Double Beta Decay Experiments

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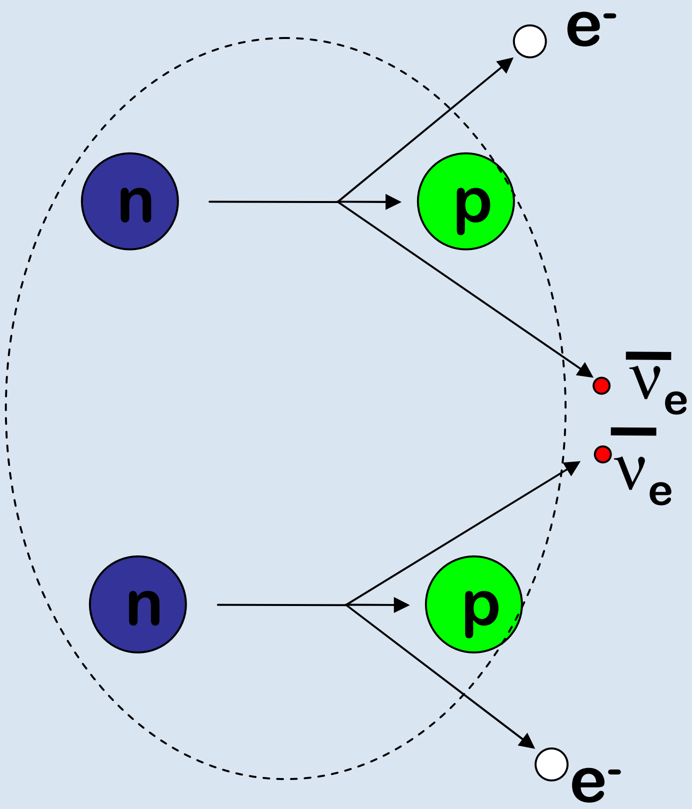
29/06/05, RAL

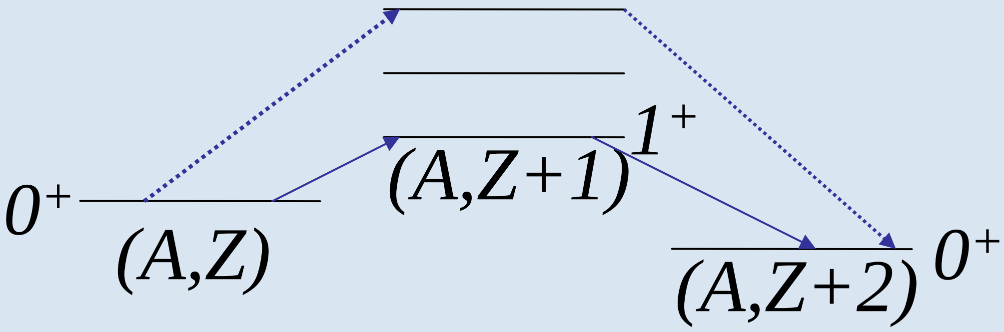
Contents

- What is double beta decay and what can it tell us?
- Experimental requirements
- Experimental status
- A closer look at a selection of experiments

Double Beta Decay ($2\nu\beta\beta$)

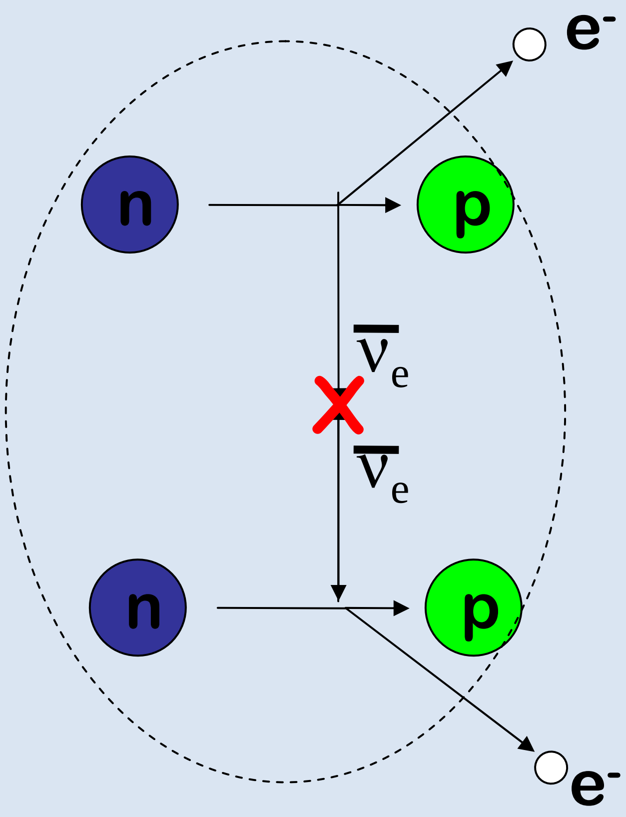


$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$



Only 35 isotopes known in nature

Neutrinoless mode ($0\nu\beta\beta$)



$$\Delta L = 2$$

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

What Can We Learn?

- Dirac or Majorana?

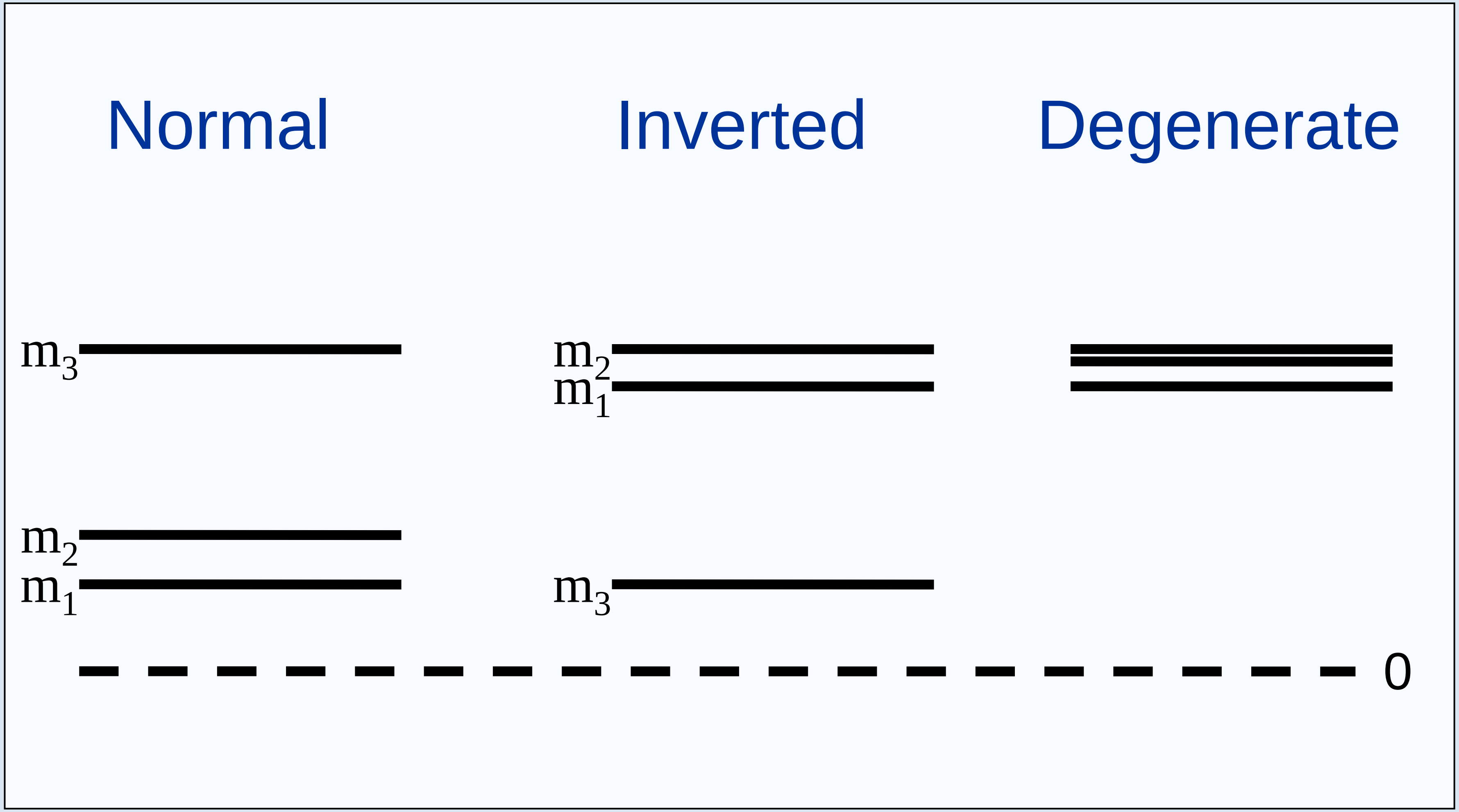
$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\downarrow \\ \bar{\nu}_\uparrow \end{pmatrix} \quad \textbf{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

