Studying Neutrinos with the EXO Experiment

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Neutrinos

What are Neutrinos?

- Massive, but lighter than any known particle
- Important in nuclear-, particle-, and astro-physics
- Only interact weakly
- Leptons, paired with the electron (and its heavier siblings the muon and tau)

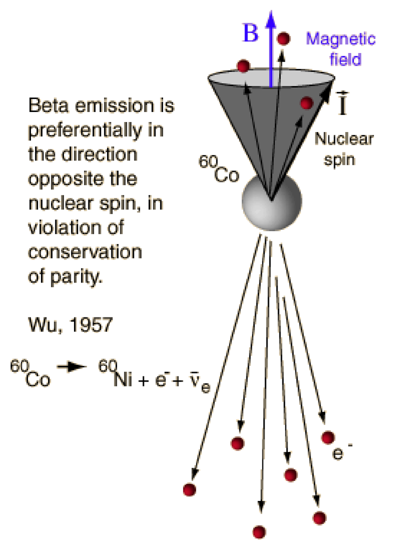
Neutrino Properties	
Spin	1/2
Charge	0
Types	e, μ, τ
Lifetime	stable
Theorized (ν_e)	1930
ν_e Discovered	1956

Neutrinos and Beta Decay

Beta decay is a standard radioactive decay:

$$n^0 \to p^+ + e^- + \bar{\nu}_e$$

It provided the first evidence for neutrinos as energy-mass conservation appeared broken. Additionally, the classic beta-decay experiment by C.S. Wu showed that there is not a symmetry between 'right-handed' and 'left-handed' decays. We observe that neutrinos are always left-handed and anti-neutrinos are right-handed.



Neutrino Mass

Neutrino mass is an important question in particle physics:

- How do neutrinos get mass?
- Why is the neutrino so much lighter than all particles?
- What does this mean for CP-violation and handedness?

The observation of neutrino oscillation in the 1990's proved that neutrinos are not massless. The flavor eigenstates (e, μ, τ) are different from the mass eigenstates, which allows a neutrino produced as a ν_μ to later be detected as a ν_e. A large part of neutrino physics is measuring these mixing parameters.

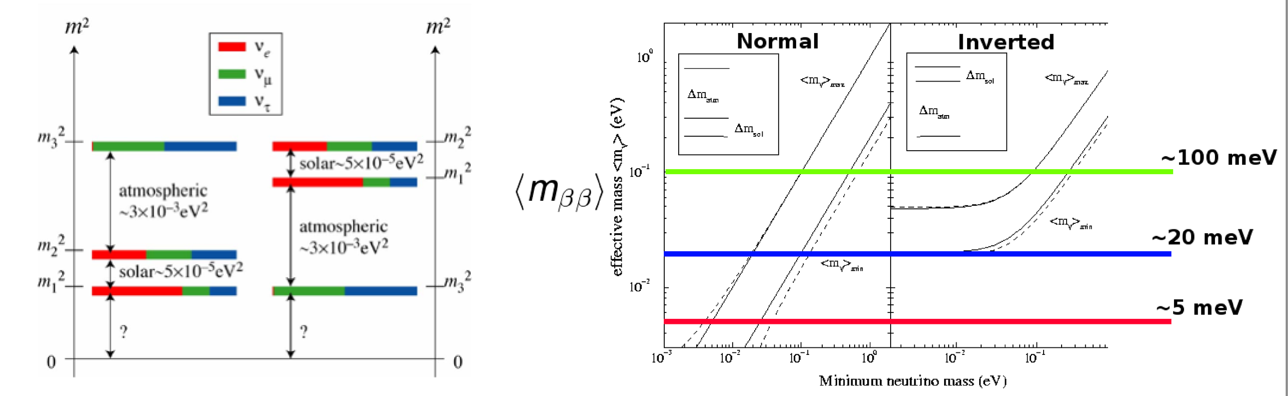


Figure: *Oscillation experiments* have provided the mass differences between the 3 types of neutrinos, we don't know the overall mass scale or the mass ordering.

