Neutrinoless Double Beta Decay and COBRA

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Neutrino Physics and the Neutrinoless Double Beta Decay

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- What we don't know about Neutrinos
- Dirac and Majorana Particles
- The Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

What we know about Neutrinos I

- From Z^0 decay: $N_\nu = 2.980 \pm 0.025$
- Flavour eigenstates $\neq$ mass eigenstates, they mix:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} \, |\nu_i\rangle$$

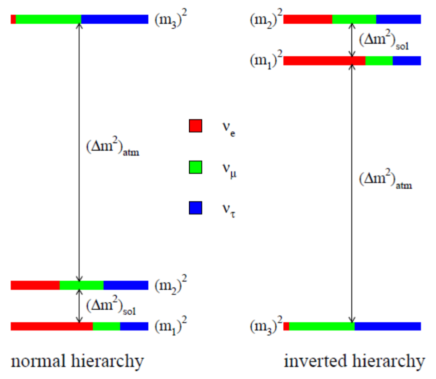
U is called PMNS–Matrix (Pontecorvo, Maki, Nakagawa, Sakata).
Parameters (values from *Schwetz et al., New. J. Phys. 10 (2008) 113011.*):

- $\sin^2(\theta_{12}) = 0.304^{+0.022}_{-0.016}$
- $\sin^2(\theta_{23}) = 0.50^{+0.07}_{-0.06}$
- $\sin^2(\theta_{13}) = 0.01^{+0.016}_{-0.011}$
- 1 CP–violating phase
- 2 additional phases if neutrinos are Majorana particles

What we know about Neutrinos II

From oscillation experiments (*Schwetz et al., New. J. Phys. 10 (2008) 113011.*):

- $\Delta m^2_{21} = \Delta m^2_{sol} = 7.65^{+0.23}_{-0.20} \cdot 10^{-5}\ \mathrm{eV}^2$
- $|\Delta m^2_{31}| = |\Delta m^2_{atm}| = 2.40^{+0.12}_{-0.11} \cdot 10^{-3}\ \mathrm{eV}^2$



What we don't know

Open questions:

- What is the nature of neutrinos (Dirac vs. Majorana)?
- Is the charge/parity (CP) symmetry broken?
- What are the precise values of neutrino masses and mixing?
- Are there sterile neutrinos? Is the standard picture right?

A wide experimental program is going to address these questions in the future.

What we don't know

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$0\nu\beta\beta$ experiments

- are the only known way to distinguish between Dirac and Majorana neutrinos
- can determine the absolute neutrino mass

Dirac Particles

In quantum field theory:
Spin-1/2 particles are described by four–component spinors which obey the Dirac equation.

The four independent components correspond to:

- Particles with Helicity ± 1
- Antiparticles with Helicity ± 1

All charged leptons (e, μ, τ) have to be Dirac particles.

Majorana Particles

Experimental fact:
Only left–handed neutrinos (H = -1) and right–handed antineutrinos (H = +1) are observed.

If neutrinos are Dirac particles:

- Two states are not realised in nature or are sterile

A two–component description should be sufficient (Weyl spinors).

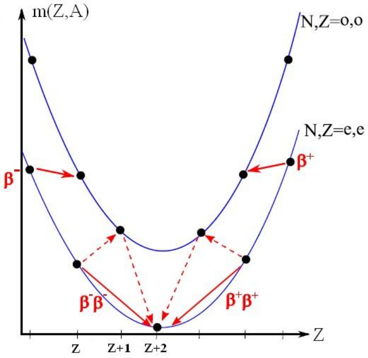
If neutrinos are Majorana particles:

- Particles = Antiparticles ($\nu_L = \overline{\nu}_L$, $\nu_R = \overline{\nu}_R$)
- Neutrinos don't carry a lepton number

Double Beta Decay

Goeppert–Mayer (1935):

- $(Z, A) \rightarrow (Z+2, A) + 2e^{-} + 2\overline{\nu}_e$
- Simultaneous decay of two neutrons



Requirements:

- Nucleus with even A: Separation of $m(Z, A)$ in 2 parabolas
- $m(Z, A) > m(Z+2, A)$
- $m(Z, A) < m(Z+1, A)$ (single β decay forbidden)

Double Beta Decay

36 $2\beta^-$ isotopes are known today.

