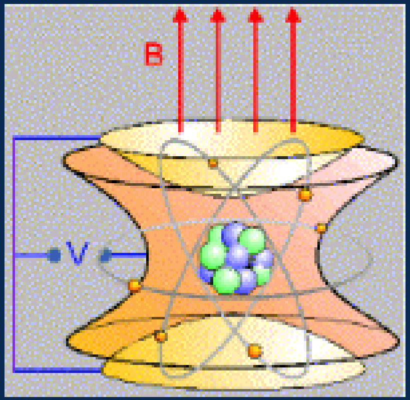
TECHNISCHE UNIVERSITÄT DRESDEN

Mathematik und Naturwissenschaften Institut für Kern- und Teilchen Physik

New Approaches (CoBRA, ECHO, Q-Value determination)

Valentina Lozza

ECHO Experiment



Astroteilchenphysik in Deutschland: Status und Perspektiven, 20-21.09.2012 – Zeuthen (Berlin)

Outline

- Measure the neutrino mass
- Double Beta Decay process
- The COBRA Experiment
  - Location
  - Isotope
  - Detector working principle
  - Background/signal discrimination
- Electron Capture and Double Electron Capture process
- Q-value determination: Penning-traps (ISOLTRAP)
  - Working principle
  - Isotopes investigate
- The ECHO Experiment
  - Isotope
  - Detector Working principle
  - Detector's tests

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Measure the neutrino mass

Oscillation measurements
- relative masses
- provide lower bound
  - m1 = 0 (normal)
  - m3 = 0 (inverted)

Δm_{ij}

Direct kinematic measurements
model independent

m_{ν}

Time of flight from supernovae
model dependent

m_{bb}

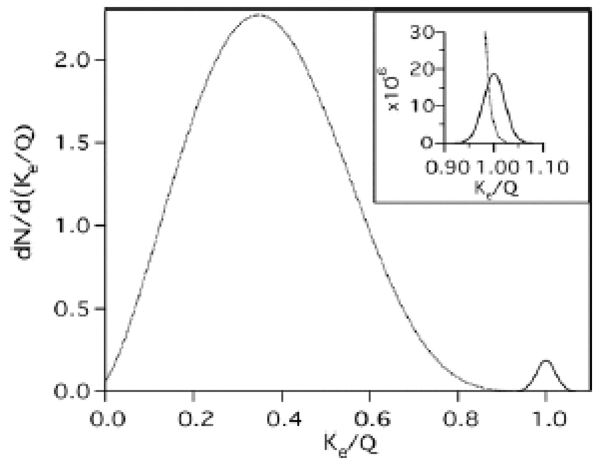
0vbb decay (model dependent)
- if neutrinos are Majorana particles
- accurate calculation of nuclear matrix element

Σm_i

Cosmology and astrophysics
(model dependent)
- measures $\Sigma m\nu$
- based on assumptions of number density in early Universe and cosmological model(s)

Double Beta Decay Process

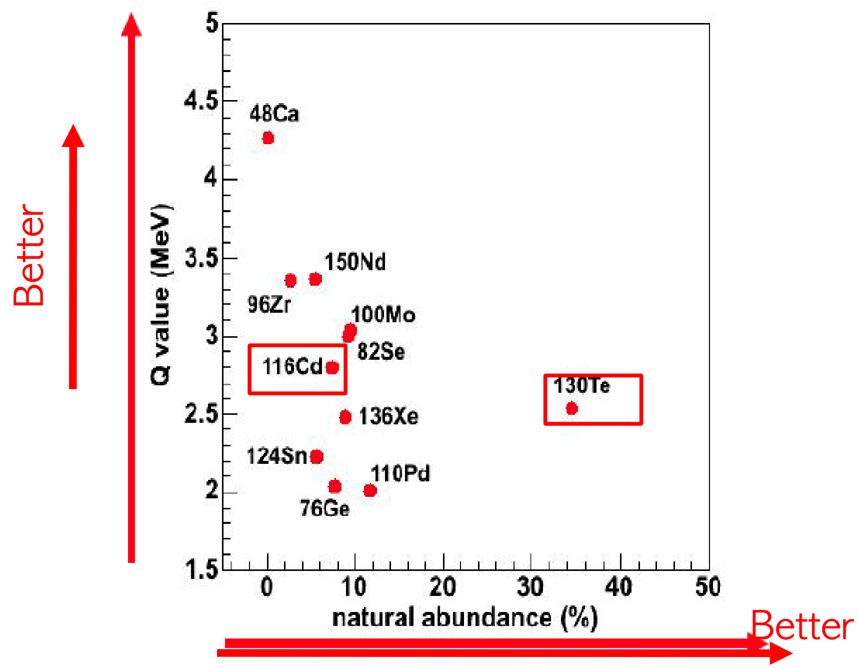
- Can only happen if neutrinos are Majorana particles
- From the events in the signal peak it is possible to determine the half-life of the decay



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2$$

$M^{0\nu}$ is model dependent → major theoretical challenge today

35 known isotopes



CoBRA Experiment

- TU Dortmund
- TU Dresden
- Freiburg Materials Research Center
- University of Hamburg
- University of Erlangen
- Czech Technical University in Prague
- Laboratori Nazionali del Gran Sasso
- Washington University at St. Louis
- University of Bratislava
- University of Jyvaskyla
- University of La Plata
- JINR Dubna

Supporting Institutes: Jagellonian University(Poland), University of Michigan (USA)

Slides from: O. Schultz, NDM2012, Nara 11-16 June 2012
C. Oldorf, TAUP2011, Munich, 5-9 September 2011
M. Frittz courtesy

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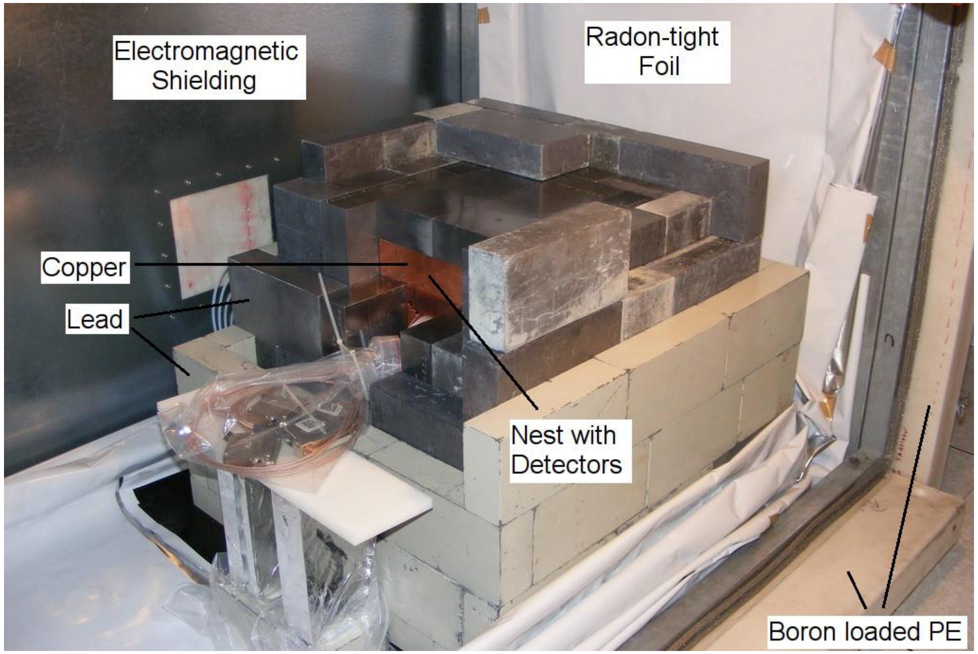
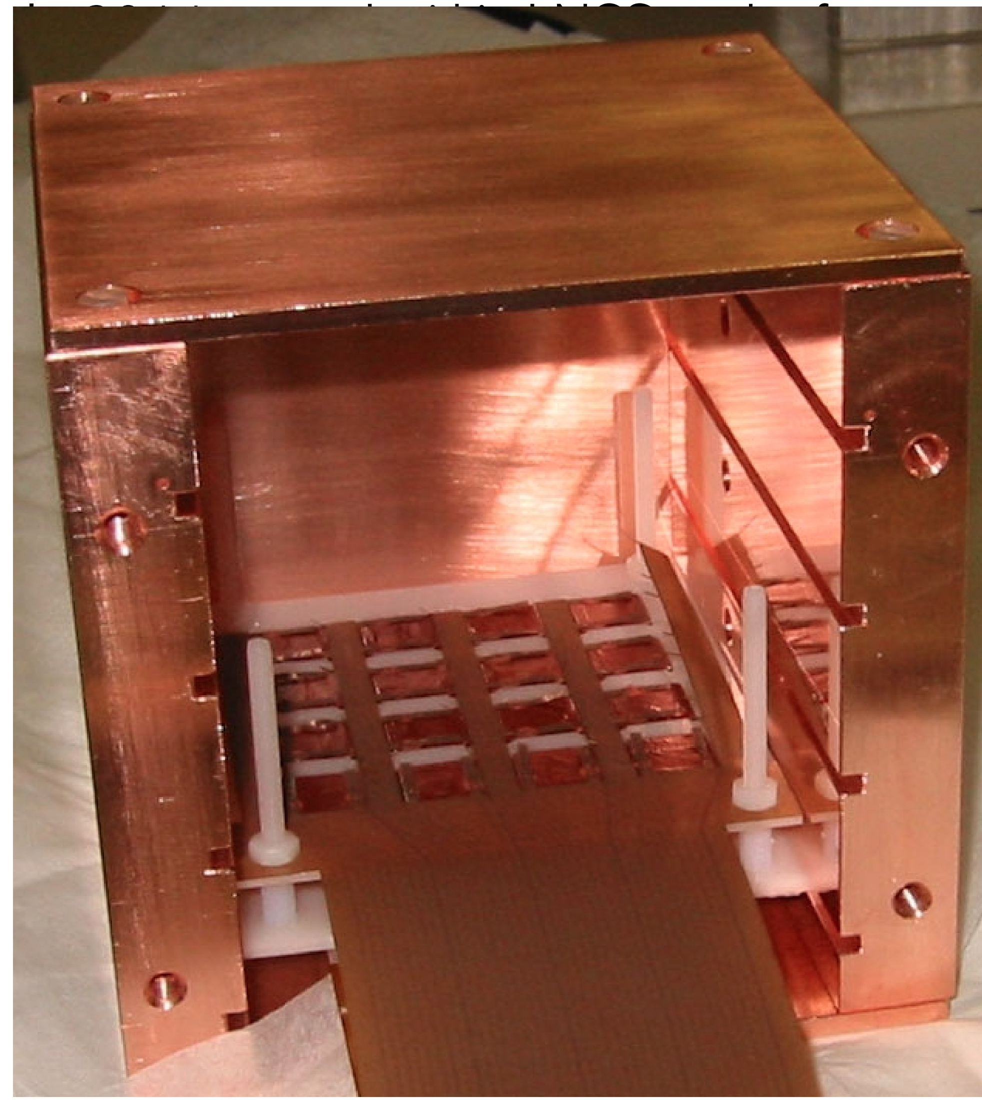
CoBRA-Location

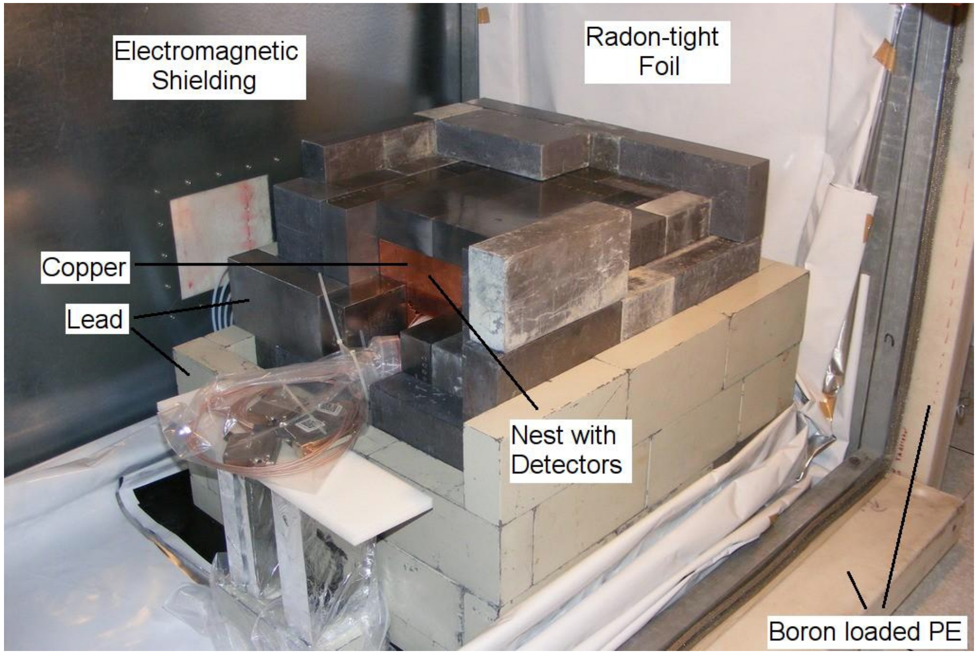
COBRA experimental setup located at Laboratori Nazionali del Gran Sasso (LNGS), Italy
(1400 m under Gran-Sasso massif, 3700 m.w.e.)

