Experimental Investigations of Ternary Fission of Heavy Nuclei

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Contents

- **Introduction: What is Ternary Fission?**
- **Experimental Access by Advanced Correlation Experiments:**

Crystal Ball (NaI) experiment

^{252}Cf(sf) – MPI Heidelberg

Super-Clover Ge (VEGA) experiment

^{252}Cf(sf) – GSI Darmstadt

Neutron-induced fission at ILL (Grenoble)

^{235}U(n,f) – ILL Grenoble

Full energy spectrum of α-particles

^{252}Cf(sf) – JYFL Jyvaskyla

Quaternary Fission experiments

^{252}Cf(sf) – GSI Darmstadt

^{233,235}U(n,f) – ILL Grenoble

Selected Results:

- Neutron emission in TF $\Rightarrow$ Formation of neutron-unstable LCPs (5He, 7He, 8Li*)
- Fragment spin alignment
- Isotope yields for ^{252}Cf
- Isotope yields for ^{235}U(n,f)
- Manifestation of shell effects in ternary fission
- Deviation of α-particle energy distribution from Gaussian shape
- Formation of two LCPs (α-α, α-t): "pseudo-" and "true" quaternary fission

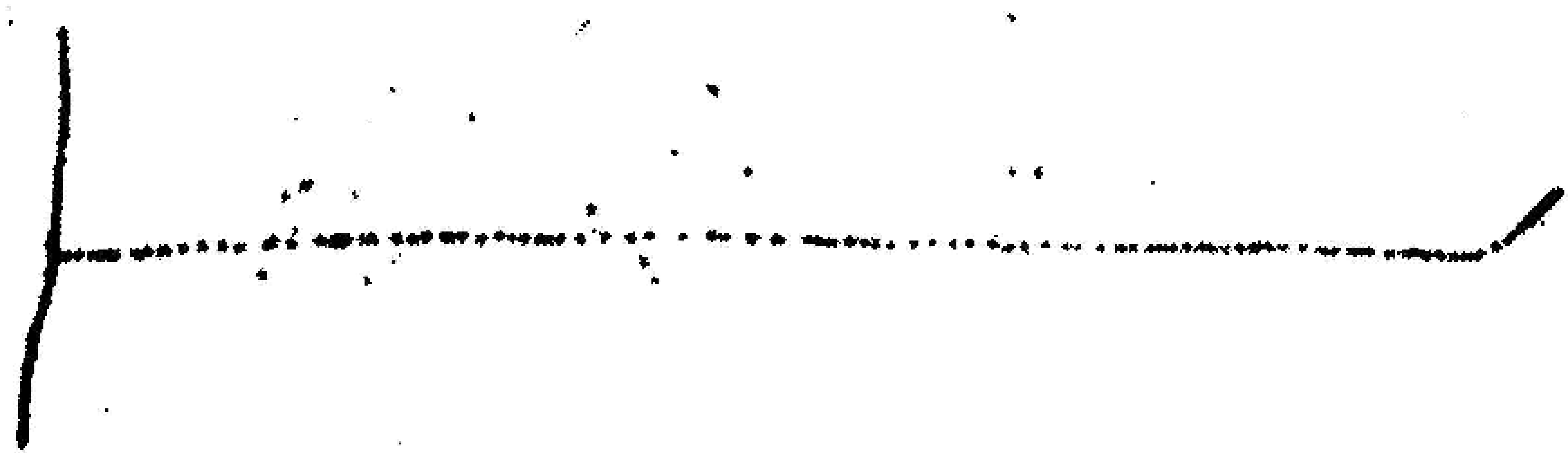
- **Summary and Outlook**

Ternary Fission – nuclear fission, accompanied by emission of a Light Charged Particle (LCP accompanied Fission)

Quaternary Fission – simultaneous emission of 2 LCP's

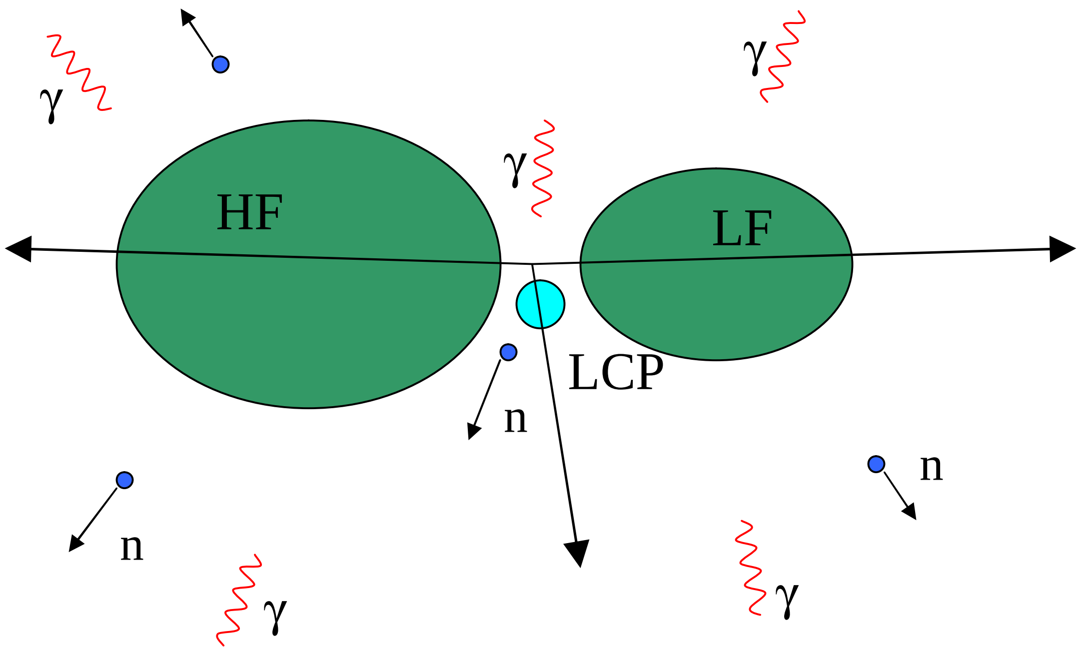
Quinary Fission – 3 LCP's

Discovery of ternary fission



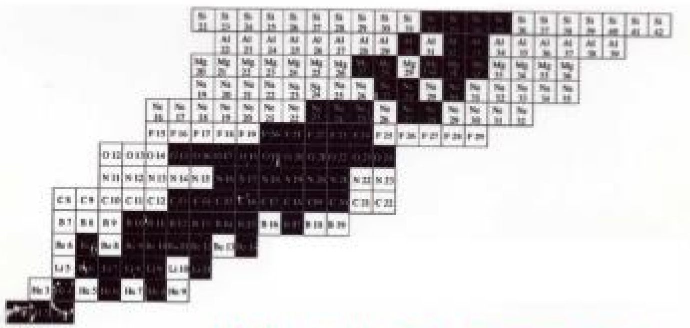
Tsien San-Tsiang *et al.*, Phys. Rev. **71**, 382 (1947)

Some Parameters of Ternary Fission

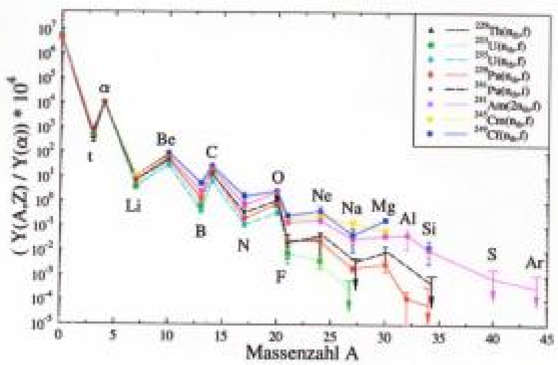


- Yield (TF) » 1/300 for ^{252}Cf (sf)
  1/500 for ^{235}U (n,f)
- LCP’s are emitted nearly perpendicular to the fission axis
- > 90% of all ternary particles are a-particles
- Yields of heavier particles drastically decreases with the increase of LCP mass
- The energy distribution of LCP has nearly Gaussian shape with <E_a> » 15 MeV
- The emission of LCP slightly changes energy and mass distributions of fission fragments as well as other parameters, e.g. `n, M_g etc.
- Ternary fission is a unique tool to study the energetics and dynamics of the fission process at scission.

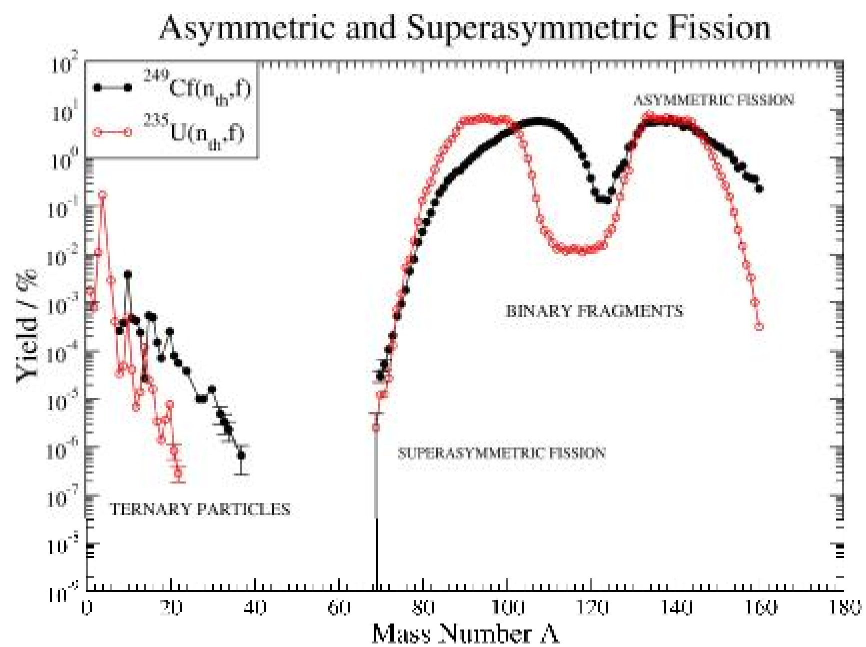
LCP yields from n_{th}- induced reactions



M- Wöstheinrich, Thesis, Tübingen (1999)



F. Gönnenwein et al., Pont d´Oye (1999)

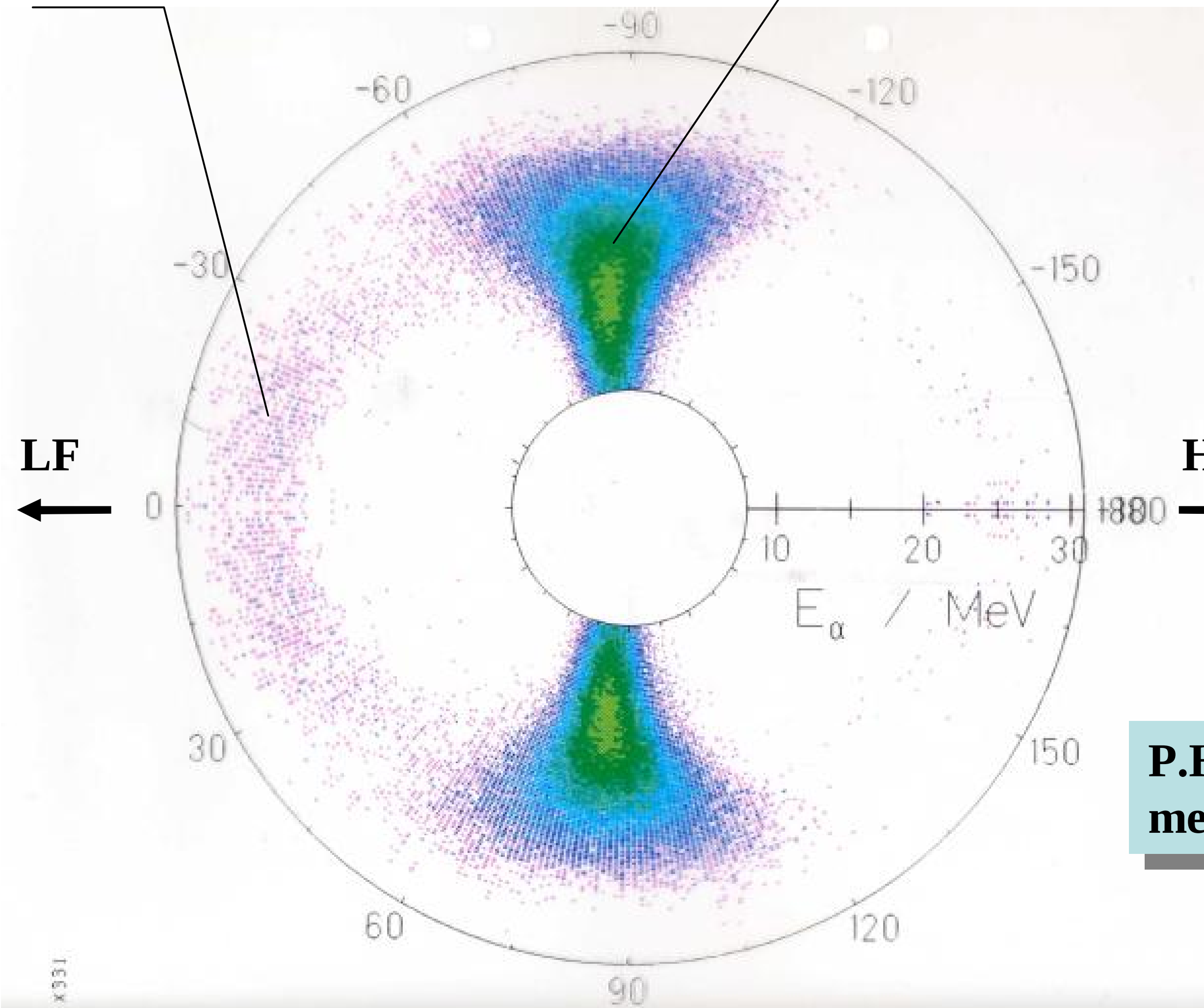


Angle-energy correlation for α-accompanied fission in polar coordinates.

Polar α's

Equatorial α's
mean angle $\theta_{\alpha L} = 83^0$

LF



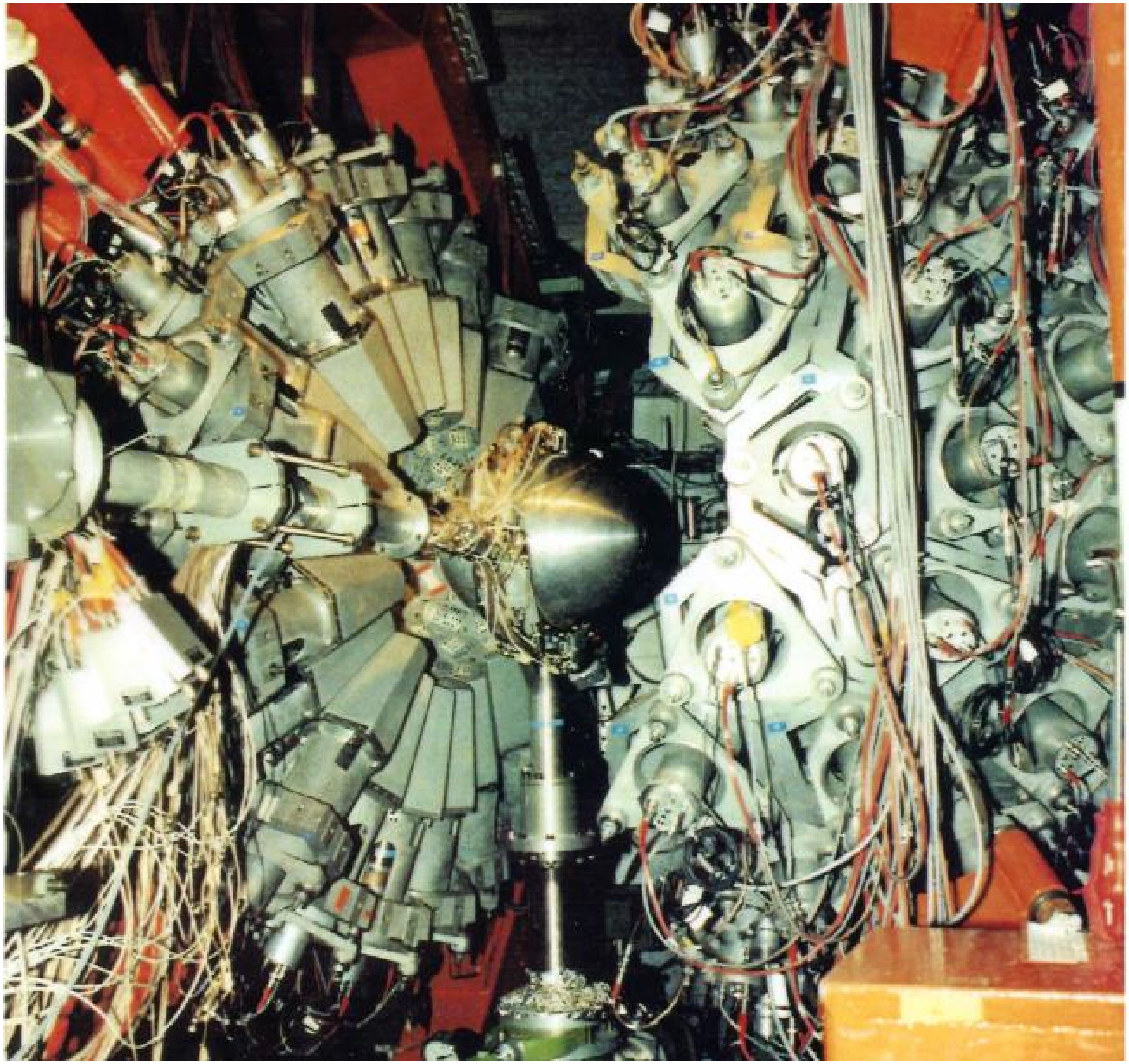
HF

P.Heeg et al. (1990)
measured with "DIOGENES"

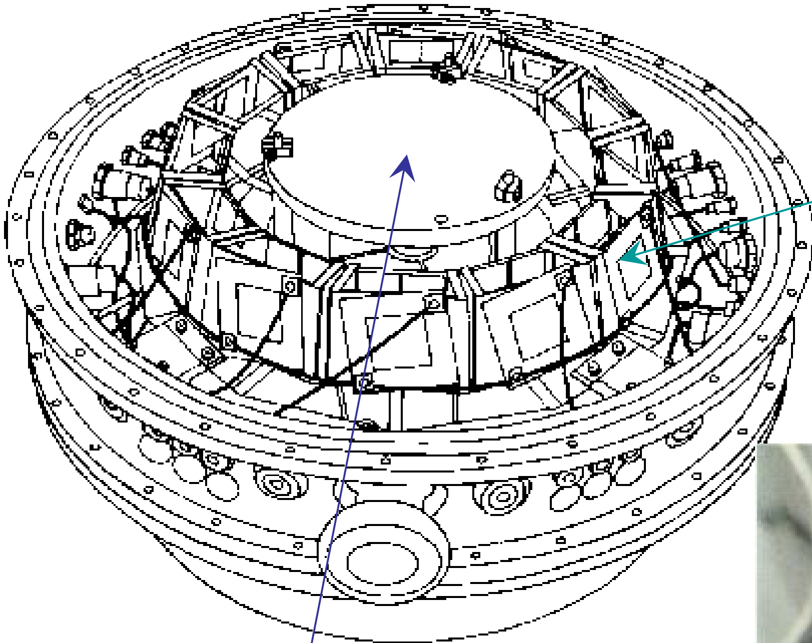
Crystal Ball Experiment for Measuring Spontaneous Ternary Fission of 252Cf

- Crystal Ball spectrometer as high efficiency neutron and gamma-ray detector
- New type of Ionization Chamber for measuring Fission Fragments
- A ring of ΔE-E telescopes for measuring Light Charged Particles

