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):

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

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

extremely small cross sections!

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

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

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

mean-free path

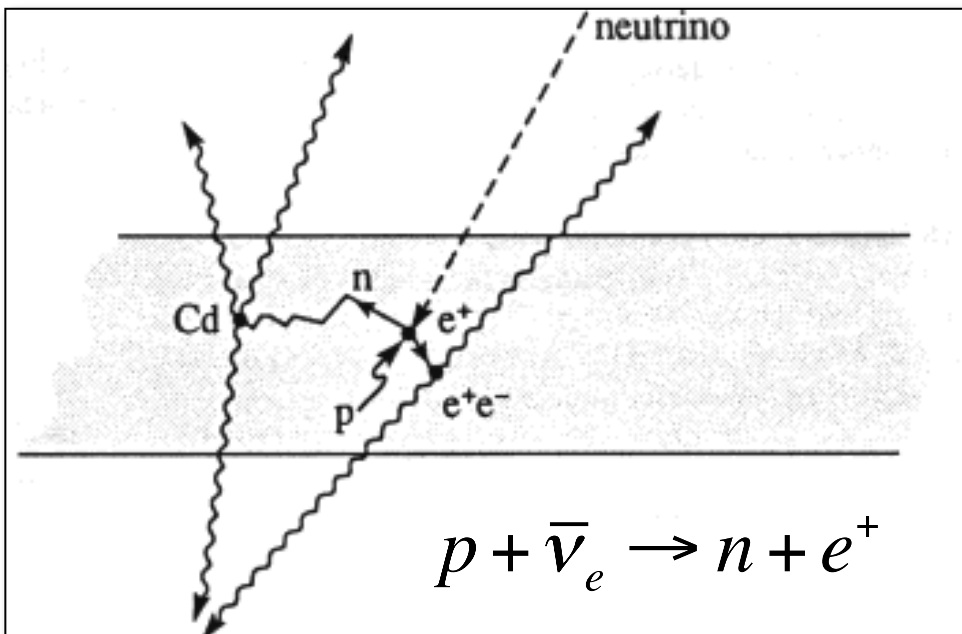
$$ \ell = \frac{1}{n\sigma} $$

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.



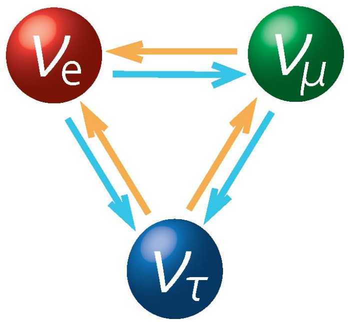
$$p + \overline{\nu}_e \rightarrow n + e^+$$

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, which participates in weak interactions, is composed of a combination of three different mass states



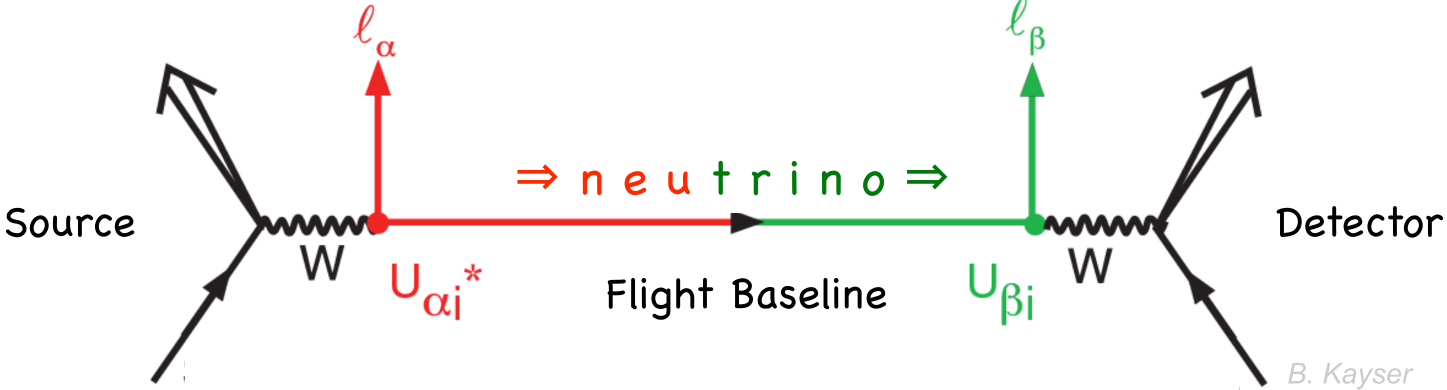
mass eigenstates ≠ flavor eigenstates

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix describes neutrino flavor mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor mass

