Application of Calorimetric Low Temperature Detectors for the Investigation of Z-Yield Distributions of Fission Fragments

Peter Egelhof

GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
and
University Mainz, Germany

24th Int. Seminar on Interaction of Neutrons with Nuclei ISINN-24
Dubna, Russia
May 23 - 27, 2016

Application of Calorimetric Low Temperature Detectors for the Investigation of Z-Yield Distributions of Fission Fragments

I. Introduction

II. Detection Principle and Basic Properties of Calorimetric Low Temperature Detectors (CLTD`s)

III. CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

IV. Investigation of Z-Distributions of Fission Fragments
  a) Idea of the Experiment
  b) Feasibility Studies at the Munich Tandem Accelerator
  c) Experiments at the ILL Grenoble

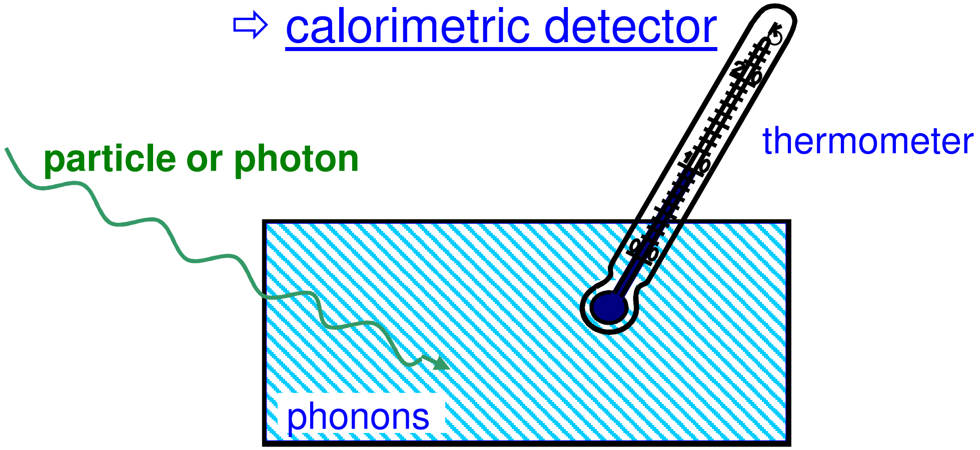
V. Summary and Future Perspectives

I. Introduction

The <u>success of experimental physics</u> and the <u>quality of the results</u> generally depends on the <u>quality of the available detection systems !</u>

⇒ <u>idea:</u> detection of radiation <u>independent of ionisation processes</u>

⇨ <u>calorimetric detector</u>



<u>interaction of radiation with matter:</u>

primary: ionization, ballistic phonons (conventional ionisation detectors)

secondary: thermalization: conversion of energy to heat

⇒ detection of thermal phonons

⇒ <u>calorimetric detectors</u>

<u>potential advantage:</u>

- energy resolution
- energy linearity
- detection threshold
- radiation hardness

⇒ various applications in many fields of physics

Applications of Low Temperature Detectors - an Overview

Astrophysics:

- dark matter
  ⇒ low detection threshold
- solar neutrinos
  ⇒ low detection threshold
- cosmic x-rays
  ⇒ high energy resolution

Particle physics:

- $\beta\beta0\nu$-decay
  ⇒ absorber = source (^{130}Te)
- neutrino mass from β- endpoint determ.
  ⇒ absorber = source (^{187}Re)

Atomic and Nuclear physics:

- X-ray detection
  ⇒ high energy resolution
- Ion detection
  ⇒ high energy resolution
  ⇒ good energy linearity

Applied physics:

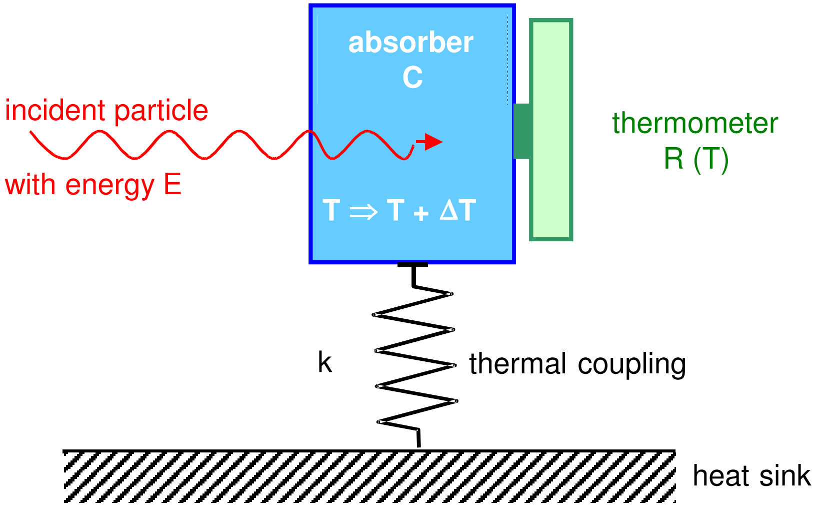
- x-ray material analysis
  ⇒ high energy resolution
- life sciences (MALDI)
  ⇒ high energy resolution

for more detailed information see:

- Cryogenic Particle Detection,
  Topics in Applied Physics 99 (2005)
- Proceedings 15th Int. Workshop on
  Low Temperature Detectors,
  JLTP (2014), 320 participants!

II. Detection Principle and Basic Properties of Calorimetric Low Temperature Detectors (CLTD`s)

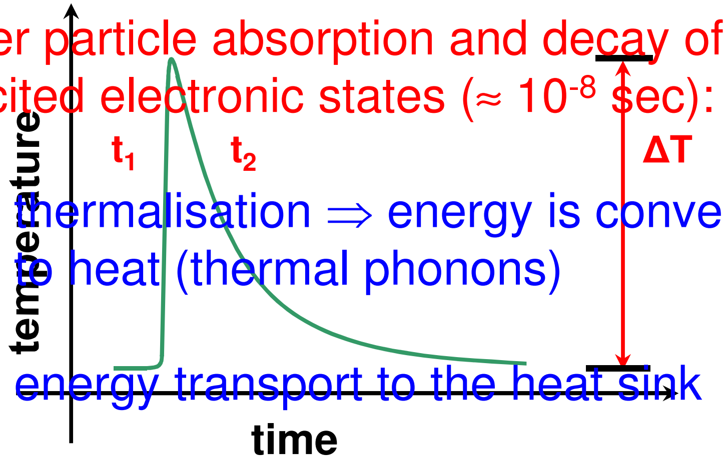
detection principle:



thermal signal:

after particle absorption and decay of excited electronic states (≈ 10^{-8} sec):

- thermalisation ⇒ energy is converted to heat (thermal phonons)
- energy transport to the heat sink



amplitude:	$\Delta T = E/C$	($C = c \bullet m$ = heat capacity)
rise time:	$\tau_1 \geq \tau_{therm}$	(≈ 1 – 10 µsec)
fall time:	$\tau_2 = C/k$	(≈ 100 µsec – 10 msec)

Optimization of the Sensitivity

a) <u>absorber:</u> maximum sensitivity $\Delta T = E/mc$ for

– small absorber mass m

– small specific heat c

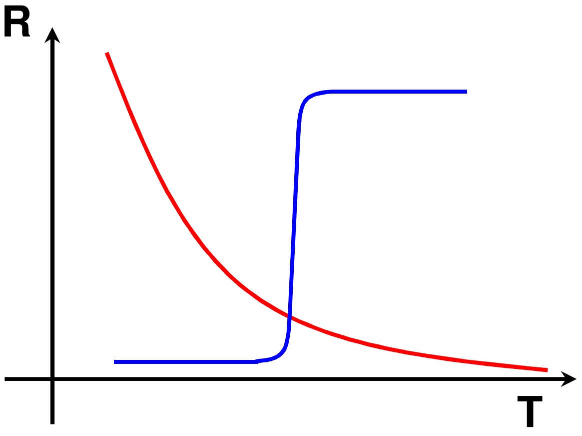
due to: $c = \underbrace{\alpha T}_{\text{electrons}} + \underbrace{\beta (T/\theta_D)^3}_{\text{lattice}}$ (θ_D = Debye-temperature)

⇒ low operating temperature ⇒ „<u>low-temperature detector</u>“

(αT dominating for $T \leq 10$K ⇒ insulators ($\alpha = 0$) or superconductors)

b) <u>thermometer:</u> for thermistor (bolometer): $\Delta T \rightarrow \Delta R \rightarrow \Delta U$

⇒ maximum sensitivity for large dR/dT



– semiconductor thermistor

due to appropriate doping ⇒ exponential behavior of R(T)

– superconducting phase transition thermometer

Potential Advantage over Conventional Detectors

- small energy gap ω

  ⇒ better statistics of the detected phonons

  semiconductor detector: $\omega \approx 1$ eV

  calorimetric detector: $\omega \leq 10^{-3}$ eV

$$\frac{\Delta E_{calorimeter}}{\Delta E_{semicond.\mathrm{det}.}} = \sqrt{\frac{N_{electr.}}{N_{phon.}}} = \sqrt{\frac{\omega_{phon}}{\omega_{electr.}}} \leq \frac{1}{30}$$

- more complete energy detection ⇒ better linearity and resolution

  energy deposited in phonons and ionisation contributes to the signal
  (for ionisation detectors: losses up to 60-80% due to: - recombination
  - direct phonon production)

- small noise power at low temperatures

- method independent on absorber material

  ⇒ optimize radiation hardness, absorption efficiency, etc.

Theoretical Limit for the Energy Resolution

for ideal calorimetric detector:

- thermodynamic fluctuations (quantum statistics)
- Johnson noise
- amplifier noise

$$\Rightarrow < \Delta E >= \underset{\text{noise}}{\xi} \bullet \underbrace{\sqrt{k_B T^5 c \; m}}_{\text{thermodynamic fluctuations}} \qquad 1 < \xi < 3$$

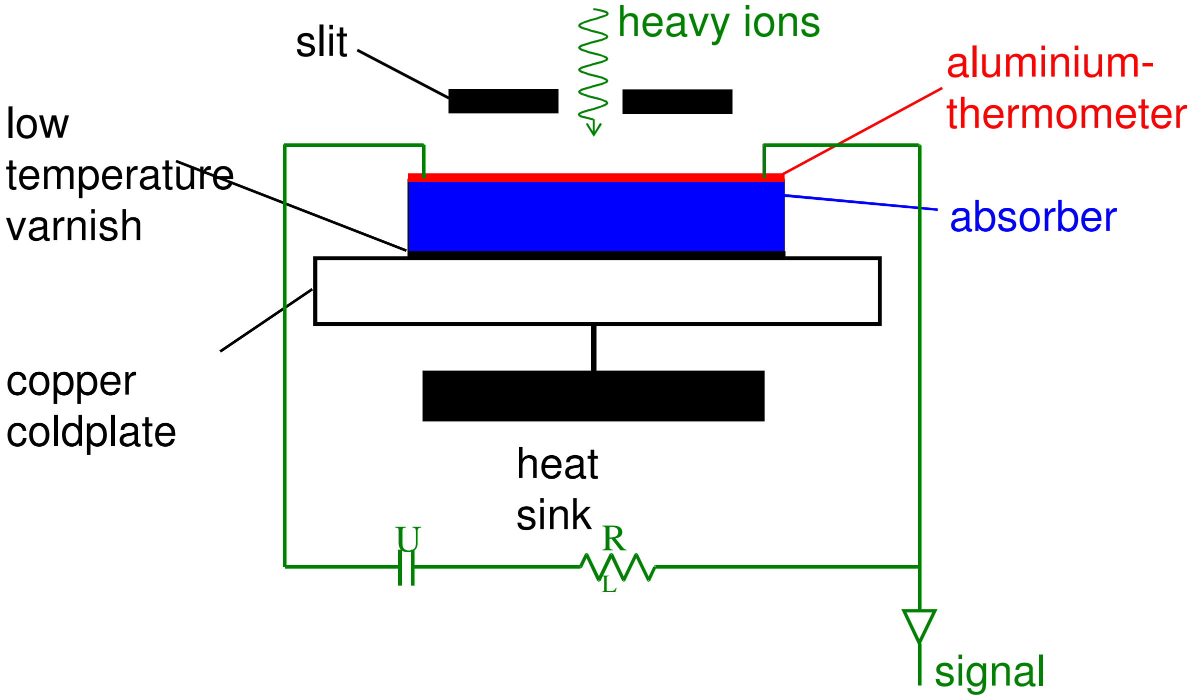
example: 1 MeV particle in a 1 mm^3 sapphire absorber

T	C	ΔT	ΔE_{theor}
300 K	$3 \bullet 10^{-3}$ J/K	$5 \bullet 10^{-11}$ K	1.8 GeV
10 K	$4 \bullet 10^{-7}$ J/K	$4 \bullet 10^{-7}$ K	700 keV
1 K	$4 \bullet 10^{-10}$ J/K	0.4 mK	2.2 keV
100 mK	$4 \bullet 10^{-13}$ J/K	400 mK	7 eV

