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lecture cource on

Astroparticle physics

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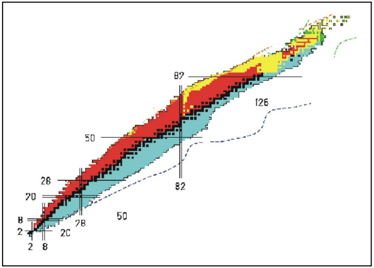
6 Double β-decay

6.1 Double β-decay

Decay processes – β and $\beta\beta$ decays



- Normal β-decay
  - $\beta^- : n \longrightarrow p + e^- + \bar{\nu}_e$
    $(Z, A) \longrightarrow (Z+1, A) + e^- + \bar{\nu}_e$
  - $\beta^+ : p \longrightarrow n + e^+ + \nu_e$
  - EC : $p + e^+ \longrightarrow n + \nu_{e^-}$
    $(Z, A) \longrightarrow (Z-1, A) + e^+ + \nu_{e^-}$
- Double β-decay
  - (1) with neutrino ($2\beta 2\nu$)
    $n_{1,2} \longrightarrow p_{1,2} + e^-_{1,2} + \bar{\nu}_{e1,e2}$
    $(Z, A) \longrightarrow (Z+2, A) + e^-_1 + e^-_2 + \bar{\nu}_{e^-_1} + \bar{\nu}_{e^-_2}$
  - (2) neutrinoless decay ($2\beta 0\nu$)
    $n_{1,2} \longrightarrow p_{1,2} + e^-_{1,2} + \bar{\nu}_{e1,e2}$
    $(Z, A) \longrightarrow (Z+2, A) + e^-_1 + e^-_2$

6.1 Double β-decay

Decay processes – semiempirical mass formula

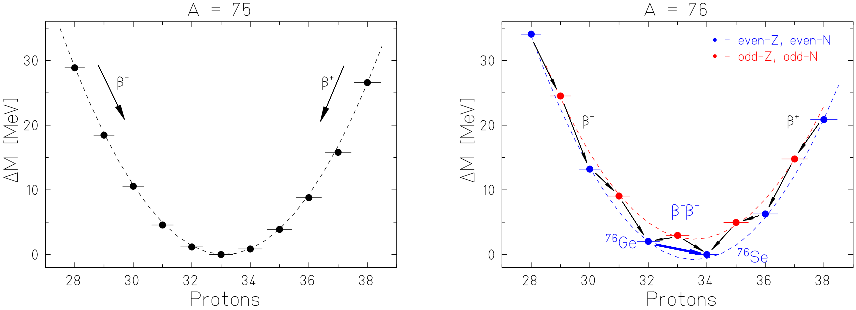
- $M(Z,A) = Zm(^1\mathrm{H}) + \mathrm{Nm_n} - \mathrm{B(Z,A)/c^2}$
- $$B(Z,A) = a_v A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3} - a_{sym}(A-2Z)^2/A + \delta_p$$
  - a_v = volume term = 15.5 MeV
  - a_s = surface term = 16.8 MeV
  - a_c = Coulomb term = 0.72 MeV
  - a_{sym} = symmetry term = 23 MeV
  - δ_p = pairing energy = $\begin{cases} +a_p A^{-3/4} & Z, N \text{ even} \quad (A \text{ even}) \\ 0 & Z \text{ or } N \text{ odd}, A \text{ odd} \\ -a_p A^{-3/4} & Z, N \text{ odd} \quad (\text{A even}) \end{cases}$

    a_p = 34 MeV

6.1 Double β-decay

Decay processes – mass parabola – fixed A

- $M(Z,A) = Zm(^1\mathrm{H}) + \mathrm{N}m_\mathrm{n} - \mathrm{B}(\mathrm{Z},\mathrm{A})/\mathrm{c}^2$
- $B(Z,A) = a_v A - a_s A^{2/3} - a_c Z(Z-1)A^{-1/3}$
  $-a_{sym}(A-2Z)^2/A + \delta$