View of the experimental setup

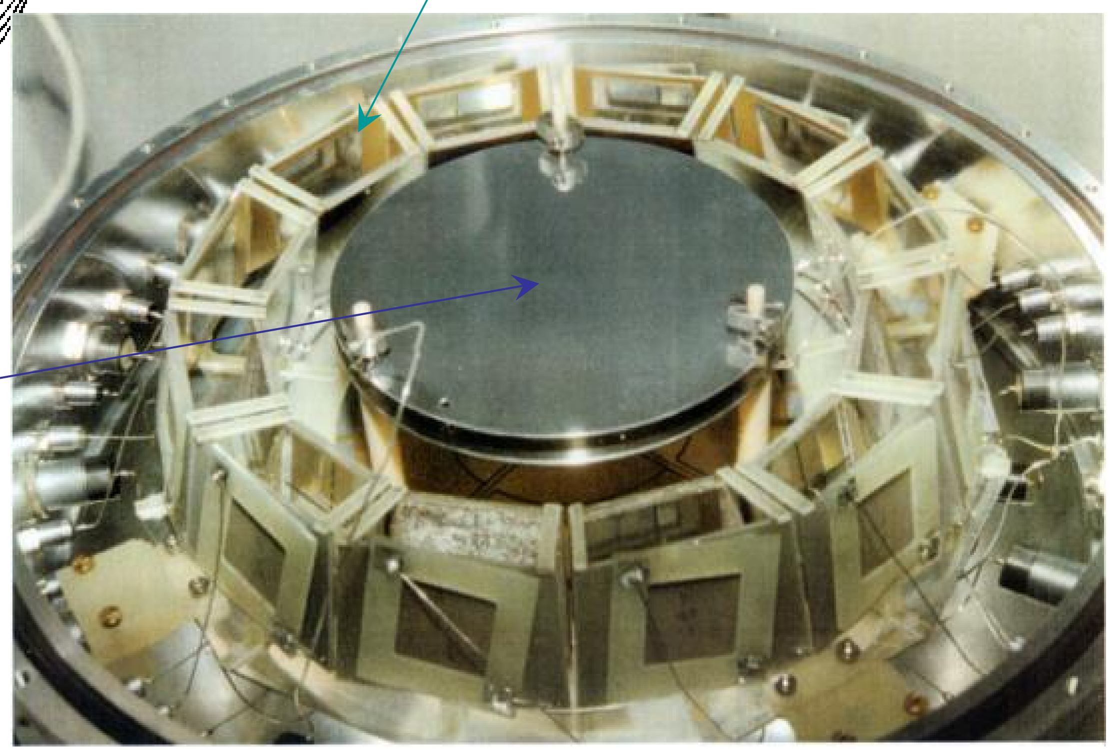


CODIS - COmpact DIogenes Setup

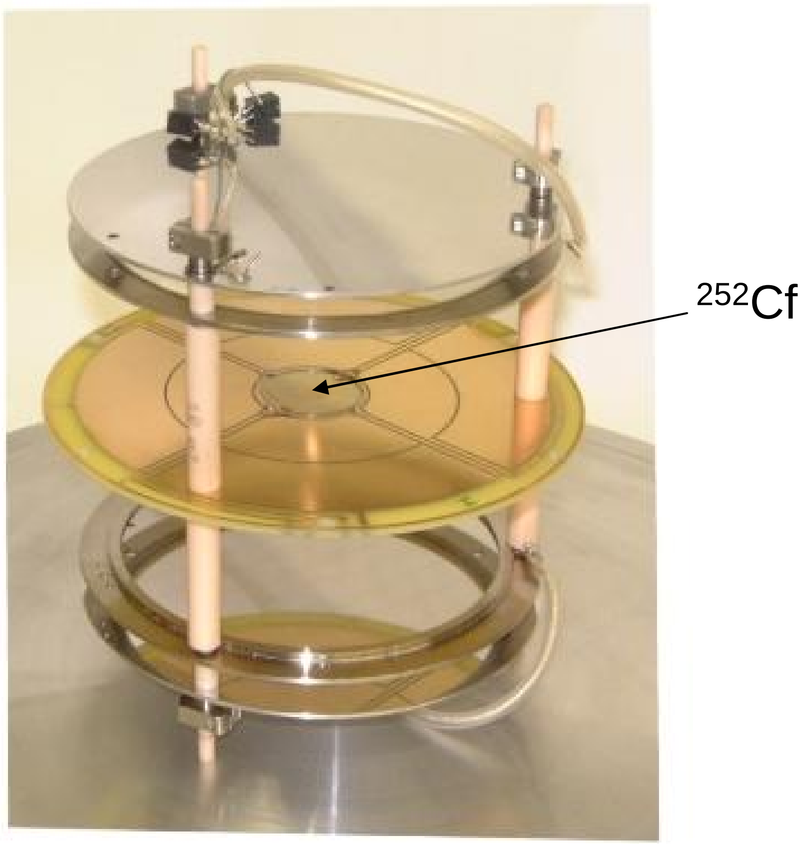


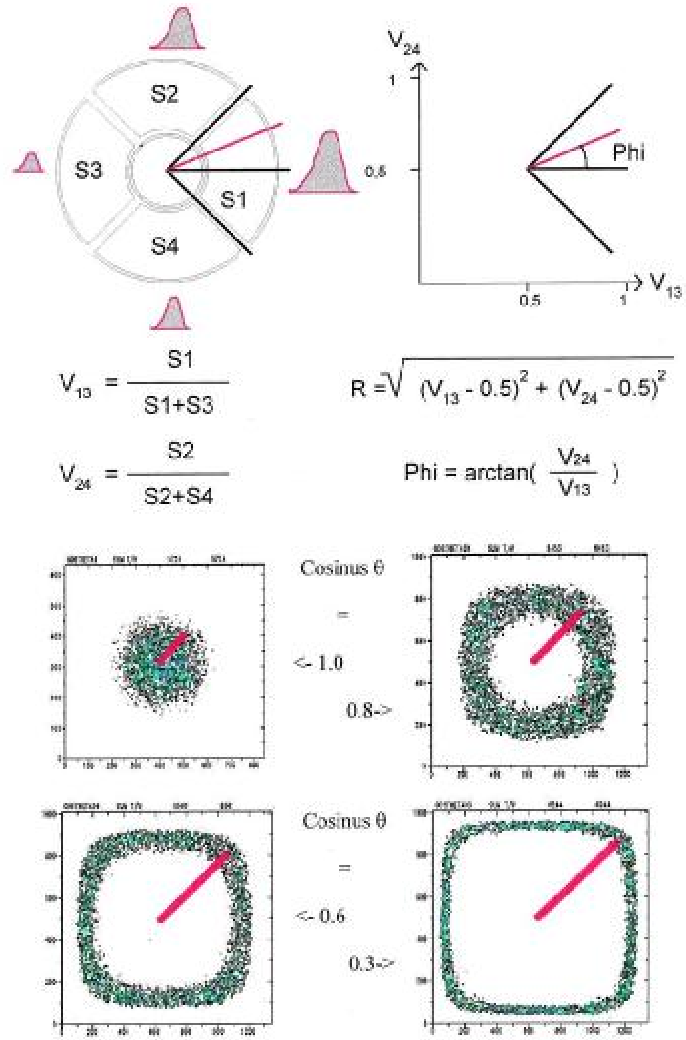
Ring of 12 DE-E telescopes

Double ionization chamber with sectored cathode



Double ionization chamber with sectored cathode

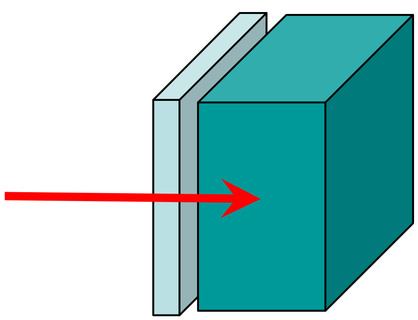




Allows to measure energies and emission angles of the fission fragments

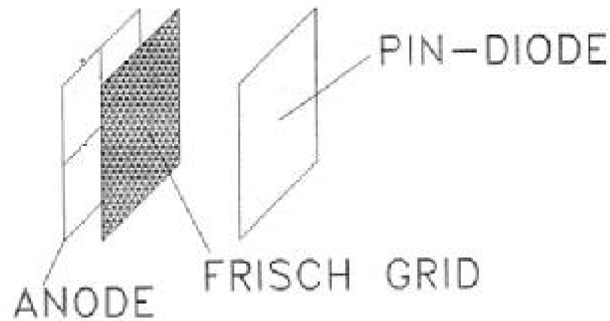
Ring of 12 DE-E Telescopes

DE-E method of identification of charge and mass of a particle

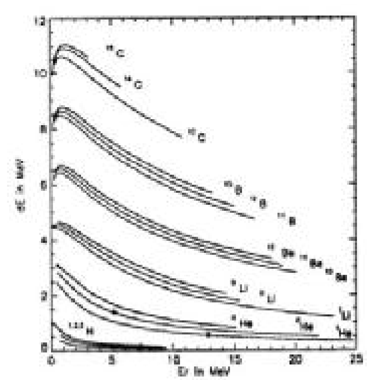


Aim: Measurement of energy, type and angle of emission of ternary particles

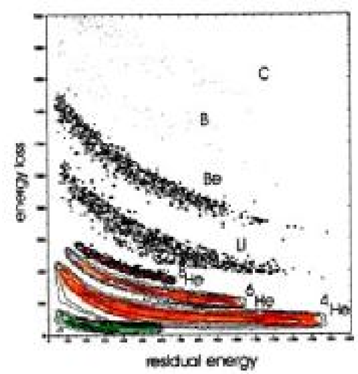
Construction:
1. **Frisch grid ionization chamber** for ΔE, using the same gas as the double ionization chamber
2. **PIN-diode** for residual energy E



Separation of different ternary particles in a ΔE-E Plot:

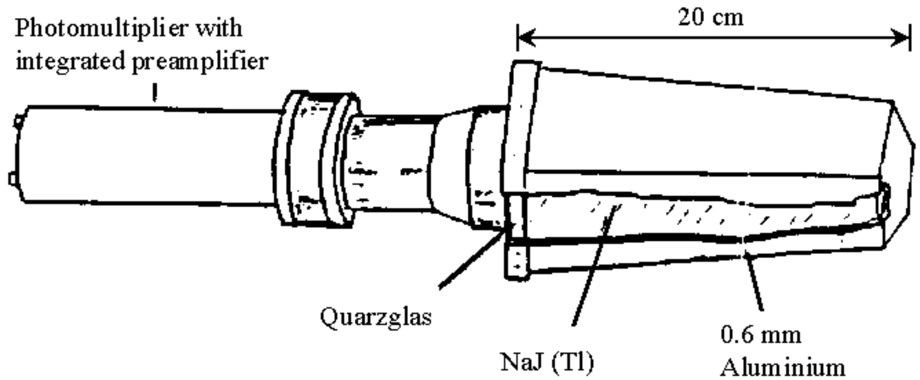


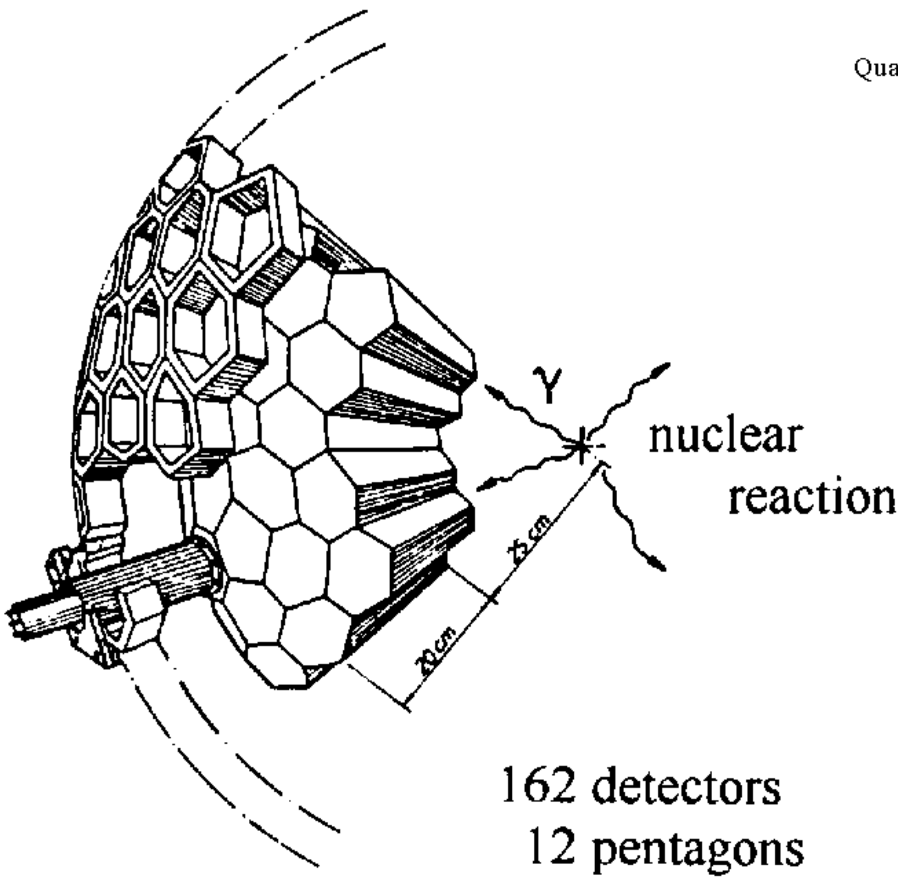
Simulation



Experiment

Crystal Ball Spectrometer

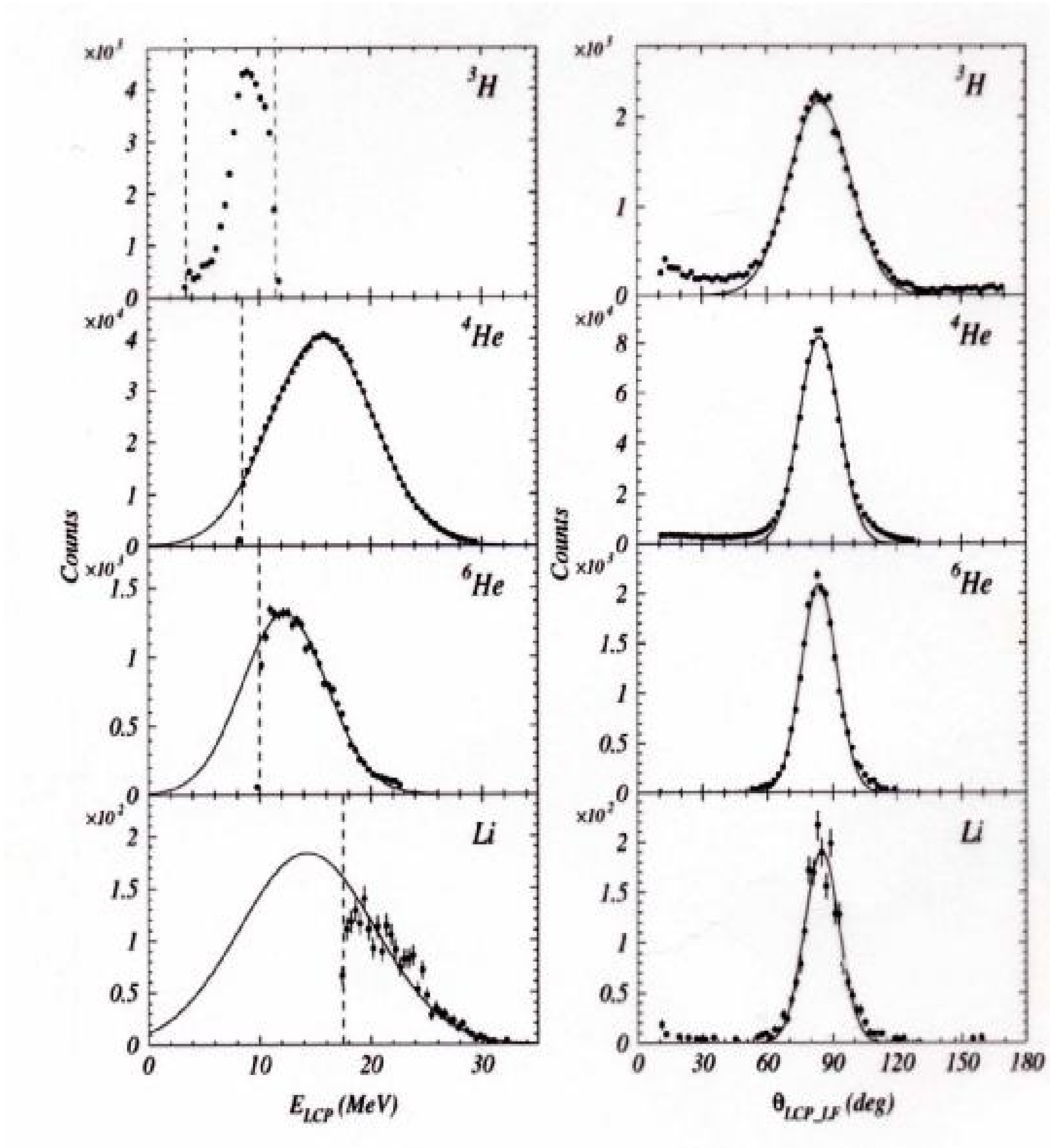




162 detectors
12 pentagons
150 hexagons

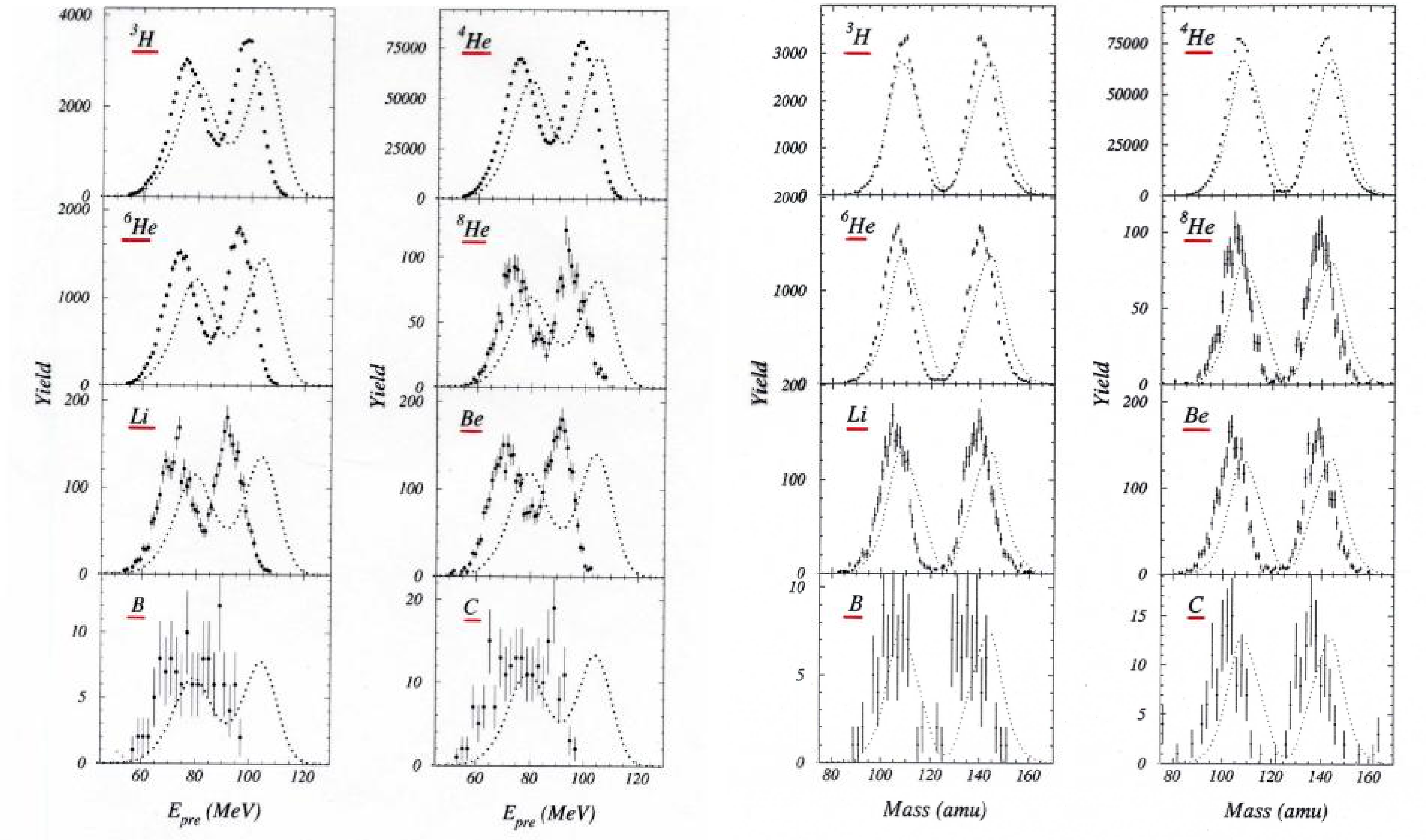
Inner diameter:	50 cm
Angular resolution:	$\pi/40$
Time resolution:	3.5 ns
γ-efficiency:	>94%
n-efficiency:	≈60%

LCP energy and angular distributions

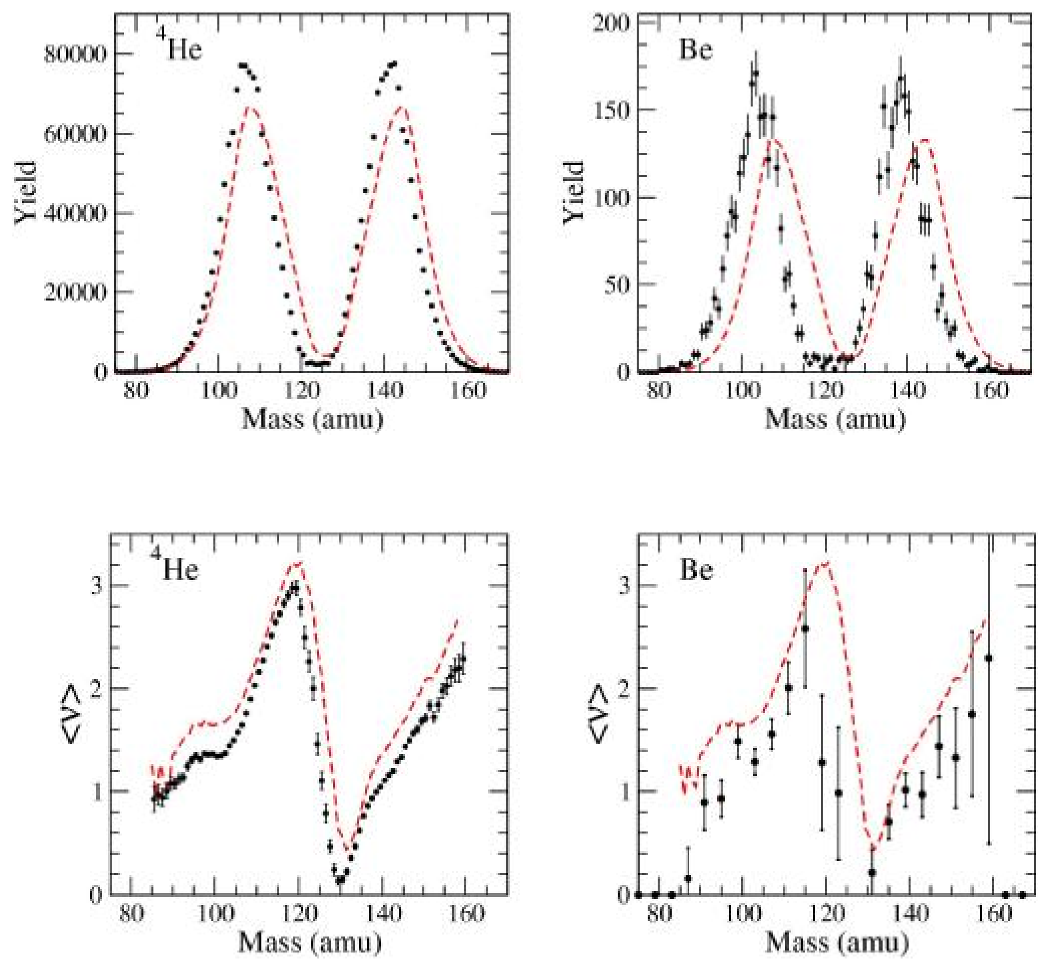


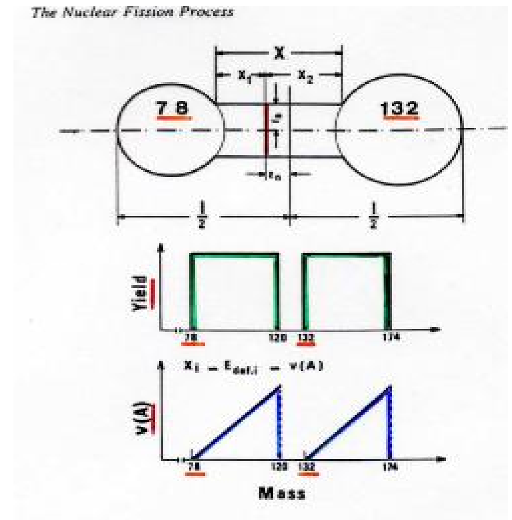
LCP	Events	E_{thres} MeV	$< E_{LCP} >$ MeV	FWHM MeV	Yield per $10^4 \alpha$	$\bar{\nu}_p$
^3H	5.6×10^4	3	8.2(6)	7.2(6)	950(90)	2.9
^4He	1.3×10^6	8	15.7(2)	10.9(2)	10^4	3.1
^6He	2.6×10^4	10	12.3(5)	9.0(5)	270(30)	2.8
Li	2.5×10^3	17	14.3(10)	14.3(10)	60(10)	2.5
binary	7×10^7	--	--	--	--	3.8

