Status and prospects of the COBRA double beta-decay experiment at LNGS

39th International School of Nuclear Physics

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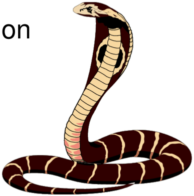


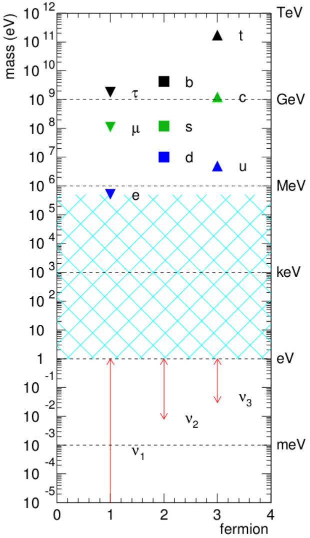
17th September 2017

GRADUIERTEN KOLLEG Masse-Spektrum-Symmetrie

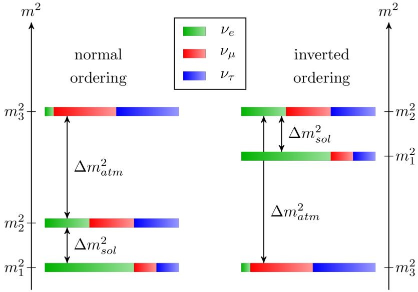
DFG Deutsche Forschungsgemeinschaft

Outline

Motivation for double beta-decay searches



Neutrino 2016, André de Gouvêa, NW University

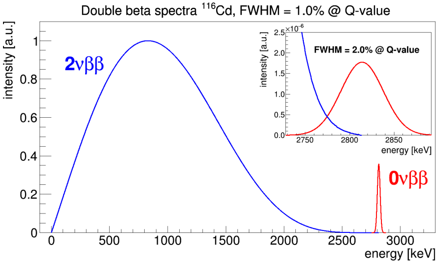


Open questions in the ν-sector

- Why are neutrino masses so **tiny**?
- Which neutrino **mass ordering** is right? Normal or inverted?
- Are neutrinos their own antiparticles? Dirac or Majorana fermions?

→ requires search for **new physics**!

Experimental search for ββ-decay



Theorist's Master formula

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \mathcal{G}^{0\nu} \cdot \left|\mathcal{M}^{0\nu}\right|^2 \cdot \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

$\mathcal{G}^{0\nu}$ ...	phase space factor
$\mathcal{M}^{0\nu}$ ...	nuclear matrix element
$m_{\beta\beta}$ ...	effective neutrino mass
m_e ...	electron rest mass

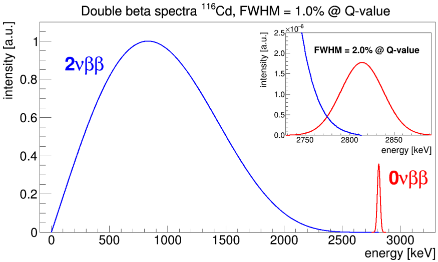
2νββ: $(Z,A) \longrightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$

- allowed process in SM
- only observable if single β-decay is strongly suppressed

0νββ: $(Z,A) \longrightarrow (Z+2,A) + 2e^-$

- requires massive neutrinos with Majorana character
- violates Lepton number conservation by $\Delta L = 2$

Experimental search for ββ-decay



Experimentalist's Master formula

$$T_{1/2}^{\mathrm{exp}} \sim a \cdot \varepsilon \cdot N \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

a ...	isotopic abundance (90% enrichment)
ε ...	total efficiency, $\varepsilon = \varepsilon_{\mathrm{det}} \cdot \varepsilon_{\mathrm{cuts}}$
N ...	number of atoms per kg
M ...	total mass ($\mathcal{O}(100\,\mathrm{kg})$ for large scale)
t ...	experimental lifetime, $\mathcal{O}(5\,\mathrm{yr})$
ΔE ...	size of peak window (ROI)
B ...	background index for ROI
	$\rightarrow$ reach less than **10^{-3} cts/(kg·keV·yr)!**

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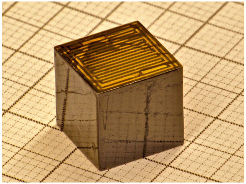
The COBRA experiment

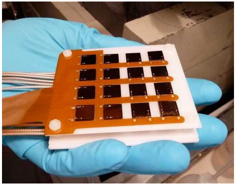
What is COBRA?

- **C**dZnTe **0**ν Double **B**eta **R**esearch **A**pparatus
- next generation double beta-decay experiment in R&D phase
- **room temperature semiconductor** with coplanar-grid (CPG) approach
  - search for 0νββ-decay in several isotopes with $T_{1/2}^{0\nu} > 10^{26}\,\mathrm{yr}$
  - principle: **detector = source** (high intrinsic detection efficiency)
- demonstrator at low background facility LNGS built of 4×4×4 crystals

Most promising isotopes:

- Cd-116: $Q = 2814\,\mathrm{keV}$
  $\rightarrow$ above highest prominent γ-line of nat. decay chains (Tl-208 $\rightarrow E_\gamma = 2614\,\mathrm{keV}$)
- Te-130: $Q = 2527\,\mathrm{keV}$
  $\rightarrow$ high nat. abundance ($a = 34.08\%$)





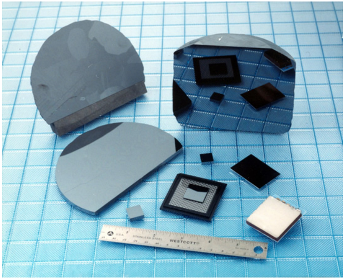
The detector material - Cadmium Zinc Telluride (CZT)

Advantages

- intrinsic semiconductor at room temperature
- high density and high atomic number
- commercially available (several suppliers)

Challenges

- low mobility lifetime product for holes
  $\rightarrow$ single charge carrier device
  $\rightarrow$ requires special readout design
- poor availability of large crystals



property	$Cd_{0.9}Zn_{0.1}Te$	Ge	Si
atomic number	**48, 30, 52**	32	14
density [g/cm^3]	**5.78**	5.33	2.33
band gap [eV]	**1.57**	0.67	1.12
pair energy [eV]	**4.64**	2.95	3.63
resistivity [Ω cm]	**3×10^{10}**	50	$< 10^4$
$(\mu\tau)_e$ [cm^2/V]	**(3-10)$\times10^{-3}$**	> 1	> 1
$(\mu\tau)_h$ [cm^2/V]	**5×10^{-5}**	> 1	≈ 1

eV Products Inc. (2013); *Semiconductor Material Properties*

Why is CZT interesting for $0\nu\beta\beta$-decay search?