CoBRA-Location





CoBRA-Location



In 2011 moved within LNGS to the former HdM Building

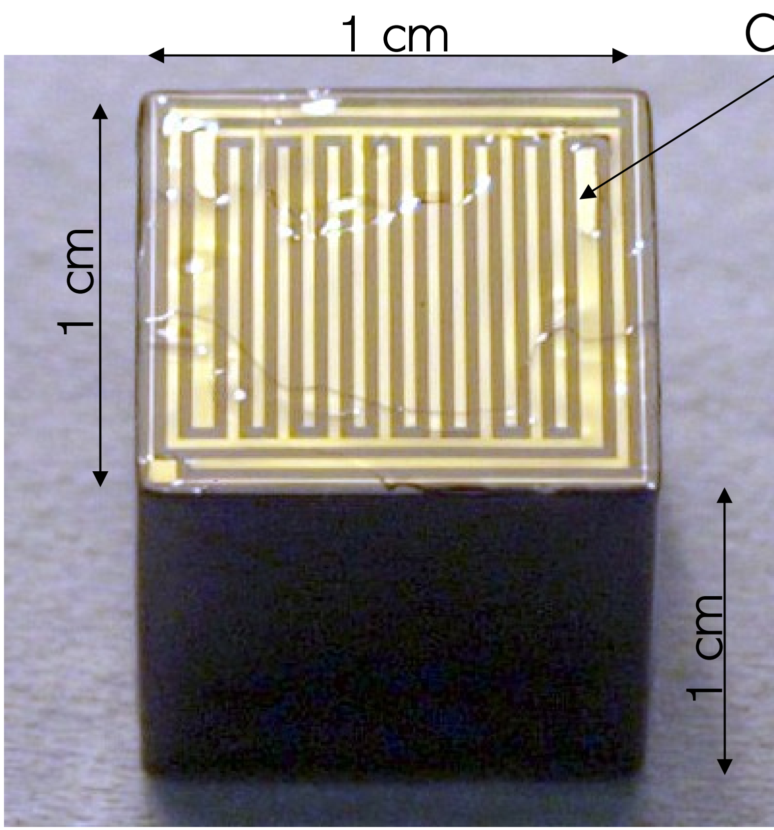
- Copper holder for 4 Delrin (POM) crystal l layers, with 16 detectors each (for 1 cm^3 CPG)
- Lead shielding with clean lead in inner layers and copper core
- Pb-shield enclosed in Rn-tight foil
- 70 mm borated PE plates as Neutron shield
- Tight Faraday-Cage (EMI shield)
- Radon shielding and N_2 flushing
- Colorless detector to reduce contamination

- New DAQ chain
- New amplifiers
- New Farday cage
- Fully digital read-out

CoBRA-Detector type A

Cadmium–Zinc–Telluride 0–neutrino double–Beta Research Apparatus

- Total mass of 420 kg, enriched in ^{116}Cd
- Sensitivity: $T^{0\nu}_{1/2} > 10^{26}$ yr ($m_\nu \approx 50$ meV)
- Total of 64 detectors (32 running)



Semiconductor detector
- Good energy resolution, intrinsically clean material

Source = Detector
- Big mass and high detection efficiency

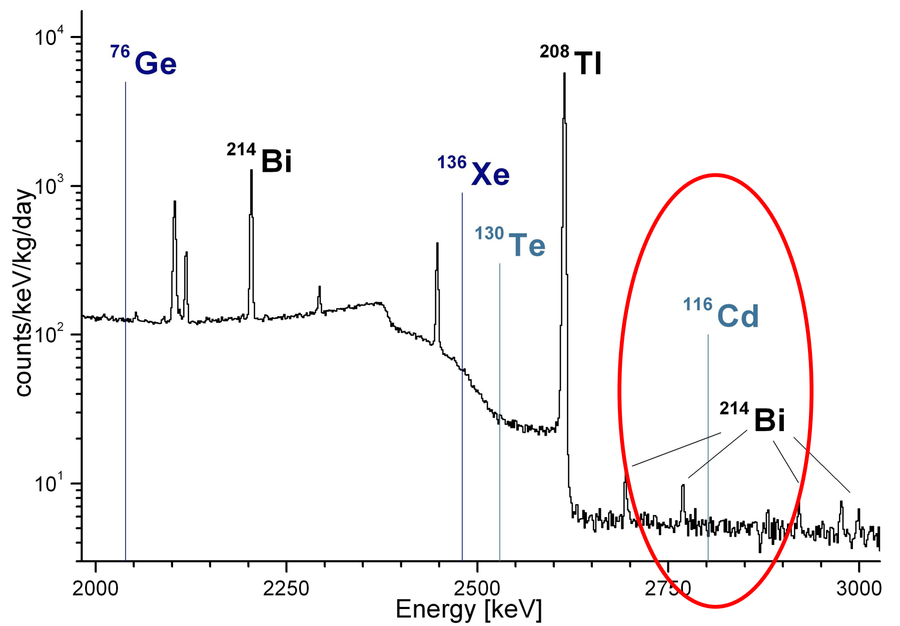
Room temperature
- No cooling needed

Modular design
- Coincidence analysis

Industrial development of CdZnTe detectors
- Maturing technology

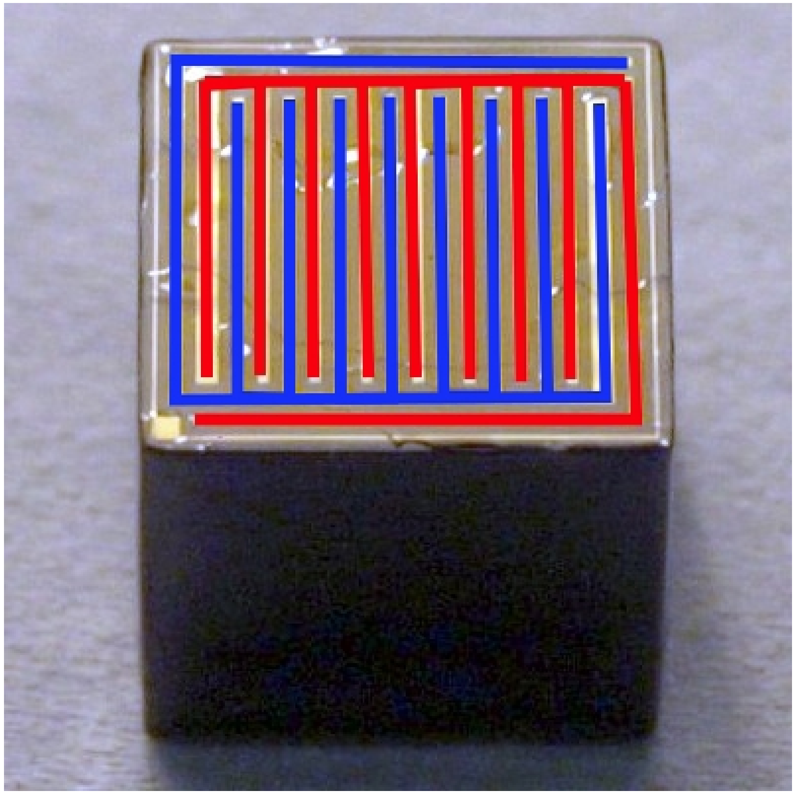
CdZnTe contains 9 0v2bcandidates, the most important:

	Q (keV)	Mode	Nat. Ab (%)
^{116}Cd	2814	b^-b^-	7.5
^{106}Cd	2771	b^+b^+	1.2
^{130}Te	2527	b^-b^-	33.8

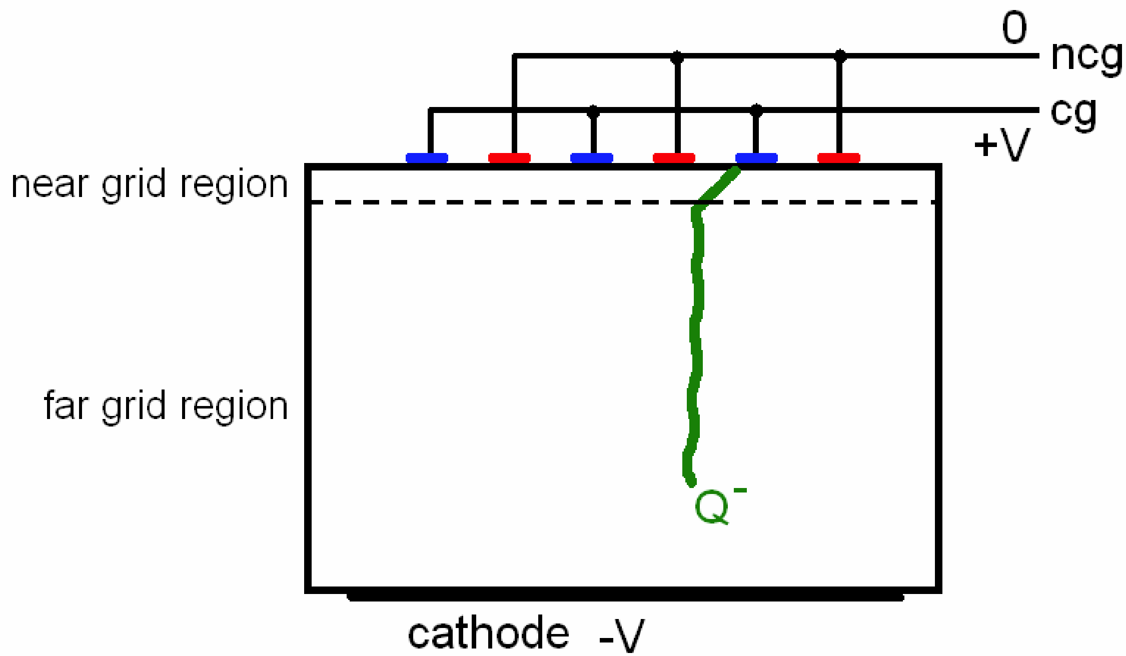


C. Oldorf, TAUP2011

CoBRA-Det. A Working principle



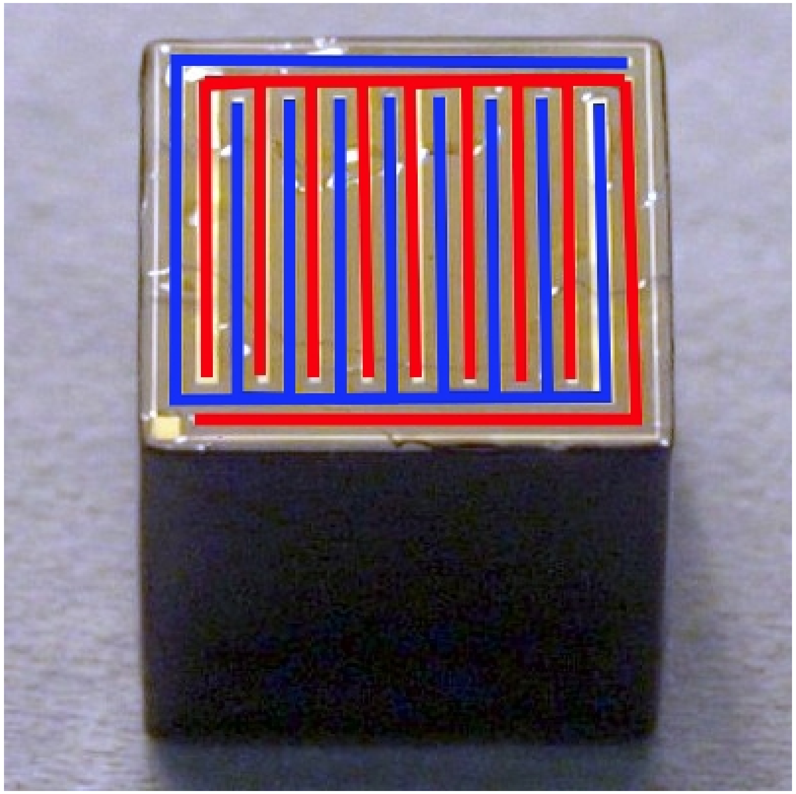
Two comb-shaped, differently biased anode grids create virtual "small pixel effect"