- Absolute Mass Scale

$$\Gamma_{0\nu} = (T_{1/2})^{-1} = \underbrace{G_{0\nu}}_{\text{Phase space factor}} |\underbrace{M_{0\nu}}_{\text{Nuclear Matrix element}}|^2 m_\nu^2$$

- Mass Hierarchy?

Mass Hierarchy



What Can We Learn?

- Dirac or Majorana?
- Absolute Mass Scale
- Mass hierarchy?
- CP violation?
- Matter-Antimatter Asymmetry

CP Violation?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow \frac{m_i^{\ 2}}{2E_\nu} \Rightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta_1} & 0 \\ 0 & 0 & e^{i\beta_2} \end{pmatrix}$$

Solar

Atmospheric

If sin $\theta_{13} \neq 0 \rightarrow$ CP-violation

Majorana : U= U_{PMNS} diag(1,$e^{i\beta 1}$,$e^{i\beta 2}$)

The Neutrino Mass

$$\langle m_\nu \rangle \equiv m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k \left| U_{ek} \right|^2 e^{i\alpha_{ek}} m_k \right|$$

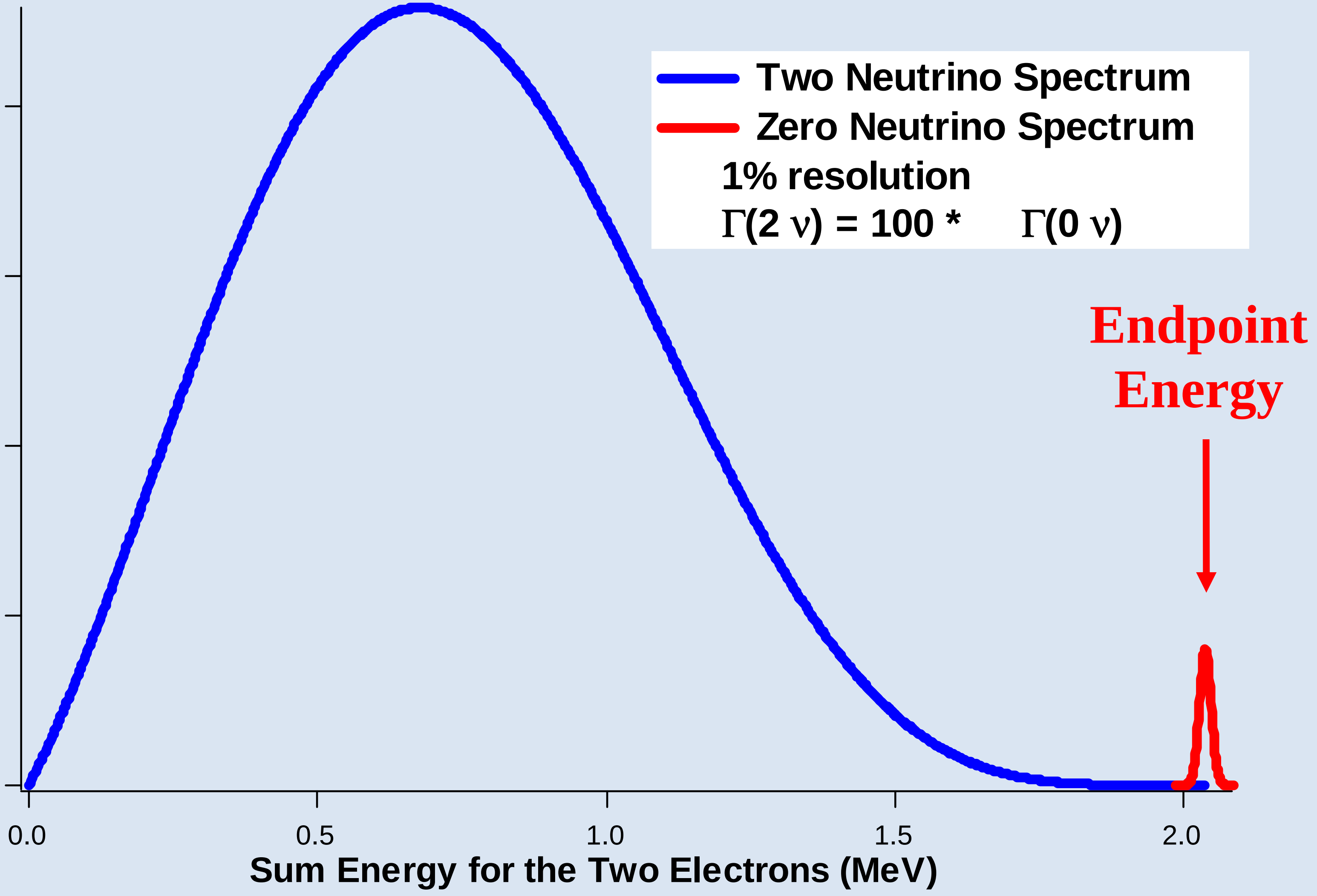
$$m_{ee} = U_{e1}{}^2 m_1 \pm U_{e2}{}^2 m_2 \pm U_{e3}{}^2 m_3$$

relative CP phases = ±1

$$m_e = \Sigma \, |U_{ek}|^2 \, m_k$$

Experimental Requirements

ββ Decay

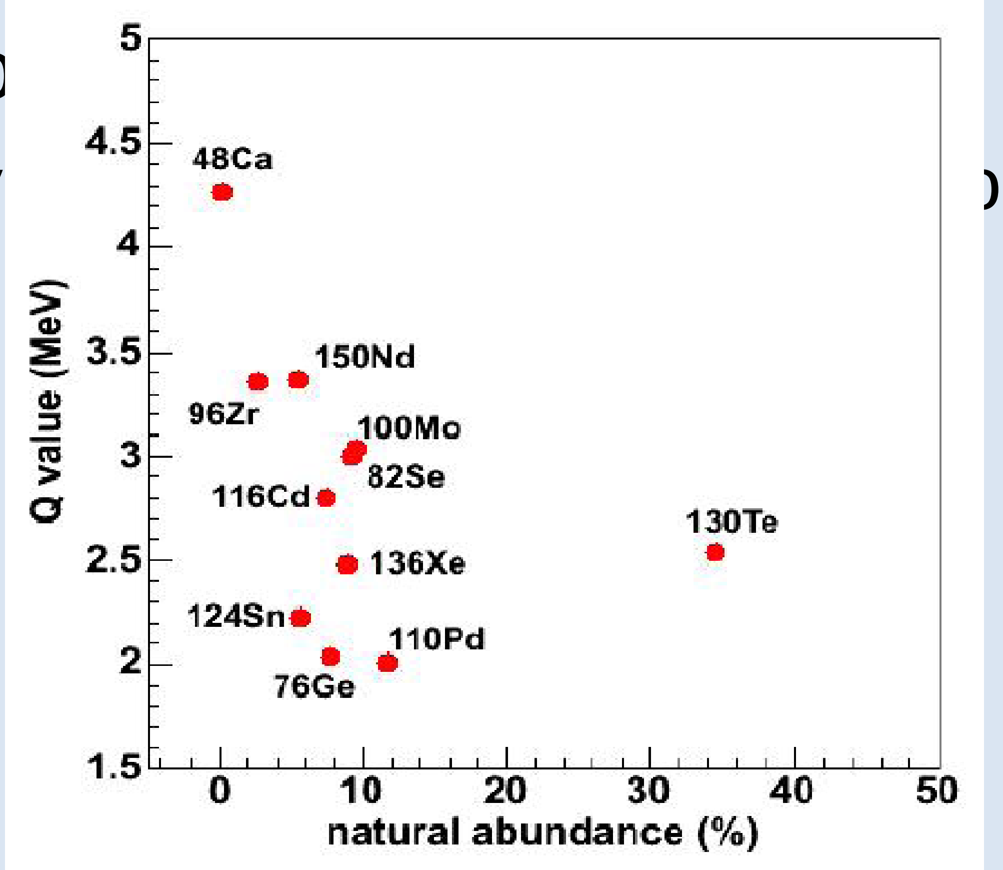

Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2 ν) = 100 * Γ(0 ν)
Endpoint Energy
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)