- CZT contains **nine potential double beta isotopes** (several decay modes)
- recent peak search analysis: focus on five $\beta^-\beta^-$ g.s. to g.s. transitions
  - achieved Bayesian limits (90% C.L.) of 10^{19}-10^{21} yr (world best for Cd-114!)

    Publication: **J. Ebert et al., *Results of a search for neutrinoless double beta-decay using the COBRA demonstrator*, PhysRevC.94:024603, 2016**

isotope	decay mode	nat. abund.[1]	Q-value [keV]
Zn-64	β^+/EC, EC/EC	49.17%	1095.70[2]
Zn-70	$\beta^-\beta^-$	0.61%	998.50[2]
Cd-106	$\beta^+\beta^+$, β^+/EC, EC/EC	1.25%	2775.01[3]
Cd-108	EC/EC	0.89%	272.04[3]
Cd-114	$\beta^-\beta^-$	28.73%	542.30[4]
Cd-116	$\beta^-\beta^-$	7.49%	2813.50[5]
Te-120	β^+/EC, EC/EC	0.09%	1714.81[6]
Te-128	$\beta^-\beta^-$	31.74%	865.87[6]
Te-130	$\beta^-\beta^-$	34.08%	2526.97[5]

[1] IUPAC, 2009; [2] Belli et al., 2008; [3] Smorra et al., 2012; [4] AME, 2012; [5] Rahaman et al., 2011; [6] Scielzo et al., 2009;

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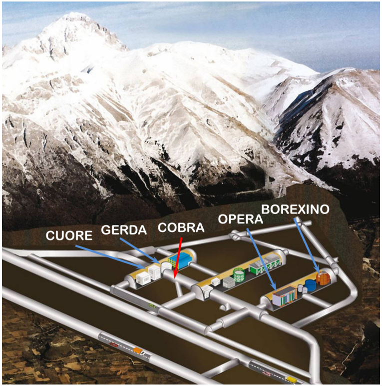
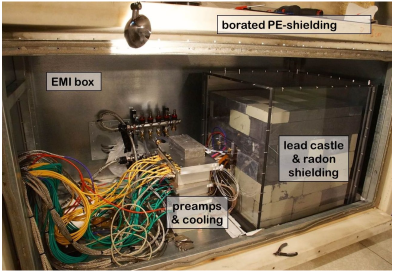
COBRA at Laboratori Nazionali del Gran Sasso

Operation at LNGS – deep underground

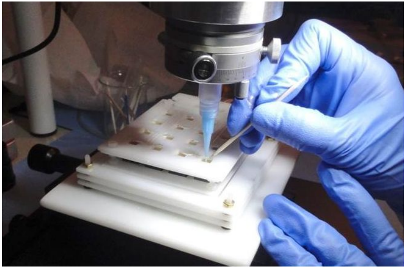


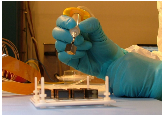


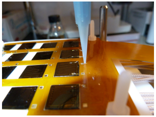
Outer shielding

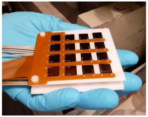
- 1400 m rock coverage (3700 m.w.e.)
- 7 cm boron-loaded polyethylene
- EMI box against electromagnetic interference
- radon shield and permanent N_2-flushing

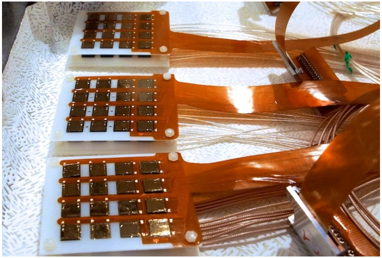
On-site detector layer assembly at LNGS

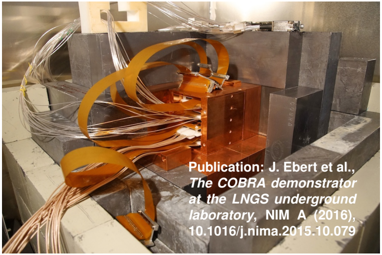








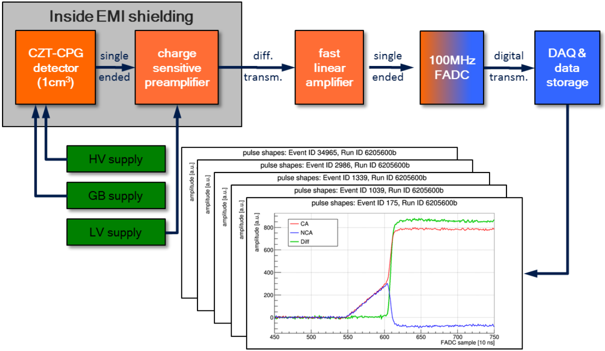




Inner shielding

- 5 cm of low level alpha lead (A<3 Bq/kg) and 15 cm standard lead (total 2.3 t)
- housing: 5 cm of pure OFHC copper
  - $\rightarrow$ setup completed in Nov. ’13

Data acquisition of LNGS demonstrator



- 64 × 1 cm^3 CPG detectors inside EMI shielding
- 128 pre-amp (CR-110) and linear amplifier channels
- 128 FADC channels (SIS3300, 100 MHz, 12-bit)

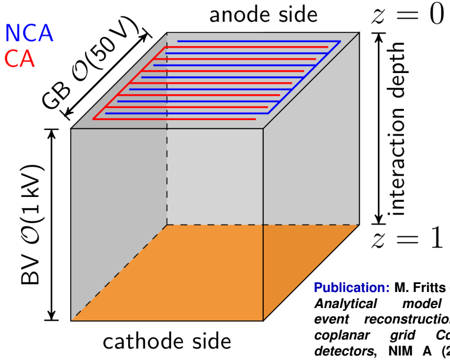
→ **pulse-shape sampling** allows for:
event classification, interaction depth reconstruction, fiducial cuts, coincidence analysis, vetoing...