Furthermore possible:

- $\beta^+\beta^+$: $(Z,A) \rightarrow (Z-2,A) + 2e^+ + 2\nu_e$ (6 isotopes)
- $\beta^+ + \mathrm{EC}$: $(Z,A) + e^- \rightarrow (Z-2,A) + e^+ + 2\nu_e$
- EC/EC: $(Z,A) + 2e^- \rightarrow (Z-2,A) + 2\nu_e$

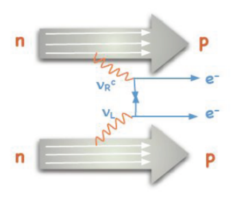
Definition *Q value*:

- Decay energy available for the leptons
- $Q = E_{e1} + E_{e2} + E_{\nu 1} + E_{\nu 2}$

$0\nu\beta\beta$ Decay

Furry (1939):

- $(Z, A) \rightarrow (Z+2, A) + 2e^-$



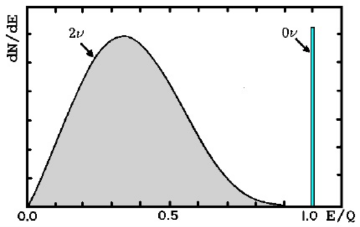
Racah sequence:

- $(Z, A) \rightarrow (Z+1, A) + e^- + \overline{\nu}_{e,R}$
  $(Z+1, A) + \nu_{e,L} \rightarrow (Z+2, A) + e^-$

Helicity flip is required: Suppression of $0\nu\beta\beta$ by $\sim 10^{-5}$

0νββ Decay

Experimental confirmation:
Peak at the Q value of the decay
$Q = E_{e1} + E_{e2}$



Determination of neutrino mass from 0νββ:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \overbrace{G^{0\nu}(Q,Z)}^{\text{phase space factor}} \cdot \underbrace{\left|M_{GT}^{0\nu} - M_{F}^{0\nu}\right|^2}_{\text{nuclear matrix element}} \cdot \frac{\overbrace{\langle m_{\nu_e}\rangle^2}^{\text{effective Majorana neutrino mass}}}{m_e^2}$$

$$\langle m_{\nu_e}\rangle = \left|\sum_i U_{ei}^2 m_i\right| \neq m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

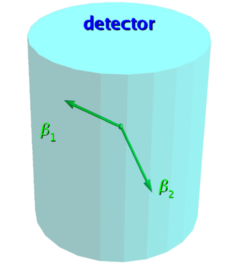
Experimental Considerations

- General Concepts and Detection Limit
- Background Reduction
- The Favourite Isotopes

General Detector Concepts

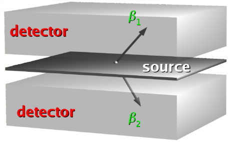
Source = detector:

- − Constraints on material selection
- + Big masses achievable
- + High energy resolution
- + For some isotopes reconstruction of event topology possible (LXe)



Source ≠ detector:

- + Precise reconstruction of event topology
- + Analysis of different isotopes
- − Big masses problematic



Detection Limit

Without background: $T_{1/2}^{limit} \propto a \cdot \epsilon \cdot M \cdot t$

a	...	abundance
ϵ	...	detection efficiency
M	...	mass
t	...	measuring time

Detection Limit

Without background: $T_{1/2}^{limit} \propto a \cdot \epsilon \cdot M \cdot t$

With background: $T_{1/2}^{limit} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{\Delta E \cdot B}}$

a	...	abundance
ϵ	...	detection efficiency
M	...	mass
t	...	measuring time
ΔE	...	energy resolution
B	...	background event rate

Background

Benchmark for all future experiments:
Background $< 10^{-3}$ counts /kg/keV/yr

For an experiment with $M = 1$ ton: 1 count/yr at $Q \pm 0.5$ keV

Background

Benchmark for all future experiments:
Background $< 10^{-3}$ counts /kg/keV/yr

For an experiment with $M = 1$ ton: 1 count/yr at Q ± 0.5 keV

Main contributions to background:

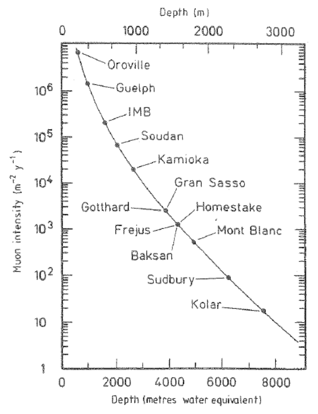
Cosmic rays/muons → underground laboratory
Cosmogenic radioisotopes → underground laboratory
Neutrons → shielding
Radioisotopes ^{238}U, ^{232}Th, ^{40}K → shielding + clean environment
$2\nu\beta\beta$ → high energy resolution

Underground Laboratories

Rock–shielding decreases μ–flux and hence cosmogenic radioisotopes

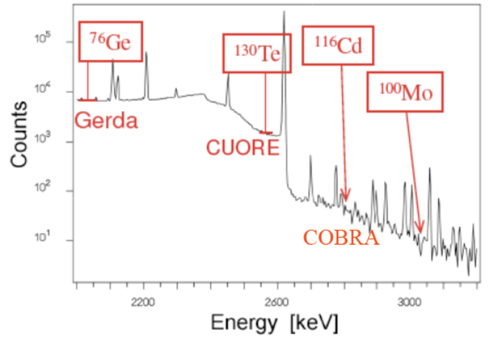
Laboratori **N**azionali del **G**ran **S**asso:

- World largest underground laboratories for particle physics
- e.g. OPERA, BOREXINO, DAMA, CRESST
- $0\nu\beta\beta$: Heidelberg–Moscow, GERDA, COBRA, CUORE



Radioisotopes

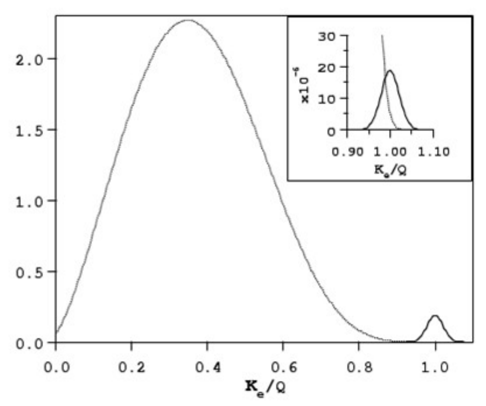
Highest γ–peak from ^{232}Th: 2614 keV



Significant decrease of γ–background with $Q > 2614$ keV

Energy Resolution

Good energy resolution helps to separate 0νββ–peak from 2νββ–background



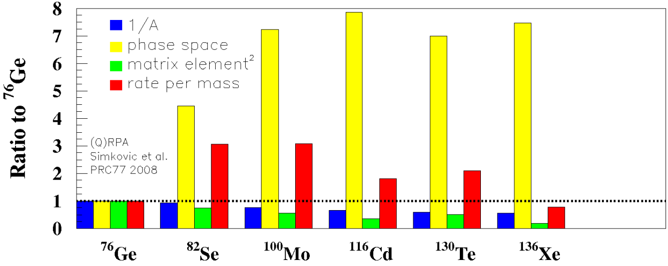
Half–life

For a given $\langle m_{\nu_e} \rangle$ the expected half–life can be calculated:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z) \cdot \left| M_{GT}^{0\nu} - M_{F}^{0\nu} \right|^2 \cdot \frac{\langle m_{\nu_e} \rangle^2}{m_e^2}$$

- Phase space factor $G^{0\nu}(Q,Z)$
  - precise calculation possible
- Nuclear matrix element $\left| M_{GT}^{0\nu} - M_{F}^{0\nu} \right|$
  - calculations are not precise and model–dependent
  - → different isotopes have to be investigated

Combination of Matrix Elements and Phase Space



Expected $0\nu\beta\beta$ rates per mass vary with a factor ≈ 4.

Favoured Isotopes

Requirements for an experiment:

- High detection limit of the detector
- Low calculated half–life of the isotope

36 $2\beta^-$ isotopes are known today, but only 9 are considered for $0\nu\beta\beta$ experiments:

			nat. abundance	Q [keV]
^{48}Ca	→	^{48}Ti	0.19 %	4271
^{150}Nd	→	^{150}Sm	5.6 %	3367
^{100}Mo	→	^{100}Ru	9.6 %	3034
^{82}Se	→	^{82}Kr	9.2 %	2995
^{116}Cd	→	^{116}Sn	7.5 %	2809
^{130}Te	→	^{130}Xe	33.8 %	2529
^{136}Xe	→	^{136}Ba	8.9 %	2479
^{124}Sn	→	^{124}Te	5.6 %	2288
^{76}Ge	→	^{76}Se	7.8 %	2039

Experiments in Past, Presence and Future

- The Heidelberg–Moscow Experiment
- Overview on Upcoming Experiments
- The GERDA Experiment

Heidelberg–Moscow Overview

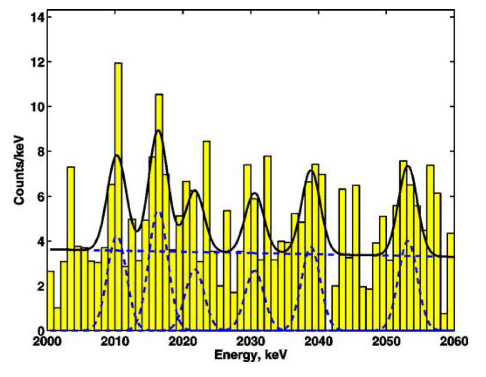
- Five p–doped HPGe semiconductor detectors
- 10.96 kg active mass
- ^{76}Ge enriched to 86%

- 1986: Proposal for this experiment by Prof. Klapdor-Kleingrothaus (Uni Heidelberg)
- 1990: Installation of first detector at LNGS (Central Italy)
- 1995: Completion of the experimental setup
- 2001: Exit of Kurchatov Institute
- 2003: End of data taking

