Beta decay: the neutrino

One of the most pervasive forms of matter in the universe, yet it is also one of the most elusive!

http://www.interactions.org/pdf/neutrino_pamphlet.pdf

inverse beta processes

Shortly after publication of the Fermi theory of beta decay, Bethe and Peierls pointed out the possibility of inverse beta decay (neutrino capture):

$$ {}^{A}_{Z}X_N + \nu_e \rightarrow {}^{A}_{Z+1}X_{N-1} + e^- $$

$$ {}^{A}_{Z}X_N + \bar{\nu}_e \rightarrow {}^{A}_{Z-1}X_{N+1} + e^+ $$

extremely small cross sections!

Let us first consider $p + \bar{\nu}_e \rightarrow n + e^+$

cross section = effective collision area

$$ \sigma_c = \mathcal{W}_{i\rightarrow f}\frac{V}{c} = \frac{2\pi V}{\hbar}\left|M_{fi}\right|^2 \rho_f $$

neutrino flux

$E_{\bar{\nu}_e}/m_e c^2$	$E_{e^+}/m_e c^2$	$\sigma/10^{-44}\,\mathrm{cm}^2$
4.5	2.0	8
5.5	3.3	20
10.8	8.3	180

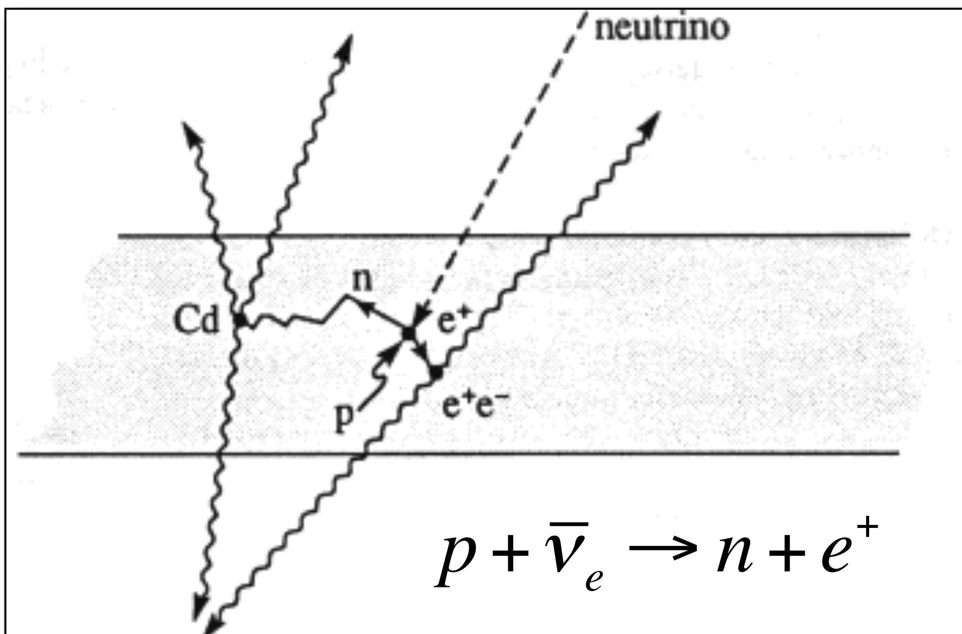
mean-free path $\quad \ell = \dfrac{1}{n\sigma}$

n=number of nuclei per cm^3

For protons in water n~3·10^{22}.
This gives the mean-free path of 3·10^{20} cm or ~300 light years!

Beta decay: (anti)neutrino detection

In **1951** Fred Reines and Clyde Cowan decided to work on detecting the neutrino. Realizing that *nuclear reactors* could provide a flux of 10^{13} antineutrinos per square centimeter per second, they mounted an experiment at the Hanford (WA) nuclear reactor in 1953. The Hanford experiment had a *large background* due to cosmic rays even when the reactor was off. The detector was then moved to the new Savannah River (SC) nuclear reactor in 1955. This had a *well shielded location* for the experiment, 11 meters from the reactor center and 12 meters *underground*. The target was *water* with $CdCl_2$ dissolved in it. The positron was detected by its slowing down and annihilating with an electron producing two 0.5 MeV gamma rays in opposite directions. The pair of gamma rays was detected in time coincidence in liquid scintillator above and below the water by photomultiplier tubes detecting the scintillation light. The neutron was also slowed by the water and captured by the cadmium. In the capture several gamma rays were emitted which were also detected in the scintillator as a delayed coincidence after the positron's annihilation gamma ray detection.



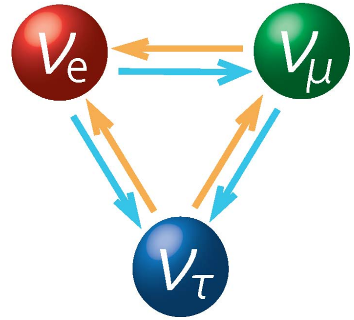
$$p+\bar{\nu}_e \rightarrow n+e^+$$

The signal rate was about three events per hour in the entire detector and the signal-to-background ratio was about four to one. Thus in **1956** was born the field of experimental neutrino physics. This discovery was recognized by honoring Frederick Reines with the Nobel Prize in 1995 (with Martin Perl – for discovery of the tau lepton). Clyde Cowan died in 1974….