Basics of signal reconstruction

Shockley-Ramo-Theorem:

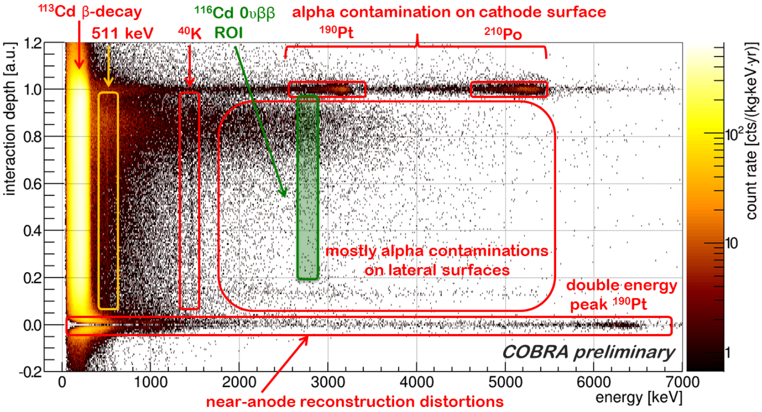
The **signal** from an electrode is the **induced charge** caused by the **drift of a charge cloud** through the detector volume.

- recorded signals
  - collecting anode (CA)
  - non-collecting anode (NCA)
- reconstructed signals
  - Diff = CA − NCA
  - Cath = CA + NCA
- information from pulse height
  - energy of interaction
  - depth of interaction: $z \sim \text{Cath}/\text{Diff}$



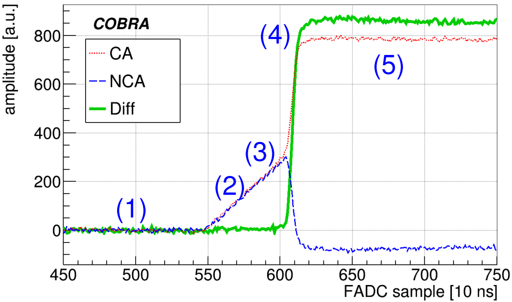
Publication: M. Fritts et al., ***Analytical model for event reconstruction in coplanar grid CdZnTe detectors***, NIM A (2013), 10.1016/j.nima.2013.01.004

Identified background features



- background features identifiable via **interaction depth**
  → cathode surface at $z = 1$, CPG anode at $z = 0$
- Cd-116 region of interest dominated by α-emitting surface contaminations
- strongest signal caused by homogeneously distributed **Cd-113 isotopes**
  → intrinsic non-unique four-fold forbidden β-decay (sensitive to effective g_A)

Single-site character of ββ-decays



General features

(1) pre-baseline before trigger
(2) common initial rise
(drift of charge in BV potential)
(3) splitting point
(charge feels localized GB potential)
(4) charge collection
(electrons collected at CA electrode)
(5) final pulse height
(decreases exponentially)

- difference signal proportional to amount of collected charge
- full trace length of 1024 samples ($\sim$ 10 µs)
- signal of **0νββ-decay** expected to be a **single-site event (SSE)**
  - → point-like energy deposition within a single crystal
  - → veto multi-detector events and multiple energy depositions

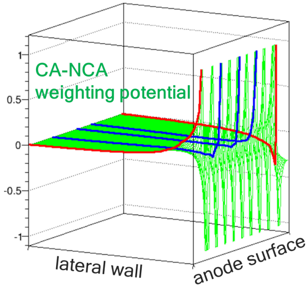
Identification of Lateral Surface Events (LSEs)

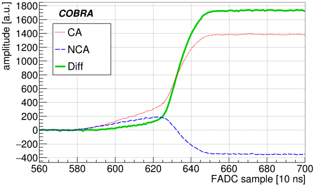
- distortions of **weighting potential** for events near detector walls
- quantified as **early rise** and **dip** of difference pulse

→ characteristically larger for LSEs than for central events

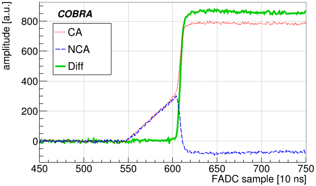
→ combined $\varepsilon^{\text{sig}}_{\text{LSE}}$ tuned to 80%

Publication: **M. Fritts, J. Tebrügge et al., *Pulse-shape discrimination of surface events in CdZnTe detectors for the COBRA experiment*, NIM A (2014), 10.1016/j.nima.2014.02.038**

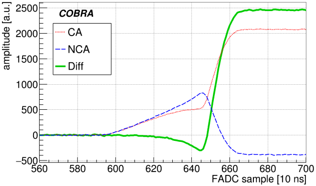




CA-side event

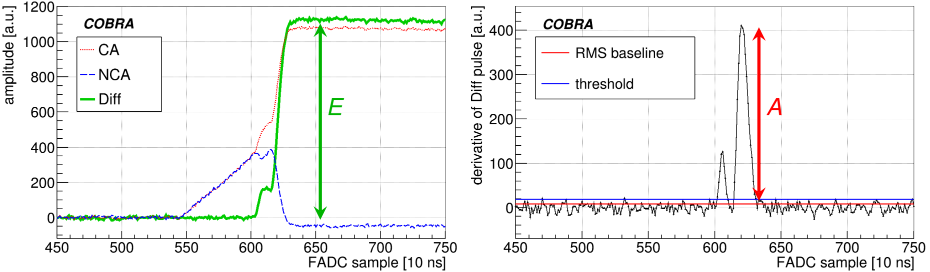


central event



NCA-side event

Identification of Multi-Site Events (MSEs)