Requirements for 0νββ Searches

- High Q value
- High Isotopic Abundance
- Backgro
  - Ideally

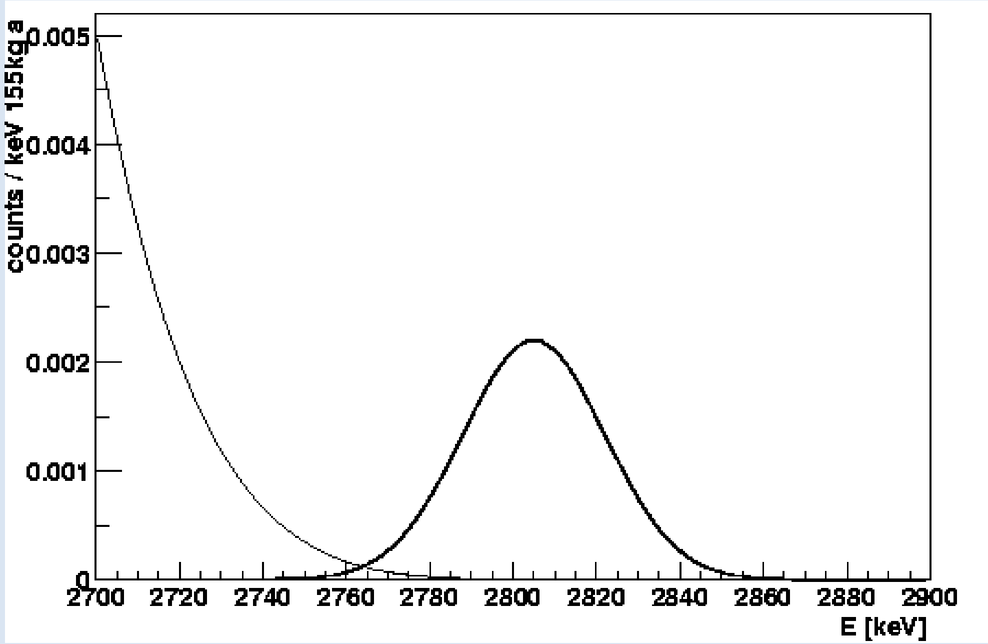
  OR
  - Clear i

on



2νββ Decays

- The ultimate, irreducible background



^{76}Ge (Diode) 0.2%

^{130}Te (Bolometer) 0.4%

^{136}Xe (TPC) 3.3%

CdZnTe (Semiconductor) 3-4%

$$F = \frac{8Q(\Delta E/Q)^6}{m_e} = 3.7 * 10^{-10}$$

^{100}Mo, ^{82}Se (Plastic scintillator) ~14%

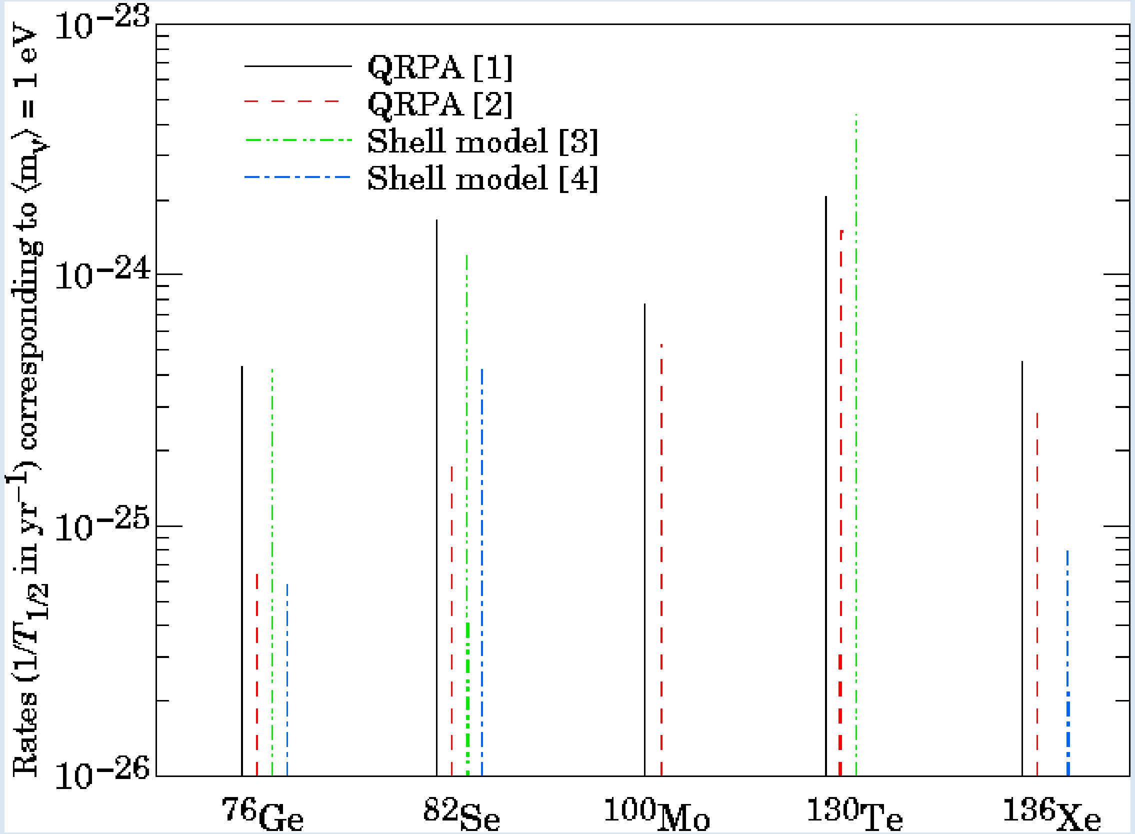
S. Elliott, P. Vogel, Ann. Rev. Nucl. Part. Sci. 2002

Requirements for 0νββ Searches

- High Q value
- High Isotopic Abundance
- Background Rejection
- Good Energy Resolution
- Theory

