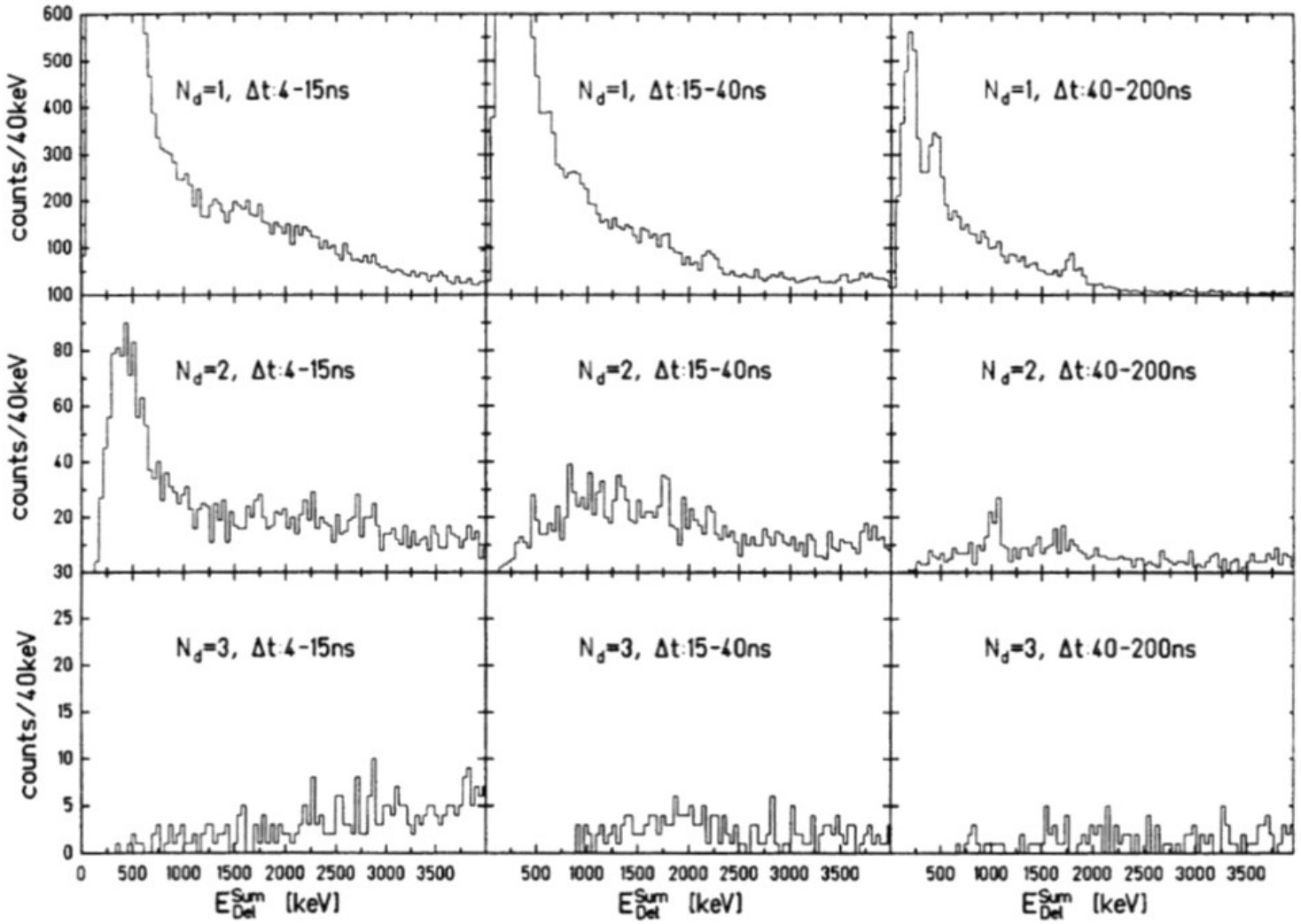

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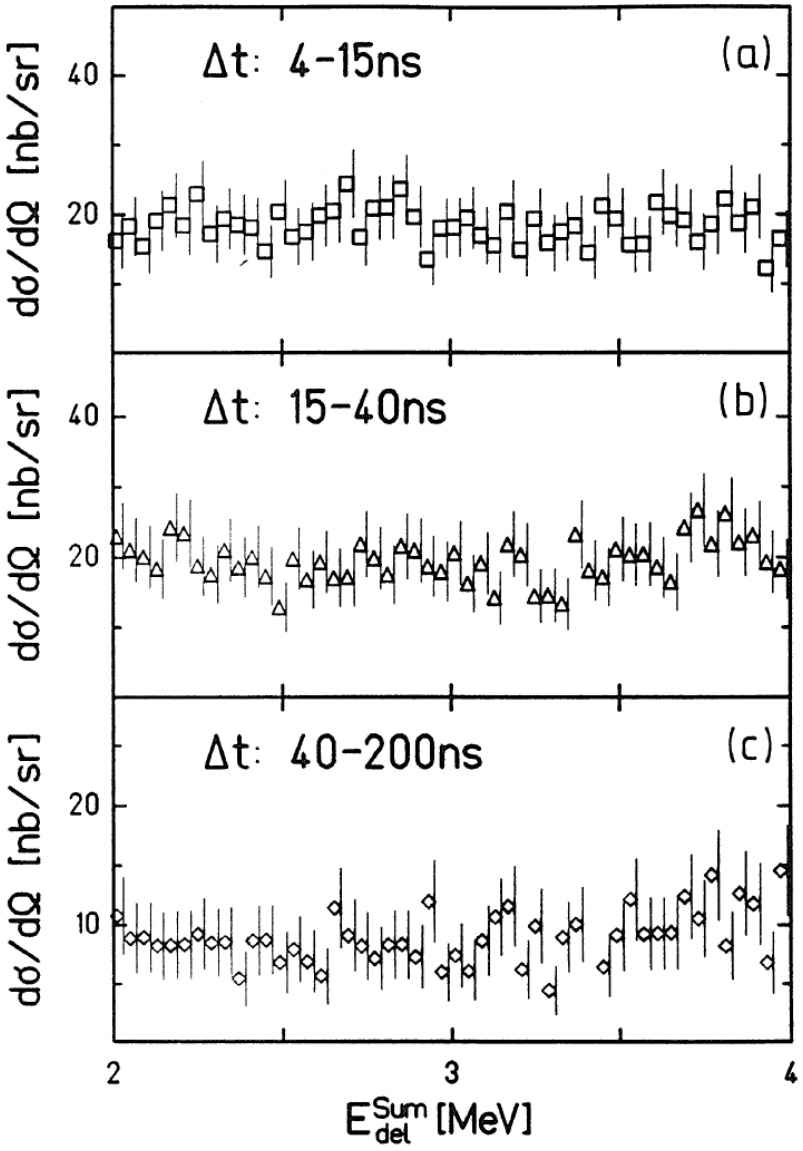

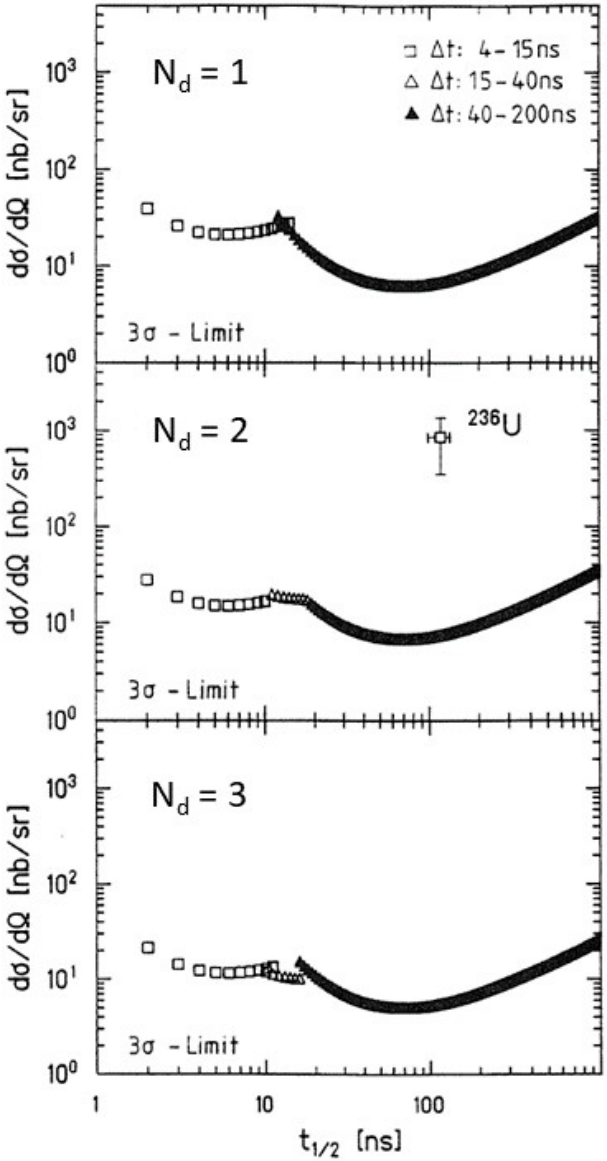

Conclusion

Compelling evidence for isomeric γ decay and fission decay of ^{236m}U:

- half-life
- excitation energy spectrum
- missing prompt energy E_{Miss}
- prompt γ-ray energy spectra

The γ-decay branch yielded improved statistical accuracy:

- excitation energy of the shape isomer: E=2814 keV
- five decay cascades via known 1^- states of the normally deformed ^{236}U.
- two E1 transitions populating the 1^- states at 688 keV and 967 keV, $B(E1) = 6.58 \times 10^{-11}\ e^2fm^2$ and $B(E1) = 1.71 \times 10^{-10}\ e^2fm^2$
- no single-step gamma decay of ^{236m}U into first excited 2^+ state at E=45keV of ^{236}U, lower limit $B(E2) < 6.76 \times 10^{-7}\ e^2fm^4$

P. Reiter, D. Habs, D. Schwalm, P.G. Thirolf, Eur. Phys. J. A **61**(7), 158 (2025)

No evidence was found for isomeric γ decay in ^{233}Th.

→ Indirect evidence that ^{236m}U result is not caused by spurious delayed γ decay.

P. Reiter, D. Habs, D. Schwalm, P.G. Thirolf, Eur. Phys. J. A **62**(2), 29 (2026)