Calorimetric Low Temperature Detectors: An Option for A – Identification of Super-Heavy Elements?

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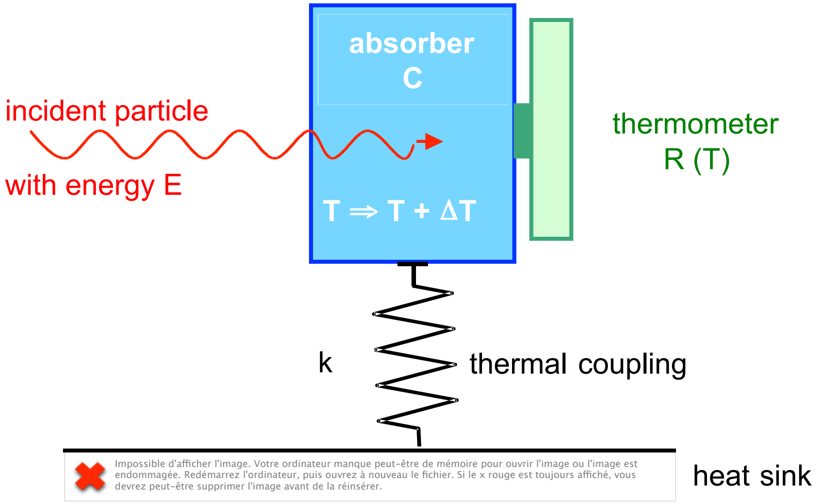
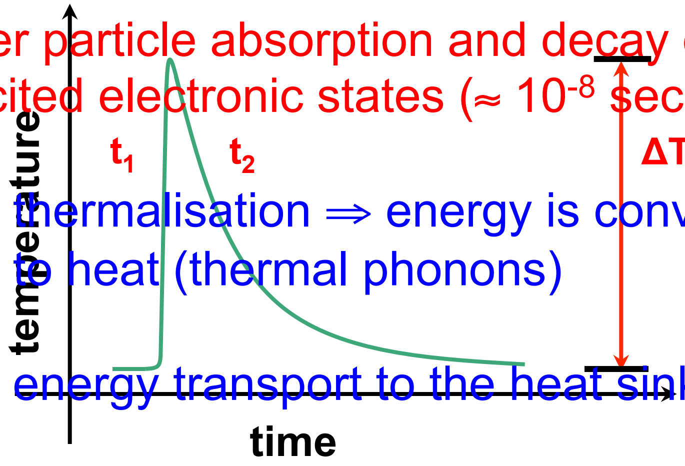
Detection Principle and Basic Properties of Calorimetric Low Temperature Detectors

detection principle:



Impossible d'afficher l'image. Votre ordinateur manque peut-être de mémoire pour ouvrir l'image ou l'image est endommagée. Redémarrez l'ordinateur, puis ouvrez à nouveau le fichier. Si le x rouge est toujours affiché, vous devrez peut-être supprimer l'image avant de la réinsérer.

thermal signal:



after particle absorption and decay of excited electronic states ($\approx 10^{-8}$ 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) absorber: maximum sensitivity $\Delta T = E/mc$ for

– small absorber mass m

– small specific heat c

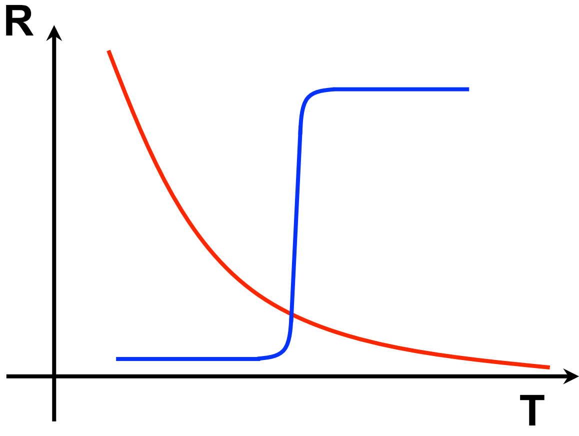
due to: $c = \underbrace{\alpha T}_{\text{electrons}} + \underbrace{\beta (T/\theta_D)^3}_{\text{lattice}}$ (θ_D = Debye-temperature)

⇒ low operating temperature ⇒ „low-temperature detector“

(for insulators : $\alpha = 0$)

b) thermometer: 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

  $\Rightarrow$ better statistics of the detected phonons

  semiconductor detector: $\omega \approx 1$ eV

  calorimetric detector: $\omega \lesssim 10^{-3}$ 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 $\Rightarrow$ better linearity and resolution

