Rotation of Nuclei

following capture of cold polarised neutrons as observed in experiments on ternary fission

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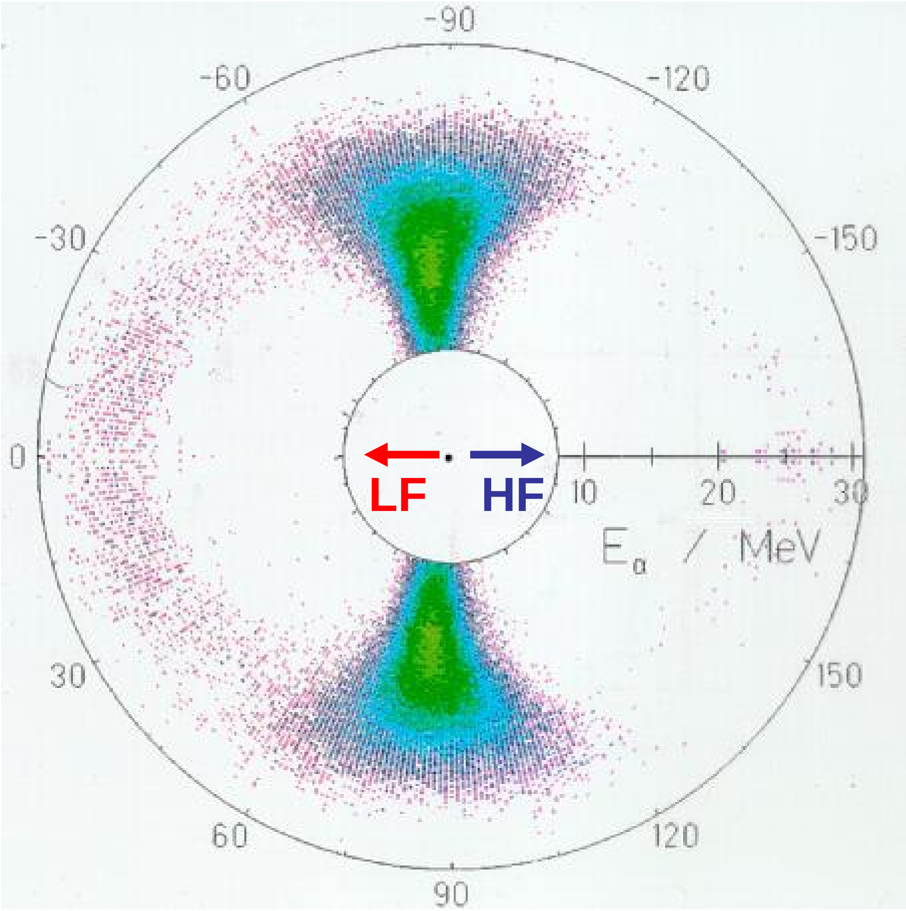
Ternary Fission

^{252}Cf(sf)



In ternary fission besides the two Fission Fragments (LF +HF) a third light charged particle (TP) is emitted.

Most Ternary Particles (TP) are α`s.

Based on the characteristics of angular distributions, two categories of TPs are distinguished :

Equatorial and polar TPs,

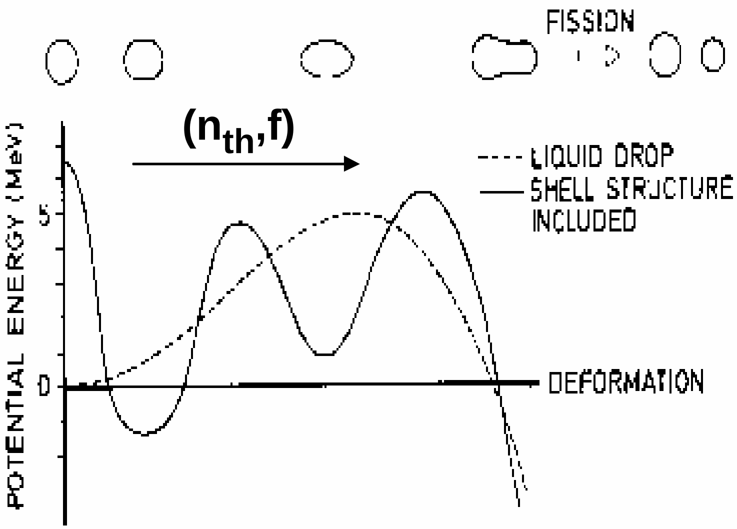
the fission axis serving as polar axis.

TP emission angles θ are given relative to the direction of flight of the LF.

The average θ is $\langle\theta\rangle \approx 82°$.

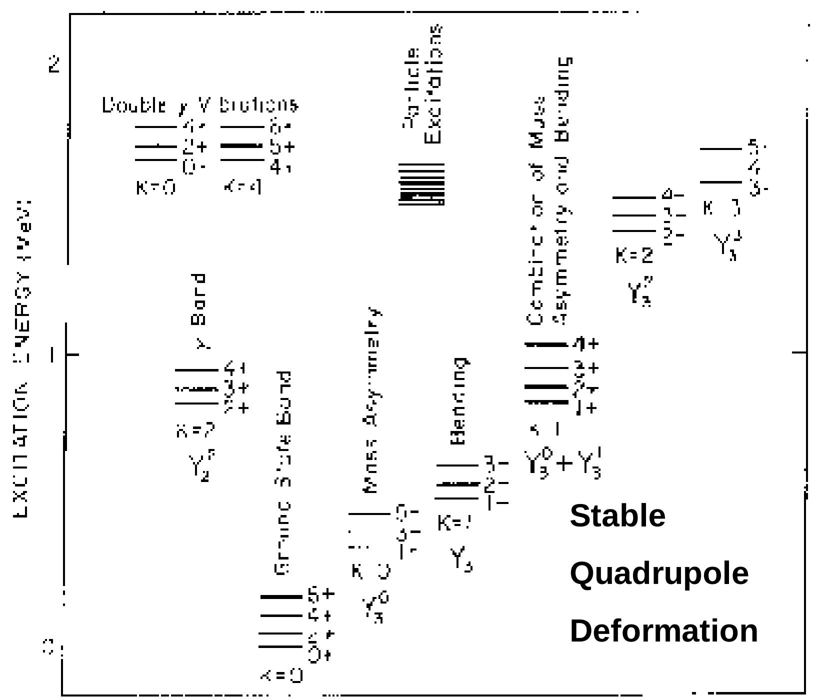
Transition States

For fission induced in fissile nuclei by thermal neutrons the transition states at the saddle point of deformation lie in the gap between the barrier and single-particle excitation. The transition states are hence collective in character



From „The Nuclear Fission Process“

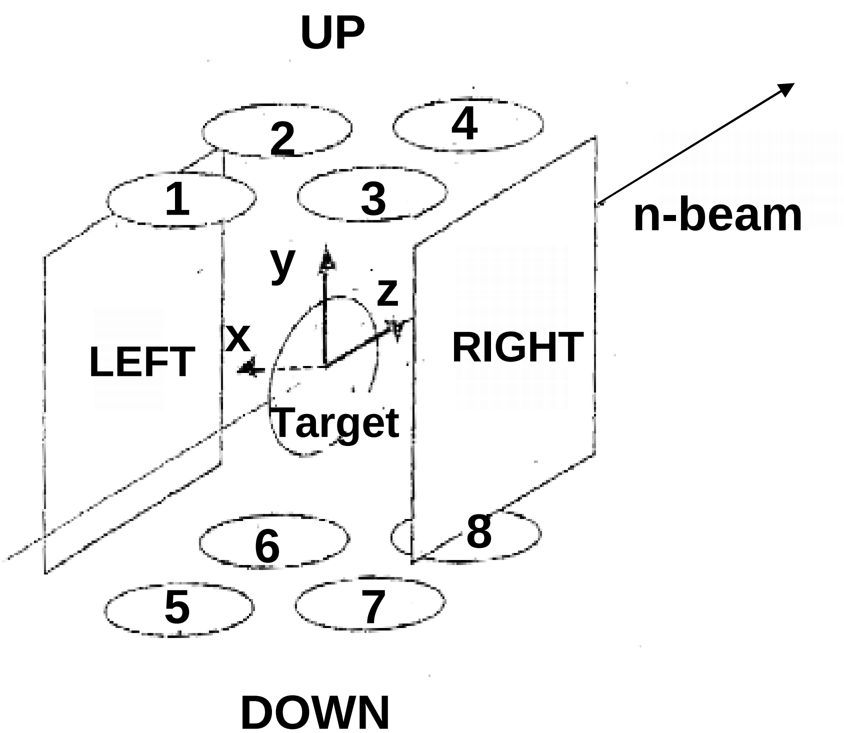
C. Wagemans ed.



From „Nuclear Fission“

Vandenbosch-Huizenga

Experimental Setup



The polarised cold neutron beam hits the ^{235}U target and defines the **+z** axis.

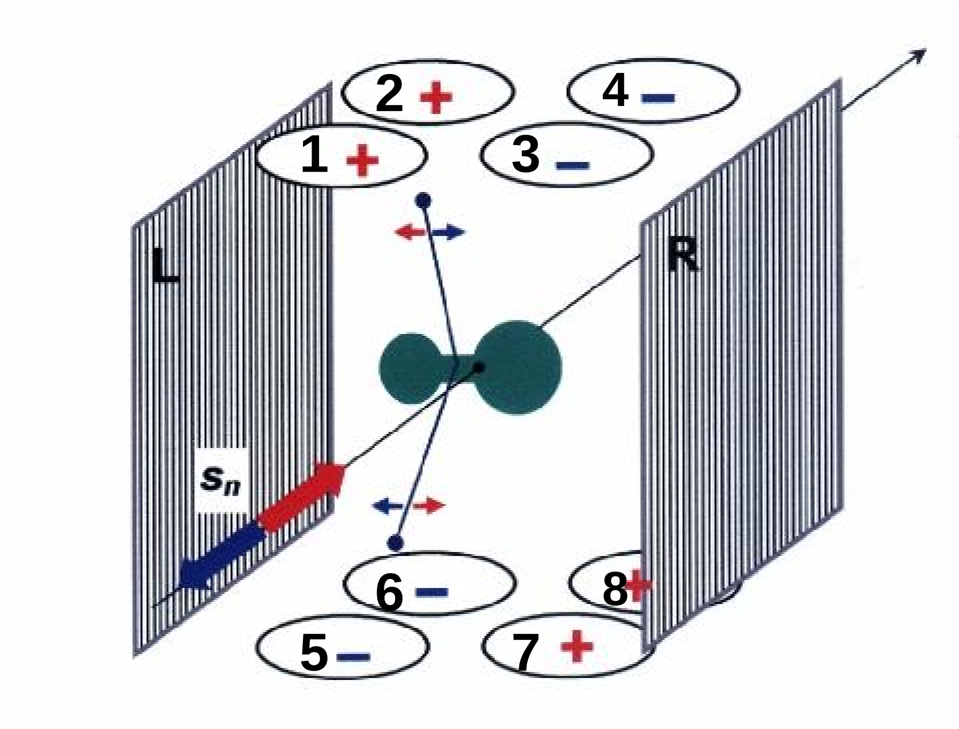
Fission fragments are detected by MWPCs mounted on the **x** axis.