$$\boxed{\Gamma_{0\nu} = (T_{1/2})^{-1} = G_{0\nu} |M_{0\nu}|^2 m_\nu{}^2}$$

Nuclear Matrix Elements



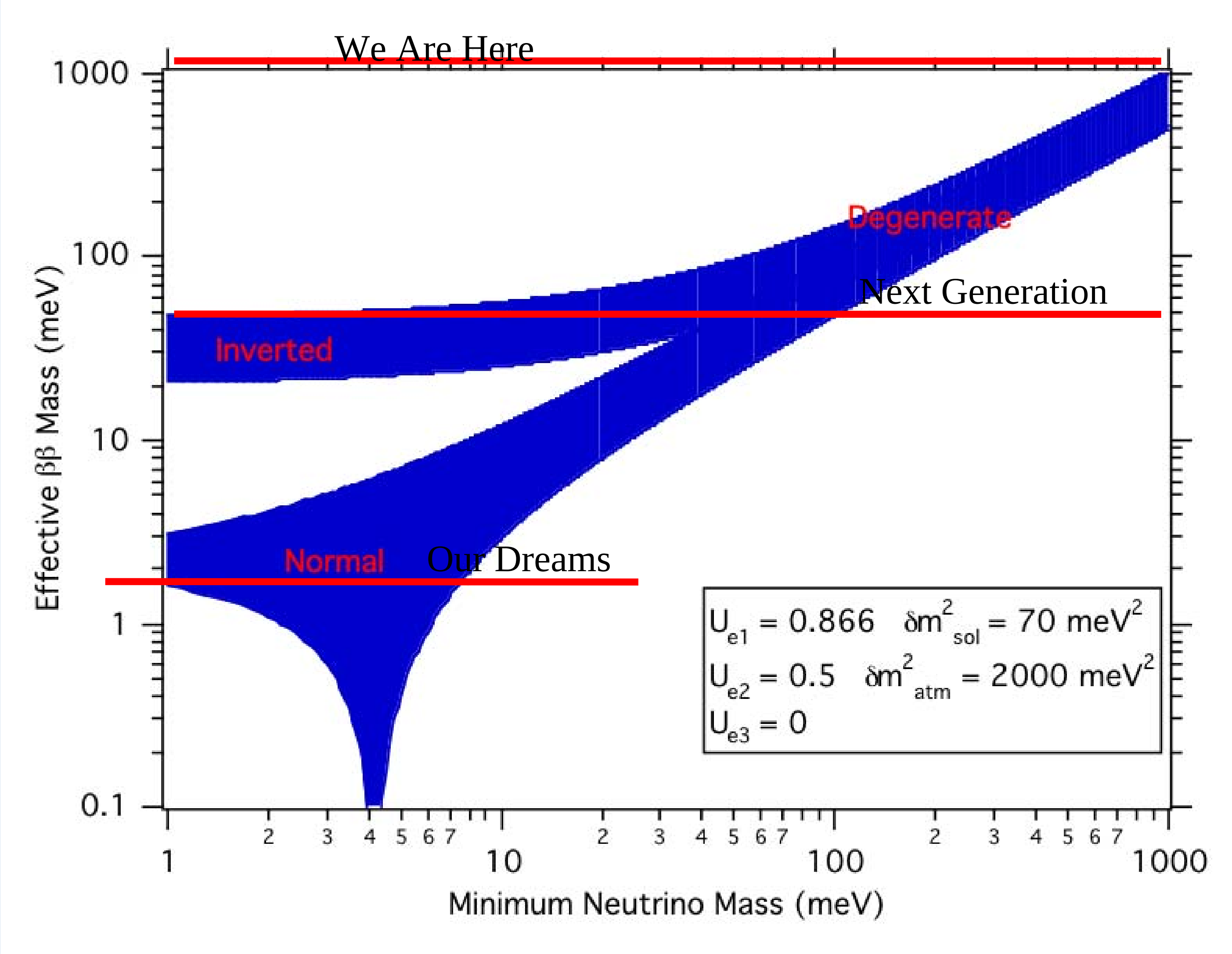
P. Vogel,
PDG 02

A factor 3 uncertainty in the NME means a factor of ~10 in half-life.

Requirements for $0\nu\beta\beta$ Searches

- High Q value
- High Isotopic Abundance
- Background Rejection
- Good Energy Resolution
- Theory
  - possibility to measure $2\nu\beta\beta$ modes too
- Large Isotope Sample

How Much Mass?



^{76}Ge

~ 10^{25} yrs

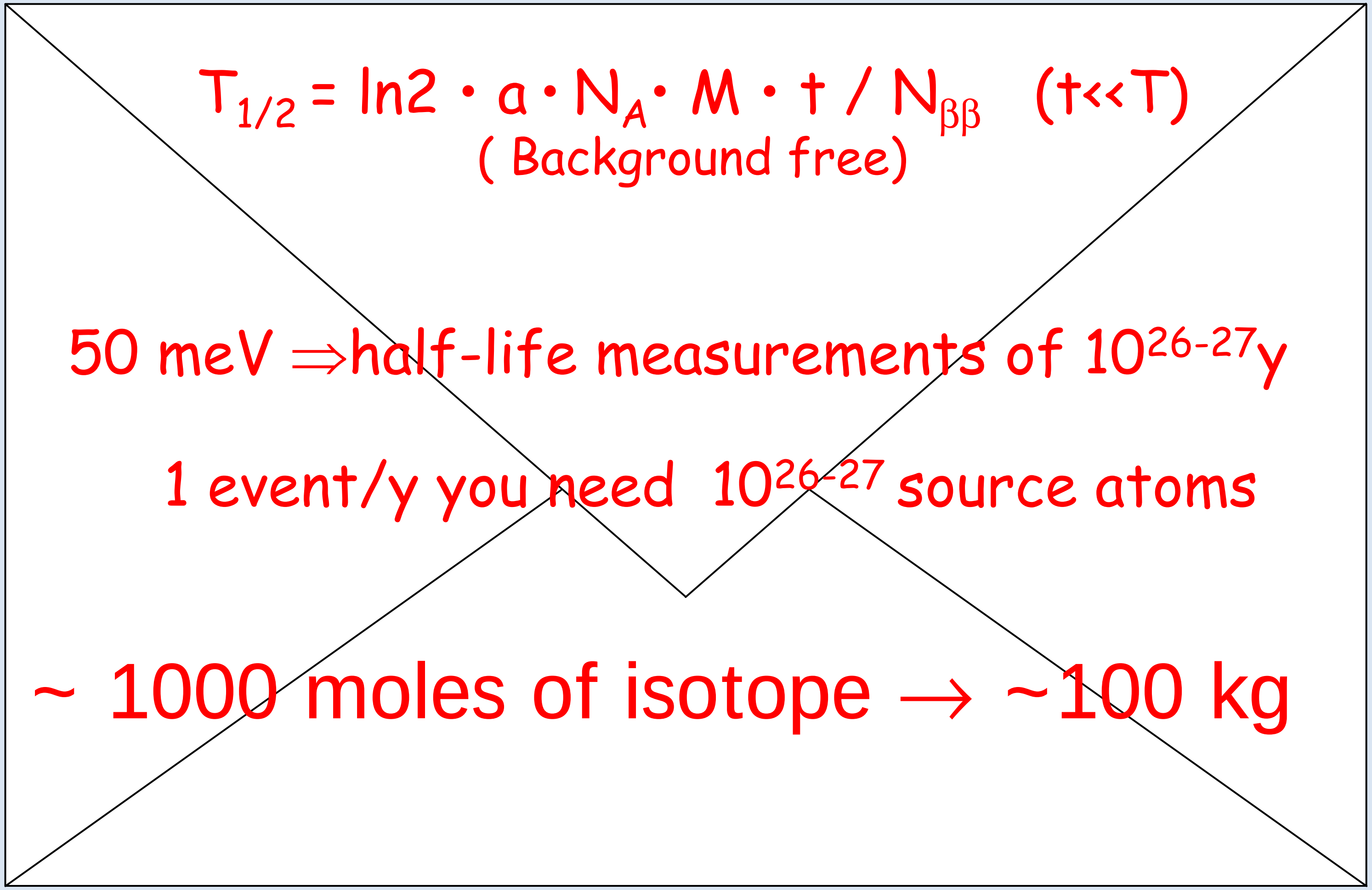
~ 10^{26} yrs

~ 10^{27} yrs

~ 10^{28} yrs

~ 10^{29} yrs

How Much Mass?