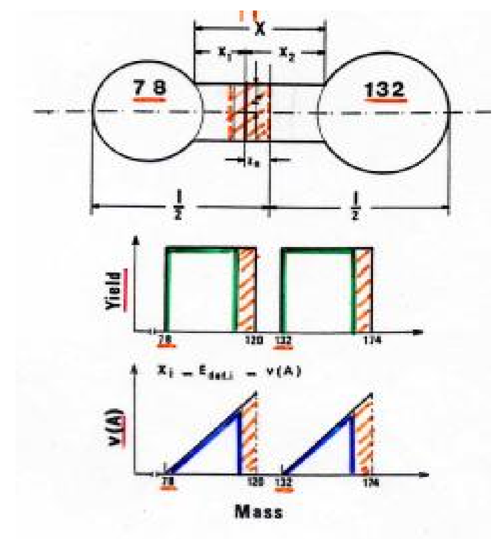
Fission Fragment kinetic energy and mass distributions for different ternary fission modes



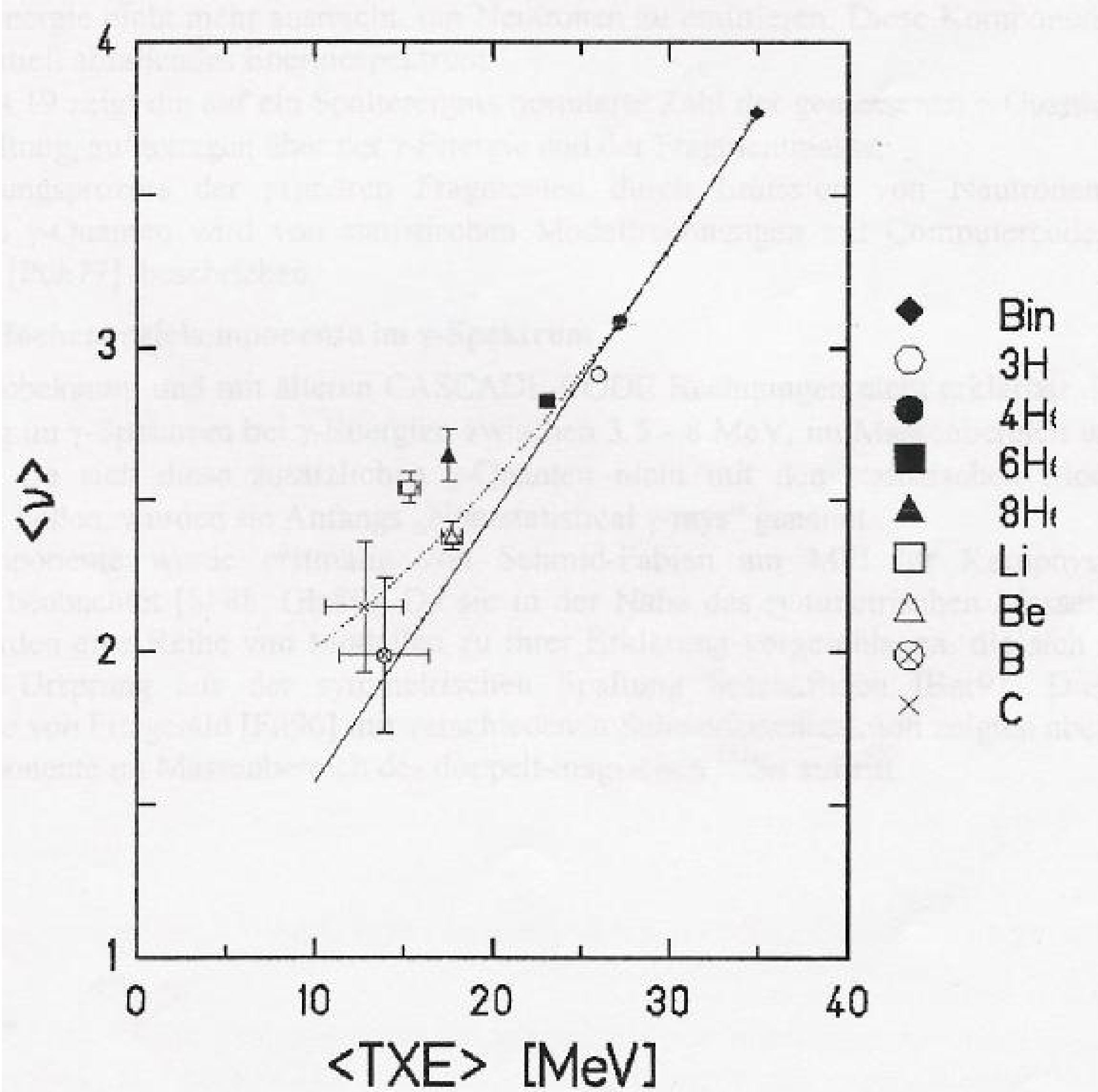
Simplifies random neck rapture model







Average neutron multiplicity from fission fragments vs Total Excitation Energy



Possible additional sources of neutrons in ternary fission

$$^{5}He(3/2^{-}) \rightarrow {}^{4}He + n \quad \tau = 1.1 \times 10^{-21}\mathrm{s} \quad Q = 0.85 \text{ MeV}$$

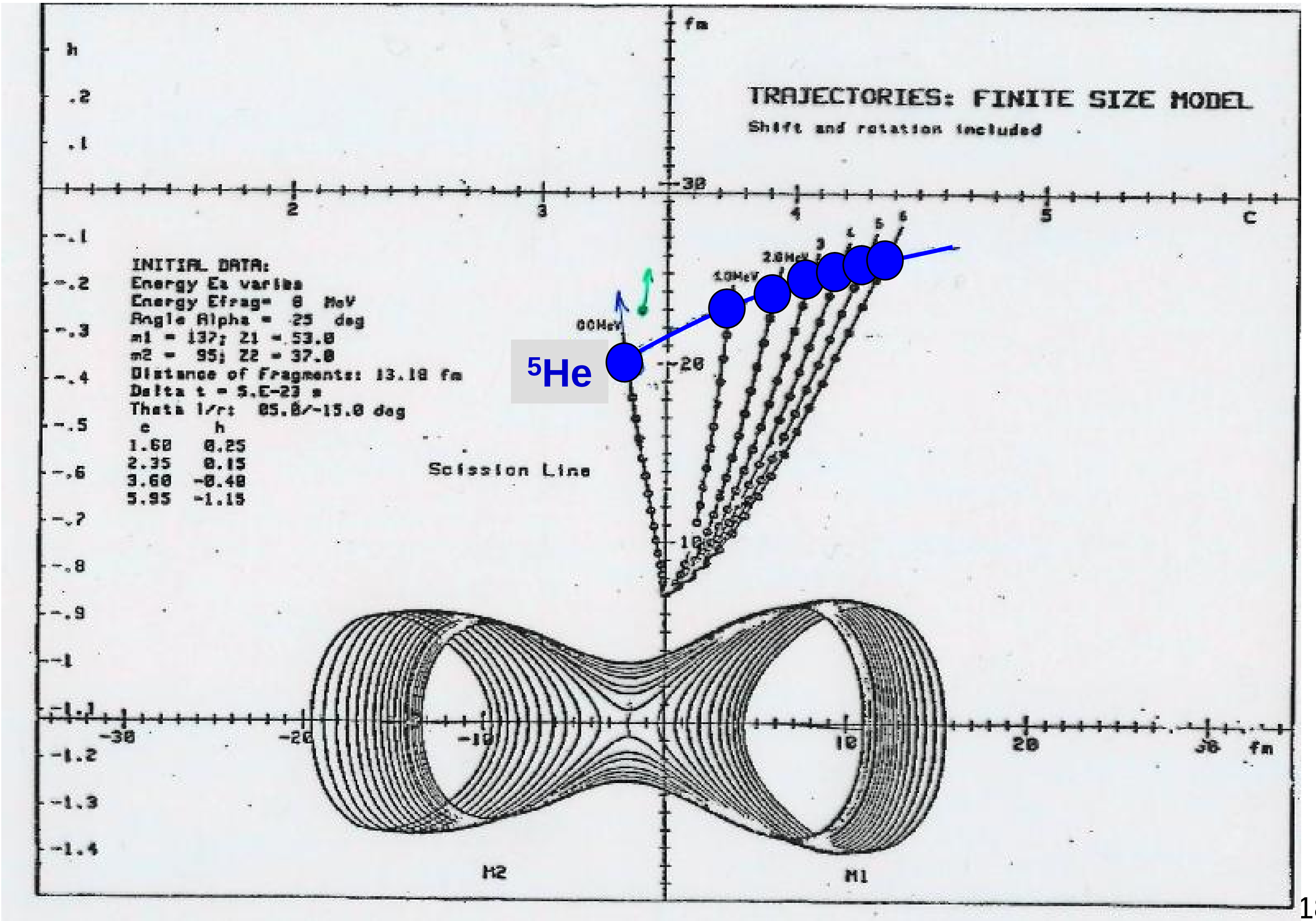
$$^{7}He(3/2^{-}) \rightarrow {}^{6}He + n \quad \tau = 4.1 \times 10^{-21}\mathrm{s} \quad Q = 0.44 \text{ MeV}$$

$$^{8}Li^{*}(3^{+}) \rightarrow {}^{7}Li + n \quad \tau = 2 \times 10^{-20}\mathrm{s} \quad Q = 0.25 \text{ MeV}$$

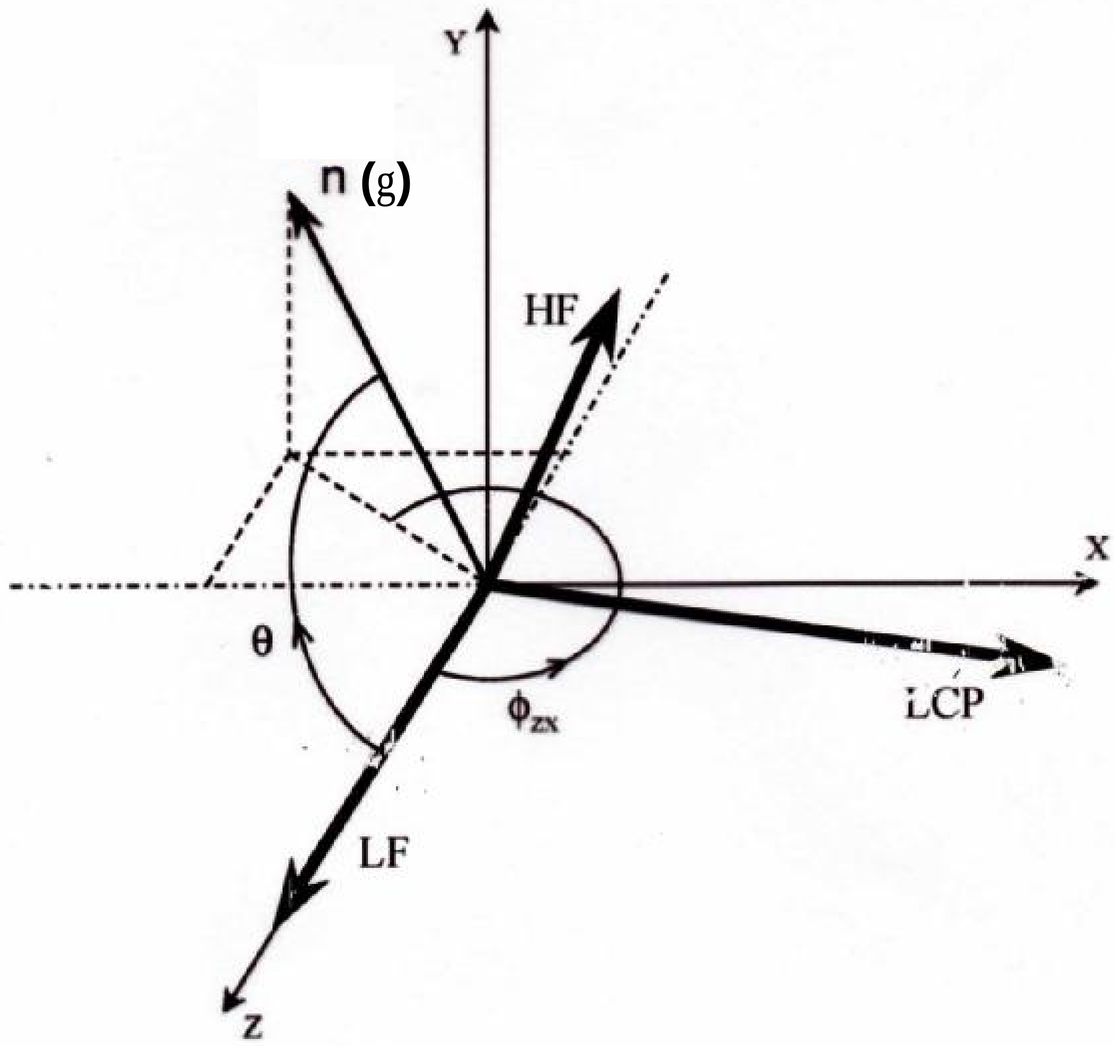
$$^{6}He^{*}(2^{+}, E^{*} = 1.8 \text{ MeV}) \rightarrow {}^{4}He + 2n \quad \tau = 6 \times 10^{-21}\mathrm{s} \quad Q = 0.90 \text{ MeV}$$

$$^{8}He^{*}(2^{+}, E^{*} = 2.8 \text{ MeV}) \rightarrow {}^{6}He + 2n \quad \tau =? \quad Q = 0.69 \text{ MeV}$$

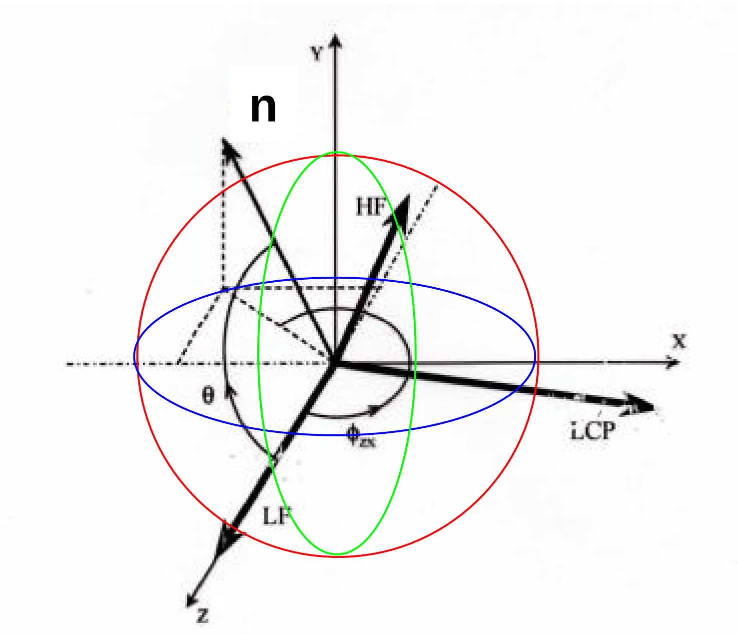
Trajectory calculations of ternary fission