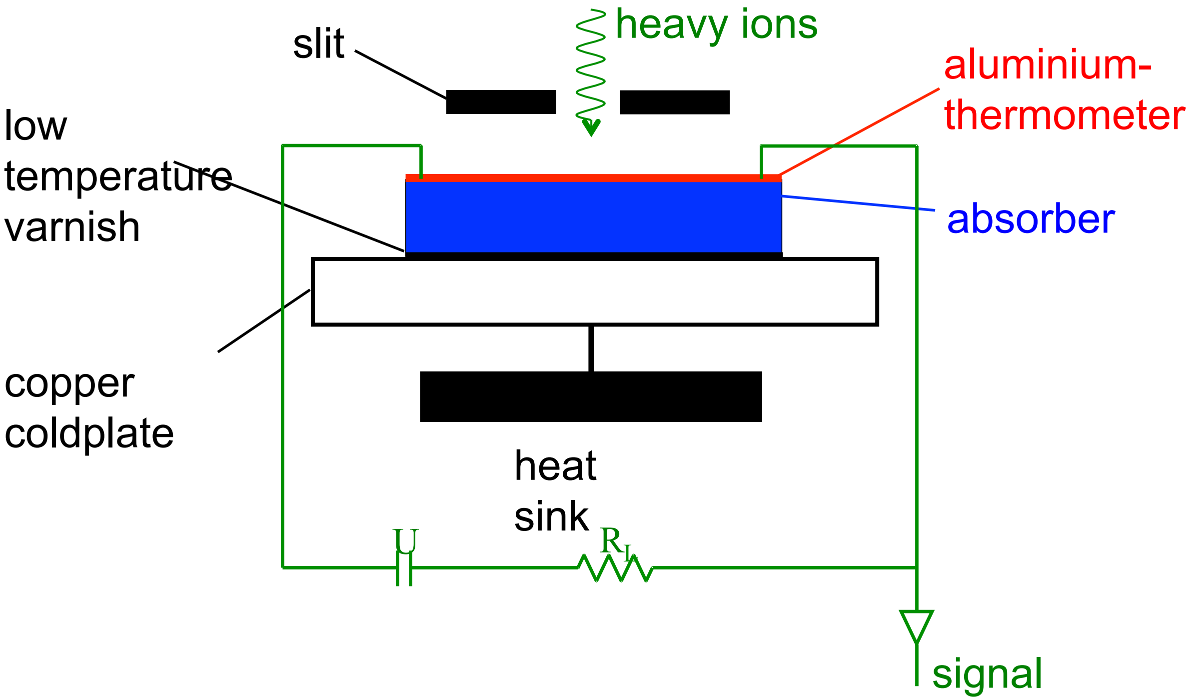
  energy deposited in phonons and ionisation contributes to the signal

  (for ionisation detectors: losses up to 60-80% due to: - recombination

  - direct phonon production)

CLTD`s for High Resolution Detection of Heavy Ions - Status and Perspectives

Detector Design and Perfomance:



absorber: sapphire-crystal: V= 3 x 3 mm^2 x 300 μm

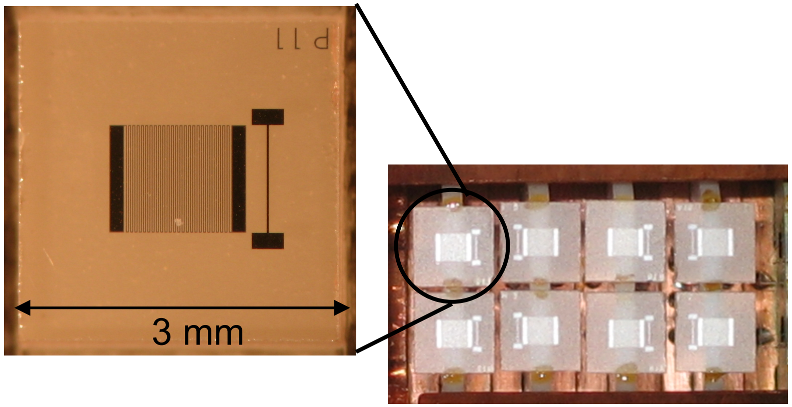
thermometer: aluminium-film (d = 10 nm), $T_C \approx 1.5$°K (in the range of a ^{4}He-cryostat)
(for impedance matching to the amplifier: ⇒ meander structure)

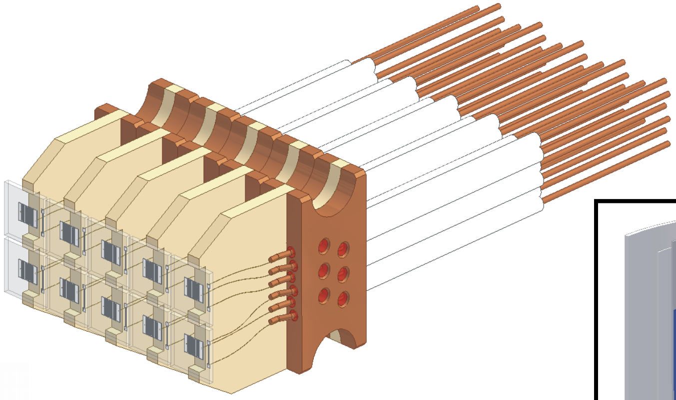
readout: conventional pulse electronics +Flash-ADC`s +Digital Filtering

CLTD`s for High Resolution Detection of Heavy Ions - Status and Perspectives

detector design:

- sapphire absorber
- pixel size: 3 x 3 mm^2
- operated at T_c = 1.4 – 1.6 K
- superconducting Al thermistor
  10 nm Meander structure
  ⇒ photolithography (high purity!





detector array:

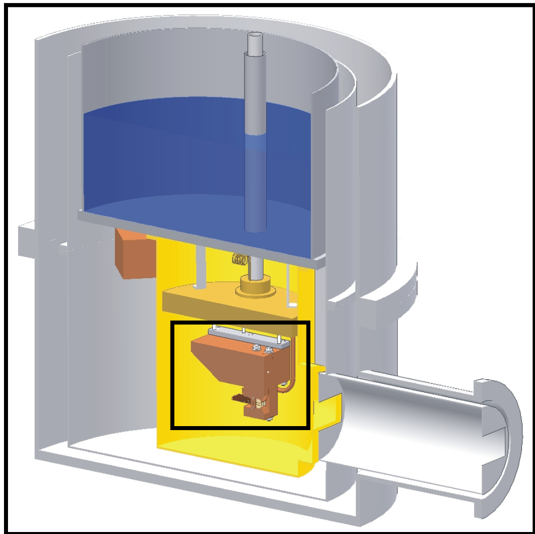
- 8 pixels with individual temperature stabilization in operation
- active area: 12 x 6 mm^2

cryostat:

-windowless

^{4}He bath cryostat

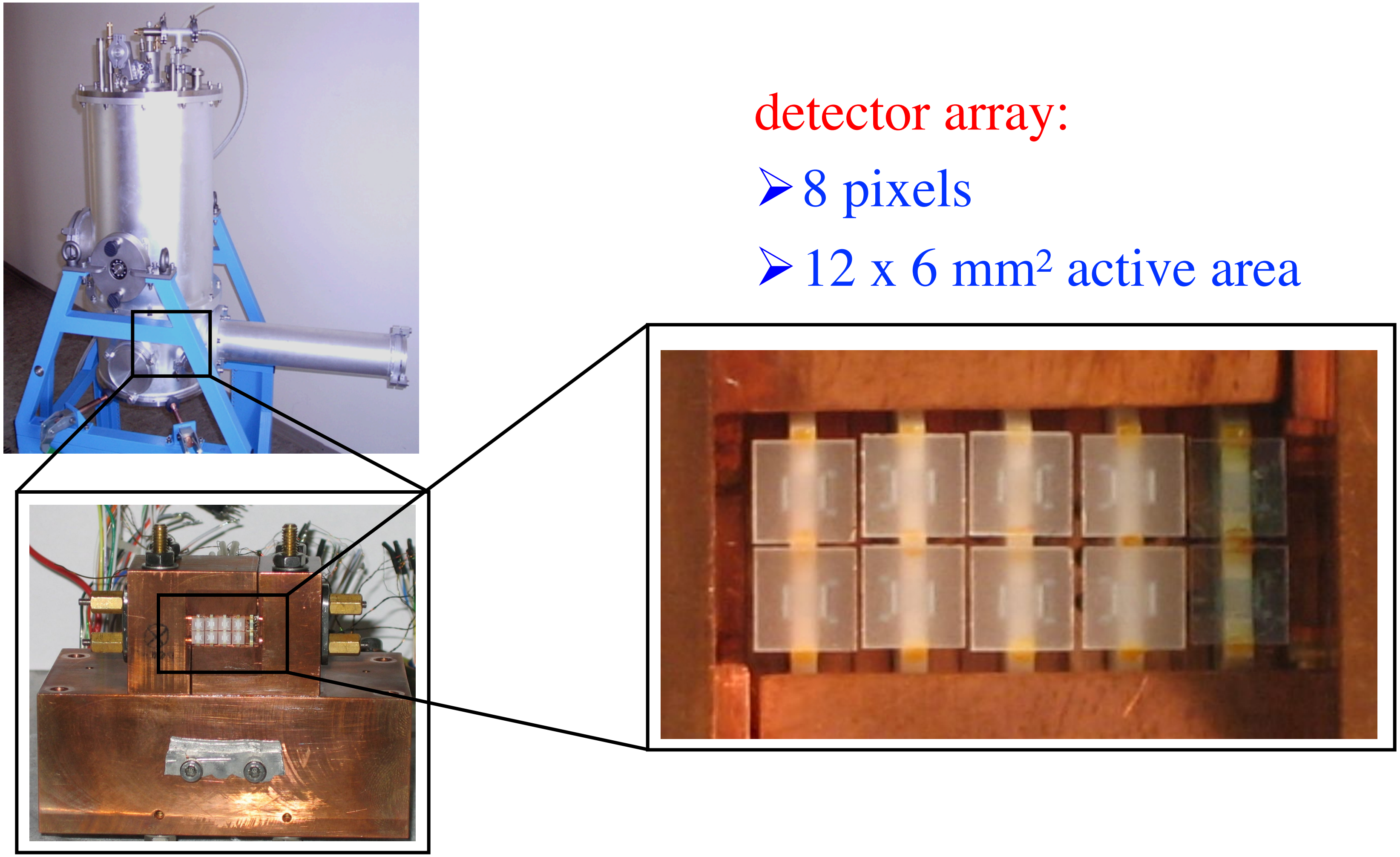
- operated at 1.4 -1,6 K



Implementation in the Cryostat

detector array:

- 8 pixels
- 12 x 6 mm² active area



CLTD`s for High Resolution Detection of Heavy Ions
- Status and Perspectives

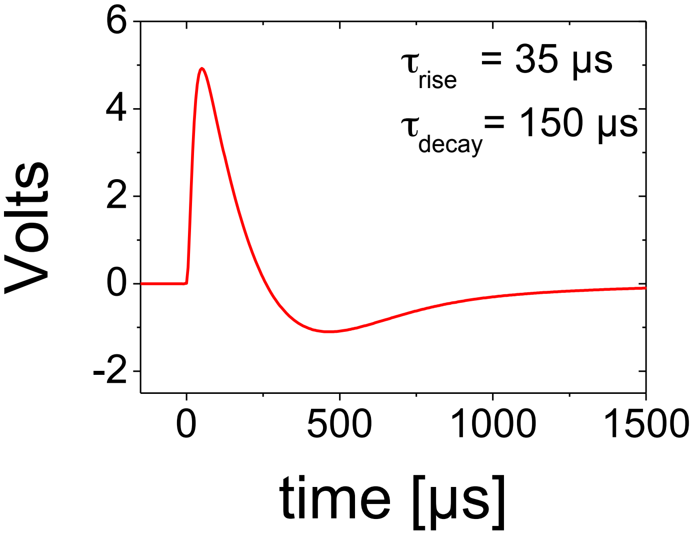
detector performance: response to ^{32}S ions @ 100 MeV