6.1 Double β-decay

Decay processes

Then

- Double β-decay may exist for even-even isotopes at the bottom of the valley of stability
- Approximately 40 candidiate isotopes exist, out of which most are $2\beta^-$ type

Morever

- Double β-decay is weak interaction process of the second order
  ☞ half lives are long
- Neutrinoless double β-decay violates lepton number conservation (is forbidden in the standard electroweak theory)
- First ideas: Majorana, Racah (1937) and Furry (1939)

6.1 Double β-decay

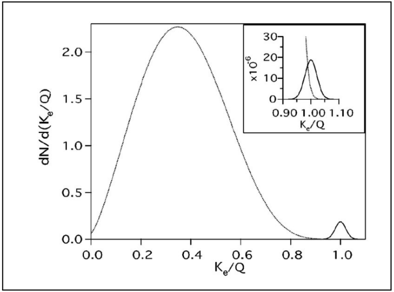
Decay processes

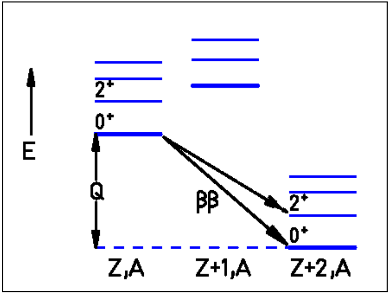
Decay energy ($Q_{\beta\beta}$-value) $\quad$ $Q_{\beta\beta} = \Delta({}^{A}_{Z}\mathrm{X}) - \Delta({}^{A}_{Z+2}\mathrm{X})$

$\Delta({}^{A}_{Z}\mathrm{X})$ is the mass defect of isotope $({}^{A}_{Z}\mathrm{X})$ (from tables)

For example $Q_{\beta\beta}({}^{76}_{32}\mathrm{Ge}) = \Delta({}^{76}_{32}\mathrm{Ge}) - \Delta({}^{76}_{34}\mathrm{Se})$

$= -73212\ \mathrm{keV} + 75251\ \mathrm{keV} = 2.039\ \mathrm{MeV}$





6.2 Double β-decay

Motivation – Neutrinoless case

- Neutrinoless double β-decay is important process for probing the fundamental character of neutrino
- If it exist, it requires that
  - lepton-number conservation is violated
  - neutrino has non-vanishing mass
  - neutrinos are Majorana particles (neutrino is identical to antineutrino)
- Absolute mass of the neutrino can be determined

- Neutrino experiments show that neutrinos oscillate which means that they should have finite mass
  - the upper current limit (of one flavour) is approximately 40 meV
- The next-generation $0\nu2\beta$ experiments should go below that limit
  - $t_{1/2}$ comparable to proton decay
  - material problems does not allow massive detectors ☞

6.3 Double β-decay

Candidate isotopes – $Q_{\beta\beta} \geq 1.7$ MeV

Nuclide	$Q_{\beta\beta}$ [keV]	Abun δ [%]	$T^{2\nu}_{1/2}$(exp.) [years]	$T^{0\nu}_{1/2}$(exp.) [years]	$\langle m_\nu \rangle$ [eV]
^{48}Ca	**4272**	0.187	$(4.2 \pm 1.2) \times 10^{19}$	$> 9.5 \times 10^{21}$	< 8.3
^{76}Ge	2039	7.61	$(1.3 \pm 0.1) \times 10^{21}$	$> 1.9 \times 10^{25}$	< 0.35
				$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$
^{82}Se	**2995**	8.73	$(9.2 \pm 1.0) \times 10^{19}$	$> 2.7 \times 10^{22}$	< 5
^{96}Zr	**3350**	2.80	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$		
^{100}Mo	**3034**	9.63	$(8.0 \pm 0.6) \times 10^{18}$	$> 5.5 \times 10^{22}$	< 2.1
^{110}Pd	2000	11.72			
^{116}Cd	**2805**	7.49	$(3.2 \pm 0.3) \times 10^{19}$	$> 7 \times 10^{22}$	< 2.6
^{124}Sn	2287	5.79			
^{130}Te	**2529**	**34.08**	$(2.7 \pm 0.1) \times 10^{21}$	$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$
^{136}Xe	**2468**	8.87	$> 8.1 \times 10^{20}$	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{148}Nd	1929	5.7			
^{150}Nd	**3367**	5.6	$(7.0^{+11.8}_{-0.3}) \times 10^{18}$	$> 1.2 \times 10^{21}$	< 3
^{160}Gd	1730	**21.86**			