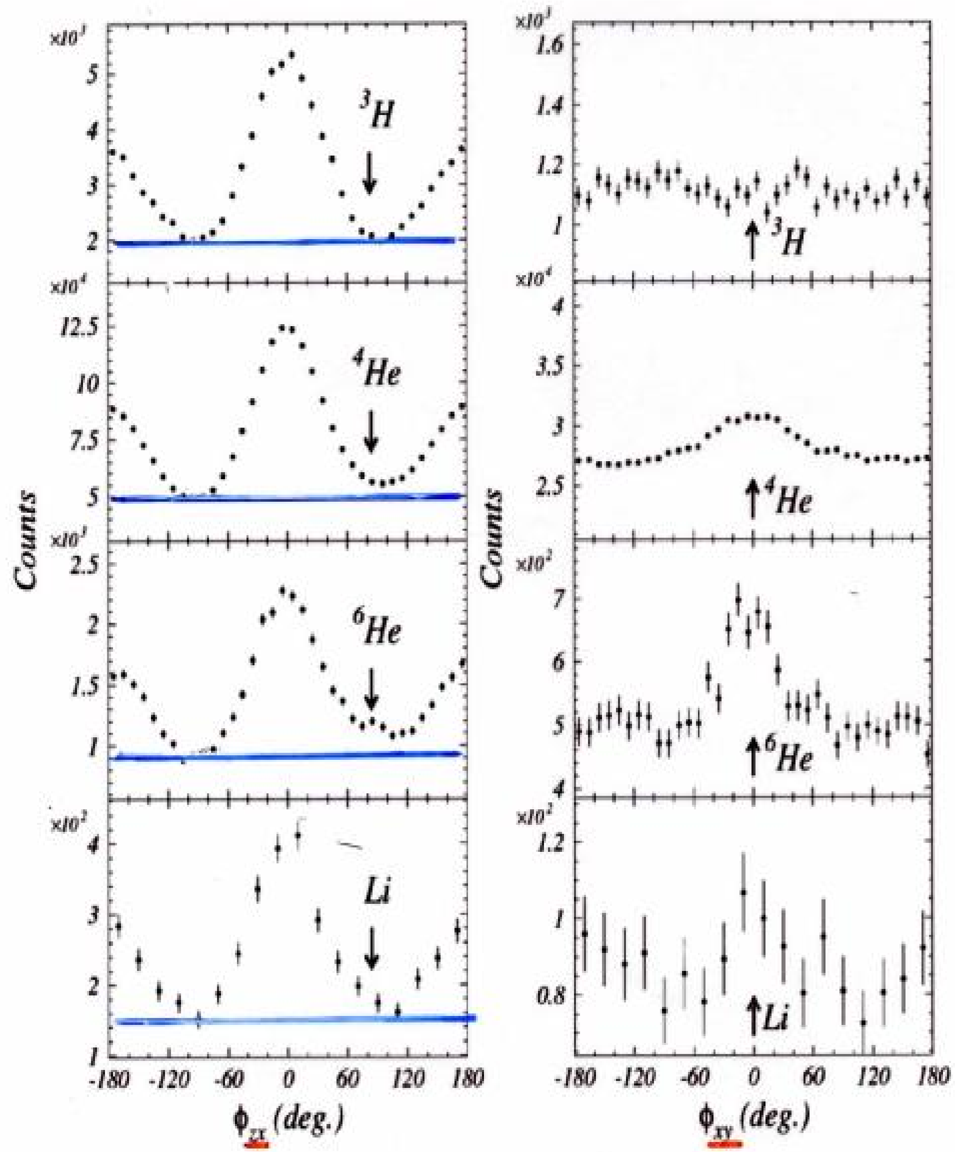


Neutron- and gamma-ray angular correlations: *"in situ"* coordinate system

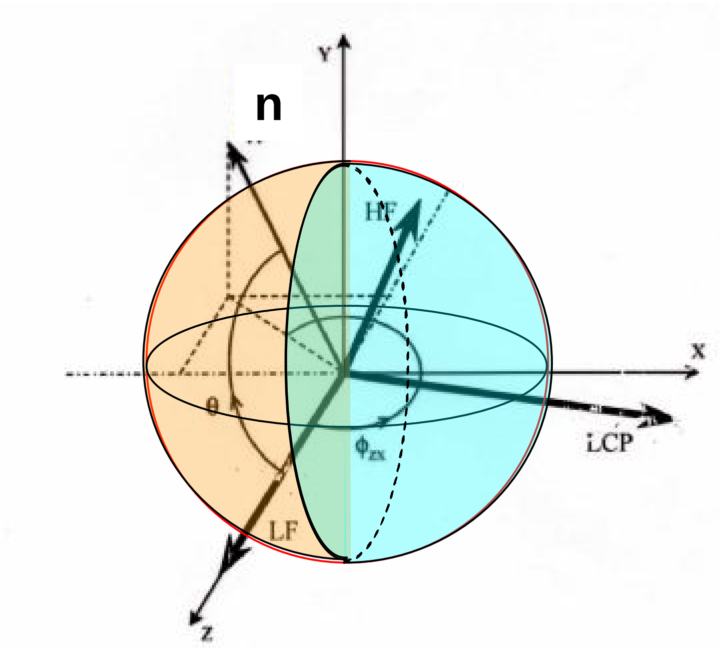


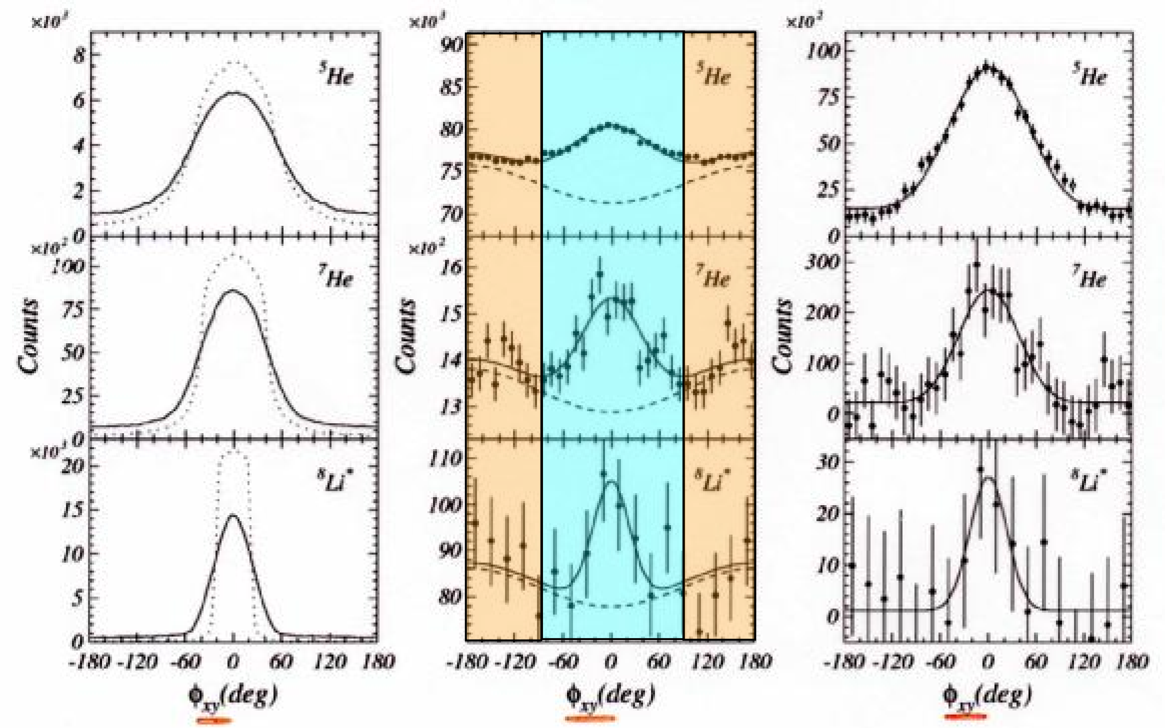
Correlation of neutrons and LCPs





Correlation of neutrons and LCPs

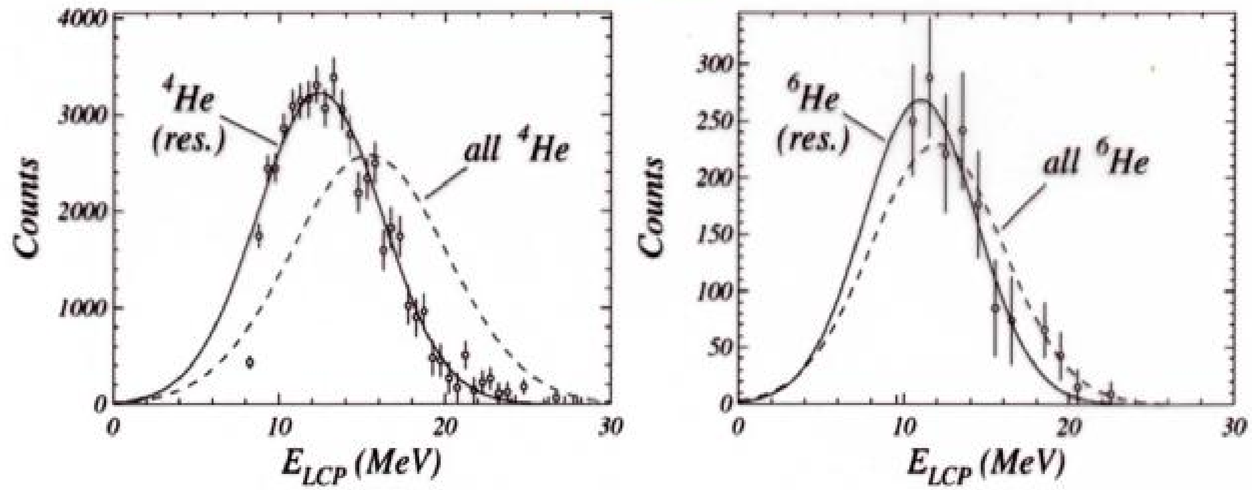




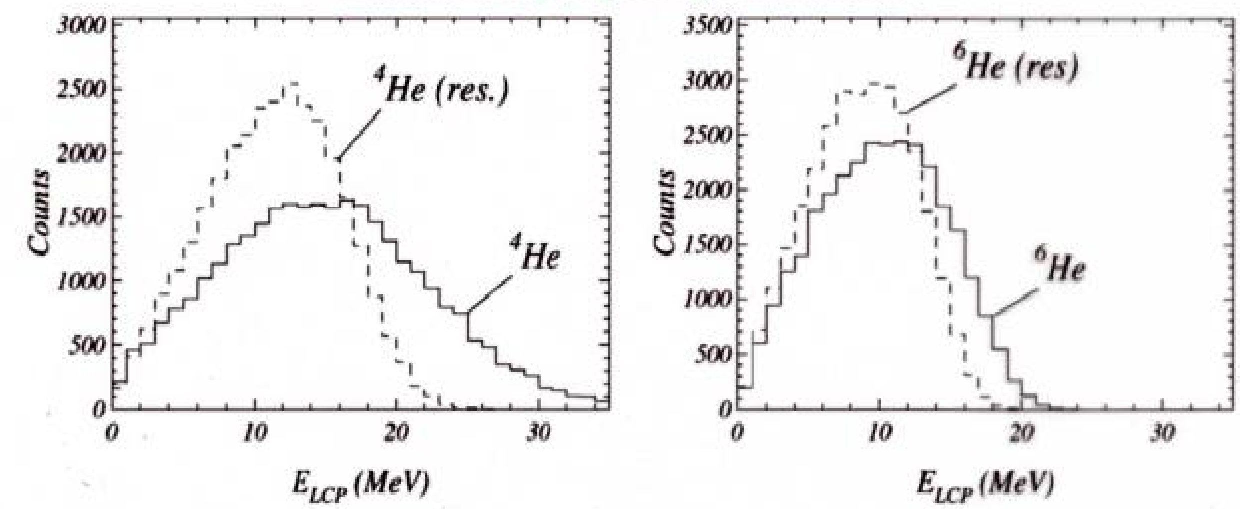
Intermediate LCP	Resonance width, Γ	Lifetime, τ	Q-value
$^5He(3/2^-) \to {}^4He + n$	600 (20) keV	1.1×10^{-21} s	0.89 MeV
$^7He(3/2^-) \to {}^6He + n$	160 (30) keV	4.1×10^{-21} s	0.44 MeV
$^8Li^* \to {}^7Li + n$	33 (6) keV	2×10^{-20} s	0.25 MeV

Energies of ^{4}He and ^{6}He residues from ^{5}He and ^{7}He

Experiment:



Simulated by trajectory calculation:

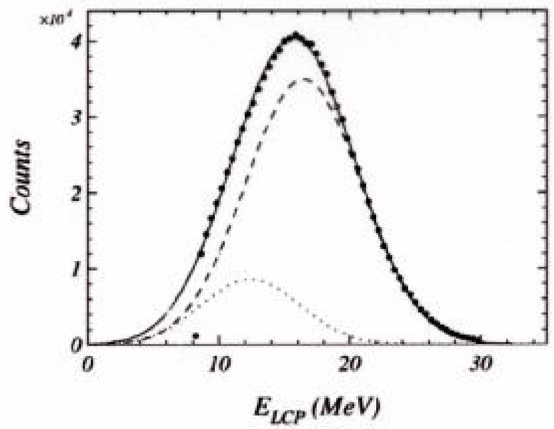


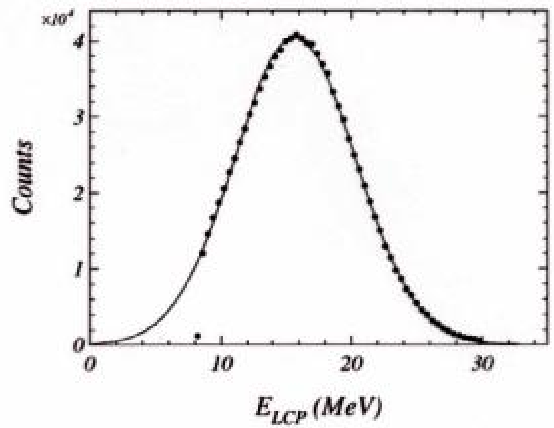
Ternary α-particle spectrum of $^{252}Cf(sf)$

True ternary α´s and residues from ^{5}He decay:

Two-Gaussian Fit:

One-Gaussian Fit:





Results:

		Experiment		Calculation	
LCP	< E > MeV	FWHM MeV	χ^2/N	< E > MeV	FWHM MeV
^{4}He	15.7 (2)	10.9 (2)	5.9	--	--
true ^{4}He	16.4 (3)	10.3 (3)	6.6	14.4	18.2
^{5}He residues	12.4 (3)	8.9 (5)	--	11.1	11.0
^{6}He	12.3 (5)	9.0 (5)	2.2	--	--
true ^{6}He	12.6 (5)	8.9 (5)	2.2	9.9	10.5
^{7}He residues	11.0 (15)	8 (2)	--	8.6	8.6

E_a is 0.7 MeV higher than usually measured!

Super-Glover (VEGA) Experiment on ^{252}Cf(sf) at GSI

Experimental Setup / Detectors

- New compact and high-efficiency fission-fragment and light-particle detector system "CODIS2"
- Two segmented large-volume super-clover Ge spectrometers (VEGA) as high-resolution γ-ray detectors

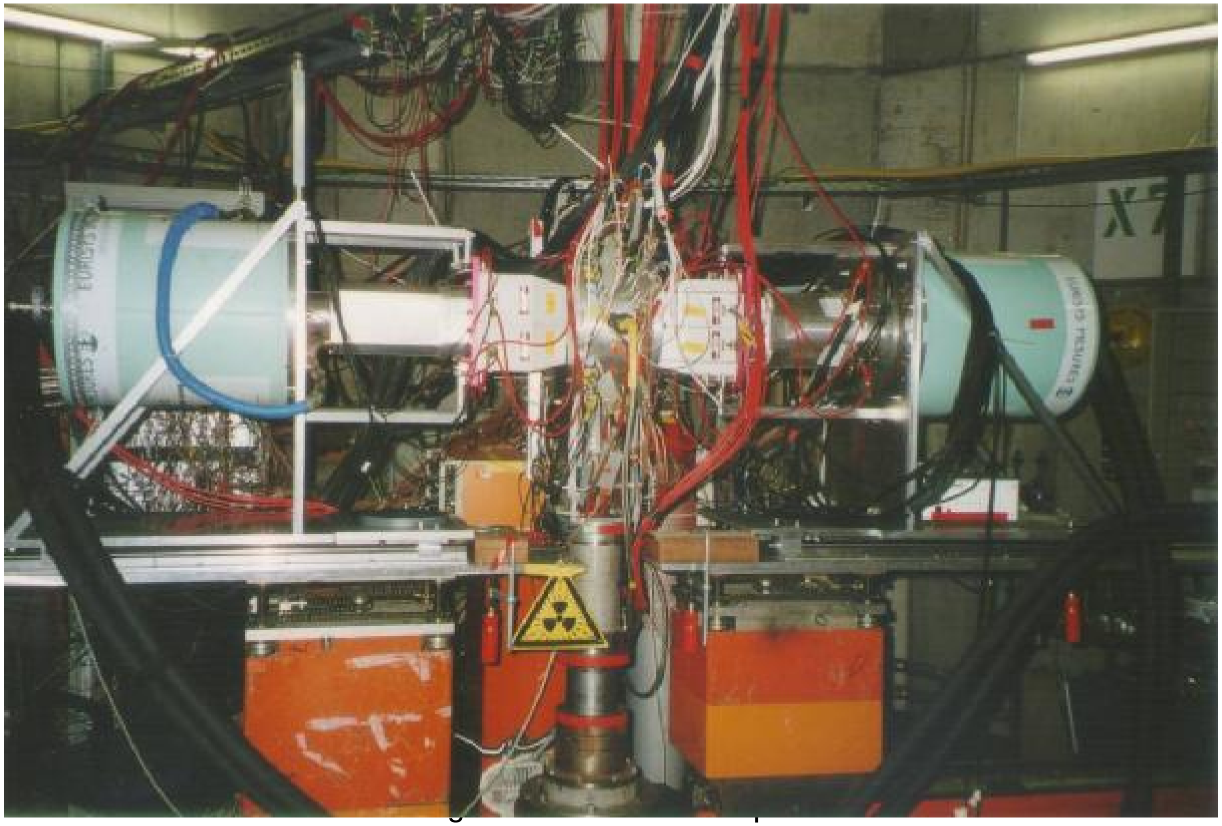
Experimental parameters

- high efficiency for ffs (≥ 90%) and LCPs (≈ 15%)
- good fragment energy resolution at high count-rate (2.5 x 10^4 s-1)
- good isotopic LCP separation by dE-E (gas IC – Si)
- ternary fission count-rate: 7 s-1 (4 x 10^6 events total)
- large-volume high-resolution γ-ray detectors in close geometry

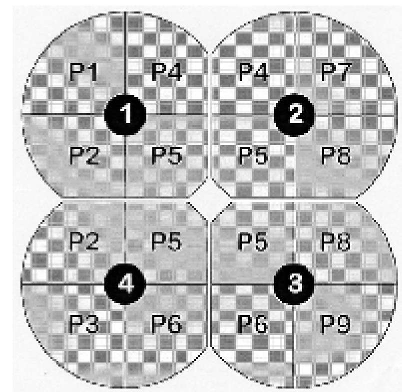
Aim of the experiment

- γ-ray spectroscopy of fission fragments in binary and ternary fission (Doppler-shift correction for emission from fission fragments in flight).
- Angular anisotropy of individual fragment γ-rays in binary and ternary fission.
- Excited states in LCPs decaying by γ-rays. (Doppler-shift correction for emission from LCPs in flight). Li and Be isotopes including ^{10}Be.
- Isotopic LCP yields (Li and Be) due to improved dE-E resolution of CODIS2.
- Improved data on the energy correlation between LCPs and FFs due to better LCP separation and statistics.

Experimental setup

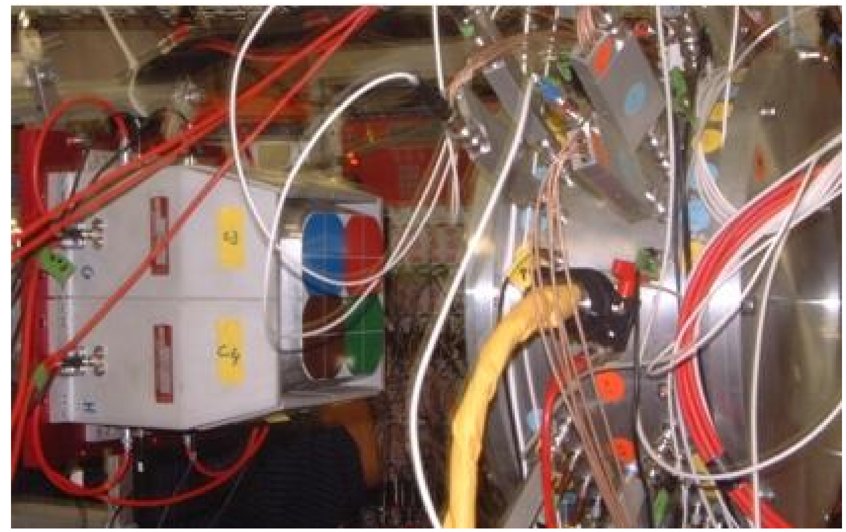


Segmented Clover Ge detector



Experimental Set-up

Chamber and one of the two segmented clover Ge detectors



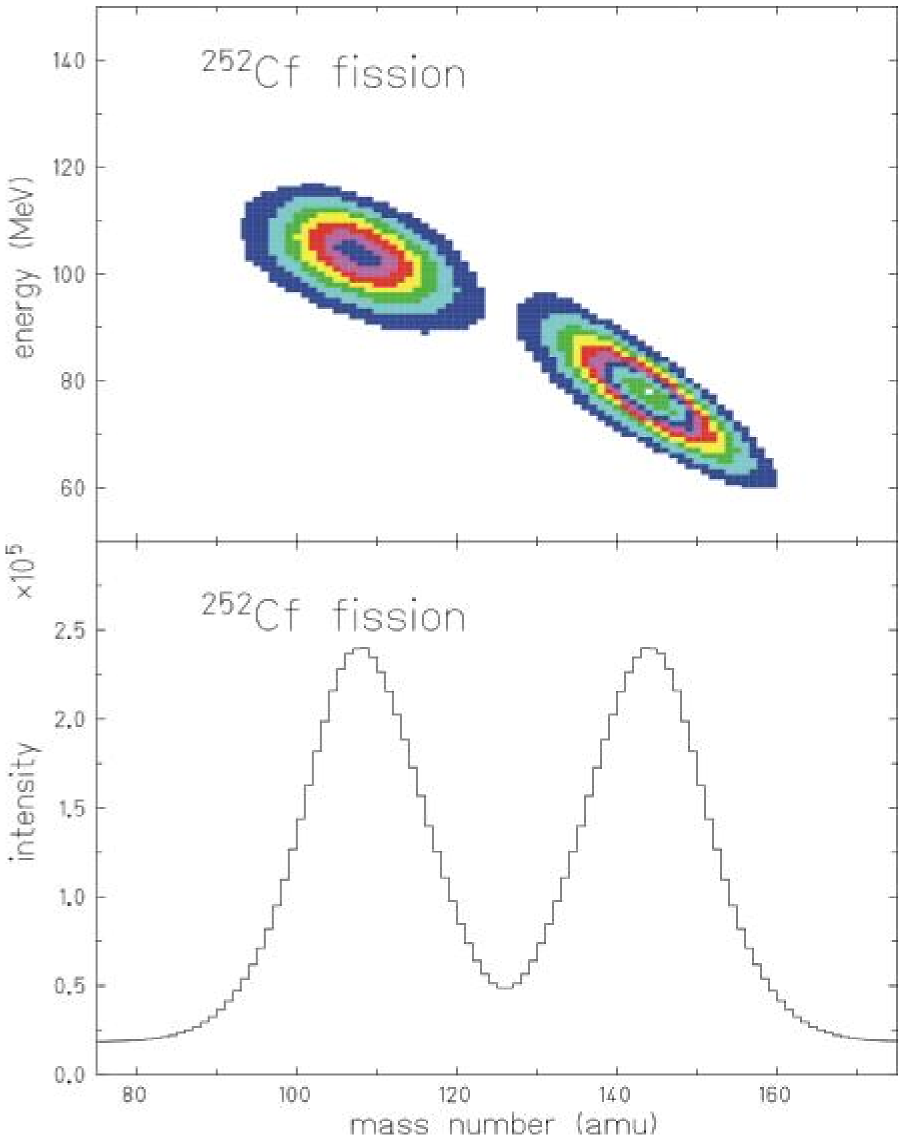
Measured parameters

Fragments: **E,** J**,** j Þ **M, v**

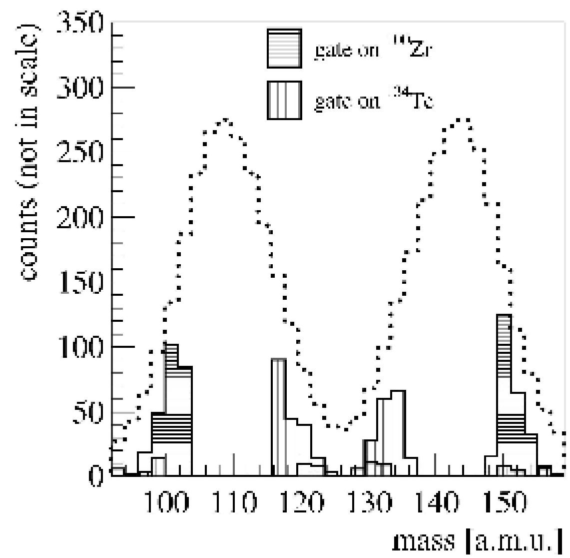
LPCs: **E,** D**E,** J**,** j Þ **Z, M, v**