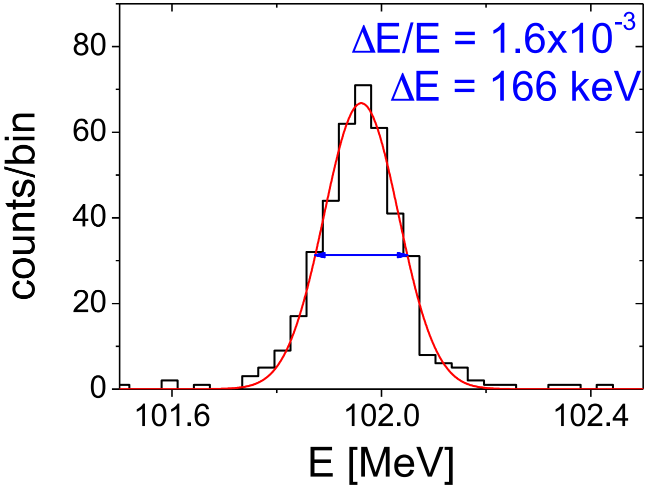
rate capability:

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

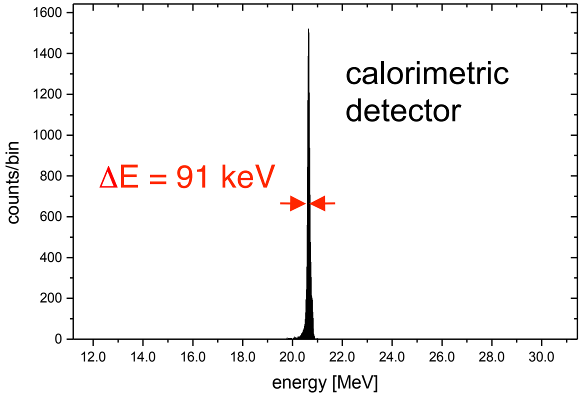
⇒ for heavy ions: ≥ 10 x improvement over conventional Si detectors

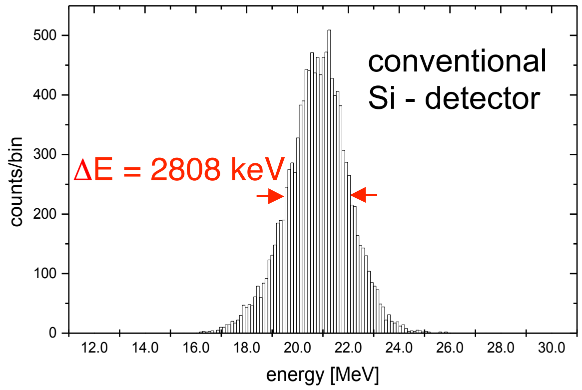
Comparison of Detector Performance: CLTD – Conventional Si Detector

energy resolution:

example:

^{238}U @ 20.7 MeV)

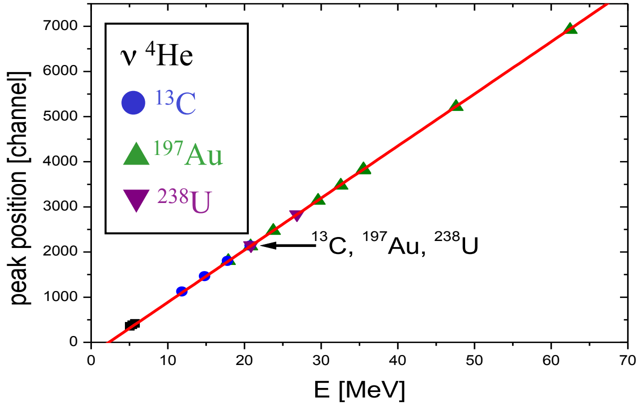


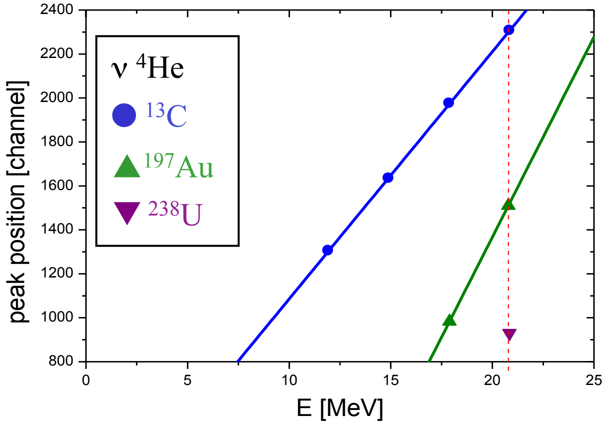


energy linearity:

example:

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





for conventional ionization detector:

high ionization density leads to charge recombination

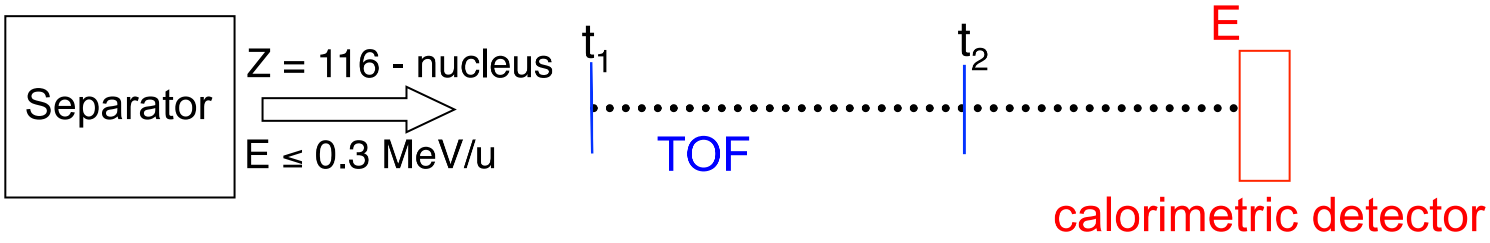
⇒ pronounced pulse height defects ⇒ nonlinear energy response

⇒ fluctuation of energy loss processes ⇒ limited energy resolution

Application for Identification of Super-Heavy Elements

for $Z \geq 112$: decay chains do not feed a known α-chain

$\Rightarrow$ mass identification of the superheavy nucleus required



Separator

$Z = 116$ - nucleus

$E \leq 0.3$ MeV/u

t_1

t_2

TOF

E

calorimetric detector

$$\left(\frac{\Delta m}{m}\right)^2 = 2\left(\frac{\Delta v}{v}\right)^2 + \left(\frac{\Delta E}{E}\right)^2$$

ultrathin ^{12}C-foils + channelplates

$$\frac{\Delta v}{v} \leq 1 \cdot 10^{-3}$$

(energy straggling in ^{12}C-foils negligible!)

calorimetric detector:

$$\frac{\Delta E}{E} \approx 2 - 3 \cdot 10^{-3}$$

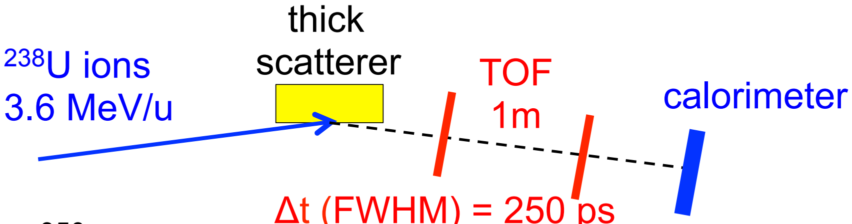
(semiconductor detector: $\Delta E/E \geq 5 \cdot 10^{-2}$)