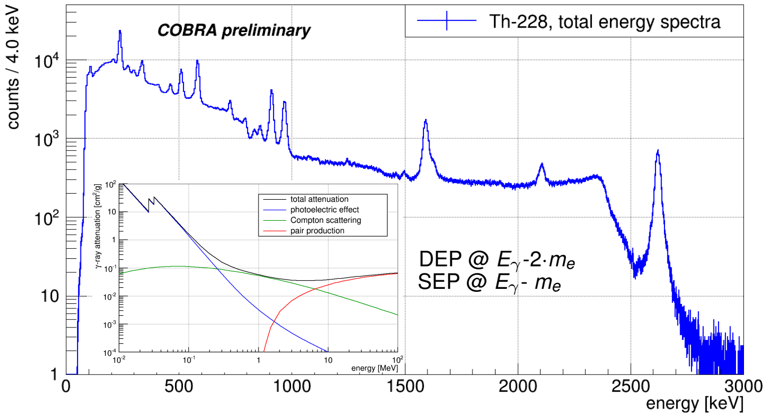


- **plateau feature** in difference signal due to collection of separated charge clouds
- identify MSEs using **derivative of charge pulse** $\longrightarrow$ **current signal**
- two methods are under investigation
  - (1) **peak search (PS)**: multiple peaks for MSE versus single peak for SSE
  - (2) **A/E-criterion**$^{(*)}$: maximum amplitude of current signal divided by energy

$\rightarrow$ reduce background of multiple scattered high-energetic photons

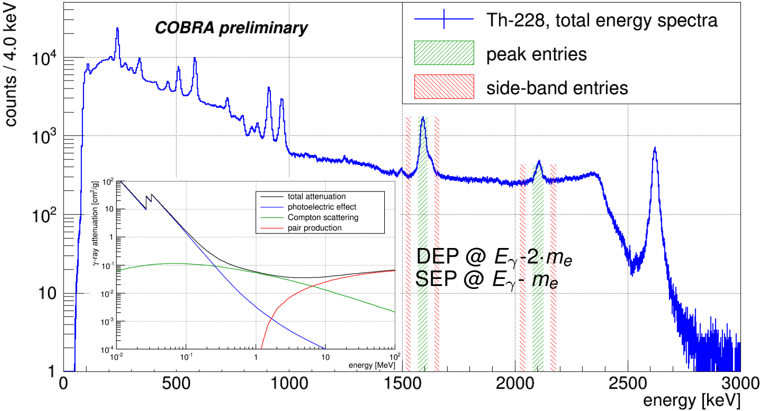
$^{(*)}$ **M. Agostini et al., *Pulse shape discrimination for GERDA Phase I data*, Eur.Phys.J. C73 (2013)**

Optimization with calibration data



- high energetic Th-228 γ-source provides **pair creation** within CZT crystal
  - double-escape peak: both annihilation γ's escape ⟶ SSE
  - single-escape peak: one annihilation γ gets absorbed ⟶ MSE
- event topology can be used to optimize selection algorithms
  → **optimize sensitivity** defined as $s = (n_p\text{-}n_{sb})/\sqrt{n_{sb}}$

Optimization with calibration data



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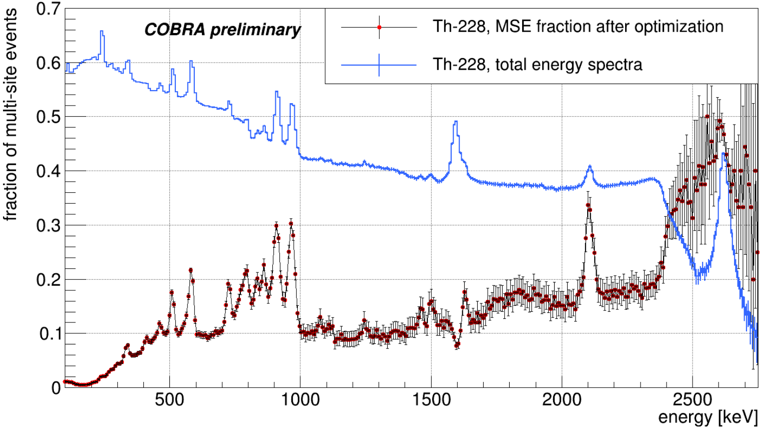
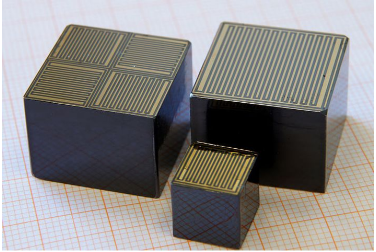
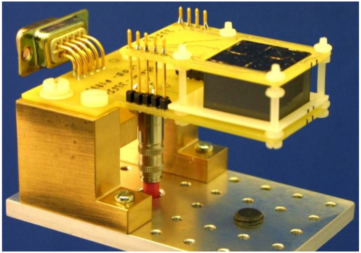
Efficiency estimate for A/E



- increased fraction of MSEs for full energy deposition of γ-lines
- expected **dip for double-escape** and **strong increase for single-escape peak**
  - → signal acceptance: $\varepsilon_{\text{acc}}^{\text{sig}} = (91.1 \pm 1.4)\%$
  - → background rejection: $\varepsilon_{\text{rej}}^{\text{bg}} = (66.3 \pm 4.3)\%$

New detector generation for COBRA XDEM



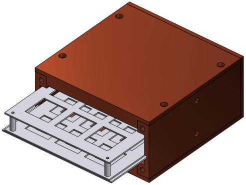


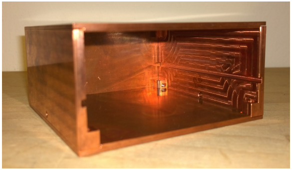
- switch to **larger crystals** $(2.0\times2.0\times1.5)\,\mathrm{cm}^3$ (36 g per detector)
  - higher detection efficiency
  - reduces surface contribution due to smaller surface-to-volume ratio
- concentrate on **quad-CPG** approach – hybrid of CPG and pixel detector
  - improve detector yield, reduce costs
  - possibility of single-sector vetoing
  - improved PSD capabilities

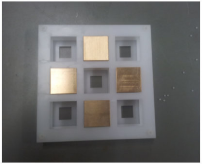
Publication: **J. Ebert et al., *Characterization of a large CdZnTe coplanar quad-grid semiconductor detector*, NIM A (2016), 10.1016/j.nima.2015.09.116**