Gammas: **E,** J**,** j

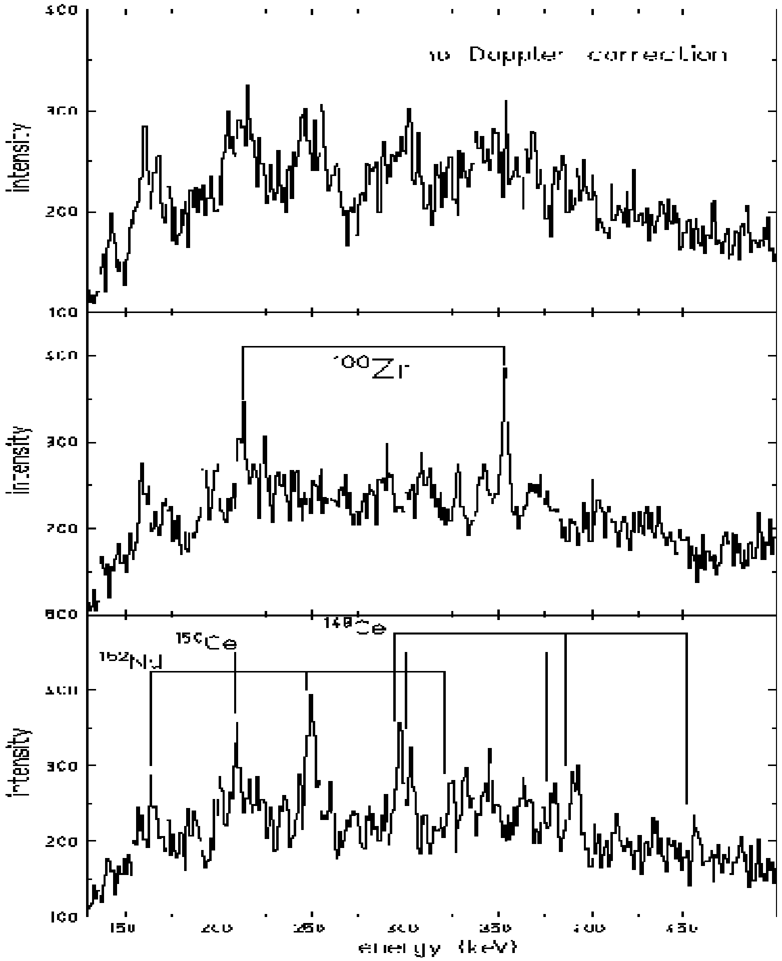
Examples of measured spectra



Fission fragments observed with DIC



Doppler-shift corrected g-ray spectra

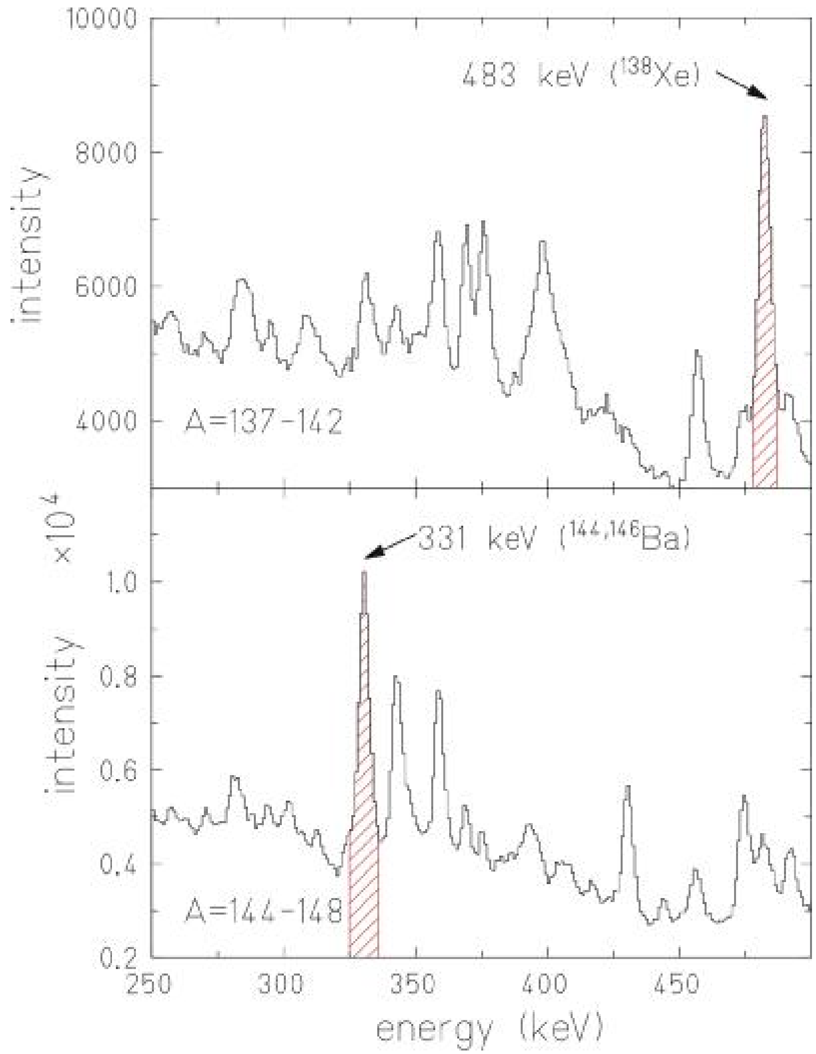


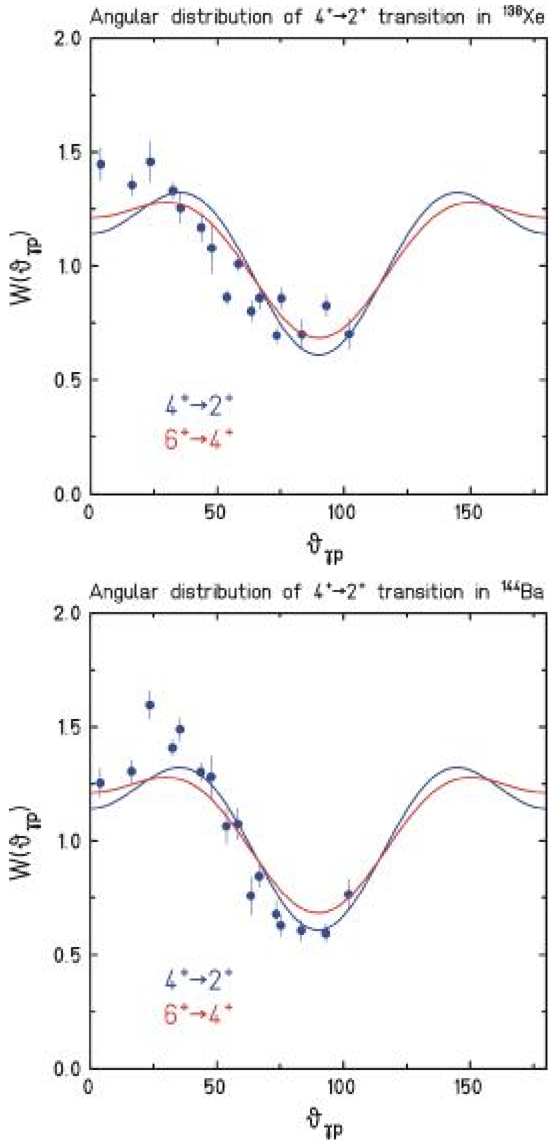
No Doppler correction

LF-corrected spectrum

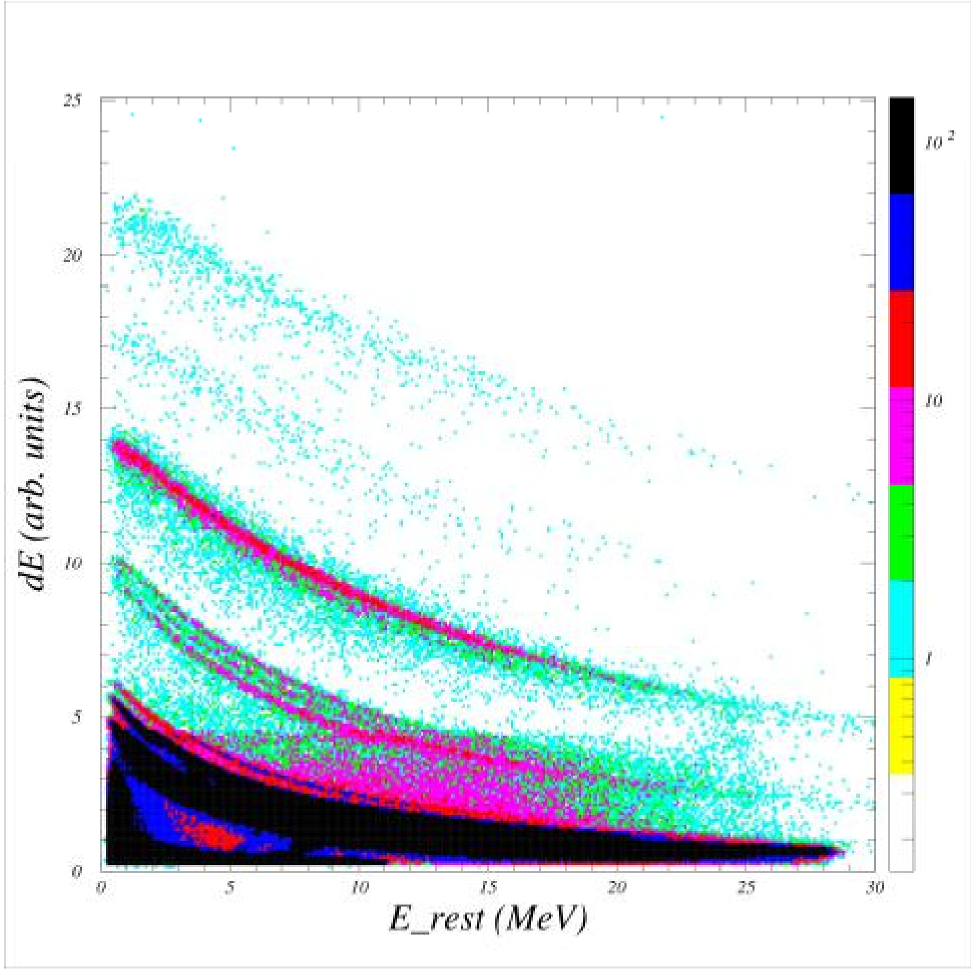
HF-corrected spectrum

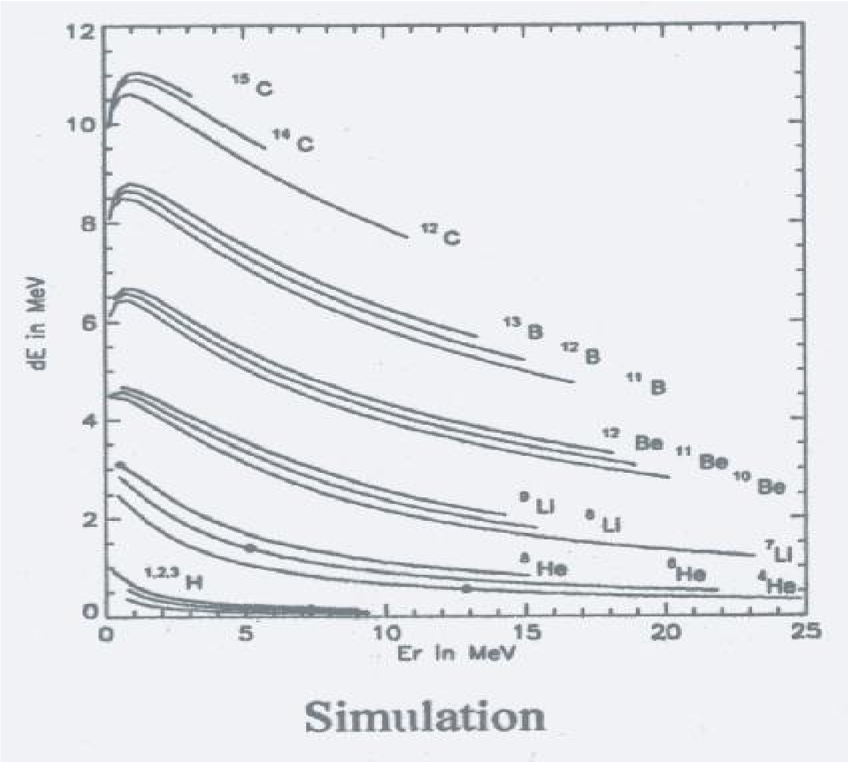
Fragment-gamma angular correlations





DE-E separation of LCPs



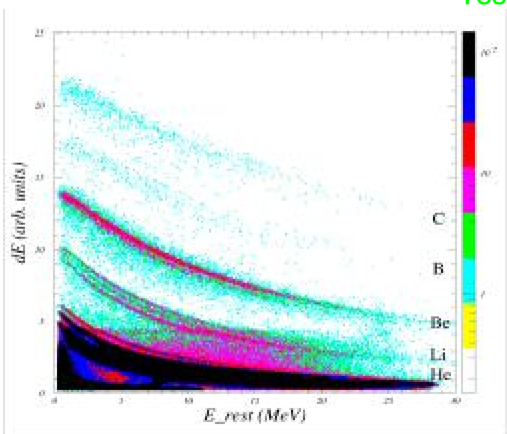


Experimental and simulated ΔE-E distributions for identification of LCPs

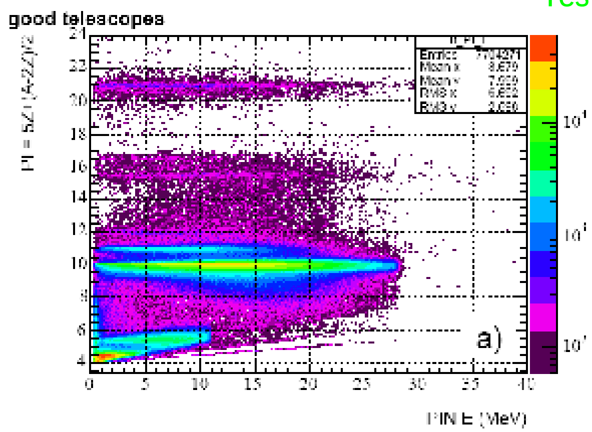
Particle discrimination with the CODIS2 ΔE-E telescopes

The various steps in the analysis of LCP yields:

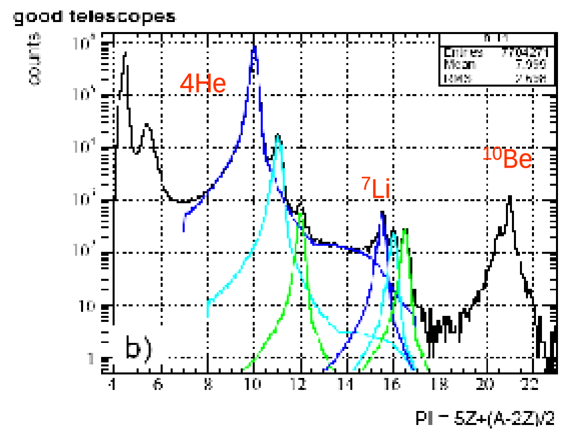
$\Delta E - E_{res}$



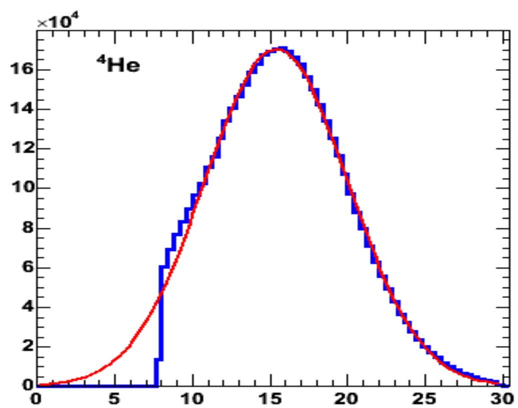
PI-E $_{res}$

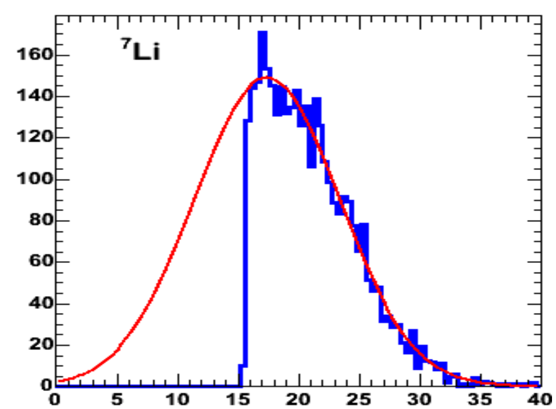


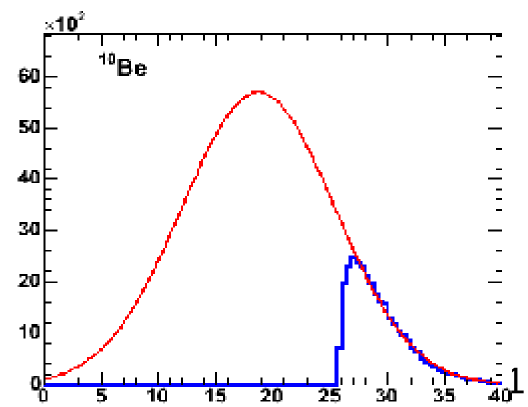
dN-PI



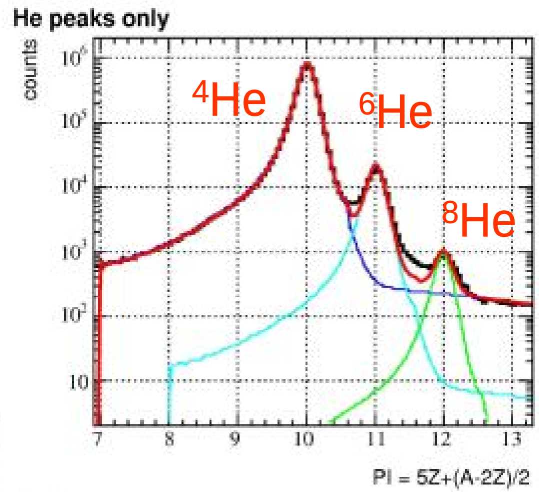
Sample spectra: ^{4}He ^{7}Li ^{10}Be

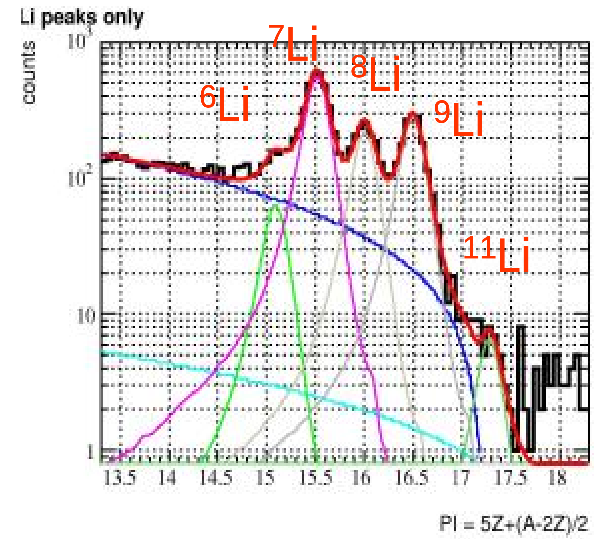


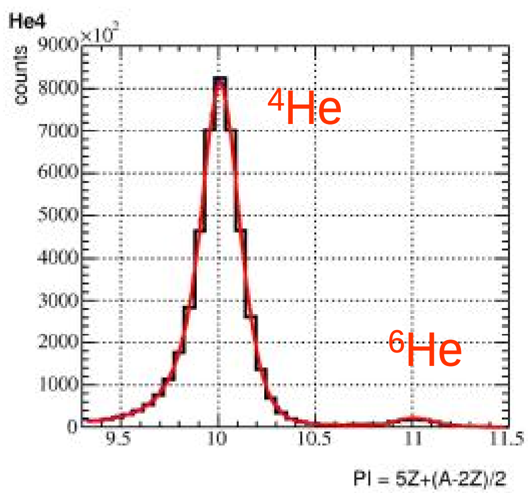


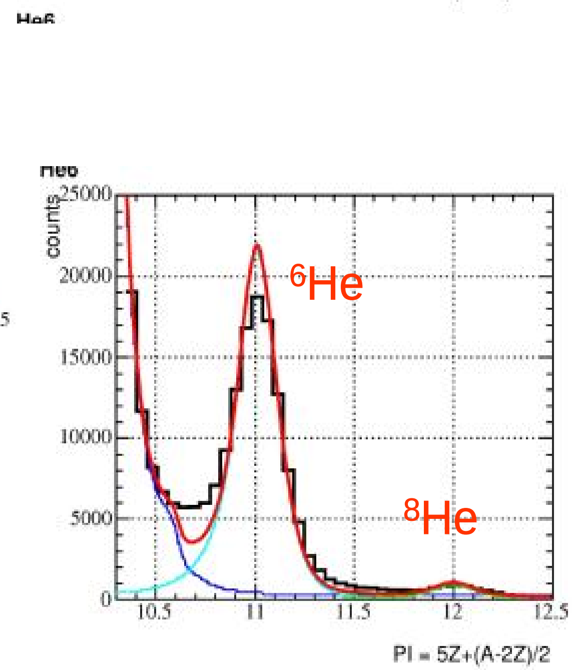


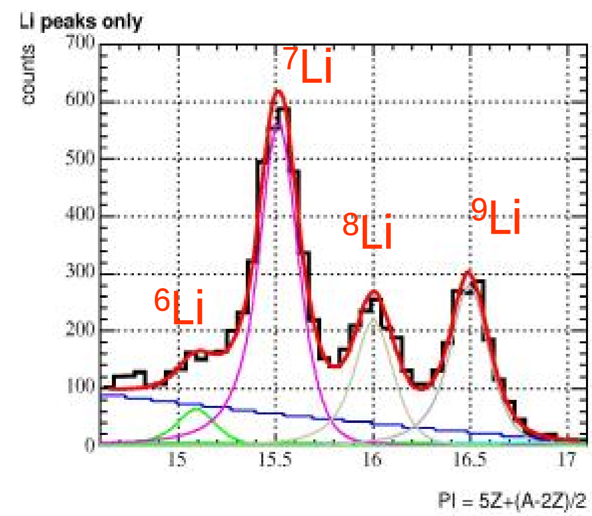
Identification of the He and Li Isotopes









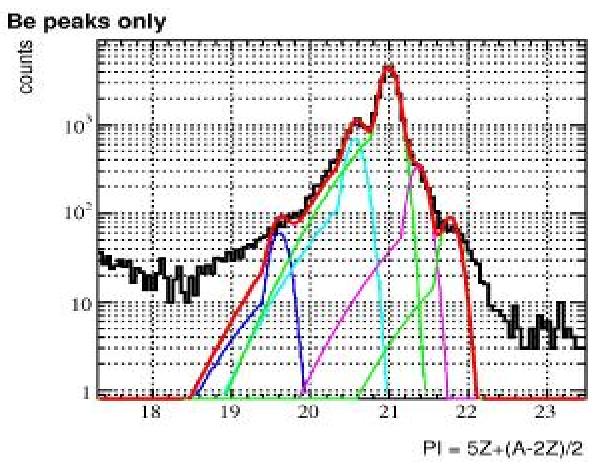


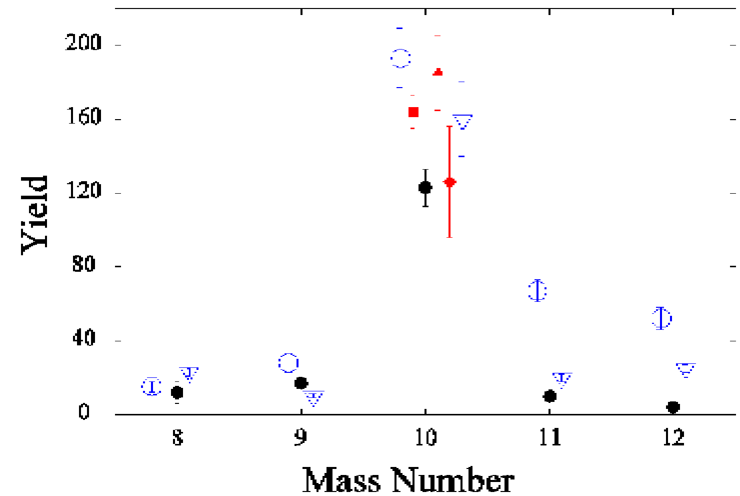
Isotopic yields of He and Li LCPS in $^{252}Cf(sf)$

(relative to 10^4 α-particles)

Isotope	^6He	^8He	^6Li	^7Li	^8Li	^9Li	^{11}Li	
	315(20)	19(2)	1.2(3)	11.1(4)	5.4(2)	10.9(4)	≤ 0,3	This work (preliminary analysis)
	386(12)	-----	-----	∑ Li =	55(4)	-----	-----	G T Grachev et al.,1988. experiment
	403(26)	25(4)	------	17(4)	10(5)	25(11)	-----	Z. Dlouhy et al., 1992, experiment
	315(60)	25(5)	------	∑ Li =	52(5)	-----	-----	P Singer, PHD, Darmst.,1997, exp
	369(15)	31(3)	0.3(1)	16 (2)	13(2)	32(3)	-----	G.V. Valskii, 2004, model

First measurement of isotopic Be yields in ^{252}Cf(sf)





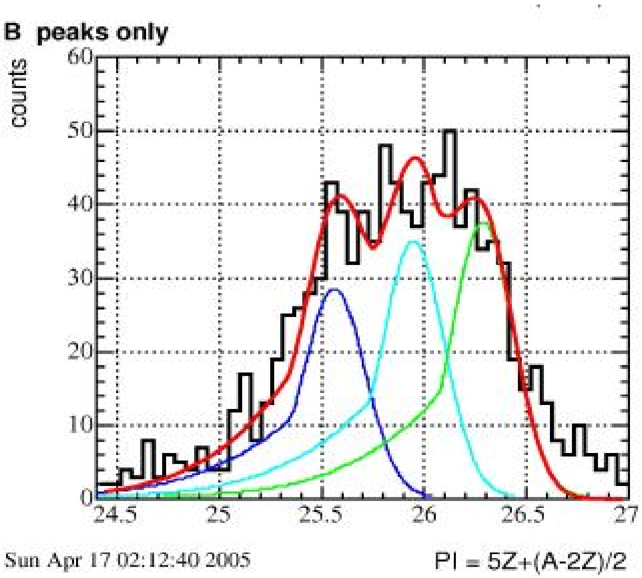
O Valskii ▼ Baum /Pik-Pichak
■ Grachev ▲ Dlouhy ♦ Singer
● GSI Experiment

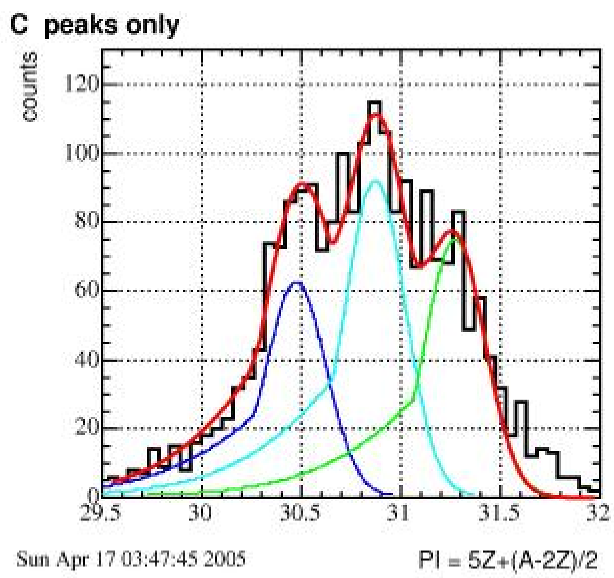
Isotope	^{7}Be	^{8}Be$^{*)}$	^{9}Be	^{10}Be	^{11}Be	^{12}Be	
	?	10(6)*	17(3)	123(10)	10(4)	4(2)	This work (preliminary analysis)
	1.3x10^{-4}	15(3)	28(5)	193(16)	[67(6)]	[52(6)]	G V Valskii, 2004, model
		23(2)	10(1)	160(20)	20(2)	25(2)	W Baum, PHD,Darmst., 1992, model
	-----	-----	∑Be =	164(9)	-----	-----	G T Grachev et al.,1988. experiment
		-----	∑Be =	185(9)	-----	-----	Z. Dlouhy et al., 1992, experiment
		-----	∑Be =	126(9)	-----	-----	P Singer, PHD, Darmst.,1997, exp.