The PMNS matrix is usually parametrized in terms of mixing angles, e.g., θ_{ij}

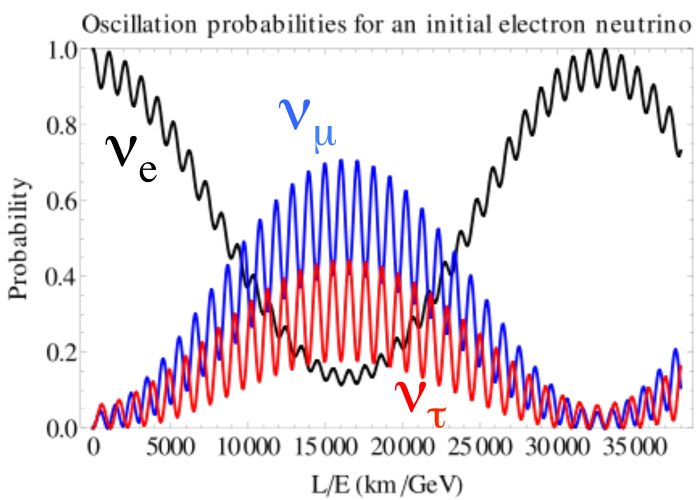


$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2\left(\Delta m_{ij}^2 \frac{L}{4E}\right)$$

$$\pm 2\sum_{i>j} \mathrm{Im}[U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin\left(\Delta m_{ij}^2 \frac{L}{2E}\right)$$

Mass-squared splittings.

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

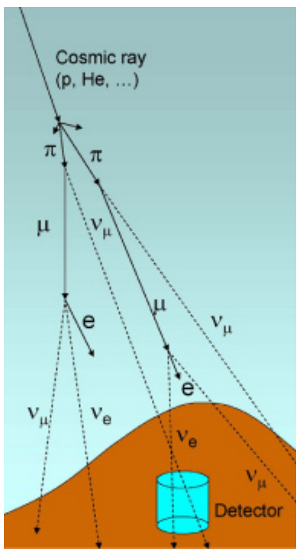


Two-Flavor mixing:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$= \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Observation of Neutrino Oscillations



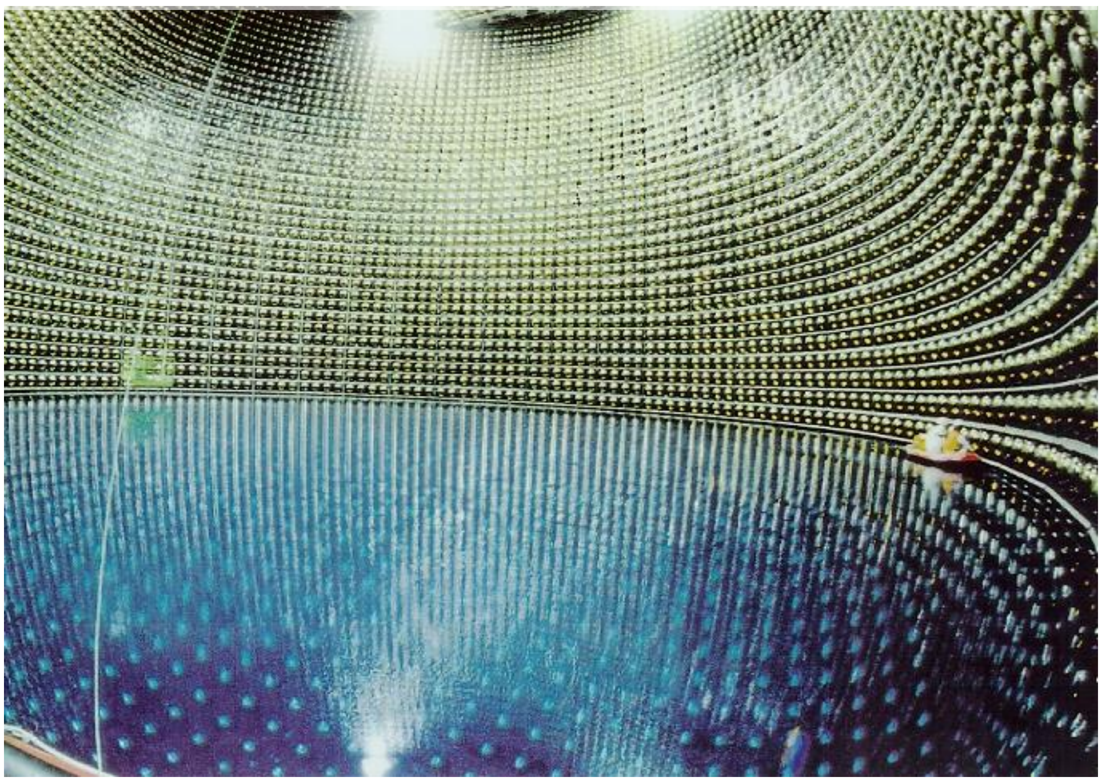
Neutrino source	Experiment	Comments
Solar neutrinos $p + p \rightarrow d + e^+ + \nu_e$	Radio-chemical exp.: Homestake Cl exp., GALLEX, SAGE	First observation of "neutrino disappearance" dates more than 20 years ago: "Solar neutrino problem"
	Water experiments: (Super)Kamiokande, IMB	Confirm disappearance 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