⇒ for low temperature: microscopic particle affects the properties of a macroscopic absorber

III. CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

Detector Design and Perfomance:



for an overview see:

P. Egelhof and

S. Kraft-Bermuth,

Top. Appl. Phys. 99 (2005) 469

absorber: sapphire-crystal: V= 3 x 3 mm² x 430 µm

thermometer: aluminium-film (d = 10 nm), $T_C \approx 1.5°K$ (in the range of a ^{4}He-cryostat)
(for impedance matching to the amplifier: ⇒ meander structure)

readout: conventional pulse electronics +Flash-ADC`s +Digital Filtering

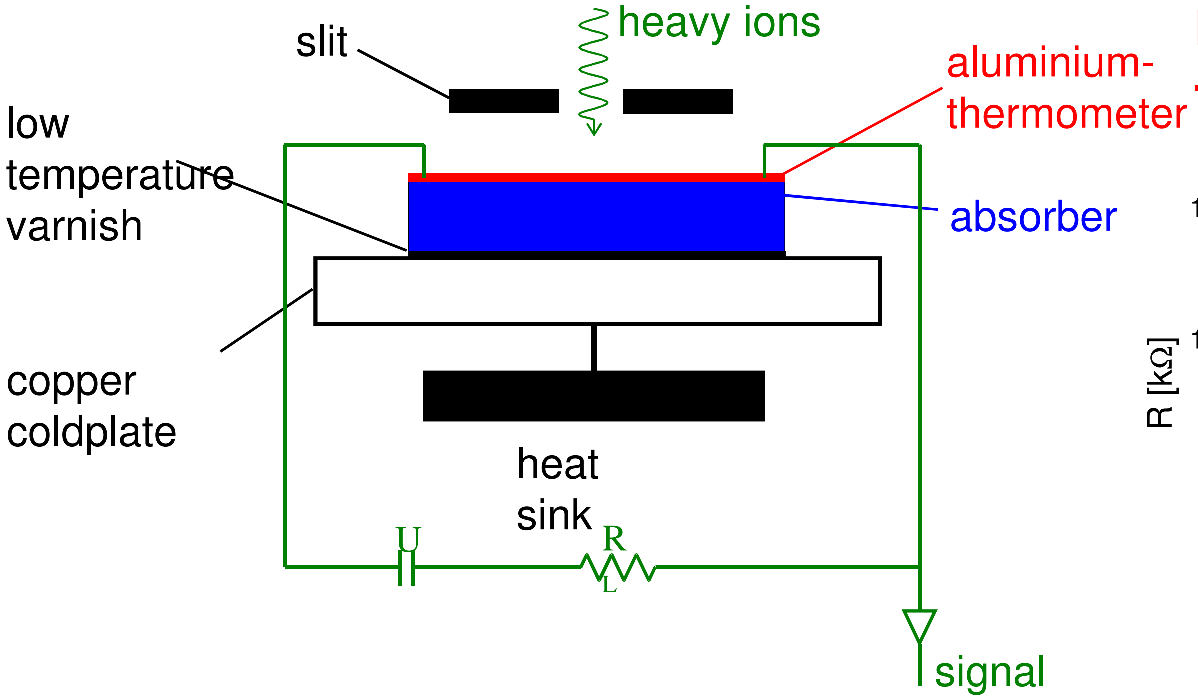
III. CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

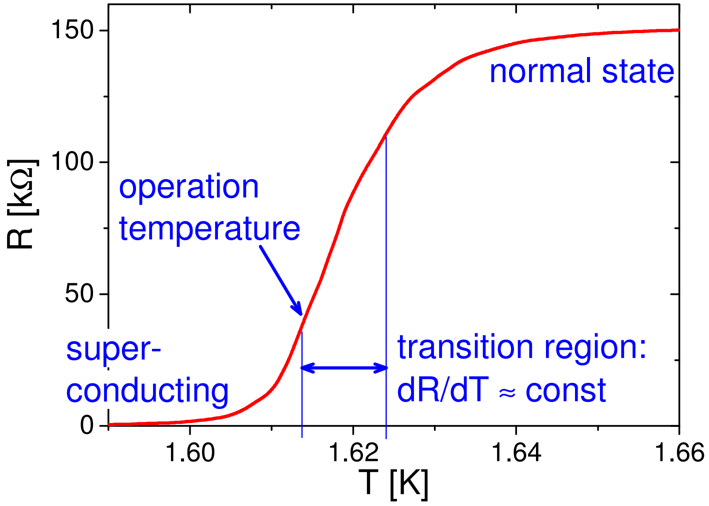
Detector Design and Perfomance:

for an overview see:

P.E. and S. Kraft-Bermuth,

Top. Appl. Phys. 99 (2005) 469





absorber: sapphire-crystal: V= 3 x 3 mm² x 430 µm

thermometer: aluminium-film (d = 10 nm), $T_C \approx 1.5°K$ (in the range of a ^{4}He-cryostat) (for impedance matching to the amplifier: ⇒ meander structure)

readout: conventional pulse electronics +Flash-ADC`s +Digital Filtering

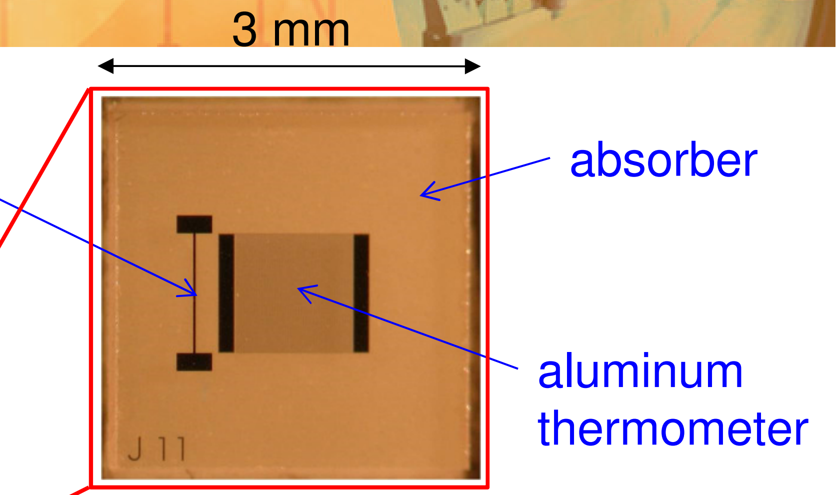
CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

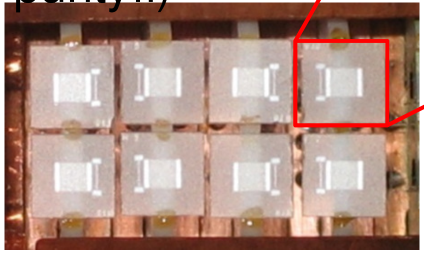
detector pixel:

- absorber:
  $3 \times 3 \times 0.43$ mm^3 sapphire (Al_2O_3)
- thermometer:
  Transition Edge Sensor (TES)
  10 nm thick meander shaped Al-layer
  ⇒ photolithography (high purity!!)
- heating resistor:
  Au/Cr strip
- operation temperature:
  $T_c = 1.5 - 1.6$ K

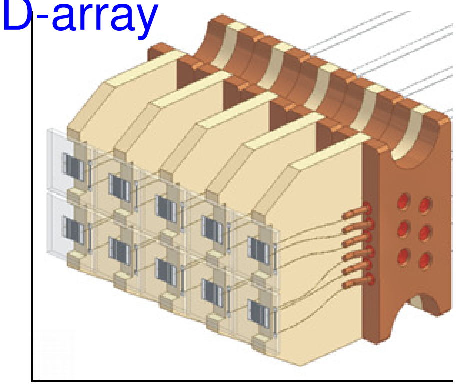
detector array:

- 8 pixels with individual temperature stabilization in operation
- active area: 12 mm x 6 mm
- windowless coupling of cryostat to beam line





CLTD-array

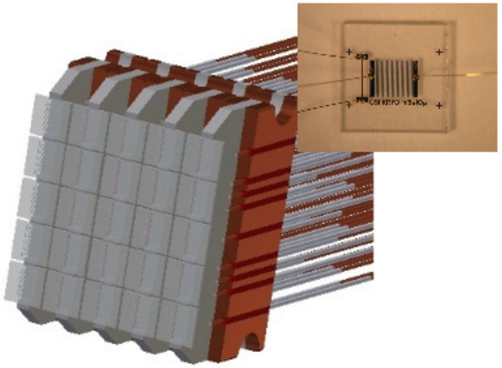


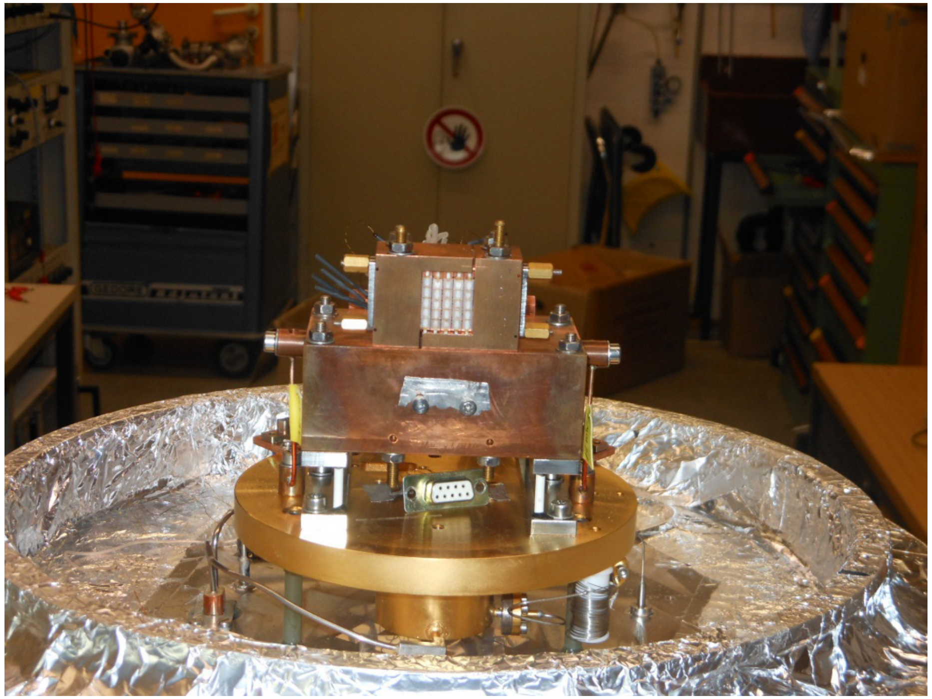
cryostat

New Large Solid Angle Detector Array

number of pixels: 25

active area: 15 X 15 mm^2





CLTD`s for High Resolution Detection of Heavy Ions - Design and Performance

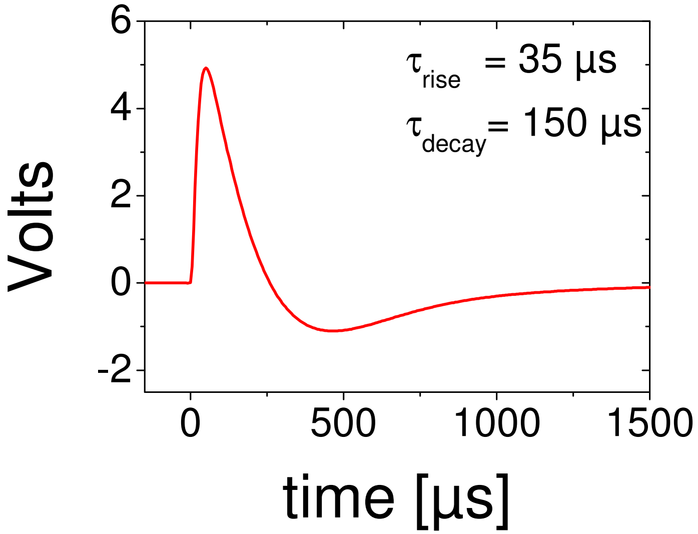
detector performance: response to ^{32}S ions @ 100 MeV

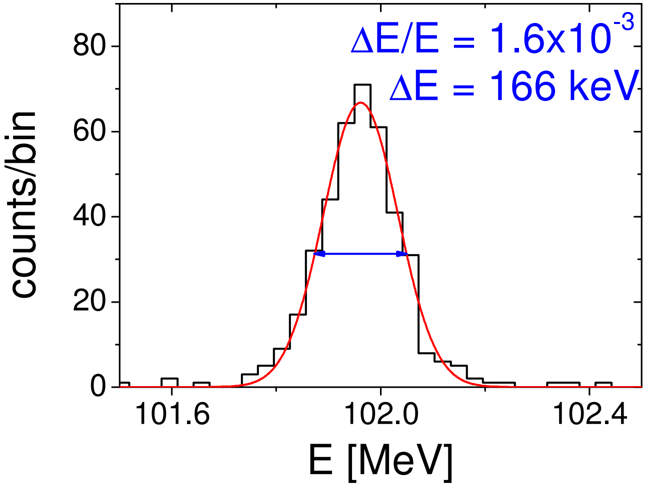
rate capability:

≥ 200 sec^{-1}

resolution:

$\Delta E/E = 1.6 \times 10^{-3}$





systematical investigation of energy resolution:

with UNILAC-beam: for ^{209}Bi, E = 11.6 MeV/u ⇒ $\Delta E/E = 1.8 \times 10^{-3}$
with ESR-beam: for ^{238}U, E = 360 MeV/u ⇒ $\Delta E/E = 1.1 \times 10^{-3}$
with Tandem-beam: for ^{152}Sm, E = 3.6 MeV/u ⇒ $\Delta E/E = 1.6 \times 10^{-3}$

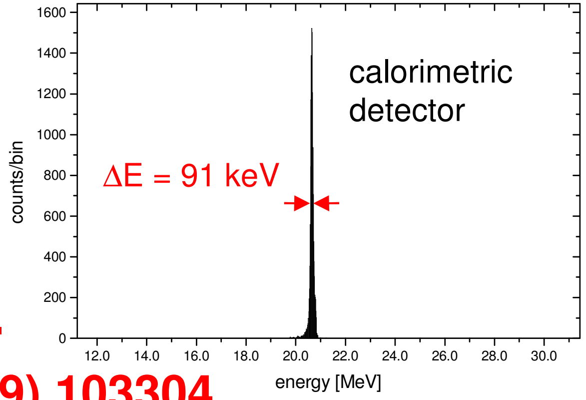
⇒ for heavy ions: ≥ 20 x improvement over conventional Si detectors

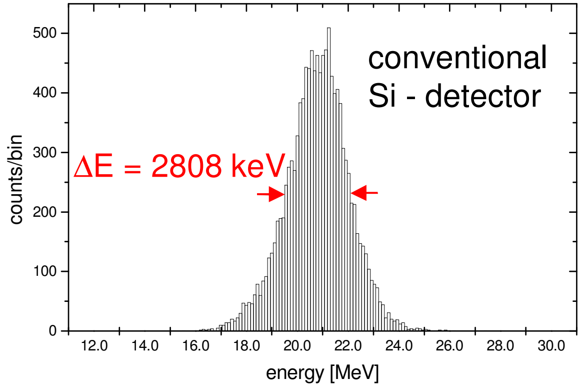
Comparison of Detector Performance: CLTD – Conventional Si Detector

energy resolution:

example:

^{238}U @ 20.7 MeV)





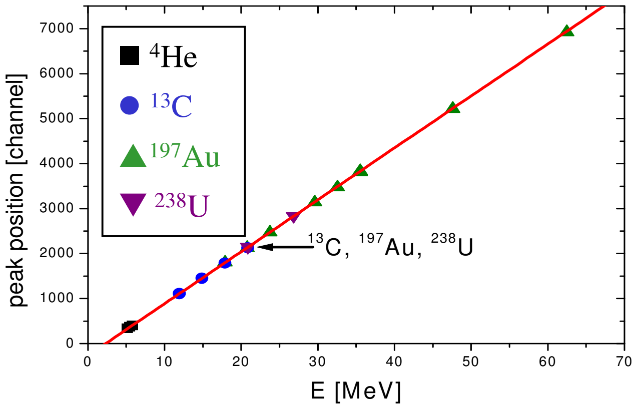
S. Kraft-Bermuth et al.

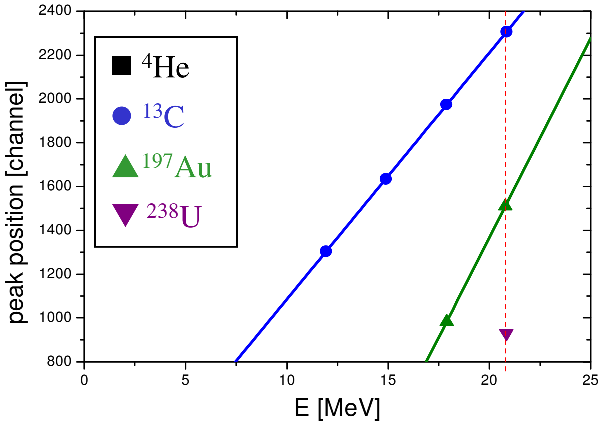
Rev. Sci. Instr. 80 (2009) 103304

energy linearity:

example:

^{13}C, ^{197}Au, ^{238}U



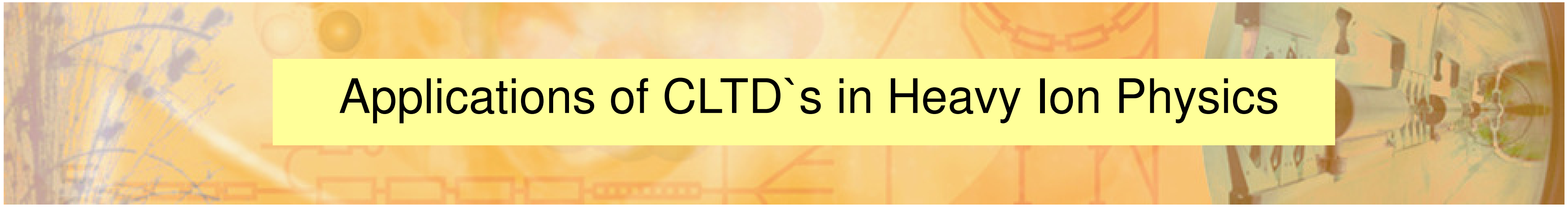


for conventional ionization detector:

high ionization density leads to charge recombination (E- and Z- dependent)

⇒ pronounced pulse height defects ⇒ nonlinear energy response

⇒ fluctuation of energy loss processes ⇒ limited energy resolution



Applications of CLTD`s in Heavy Ion Physics

- High Resolution Nuclear Spectroscopy
- Investigation of Stopping Powers of Heavy Ions in Matter
- In-Flight Mass Identification of Heavy Ions
- Investigation of Z-Distributions of Fission Fragments

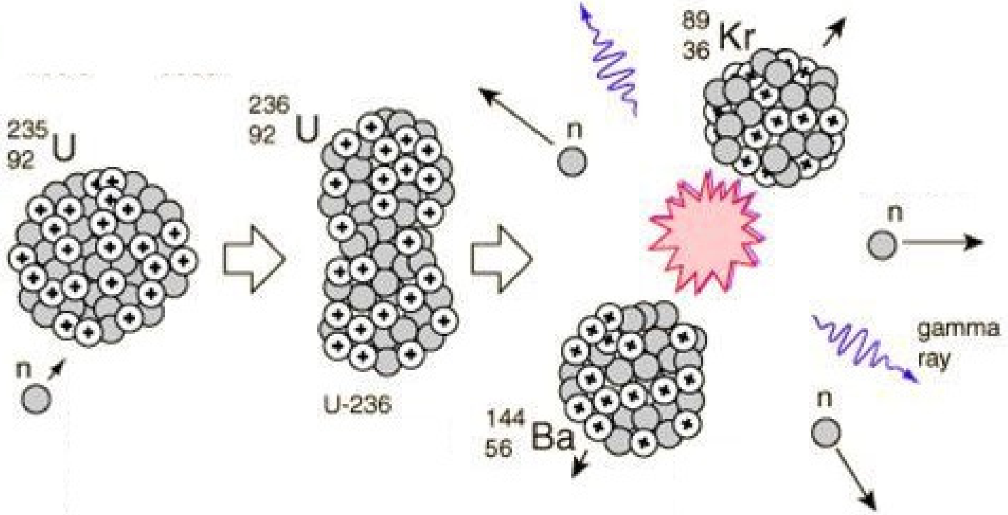
IV. Investigation of Z-Distributions of Fission Fragments

- fission of ^{235}U induced by thermal neutrons:

  ⇒ capture of a thermal neutron

  ⇒ binary scission

  ⇒ about 85% (~170 MeV)
  of the energy released
  is transferred to the kinetic
  energy of the fragments



- motivation for studying properties of fission fragments:

  ⇒ better understanding of the nuclear fission process

  ⇒ test of theoretical predictions

  ⇒ information about nuclear structure (shell effects, excited states, ...)

  ⇒ data relevant for reactor physics (for example for Fukushima – Accident)

Idea of the Experiment: Investigation of Z (nuclear charge) Distributions of Fission Fragments

- produce fission fragments by n → ^{235}U
  at the high flux research reactor of the ILL Grenoble

- select mass and energy in the LOHENGRIN mass seperator

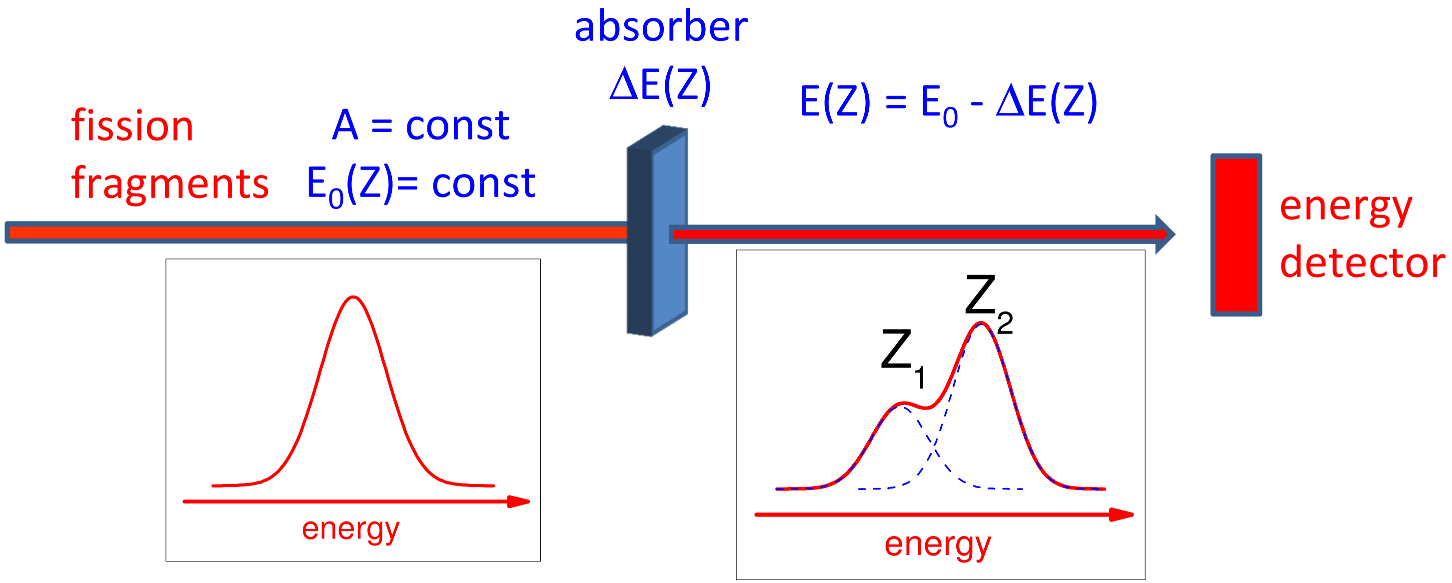
- identify Z by using the Z-dependent energy loss in an energy degrader
  (absorber method, see also U. Quade et al., NIM A164 (1979) 436
  U. Quade et al., Nucl. Phys. A487 (1988),1

- measure E_{rest} in a high resolving CLTD
  (instead of conventional ionization chamber)

Methods for Determination of Z-Distributions of Fission Fragments

- Radio chemistry
- γ-spectroscopy ⇒ restricted to particular nuclides

- Passive Absorber Method U. Quade et al., Nucl. Phys. A487 (1988) 1



absorber $\Delta E(Z)$

$E(Z) = E_0 - \Delta E(Z)$

fission fragments

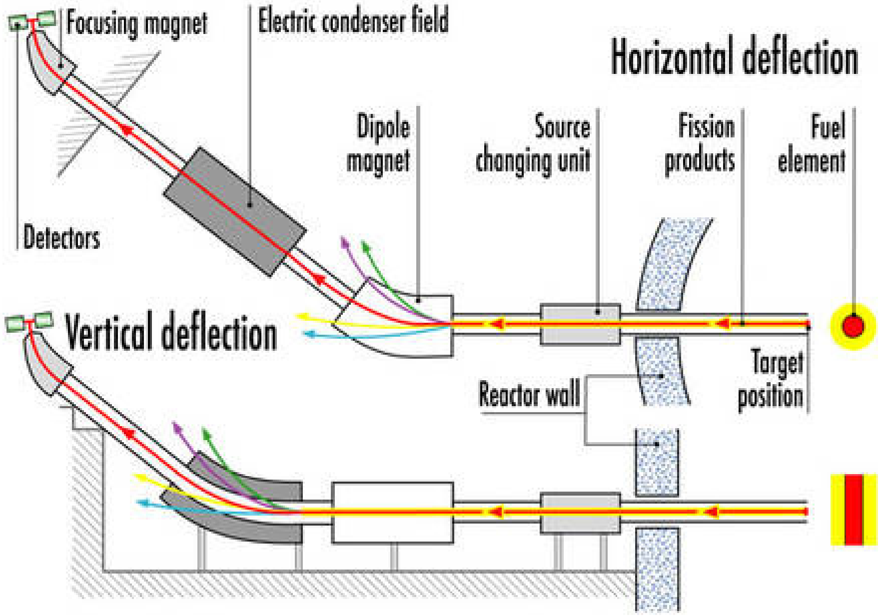
A = const

$E_0(Z)$= const

energy detector

Idea of the Experiment: Investigation of Z (nuclear charge) Distributions of Fission Fragments