Setup Heidelberg–Moscow

Results $0\nu\beta\beta$ 2004

H.V. Klapdor-Kleingrothaus et al, Phys.Lett.B586:198-212,2004



Results 0νββ 2004

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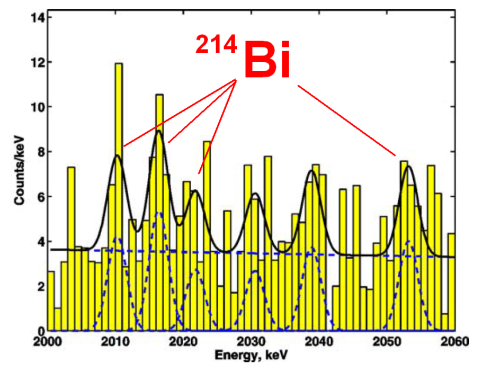

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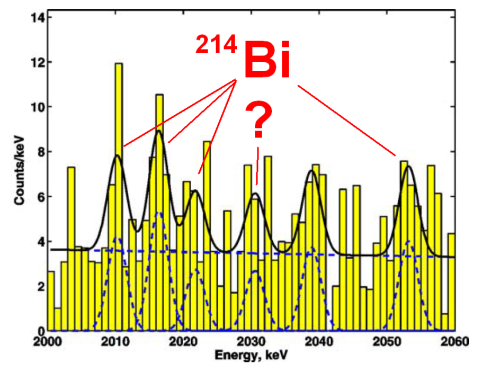

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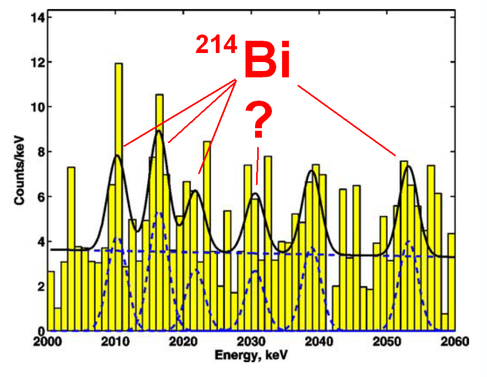
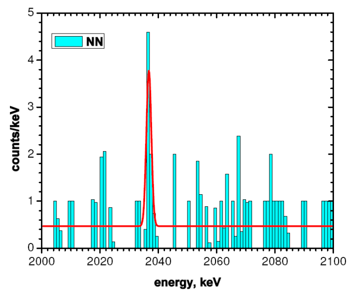


Claim of $4.2\,\sigma$ evidence for a peak at 2038.07 keV
$\rightarrow T^{0\nu}_{1/2} = 1.2 \cdot 10^{25}\,\text{yr} \rightarrow \langle m_{\nu_e} \rangle = 0.44\,\text{eV}$

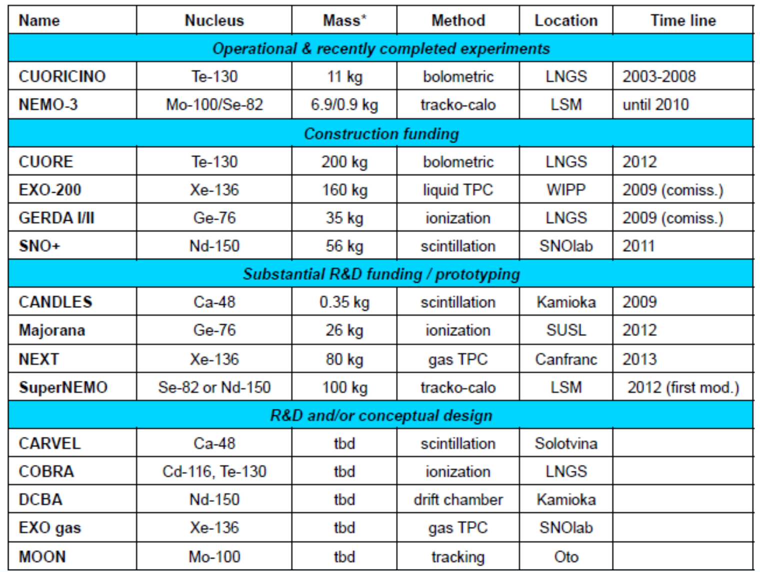
Results 0νββ 2006

H.V. Klapdor-Kleingrothaus et al, Mod.Phys.Lett.A21:1547-1566,2006



- New results with neural network and pulse shape analysis
- Claim of 6.4 σ evidence for a peak at $\sim$2039 keV
- Results are controversially discussed
- This claim has to be confirmed with other ^{76}Ge experiments