Ternary Particles are intercepted by 8 SBDs which are positioned on the **y** axis.

Reference reaction:
Light Fragment towards **+x**
Ternary particles towards **+y**

TARGET : ^{235}U

The ROT EFFECT in experiment



Reference reaction:

Light Fragment to the Left

Ternary Particle Upwards

For neutron spin polarized along the z-axis the **Asymmetry**

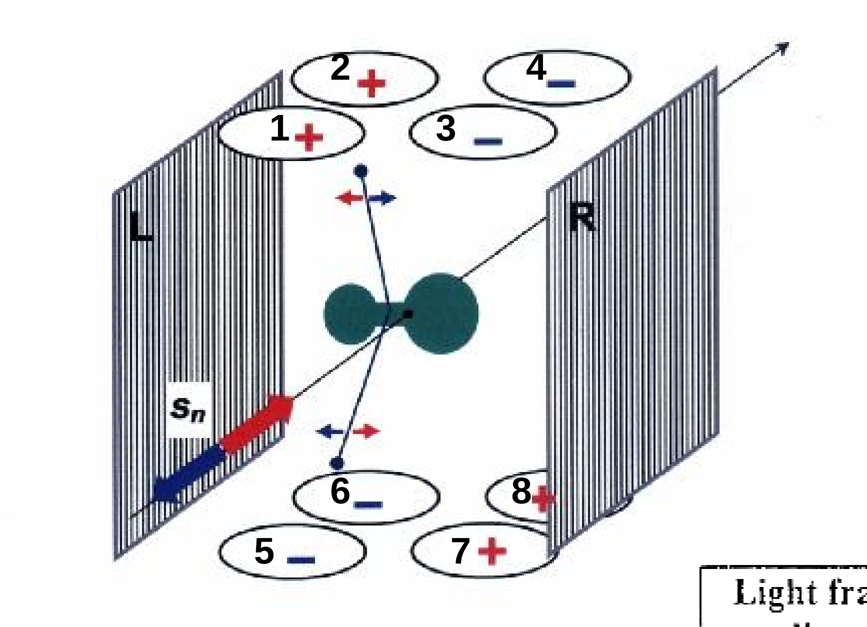
$$A_Z = (N_{+Z} - N_{-Z}) / (N_{+Z} + N_{-Z})$$

is measured by the spin flip technique.

For the reference reaction a pattern of signs for the asymmetry A is observed. All other reaction types fit into the same scheme with due account of sign flips.

The pattern suggests a rotational shift of ternary particle emission.

The Size of the ROT Effect



On average the absolute size of the asymmetry $|A_Z|$ is

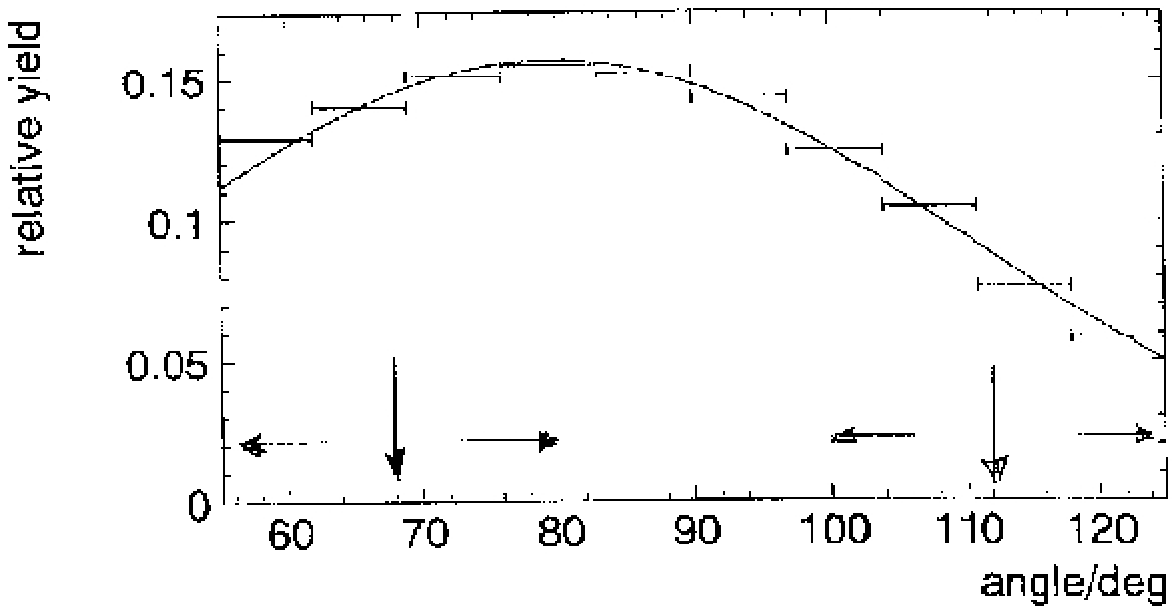
$|A_Z| = (3.3 \pm 0.13) \cdot 10^{-3}$

Per diode the ROT Effect is a

≈ 6σ Effect

Light fragment direction	Diode	$A_Z \times 10^3$	Diode	$A_Z \times 10^3$
Left	1	+ 2.85(38)	5	− 3.03(51)
Left	2	+ 3.18(41)	6	− 3.12(41)
Left	3	− 3.95(59)	7	+ 3.51(59)
Left	4	− 5.35(67)	8	+ 2.59(87)
Right	1	+ 4.31(54)	5	− 3.76(77)
Right	2	+ 4.32(60)	6	− 2.88(62)
Right	3	− 3.63(44)	7	+ 2.32(45)
Right	4	− 2.73(49)	8	+ 2.55(66)

Angular Distribution of Ternary Particles



Angular distributions of ternary particles are given for the angle θ between

Light Fragment and **Ternary Particle.**

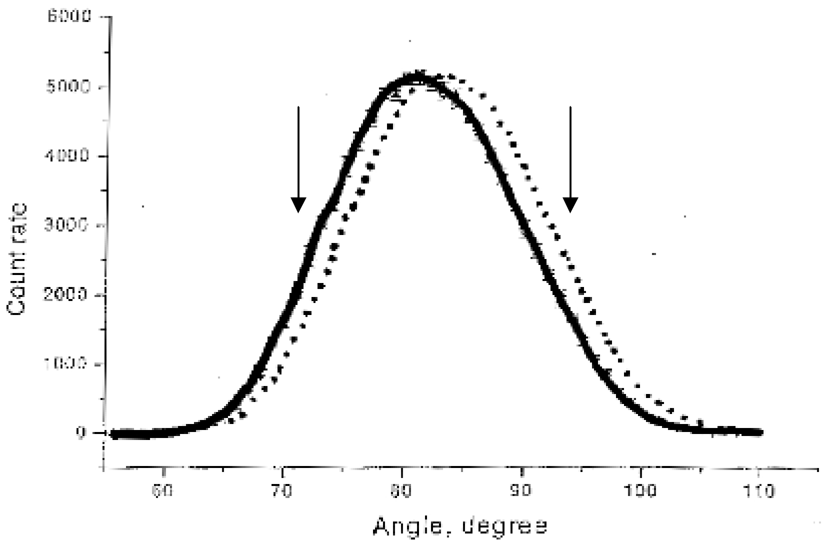
The average anlge is θ ≈ 80°.

SBDs 1,2,5 and 6 were centered at the angle θ = ± 68°.

SBDs 3,4,7 and 8 were cenetred at the angle θ = ± 112°.

From RUN 2

MODEL for ROT EFFECT



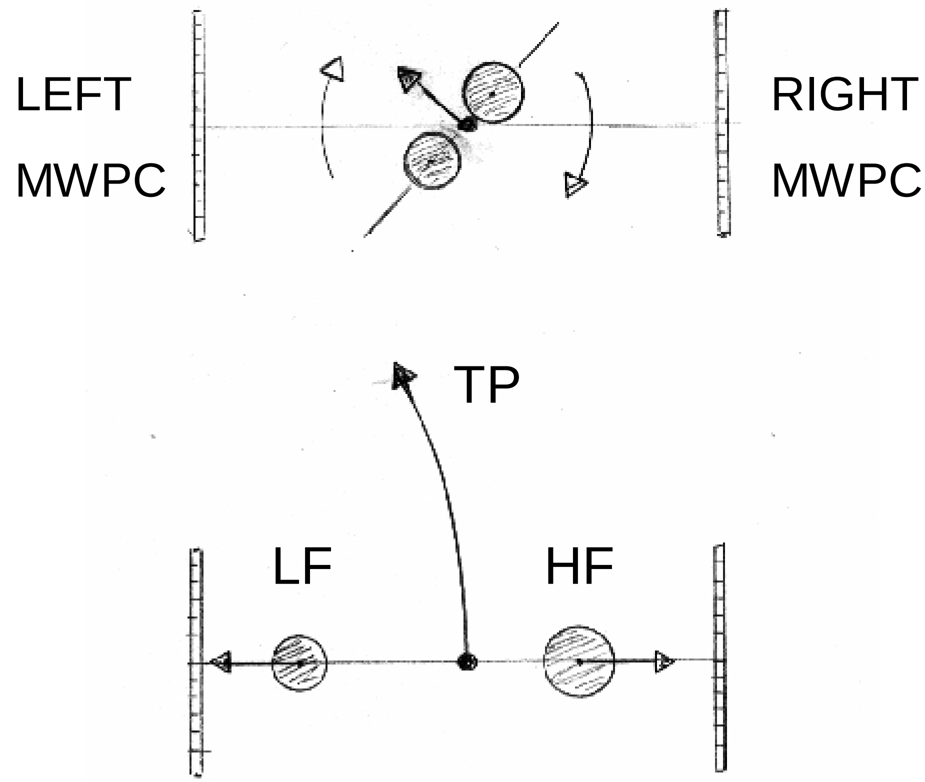
Angular Distributions for

Detector Combination: LEFT - UP

━━━━━━ $P_Z > 0 \leftrightarrow \omega_Z > 0$

⋯⋯⋯⋯ $P_Z < 0 \leftrightarrow \omega_Z < 0$

$\omega_Z > 0$ at $t = 0$ s



$\omega_Z = 0$ at $t = ..10^{-21}$ s

Fissioning Rotating Nucleus

Following capture of a polarized neutron

the nucleus is polarized

$$P(J^+) = \frac{(2I+3)}{3(2I+1)} \cdot P_n \qquad \text{for } J^+ = I + ½ = 4\hbar$$