J. Clark, Mphys thesis, University of Surrey

- Fast electron, slow holes
- Electrons reach the near grid region
  generation of a signal
- Holes remain in the far grid region
  no signal contribution

CoBRA-Det. A Working principle



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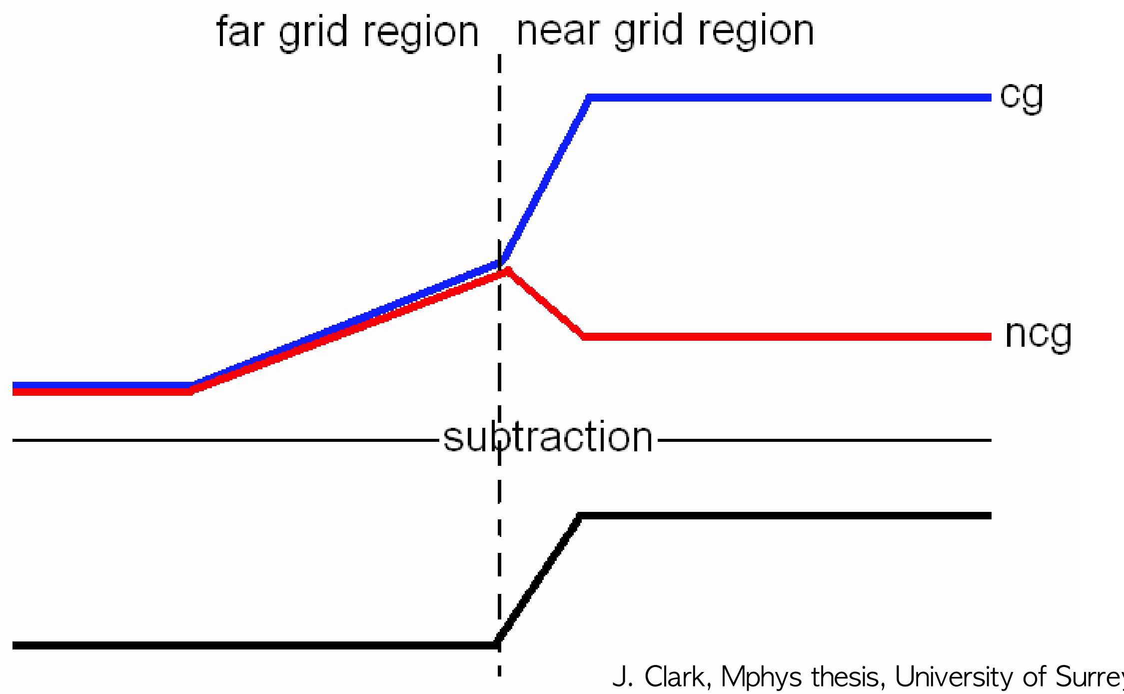
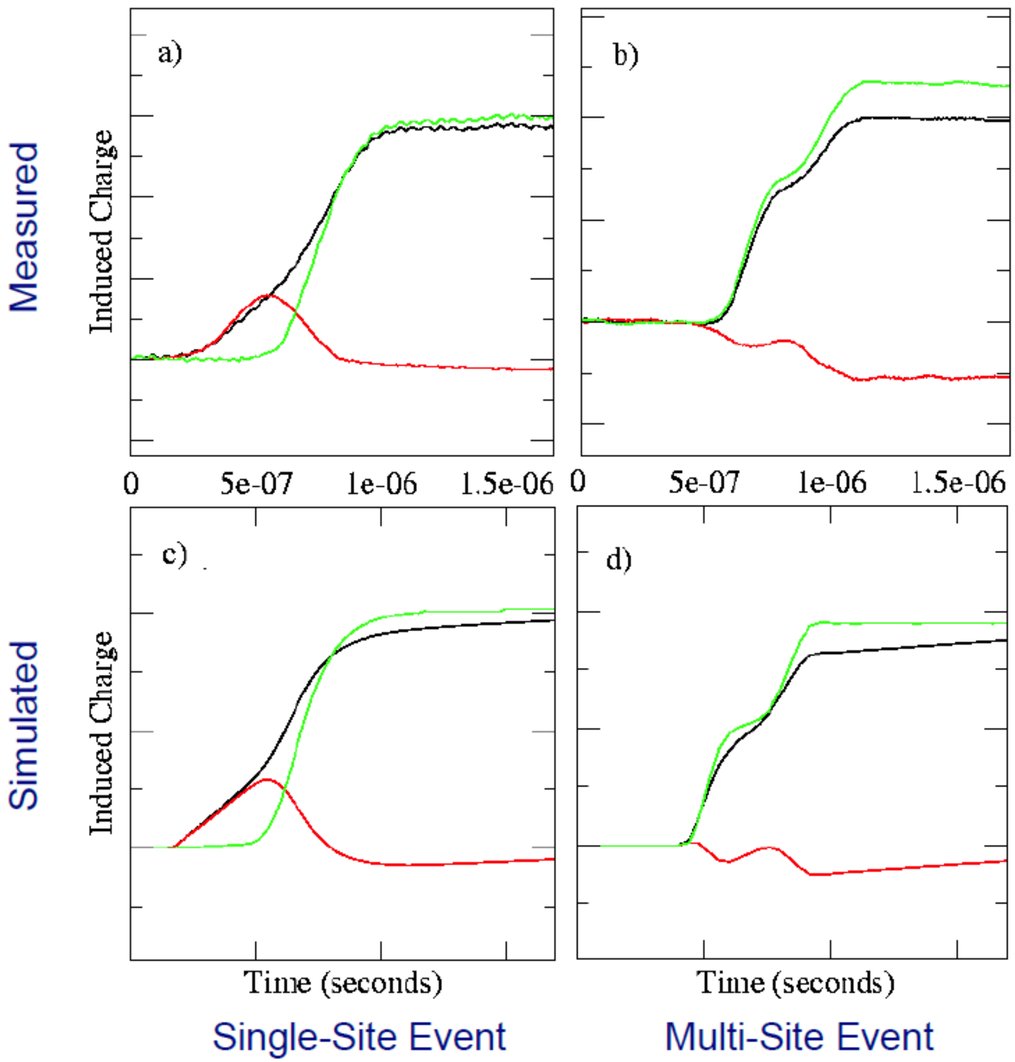