http://www.symmetrymagazine.org/article/november-2012/how-to-make-a-neutrino-beam

Super-Kamiokande

50,000 ton tank of water located 1 km underground

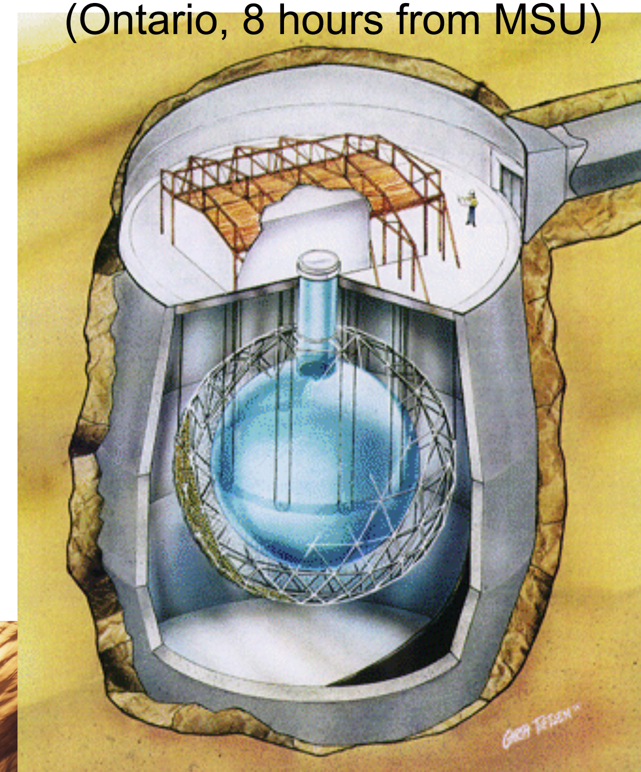
On February 23, 1987, the Super-Kamiokande detected, for the first time, neutrinos from a supernova (SN1987A) explosion. This observation confirmed that the theory of supernova explosion was correct and was the dawn of a new era in neutrino astronomy.

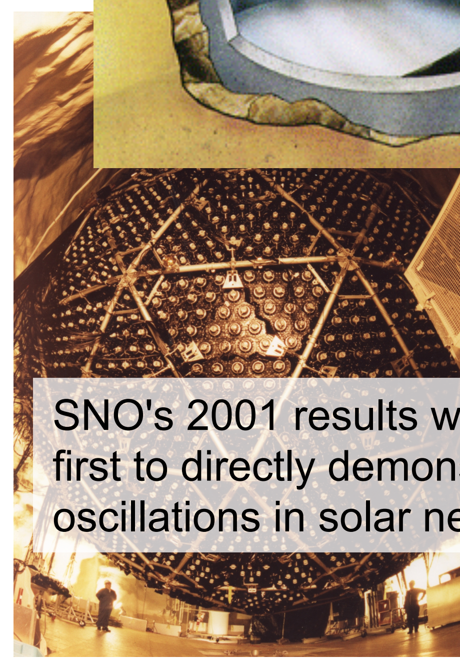


Cherenkov neutrino detectors

Cherenkov radiation is the optical equivalent to a sonic boom

Sudbury Neutrino Observatory
(Ontario, 8 hours from MSU)