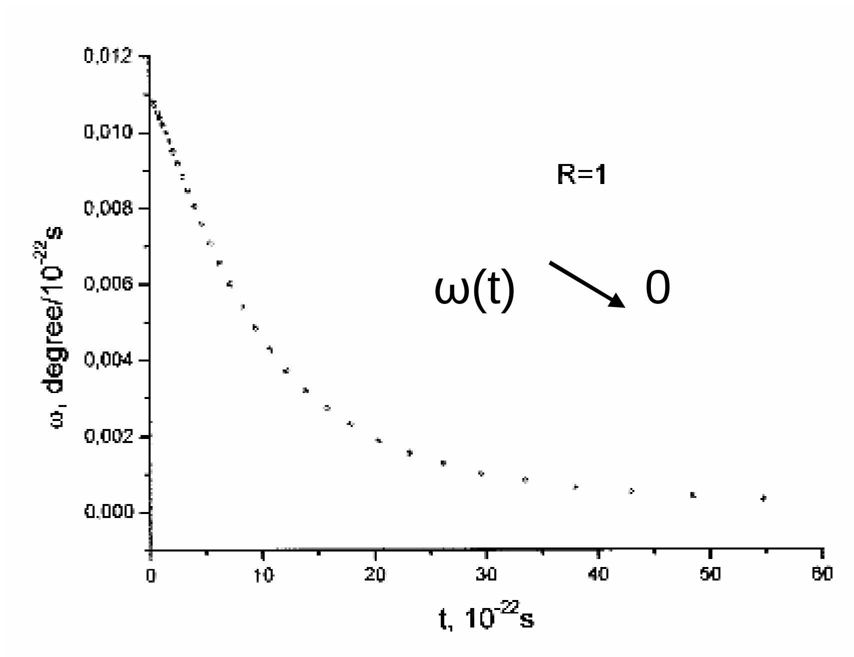
$$P(J^-) = -P_n/3 \qquad \text{for } J^- = I - ½ = 3\hbar$$

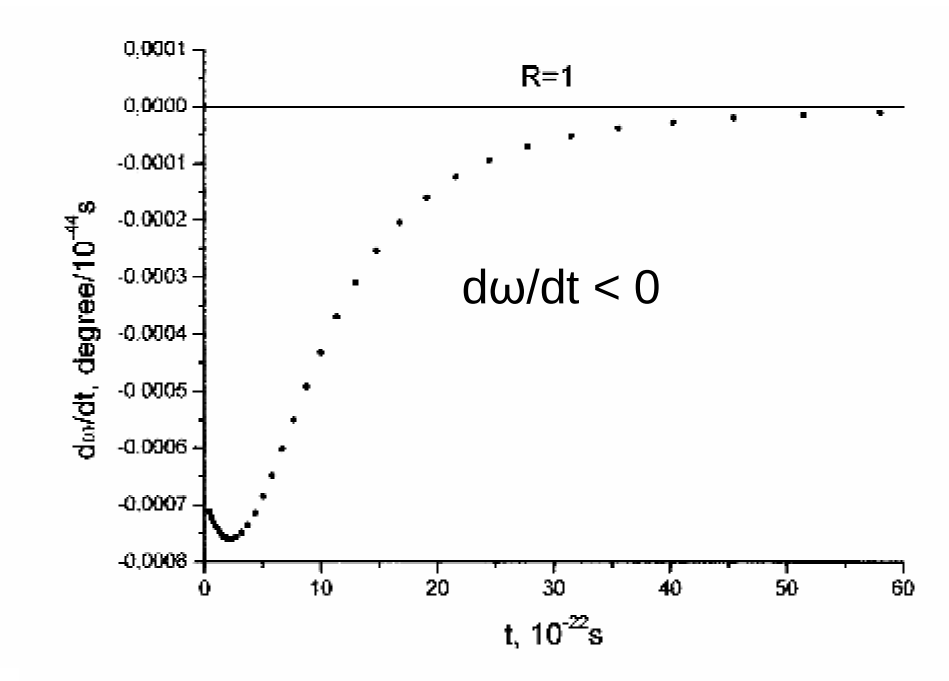
and may perform a

collective rotation

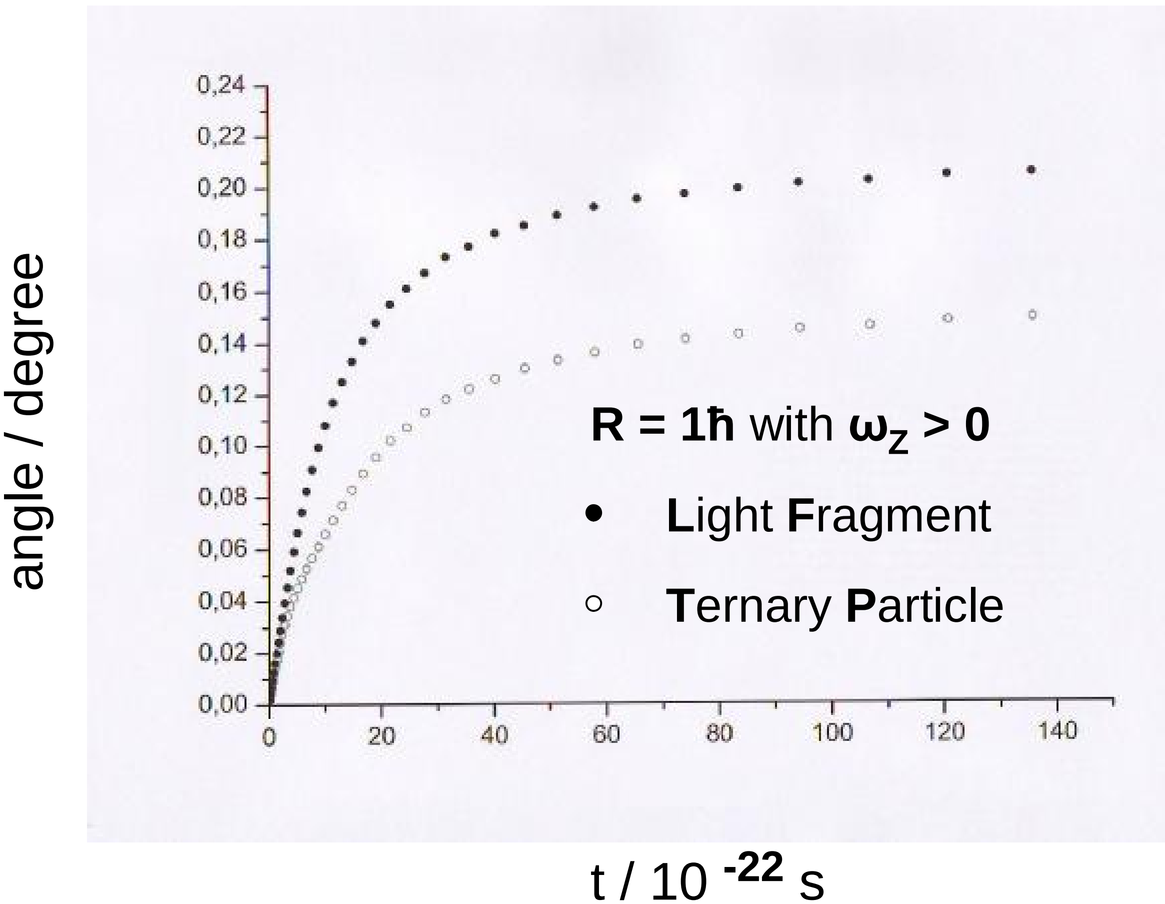
$$E_{rot} = \frac{\mathbf{h}}{2\Im_\perp}(J(J+1) - K^2)$$

$$w^2\Im_\perp^2 = \mathbf{h}^2 \cdot (J(J+1) - K^2)$$





Trajectory Calculations



While system rotates

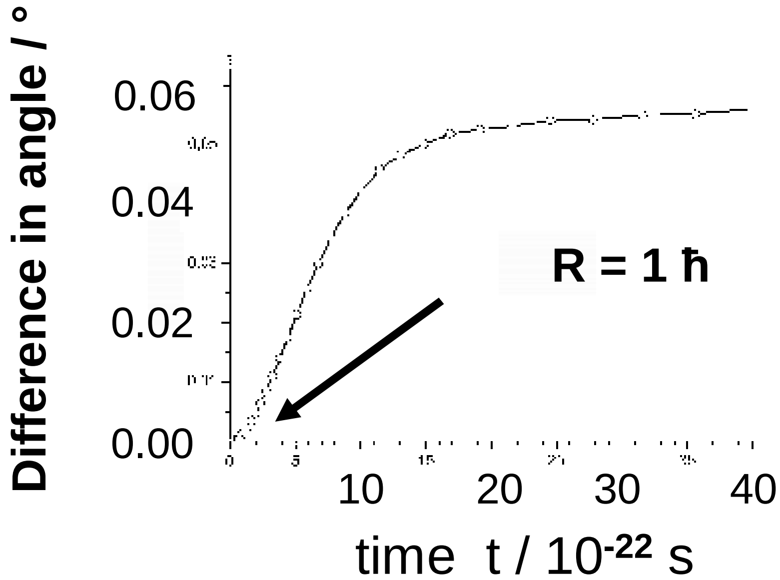
the Ternary Particle

is carried along

but lags behind

Figure is for „Left-Up“

Difference in angle between LF and TP, and particle positions as a function of time

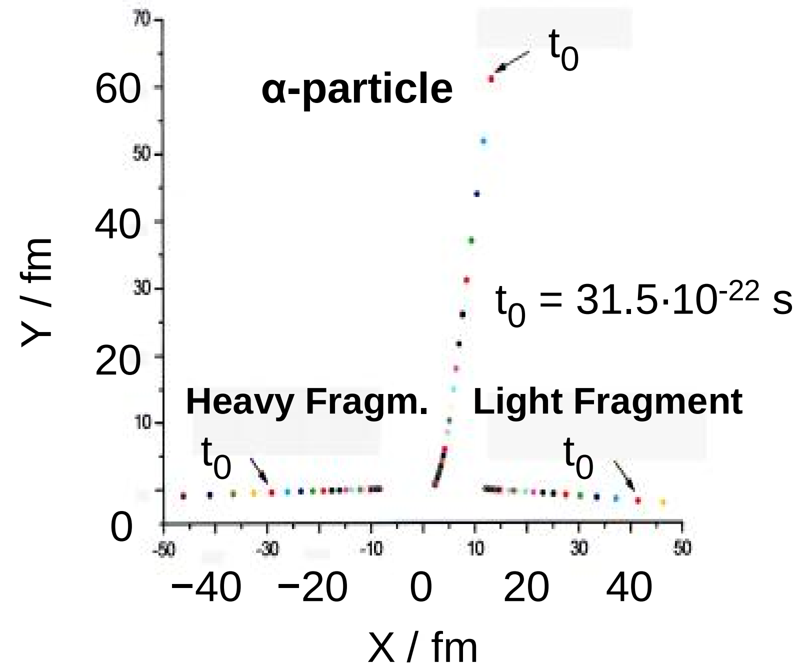


Only in the first 10^{-22} s

the TP follows closely

the rotation of the mother

nucleus (the light fragment).