a multicoincidence measurement

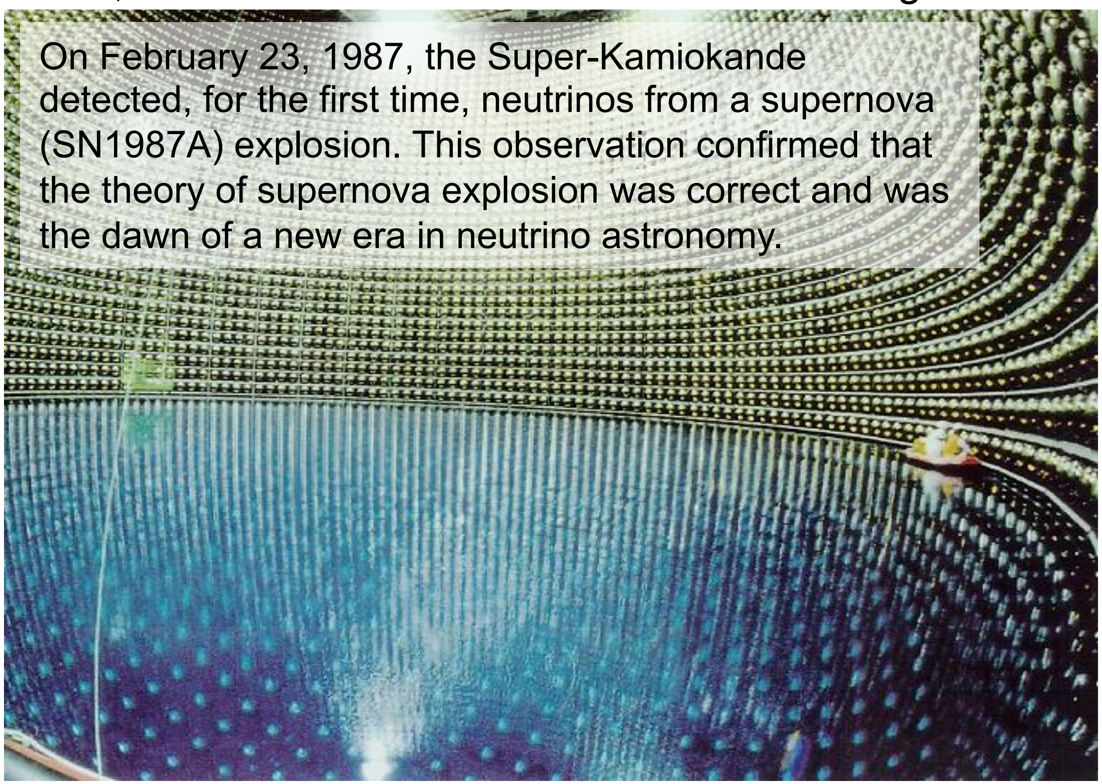
Neutrinos do oscillate!

flavor oscillations: the neutrino is composed of a combination of three different mass states

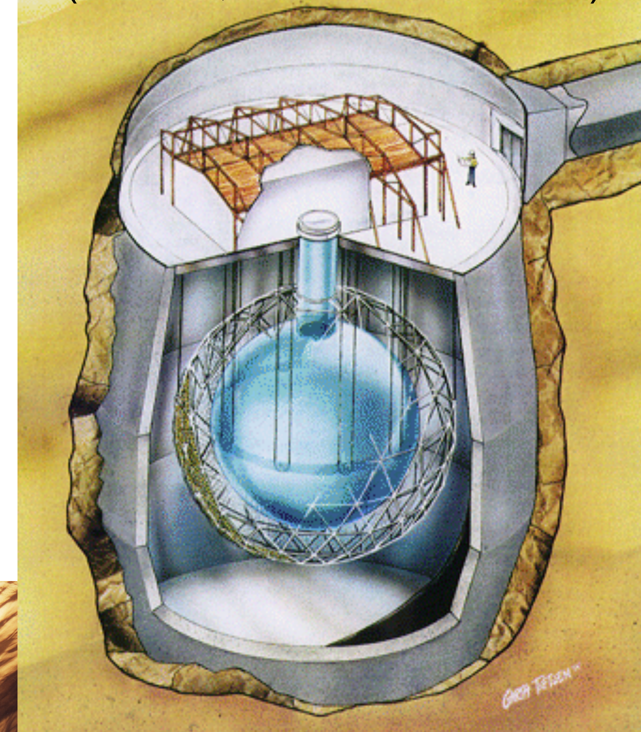


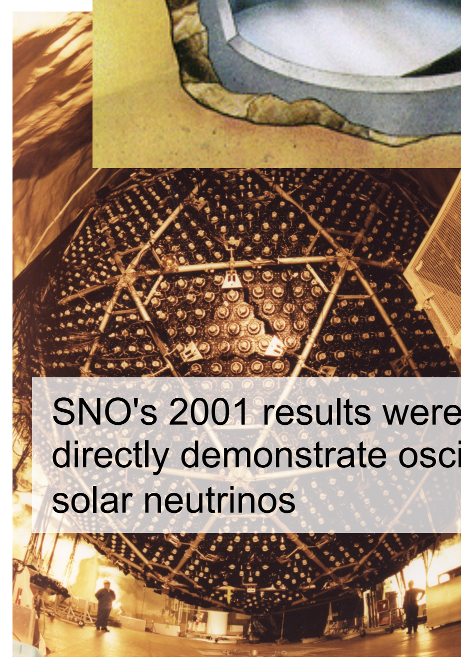
Super-Kamiokande

50,000 ton tank of water located 1 km underground



Sudbury Neutrino Observatory
(Ontario, 8 hours from MSU)