6.4 Double β-decay

Experimental neutrino-mass determination – $0\nu 2\beta$

- Half-life ($T_{1/2}$) of the decay can be measured
- The half-life ($T_{1/2}$) of $0\nu 2\beta$-decay is inversely proportional to the square of the effective mass ($\langle m_\nu \rangle$) of the Majorana neutrino, the phase-space factor ($G_{0\nu}$) and the nuclear matrix element (NME)

$$T_{1/2}(0\nu)^{-1} = G_{0\nu} \times |\mathrm{NME}|^2 \times \langle m_\nu \rangle^2$$

  - the (lower limit) of the half-life can be measured
  - phase-space factor can be calculated (not difficult)
  - the matrix element – which involves the nuclear structure information – can also be calculated
    ☞ can be calculated well enough only to few isotopes
- The effective neutrino mass, U_{ei} being the mixing matrix element and m_i the mass eigenvalue

$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_i$$

6.4 Double β-decay

Experimental neutrino-mass determination – $0\nu 2\beta$

- The lower limit of the half-life ($T_{1/2}$) is obtained from equation

$$T_{1/2} \sim \epsilon \cdot \delta \cdot \left[\frac{M \cdot \tau}{\Delta E \cdot R_{\text{bg}}} \right]^{1/2}$$

  where

  - ϵ is the efficiency of the detector
  - δ is the abundance or enrichment of the isotope
  - τ is measuring time [years]
  - M is the total amount of the isotope [kg]
  - ΔE is the energy resolution (FWHM) [keV]
  - R_{bg} is the background at the energy window of $Q_{0\nu 2\beta}$ [counts/(yr·kg·keV)]

6.4 Double β-decay

Experimental neutrino-mass determination – Ideal experiment – 1

- The detector mass must be large enough to reach the 50-meV limit ($\sim$ 1 ton of isotope)
- The $\beta\beta(0\nu)$ source must be extremely low in radioactive contamination
- Although the use of natural isotope will be less costly, the enrichment process provides a good level of purification and also results in a (usually) smaller volume detector
- A small detector volume minimises internal background (which scale with the detector volume). It also minimises external background by allowing smaller shields and structures (active detector)
- Good energy resolution
- Ease of operation due to long experiments and remote locations

6.4 Double β-decay

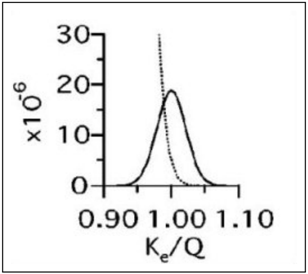
Experimental neutrino-mass determination – Ideal experiment – 2

- A large $Q_{\beta\beta}$-value gives faster $\beta\beta(0\nu)$ rate and places the region of interest above many potential background activities
- A relatively slow $\beta\beta(2\nu)$ rate helps to control the experiment
- Identifying the daughter in coincidence with the $\beta\beta$ decay would eliminate most potential background events except $\beta\beta(2\nu)$
- Good spatial resolution and timing information can help reject background processes
- The nuclear theory is better understood in some isotopes than others.
- Event reconstruction, providing kinematic data such as opening angle and individual electron energy, can aid in the elimination of background