The pulsed signal is the subtraction of the 2 grid signals

CoBRA-Det. A Working principle

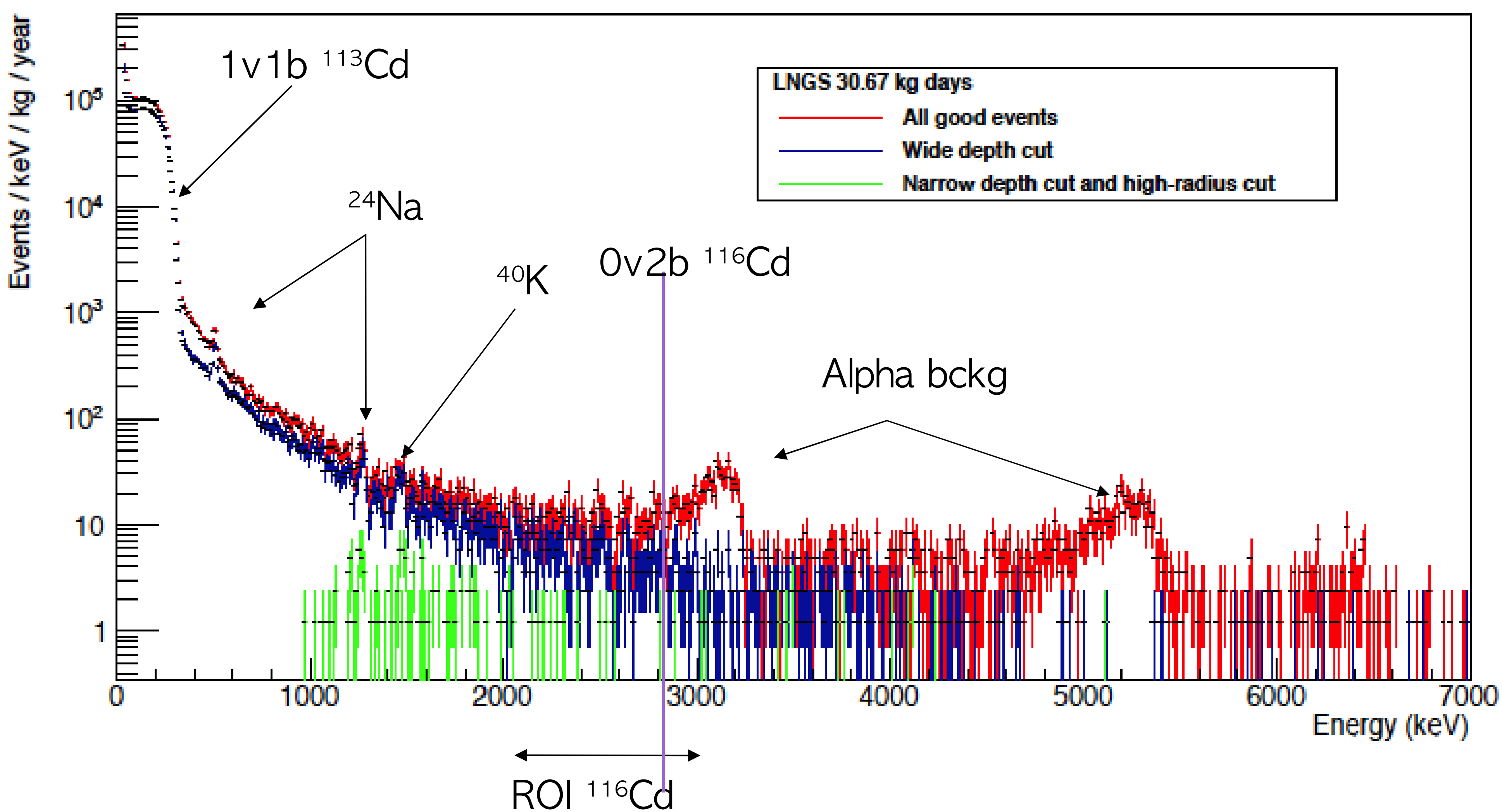


McGrath et al., acc. by NIMA, 2009

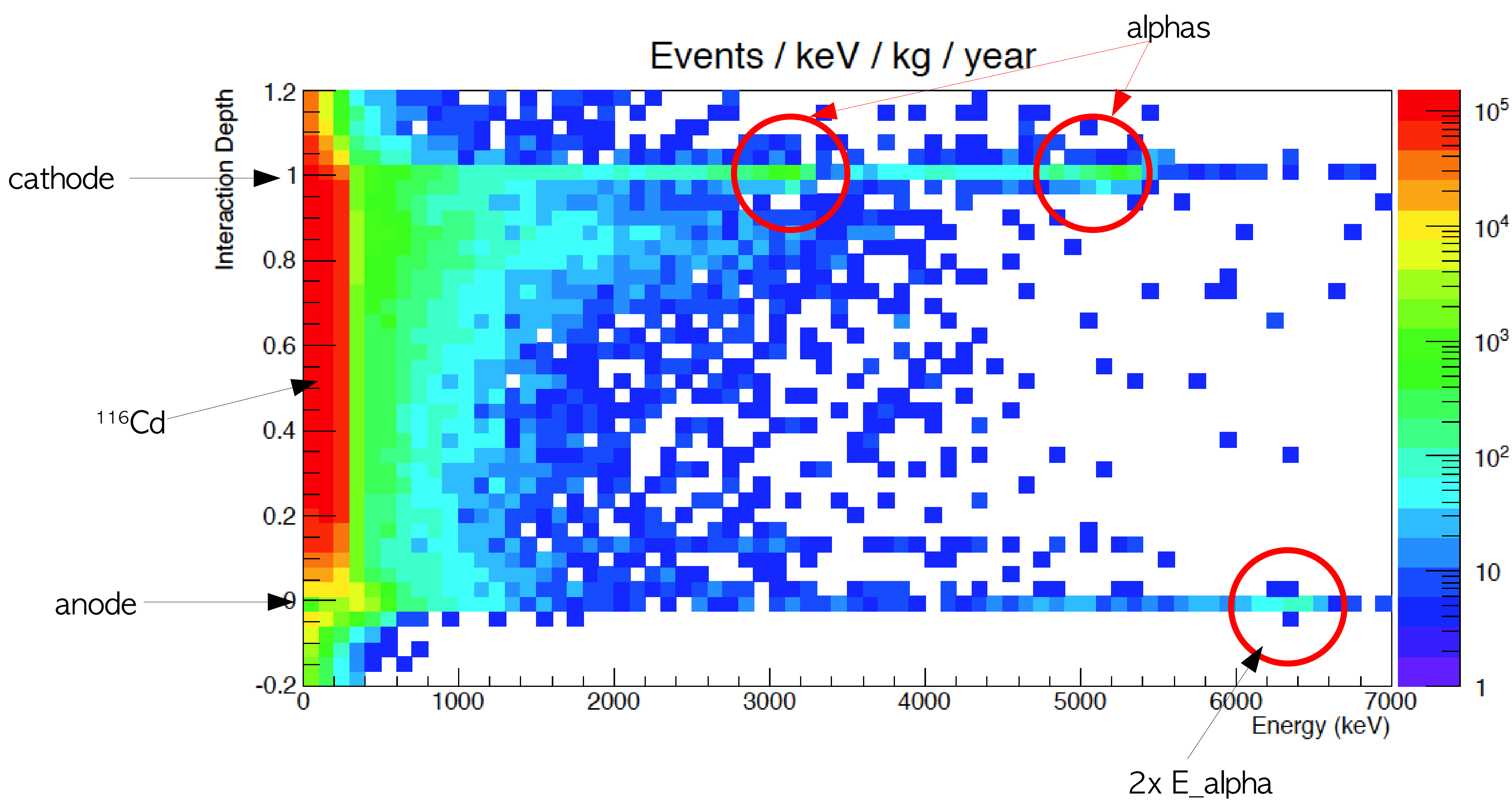
C. Oldorf, TAUP2011

- Pulse Shape with FADC readout:
  Distinguish between single site(0v2b)
  and multi site events (g–background)
- Depth–sensing allows rejection of background from surface contamination
  Identify noise events

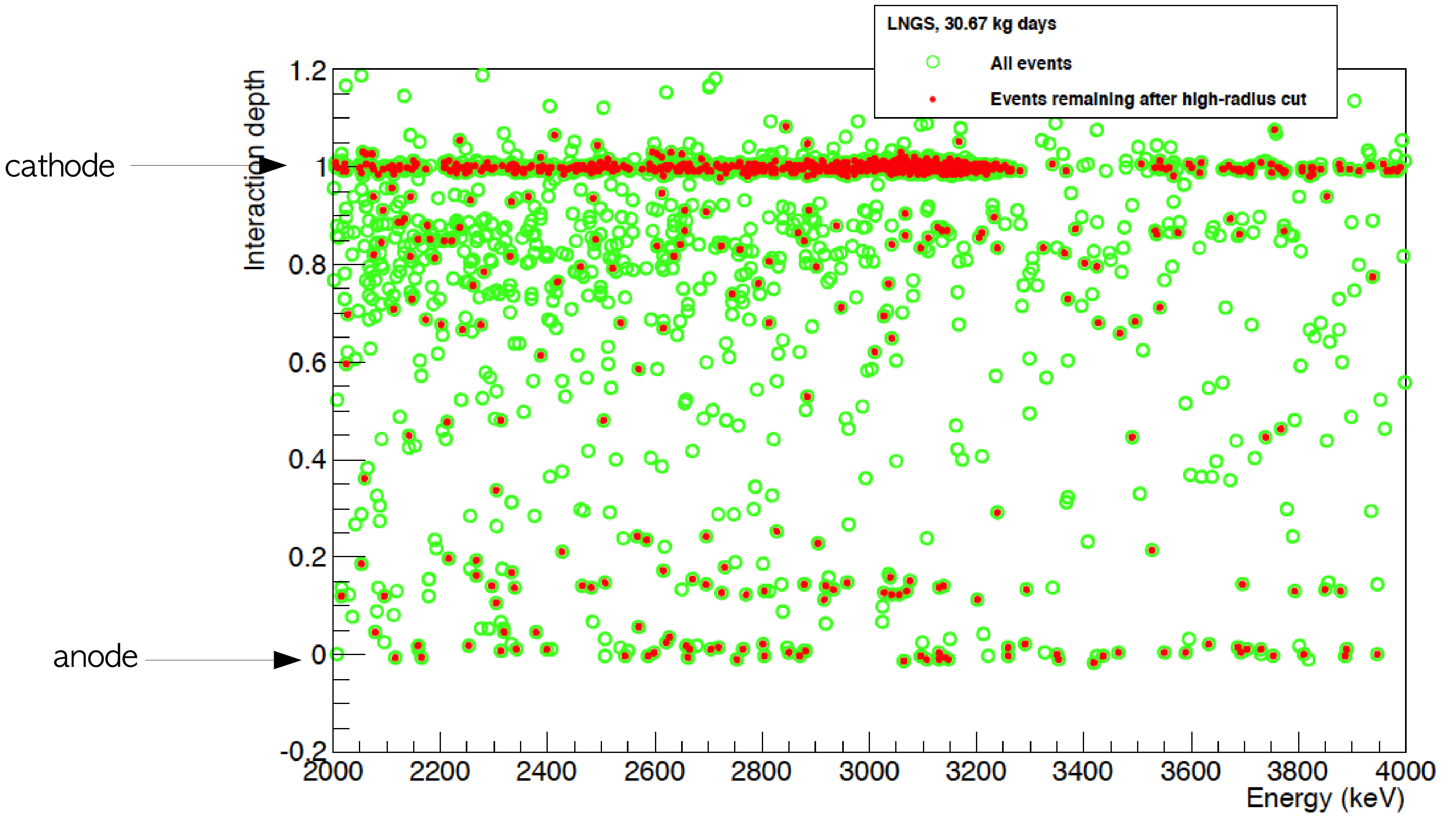
CoBRA-Spectrum



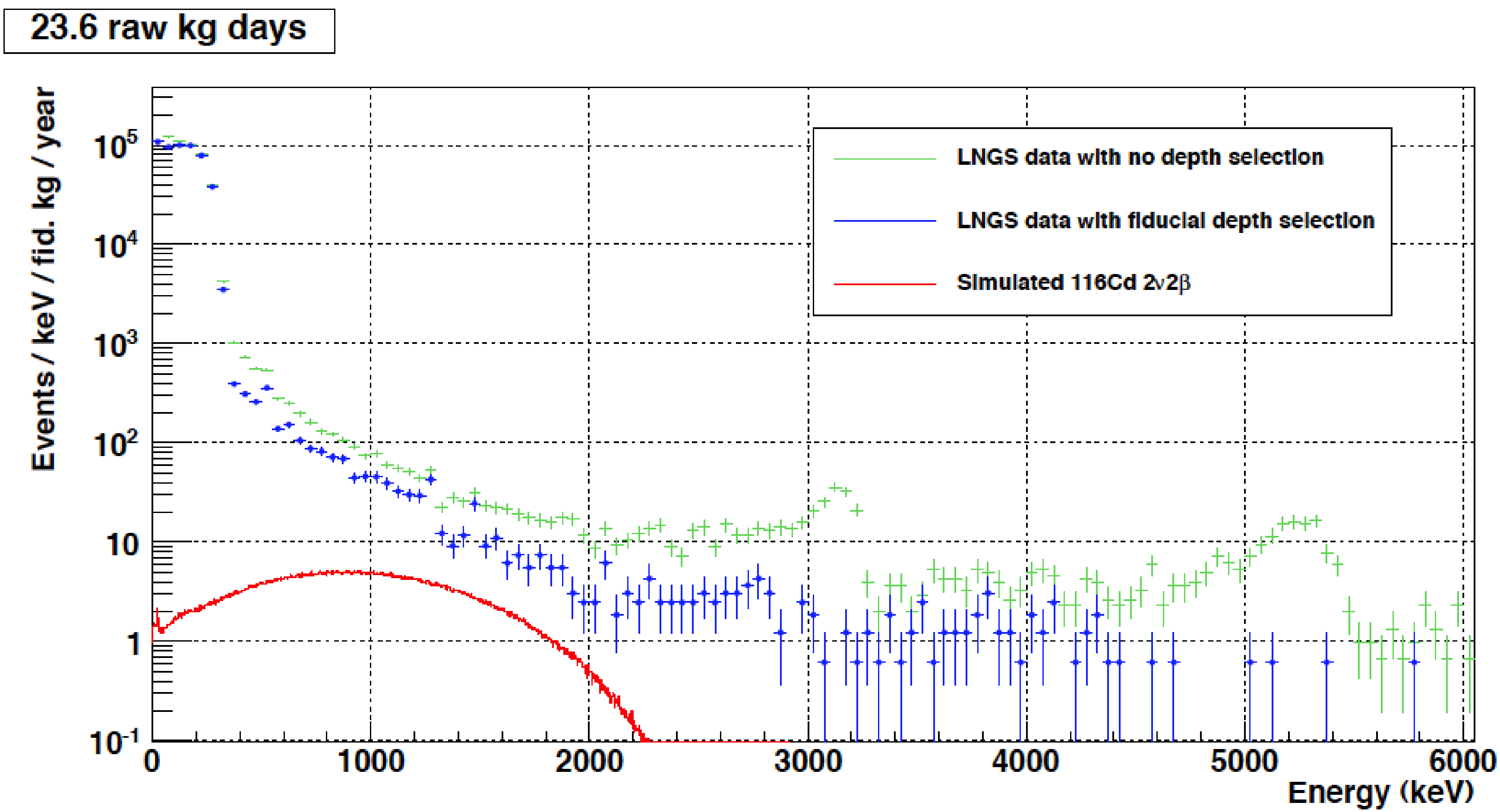
CoBRA-Spectrum



CoBRA-Spectrum



CoBRA-Spectrum



background rates for our region of interest (2.8 MeV):

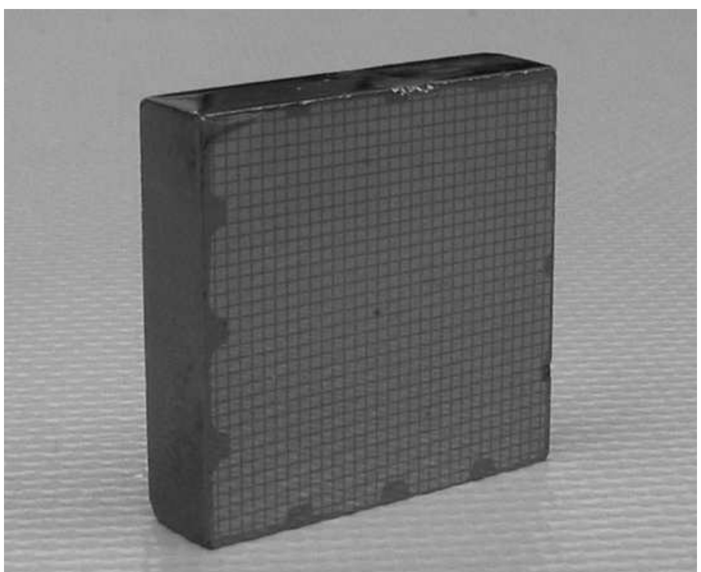
- no depth cut or radius cut: 12 /keV/kg/year
- cathode events removed: 4 /keV/kg/year
- cathode events AND high-radius events removed: 0.6 /keV/kg/year
- optimized (narrower) depth cut and high-radius events removed: 0.13 /keV/kg/year