SNO

1,000 tons of heavy water;
2 km underground

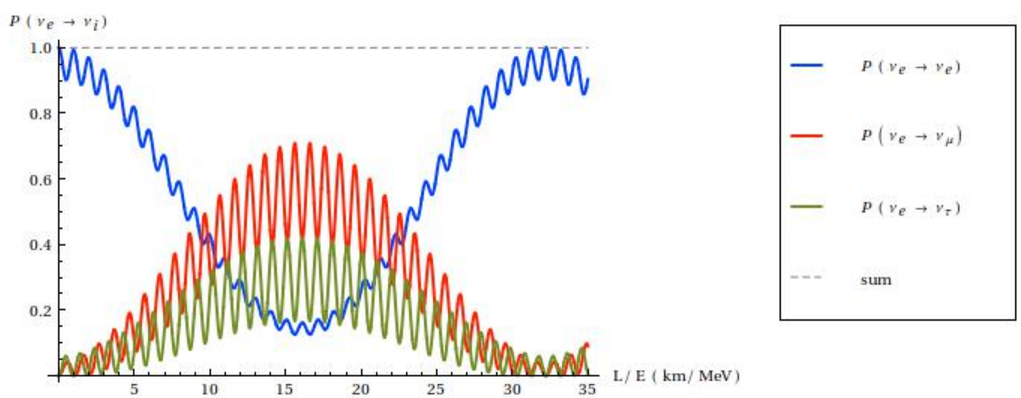
Cherenkov neutrino detectors

Cherenkov radiation is the optical equivalent to a sonic boom

Observation of Neutrino Oscillations

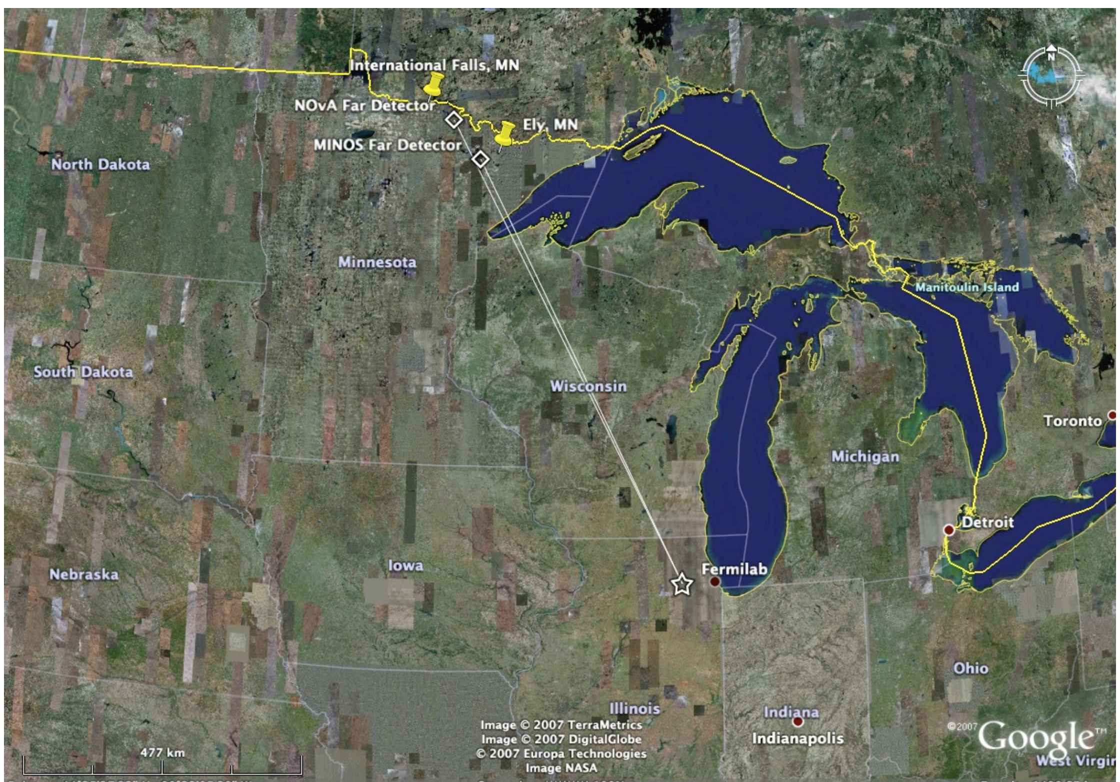
Neutrino source	Experiment	Comments
Solar neutrinos	Radio-chemical exp.: Homestake Cl exp., GALLEX, SAGE	First observation of “neutrino disappearance” dates more than 20 years ago: “Solar neutrino problem”
	Water experiments: (Super)Kamiokande, IMB	Confirm disappearance of solar neutrinos
	Heavy water: SNO	Ultimate “solar neutrino experiment”: proves the oscillation of solar ν
Atmospheric neutrinos	(Super)Kamiokande	Oscillation signal
Accelerator	LSND much disputed KARMEN and MiniBooNE	Oscillation signal refuted
	K2K	Clear disappearance signal
	MINOS	Clear disappearance signal
Reactor	KamLAND, CHOOZ	Clear disappearance signal

Two-Flavor mixing: $$P(\nu_\alpha \to \nu_\beta; t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$



NOvA (NuMI Off-Axis ν_e Appearance) is an experiment designed to detect neutrinos in Fermilab's beam. NOvA will consist of two detectors, one at Fermilab, and one in northern Minnesota. Neutrinos from NuMI will pass through 810 km of Earth to reach the far detector. NOvA's main goal is to observe the oscillation of muon neutrinos to electron neutrinos. By observing how many neutrinos change from one type to the other, NOvA hopes to accomplish three things:

- Measurement of the mixing angle θ_{13}
- Measurement of the CP-violating phase δ
- Determination of the neutrino mass hierarchy