6.4 Double β-decay

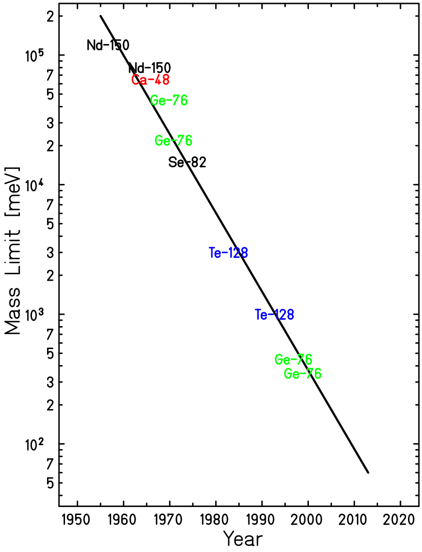
Experimental neutrino-mass determination – Background

- Double β-decay (both $2\nu2\beta$ and $0\nu2\beta$) experiments are essentially a hard struggling and protection against background radiations
- The background can be divided into three groups
  - natural and man-made activity: Uranium and Thorium chains and Potassium
    ☞ (^{208}Tl, ^{214}Bi, ^{40}K)
    artificial isotopes
    ☞ (^{239,240}Pu, ^{137}Cs, ^{90}Sr, ^{42}Ar, ^{85}Kr)
  - Cosmic-ray induced activity
  - $2\nu2\beta$-decay for $0\nu2\beta$-decay



6.4 Double β-decay

Experimental neutrino-mass determination – the Moores law for the sensitivity



6.5 Double β-decay

Performed experiments

The first $2\beta0\nu$ experiment : Fireman 1948 [Phys. Rev. 74 (1948) 1238]

Since then $2\beta0\nu$ decay studied for 28 isotopes

No $2\beta0\nu$ decay observed, $2\beta2\nu$ decay observed for 7 isotopes

Isotope	Experimental $T_{1/2}(2\nu)$ [yr]	Experimental $T_{1/2}(0\nu)$ [yr]	$\langle m_\nu \rangle$ [eV]	Experiment / Reference
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$	$> 9.5 \times 10^{21}$	< 8.3	You Ke *et al.*, Phys. Lett B265 (1991) 53
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$	$> 1.9 \times 10^{25}$	< 0.35	Heidelberg Moscow (1999)
		$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$	IGEX (1999)
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$	$> 2.7 \times 10^{22}$	< 5	S.R. Elliott *et al.*, PRC46 (1992) 1535
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$	$> 5.5 \times 10^{22}$	< 2.1	ELEGANTS (2001)
^{116}Gd	$(3.2 \pm 0.3) \times 10^{19}$	$> 7.0 \times 10^{22}$	< 2.6	F.A. Danevich *et al.*, PRC62 (2000) 044501
^{128}Te		$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$	T. Bernatowicz *et al.*, PRC47 (1993) 806
^{130}Te		$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$	MIBETA (2000)
^{136}Xe		$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$	GOTTHARD TUNNEL (1998)

The sensitivity should be improved at least two orders of magnitude

6.5 Double β-decay

Performed experiments – MIBETA – 1

- Material ^{128,130}Te
- Detector: Bolometer
  - utilised the low heat capasity of the crystal at low temperature
  - small energy deposit causes significant temperature increment in the crystal
  - good energy resolution
- Consisted of 20 TeO_2 crystals, each of size of $3\times3\times6$ cm^3, and total mass 6.8 kg
- Cooled down to $\sim$10 mK
- Heat and background protection
  - high-purity electrolytically manufactured copper (2.2 cm)
  - low-activity lead (Roman lead, $<$ 4 mBq/kg ^{210}Pb) 10 cm
  - normal lead (16$\pm$4 Bq/kg ^{210}Pb)