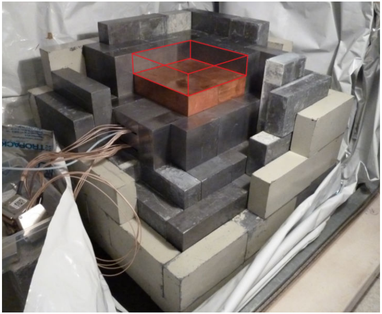
- **DFG funding** to develop detector module consisting of $9\times6\,\mathrm{cm}^3$ CZTs

Status of XDEM implementation





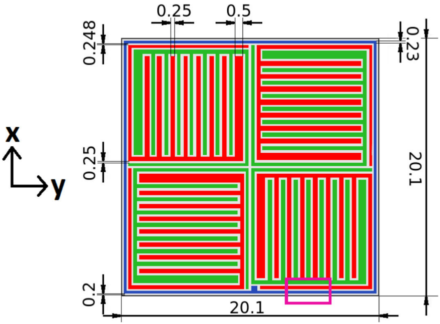


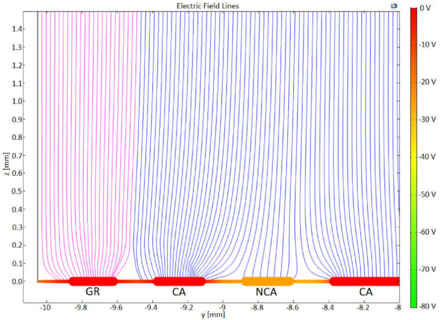


- adapt shielding of existing demonstrator
  - housing: OFHC electro-formed copper stored underground for years
  - cable feedthrough in production: ULA lead ($A < 3$ Bq/kg)
- detector status
  - new crystals arrived in summer (eV Products, Redlen)
  - 5 out of 10 characterized

→ **installation planned for early 2018!**

Instrumentation of guard-ring electrode (GR)

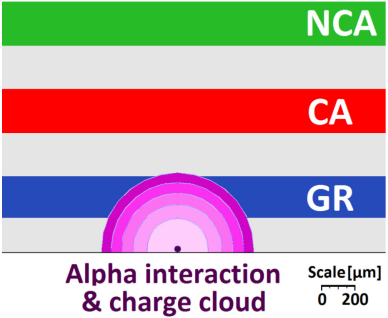




- **idea:** instrument GR as additional collecting anode to veto LSEs
  - electric field simulations using COMSOL multi-physics
  - only small reduction of fiducial volume in simulation ($\sim 0.5\,\mathrm{mm}$)
  - efficiency loss determined to be $\varepsilon_{\mathrm{fid}} = 87.7\%$

Publication: **J.-H. Arling et al.,** ***Suppression of alpha-induced lateral surface events in the COBRA experiment using CdZnTe detectors with an instrumented guard-ring electrode*****, submitted to JINST, pre-print: arXiv:1701.07432v1**

Expected charge cloud dimensions



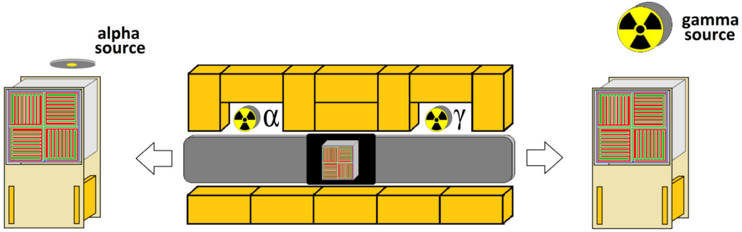
- thermal diffusion
  $\sigma_{\text{diff}}(x) = \sqrt{\frac{2k_B T x}{eE}} \approx 100\,\mu\text{m}$
- mutual repulsion
  $\sigma_{\text{rep}}(x) = \sqrt[3]{\frac{3eNx}{4\pi\varepsilon_0\varepsilon_r E}} \approx 420\,\mu\text{m}$
- combined effect (quadratic sum)
  $\sigma_{\text{max}} \approx 430\,\mu\text{m}$

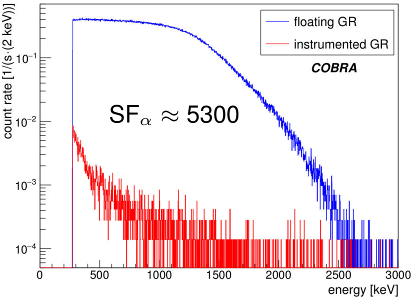
- penetration depth of 5 MeV alpha particle in CZT is around 20 µm
- magenta color code: expansion after drift length of 1, 3, 6, 10 and 15 mm

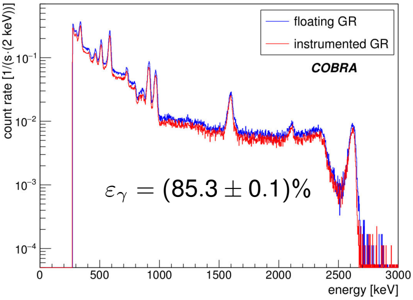
→ **clear separation** of α-induced lateral surface and central events!

Master thesis: J.-H. Arling, ***Characterization of Coplanar Grid CdZnTe Detectors and Instrumentation of the Guardring for the COBRA Experiment***, TU Dortmund (2016)

Background suppression in lab measurements







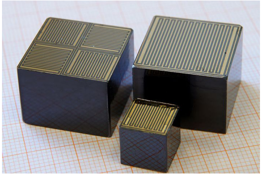
Summary and outlook

Summary

- → COBRA is aiming to search for $0\nu\beta\beta$-decay with CZT detectors
- → long-term operation of $4\times4\times4$ demonstrator array at LNGS
- → identification of background components via PSD
- → α-suppression of more than 10^3 for instrumented GR detectors

Outlook and further activities

- → evaluate A/E criterion in terms of efficiency and background rejection capabilities
- → ongoing analysis of Cd-113 spectral shape to determine effective g_A inside nucleus
- → finish detector characterization and upgrade to COBRA XDEM in early 2018

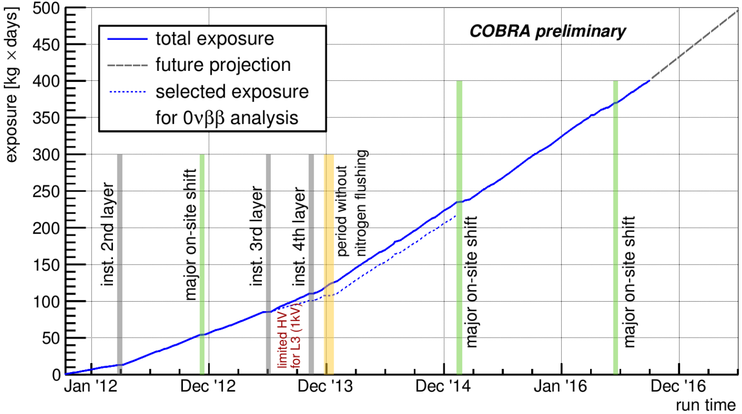


Thank you for your attention!