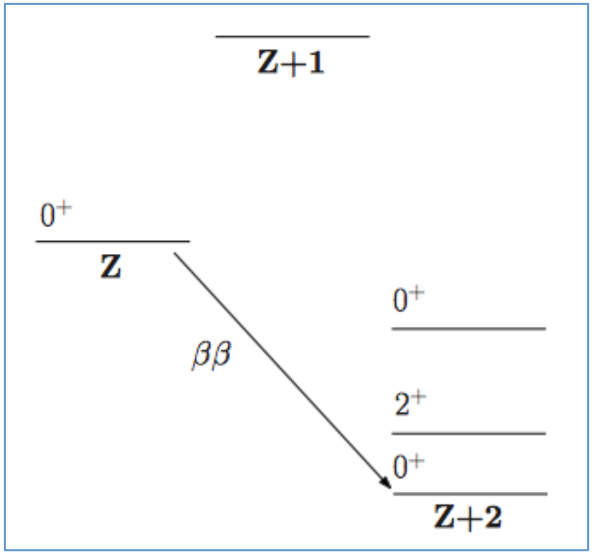


Map of neutrino oscillation experiments:

https://www.google.com/maps/d/viewer?mid=zce_hWSL7m0M.kN6wN7ec_r28

Double beta decay

http://journals.aps.org/rmp/abstract/10.1103/RevModPhys.80.481



Seen in: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{150}Nd,…

a second-order weak process
(a very weak indeed!)

$$\langle f|V_{\text{int}}|i\rangle = \sum_n \frac{\langle f|V|n\rangle\langle n|V|i\rangle}{E_i - E_n}$$

$$\boxed{{}^{A}_{Z}X_N \rightarrow {}^{A}_{Z+2}Y_{N-2} + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e}$$

A list of the values of ννββ half-lives

Isotope	$T^{2\nu}_{1/2}$ (yr)	Isotope	$T^{2\nu}_{1/2}$ (yr)
^{48}Ca	$(4.2^{+2.1}_{-1.0})\times 10^{19}$	^{128}Te	$(2.5\pm0.3)\times 10^{24}$
^{76}Ge	$(1.5\pm0.1)\times 10^{21}$	^{130}Ba EC-EC(2ν)	$(2.2\pm0.5)\times 10^{21}$
^{82}Se	$(0.92\pm0.07)\times 10^{20}$	^{130}Te	$(0.9\pm0.1)\times 10^{21}$
^{96}Zr	$(2.0\pm0.3)\times 10^{19}$	^{150}Nd	$(7.8\pm0.7)\times 10^{18}$
^{100}Mo	$(7.1\pm0.4)\times 10^{18}$	^{238}U	$(2.0\pm0.6)\times 10^{21}$
^{116}Cd	$(3.0\pm0.2)\times 10^{19}$	^{136}Xe	2.2×10^{21}

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.107.212501

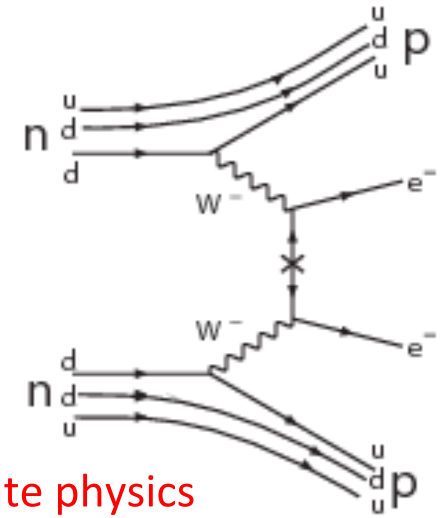
Typical lifetimes are of the order of 10^{21} years. To be compared with 13.8 billion years = $13.8\cdot 10^9$ years.

Neutrinoless double beta decay

It was suggested that neutrino can be identical or different to its charge conjugate:

$$\mathcal{C}|\upsilon\rangle \equiv |\overline{\upsilon}\rangle = |\upsilon\rangle \quad \text{(Majorana particle)}$$

$$\mathcal{C}|\upsilon\rangle \equiv |\overline{\upsilon}\rangle \neq |\upsilon\rangle \quad \text{(Dirac particle)}$$



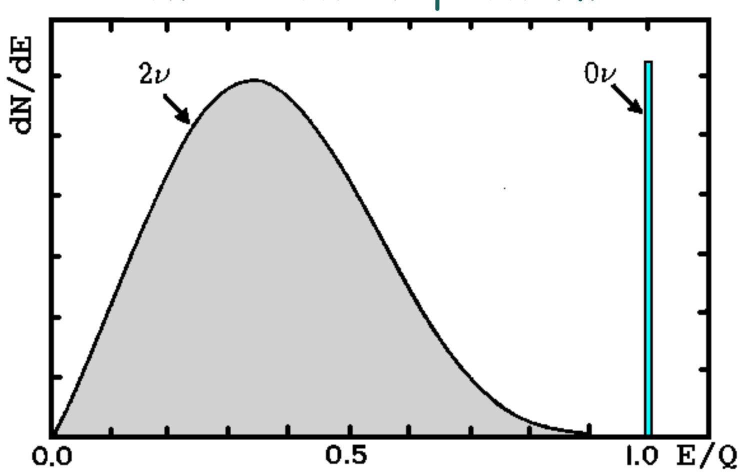
Majorana particles appear in a natural way in GUT theories that unify the strong and electroweak interactions with the possibility that *the lepton number is no longer conserved*, since now the emitted antineutrino could be absorbed as neutrino.