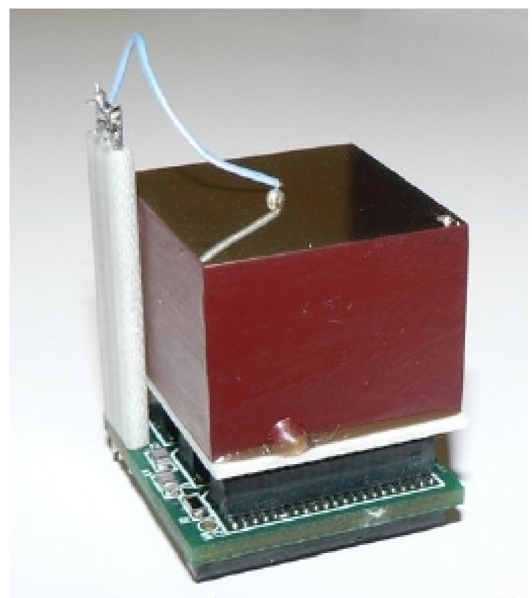
CoBRA-Detector type B

Pixel detector technology

Two types of detectors under investigation:

- Large volume (2 – 6 cm^3) with large pixel pitch (~ 1 mm)
  Washington University of St. Louis and Polaris System
- Thin detectors (0.3 - 2 mm) with small pixel pitch (~100 um)
  Timepix detector developed by the Medipix2 Collaboration

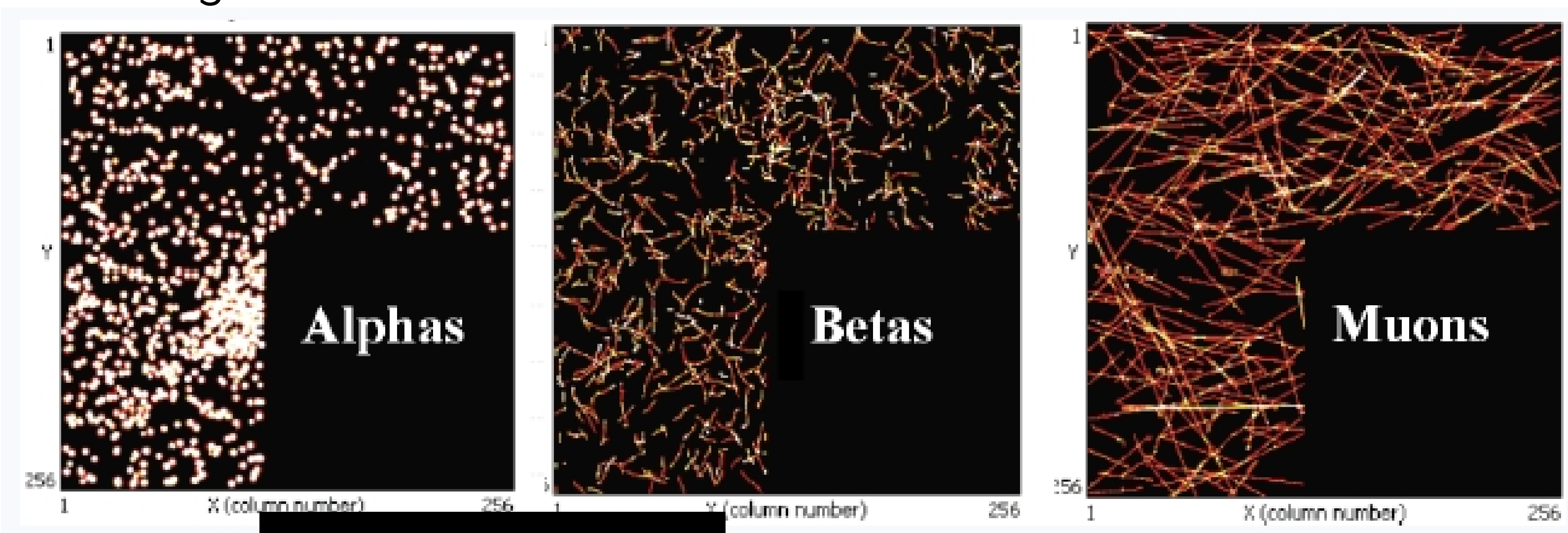


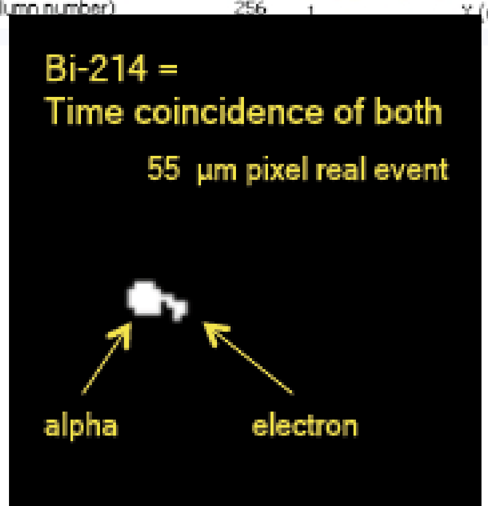


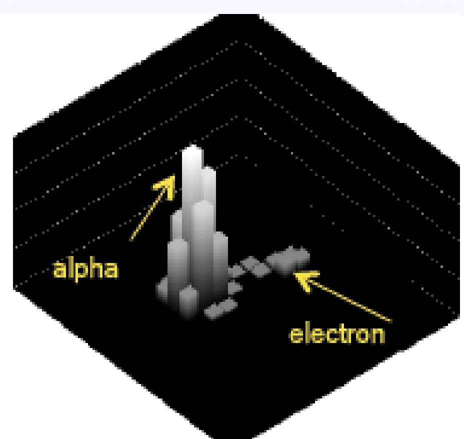
CoBRA-Detector type B - Timepix

- 2 Si systems: 14×14×0.3mm3
- 2 CdTe systems: 14×14×1mm3
- 256×256 pixel systems
- 128×128 pixel systems

  Particle tracking with a solid-state TPC







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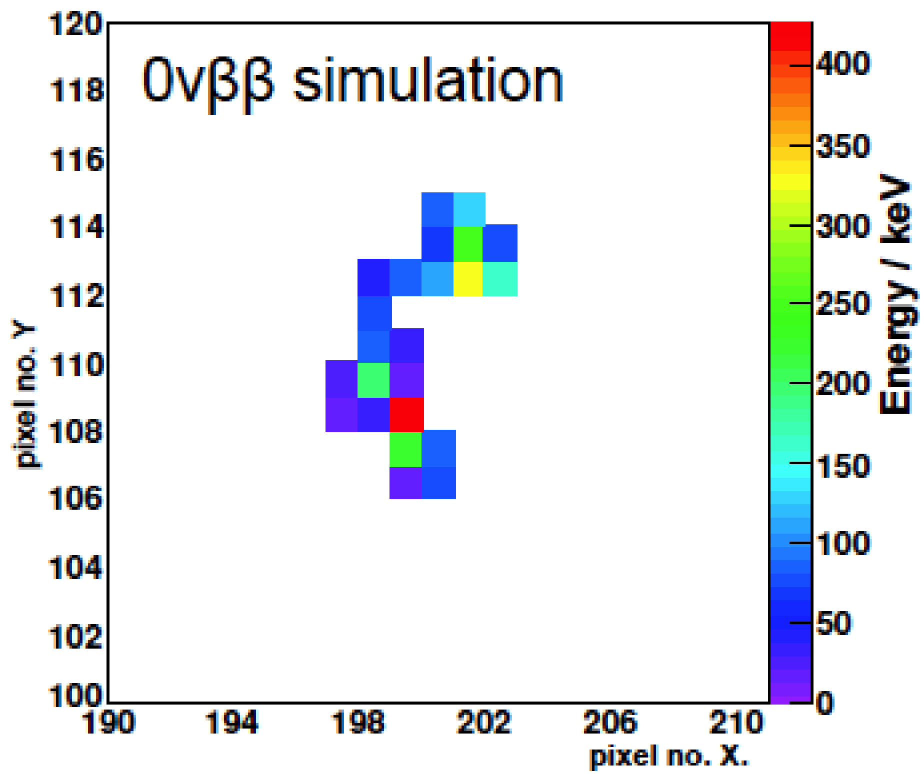
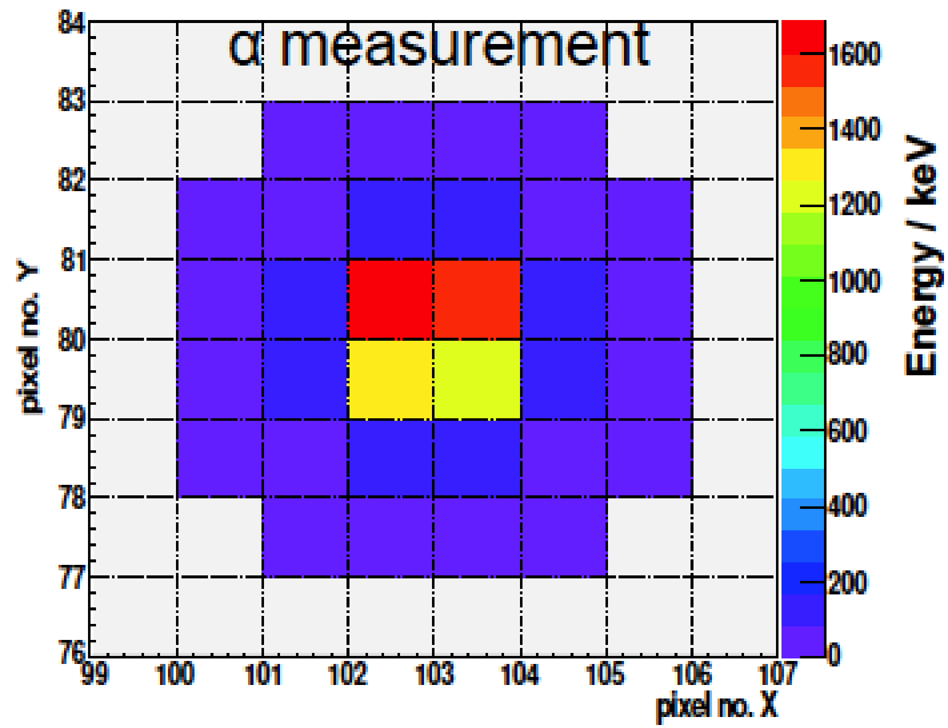
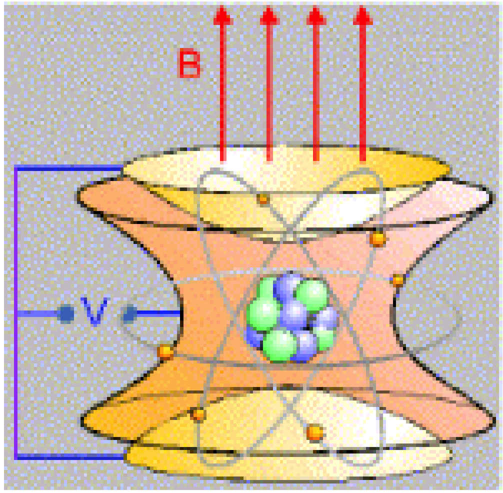