The LOHENGRIN Mass Separator

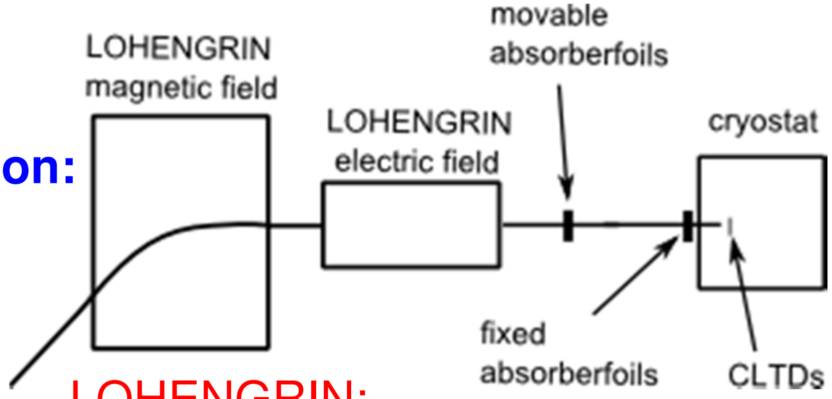


- production of fission products by n → ^{235}U
- separation according to A/Q (magnetic field) and E/Q (electric field)
- but no Z –selectivity!!

Z - Identification via the Absorber Method

Quality of Z – Separation depends on:

- proper choice of ΔE (absorber foil)
- homogenity of absorber foil
- energy resolution of CLTD`s



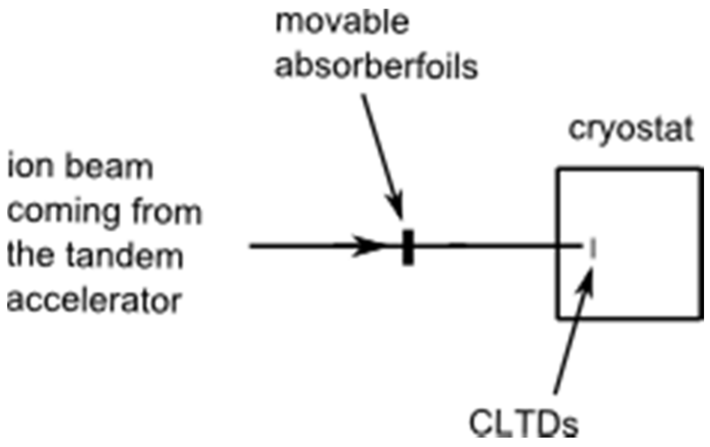
LOHENGRIN: fixed E,A,Q

$\Delta E \sim Z^2$

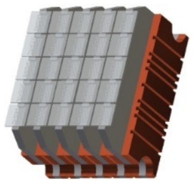
E_{Rest} (Z-dependent)

Feasibility Studies at the Munich Tandem Accelerator

- from the Tandem Accelerator:
  - ⇒ stable beams of ^{109}Ag (E = 80 MeV)
    and ^{127}I (E = 68.7 MeV)
    (at same velocity)



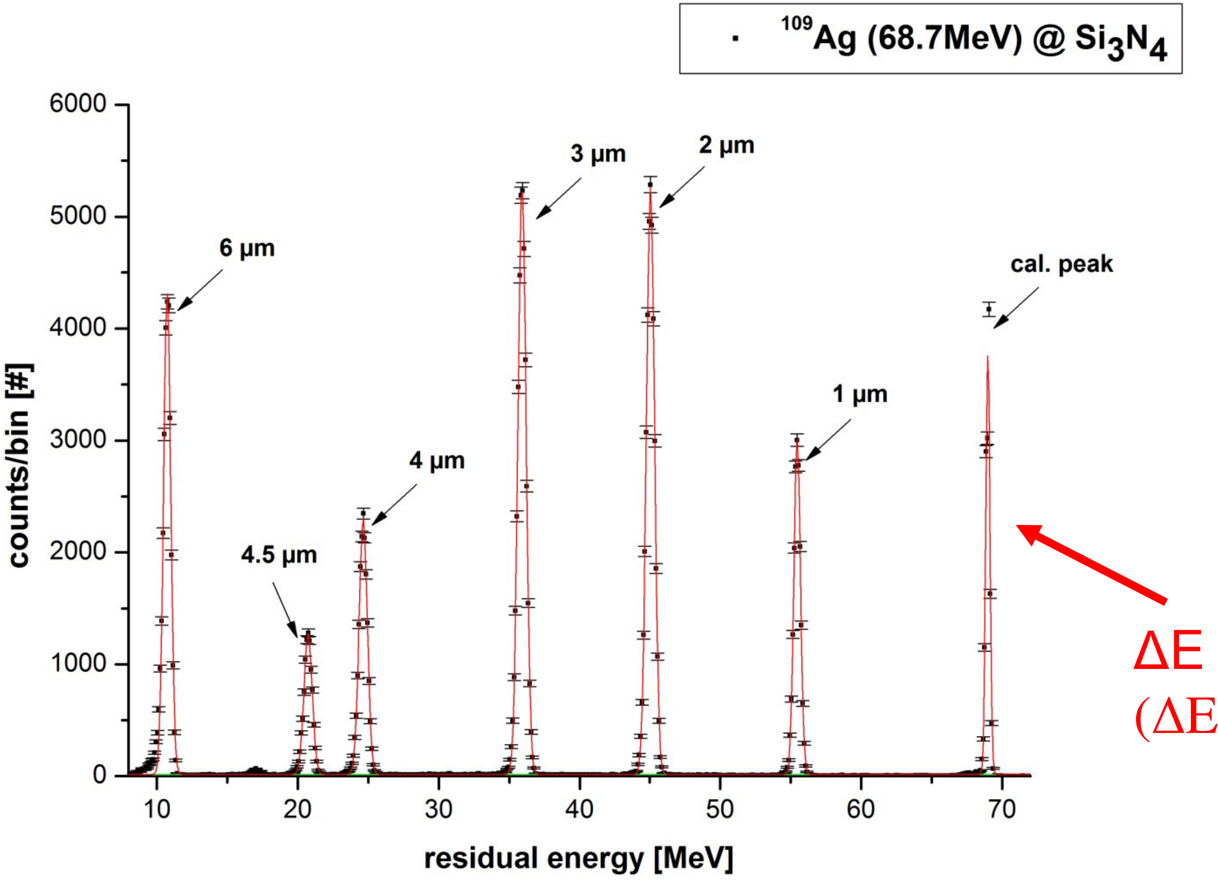
- aim of the experiment:
  - ⇒ first test of the new 25 pixel array
  - ⇒ check of quality of Z – separation
    dependent on:
    - type of absorber foil
    - thickness of absorber foil
    - homogenity of absorber foil
    - amount of energy straggling



- **25 pixel CLTD array**
- **individual temperature stabilization**
- **active area ~ (15x15)mm²**

Energy Loss of ^{109}Ag in Si_3N_4 for different Thickness of the Absorber Foil

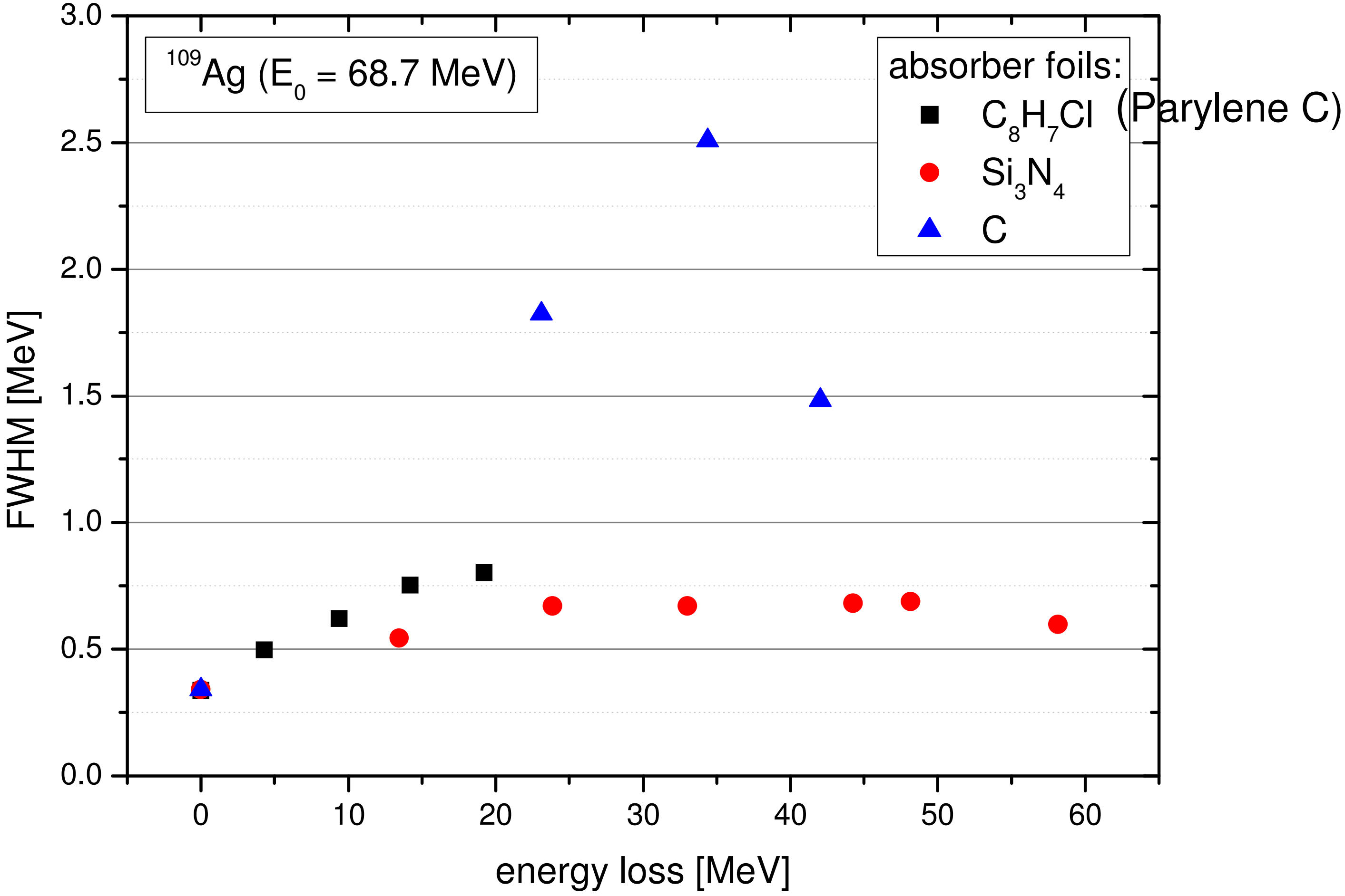
P. Grabitz et al., Journal of Low Temperature Physics (2016) in press