Measuring the mass of the neutrino can be done in a variety of ways, including:

Field	Technique	Limit (eV)
Particle Physics	Double Beta Decay	$\langle m_{\beta\beta} \rangle$<0.22 - 0.41
Particle Physics	Tritium Endpoint	m_{ν_e}<2
Astrophysics	CMB+LLS+SN1A	Σm_ν<0.66
Astrophysics	WMAP+SDSS	Σm_ν<1.3

Neutrinoless double beta decay can not only measure the mass scale, but (if seen) will establish that the neutrino is its *own antiparticle*. Additionally, if the effective neutrino mass is below about 20 meV then the inverted hierarchy will be ruled out.

A. S Barabash. *0807.2948*, July 2008.
Otten, E. W. and Weinheimer, C. *Rept. Prog. Phys.* 71, 2008
D. N. Spergel et al. *Astrophys. J. Suppl.*, 170:377, 2007.

Double Beta Decay

Double Beta Decay

Standard Model process, second order:

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

The half life is given by:

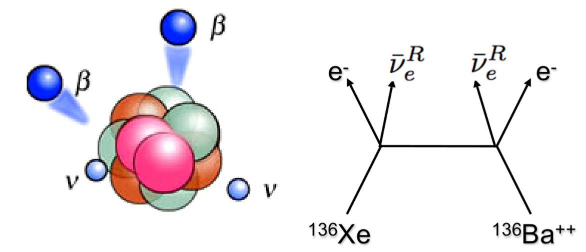
$$\left[T^{2\nu}_{1/2}\right]^{-1} = G^{2\nu}(E,Z)\left|M^{2\nu}_{GT}\right|^2$$

where

- $G^{2\nu}(E,Z)$ is a phase space dependence that is accurately calculable
- $\left|M^{2\nu}_{GT}\right|^2$ is the Nuclear Matrix Element, a unitless number of order 1 that is derived from nuclear theory

To see evidence of double beta decay:

- The isotope cannot undergo single beta decay (or another decay).
- A large number of atoms is needed.
- A higher Q-value increases the rate substantially.



Isotope	2ν Half life (yrs)	Q (MeV)
^{48}Ca	4.3×10^{19}	4.27
^{76}Ge	1.5×10^{21}	2.04
^{82}Se	0.9×10^{20}	3.00
^{100}Mo	7.1×10^{18}	3.03
^{116}Cd	3.0×10^{19}	2.81
^{130}Te	0.9×10^{21}	2.53
^{136}Xe	$>1\times10^{22}$	2.46

A. S Barabash. *0807.2948*, July 2008.

Neutrinoless Double Beta Decay

Similar to 'normal' double beta decay, except no neutrinos are emitted:

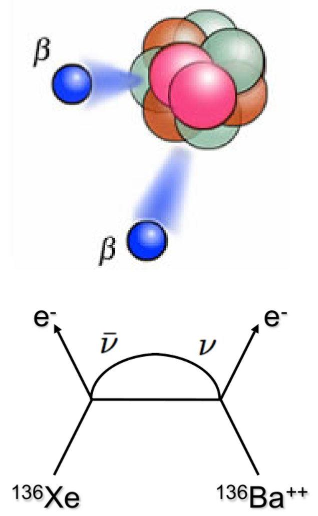
$$(A,Z) \to (A,Z+2) + 2e^-$$

Only occurs if:

- $\nu = \bar{\nu}$ Neutrinos are their own antiparticle
- $m_\nu \neq 0$ Neutrinos are massive
- $\Delta L_e = 2$ Lepton number is not conserved