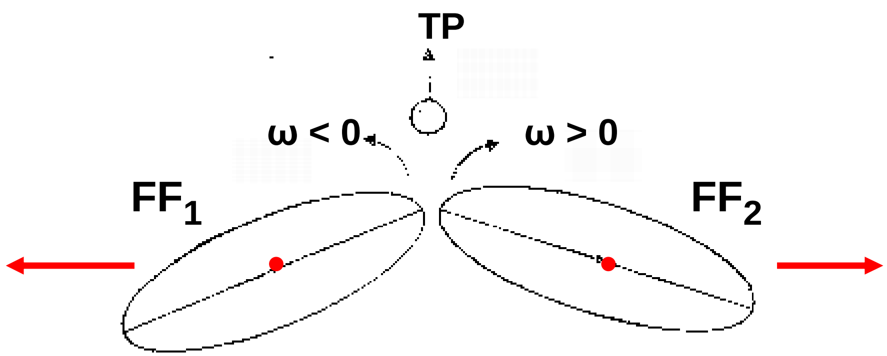


Trajectory calculations show that in

the first Δ t = 10·10-22 s = 1 zs

the α-particles travel about 10 fm

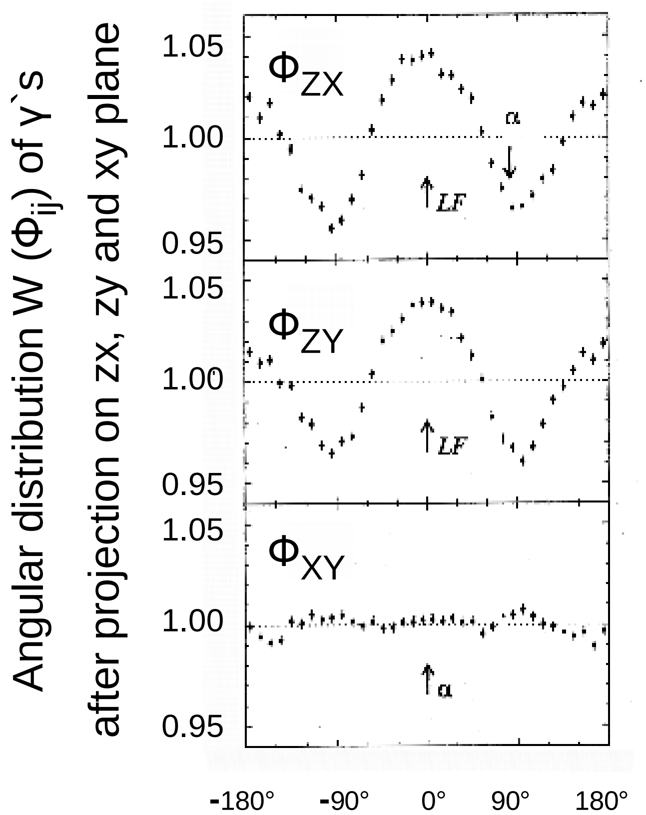
Fragment Spin and TP Emission



$I_{FF} \perp$ plane of figure

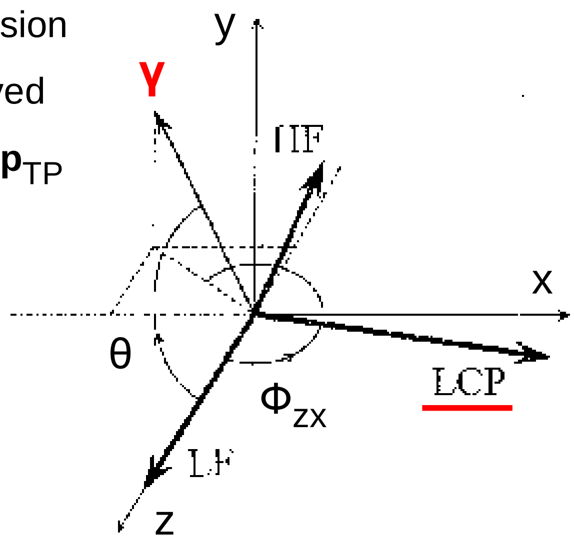
Spins of Fission Fragments

1) Spins are large: up to 10ħ and beyond
2) Spins do not depend on compound spin
3) Spins are oriented ⊥ fission axis
4) In the fashionable bending model of FF spin a correlation spin ⟷TP emission is suggested



In $^{252}Cf(sf)$ experiment by Yu.Kopatch et al. (1999) :

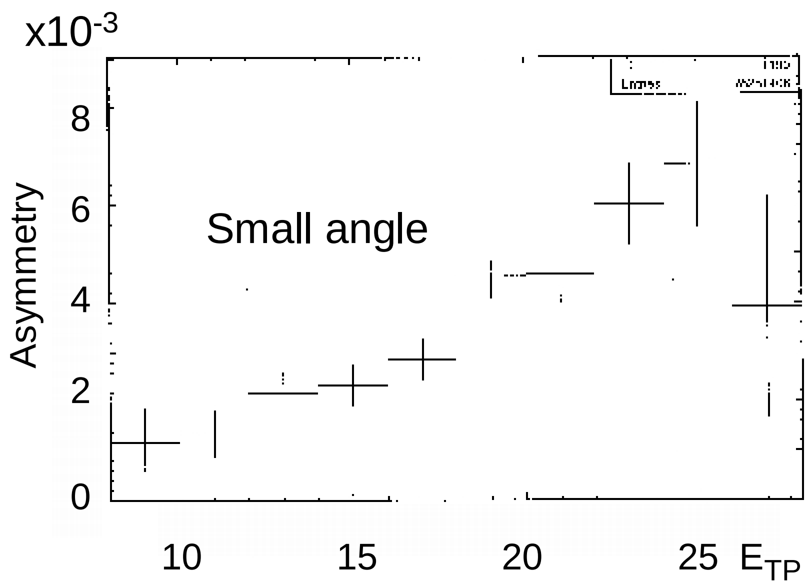
1) Anisotropy of (γ,LF) correlation the same in bin. and ternary Fission
2) No correlation (γ,TP) is observed though expected in case $I_{FF} \perp p_{TP}$