$\Delta E = 330$ keV

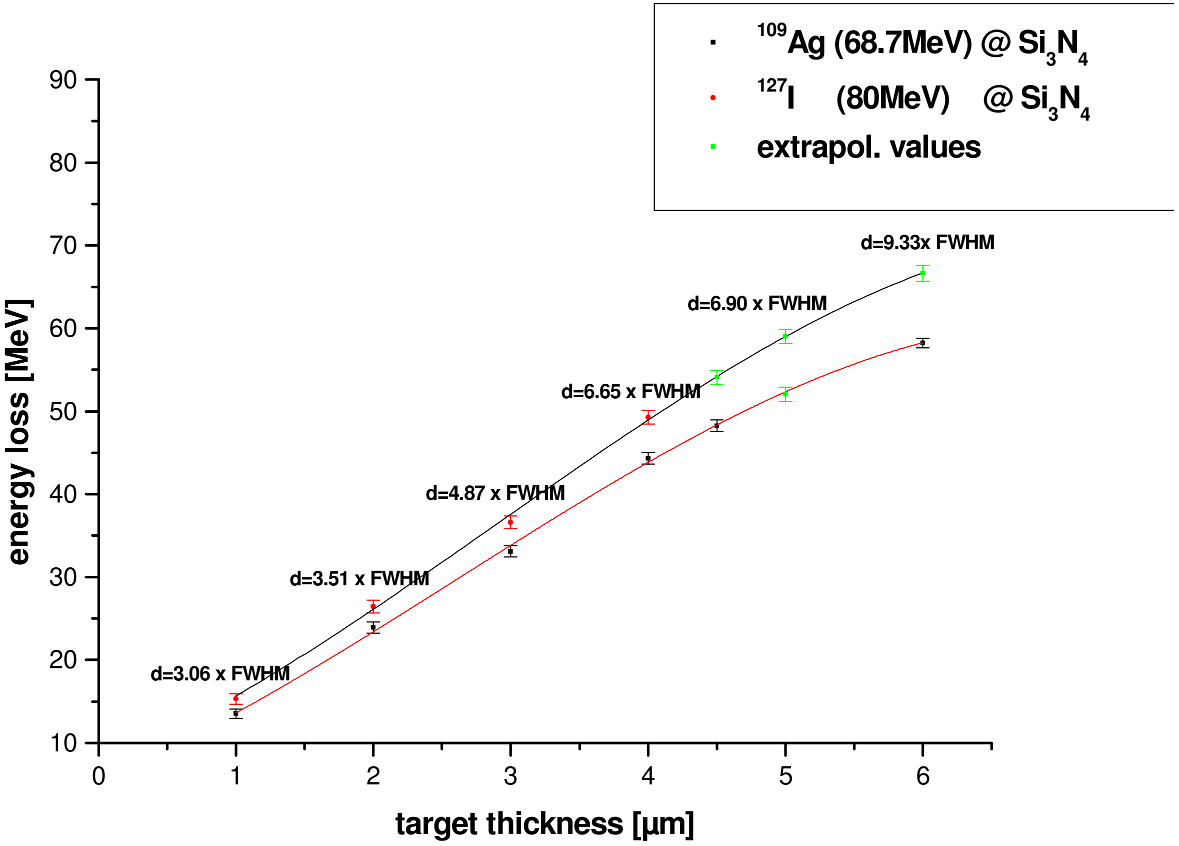
$(\Delta E/E = 0.5\ \%)$

FWHM for different Types of Absorber Foils



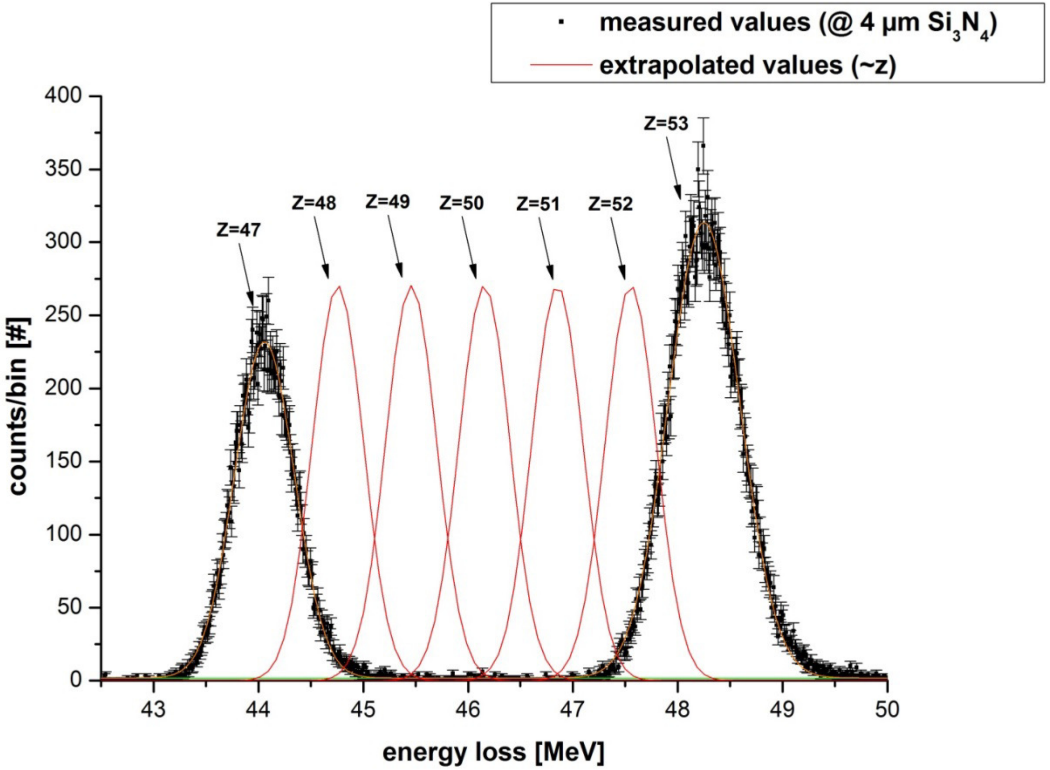
best performance found for Si_3N_4
as compared to previously used Parylene C

Energy Loss for ^{109}Ag (Z = 47) and ^{127}I (Z = 53)



Z - separation sufficient for absorber thickness ≥ 4µm

Expected Z - Separation



results:

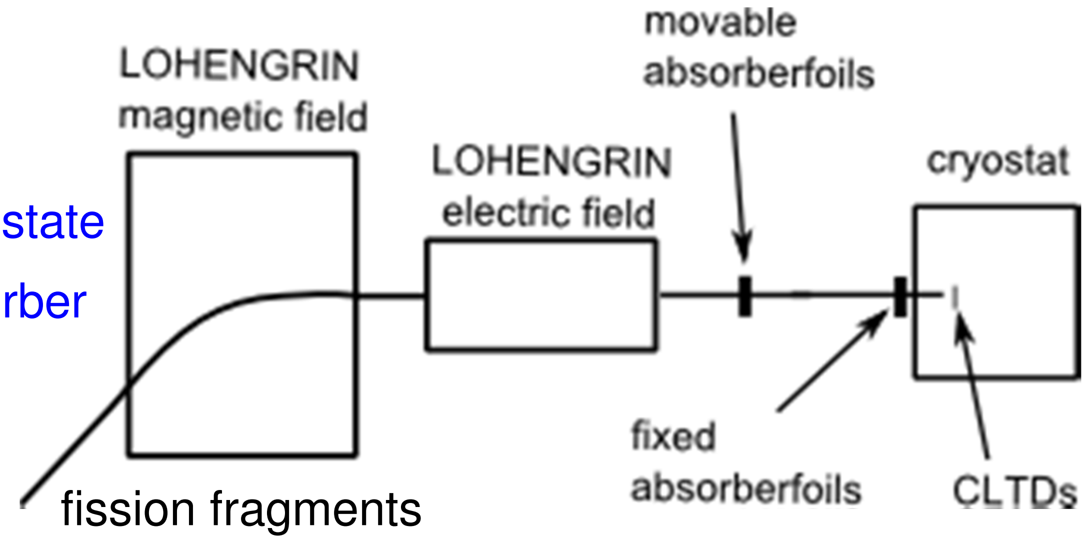
- new 25 pixel array works well
- Si3N4 is the best choice for absorber foil
- expected separation sufficient for d ≥ 4 µm

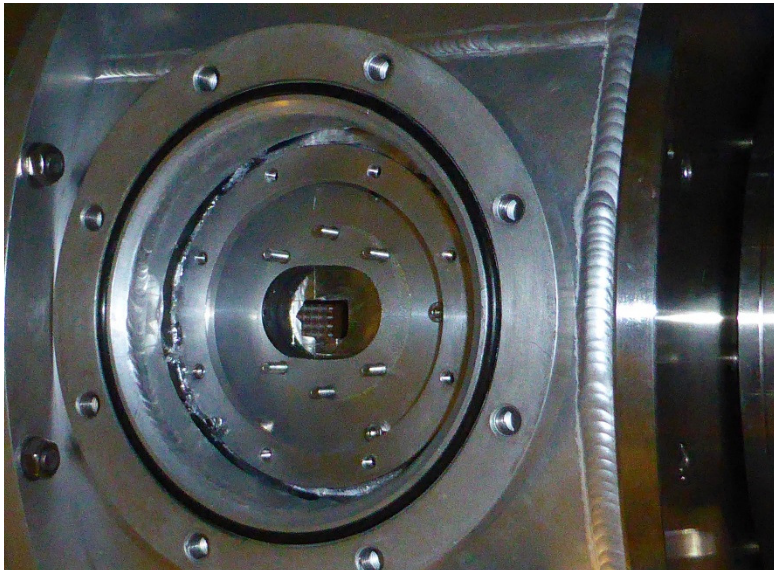
but: **A – dependence of energy loss may influence the Z – separation (to be explored)**

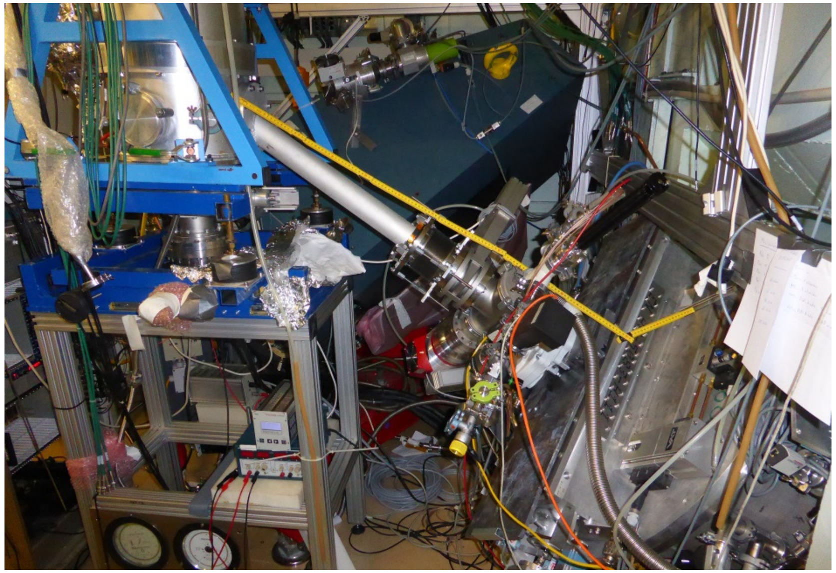
Investigation of Fission Fragments at the Research Reactor of ILL Grenoble

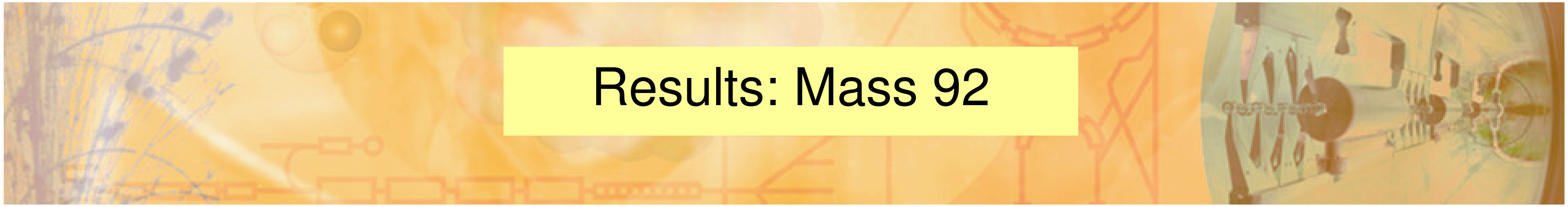
Experimental Setup:

- after LOHENGRIN: well defined mass, energy, charge state
- Z – dependent energy loss in absorber