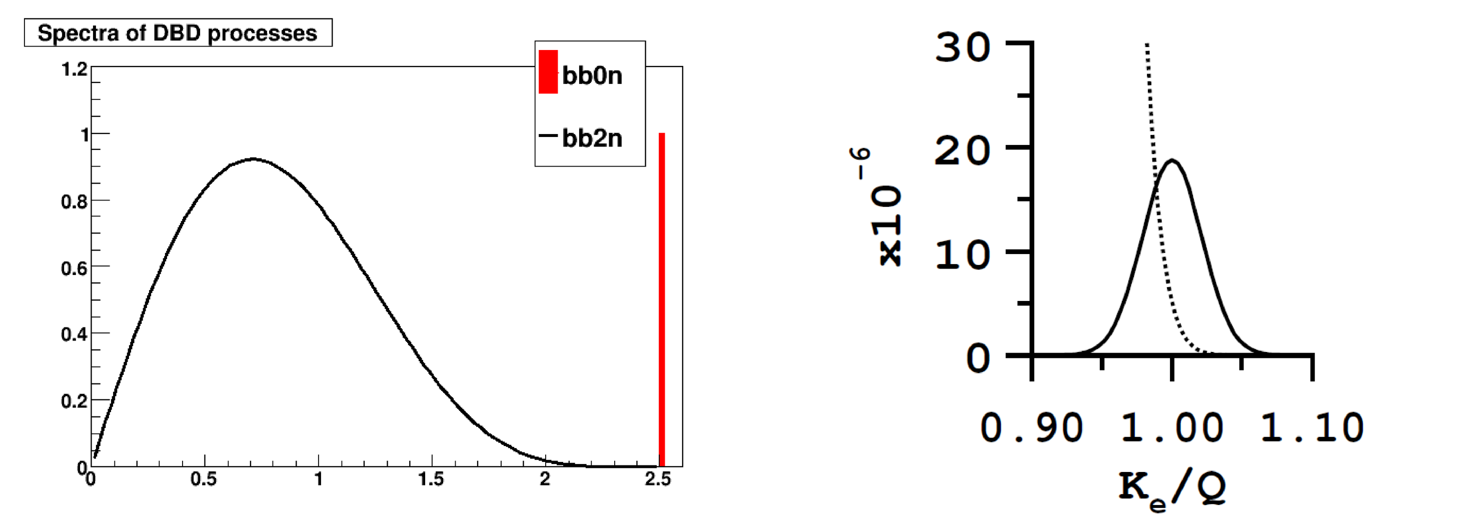
The half life is given by:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$



where

- $G^{0\nu}(E_0,Z)$ is a phase space dependence that is accurately calculable
- $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U^2_{e,i} m_i e^{i\phi_i}\right|^2$ is the effective neutrino mass
- $\left|M^{0\nu}\right|^2$ is the Nuclear Matrix Element, a unitless number of order 1 that is derived from nuclear theory and includes more than the Gamow-Teller term that is in the 2ν equation.



(a) In the 0ν all of the energy is in the 2 electrons, but in the 2ν neutrinos carry away energy, making the two processes easily distinguishable. (b) The 0ν signal will likely be a small bump on the end of the 2ν spectrum. This illustrates the relative sizes if the rate is 10^6 higher for the 2ν mode with 5% resolution.

The sensitivity to neutrinoless double beta decay is given by:

$$S^{0\nu}_{1/2} \propto \epsilon\frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2}$$

ϵ=efficiency, a=isotopic abundance
A=atomic mass, M=source mass
T=running time, B=background
Γ= resolution.

So the goal of the experiment is to **maximize** the time, enrichment, and mass while **minimizing** the background and **improving** resolution.