Penning Traps: determination of Q-value



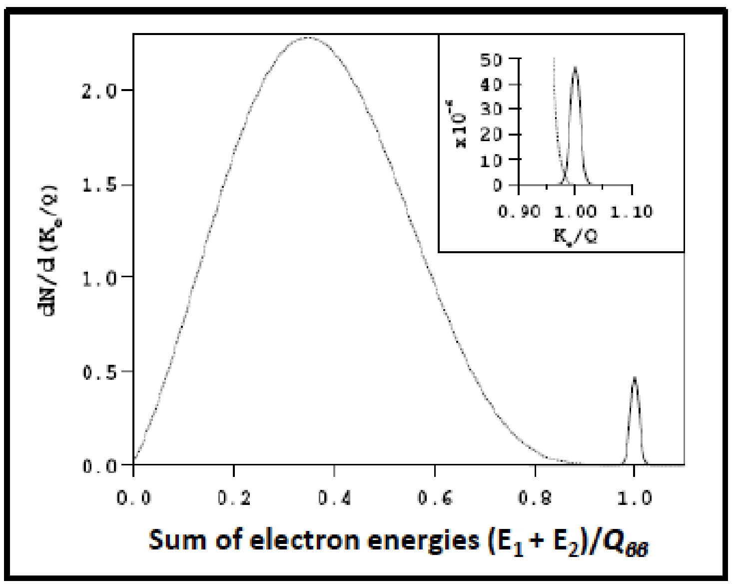
C. Droese, G. Marx, M. Rosenbusch, R. Wolf, L. Schweikhardt, K. Zuber, K. Blaum, C. Böhm, C. Borgmann, R. B. Cakirli, S. Eliseev, D. Fink, S. Kreim, D. Neidherr, D. Beck, M. Block, F. Herfurth, J. Kluge, E. M. Ramirez, G. Audi, D. Lunney, S. Naimi, M. Wang, A. Herlert, M. Kowalska, S. George, S. Schwarz, M. Breitenfeldt

Slides from: J. Stanja, IKTP Seminar, TU Dresden, 2010
M. Redshaw, ECT, Trento, 3-7 September 2012*

Penning Traps: Why

- The mass is a fundamental property which is of interest in different kinds of physics (general physics, nuclear structure physics, etc.)
- Important for determination of Q-values e.g. of neutrinoless double-beta-decay
- There the small amount of signal and the possible vicinity of background lines require precise knowledge of the Q-value
- Few experiments deal with high precision mass measurement using Penning traps like ISOLTRAP at ISOLDE/CERN

$Q_{\beta\beta}$ corresponds to location of 0νββ signal



$$Q_{\beta\beta} = \left[M({}^{A}_{Z}X) - M({}_{Z+2}^{\ A}Y)\right]c^2$$

$Q_{\beta\beta}$ is required for phase space factor calculation

2νββ : $G_{2\nu} \sim Q_{\beta\beta}^{11}$

For $\frac{\sigma_Q}{Q_{\beta\beta}} = \frac{10\ \text{keV}}{2\ \text{MeV}} \Rightarrow \frac{\sigma_G}{G_{2\nu}} = \mathbf{5.5\ \%}$

0νββ : $G_{0\nu} \sim Q_{\beta\beta}^{5}$

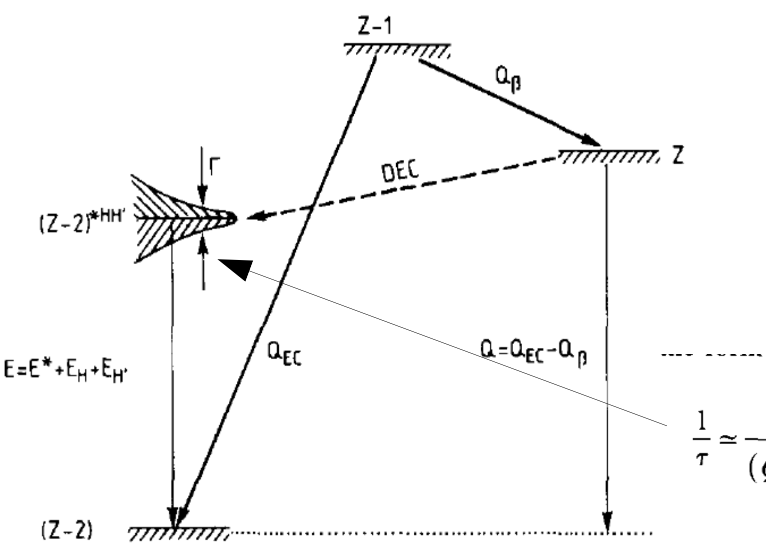
For $\frac{\sigma_Q}{Q_{\beta\beta}} = \frac{10\ \text{keV}}{2\ \text{MeV}} \Rightarrow \frac{\sigma_G}{G_{0\nu}} = \mathbf{2.5\ \%}$

Penning Traps: Double EC

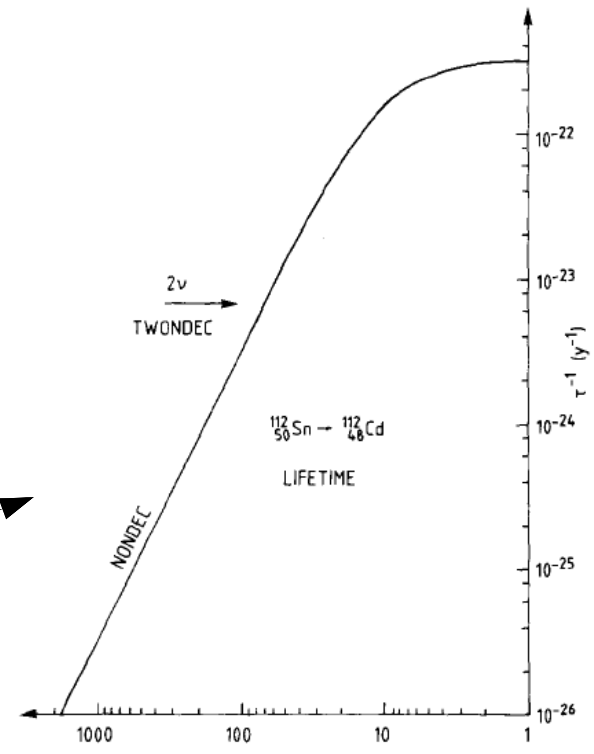
Figure from J. Bernabeu, Nuc. Phys. B **223**, 15 (1983)

$$(Z, A) \to (Z-2, A)^{*HH'} + 2\nu_e$$
$$\quad \hookrightarrow (Z-2, A) + \cdots$$

$$(Z, A) \to (Z-2, A)^{*HH'}$$
$$\quad \hookrightarrow (Z-2, A) + \cdots$$

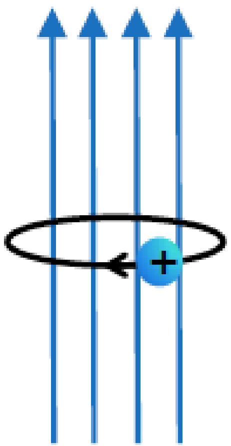


$$\frac{1}{\tau} \simeq \frac{(\Delta M)^2}{(Q-E)^2 + \frac{1}{4}\Gamma^2}\Gamma,$$



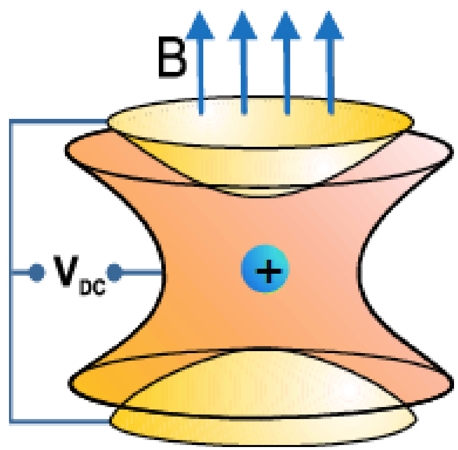
Penning Traps: Working principle

Uniform B-Field



+

Quadrupole E-Field



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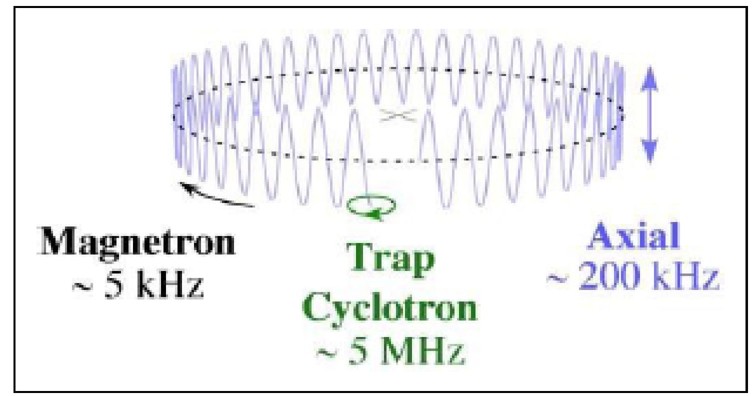
Three Normal Modes



$$\omega_c \approx \omega_{ct} >> \omega_z >> \omega_m$$

$$\omega_c = \frac{qB}{m}$$

$\omega_c/2\pi$ = cyclotron frequency
m = mass
q = charge
B = magnetic field strength

$$\omega_c^2 = \omega_{ct}^2 + \omega_z^2 + \omega_m^2$$

$$\omega_c = \omega_+ + \omega_-$$

M. Redshaw, ECT*, Trento

Penning Traps: Working principle

Uniform B-Field

+

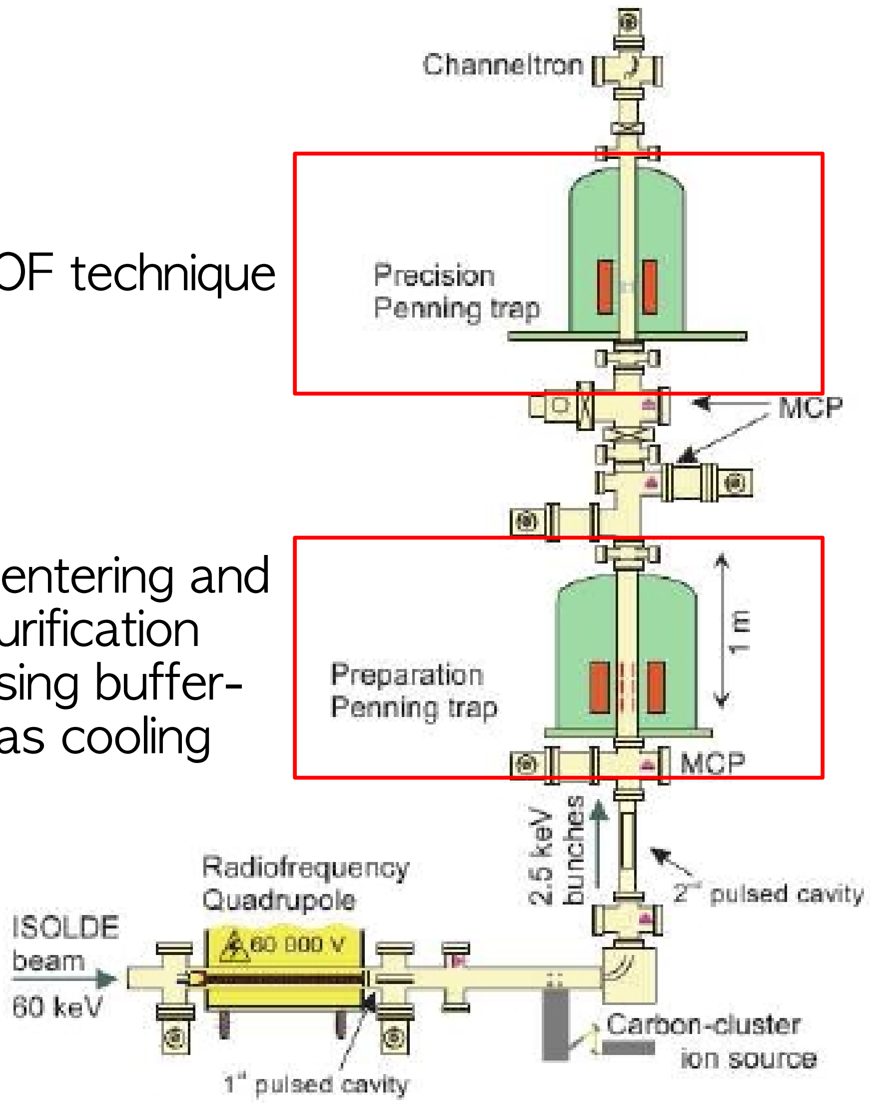
Quadrupole E-Field

M. Redshaw, ECT*, Trento

Penning Traps: ISOLTRAP

TOF technique

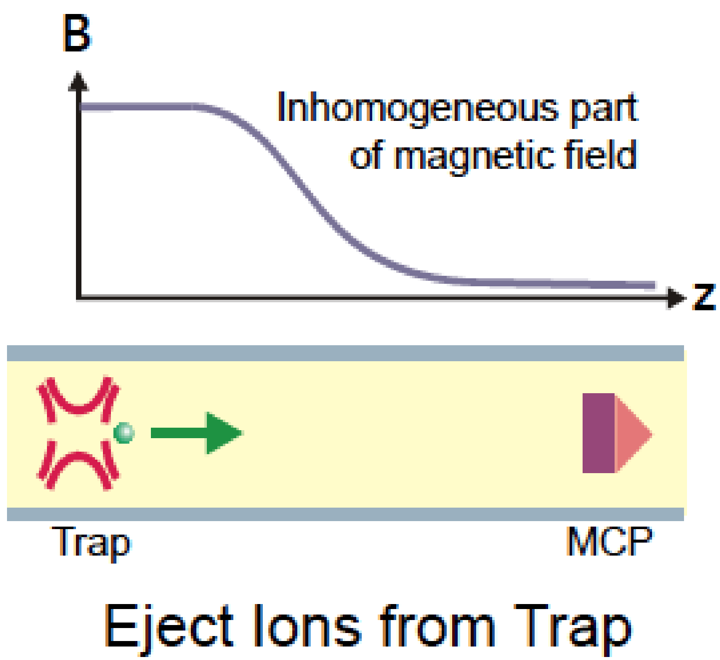
Centering and purification using buffer-gas cooling