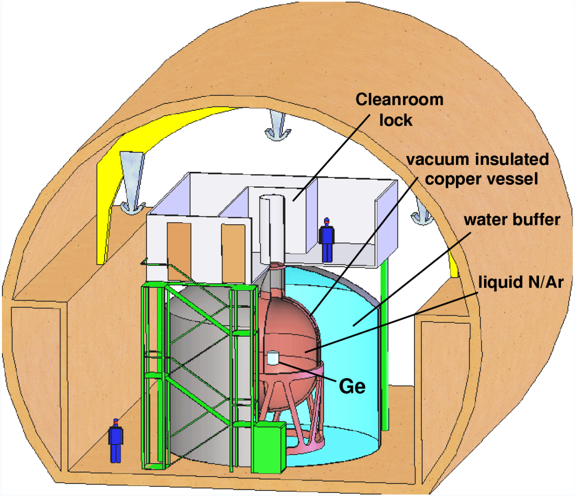
Future Experiments



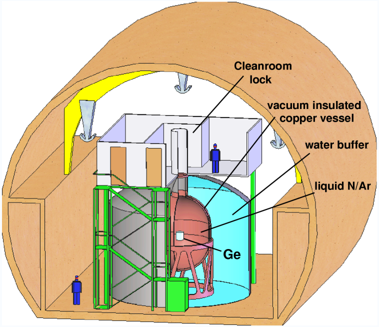
Name	Nucleus	Mass*	Method	Location	Time line
Operational & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2009 (comiss.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (comiss.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48	tbd	scintillation	Solotvina	
COBRA	Cd-116, Te-130	tbd	ionization	LNGS	
DCBA	Nd-150	tbd	drift chamber	Kamioka	
EXO gas	Xe-136	tbd	gas TPC	SNOlab	
MOON	Mo-100	tbd	tracking	Oto	

GERDA

GERmanium **D**etector **A**rray



GERDA



- 2 m / 64 m^3 liquid Ar as inner shielding and for cooling
- 3 m / 650 m^3 high–purity water: Shielding against neutrons and μ–veto (Water–Cherenkov–Detector)
- Clean room for preparation of detectors without contamination

Phases

Phase I

- 15 kg ^{Nat}Ge detectors - background evaluation
- 18 kg ^{76}Ge detectors - from Heidelberg–Moscow and IGEX
- Proof of Hd–M (2004) results within 1 year of data taking
- Expected: 6 events with 0.5 background events → $5\,\sigma$

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- Expected: 6 events with 0.5 background events → 5 σ

Phase II (simultaneous to Phase I)

- Development of new detectors
- Background reduction by 3 orders of magnitude
- Within 3 years of data taking:
    - Limit on $T^{0\nu}_{1/2} : 2 \cdot 10^{26}$ yr
    - $0.09\,\text{eV} < \langle m_{\nu_e} \rangle < 0.29\,\text{eV}$

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Phase III

- ~ 1 ton ^{76}Ge (together with MAJORANA)
- $\langle m_{\nu_e} \rangle \sim 10\,\text{meV}$

The COBRA Experiment

- The COBRA Collaboration
- Detector Concepts under Investigation
- CdZnTe Semiconductors in Liquid Scintillator

The COBRA Collaboration

TU Dortmund

TU Dresden

Freiburger Materialforschungszentrum

Universität Hamburg

Universität Erlangen

Tschechische TU Prag

Laboratori Nazionali del Gran Sasso

Washington University at St. Louis

Universität Bratislava

Universität Jyvaskyla

Universität La Plata

JINR Dubna

Kooperationen: Jagiellonen-Universität (Polen), Los Alamos Nat. Lab. (USA), University of Michigan (USA)

Isotopes

Cadmium–Zinc–Telluride **O**–neutrino double–**B**eta **R**esearch **A**pparatus

CdZnTe semiconductor detectors contain 9 ββ–isotopes:

Isotope	decay mode	Q (keV)	nat. abundance
^{70}Zn	$2\beta^-$	1001	0.62 %
^{114}Cd	$2\beta^-$	534	28.7 %
^{116}**Cd**	$2\beta^-$	2809	7.5 %
^{128}Te	$2\beta^-$	868	31.7 %
^{130}**Te**	$2\beta^-$	2529	33.8 %
^{106}**Cd**	$2\beta^+$	2771	1.21 %
^{64}Zn	β^+/EC	1096	48.6 %
^{120}Te	β^+/EC	1722	0.1 %
^{108}Cd	EC/EC	231	0.9 %

Advantages of CdZnTe

- Source = detector (large mass)
- Semiconductor (good energy resolution, clean)
- Room temperature, no cryostat needed
- Modular design (coincidences)
- Tracking („Solid state TPC“)
- Industrial development of CdZnTe detectors
- Two isotopes at once
- ^{116}Cd above 2614 keV