Yields per 10^4 α-particles

*) Kopatch et al., Phys.Rev.C65,044614 (2002)

Identification of the B and C Isotopes





----- ^{11}B

----- ^{12}B

----- ^{13}B

----- ^{13}C

----- ^{14}C

----- ^{15}C

no or weak evidence for 12C ?

The LCP-FF correlation experiment on TF and QF of $^{235}U(n_{th},f)$ at the ILL-PF1

Experimental Setup / Detectors

- The compact and high-efficiency fission fragment and light particle detector system "CODIS2"
- Intense neutron beam PF1 (3×10^9 n cm^{-2} s^{-1}) from the ILL high-flux reactor

Experimental parameters

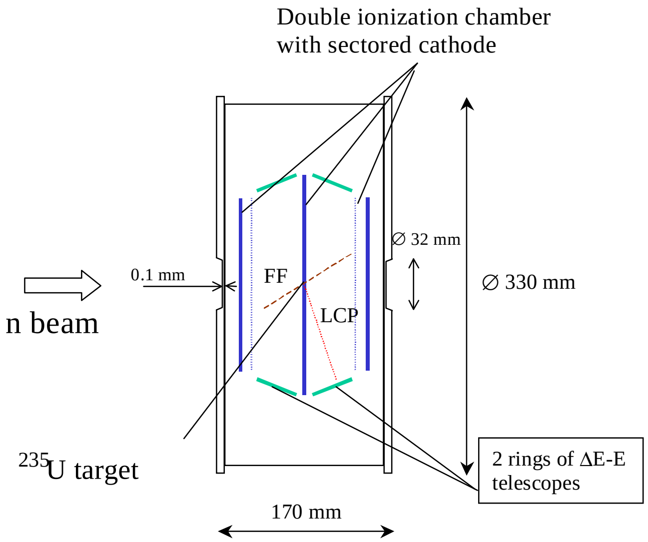
- high efficiency for ffs and LCPs
- good fragment energy resolution at very high count-rate (2.5×10^5 s^{-1})
- (good) isotopic LCP separation by dE-E
- ternary fission count-rate: 70 s^{-1} (4×10^7 events total)
- quaternary fission count-rate: 7×10^{-4} s^{-1} (4×10^2 events total)

Aim of the experiment

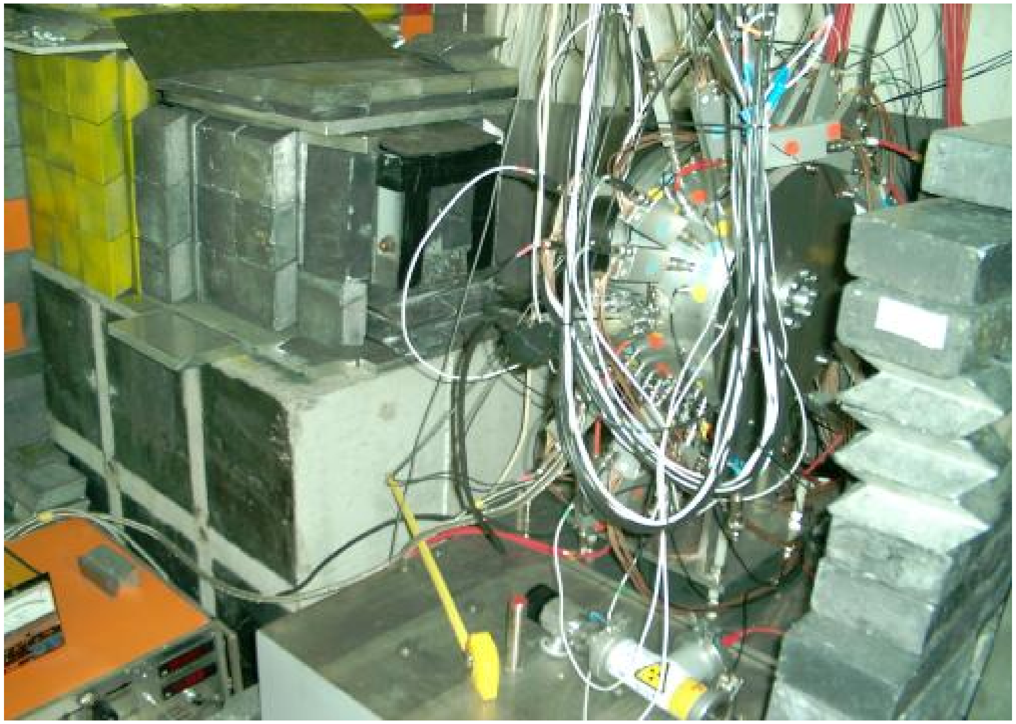
- Energy spectra and yields of light LCPs due to improved dE-E resolution of CODIS2.
- Novel data on the energy correlation between ternary α's and FF's due to good LCP separation and high statistics.
- Data on the fragment energy and mass distributions correlated with LCPs other than ternary α's.
- First data on the fragment energy and mass distributions in quaternary fission.

Correlation experiment for the study of ternary and quaternary fission of 235U(nth,f), performed at the high-flux reactor of the ILL Grenoble (March/April 2004)

Detector system CODIS2

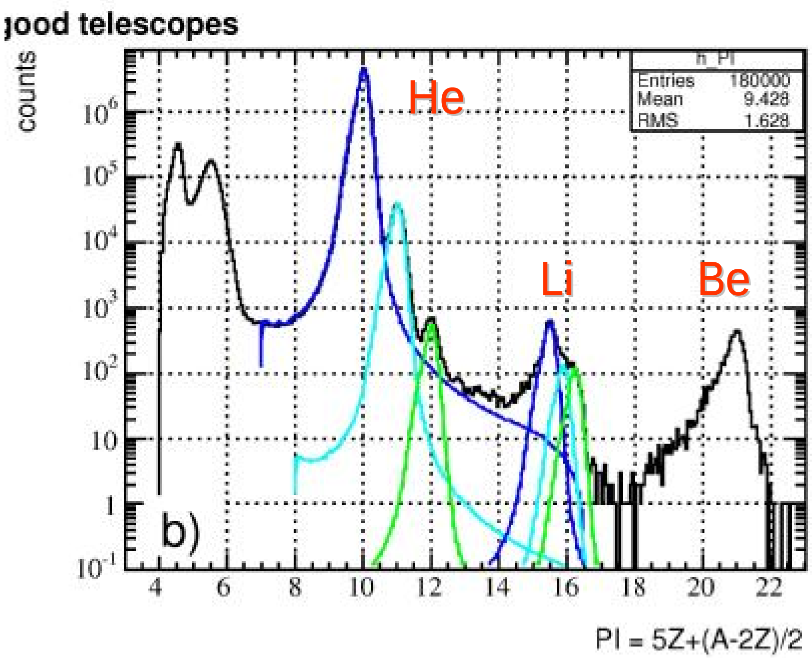


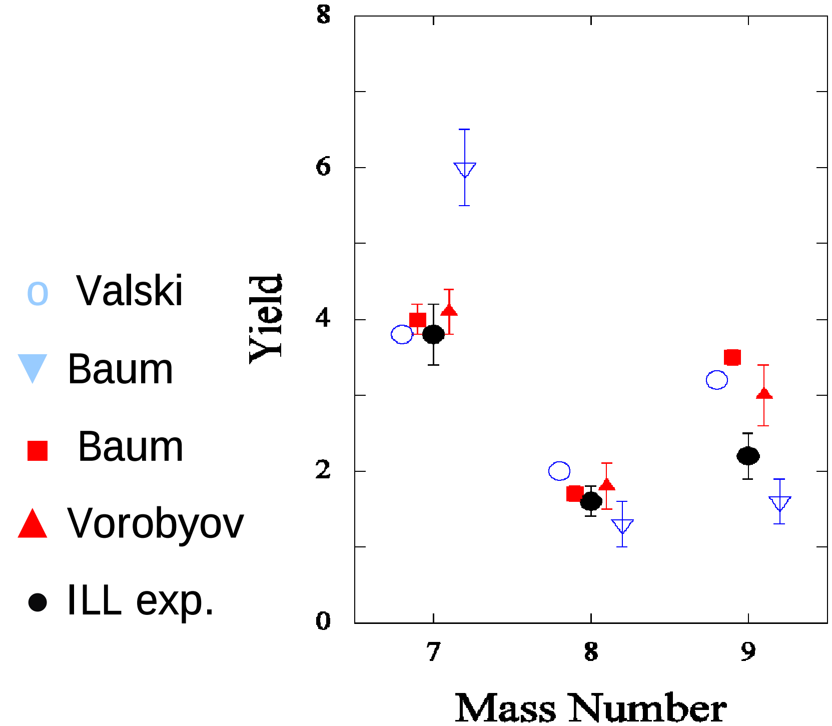
Schematic view



At the casemate of PF1 at the ILL

Ternary He and Li yields in $^{235}U(n_{th},f)$



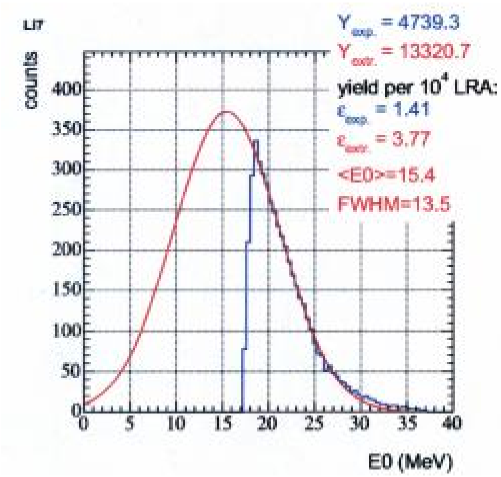


Yields per 10^4 α - particles

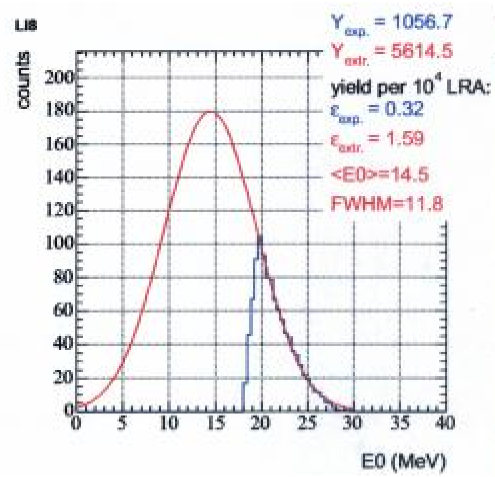
Isotope	^6He	^8He	^7Li	^8Li	^9Li	
	154(10)	4.5(3)	3.8(4)	1.6(2)	2.2(3)	Present work, preliminary
	191(8)	8.2(6)	4.1(3)	1.8(1)	3.0(4)	A.A. Vorobyov, 1972, exp.
	169(2)	7.4(8)	4.0(2)	1.7(1)	3.5(1)	W. Baum, PHD, Darmstadt, 1992, exp.
	140(70)	4.6(5)	3.6(2)	1.9(1)	3.4(3)	G.V. Valskii, 2004, model
			6.0(5)	1.3(3)	1.6(3)	W. Baum, PHD, Darmst., 1992, model

Spectra of ternary Li isotopes from $^{235}U(n_{th},f)$

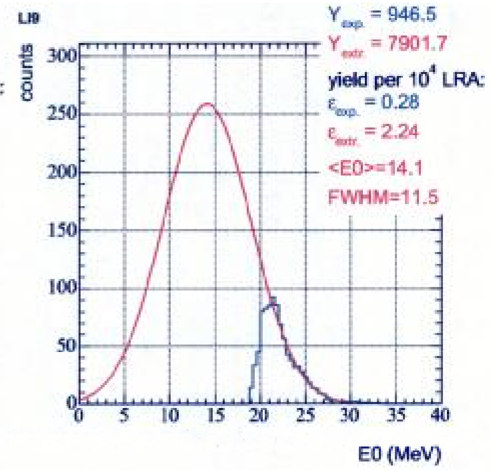
^{7}Li



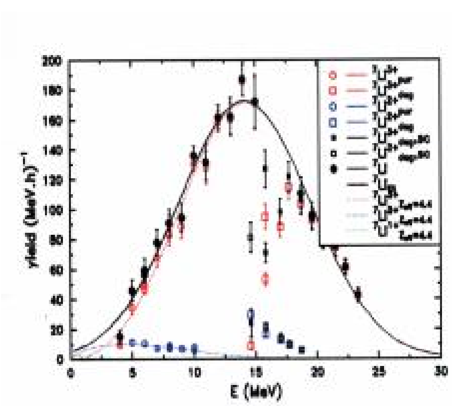
^{8}Li

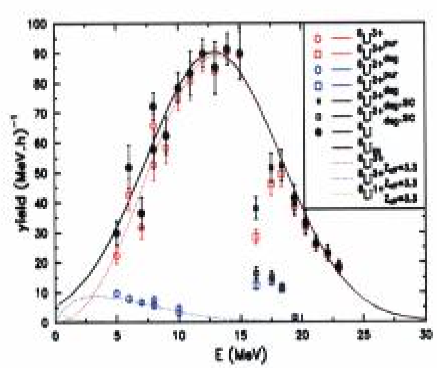


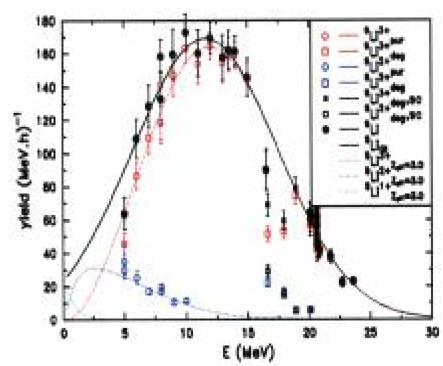
^{9}Li



Present Experiment







LOHENGRIN data

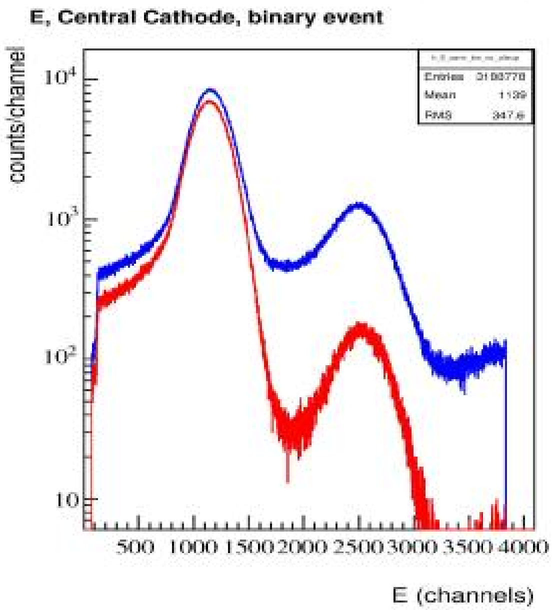
ILL Report 3-01-380, S Oberstedt et al. 2000

$^{235}U(n_{th},f)$ Mass Distribution from CODIS2

Fission count rate: $2.5 \times 10^5\ s^{-1}$ in 4π

Current-sensitive preamps

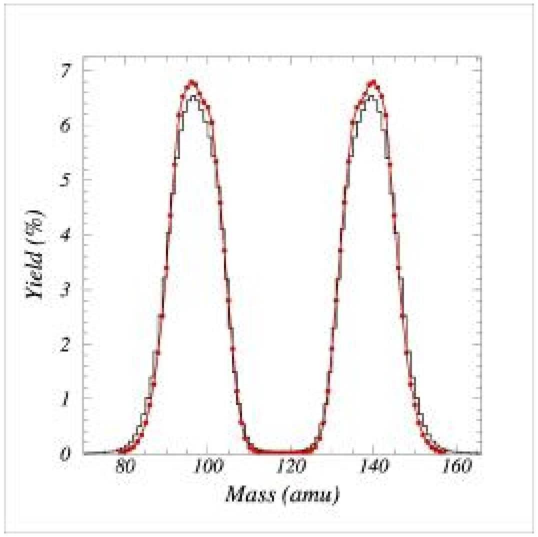
Pile-up rejection: ≈ 30%



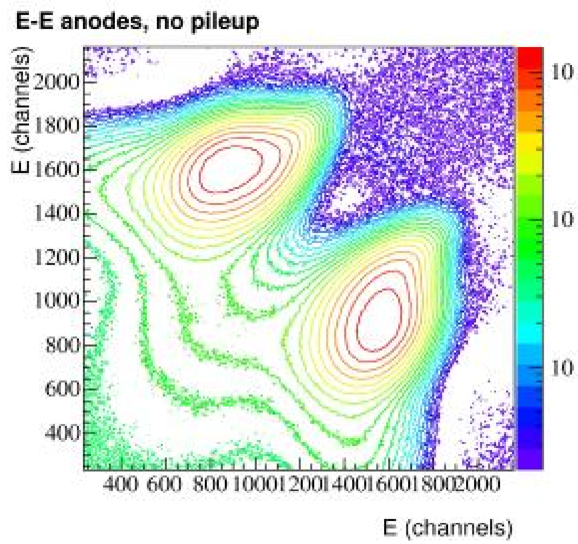
Amplitude of central cathode with and without pile-up filter activated

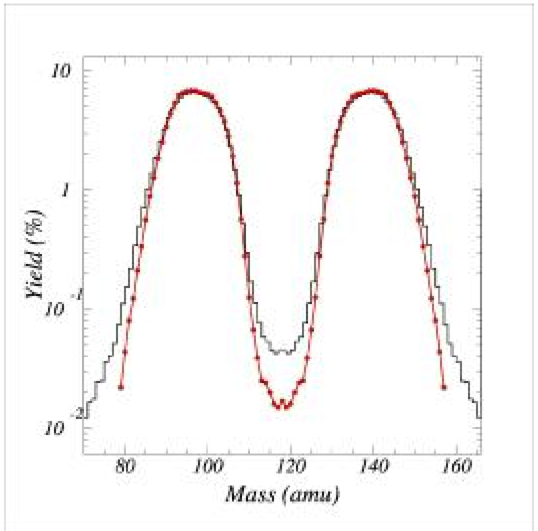
Mass spectrum lin/log

(compared with literature data)