Backup slides

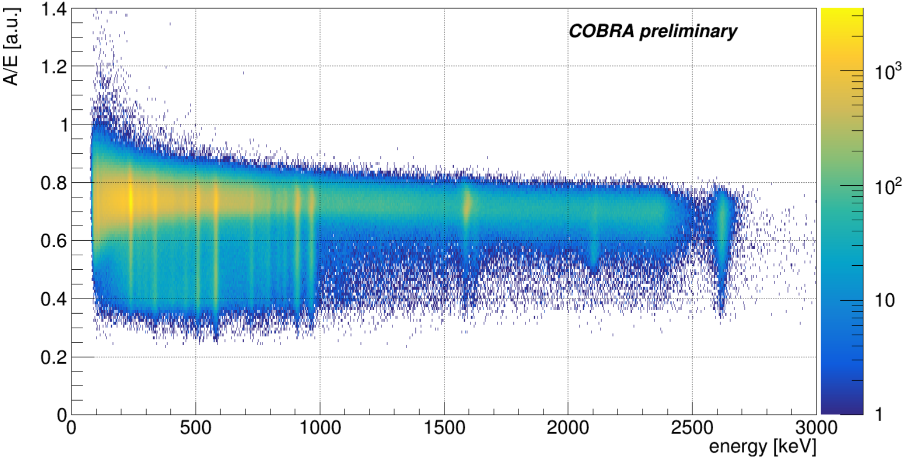
COBRA Collaboration, October 2013

LNGS data-taking and exposure



- complete redesign of experimental environment in Sept. ’11
  - → EMI-box, N_2-flushing, DAQ electronics, pulse-shape sampling, ...
- 64 crystals installed since Nov.’13
- evaluated exposure: 400.1 kg×days (1.1 kg×year)

A/E vs E – energy dependency



- formation of clear single-site band and peak for DEP region
- small energy dependency visible (linear correction possible)

Interplay and prospects of A/E

LSE cut

+ well-established for COBRA
+ rather simple optimization
- limited efficiency (80%)
- also sensitive to multi-site events
- no α-calibration at LNGS

MSE PS cut

+ very robust, self-organized
+ simple result: SSE or MSE
- quite generic definition
- complicated optimization
- peaks have to be well-separated

A/E discrimination

+ combine LSE and MSE cut (only one efficiency)
+ high signal efficiency for DEP found (can be tuned to $>$90%)
+ very flexible and rather easy to implement
- expected to show detector dependence (has to be calibrated)
- not yet tested in details (but very promising results!)

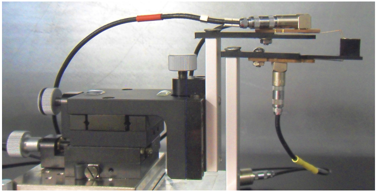
A/E optimization and efficiency estimates

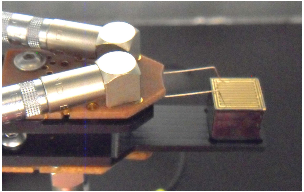
n_{smooth}	A/E	$\varepsilon_{\text{acc}}^{\text{sig}}$	$\varepsilon_{\text{rej}}^{\text{bg}}$	$\varepsilon_{\text{acc}}^{\text{sig}} / \varepsilon_{\text{rej}}^{\text{bg}}$
2	0.34	$(91.2 \pm 1.4)\%$	$(33.5 \pm 3.0)\%$	2.720 ± 0.091
4	0.52	$(91.7 \pm 1.4)\%$	$(60.8 \pm 4.1)\%$	1.509 ± 0.065
6	**0.61**	$\mathbf{(91.1 \pm 1.4)\%}$	$\mathbf{(66.3 \pm 4.3)\%}$	$\mathbf{1.374 \pm 0.063}$
8	0.66	$(90.7 \pm 1.4)\%$	$(65.8 \pm 4.3)\%$	1.378 ± 0.062
12	0.71	$(91.3 \pm 1.4)\%$	$(62.5 \pm 4.1)\%$	1.460 ± 0.063
16	0.74	$(90.3 \pm 1.4)\%$	$(61.6 \pm 4.1)\%$	1.466 ± 0.063
32	0.77	$(95.0 \pm 1.4)\%$	$(41.1 \pm 2.9)\%$	2.315 ± 0.075
PS cut	-	$(92.5 \pm 1.4)\%$	$(63.0 \pm 4.2)\%$	1.468 ± 0.065

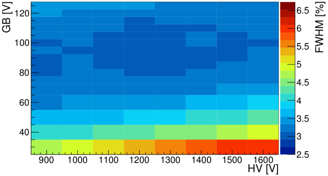
- assume set of A/E cut values in a certain range (based on sensitivity)
- divide data into signal and background $\longrightarrow$ sig and bg spectra
- determine A/E for at least 90% signal acceptance (DEP)
- find optimal smoothing window size for minimal ratio $\varepsilon_{\text{acc}}^{\text{sig}} / \varepsilon_{\text{rej}}^{\text{bg}}$

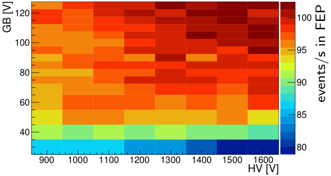
CZT crystal characterization at TUD

- investigated all 64 LNGS detectors to **optimize resolution and efficiency**
  - → contacting via needle probes: removable, contamination-free and reliable
  - → match opening for anodes with mechanical 3d-micromanipulator
- find **optimal working point** by varying HV and GB (analyze $\sim 100\times$Cs-137 spectra)
- localized radiation ($<$1 mm^2) to probe efficiency and crystal homogeneity