$$\Rightarrow \quad \frac{\Delta m}{m} \leq 3 \cdot 10^{-3}$$

for $m = 300 \Rightarrow \Delta m \leq 1$ amu

High Resolution Mass Identification

experimental setup: low energetic ^{238}U ions @ UNILAC accelerator at GSI



^{238}U ions
3.6 MeV/u

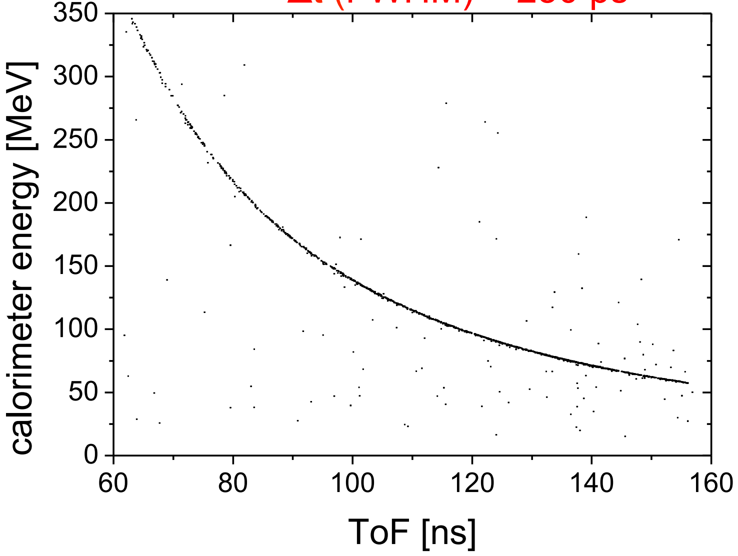
thick
scatterer

TOF
1m

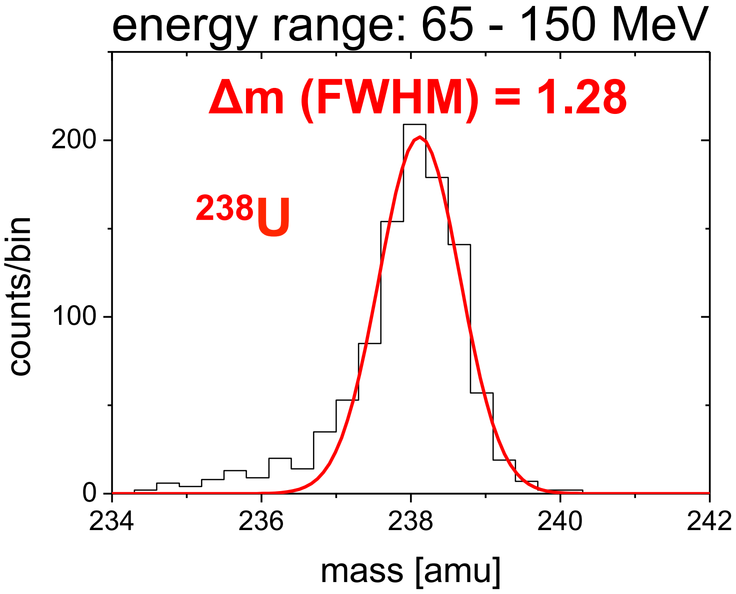
calorimeter

Δt (FWHM) = 250 ps

→ broad energy distribution
(0 - 3.6 MeV/u)



energy range: 65 - 150 MeV



Data: A. Echler, PHD thesis (2012)

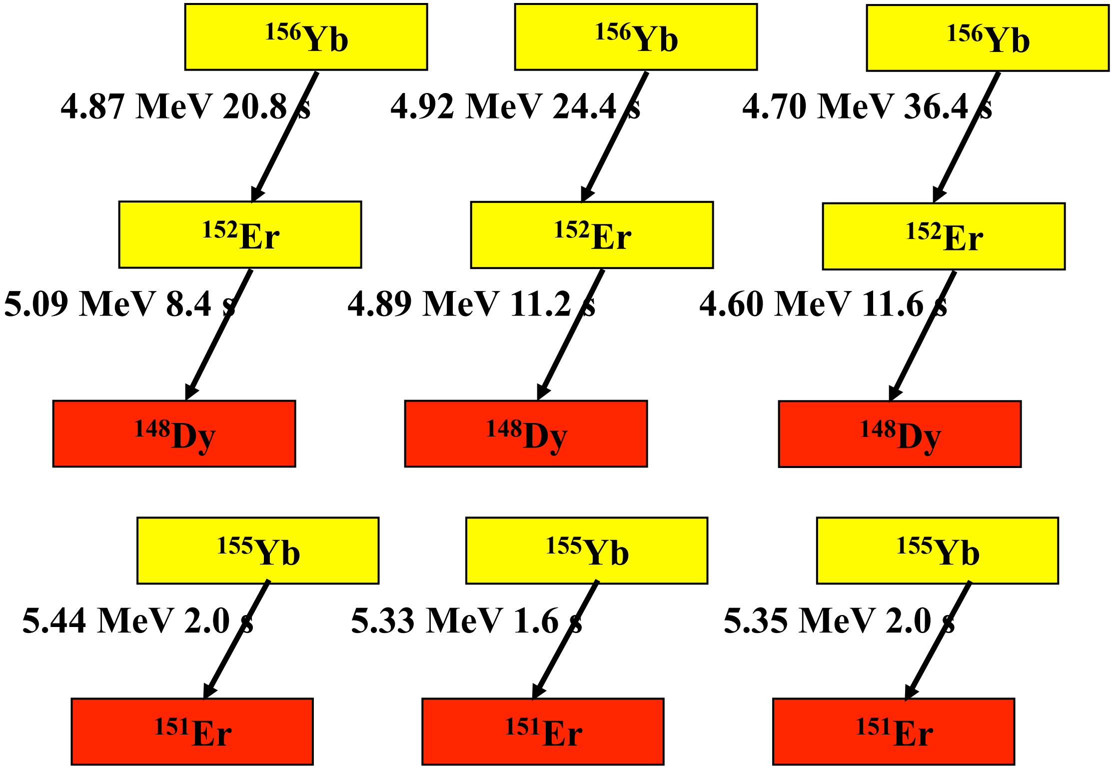
- not reachable with conventional E-ToF system
- advantage to Bρ-ToF method:
  - high dynamic range
  - not affected by charge state ambiguities

most recent result from measurements at Jyväskylä: **Δm (FWHM) = 0.83 for ^{131}Xe ions**

First Test Experiment at SHIP

S. Kraft-Bermuth, PHD Thesis (2004)
(in cooperation with: D. Ackermann, F.Hessberger, S. Hofmann, G. Münzenberg)

reaction: $^{58}\mathrm{Ni} + {}^{102}\mathrm{Ru} \Rightarrow {}^{160}\mathrm{Hf}^{*} \Rightarrow {}^{155(156)}\mathrm{Yb} + 2p + 2(3)n$



^{156}Yb **^{156}Yb** **^{156}Yb**

4.87 MeV 20.8 s **4.92 MeV 24.4 s** **4.70 MeV 36.4 s**

literature: 4.69 MeV 26.1 s

^{152}Er **^{152}Er** **^{152}Er**

5.09 MeV 8.4 s **4.89 MeV 11.2 s** **4.60 MeV 11.6 s**

literature: 4.80 MeV 10.3 s

^{148}Dy **^{148}Dy** **^{148}Dy**

^{155}Yb **^{155}Yb** **^{155}Yb**

5.44 MeV 2.0 s **5.33 MeV 1.6 s** **5.35 MeV 2.0 s**

literature: 5.20 MeV 1.8 s

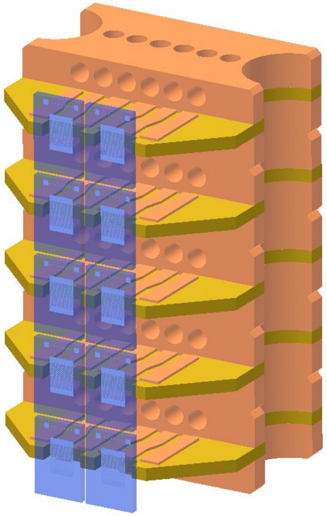
^{151}Er **^{151}Er** **^{151}Er**

⇒ **dynamic range sufficient to detect heavy ion and its α-decay time-resolved**

Design of a Next Generation Array

detector-layout:

96 pixels with F = 5 x 5 mm^2 each



active area:	3 x 8 cm^2
position resolution:	5 mm
α-resolution:	$\Delta E \leq 30$ keV
mass resolution:	$\Delta E/E \leq 3 \times 10^{-3} \Rightarrow \Delta m \leq 1$ amu
rate capability:	$\geq 300\ \text{sec}^{-1}$/pixel

CLTD Collaboration

A. Bleile[1,2], A. Echler[1,2], P. Egelhof[1,2], P. Grabitz[1,2], S. Ilieva[1],
S. Kraft-Bermuth[3], J.P. Meier[1], K. Müller[3], M. Mutterer[1]

1 GSI Darmstadt
2 Univ. Mainz
3 Univ. Gießen

High Resolution Mass Identification

important for many applications: isotope mass identification

standard method:

B • ρ ⇒ p
TOF ⇒ v

$$\left.\begin{array}{l} B \cdot \rho \Rightarrow p \\ \mathrm{TOF} \Rightarrow v \end{array}\right\} \boxed{m = \frac{p}{v}}$$

disadvantage:

- needs big magnet spectrometer
- small solid angle
- charge state ambiguity because of B • ρ = p/Q (especially for slow heavy ions!)

alternative method:

energy ⇒ E
TOF ⇒ v

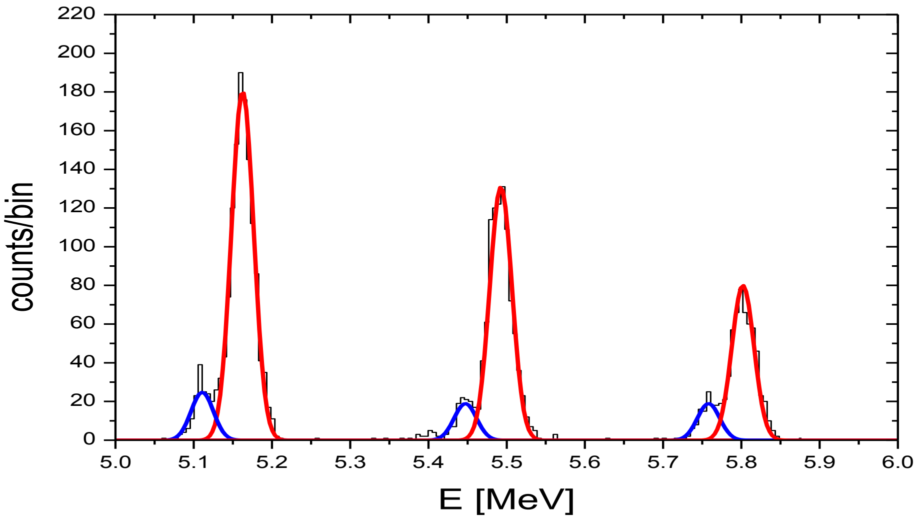
$$\left.\begin{array}{l} \mathrm{energy} \Rightarrow E \\ \mathrm{TOF} \Rightarrow v \end{array}\right\} \boxed{m = \frac{2E}{v^2}}$$

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta E}{E}\right)^2 + \left(2\frac{\Delta t}{t}\right)^2$$