$T_{1/2} = ln2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta}$ $(t \ll T)$

(Background free)

50 meV ⇒half-life measurements of 10^{26-27}y

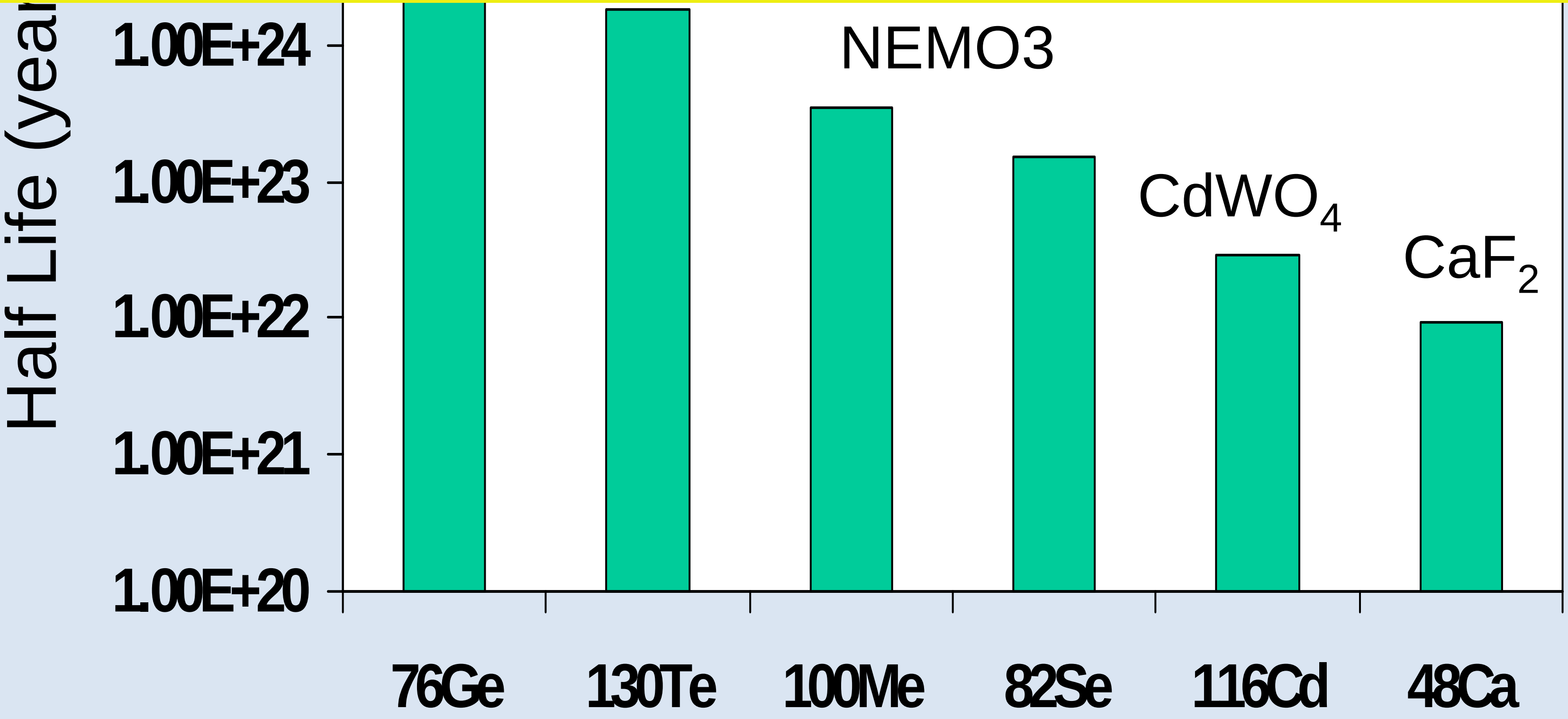
1 event/y you need 10^{26-27} source atoms

~ 1000 moles of isotope → ~100 kg

Experiments

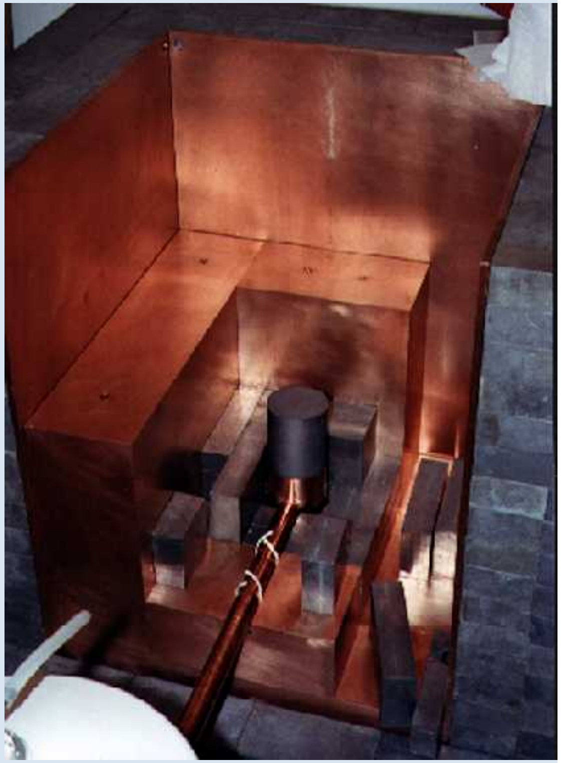
Experimental Status

Disclaimer : This is not a complete list of experiments!!!



Heidelberg-Moscow

- 11kg ^{76}Ge (86-88% enrichment)
  - 5 crystals
- Aug 1990 – May 2003 (71.7 kgy)
- 0.2% or better energy resolution



2001 – Evidence for $0\nu\beta\beta$ peak at 2039keV

References

Evidence

H.V. Klapdor-Kleingrothaus et al., Mod. Phys. Lett. A 16,2409 (2001)

Critical comments

F. Feruglio et al., hep-ph/0201291

C.A. Aalseth et al., hep-ex/0202018

Reply

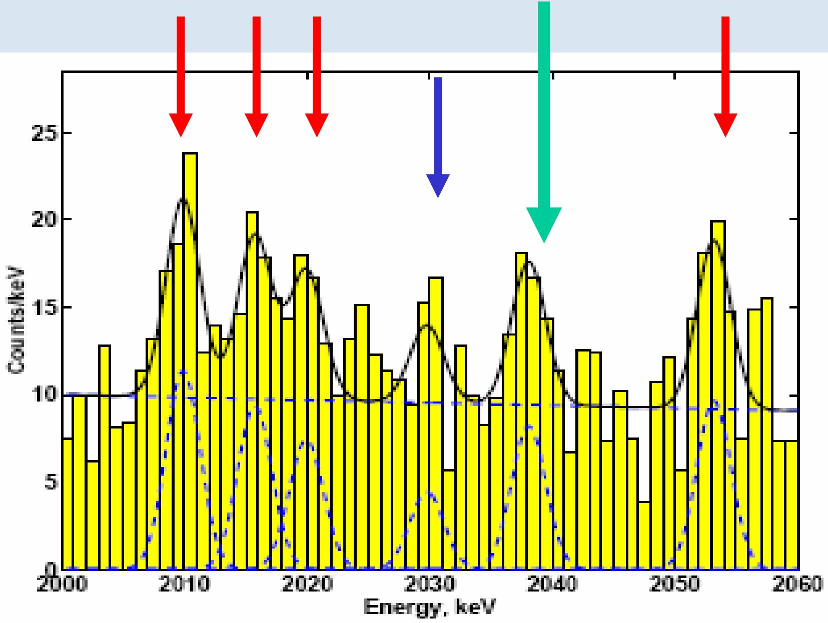
H.V. Klapdor-Kleingrothaus, hep-ph/0205228

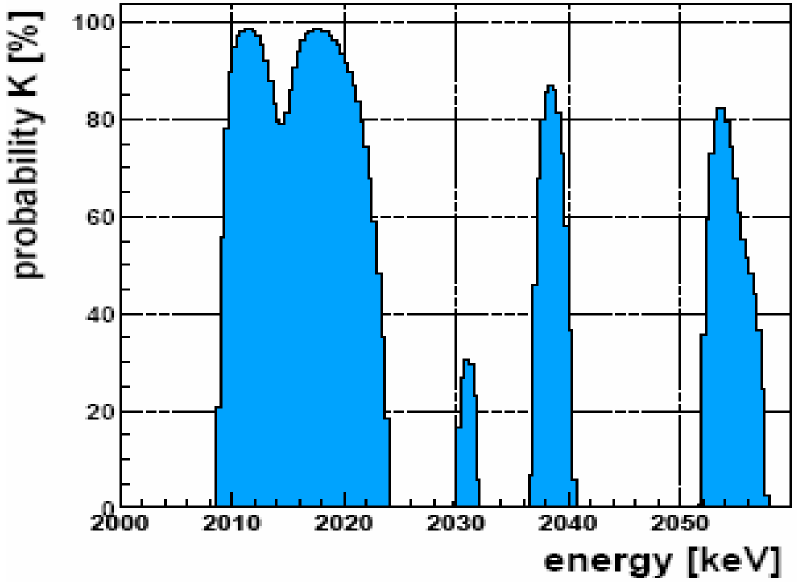
H.L. Harney, hep-ph/0205293

Latest Heidelberg-Moscow results

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

Evidence?