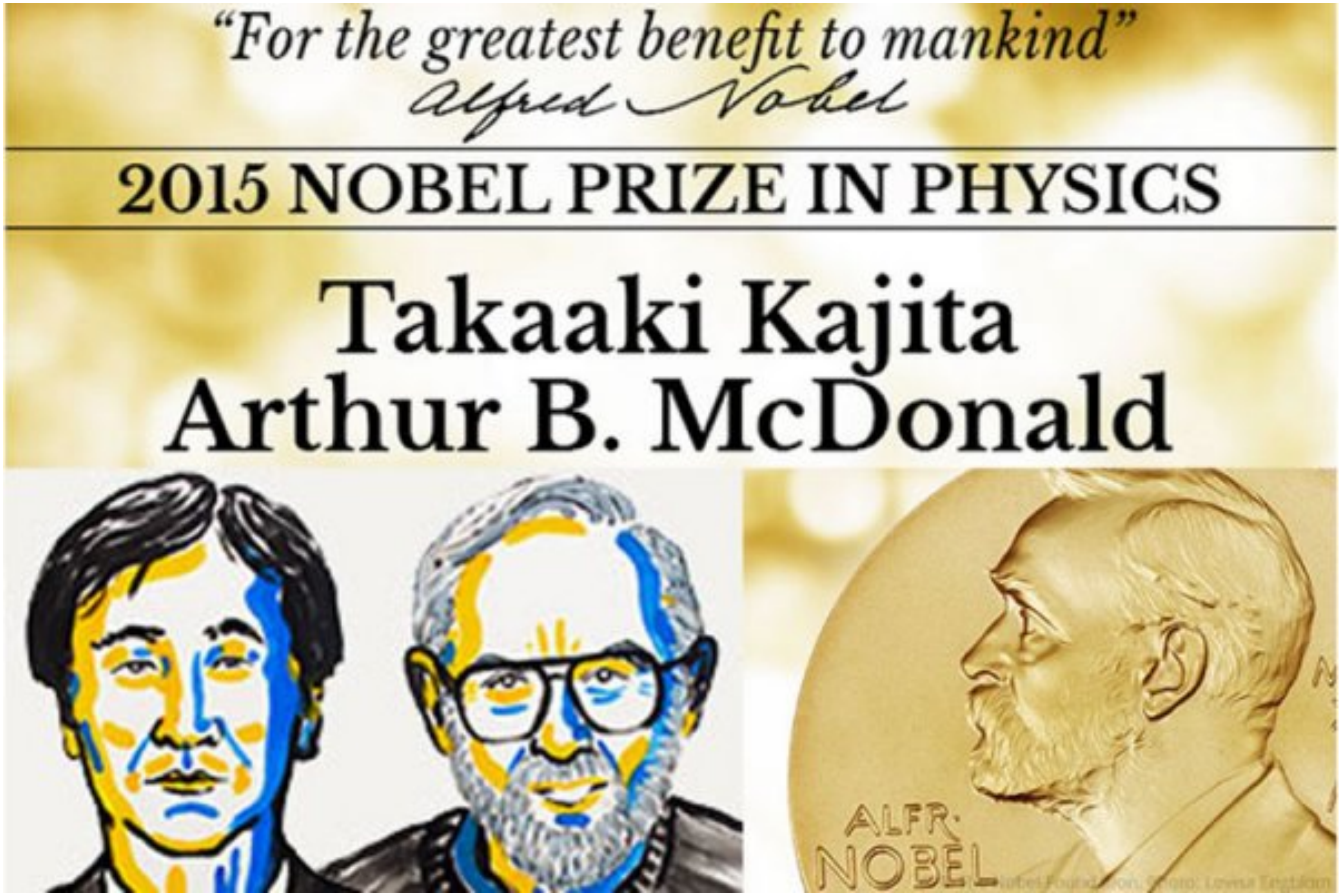
SNO

SNO's 2001 results were the first to directly demonstrate oscillations in solar neutrinos