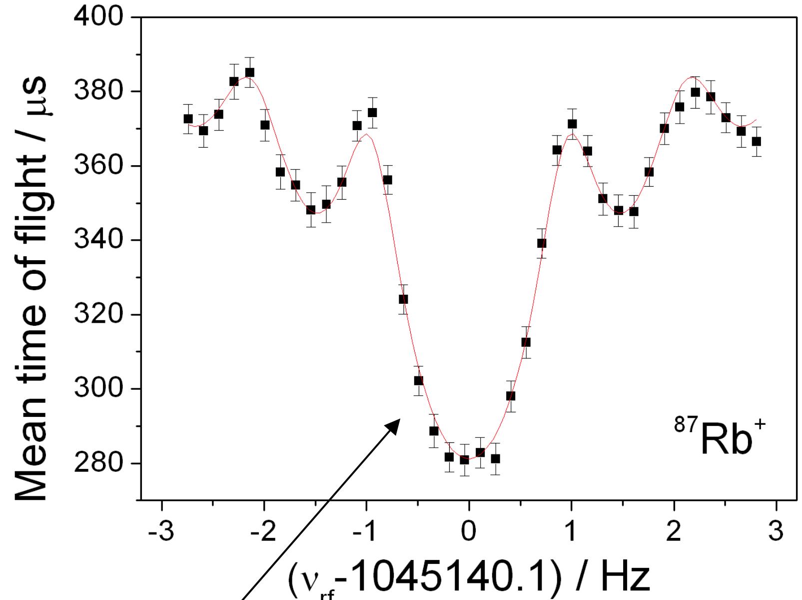


- uses up to 60 keV continuos beam of monocharged ions
- reaches a relative uncertainty of $\delta m/m \sim 10^{-8}$
- ions with halflifes of less then 100 ms can be measured
- consists of two Penning traps

J. Stanja, IKTP Seminar

Penning Traps: TOF





Minimum at cyclotron frequency

$$Q = m_m - m_d = \left(\frac{\omega_d}{\omega_m} - 1 \right) (m_d - m_e)$$

Penning Traps: Example

Isotopes of interest

Mother	Daughter	Q-Value (keV)
$^{48}_{20}Ca$	$^{48}_{22}Ti$	4274 ± 4
$^{96}_{40}Zr$	$^{96}_{42}Mo$	3347.7 ± 2.2
$^{110}_{46}Pd$	$^{110}_{48}Cd$	2004 ± 11
$^{116}_{48}Cd$	$^{116}_{50}Sn$	2809 ± 4
$^{150}_{60}Nd$	$^{150}_{62}Sm$	3367.7 ± 2.2

Data	Ratio r	Q value/keV
30-840-30 ms	1.000 019 713 1(89)	2018.09(90)
50-600-50 ms	1.000 019 708 1(89)	2017.60(90)
Weighted average	1.000 0197 106(63)	2017.85(64)
AME2003		2004(11)

~ 13 keV difference

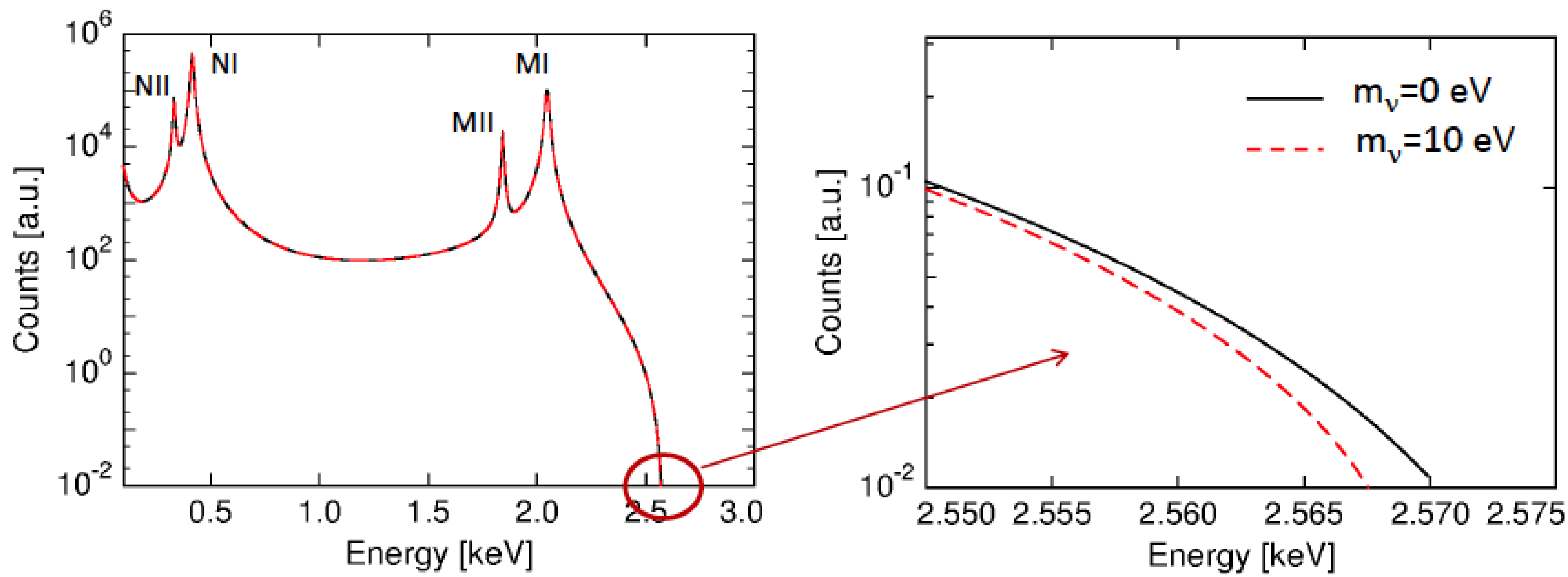
Penning Traps: The case of ^{163}Ho

L.Gastaldo courtesy

$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

$$^{163}_{66}\mathrm{Dy}^* \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

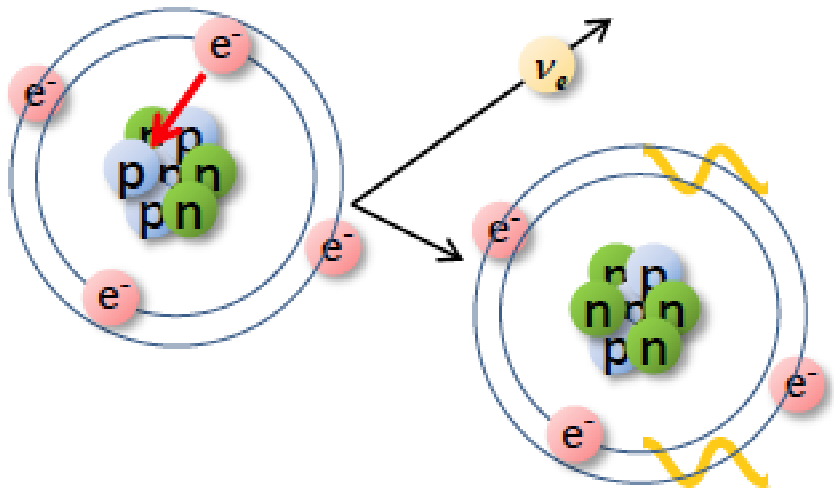
- $Q_{EC} \cong 2.5$ keV
- $\tau_{1/2} \cong 4570$ years



Extremely important to measure the end-point VERY precisely

Penning Traps: The case of ^{163}Ho

L.Gastaldo courtesy



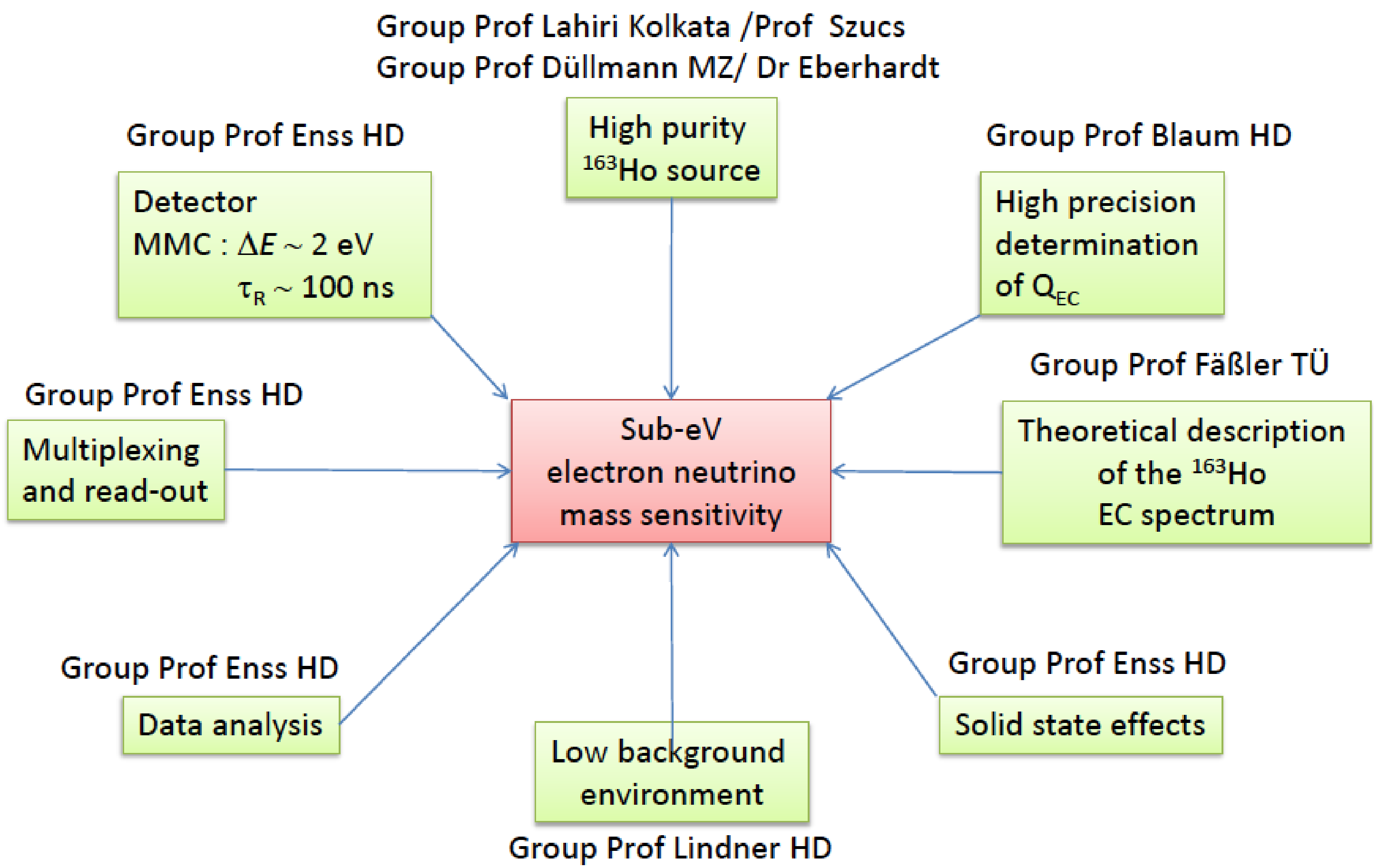
The atomic de-excitation is accompanied by:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