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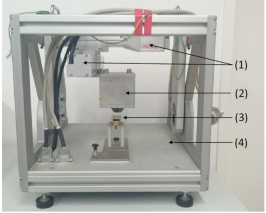
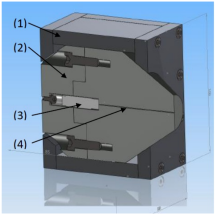
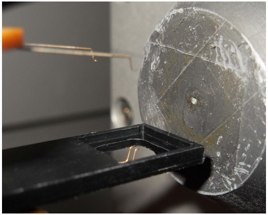
- **localized radiation** (<1 mm^2) to probe efficiency and crystal homogeneity







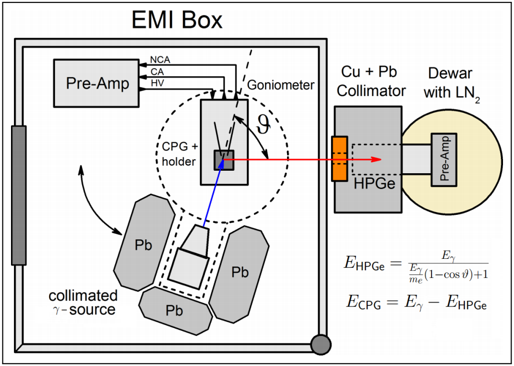
2-dim scan table

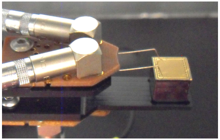
(1) motorized axis
(2) collimated source
(3) CZT detector
(4) rotatable holder

collimated source

(1) aluminum housing
(2) lead shield (4-6 cm thickness)
(3) active Cs-137 sample (LAA type)
(4) collimator channel (d=0.5 mm, l=6 cm)

SSEs via coincident Compton scattering



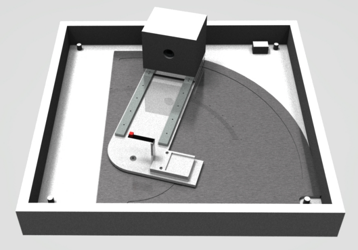


Aim and purpose

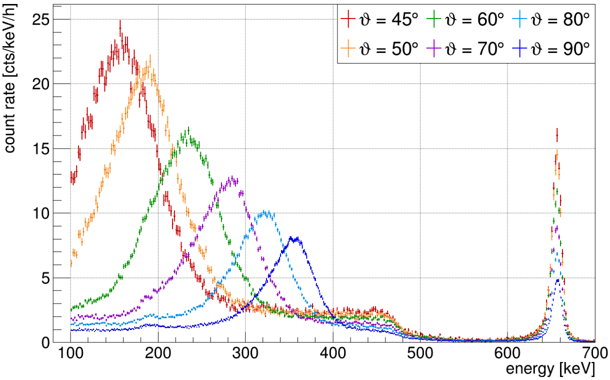
- create **pulse-shape library** of pure single-site events
- investigate SSEs for different energies and depth regions

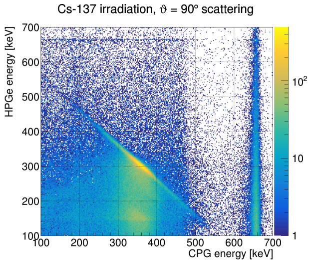
→ **optimize** MSE identification

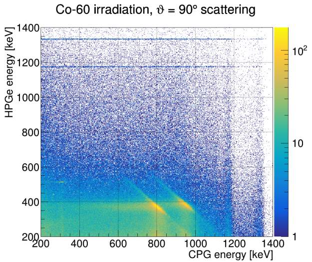
→ estimate reliable **efficiency** of discrimination power



Overview of data-taking

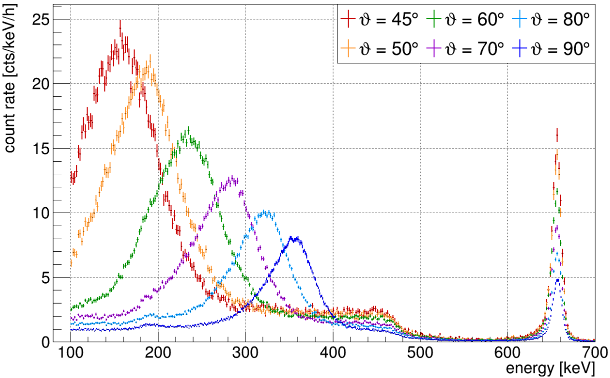


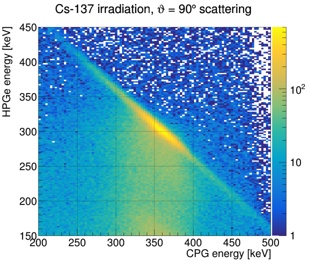


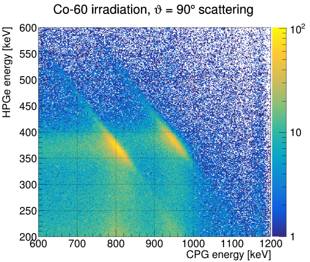


- trigger condition for coincidences: $E_{\text{dep}} > 100\,\text{keV}$
- extract single-site events for matching energy ranges
  - **pulse-shape library** of SSE for different energy ranges
  - efficiency calculation and analysis ongoing

Overview of data-taking







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COBRA limits for 5 $\beta^-\beta^-$ g.s. to g.s. transitions

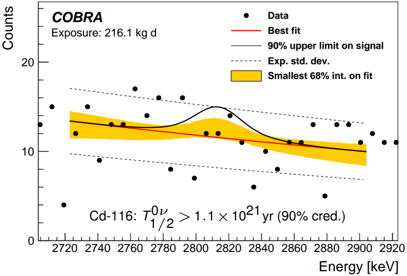
Isotope	Q-value	COBRA'09[1]	COBRA'13[2]	COBRA'15[3]
Cd-114	542.3 keV	2.0×10^{20} yr	1.1×10^{21} yr	1.6×10^{21} yr
Te-128	865.9 keV	1.7×10^{20} yr	1.4×10^{21} yr	1.9×10^{21} yr
Zn-70	998.5 keV	2.2×10^{17} yr	2.6×10^{18} yr	6.8×10^{18} yr
Te-130	2527.0 keV	5.9×10^{20} yr	3.9×10^{21} yr	6.1×10^{21} yr
Cd-116	2813.5 keV	9.4×10^{19} yr	9.2×10^{20} yr	1.1×10^{21} yr