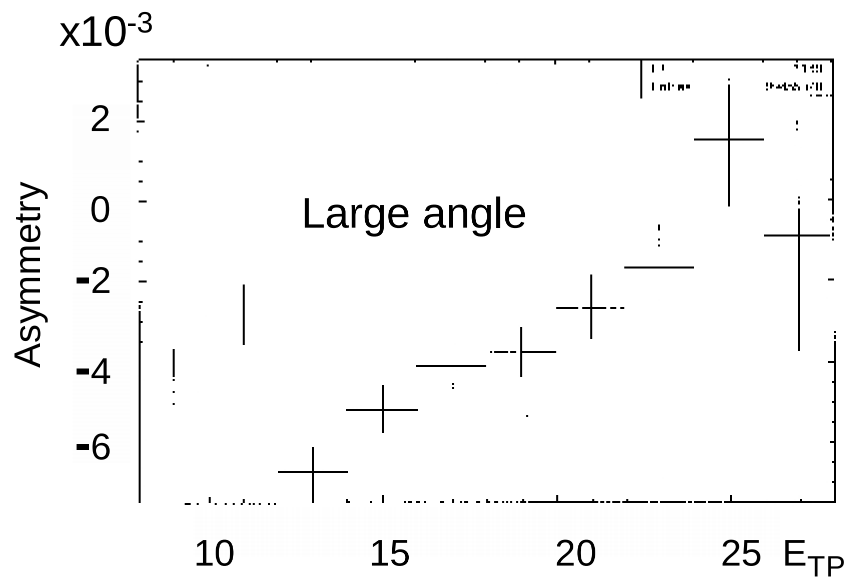


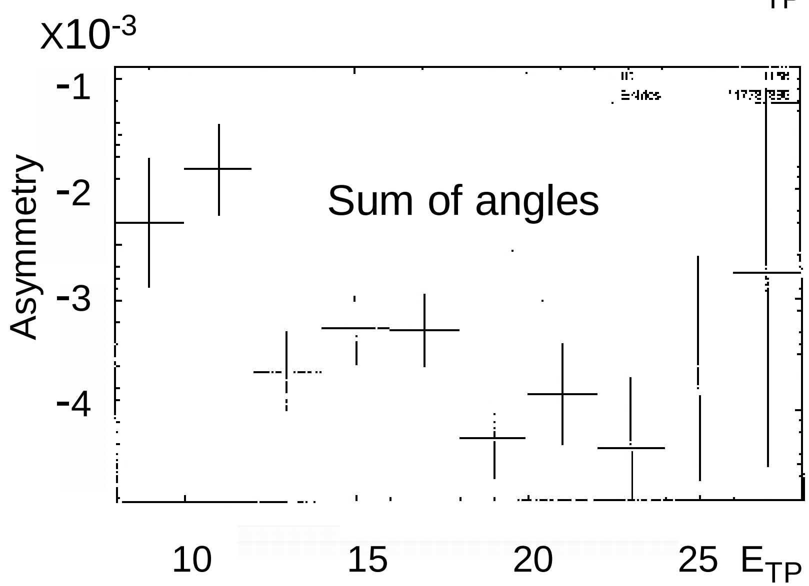
Conclusion

no correlation between Spin of FF and TP

Dependence of ROT Effect on TP Energy







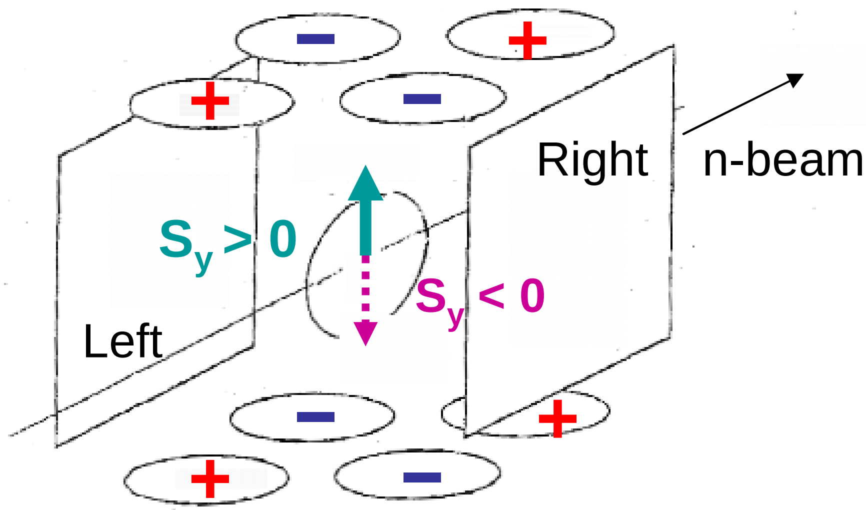
Reaction ^{235}**U(n,f)** from Run 6:

The modulus of ROT Asymmetry $|A|$

increases with E_{TP} for small θ

but decreases with E_{TP} for large θ

ROT EFFECT for Y- and X- POLARISATION



For Polarisation along

Y-axis determine

$$A_Y = (N_{+y} - N_{-y}) / (N_{+y} + N_{-y})$$

Observed:

$$|A| = 1.1(3) \cdot 10^{-3}$$

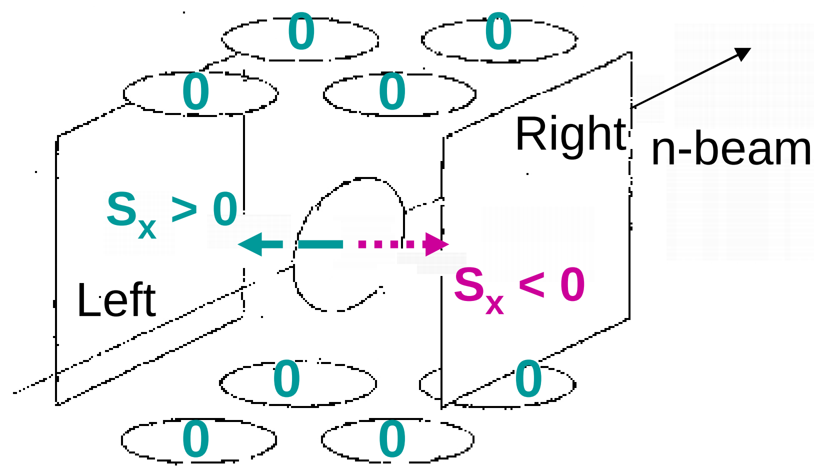
For Polarisation along

X-axis determine

$$A_X = (N_{+x} - N_{-x}) / (N_{+x} + N_{-x})$$

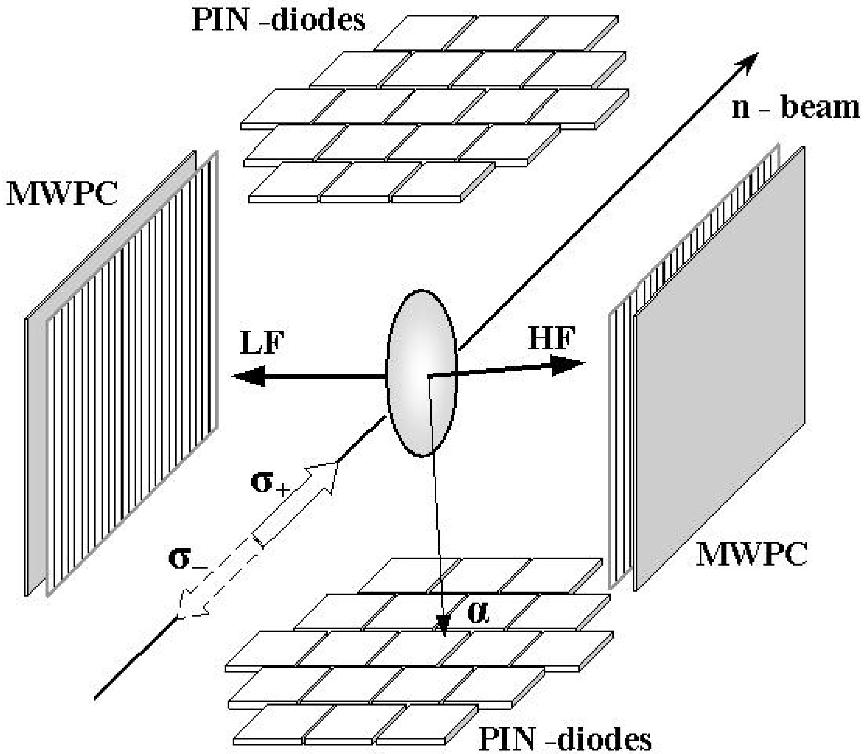
Observed:

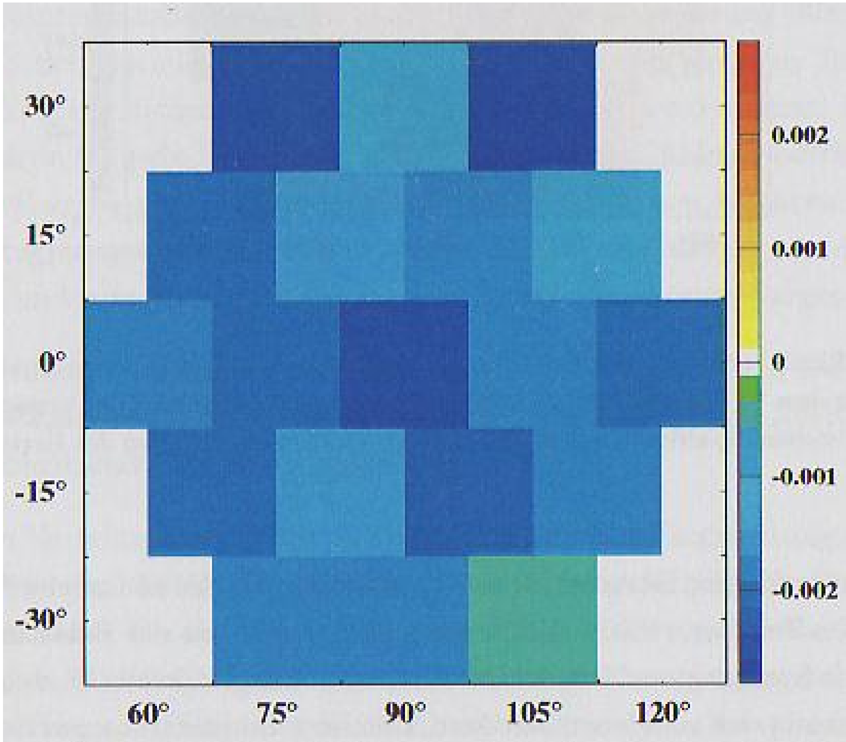
$$A = 0.06(15) \cdot 10^{-3}$$



The TRI Effect in Experiment

Reaction: $^{233}U(n_{th},f)$





From Run 2

Experimental Setup

Detector combination chosen for reference:

Light Fragment to the Left MWPC

Ternary Particles to upward array of PIN diodes

Experimental Result

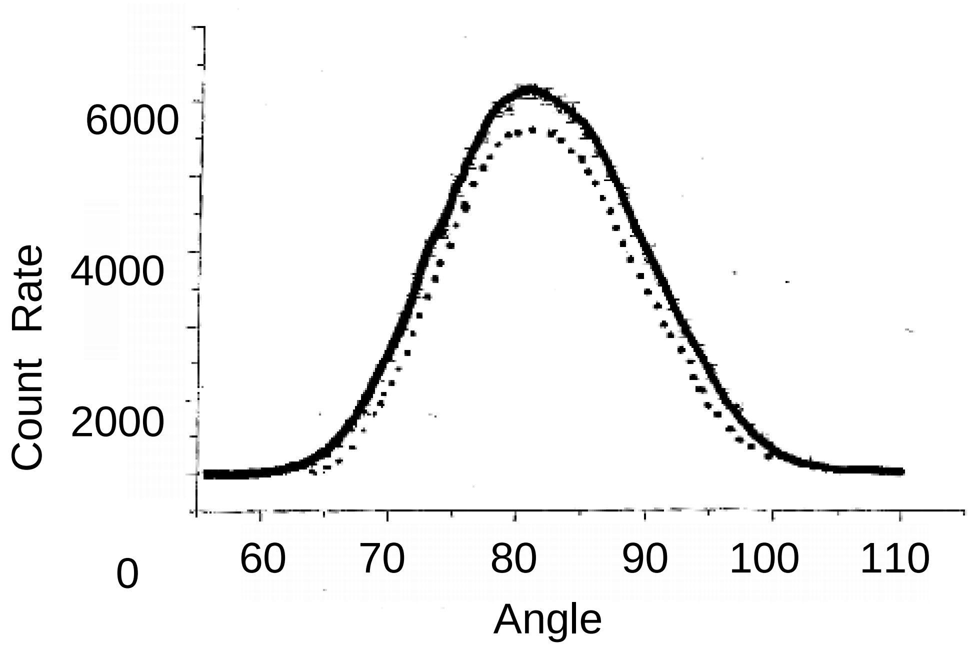
Evaluate Asymmetry A_Z

$A_Z = (N_{+Z} - N_{-Z}) / (N_{+Z} + N_{-Z})$

Note the constancy of A_Z

The TRI – Effect

Originally the experiment was motivated by the search for a T-odd triple correlation B :



Standard : LF to the Left and TP Upwards

▬▬▬▬ n-spin $s_Z = + ½ \hbar$

▪▪▪▪▪▪▪ n-spin $s_Z = - ½ \hbar$

In the example D would be D > 0

$$B = \boldsymbol{\sigma}\cdot[\mathbf{p}_{LF} \times \mathbf{p}_{TP}] = \mathbf{p}_{TP} \cdot[\boldsymbol{\sigma} \times \mathbf{p}_{LF}]$$

(note: all vectors are unit vectors)

Expected angular distribution of TPs :

$$W(\theta)\, d\Omega \sim \{1 + DB(\theta)\}\, d\Omega$$

where D measures size of correlation.