1,000 tons of heavy water;
2 km underground

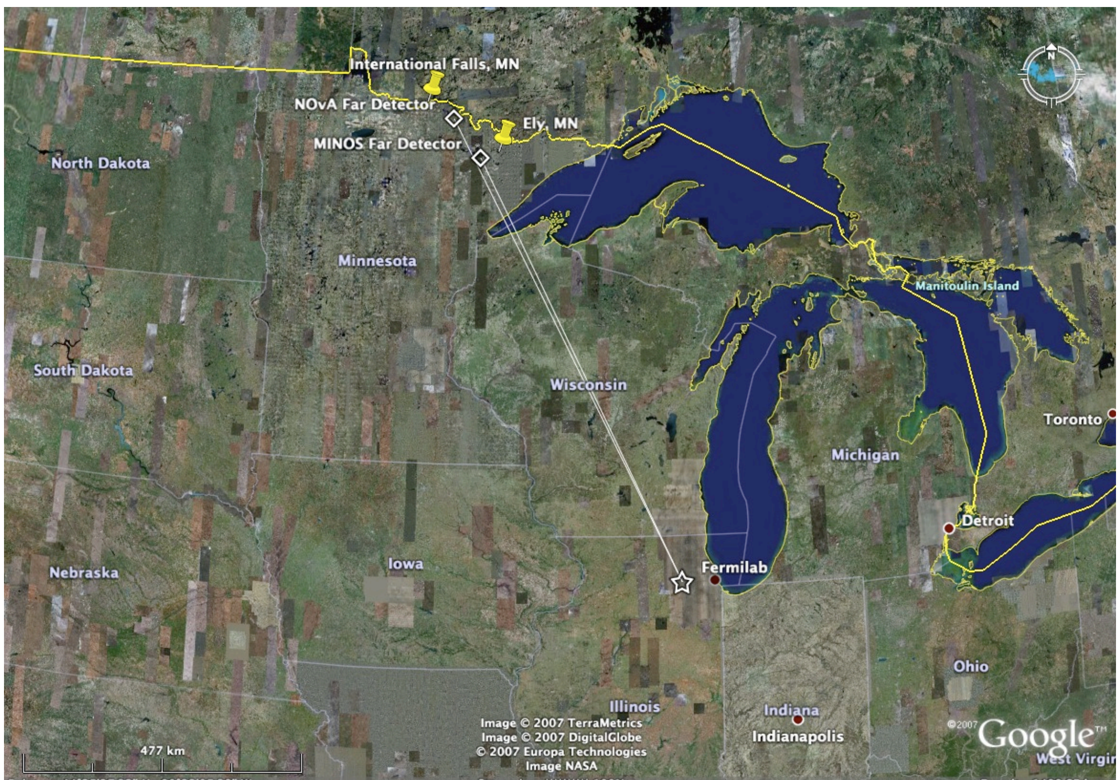
Nobel Prize 2015: Neutrinos Oscillate

The 2015 Nobel Prize in Physics has been awarded to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".



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

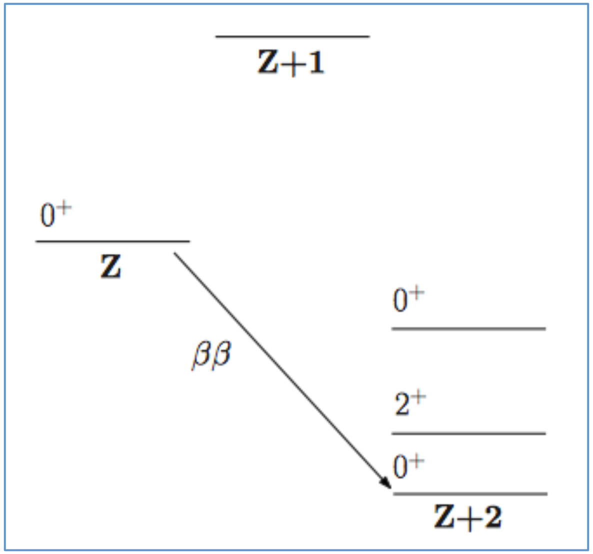


Map of neutrino oscillation experiments:

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	$(4.2^{+2.1}_{-1.0})\times10^{19}$	^{128}Te	$(2.5\pm0.3)\times10^{24}$
^{76}Ge	$(1.5\pm0.1)\times10^{21}$	^{130}Ba EC-EC(2ν)	$(2.2\pm0.5)\times10^{21}$
^{82}Se	$(0.92\pm0.07)\times10^{20}$	^{130}Te	$(0.9\pm0.1)\times10^{21}$
^{96}Zr	$(2.0\pm0.3)\times10^{19}$	^{150}Nd	$(7.8\pm0.7)\times10^{18}$
^{100}Mo	$(7.1\pm0.4)\times10^{18}$	^{238}U	$(2.0\pm0.6)\times10^{21}$
^{116}Cd	$(3.0\pm0.2)\times10^{19}$	^{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.