EXO

EXO-200

- 200 kg Liquid Xenon, enriched to 80% in ^{136}Xe.
- Time Projection Chamber (TPC) Design
- Constructed with ultrapure materials in clean room
- LXe temp (160K) maintained in double cryostat

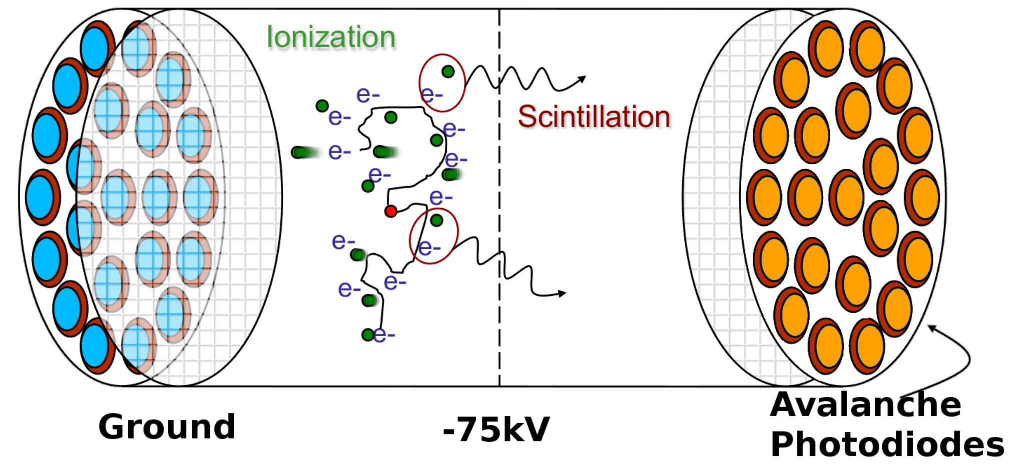


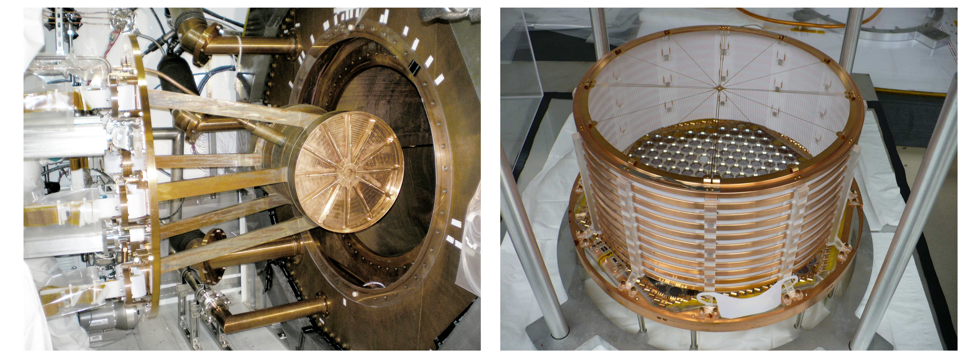
Figure: Diagram of the concept of our TPC. The scintillation provides the time the event occurred, the drift time is used to determine the distance of the event along the axis, and the wires the electrons are collected on determine the r, θ position.

Table: The predicted EXO-200 sensitivity to neutrinoless double beta decay, based upon nominal experimental parameters and recent nuclear matrix element calculations.

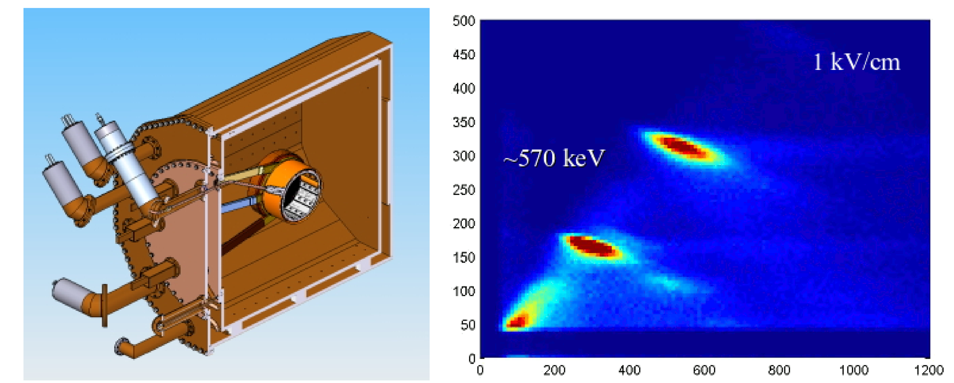
Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @2.5 MeV (%)	Back-ground (events)	$T^{0\nu}_{1/2}$ (yr) 90%CL	Majorana Mass (meV) QRPA	NSM
0.2	70	2	1.6	40	6.4×10^{25}	133	186