COBRA Concept

Aim:

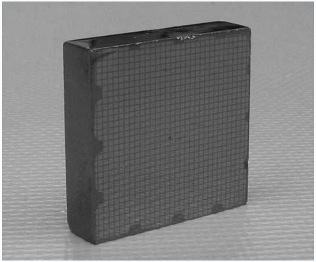
- Large–scale experiment with $M = 420\,\mathrm{kg}$
- Main isotope: ^{116}Cd enriched to $\sim 90\,\%$
- Technical Design Report by end of 2012

Two detector concepts under investigation:

Coplanar grid detectors

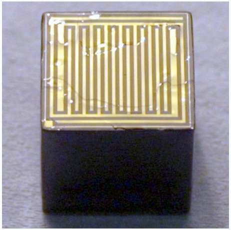
Energy measurement only

Pixel detectors



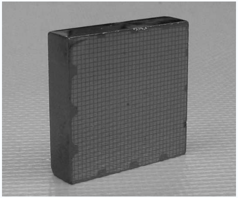
Energy measurement and tracking

Coplanar Grid Detectors (CPG)



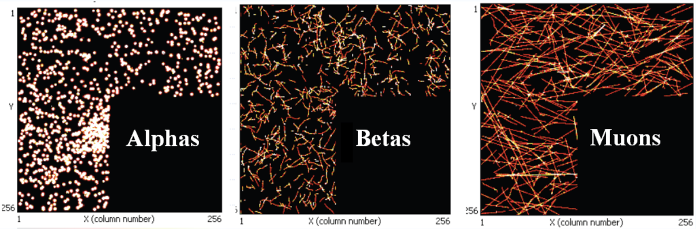
- Readout of two anodes to compensate signals from the holes (Trapping)
- CPGs are currently used in our test setup at LNGS
- Quite large volumes available (from $1\,\mathrm{cm}^3$ to $2\,\mathrm{cm}^3$)
- Only few readout channels per mass
- Energy resolution around 2 % FWHM at 2800 keV

Pixel Detectors



- Particle identification: Background reduction by $\approx 10^{-3}$

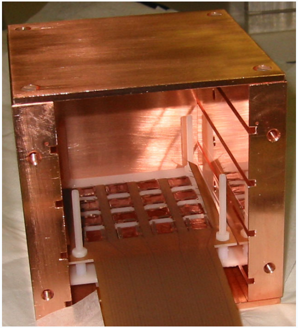
Real data with Si–Timepix (256x256 pixels):

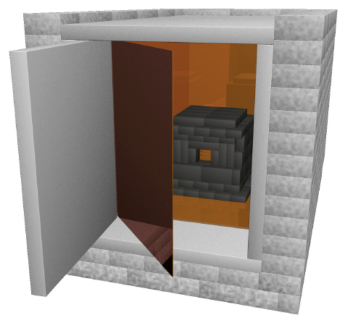


Test Setup at LNGS

Upgrade summer 2010:

- 64 CPGs (4 × 4 × 4)
- Installation of Flash–ADCs
- New HV and LV





Contribution of Uni Hamburg

- Shielding of large scale experiment
  - Monte Carlo studies
  - Design of alternative shielding concepts
  - Construction of prototypes and material selection
- Analysis of data from LNGS test setup
- Operation of CdZnTe in liquid scintillator

CdZnTe in LSc: Motivation

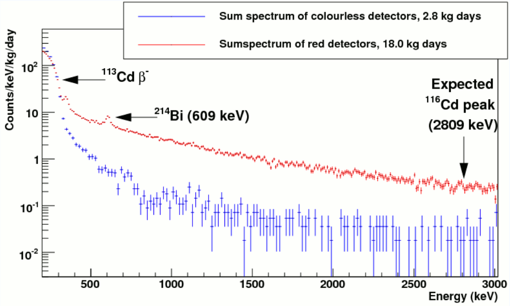
CPGs need passivation:

- to prevent CdZnTe from oxidation
- to avoid mechanical damage to the detector and the anodes

Passivations used so far:

- Red lacquer (EI Detection & Imaging Systems)
- Transparent lacquer (EI Detection & Imaging Systems)
- Cyclotene (Dow Chemicals)

CdZnTe in LSc: Motivation



Passivations used so far:

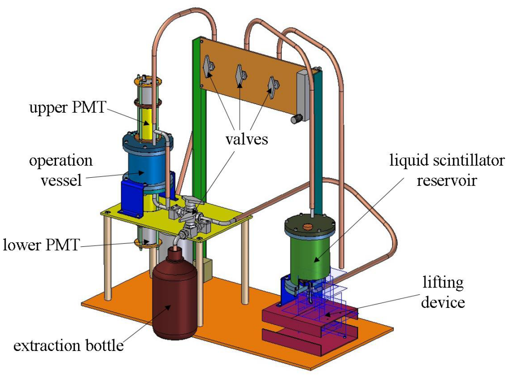
- Red lacquer (EI Detection & Imaging Systems)
- Transparent lacquer (EI Detection & Imaging Systems)
- Cyclotene (Dow Chemicals)