- Weak ^{214}Bi lines

2010.7, 2016.7, 2021.8, 2052.9keV

- $0\nu\beta\beta$ peak
- ? Electron conversion of 2118keV γ line 2030keV

- 2039keV peak has 4.2σ significance

$$\langle m_\nu \rangle = 0.2\text{-}0.6 \text{ eV}$$

Improvements

- More statistics – data taking till May 2003
- Stricter acceptance conditions

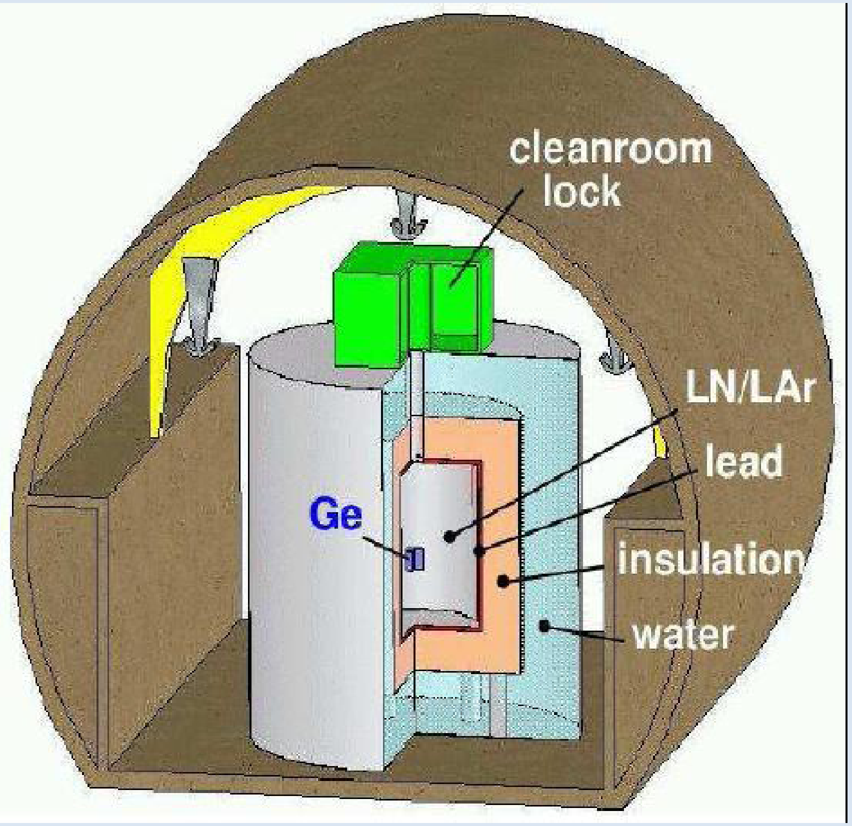
  54.98 kgy → 50.57 kgy
- Refined summing procedure
- Better E calibration of individual runs
- Various fit methods
  - Simultaneous fit 2000-2060keV
- Time structure of events – pulse shape for single site events

New Germanium Experiments

GERDA

GERDA

- GERmanium Detector Array
- At LNGS, (Italy, Russia, Germany, Poland)
- Germanium Diodes
  - – Inherited from HM, IGEX
- Cu cryostat filled with liquid N
- 3m thick Čerenkov H_2O shield



GERDA

Phase I

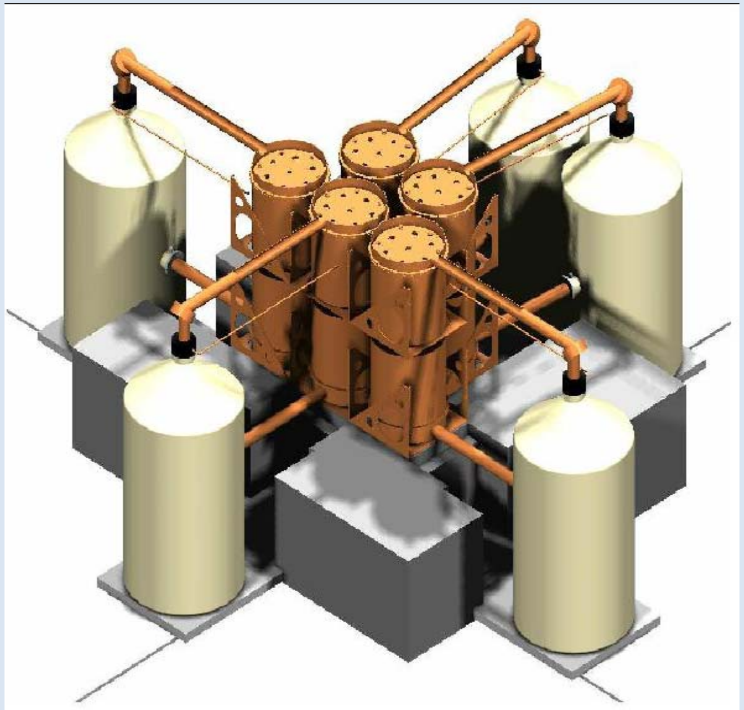
- Nearly 20kg Ge (86% enrichment)
- Crystal characterisation
- Install in cryostat, summer 2006
- $T_{1/2}>1.2\ 10^{25}$ sensitivity in 1 year

Phase II

- New crystal material – working on purity and efficiency of crystal growing
- Crystal segmentation
- LAr in cryostat for background suppression
- 100kg years → $T_{1/2}>2\ 10^{26}$ sensitivity

Majorana

- 500kg enriched Ge Segmented detectors
- Based on IGEX technology
  - – background reduced by >50
  - – cosmogenic n spallation



- 10 years → $T_{1/2}$>4 10^{27} years

  $<m_\nu> \sim 0.03\text{-}0.04$ eV

Majorana

- Design optimisation underway
- DoE review process in progress
- Start with 180kg experiment
  - Easily extendable to 500kg or 1 ton.
- Collaboration with GERDA experiment for simulations.

- Possibly combine for ton scale experiment

Tellurium Experiments

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA ♥ CUORE

Tellurium Experiments

MiBETA 6.8kg TeO_2

→Cuoricino 40.7 kg TeO_2

→CUORE ~ 750 kg TeO_2

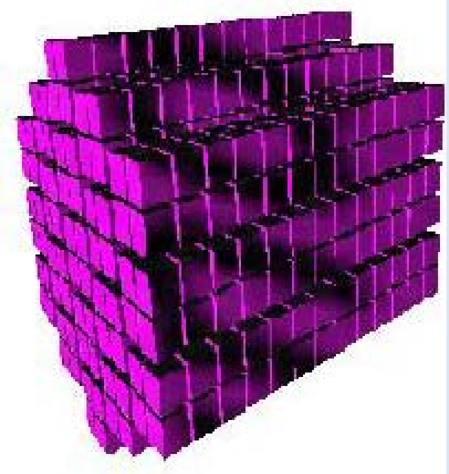
- Bolometers – E release in crystals gives measurable T increase at ~10mK (~1MeV/0.1mK)
- Detector anticoincidence for bkg suppression