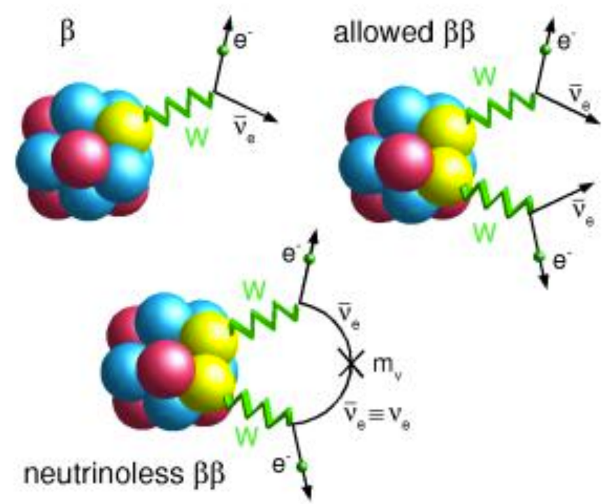
Majorana Fermions in nuclear, particle and solid-state physics
(RMP Colloquium, http://arxiv.org/abs/1403.4976)

$$\boxed{{}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+2}Y_{N-2} + e^{-} + e^{-}}$$

The estimated transition probability for the 0νββ decay is more than 10^5 shorter than the 2νββ decay

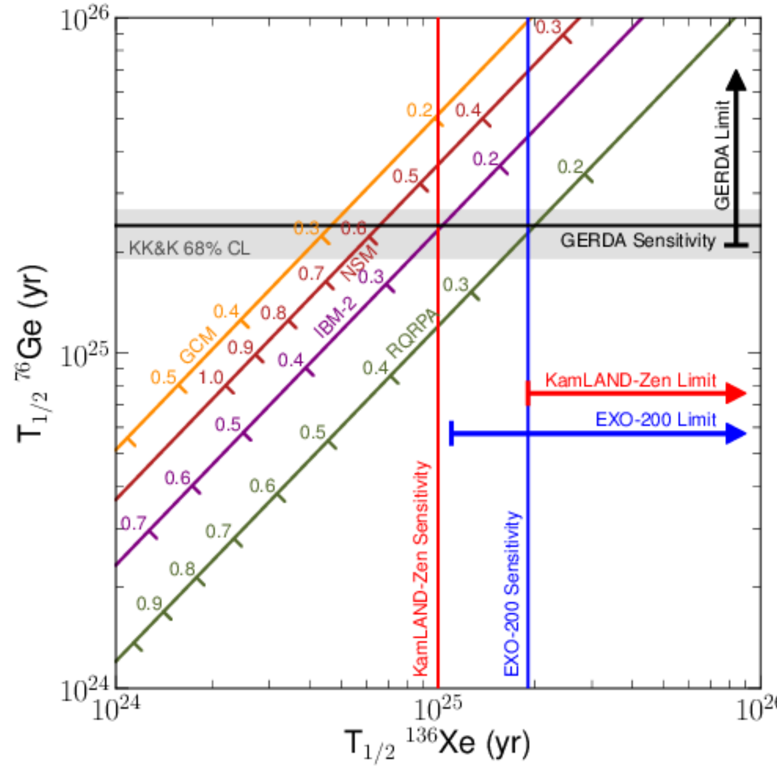
two-electron spectrum





The Enriched Xenon Observatory (EXO-200) uses large amounts of ^{136}Xe

Recent searches carried out with ^{76}Ge (the GERDA experiment) and ^{136}Xe (the KamLAND-Zen and EXO (Enriched Xenon Observatory)-200 experiments) have established the lifetime of this decay to be longer than 10^{25} years, corresponding to a limit on the neutrino mass of 0.2–0.4 electronvolts. Recently, EXO-200 found no statistically significant evidence for $0\nu\beta\beta$ decay and set a half-life limit of 1.1×10^{25} years at the 90 per cent confidence level.



http://www.nature.com/nature/journal/v510/n7504/full/nature13432.html
http://physicsworld.com/cws/article/news/2014/jun/11/exo-200-narrows-its-search-for-majorana-neutrinos
http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.109.032505