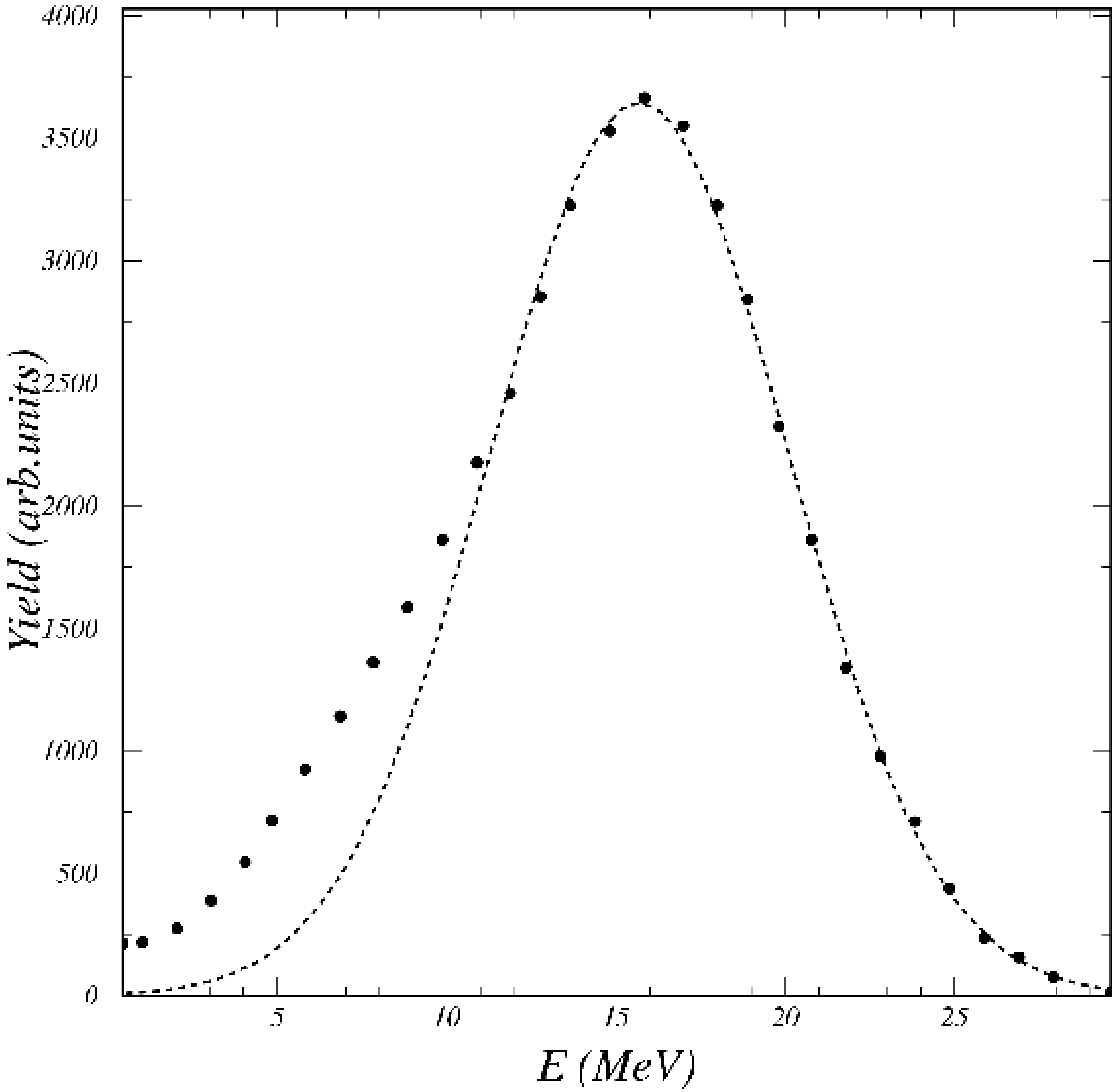


E_1-E_2 distribution with pile-up filter activated





Measurement of Full a-particle Energy Spectrum
Jyvaskyla (September-December 2005)



W. Loveland, 1974

Low energy tail in ternary alpha spectrum of ^{252}Cf TF

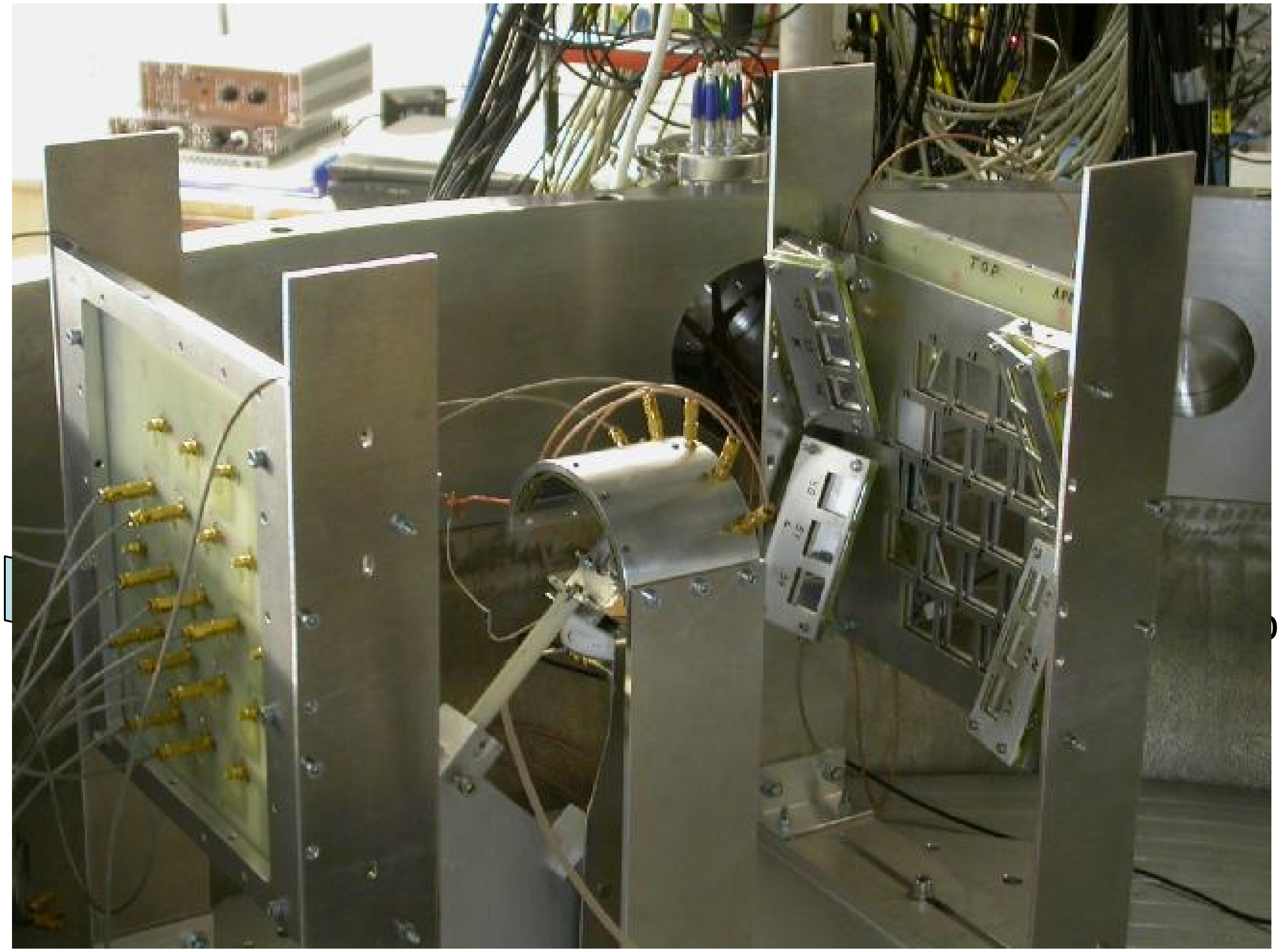
V. Tishchenko, 2002

Deviation from Gaussian shape is confirmed

C.Wagemans

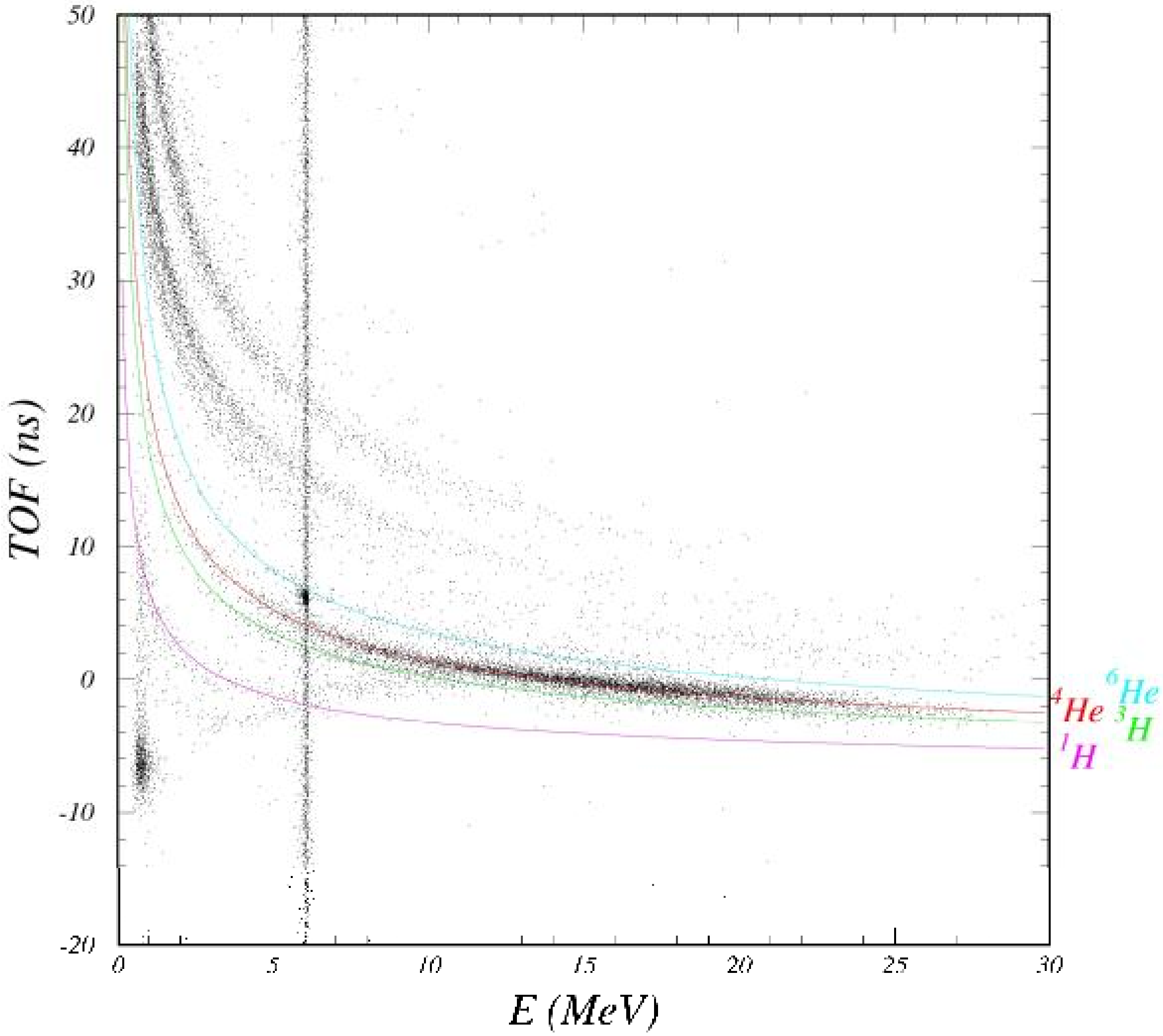
Tail is due to ^{5}He decay contribution

Measurement of Full α-particle Energy Spectrum Jyvaskyla (September-December 2005)



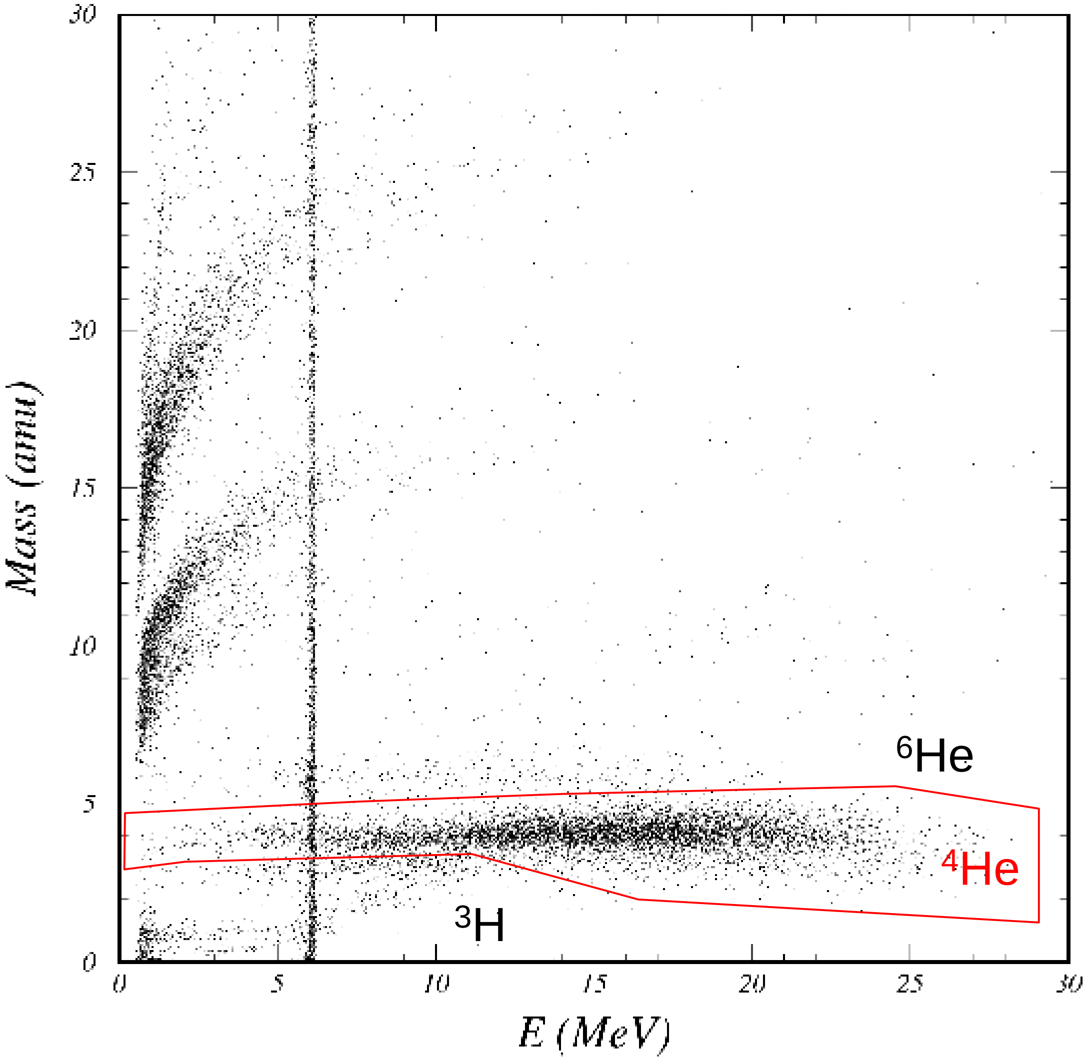
Schematic view

Measurement of Full a-particle Energy Spectrum Jyvaskyla (September-December 2005)



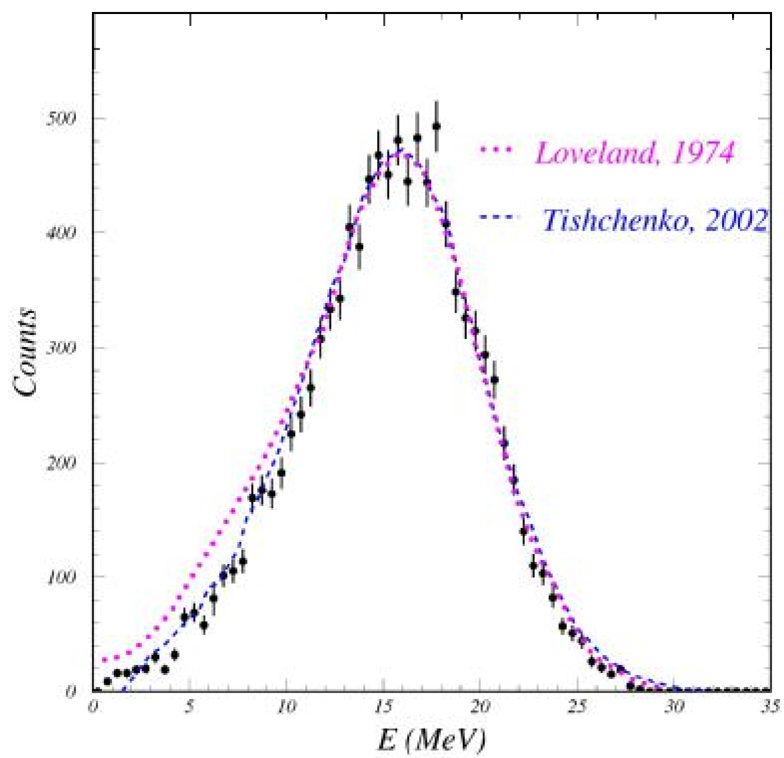
TOF-E identification plot

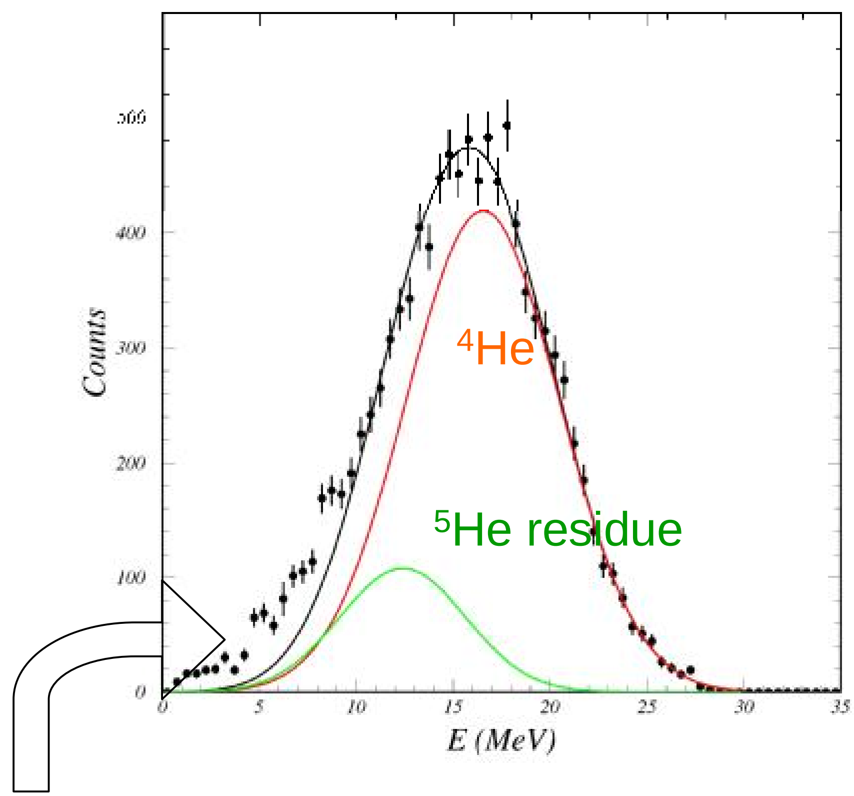
Measurement of Full a-particle Energy Spectrum Jyvaskyla (September-December 2005)



Mass identification

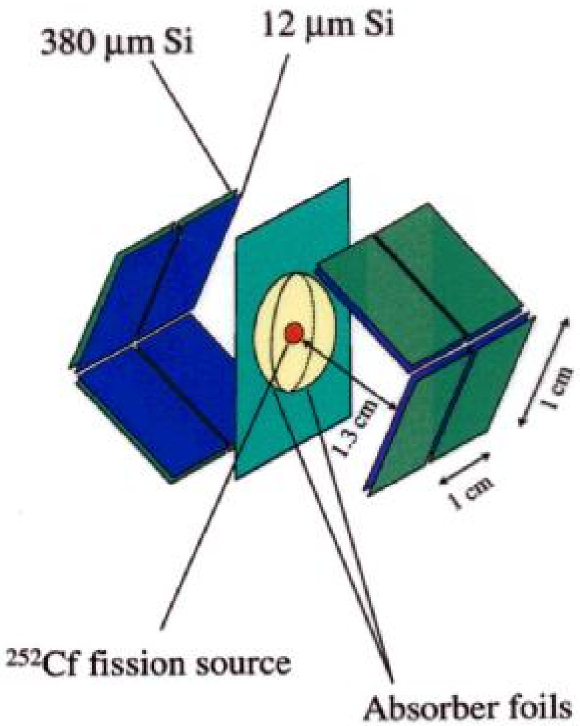
Measurement of Full a-particle Energy Spectrum
Jyvaskyla (September-December 2005)

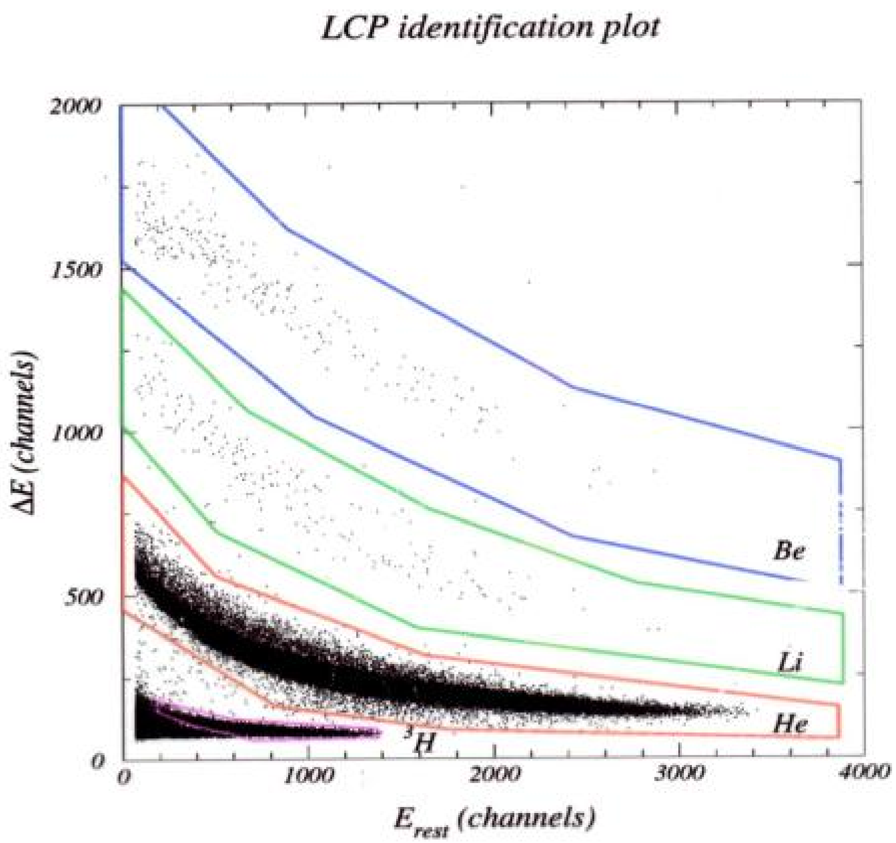




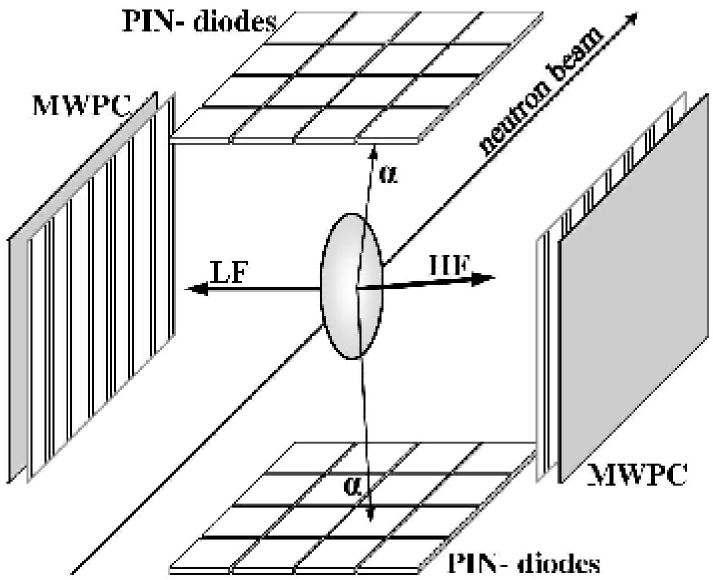
Low energy component which is not explained by ^{5}He decay