6.5 Double β-decay

Performed experiments – MIBETA – 2

- Energyresolution (FWHM) at 2615 keV : $\Delta E \sim 9$ keV
- $\delta(^{130}\mathrm{Te}) = 34\% \longrightarrow$ enrichment not necessary, still
  2 crystals $\delta(^{130}\mathrm{Te}) = 93\%$, and
  2 crystals $\delta(^{128}\mathrm{Te}) = 95\%$
- Background
  - $R_{bg} \sim 0.5$ counts/(yr·kg·keV) @ $Q_{\beta\beta}(^{130}\mathrm{Te}) = 2529$ keV
  - most of it from α-activity
- Measurement
  - Gran Sasso, 3500 mwe
  - 66995 h $\times$ crystal $\longrightarrow$ 0.66 kg $\times$ yr ^{130}Te :

  ☞ $T_{1/2}(0\nu) \geq 1.44 \times 10^{23}$ yr (^{130}Te)

  ☞ $T_{1/2}(0\nu) \geq 8.6 \times 10^{22}$ yr (^{128}Te)

6.5 Double β-decay

Performed experiments – Gotthard tunnel

- Material ^{136}Xe
- Detector: TPC (Time Projection Chamber)
- Active vlume 180 litres of Xe gas
  - $(\delta(^{136}\mathrm{Xe}) = 62.5\%)$ at pressure of 5 atm ☞ 9.1×10^{24} atomia
- e^- tracking $\longrightarrow$ reducing background
- Energyresolution (FWHM) at $Q_{\beta\beta}(^{136}\mathrm{Xe}) = 2481$ keV : $\Delta E \sim 165$ keV (6.6 %)
- Background
  - $R_{bg} \sim 0.02$ counts/(yr·kg·keV) @ $Q_{\beta\beta}(^{136}\mathrm{Xe}) = 2480$ keV
  - dominating background at $2\beta0\nu$ was due to Compton-scattered electrons which were created by natural activity
- Measurement
  - Gotthardin highway tunnel (Switzerland?)
  - 6830 h + 6013 h (~530 days) $\longrightarrow$ 4.9 kg $\times$ yr :

    ☞ $T_{1/2}(0\nu) \geq 4.4 \times 10^{23}$ yr (^{136}Xe)

6.5 Double β-decay

Performed experiments – Heidelberg & Moscow

- Detector
  - 5 Ge crystals (HPGe), $\delta(^{76}\mathrm{Ge}) = 86\%$, mass 10.96 kg (125.5 moles)
  - passive and aktive background shielding, PSA
  - Energyresoluution (FWHM) at $Q_{\beta\beta}(^{76}\mathrm{Xe}) = 2039$ keV: $\Delta E \sim 3.9$ keV
- Background
  - $R_{bg} \sim 0.06$ counts/(yr·kg·keV) (with PSA)
    $R_{bg} \sim 0.20$ counts/(yr·kg·keV) (without PSA)
    @ $Q_{\beta\beta}(^{76}\mathrm{Xe}) = 2039$ keV
- Measurement
  - Heidelberg–Moscow collaboration
  - Gran Sasso
  - 24 kg $\times$ yr :

    ☞ $T_{1/2}(0\nu) \geq 1.6 \times 10^{25}$ yr (^{76}Ge)

6.5 Double β-decay

Performed experiments – IGEX

- IGEX – International Germanium EXperiment
- Detector
  - 2 kg enriched ^{76}Ge, $\delta(^{76}\mathrm{Ge}) = 88\%$ (HPGe)
  - PSA, plastic scintillation detector for muon veto
  - background shielding consisted of 2.5 tons argeological and 10 tons of 70-year-old low-activity lead
  - Energyresoluution (FWHM) at $Q_{\beta\beta}(^{76}\mathrm{Xe}) = 2039$ keV: $\Delta\mathrm{E} \sim 4$ keV
- Background
  - $\mathrm{R}_{bg} \sim 0.06$ counts/(yr·kg·keV) (with PSA) @ $Q_{\beta\beta}(^{76}\mathrm{Xe}) = 2039$ keV
- Measurement
  - Canfranc Underground Laboratory (Spain)
  - 8.87 kg $\times$ yr (116.75 mol·yr) :