Passivation with Liquid Scintillator

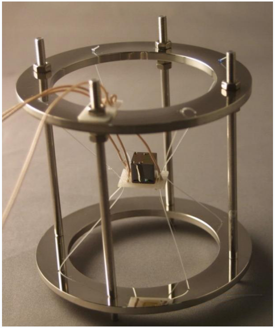
Advantages of LSc:

- High impedance → good isolator
- Offers possibility to control temperature stability
- Serves as active veto
- High purity with regard to radioactive nuclides
  → e.g. BOREXINO or KamLAND

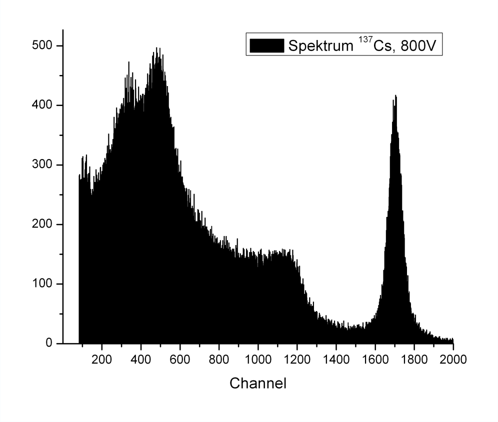
Experimental Setup



1 cm^3 CdZnTe, not passivated:

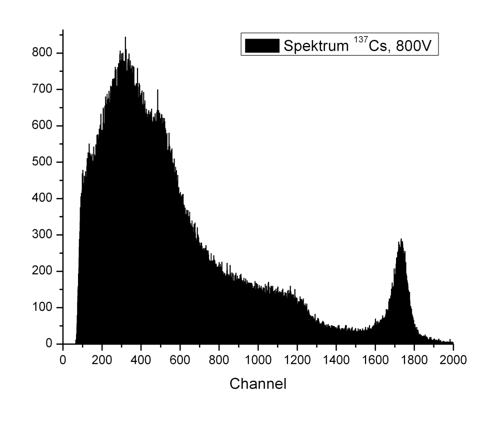


^{137}Cs in Nitrogen



Energy resolution: 5.0% FWHM @ 662 keV

^{137}Cs in Liquid Scintillator



Energy resolution: 5.1% FWHM @ 662 keV

First Results and Outlook

- CdZnTe detectors are operational in LSc with constant energy resolution

- Check for long term stability
- Investigation of different LSc mixtures
- Use LSc as active veto
- Upgrade of test setup to 8 detectors
- Operation of test setup in underground lab (Dresden or LNGS)

Summary

- $0\nu\beta\beta$ experiments are the only known way to distinguish between Dirac and Majorana neutrinos
- Claim of $0\nu\beta\beta$ discovery has to be confirmed
- Huge efforts are made for many different experiments
- COBRA can be the major and unique step beyond existing double beta experiments
- Operation of CdZnTe in liquid scintillator is an important contribution to the COBRA R&D programme

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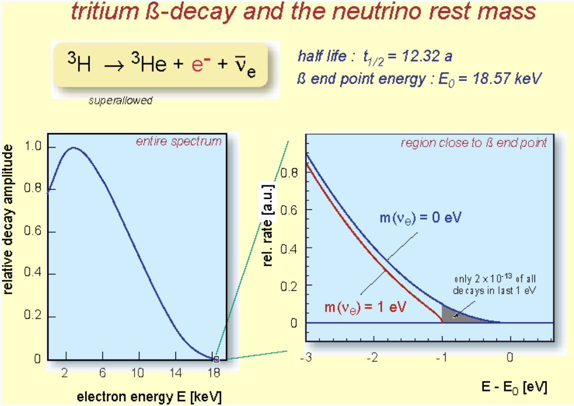
Thank you for your attention!