The MAJORANA Neutrinoless Double-beta Decay Experiment

http://www.npl.washington.edu/majorana/

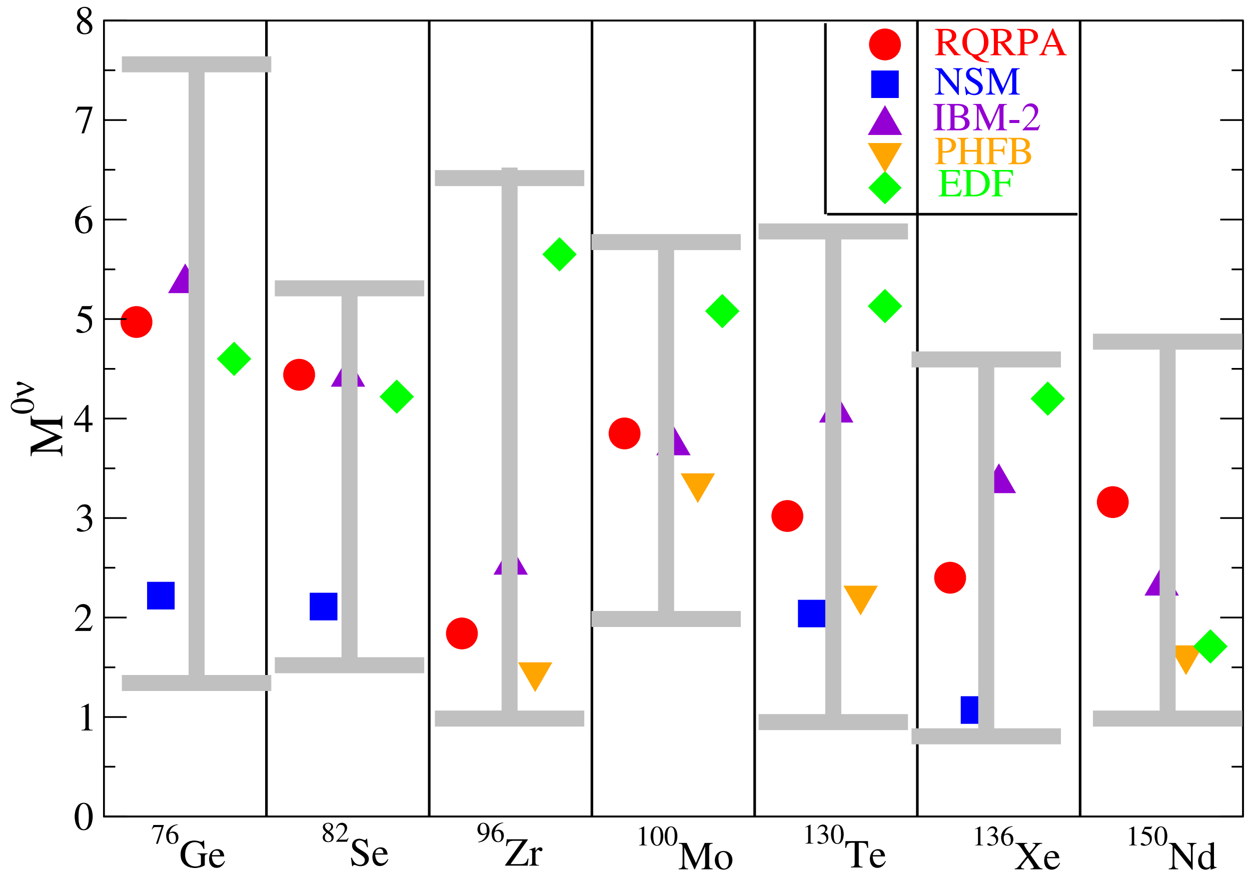
The MAJORANA Collaboration proposes to search for neutrinoless double-beta decay using an array of germanium crystals enriched in ^{76}Ge. Of the candidate isotopes for $0\nu\beta\beta$, ^{76}Ge has some of the most favorable characteristics. Germanium-diode detectors are a well established technology, and in searches for $0\nu\beta\beta$ of ^{76}Ge, the detectors can work as both source and detector.

TABLE II A summary list of the $\beta\beta(0\nu)$ proposals and experiments. The Q-Value is the available energy for the decay as referenced in the text.

Isotope	Q-Value (MeV)	Technique	Collaborations
^{48}Ca	4.274	CaF_2 scintillating crystals	CANDLES(Umehara *et al.*, 2008), CARVEL(Zdesenko *et al.*, 2005)
^{82}Se	2.995	ZnSe scintillating bolometers Thin foils and tracking	LUCIFER(Arnaboldi *et al.*, 2011) SuperNEMO(Barabash *et al.*, 2012)
^{76}Ge	2.039	high purity Ge semiconductor detectors	GERDA(Agostini *et al.*, 2013), MAJORANA(Abgrall *et al.*, 2013)
^{100}Mo	3.034	$CaMoO_4$bolometers Thin foils and tracking $ZnMoO_4$bolometers	AMoRE(Lee *et al.*, 2011) MOON(Ejiri *et al.*, 2000) Mo Bolometer(Beeman *et al.*, 2012)
^{116}Cd	2.809	CZT semiconductor detectors	COBRA(Dawson *et al.*, 2009)
^{130}Te	2.528	TeO_2bolometers Te disolved in scintillator	CUORE(Alessandria *et al.*, 2011) SNO+(Hartnell, 2012)
^{136}Xe	2.458	liquid Xe time projection chamber Gaseous Xe time projection chamber Xe dissolved in scintillator Scint. liq. Xe within Graphene sphere	EXO-200(Auger *et al.*, 2012), nEXO, LZ(Akerib *et al.*, 2013a) NEXT(Gómez *et al.*, 2011) KamLAND-Zen(Gando *et al.*, 2013) GraXe(Gómez-Cadenas *et al.*, 2012)
^{150}Nd	3.371	thin foils and tracking	DCBA(Ishihara *et al.*, 2000)
^{160}Gd	1.730	Cd_2SiO_5:Ce scint. crystals in liq. scint.	GSO(Wang *et al.*, 2002)
Various		Quantum dots in liquid scintillator	Quantum Dots(Aberle *et al.*, 2013; Winslow and Simpson, 2012)