V.A. Rodin, Amand Faessler, F. Simkovic, and Petr Vogel. *Nuc. Phys. A*, 793(1-4):213 – 215, 2007.
E. Caurier, J. Menéndez, F. Nowacki, and A. Poves. *Phys. Rev. Lett.*, 100(5):052503, 2008.

(a) The avalanche photodiodes (APDs) and readout circuits, which is copper traces on kapton. (b) The detection side of the APDs and the charge collection wires. All connections were made with springs to reduce material and not introduce contaminants through solder.



(c) The vessel containing the TPC inserted into the cryostat. The copper 'legs' circulate LXe and contain the readout cables. (d) Top view of half of the TPC showing the field shaping rings and cathode plane.



(e) Diagram of vessel in cryostat. The HFE that surrounds the TPC helps block neutrons . (f) EXO measurements of ionization-scintillation coincidence, which demonstrates an improved resolution from measuring only one of the signals.

WIPP

The Waste Isolation Pilot Plant (WIPP) is a facility in southeastern New Mexico to demonstrate the permanent disposal of transuranic waste in underground salt.

- 2150 ft (700m) underground
- Salt overburden provides 1500 m.w.e. muon stopping power
- Salt is naturally low in radioactivity

Underground 6 clean room modules are installed, with 10 support 'buildings'

- Clean rooms moved from Stanford to WIPP with cryostat inside
- Cryostat in class-100 clean environment
- UPS provides 2 days critical electrical power
- Personal underground machine shop

Figure: The TPC in the mine, about to enter the cleanrooms

The Future of EXO

The EXO collaboration is in the R&D process for a ton-scale experiment. A major focus of the research is on methods to identify single ions of Ba^{136}, enabling the rejection of all backgrounds.

Table: Ton-Scale EXO sensitivities to neutrinoless double beta decay in two possible cases. These assume barium-tagging removes all radioactive backgrounds but has a 70% detection efficiency. The aggressive estimate assumes we are successful in improving our resolution.

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @2.5 MeV (%)	2νββ BG (events)	$T^{0\nu}_{1/2}$ (yr) 90%CL	Majorana Mass (meV) QRPA	NSM
Conserv.	1	70	5	1.6	0.5 (use 1)	2×10^{27}	24	33
Aggress.	10	70	10	1	0.7 (use 1)	4.1×10^{28}	5.3	7.3

V.A. Rodin, Amand Faessler, F. Simkovic, and Petr Vogel. *Nuc. Phys. A*, 793(1-4):213 – 215, 2007.
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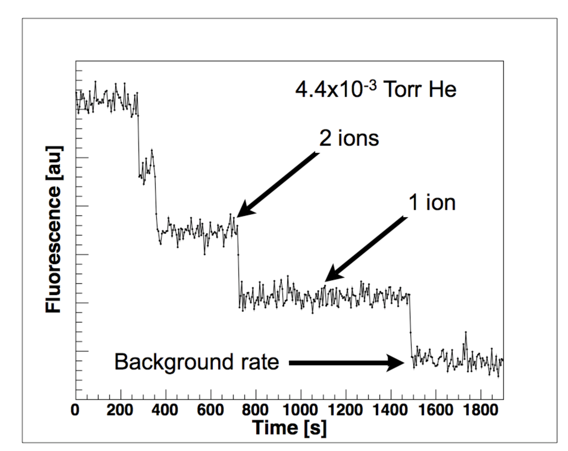

Figure: Data showing the ability to detect single barium ions.