mass resolution is limited by energy resolution! ⇒ calorimetric detectors

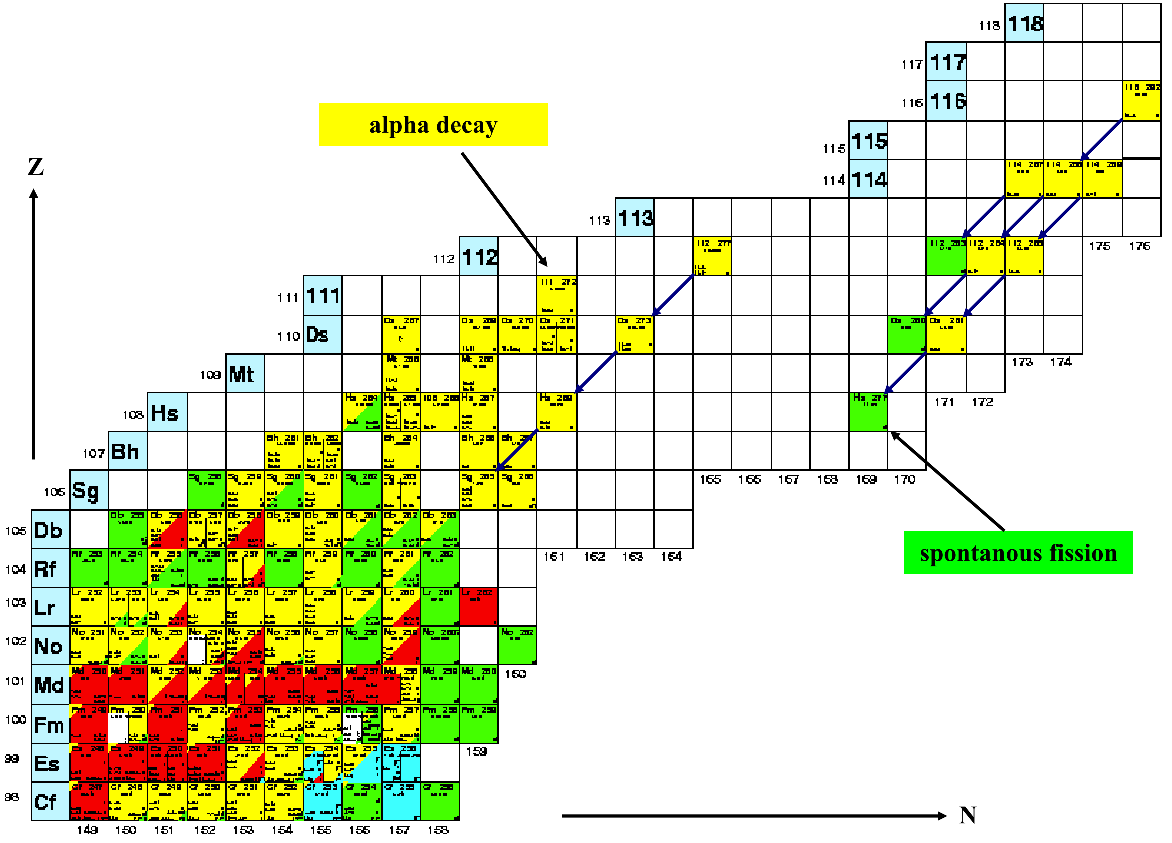
First Test Experiment at SHIP

1. Detector performance by irradiation with 5 MeV α-particles of a 3-line-source in the laboratory:



$\Delta E = 30$ keV, $\Delta E/E = 5.5 \times 10^{-3}$

Identification of Superheavy Elements



alpha decay

spontanous fission

Theoretical Limit for the Energy Resolution

for ideal calorimetric detector:

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

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

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

Calorimetric Low Temperature Detectors for Applications in Atomic and Nuclear Physics

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 - Status and Perspectives

IV. CLTD`s for High Resolution X-Ray Spectroscopy - Status and Perspectives

V. Conclusions

Perspectives for Applications

High Resolution Mass Identification for:

- identification of reaction products from reactions with radioactive beams
  (for slow heavy ions: no charge state ambiguities, high dynamic range)
  ⇒ potential application at NUSTAR LEB, VAMOS, etc.

- identification of isotopes after in-flight gamma spectroscopy
  ⇒ potential application at NUSTAR HISPEC (LYCCA)

- identification of superheavy elements (for $Z \geq 113$: decay chain does not feed a known α chain): $\Delta m \leq 1$ for $m = 300$ reachable

- identification of rare isotopes in accelerator mass spectrometry
  ⇒ high sensitivity

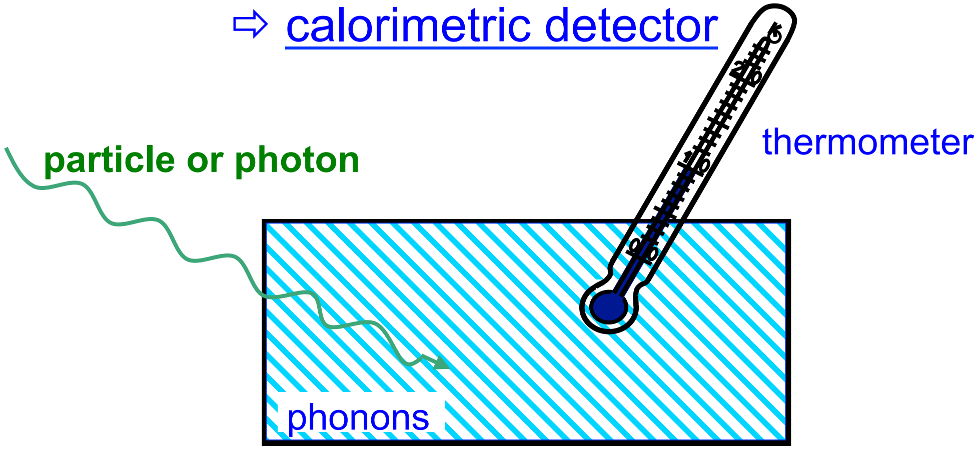
- identification of fission fragments
  (replace the COSI FAN TUTTE spectrometer)
  ⇒ investigate structures in the mass distribution

I. Introduction

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

⇒ idea: detection of radiation independent of ionisation processes

⇨ calorimetric detector



interaction of radiation with matter:

primary: ionization, ballistic phonons (conventional ionisation detectors)

secondary: thermalization: conversion of energy to heat

⇒ detection of thermal phonons

⇒ calorimetric detectors

potential advantage:

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

⇒ various applications in many fields of physics

V. Conclusions

- Calorimetric Low Temperature Detectors have Substantial Advantage over Conventional Detection Systems concerning Resolution, Linearity, etc.

- CLTD`s for Heavy Ion Physics have been designed, tested and used in First Experiments.

- Possible Applications within NUSTAR, SPARC and other Projects seem to be attractive.