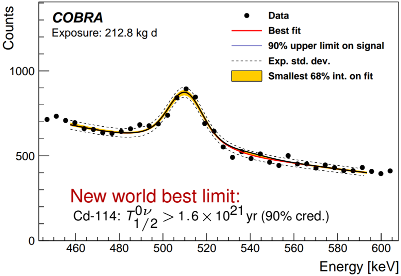
[1] PhysRevC80:025502, 2009; [2] internal FC-analysis of 82 kg d of 2-layer operation; [3] PhysRevC94:024603, 2016;

- switched to Bayesian analysis technique (90% credibility lower limits)
- improved all limits since last publication by at least one order of magnitude
- achieved world best limit for Cd-114

[3] Publication: J. Ebert et al., *Results of a search for neutrinoless double beta-decay using the COBRA demonstrator*, PhysRevC.94:024603, 2016

Fit examples of Bayesian analysis



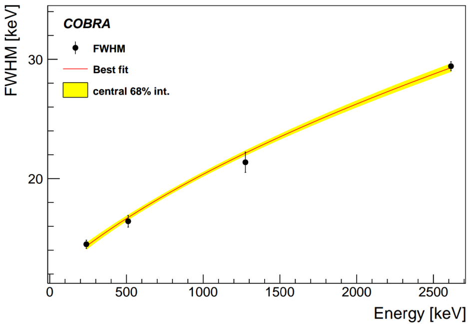


- Bayesian analysis using BAT (Bayesian Analysis Toolkit$^{(*)}$)
  - $\rightarrow$ flat priors, 90% credibility limit, uncertainties incorporated via prior probabilities, average resolution calculated from energy calibrations
- purely data driven (Monte Carlo support only for efficiencies)
- incorporated known background γ-lines

$^{(*)}$ Journal of Physics: Conference Series 219 (2010), doi:10.1088/1742-6596/219/3/032013;

Publication: **J. Ebert et al., *Results of a search for neutrinoless double beta-decay using the COBRA demonstrator*, PhysRevC.94:024603, 2016**

More details of recent 0νββ-analysis



Isotope	ϵ / kg d	ε_{int}	ε_{tot}
Cd-114	212.8	0.96	0.54±0.07
Te-128	216.1	0.92	0.52±0.07
Zn-70	216.1	0.90	0.51±0.07
Te-130	216.1	0.66	0.38±0.05
Cd-116	216.1	0.62	0.37±0.05

ϵ … exposure selected for analysis

ε_{int} … intrinsic efficiency, MC based

ε_{tot} … total efficiency, $\varepsilon_{tot} = \varepsilon_{int} \times \varepsilon_{cuts}$

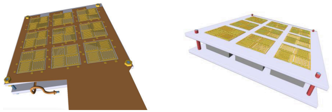
ε_{cuts} … cut efficiency, data based

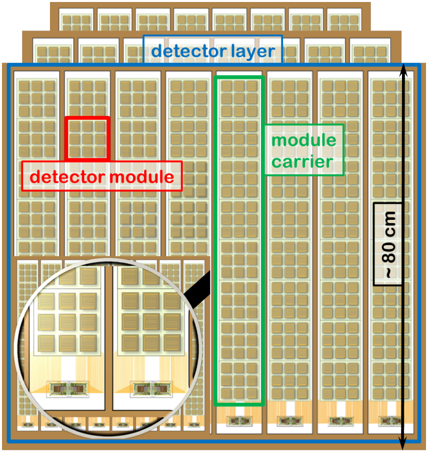
- average resolution fit based on all available calibration measurements
  $\rightarrow \Delta E = 1.1\%$ @ 2.6 MeV
- intrinsic detection efficiency determined with MC simulation
- cut efficiencies determined from calibration data

How to build a large scale experiment?

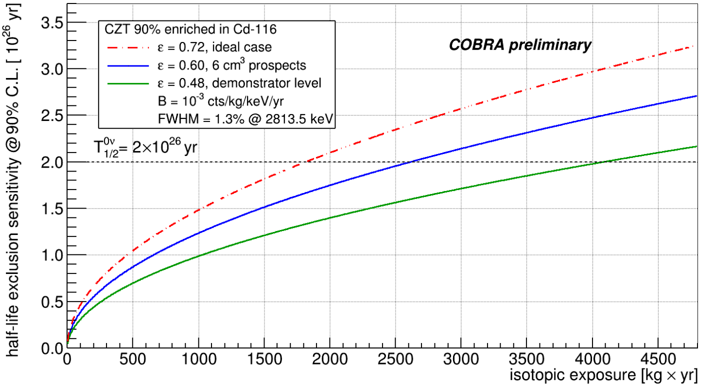
- scalable design as for demonstrator
  → make use of high granularity
- in total 20 layers (11520 units, 415 kg)
  → detector array fits into 1 m^3
- update DAQ electronics
  (ASIC/FPGA, first lab tests performed)
- ongoing MC campaigns
  (shielding, background estimate)
- approved DFG grant
  (German Research Foundation)

→ funding to build *XDEM* detector module with ASIC and FPGA based readout





Projected half-life sensitivity of KING-COBRA



$$T_{1/2}^{\text{exp}} \sim a \cdot \varepsilon \cdot N \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$$

→ a, isotopic abundance (Cd-116, 90% enrichment)

→ $\varepsilon = \varepsilon_{\text{det}} \cdot \varepsilon_{\text{cuts}}$, total efficiency
→ N, number of atoms per kg
→ M, total mass of sensitive detector volume
→ t, experimental lifetime
→ $\Delta E = 2 \times$ FWHM, size of energy window
→ B, background index for ROI
→ aim for **10^{-3} cts/kg/keV/yr**