Experiment: $D = (N_{+z} – N_{-z}) / (N_{+z}+N_{-z})$

Result : **count rates** for LF to the Left and TP upwards are **different** for $s_Z = +½\hbar$ and $s_Z = −½\hbar$, but (almost) independent of angle θ.

This is visualised in the figureto the left.

Note difference between TRI and ROT

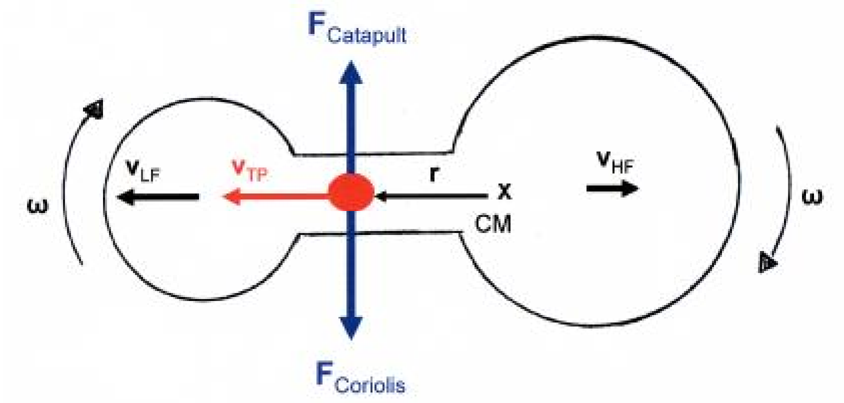
For $^{233}U(n.f)$: **D ≈ - 4·10^{-3}**

Naive Model of the TRI Effect

Equation of Motion in the intrinsic coordinate system of a rotating nucleus

$$m\, d\mathbf{v}/dt = -\,\partial U / \partial \mathbf{r} + 2m\mathbf{v} \times \boldsymbol{\omega} + m\boldsymbol{\omega} \times (\mathbf{r} \times \boldsymbol{\omega}) + m\mathbf{r} \times d\boldsymbol{\omega}/dt$$

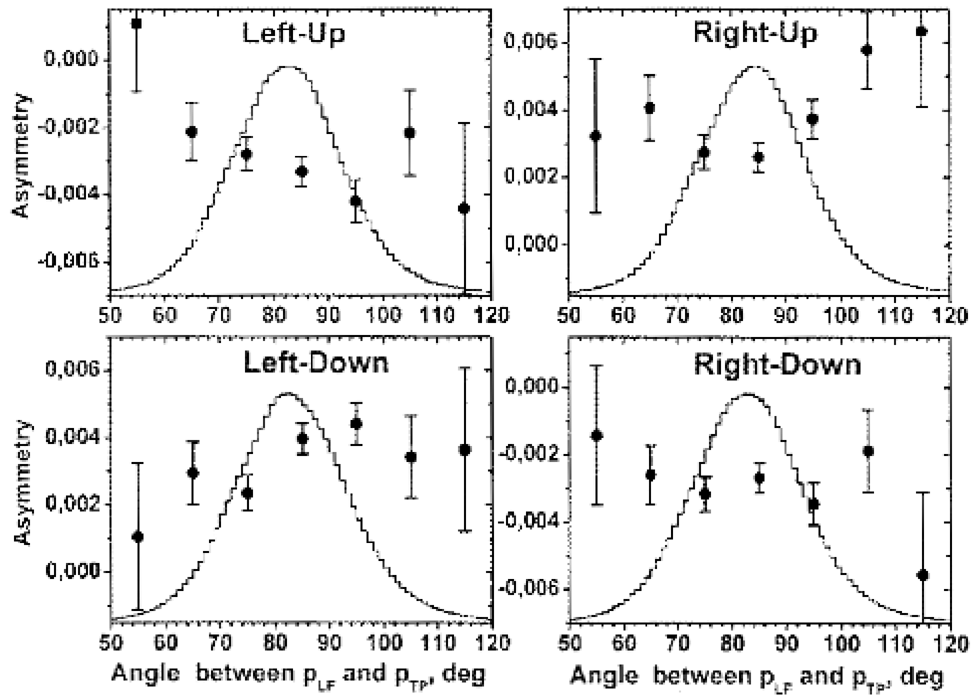
Conservative + Coriolis + Centrifugal + Catapult Forces



Note : the Coriolis force and the catapult force may cancel each other

Disentangle ROT - and TRI – Effects

in the reaction $^{233}U(n,f)$ from ILL Run 3



The dependence of asymmetry on angle LF-TP is analysed in terms

of a constant TRI effect plus an angle dependent ROT effect

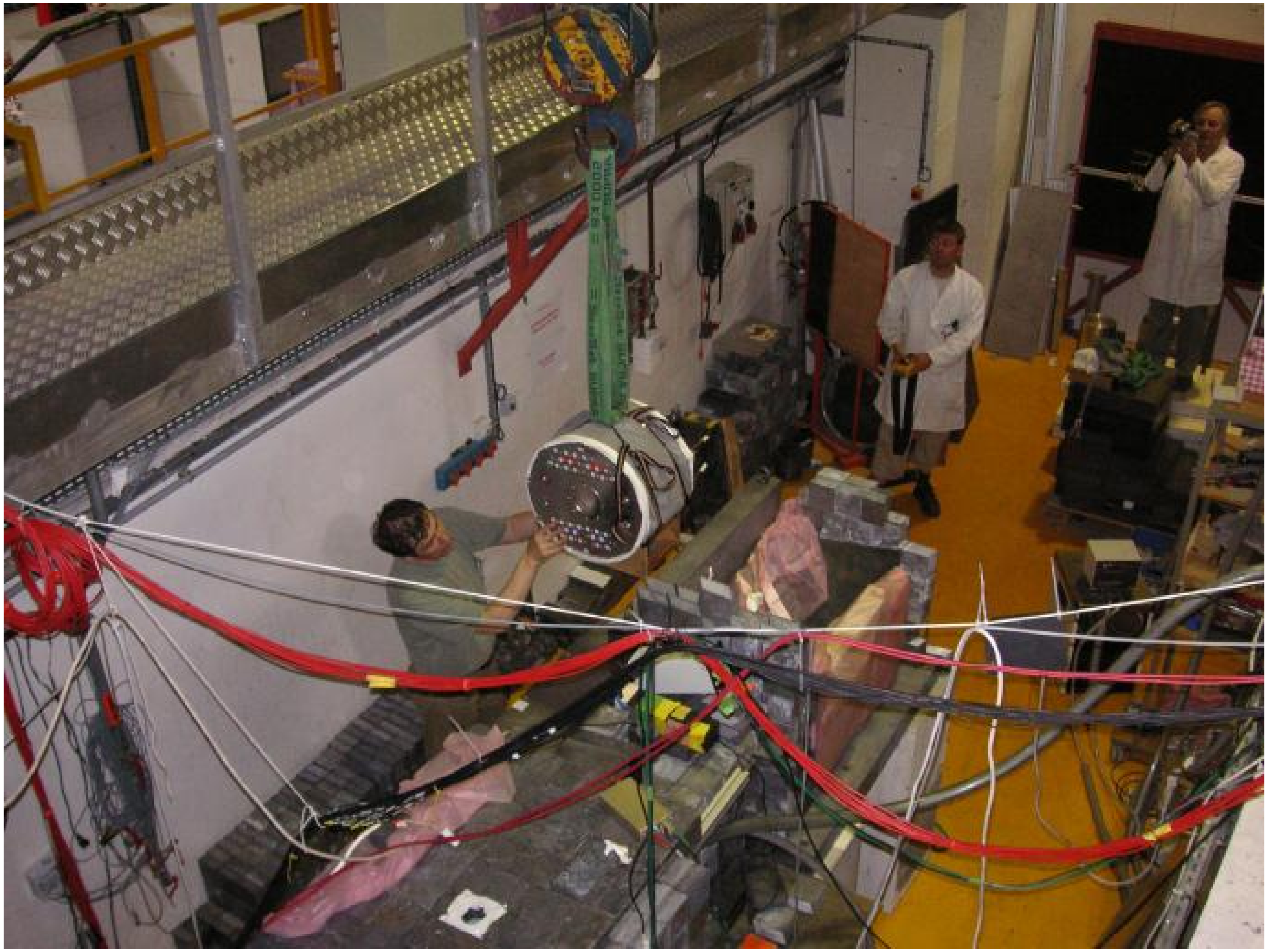
Preliminary result: **TRI effect: $D \approx 3.5 \cdot 10^{-3}$;**