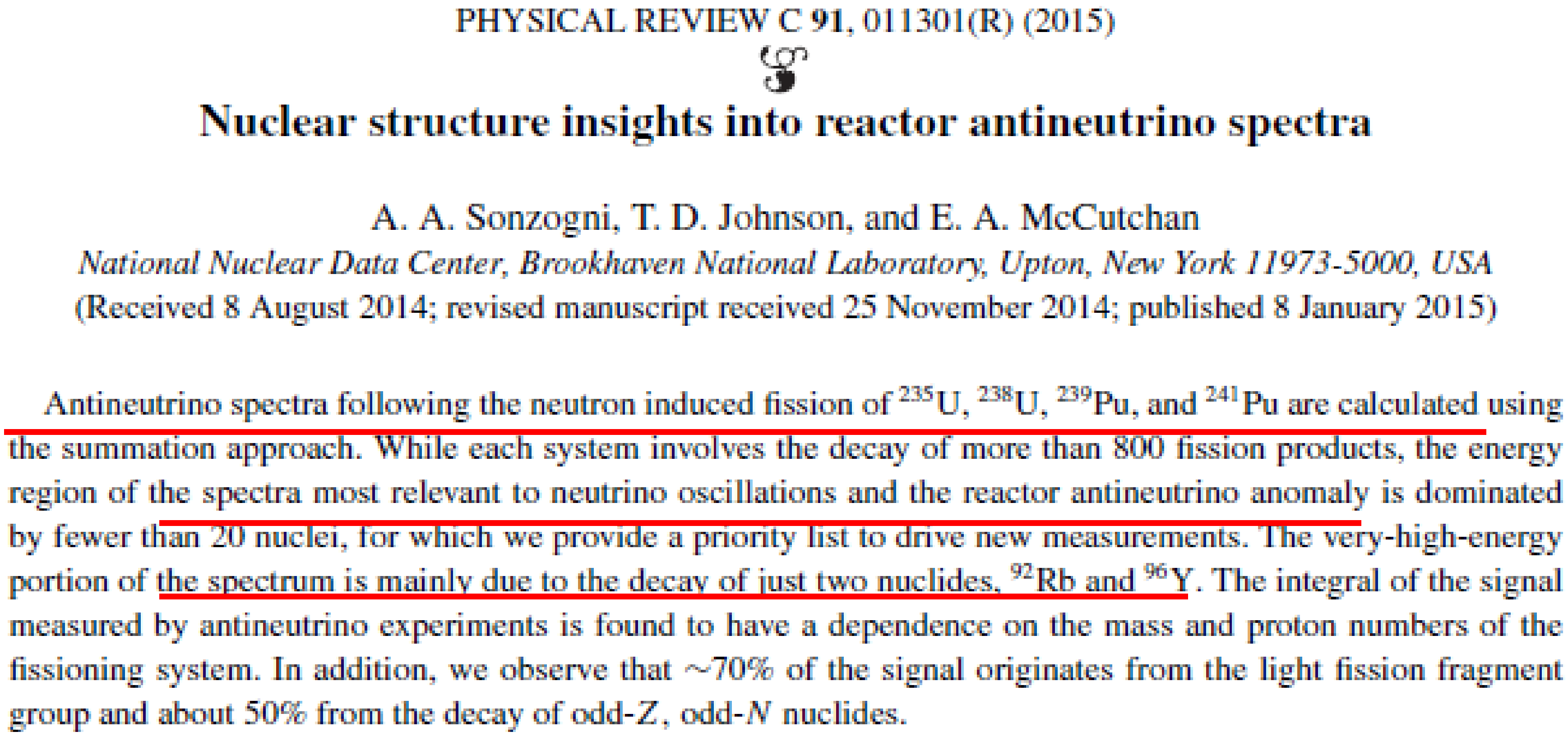






Results: Mass 92

Motivation:



PHYSICAL REVIEW C **91**, 011301(R) (2015)

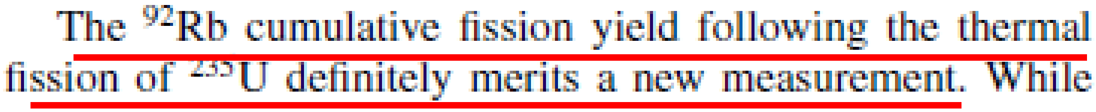
Nuclear structure insights into reactor antineutrino spectra

A. A. Sonzogni, T. D. Johnson, and E. A. McCutchan

National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York 11973-5000, USA

(Received 8 August 2014; revised manuscript received 25 November 2014; published 8 January 2015)

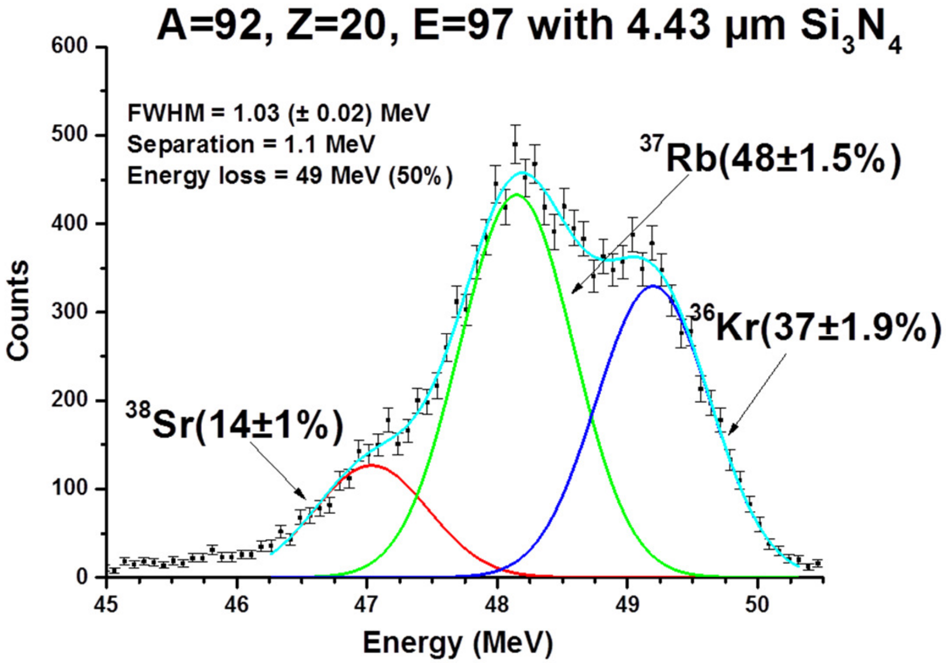
Antineutrino spectra following the neutron induced fission of ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu are calculated using the summation approach. While each system involves the decay of more than 800 fission products, the energy region of the spectra most relevant to neutrino oscillations and the reactor antineutrino anomaly is dominated by fewer than 20 nuclei, for which we provide a priority list to drive new measurements. The very-high-energy portion of the spectrum is mainly due to the decay of just two nuclides, ^{92}Rb and ^{96}Y. The integral of the signal measured by antineutrino experiments is found to have a dependence on the mass and proton numbers of the fissioning system. In addition, we observe that ~70% of the signal originates from the light fission fragment group and about 50% from the decay of odd-Z, odd-N nuclides.

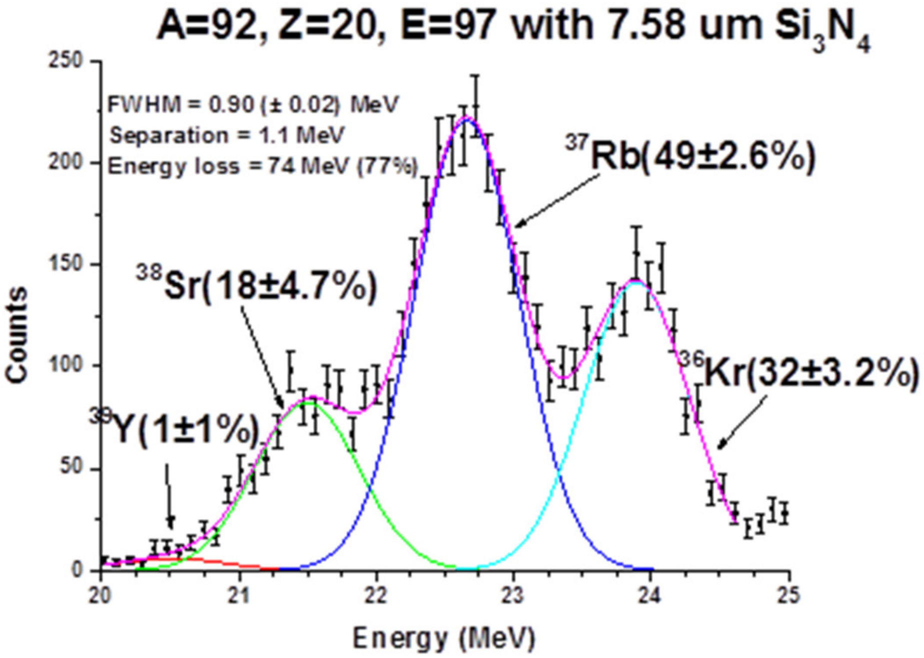


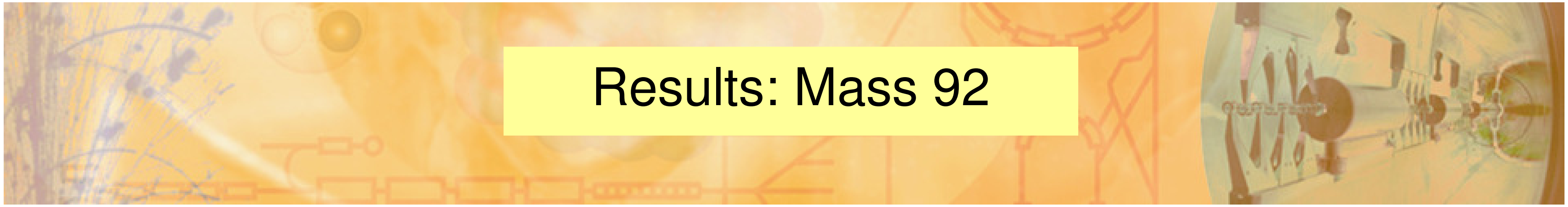
The ^{92}Rb cumulative fission yield following the thermal fission of ^{235}U definitely merits a new measurement. While

Results: Mass 92

P. Grabitz et al., Journal of Low Temperature Physics (2016) in press







Results: Mass 92

for an accurate determination of the ^{92}Rb yield:

⇒ take into account dependence on energy and charge state

⇒ many systematic measurements needed

Charge State, Q

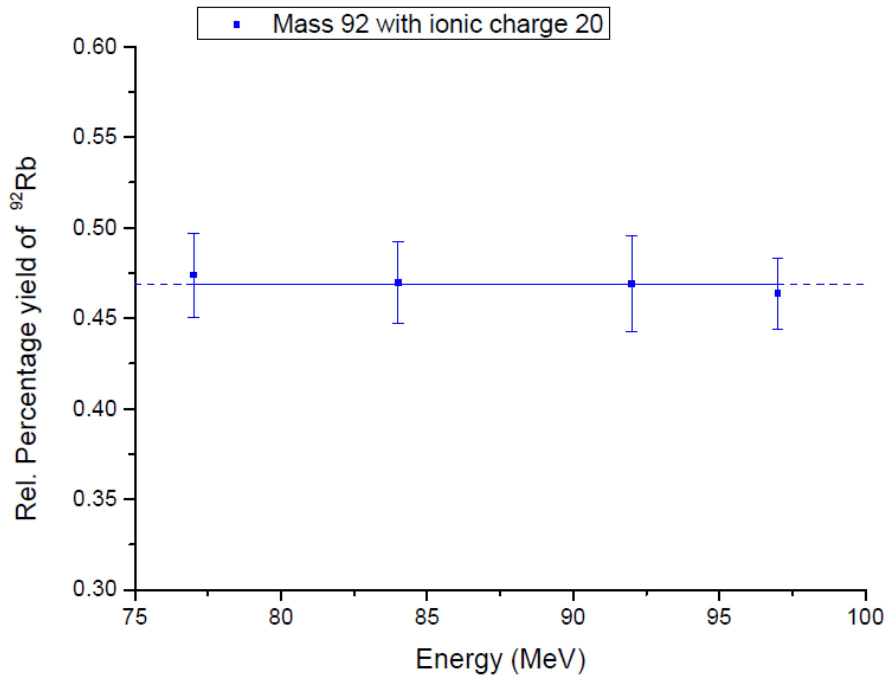
Energy, E (MeV)