Cuoricino and CUORE

Cuoricino

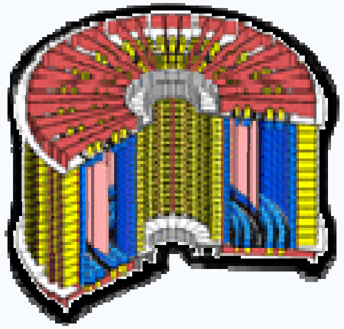
- 0.18 ± 0.01 bkg events/keV/kg/y
- Resolution ~7.5 ±2.9 keV at 2615 keV
- $T_{1/2} > 1.8 .10^{24}$ years (10.85 kgy of data)
- 5 years → 9 $.10^{24}$ years (<mν> 0.1-0.7eV)

CUORE



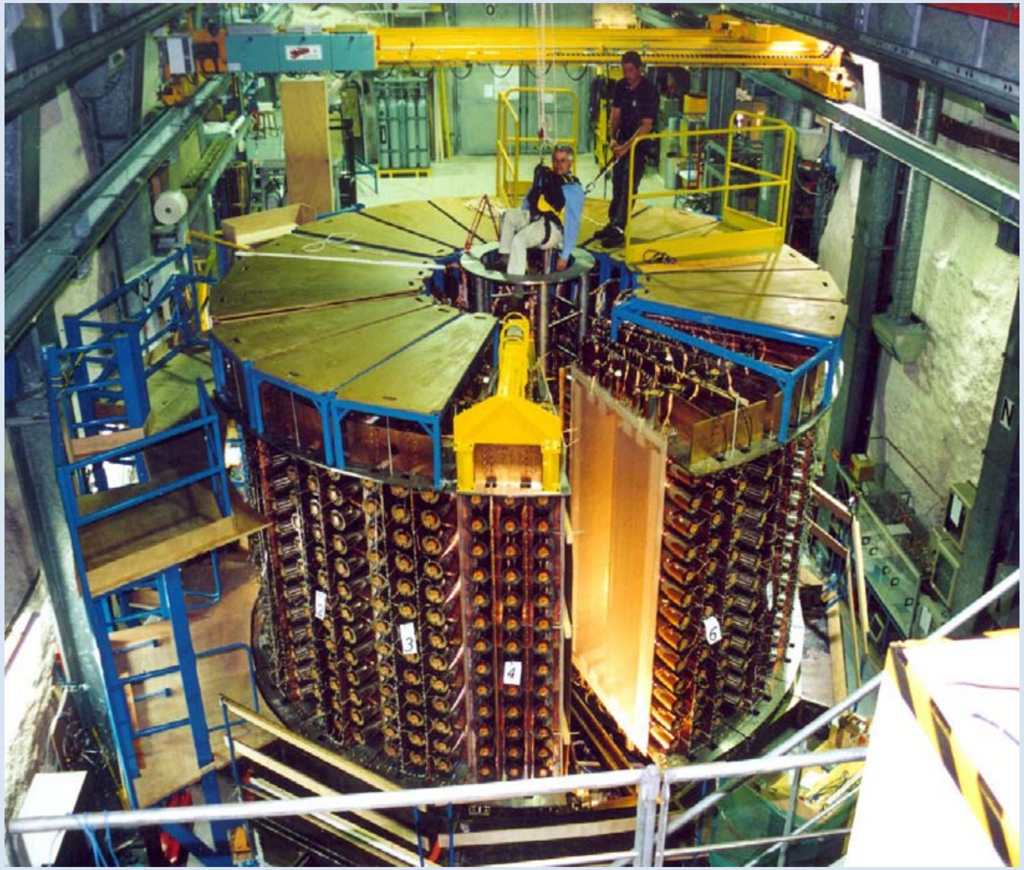
- 19 Cuorocino-like towers
- Goal 0.001-0.01 bkg events/keV/kg/y
- Sensitivity <mν> ~ 0.02-0.13eV

NEMO



NEMOIII

- Running in Frejus UG lab since Feb 2003
- 10kg $0\nu\beta\beta$ isotopes in $20m^2$ cylinder
  - Passive sources
- Event identification:
  - Drift wire tracking chamber
  - Plastic scintillator calorimeter
  - 25Gaus field



NEMOIII First Results

- ^{82}Se (Q=2995keV)

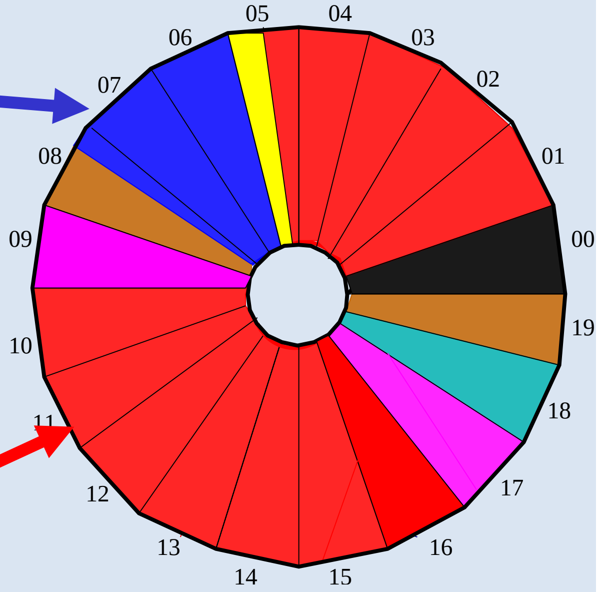
  $T_{1/2} > 1.5\ 10^{23}$ years

  $<m_\nu> = 1.3\text{-}3.0$ eV

- ^{100}Mo (Q=3034keV)

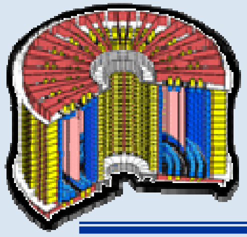
  $T_{1/2} > 3.5\ 10^{23}$ years

  $<m_\nu> = 0.65\text{-}1.0$ eV



(V-A), 90%CL

- $T_{1/2}$ ($2\nu\beta\beta$) for ^{116}Cd, ^{150}Nd, ^{96}Zr and ^{48}Ca



SuperNEMO

- NEMOIII with 5 years Radon-free data:

6914 g of ^{100}Mo $T_{1/2} > 4 .10^{24}$ y $<m_\nu> \; < \; 0.2 – 0.35$ eV

932 g of ^{82}Se $T_{1/2} > 8 .10^{23}$ y $<m_\nu> \; < \; 0.65 – 1.8$ eV

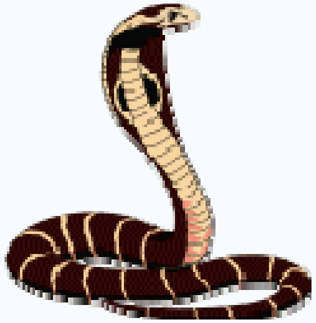
- SuperNEMO = NEMOIII*10 + better ΔE/E
- Sensitivity ~0.03 – 0.06 eV in 5 yr
- Only background from 2νββ tail
- Improve ΔE/E from (14%-16%)/√E to (7%-9%)/√E
- ^{100}Mo, ^{82}Se ^{116}Cd and ^{130}Te

EXO

EXO

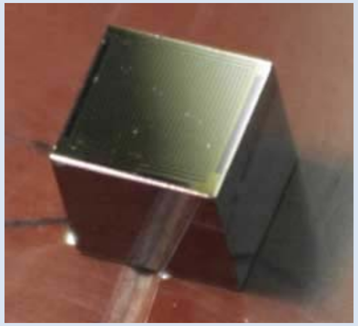
- > 1 ton Liquid Xe TPC (90% enriched ^{136}Xe)
- Ionisation + Scintillation signals → Good energy resolution
- Identification of ^{136}Ba daughter → Clear signal
  - Electrostatic probe
  - Laser fluorescence
- Prototype late 2005
  - 200kg at WIPP
  - No Ba identification