Calorimetric measurement of the energy
SOURCE=DETECTOR

$$\frac{dW}{dE_C} = A(Q_{EC} - E_C)^2 \sqrt{1 - \frac{m_\nu^{\ 2}}{(Q_{EC} - E_C)^2}} \sum_H B_H \varphi_H^{\ 2}(0) \frac{\frac{\Gamma_H}{2\pi}}{(E_C - E_H)^2 + \frac{\Gamma_H^{\ 2}}{4}}$$

The very interesting case:
- very low Q-value (Ho has an end-point energy around 2.5 keV)
- Capture energy very close to Q-value

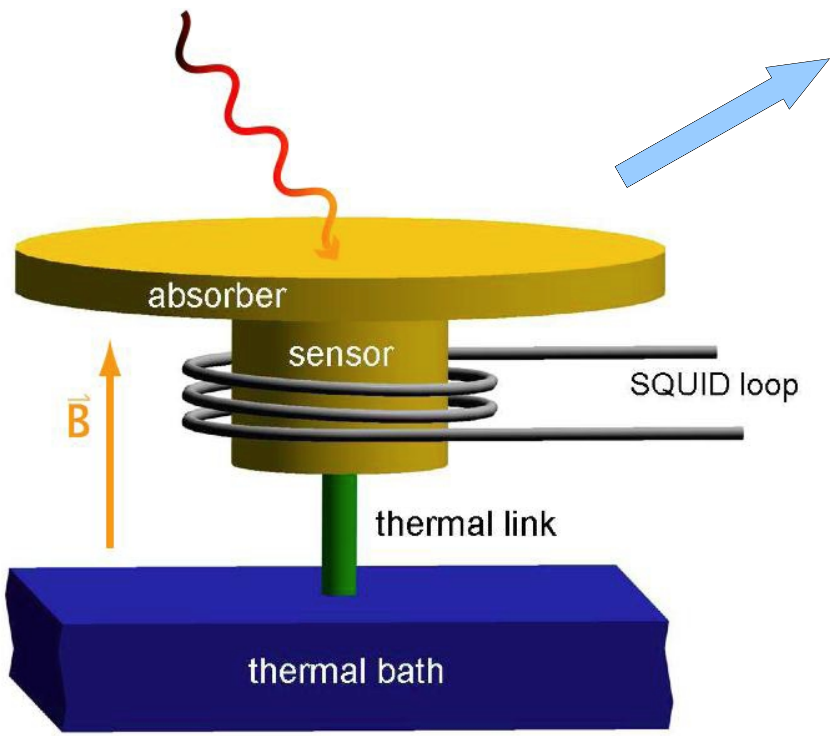
ECHO Experiment

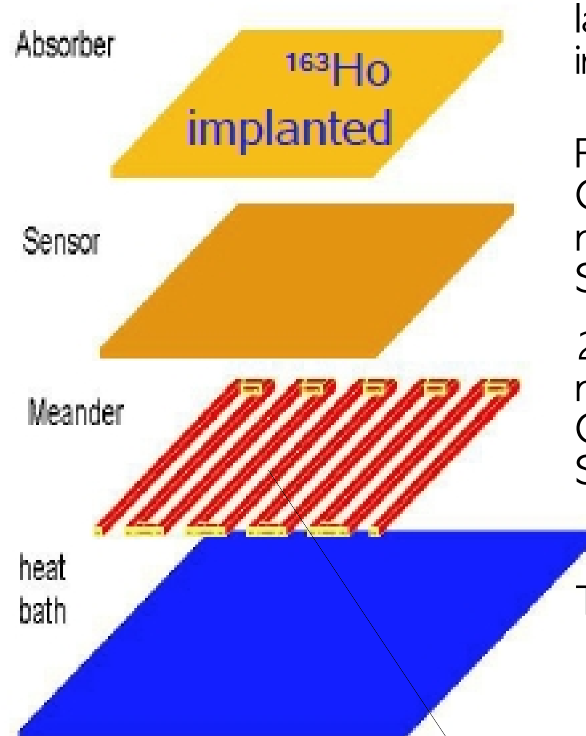


Slides from: L. Gastaldo courtesy

ECHO: Detector MMC

Metallic Magnetic Calorimeter



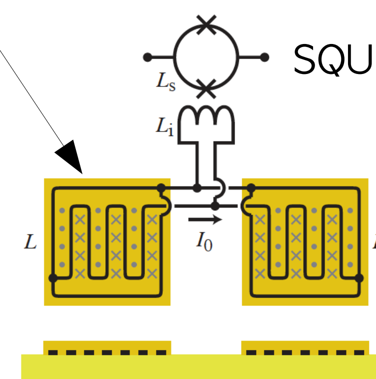


Energy is absorbed in the Au layer → temperature increases

Paramagnetic sensor (Au:Er)
Change in T → change in magnetization → read out by a SQUID loop

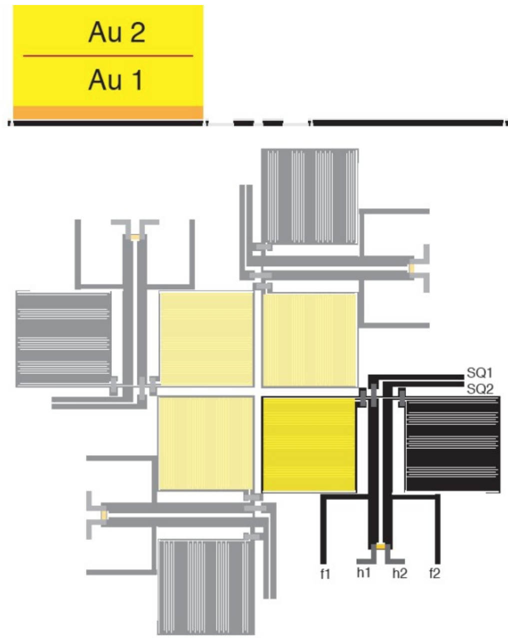
2x Meander pick-up coils to measure magnetic gradient
Connected in parallel to the SQUID loop

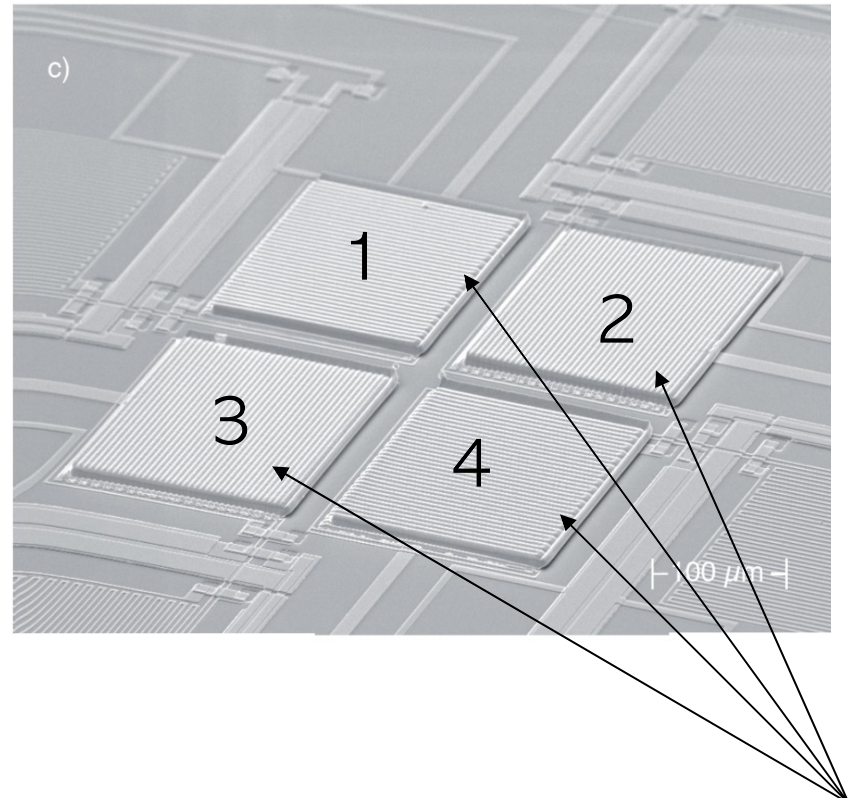
T = few mK



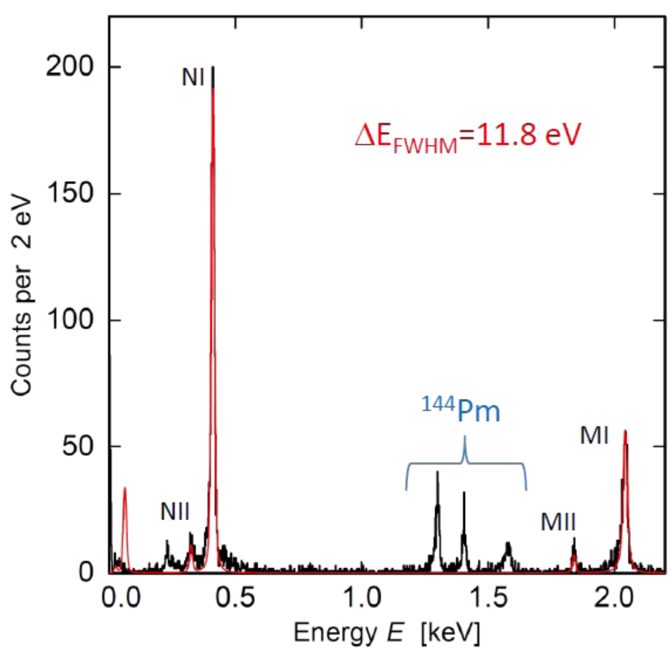
Characteristics:
- energy resolution: FWHM 2 eV @ 6keV
- rise time: 90 ns

ECHO: Detector





4 pixels device



Impurities in the flux (beam was not clean)
Main contamination ^{144}Pm

ECHO: Tests

The performance of the detector with and without the Ho layer have been tested:

- Wait 3 months after implantation in order to have short living decaying
- No deviation in temperature behavior
- No deviation in pulse shape and height
- A bit worse energy resolution (from 4.9 eV to 6.6 eV). It can be due to additional noise contribution
- Background events in nearby pixels can be discriminated by different pulse shape and rejected
- Good energy response and linearity
- Problem of background rejection if events are generated in nearby pixels (for instance coming from ^{144}Pm). Cross talks can be eliminated applying a silicone membrane as a detector substrate

the thermal properties of the implanted detector can be understood and are not affected by the implantation process

Plan for a new detector design for crosstalk reduction and better energy resolution from 12eV to 2eV

ECHO: Requirements

Required activity in the detectors:

Final experiment → 10^6 Bq (10^{17}) atoms

Pilot experiment → 10^3 Bq (10^{14}) atoms (time scale ~1 year)

Required Purity: No radioactive contaminants Ratio ^{163}Ho/other ions~1000

Chemical form: depends on the chosen absorber preparation:

ion implantation

dilute alloy

Conclusion

Q- values measurement are very important for the measurement of the neutrino mass/ Majorana neutrino mass.

NME of the 0v2b decay strongly depends on the Q-value

The possibility of measuring the neutrino mass from 2EC also strongly depends on the Q-value determination

Calorimetric experiments (ECHO) will provide an independent look at kinematical neutrino mass limits. The scalable approach and further R&D work will allow to reach a competitive level of sensitivity