The β–decay and KATRIN

β^- decay of the neutron

- $n \longrightarrow p + e^- + \overline{\nu}_e$
- $(Z, A) \longrightarrow (Z+1, A) + e^- + \overline{\nu}_e$
- e.g. KATRIN:



tritium ß-decay and the neutrino rest mass

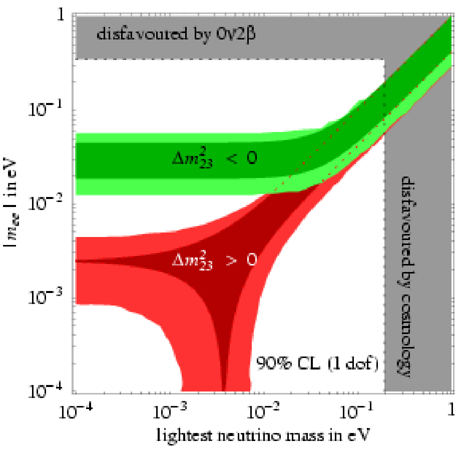
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

superallowed

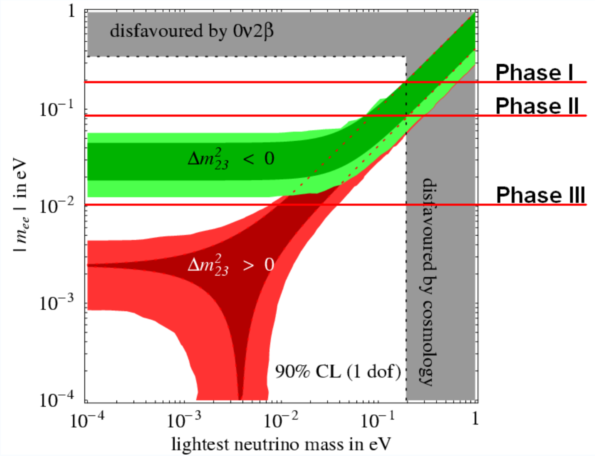
half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV

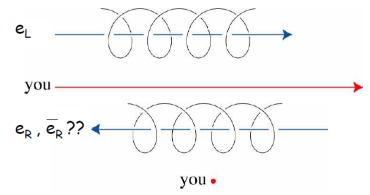
Effective Neutrino Mass



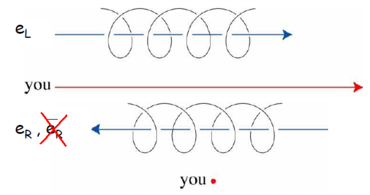
Effective Neutrino Mass and GERDA

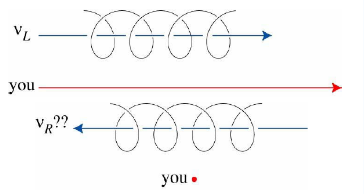


Dirac vs. Majorana



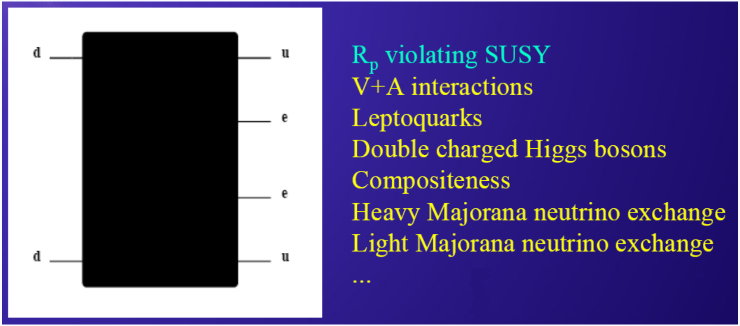
Dirac vs. Majorana





Other possible Mechanism

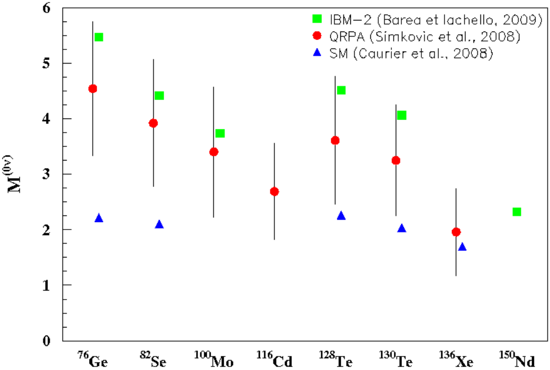
Further processes with $\Delta L = 2$ that could contribute to 0νββ:



R_p violating SUSY
V+A interactions
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
…

Schechter and Valle, 1982:
Observation of 0νββ decay ≡ neutrinos are Majorana particles!

Matrix Elements



Exact values of $\left|M_{GT}^{0\nu} - M_F^{0\nu}\right|^2$ still not known.

Natural Abundance

Enrichment of isotopes is very expensive

^{48}Ca	→	^{48}Ti	0.2%
^{76}Ge	→	^{76}Se	7.8%
^{82}Se	→	^{82}Kr	9.2%
^{100}Mo	→	^{100}Ru	9.6%
^{116}Cd	→	^{116}Sn	7.5%
^{124}Sn	→	^{124}Te	5.6%
^{130}Te	→	^{130}Xe	34.5%
^{136}Xe	→	^{136}Ba	8.9%
^{150}Nd	→	^{150}Sm	5.6%