RMP Colloquium, http://arxiv.org/abs/1403.4976

Current 0νββ predictions of nuclear matrix element

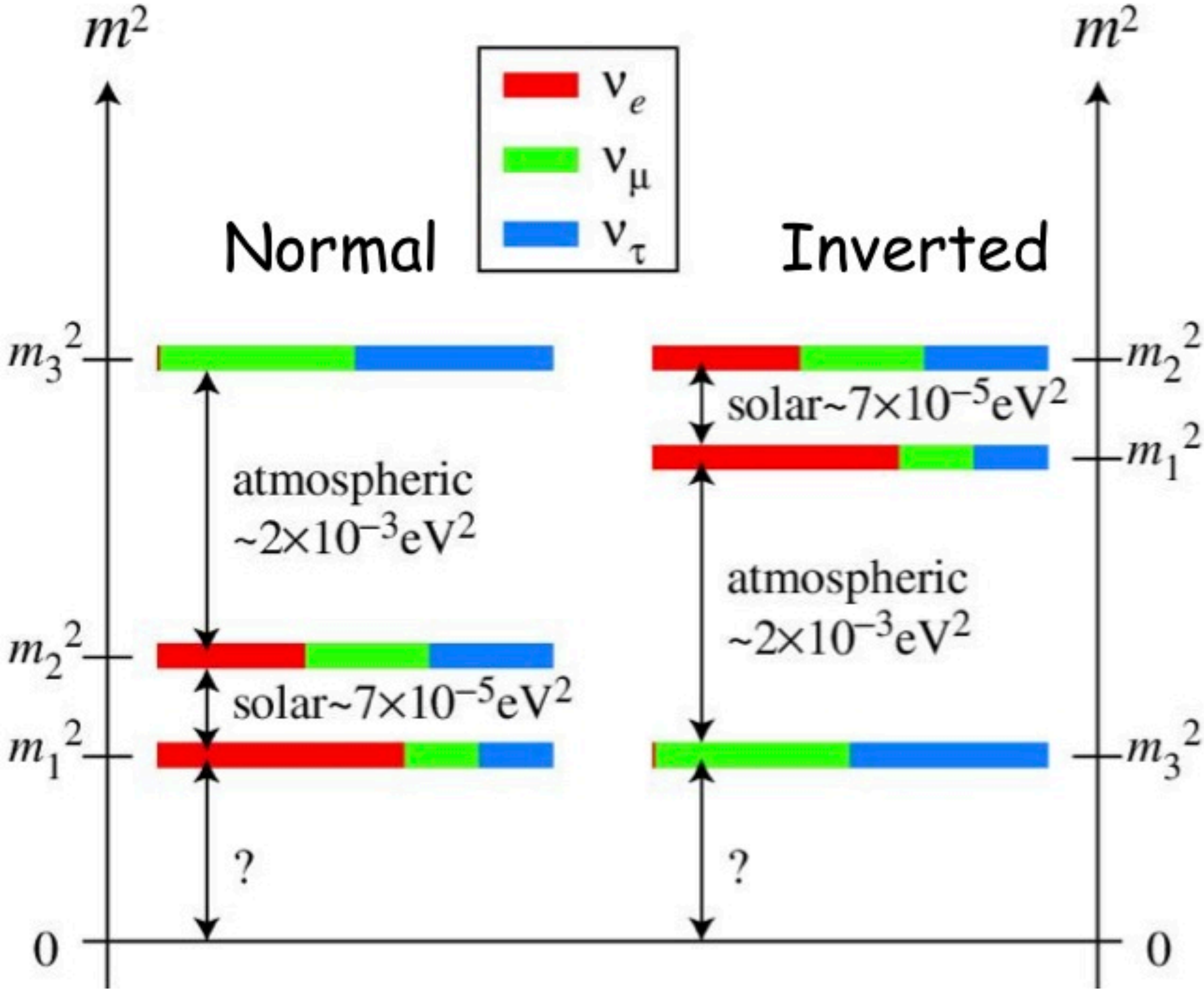


"There is generally significant variation among different calculations of the nuclear matrix elements for a given isotope. For consideration of future experiments and their projected sensitivity it would be very desirable to reduce the uncertainty in these nuclear matrix elements."

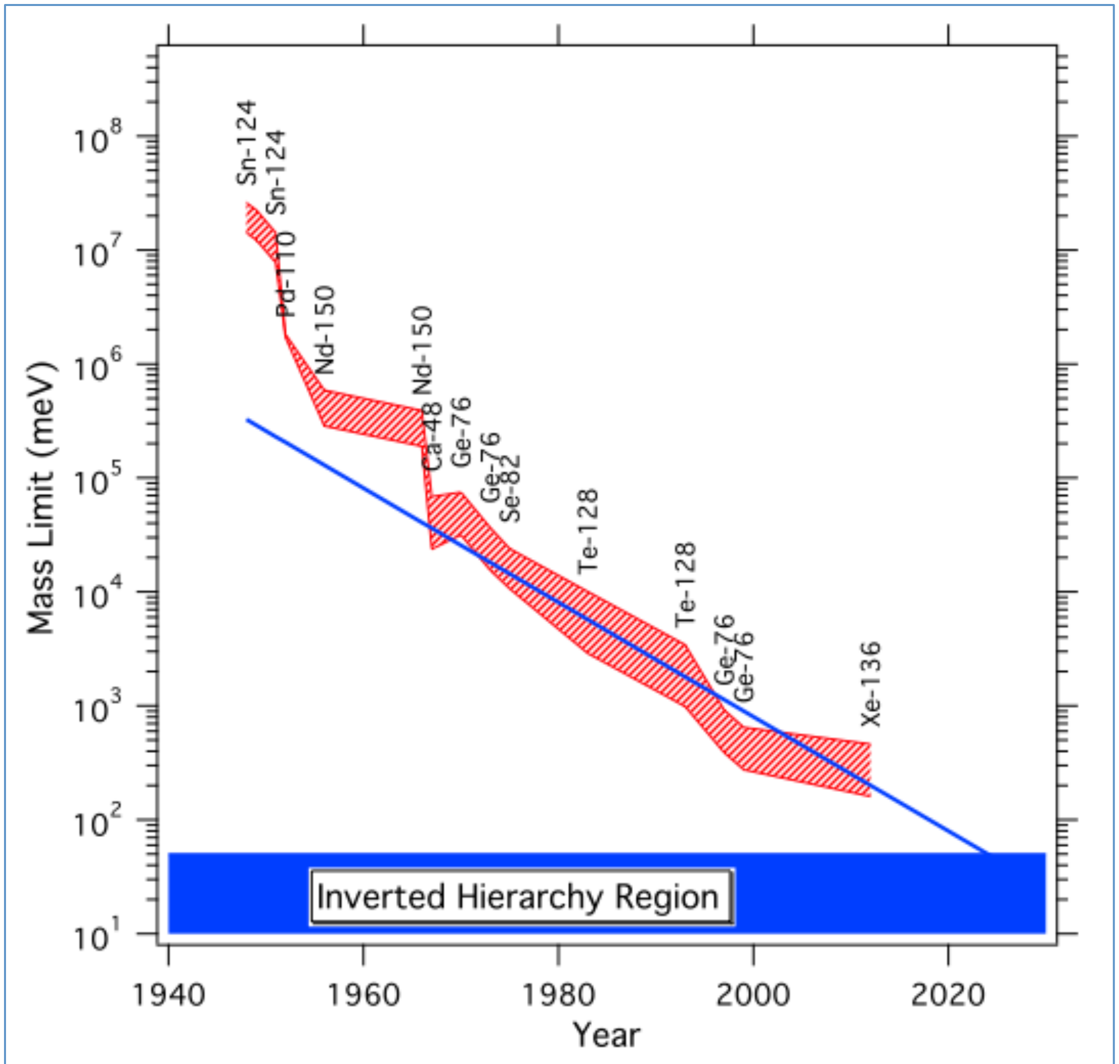
(Neutrinoless Double Beta Decay NSAC Report 2014)