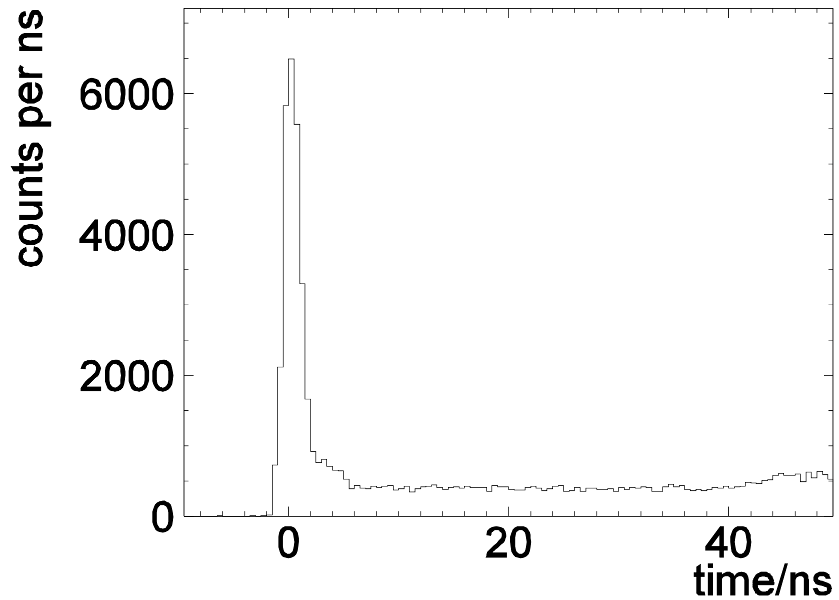
Experiment for the study of quaternary fission of $^{252}Cf(sf)$ at GSI (Darmstadt)





Experiment for the study of quaternary fission of $^{233}U(n,f)$ and $^{235}U(n,f)$ at ILL (Grenoble)

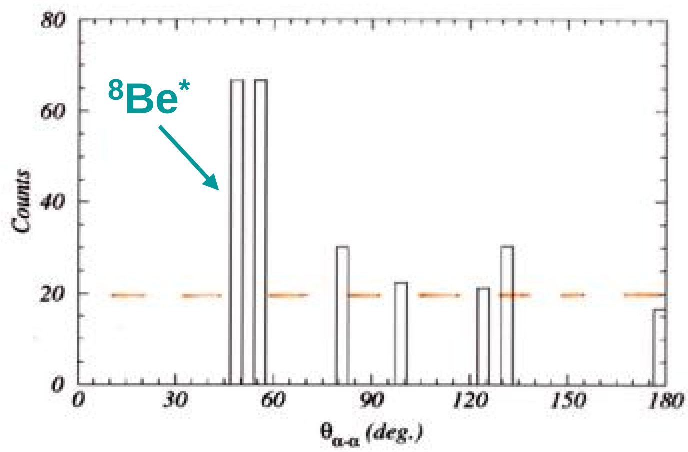




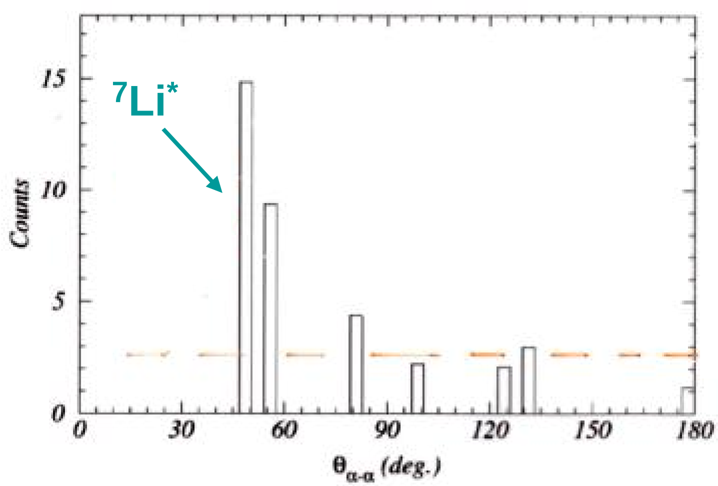
Angular distributions for a - a and a - t coincidences

$^{252}Cf(sf)$

α-α coincidences;

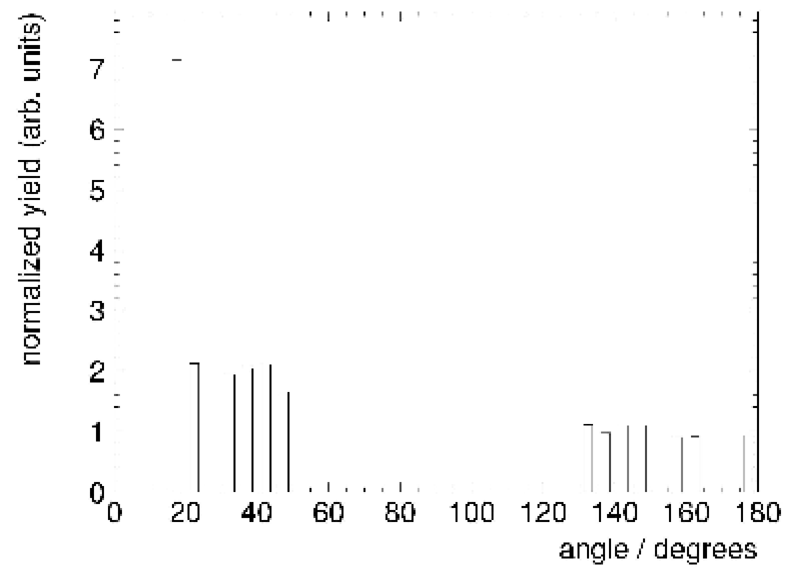


α-t coincidences:

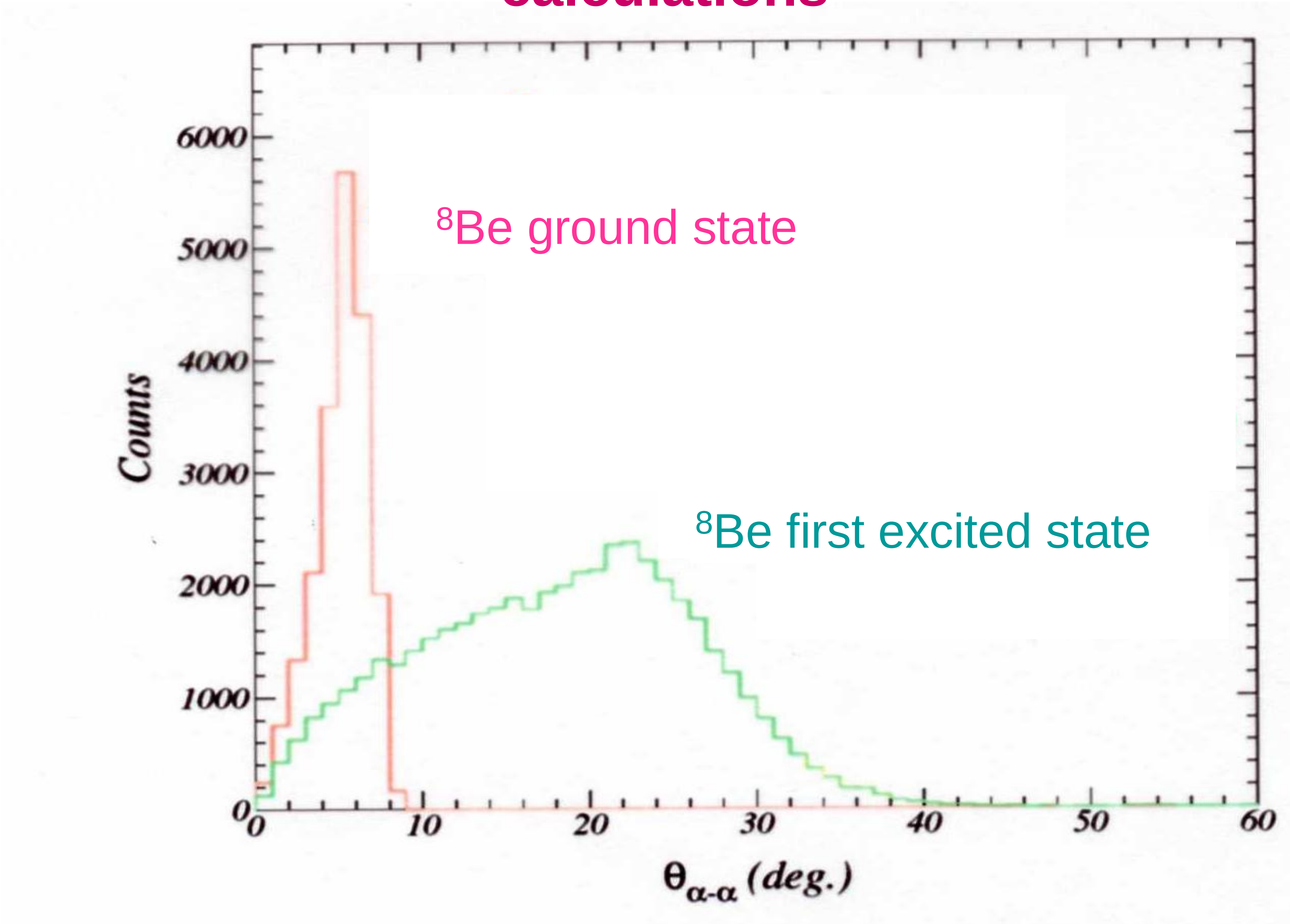


$^{233}U(n,f)$

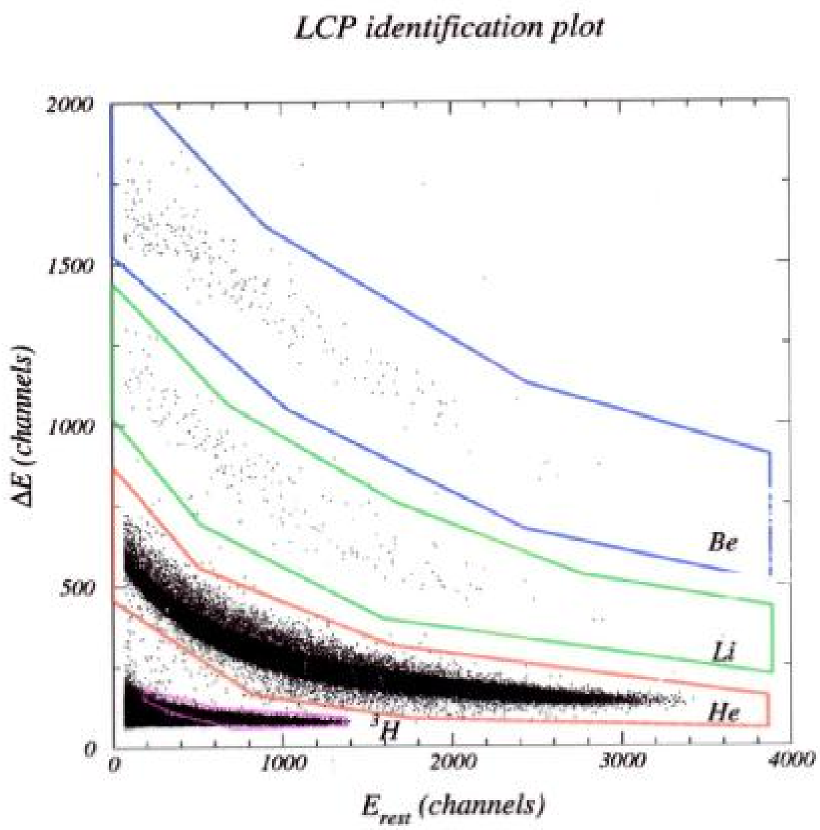
a - a coincidences

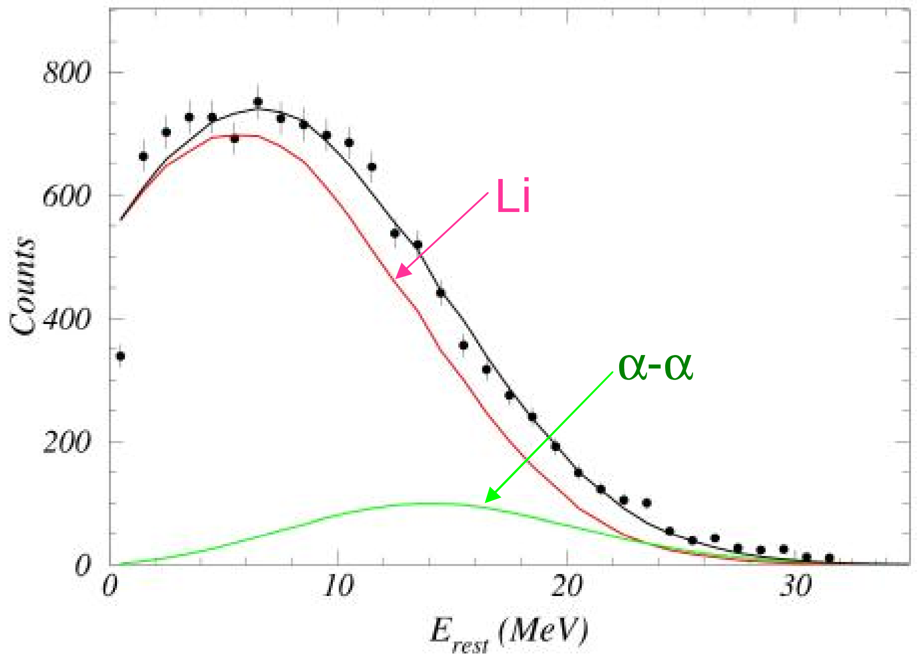


Angular distributions from trajectory calculations



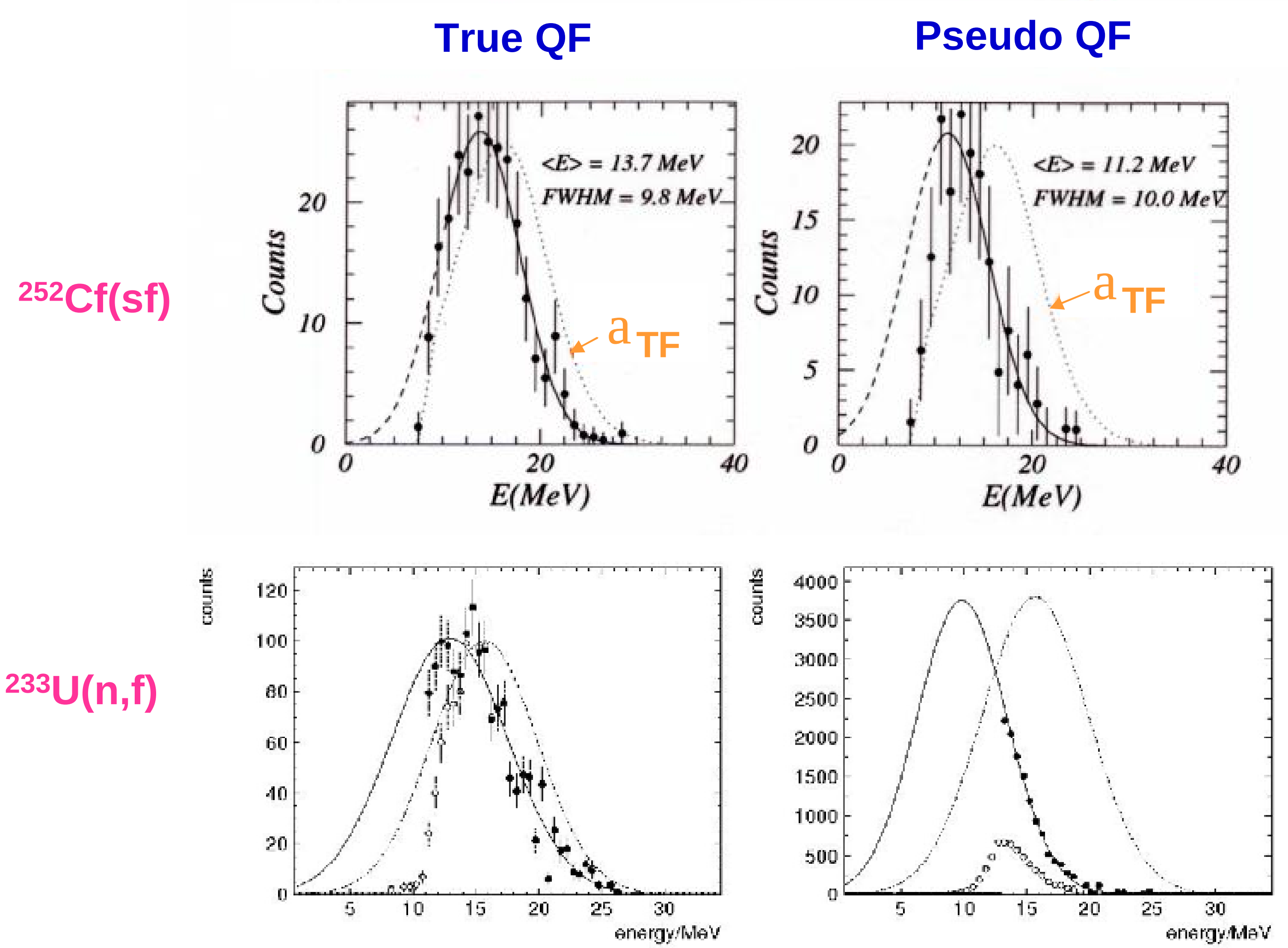
^{8}Be ground state yield determination for $^{252}Cf(sf)$



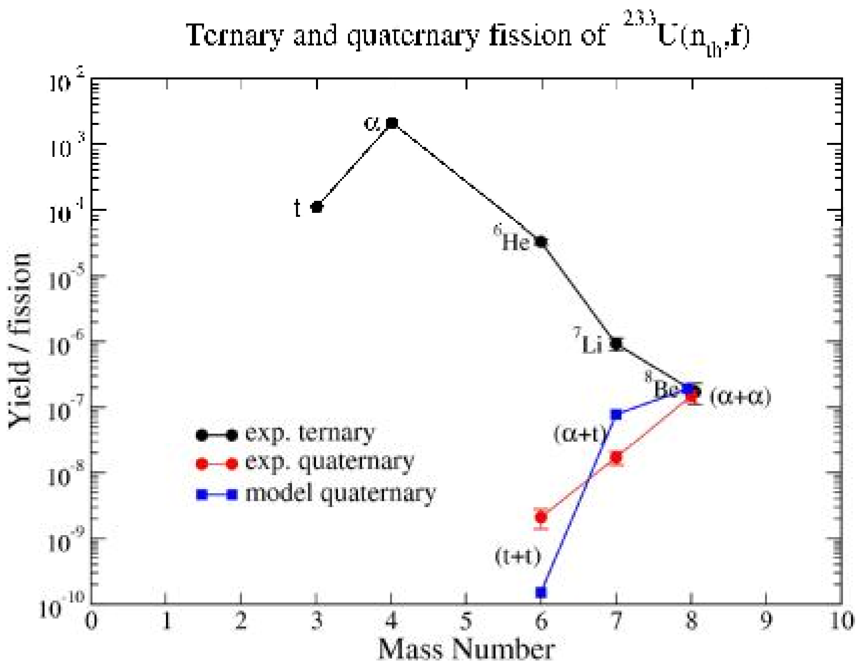


Fit of the Li energy distribution with two componenets: true Li and α-α

Energy distributions of α-particles from "true" and "pseudo" quaternary fission of $^{252}Cf(sf)$ and $^{233}U(n,f)$



Quaternary fission yields



Yields of LCPs in excited states Þ nuclear temperature in ternary fission

$\boldsymbol{Y_{g.s.}\ \mu\ exp[E/T]}$

$\boldsymbol{Y_{exc.s.}\ \mu\ exp[(E+E^*)/T]}$

$\boldsymbol{Y_{exc.s.} / Y_{g.s.} = exp(E^*/T)}$

Decay mode		Yield per 10^4 TF α's		
		^{252}Cf(sf)	^{233}U(n,f)	^{233}U(n,f)
α – per binary fission	TF	3.3×10^{-3}	2.1×10^{-3}	1.7×10^{-3}
(α, α)	QF	3(1)	0,41(13)	0,32(10)
8Be(g.s.)	QF	10(6)		
8Be*	QF	2(1)		
Σ8Be,8Be*	QF		0,94(30)	0,83(30)
10Be	TF	140(15)	43(3)	30(2)
(α,t)	QF	0,4(1)	0,03(1)	0,03(1)
7Li*	QF	0,3(1)	0,03(1)	0,04(1)
7Li	TF	17(4)	4,4(7)	4,1(3)

Summary and Outlook

- Ternary fission is a unique tool for studying the behavior of the nuclear system at the moment close to scission.
- It is only possible to get access to the nuclear fission dynamics by multiparameter measurements of all fission components.
- High resolution and high efficiency gamma-ray and neutron spectroscopy of ternary fission is a step forward in understanding of this rare process.
- It would be interesting to observe a “quinary“ fission – splitting of a nucleus into 5 fragments (2FF and 3 LCP)

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Crystal-Ball experiment with ^{252}Cf(sf) at MPI-K:

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P. Thirolf	MPI-K Heidelberg
F. Gönnenwein	Univ. Tübingen
M. Hesse	Univ. Tübingen

LCP-LCP correlation experiment with ^{252}Cf(sf) at GSI:

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H.-J. Wollersheim	GSI Darmstadt
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QF experiment with ^{233}U(n,f) and ^{235}U(m,f) at ILL:

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G.A.Petrov	PNPI Gatchina
W.H.Trzaska	Univ. Jyväskylä

Super-Clover (VEGA) experiment with ^{252}Cf(sf) at GSI:

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Ternary Fission experiment with ^{235}U(n,f) at ILL:

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A M Gagarski	PNPI Gatchina
V Nesvizhevsky	ILL Grenoble
W H Trzaska	Univ. Jyväskylä

Ternary Fission experiment with ^{235}U(n,f) at ILL:

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