ROT effect: $|A_Z| \approx 1 \cdot 10^{-3}$ at angles 70° and 95°

Setting up the neutron beam

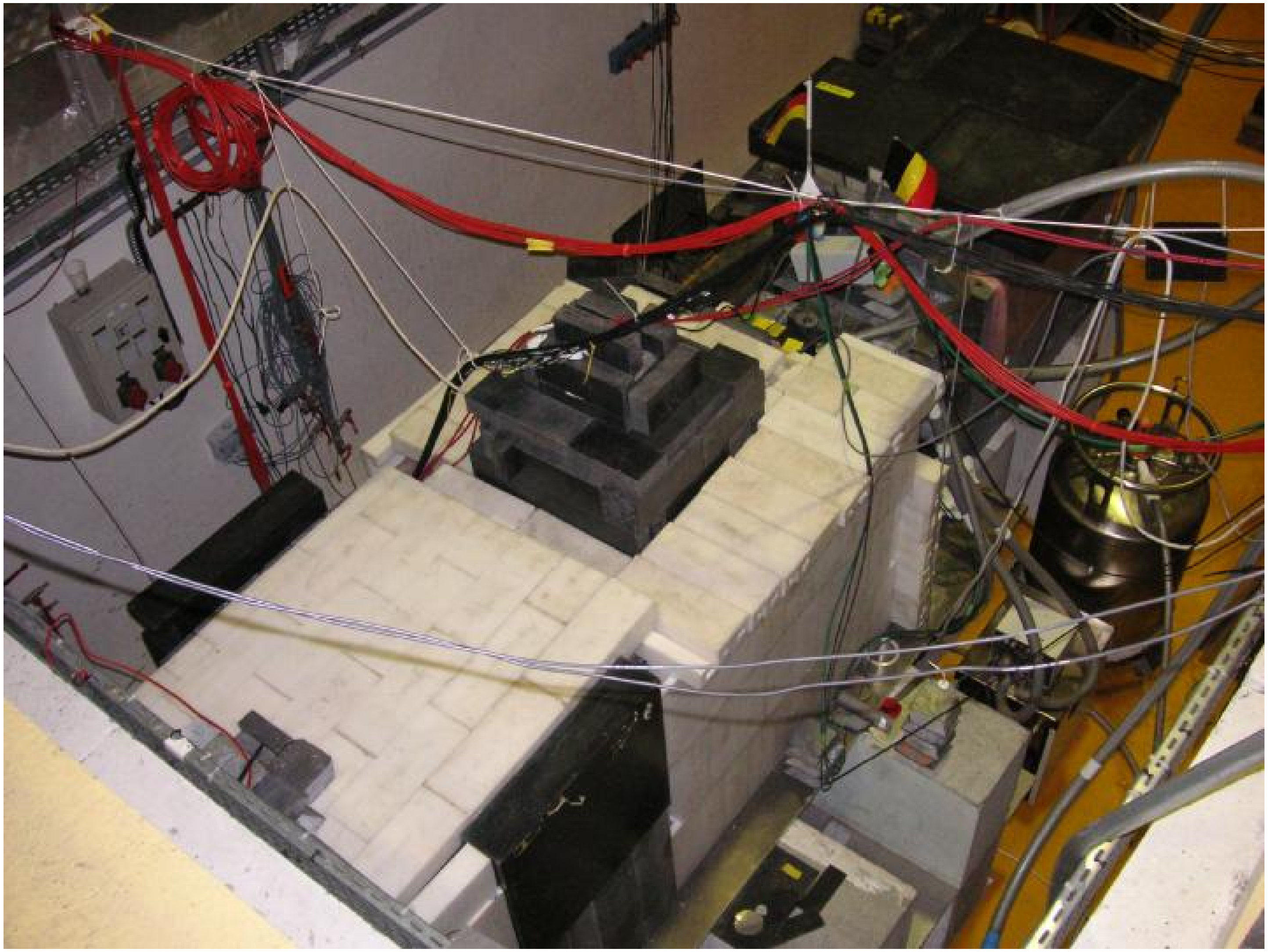
The chamber is approaching

The chamber is landing

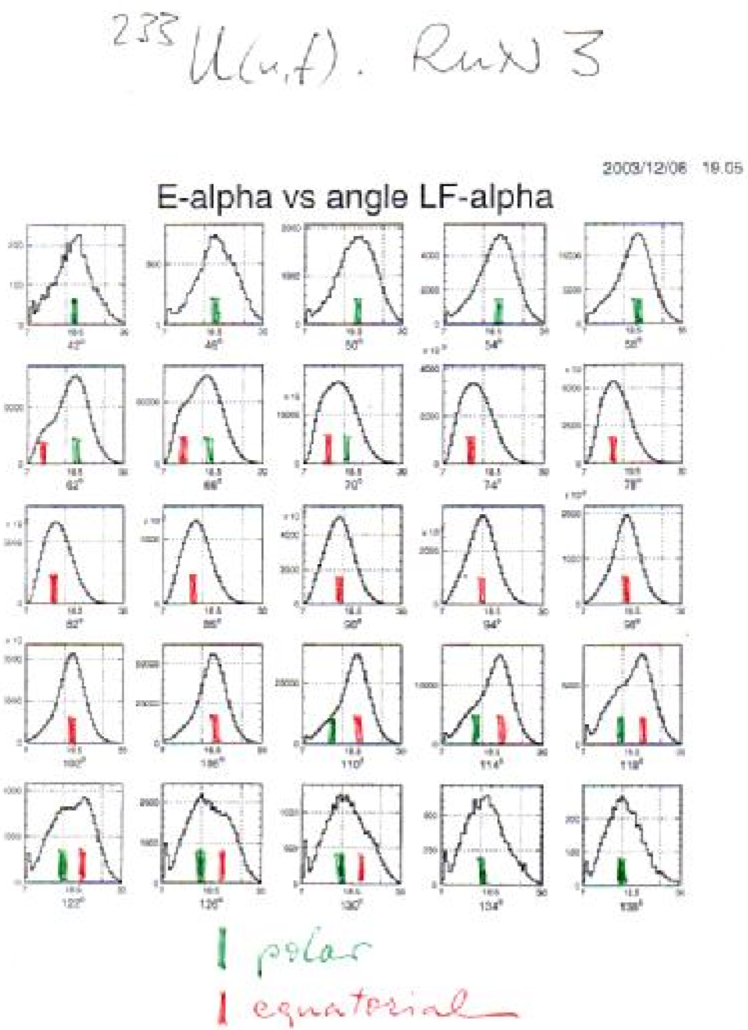


The chamber is in place

The experiment is ready to start



Energy distributions of TPs for given LF-TP angles



Reaction **^{233}U(n,f)**

from RUN 3

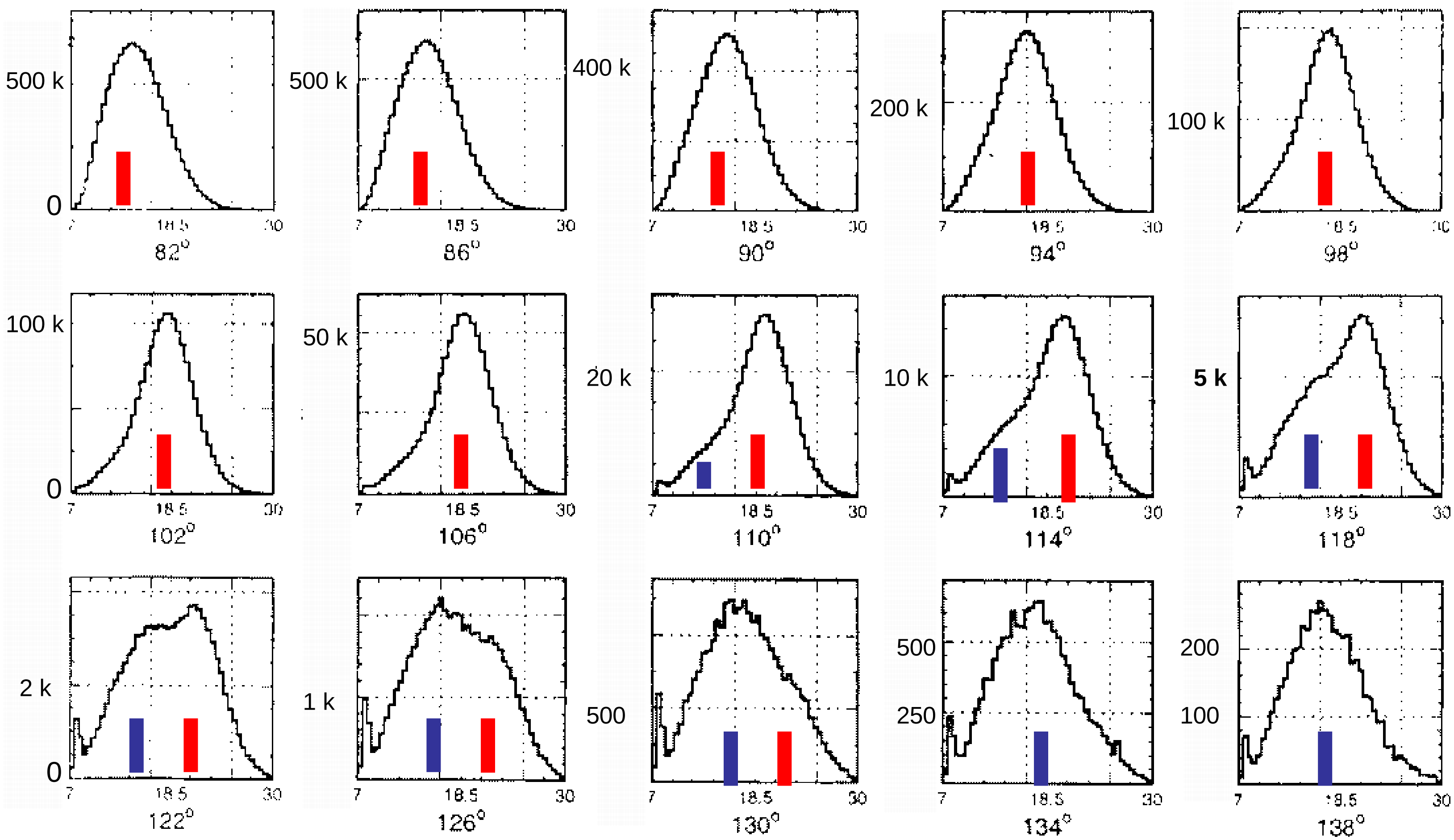
Polar TPs from LF come in Figure at angles from 42° to 70°.
They exhibit a constant TP energy

Polar TPs from HF come in Figure at angles form 110° to 138°.
They exhibit a constant TP energy

Equatorial TPS come in Figure at angles from 62° to 130°.
They exhibit a TP energy which increases from small to large angles