    ☞ $T_{1/2}(0\nu) \geq 1.57 \times 10^{25}$ yr (^{76}Ge)

6.5 Double β-decay

Performed experiments – HM & IGEX

Heidelberg & Moscow experiment versus IGEX

HM and IGEX obtained approximately the same results for the half life

Their interpretation of the background was, however, different

- HM:
  The dominant contribution was created outside the Ge crystal
- IGEX:
  The most restricting factor was the isotope ^{68}Ge that was an impurity in Ge crystal

6.5 Double β-decay

Performed experiments – ELEGANTS

- ELEctron Gamma-ray Neutrino TeleScopy
- Material ^{100}Mo
- Detector: Spectrometer ELEGANT V
  - three drift chambers for tracking electron paths
  - plastic scintillation detectors for measuring energy and times
  - NaI(Tl) scis around the spectrometer for γ-ray elimination
  - protected by copper and lead
  - two ^{100}Mo sources (δ=95 %, 20 mg/cm^2), total mass 171 g
    ☞ 171 g 95% ^{100}Mo $\Longrightarrow$ 10^{24} atoms
  - good background separation but not that efficient or not that good energy resolution than Ge crystals or bolometers
- Background
  - the most dominating background component at the $2\beta 0\nu$ energy window was concluded to arise from isotopes ^{208}Tl and ^{214}Bi which were impurities in the Mo source and other detector materials
- Measurement
  - Kamioka, Japan
  - 7582 h + 7333 h ($\sim$620 days) : ☞ $T_{1/2}(0\nu) \geq 5.5 \times 10^{22}$ yr (^{100}Mo)

6.6 Double β-decay

Future experiments – could start in 10 years

Aim to reach sensitivity couple of magnitude lower in half-life measurement
☞ measure masses below 50 meV

$$T_{1/2} \sim \epsilon \cdot \delta \cdot \left[\frac{M \cdot \tau}{\Delta E \cdot R_{bg}} \right]^{1/2}$$

- Choise of detector and detector material
  - detector efficiency ~100 %
    ☞ active detector (^{76}Ge, ^{116}Gd, ^{130}Te, ^{136}Xe)
  - good energyresolution (FWHM) ☞ at least ~4% $\times$ $Q_{\beta\beta}$
  - HM: m(^{76}Ge) ~10 kg ☞ hundreds of kilos enriched material
  - large $Q_{\beta\beta}$
- Background ☞ as small as possible at the $Q_{\beta\beta}$ range
- Measurement time long (~10 years) ☞ detector easy to operate

6.6 Double β-decay

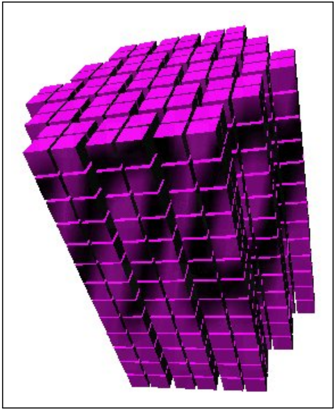
Future experiments – Proposed experiments