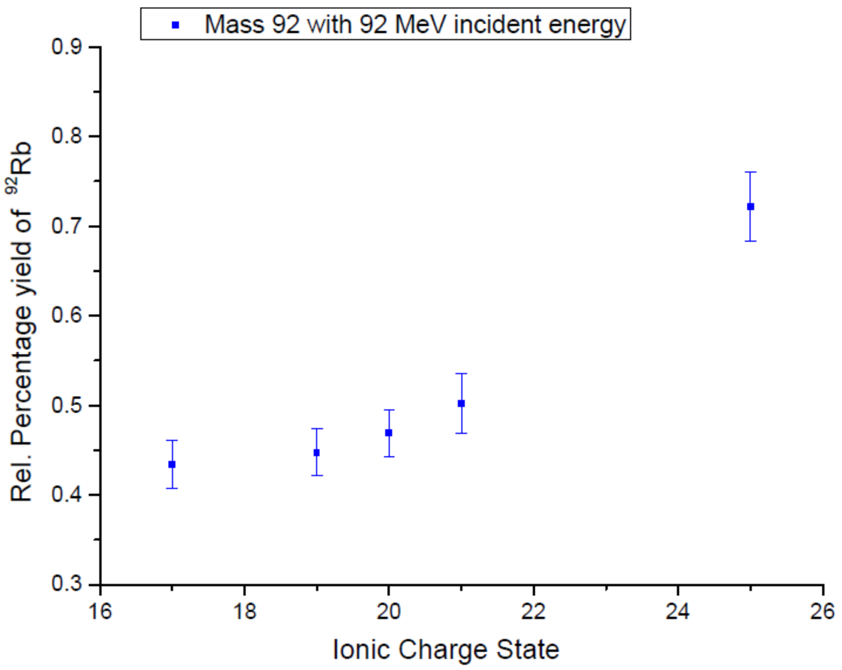
Q→ E↓	17	19	20	21	25
77	✓	✓	✓	✓	✓
84	✓		✓	✓	
92	✓	✓	✓	✓	✓
97	✓	✓	✓	✓	✓
102		✓	✓	✓	✓

data analysis in progress

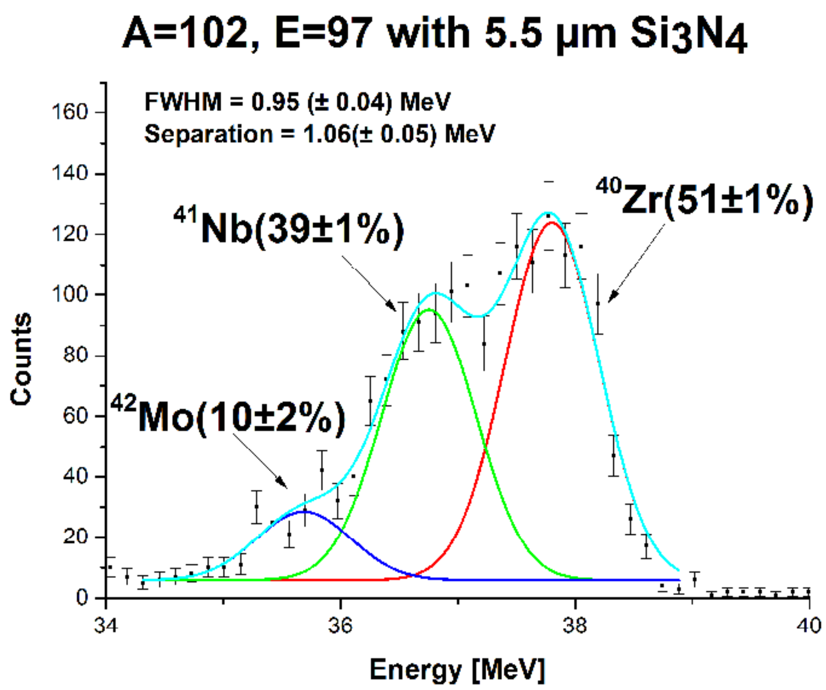
Results Mass 92:
Dependence on Energy and Charge State

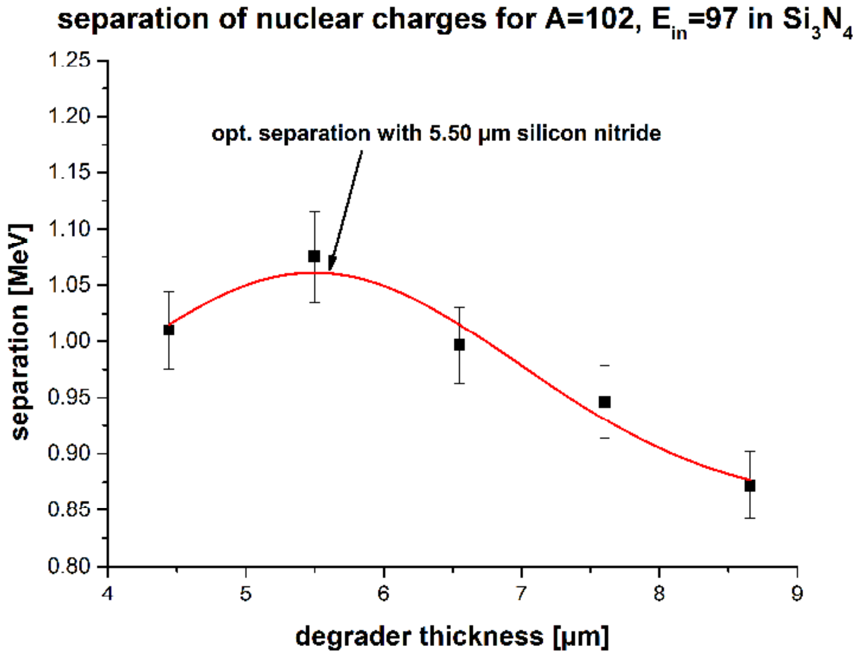
data preliminary





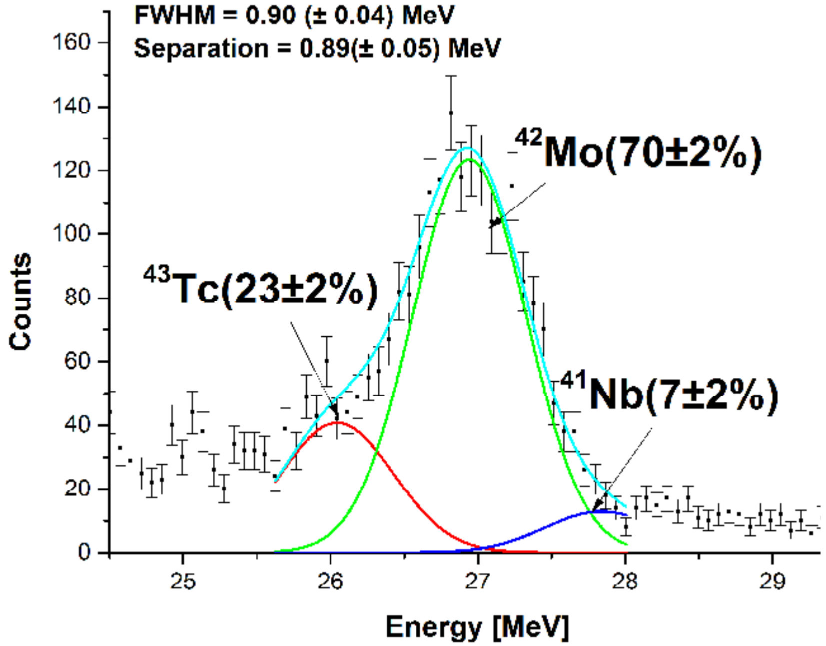
Results: Heavier Mass Region

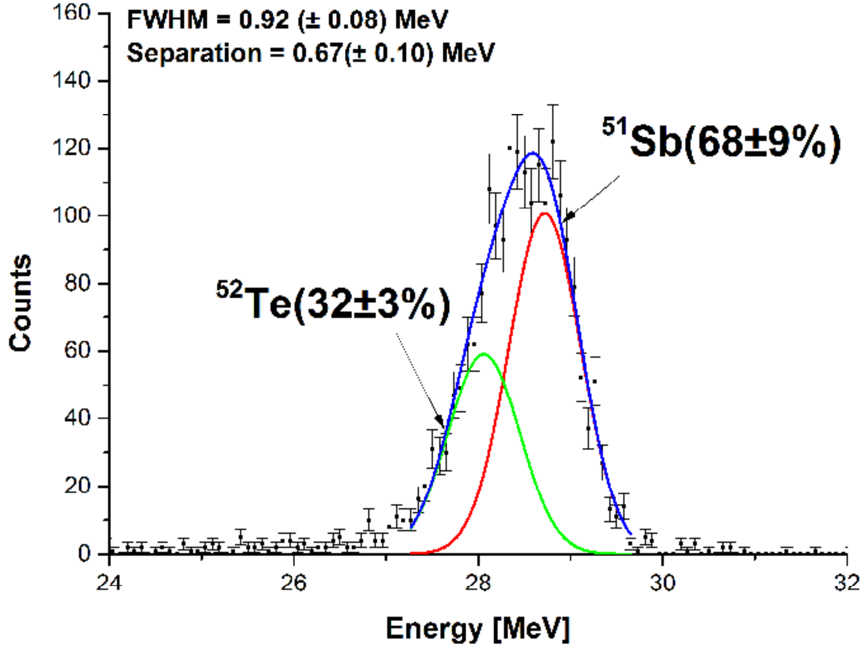




Results: Heavier Mass Region

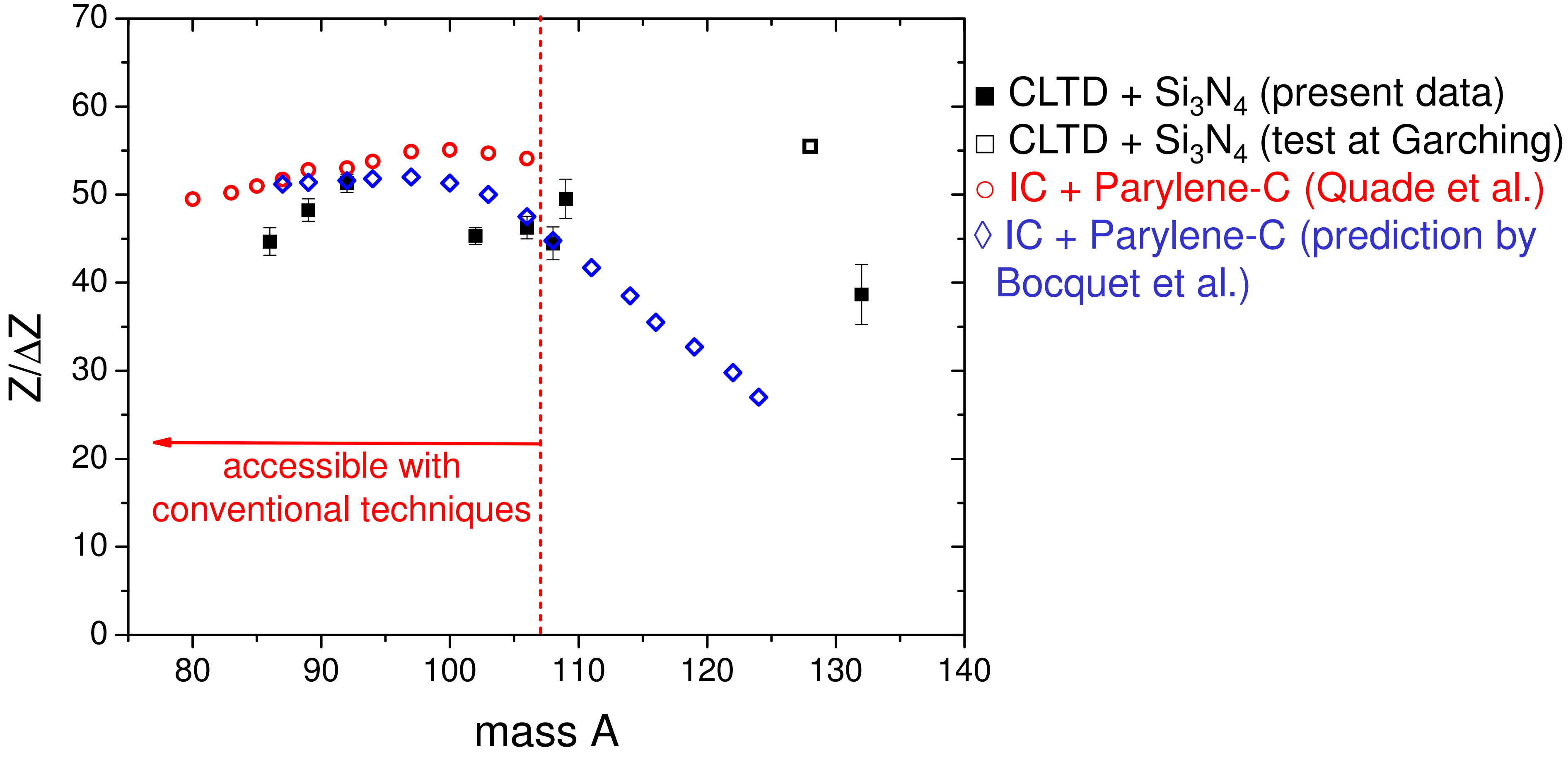
P. Grabitz et al., Journal of Low Temperature Physics (2016) in press