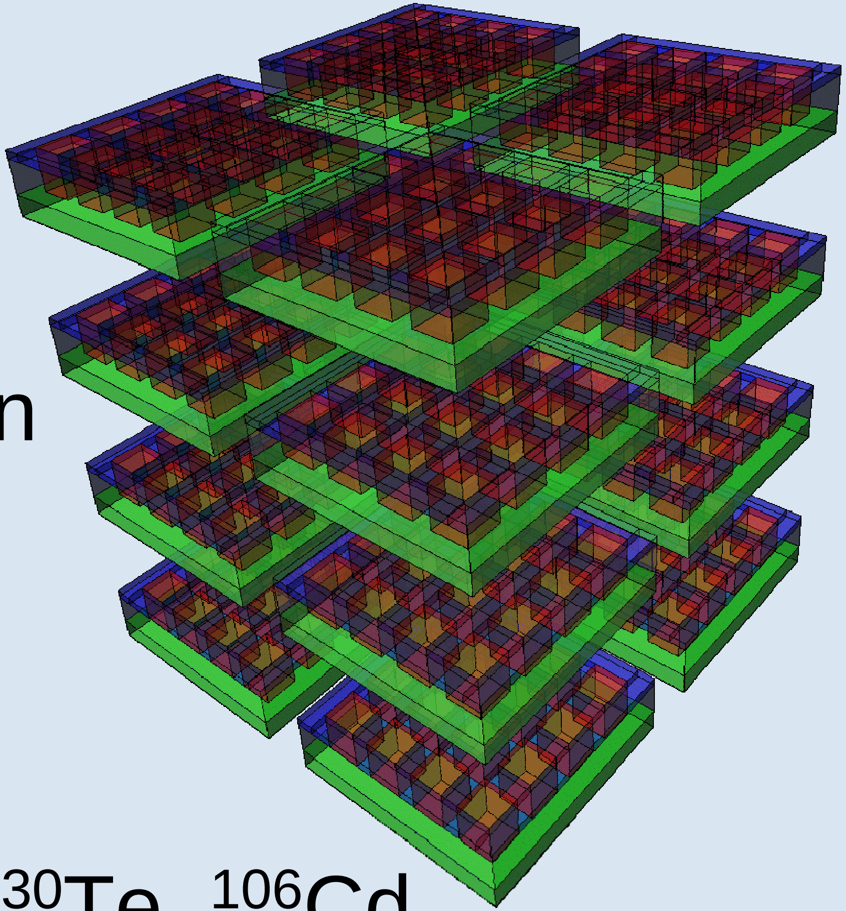
COBRA



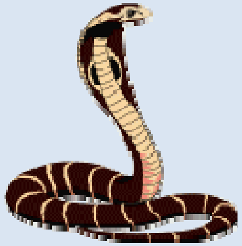
COBRA

- Large array of 1cm^3 CdZnTe semiconductor crystals

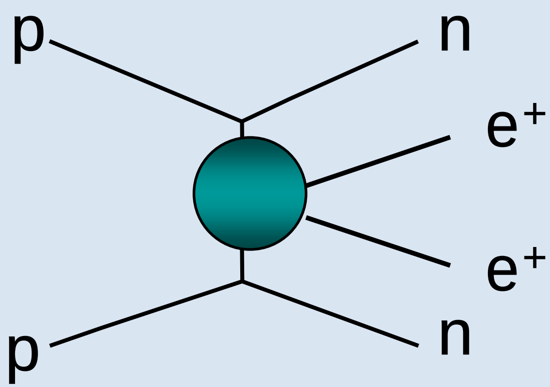




- Coincidences, pixellisation and pulse shape analysis
- Good E resolution (~4%)
- Room temperature
- Multiple isotopes, ^{116}Cd, ^{130}Te, ^{106}Cd



$\beta^+\beta^+$ Modes



- $(A,Z) \rightarrow (A,Z-2) + 2\,e^+ \; (+2\nu_e)$ $\beta^+\beta^+$ $Q-4m_ec^2$
- $e^- + (A,Z) \rightarrow (A,Z-2) + e^+ \; (+2\nu_e)$ β^+/EC $Q-2m_ec^2$
- $2\,e^- + (A,Z) \rightarrow (A,Z-2) \; (+2\nu_e)$ EC/EC Q

Enhanced sensitivity to right handed weak currents (V+A)

M. Hirsch et al., Z. Phys. A 347,151 (1994)

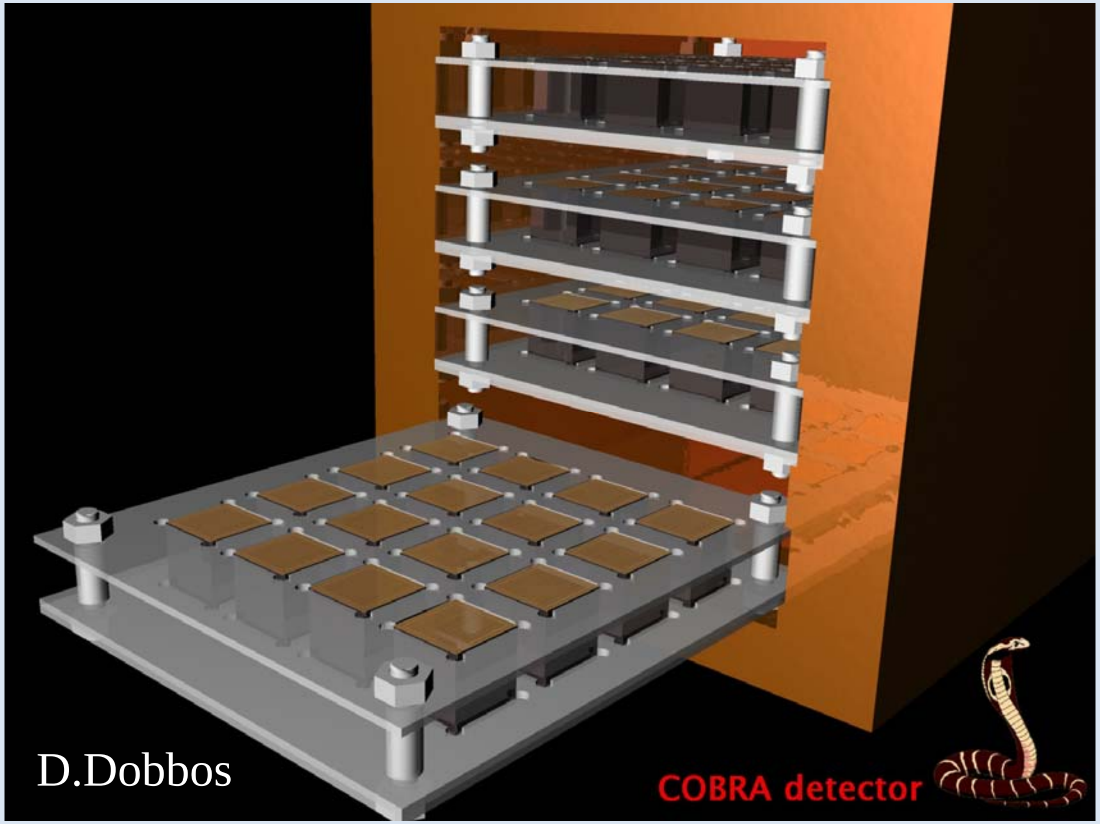
COBRA

- 0.4kg prototype (64 crystals) – Autumn 2005
- Prove background reduction and rejection
- Fully funded (UK)
- Physics:

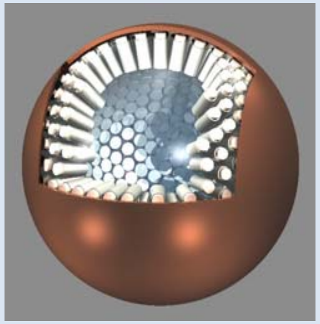
  Access to 2ν2EC

  113Cd

  2νββ $T_{1/2}$



Multipurpose Experiments



- XMass : liquid ^{136}Xe detector
  - – Solar neutrinos and Dark matter

- MOON : ^{100}Mo scintillator detector
  - – Real time studies of low E solar neutrinos
- GENIUS : ^{76}Ge in LN
  - – Dark matter
- \+ others

Summary and Outlook

- 0νββ is a gold plated channel to probe the fundamental character of neutrinos
- Large mass >100kg - ton required for 0νββ discovery
- A number of different approaches on the market