Experiment	Source	Detector description	Sensitivity to $T^{0\nu}_{1/2}$ [years]	Reference
COBRA	^{130}Te	10 kg CdTe semiconductors	1×10^{24}	K. Zuber, Phys. Lett B519 (2001) 1
DCBA	^{150}Nd	20 kg $^{\rm enr}$Nd layers between tracking chambers	2×10^{25}	N. Ishihara *et al.*, NIM A443 (2000) 101
NEMO-3	^{100}Mo	10 kg of $\beta\beta(0\nu)$ isotopes (7 kg Mo) with tracking	4×10^{24}	X. Sarazin, hep-ex/0006031
CAMEO	^{116}Cd	1 ton $CdWO_4$ crystals in liquid scintillator	$\geq 10^{26}$	G. Bellini *et al.*, EPJ C19 (2001) 43
CANDLES	^{48}Ca	several tons of CaF_2 crystals in liquid scintillator	1×10^{26}	T. Kishimoro *et al.*, Ann. Rep. Osaka Univ. Lab. Nucl. Studies (2000)
CUORE	^{130}Te	750 kg TeO_2 bolometers	2×10^{26}	F.T. Avignone *et al.*, hep-ex/0201038
EXO	^{136}Xe	1 ton ^{enr}Xe TPC (gas or liquid)	8×10^{26}	F.A. Danevich *et al.*, PR C62 (2000) 044501
GEM	^{76}Ge	1 ton ^{enr}Ge diodes in liquid N	7×10^{27}	Yu.G. Zdesenko *et al.*, J.Phys. G27 (2001) 2129
GENIUS	^{76}Ge	1 ton ^{76}Ge (enr. 86%) diodes in liquid N	1×10^{28}	H.V. Klapdor-Kleingrothaus, hep-ph/0103074
GSO	^{160}Gd	2 ton Gd_2SiO_5 crystal scintillator	2×10^{26}	F.A. Danevich *et al.*, NP A694 (2001) 375 S.C. Wang *et al.*, hep-ex/0009014
Majorana	^{76}Ge	0.5 ton 86% segmented ^{enr}Ge diodes	3×10^{27}	C.E. Aalseth *et al.*, hep-ex/0201021
MOON	^{100}Mo	34 ton ^{nat}Mo sheets between plactic scintillator	1×10^{27}	H. Ejiri *et al.*, PRL85 (2000) 2917
Xe	^{136}Xe	1.56 ton of ^{enr}Xe in liquid sci.	5×10^{26}	B. Caccianiga *et al.*, ApP14 (2001) 15
XMASS	^{136}Xe	10 ton of liquid Xe	3×10^{26}	S. Moriyama *et al.*, XENON01 Workshop, Tokyo

6.6 Double β-decay

Future experiments – Proposed experiments – CUORE

- Cryogenic Underground Observatory for Rare Events
- Successor of the MIBETA detector, in Gran Sasso
- The detector: Bolometer
  - 988 TeO_2 crystals with a mass of 750 g each and size of a cube of 5 cm^3
  - operational temperature $\sim$10 mK
  - good energy resolution: 5 – 10 keV (FWHM) at 2.5 MeV
- Background protection
  - pure copper and low-activity lead
  - estimated 0.5 – 0.05 counts/(kg·keV·yr)
- Sensitivity: $m_\nu \leq 20 - 50$ meV
- Prototype CUORICINO, a single CUORE tower is being constructed