A=108, E=95 with 6.5 μm Si_3N_4


A=132, E=74 with 4.4 μm Si_3N_4

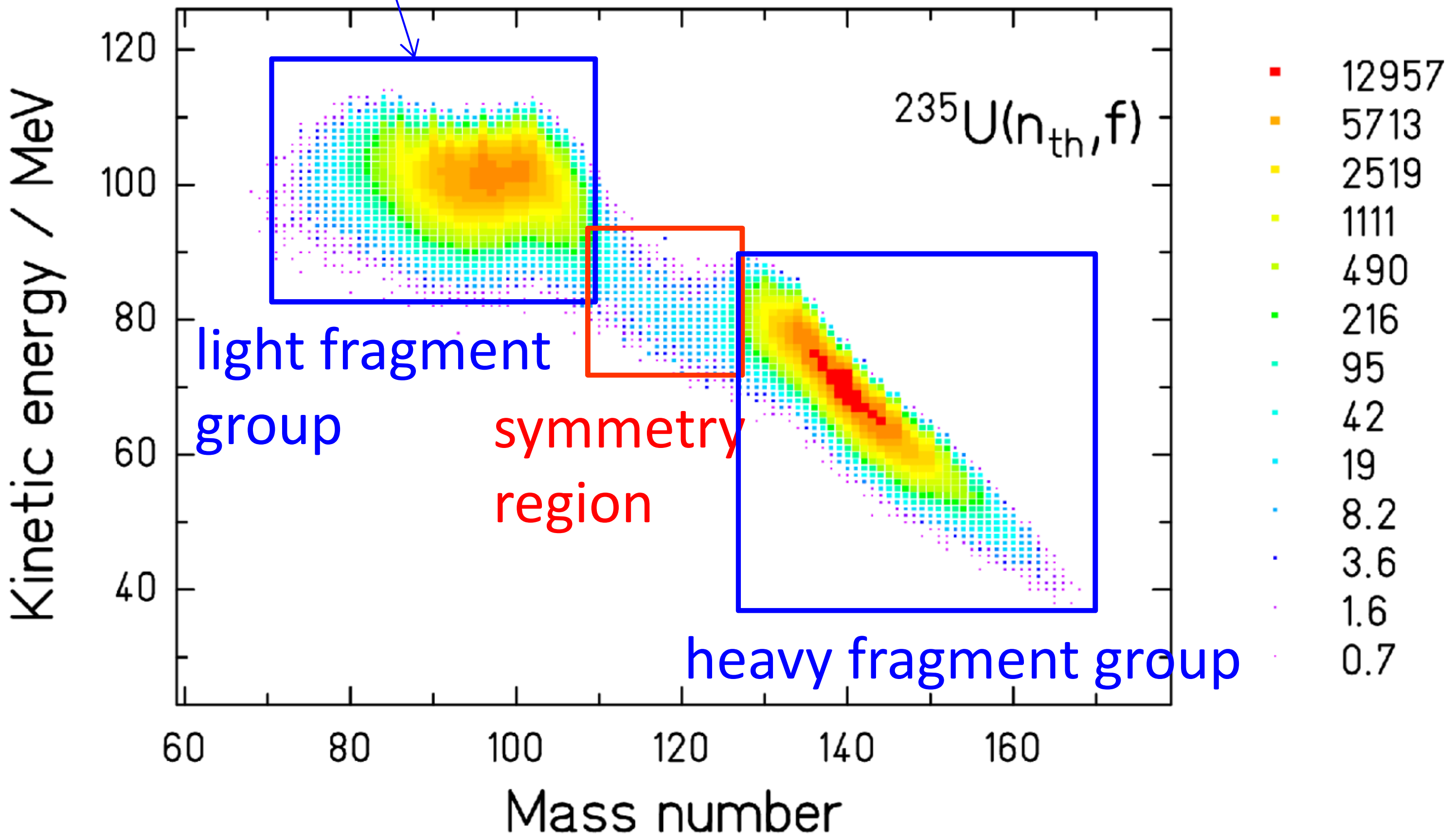
Quality of Z-Separation dependent on Nuclear Mass

quality of separation ~ Z/ΔZ with $\Delta Z \coloneqq \frac{\delta E(Z) - \delta E(Z-1)}{FWHM}$



Intensity Distribution of Fission Fragments

investigated with previously used technique



light fragment group

symmetry region

heavy fragment group

K.H. Schmidt et al., JEFF Report 24 (2014)

Results: Heavier Mass Region towards the Symmetry

mass, A (u)

Energy, E (MeV)

A→ E↓	89	91	95	99	100	102	106	107	108	109
75		✓								
89								✓	✓	✓
92			✓	✓						
95							✓	✓	✓	
97	✓					✓			✓	
100					✓					

of particular interest: odd-even staggering in the region towards symmetry

⇒ needed for a better understanding of the fission process
data analysis is in progress

Results: Heavier Mass Region

mass, u

Energy, E (MeV)

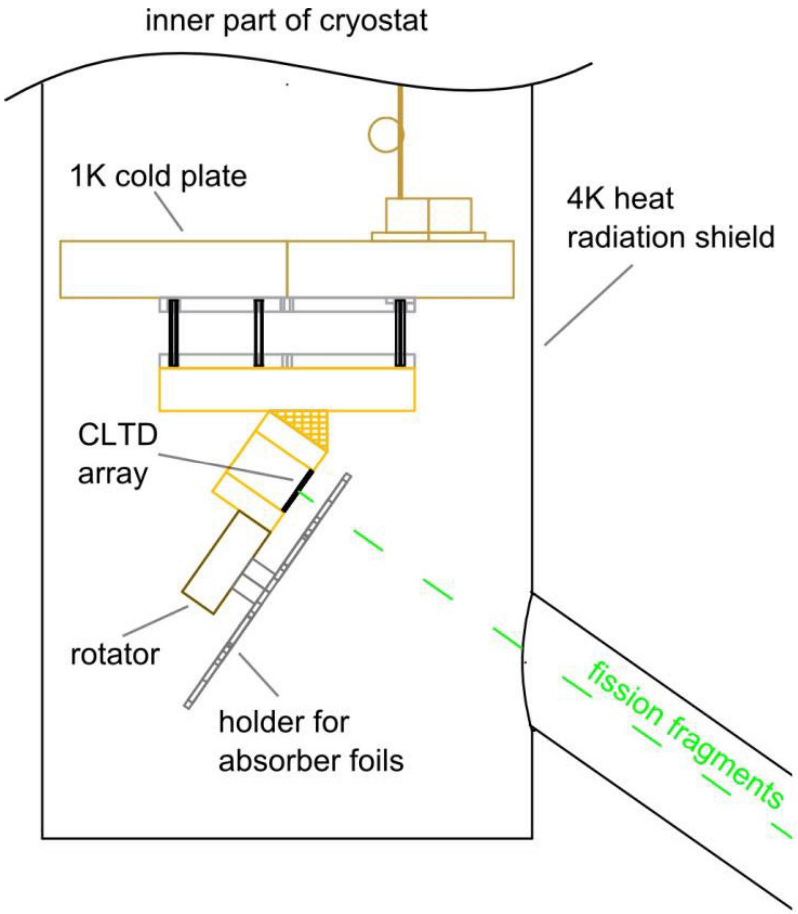
A→ E↓	132	134	136
64	✓	✓	
66	✓		
70			✓
74	✓		
80	✓		

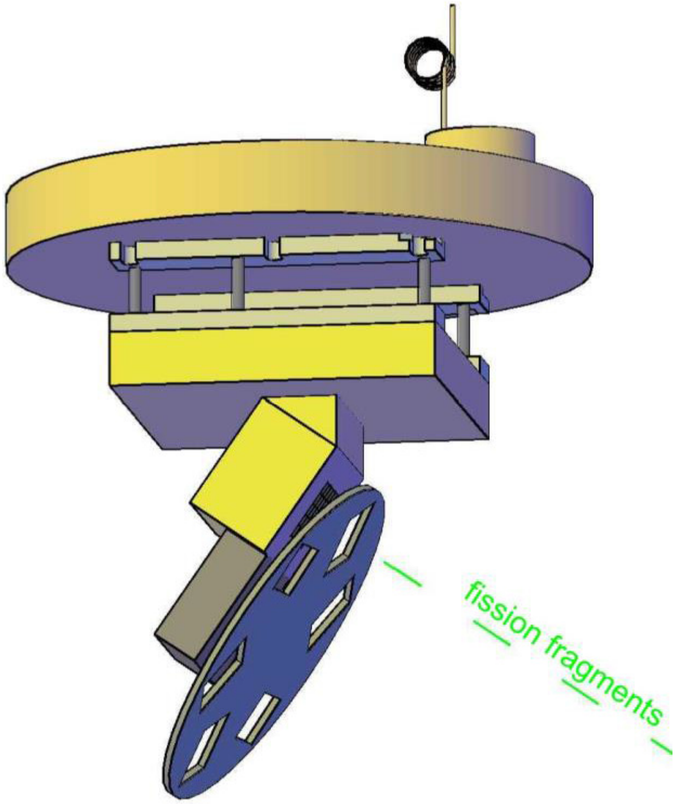
up to date unexplored region (data analysis in progress)

Perspectives for Future Investigations

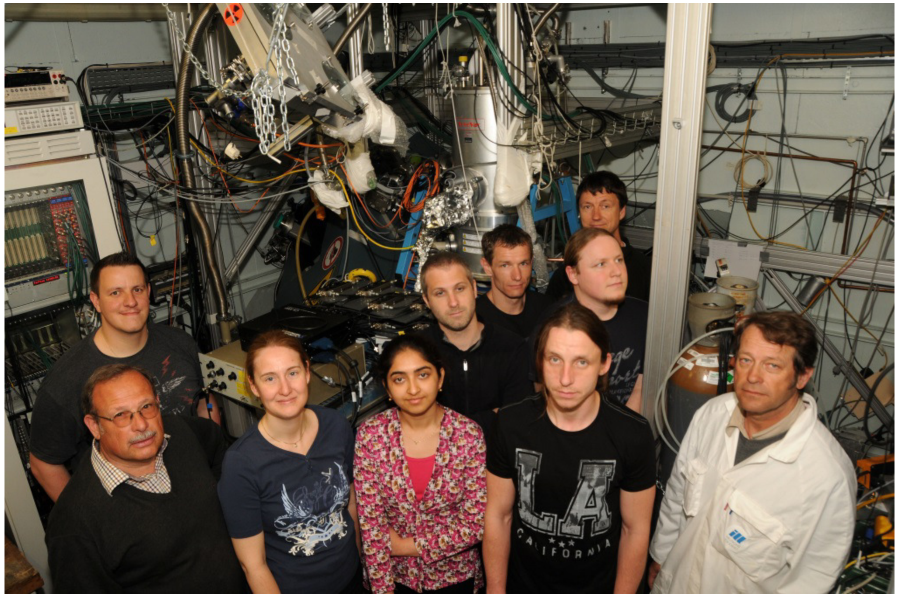
- improve the detection efficiency (absorber foils directly in front of the CLTD`s, inside the cryostat)
- improve flexibility (moveable absorber foils of different thickness)
- investigate the (low intensity) symmetry region of fission fragments which is of high interest (odd-even effect provides sensitive test of fission models)
- investigate yields for ^{96}Y (important for the understanding of antineutrino spectra), proposal of H. O. Denschlag et al.

Upgrade of Experimental Setup



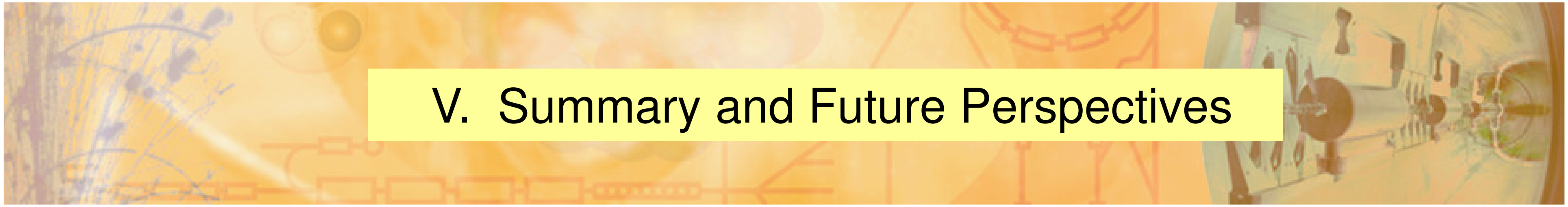


Collaboration



- Patrick Grabitz[1,2], Victor Andrianov[3] Shawn Bishop[4], Aurelin Blanc[6], Santwana Dubey[1,2], Artur Echler[1,2,3], Peter Egelhof[1,2], Herbert Faust[6] , Friedrich Gönnenwein[5], Jose Gomez[4], Ulli Köster[6], Saskia Kraft-Bermuth[3], Manfred Mutterer[5], Pascal Scholz[3], S. Stolte[2]

- [1]GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
- [2]Johannes Gutenberg Universität, Mainz, Germany
- [3]Justus-Liebig-Universität, Gießen, Germany
- [4]Technische Universität München, Germany
- [5]Universität Tübingen, Germany
- [6]Institut Laue-Langevin, Grenoble, France



V. Summary and Future Perspectives

Summary:

- CLTD`s were successfully applied for the first time for the investigation of Z-distributions of fission fragments
- a systematic study on the quality of Z – separation dependent on various parameters was performed
- the use of CLTD`s provides considerable improvement as compared to conventional techniques, in particular for heavier masses
- the new experimental technique allowed to reach the mass region beyond A = 106 up to A = 136, not accessible before
- the data obtained are expected (after the final analysis) to provide important information for nuclear structure-, reactor- and neutrino-physics

Perspectives:

- improve the detection efficiency (absorber foils directly in front of the CLTD`s, inside the cryostat)
- improve flexibility (moveable absorber foils of different thickness)
- investigate the (low intensity) symmetry region of fission fragments which is of high interest