http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf

Neutrino mass hierarchy

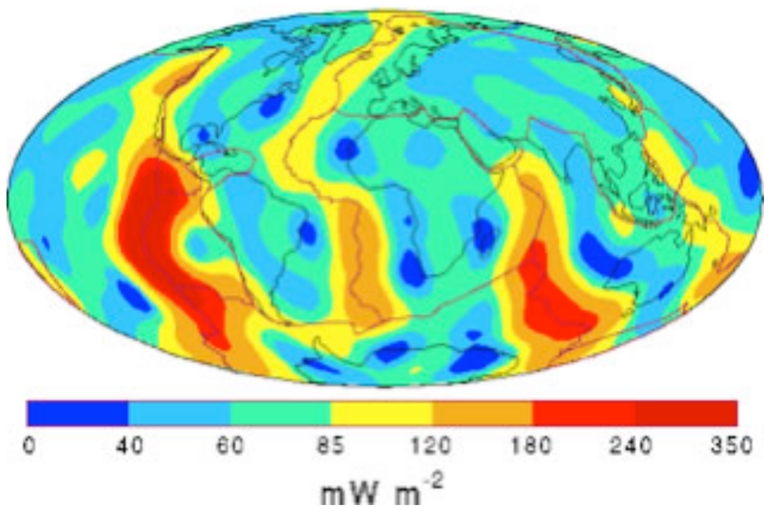


The limit improves by about a factor of 2 every 6 years. If this trend continues, the inverted-hierarchy goal for the Majorana mass sensitivity below 50 meV should be explored during the coming decade or so. Within the next few years, the presently operating experiments and those due to come online should extend the reach below 100 meV.



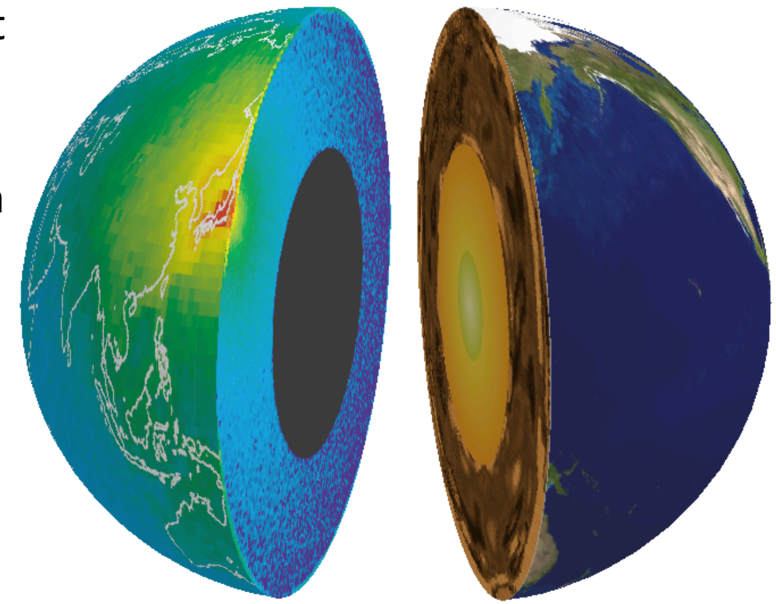
Neutrino as a tool

The total heat flow from the Earth is an estimated 40 tera-watts. Geologists believe that the most significant sources of this heat—and therefore, the likely driving force for plate tectonics, earthquakes, and the geomagnetic field— are the natural decays of uranium and thorium distributed throughout the Earth.



Distribution of the Earth's heat flow. Reviews of Geophysics 31, 267 (1993)

Geoneutrinos



Left: the production distribution for the geoneutrinos detected at KamLAND; Right: the geologic structure. Nature 436, 499 (2005). Geoneutrinos offer the only known method to directly measure the chemical composition at depths greater than a few miles.

Using antineutrinos to monitor nuclear reactors

http://physicsworld.com/cws/article/news/2014/aug/12/using-antineutrinos-to-monitor-nuclear-reactors

Neutrino Test of Lorentz Invariance

http://physics.aps.org/synopsis-for/10.1103/PhysRevD.91.052003

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.91.052003

A search for neutrino oscillations induced by Lorentz violation has been performed using 4,438 live-days of Super-Kamiokande atmospheric neutrino data. The Lorentz violation is included in addition to standard three-flavor oscillations using the nonperturbative standard model extension (SME), allowing the use of the full range of neutrino path lengths, ranging from 15 to 12,800 km, and energies ranging from 100 MeV to more than 100 TeV in the search. No evidence of Lorentz violation was observed, so limits are set on the renormalizable isotropic SME coefficients in the eμ, μτ, and eτ sectors, improving the existing limits by up to 7 orders of magnitude and setting limits for the first time in the neutrino μτ sector of the SME