Energy of TPs for angles > 80°

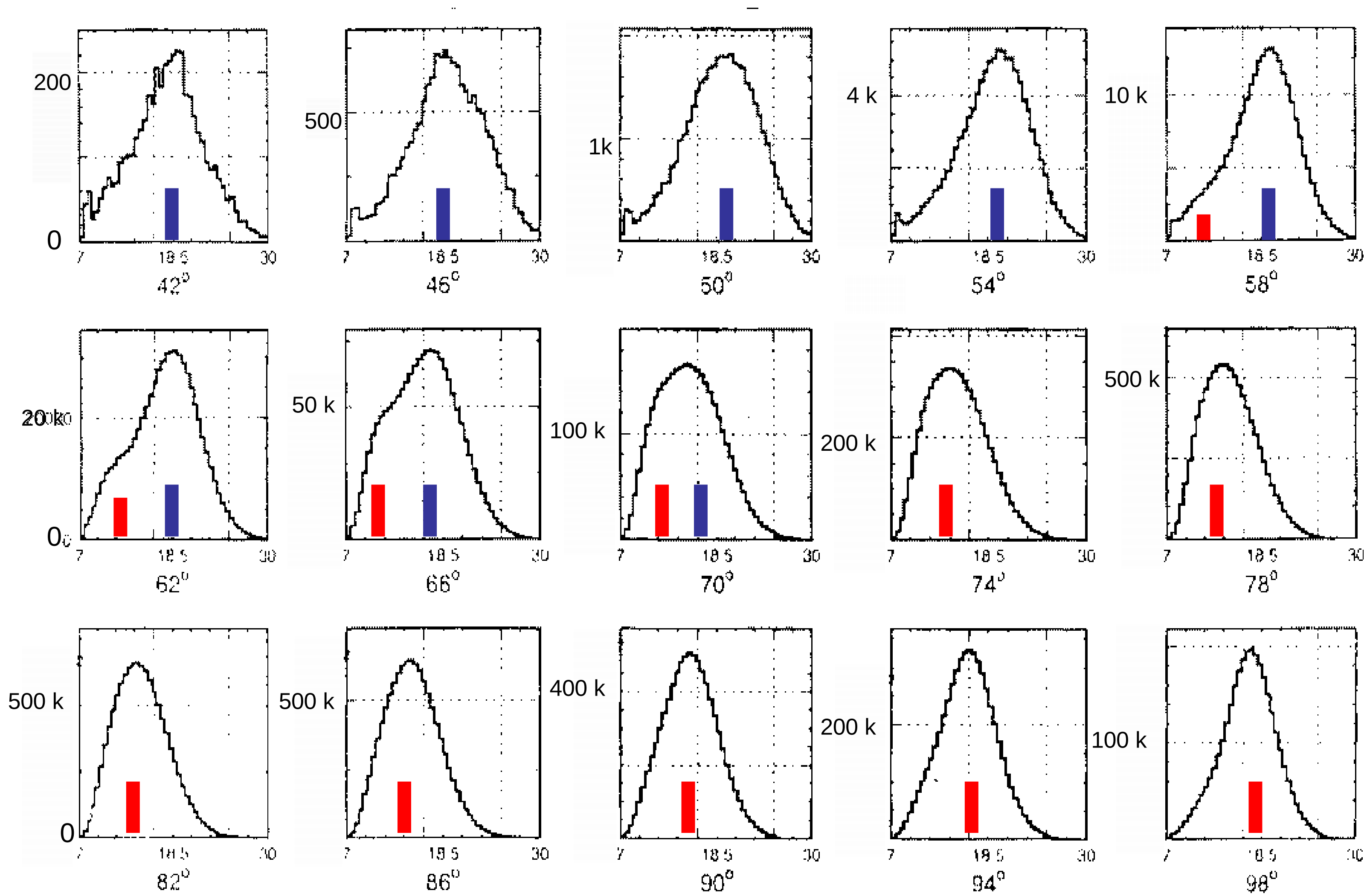
CONJECTURE : EQUATORIAL TPs POLAR TPs



AAA

Energy of TPs for angles < 100°

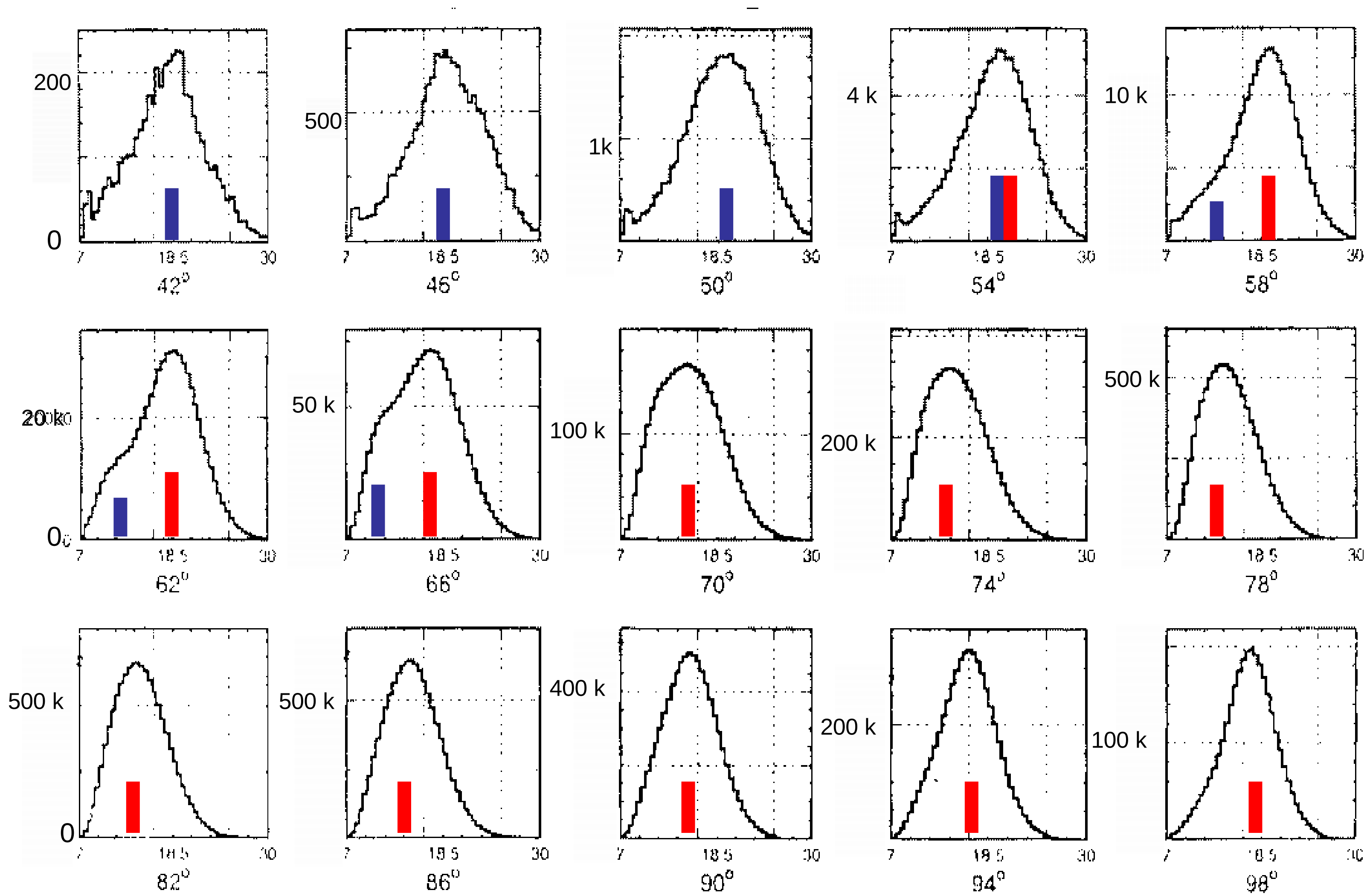
CONJECTURE : EQUATORIAL TPs POLAR TPs



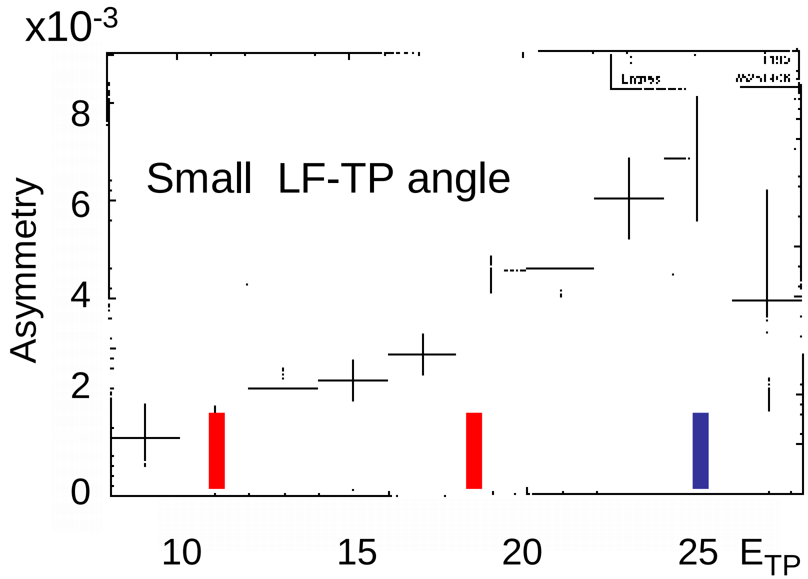
BBB

Energy of TPs for angles < 100°

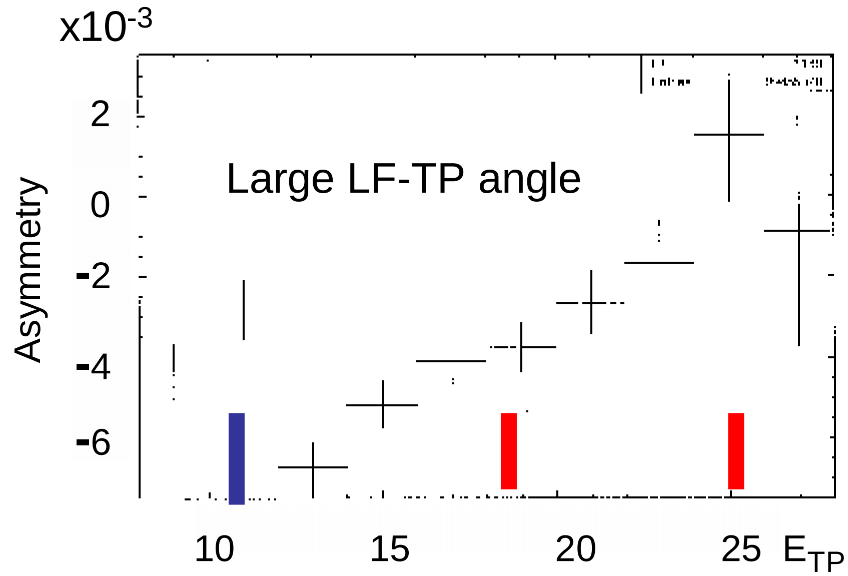
CONJECTURE : EQUATORIAL TPs (red) POLAR TPs (blue)



Polar and Equatorial TPs in the ROT Effect



Small angle: 56° - 80°



Large angle: 100° - 124°

Reaction **$^{235}U(n,f)$** from Run 6:

The modulus of ROT Asymmetry |A|

increases with E_{TP} for small θ

but decreases with E_{TP} for large θ

polar

equatorial