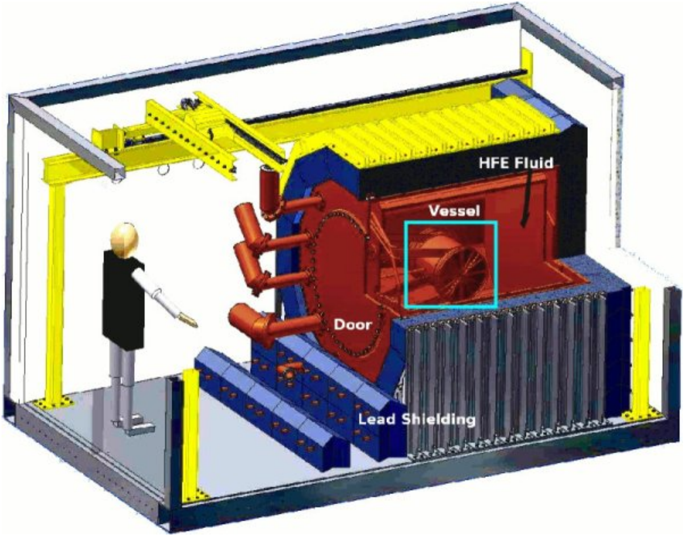
6.6 Double β-decay

Future experiments – Proposed experiments – EXO – 1

- The Enriched Xenon Observatory
- Detector: EXO-200 – 200 kg prototype experiment currently being installed at WIPP – Waste Isolation Pilot Plant, USA
- Liquid xenon TPC
- Measure $2\nu2\beta$ mode of 80% enriched ^{136}Xe $\Longrightarrow$ limit for $0\nu2\beta$
- Ultrapure materials
- EXO – a ton-scale experiment ^{136}Xe
  - under R&D (background elimination)
- ^{136}Xe
  - relatively easy to purify the LXe
  - relatively easy to enrich in Russian centrifuges
  - $Q_{\beta\beta} = 2.48$ MeV is quite high
  - liquid: scintillation and ionisation
  - background elimination by tagging in the daughter isotope ^{136}Ba

6.6 Double β-decay

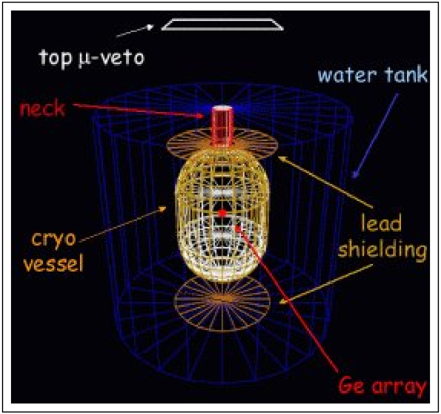
Future experiments – Proposed experiments – EXO – 2



6.6 Double β-decay

Future experiments – Proposed experiments – GERDA

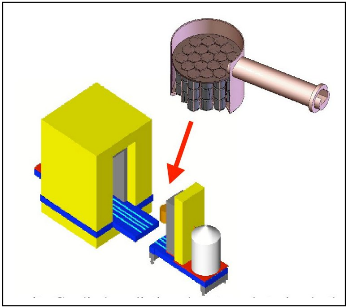
- GERDA is the successor of the HM and IGEX experiments
- New double β-decay experiment at Gran Sasso, proposed 2004
- enriched ^{76}Ge
- Aim: sensitivity of $T_{1/2}(0\nu) \geq 1.4^{26}$ yr and $m_\nu \leq 90 - 300$ keV
- Background reduction
  - cryostat filled with LN or LAr $\Longrightarrow$ radiopure materials



6.6 Double β-decay

Future experiments – Proposed experiments – Majorana

- Detector
  - 120 kg of HPGe crystals, $\delta(^{76}\text{Ge}) = 86$ %
- Background protection
  - conventional low-active cryostat, very pure copper ($< 25\ \mu$Bq/kg ^{226}Ra, 9 μBq/kg ^{228}Th)
  - detectors protected by low-activity lead and copper
  - segmented detectors and PSA
- Aim: to achieve background level of $\sim$1 counts/(ton·yr) in 4-keV region around $Q_{\beta\beta}$
  if yes $\Longrightarrow$ scale to 1 ton or larger
- If funding obtained construction started this year



6.7 Double β-decay

Enrichment of detector materials

Only enrichment plants in Russia are capable, at the moment, to produce hundreds of kilograms of enriched materials
☞ Electro Chemical Plant (ECP), Krasnojarsk

Enriched production currently

- ^{76}Ge : ∼20 kg/yr
  - with a device never used for Uranium enrichment
- ^{136}Xe : ∼300 kg/yr

With investments

- ^{76}Ge : ∼30 kg/yr ⟶ ∼50 kg/yr ⟶ ∼100 kg/yr
- ^{136}Xe : ∼2 tonnia/yr