Neutrinos: Towards the 2015 Nobel Prize and Beyond

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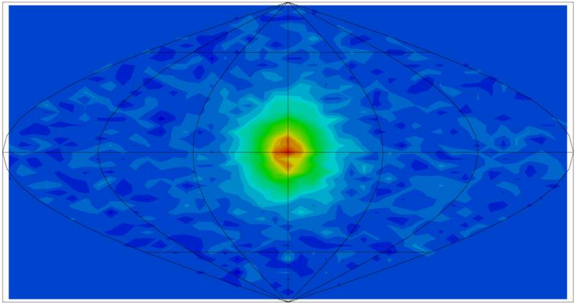
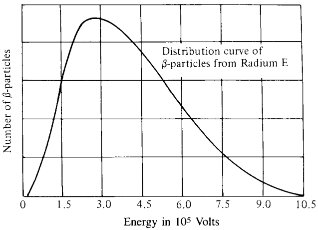


Neutrino Prehistory: Nuclear Beta Decay

- 1914: Chadwick discovers that electron energy spectrum in Nuclear Beta Decay of Radium B ($^{214}_{82}$Pb; Plumbum, Piombo, Lead) is continuous. Example: [C.D. Ellis and W.A. Wooster, 1927]



$$^{210}_{83}\mathrm{Bi} \to {}^{210}_{84}\mathrm{Po} + e^-$$

Bi = Bismuth (Radium E)

Po = Polonium

- Two-body final state $\Longrightarrow$ Energy-Momentum conservation implies that e^- has a unique energy value

- Niels Bohr proposed that energy may be conserved statistically, but energy conservation may be violated in individual decays [J. Chem. Soc. 1932, 349]

Neutrino Birth: Pauli - 4 December 1930

- 4 December 1930: Wolfgang Pauli sent a Public letter to the group of the Radioactives at the district society meeting in Tübingen

  Dear Radioactive Ladies and Gentlemen,
  ...I have hit upon a desperate remedy to save ...the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons which have spin 1/2 ... The mass of the neutron must be of the same order of magnitude as the electron mass and, in any case, not larger than 0.01 proton mass. ...

- Radium E decay: $^{210}_{83}\mathrm{Bi} \to ^{210}_{84}\mathrm{Po} + e^- +$ "neutron"
- The new particle had to be massive because it was supposed to "exist in the nuclei" as electrons and emitted in β decay (although it was not clear how an electron with Compton wavelength $\sim 10^{-10}\,\mathrm{cm}$ can be contained in a nucleus with dimensions $\sim 10^{-13}\,\mathrm{cm}$).

Neutrino Naming and Interactions: Fermi

- What we call neutron was discovered by Chadwick in 1932.
- 1933: Enrico Fermi proposes the name neutrino (Italian: small neutron) at the Solvay Congress in Brussels.
- 1933-34: Enrico Fermi formulates the theory of Weak Interactions:

Attempt at a theory of β rays

[E. Fermi, Nuovo Cimento 11 (1934) 1]

A quantitative theory of the emission of β rays is proposed in which the existence of the "neutrino" is admitted and the emission of electrons and neutrinos from a nucleus in a β decay is treated with a procedure similar to that followed in the theory of radiation in order to describe the emission of a quantum of light by an excited atom.

- At that time it was believed that particles can be emitted by a nucleus only if they existed in the nucleus before:

Attempt at a theory of the emission of β rays
[E. Fermi, Ricerca Scientifica 4 (1933) 491]

Theory of the emission of β rays by radioactive substances, based on the hypothesis that the electrons emitted by nuclei do not exist before the disintegration but are formed, together with a neutrino, in a way which is analogous to the formation of a quantum of light which accompany a quantum jump of an atom.

- Fermi used the new theory of second quantization developed by Dirac (1927), Jordan and Klein (1927), Heisenberg (1931), Fock (1932).

$$H_\gamma = e\left(\overline{\psi}\gamma^\alpha\psi\right)A_\alpha \quad \Longrightarrow \quad H_\beta = g\left(\overline{\psi_p}\gamma^\alpha\psi_n\right)\left(\overline{\psi_e}\gamma^\alpha\psi_\nu\right) + \text{H.c.}$$

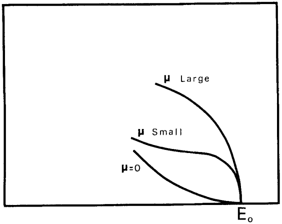
- Fermi received the 1938 Physics Nobel Prize "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons"

Neutrino Mass?

Attempt at a theory of β rays

[E. Fermi, Nuovo Cimento 11 (1934) 1]

The dependence on μ of the form of the distribution curve of the energy is especially strong near the maximum energy E_0 of the β rays.



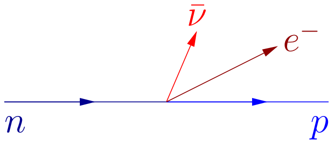
The closer similarity with the experimental curves is achieved for $\mu = 0$. Therefore we reach the conclusion that the neutrino mass is zero or, in any case, small in comparison to the electron mass.

- The same conclusion was reached with qualitative arguments by F. Perrin, Comptes Rendues 197 (1933) 1625.

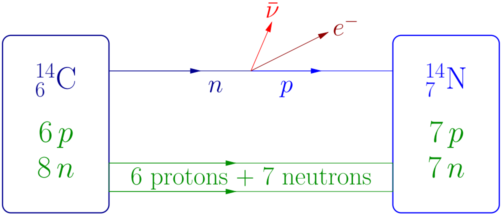
Neutrino Interactions

The Fermi theory allowed to calculate the rates of different processes of neutrino production and detection.

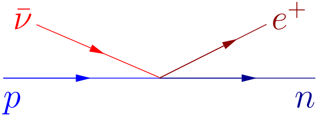
- Neutron decay: $n \to p + e^- + \bar{\nu}$



- Nuclear β decay:



- Inverse neutron decay (neutrino detection): $\bar{\nu} + p \to n + e^+$



Neutrino Detection?

- Since neutrinos interact only with Weak Interactions they very difficult to detect:

The "Neutrino"

[H. Bethe, R. Peierls, Nature 133 (1934) 532]

For an energy of $2-3\,MeV \ldots \sigma < 10^{-44}\,cm^2$ (corresponding to a penetrating power of 10^{16} km in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations.

With increasing energy, σ increases (in Fermi's model for large energies as E^2) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed.

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned one can conclude that there is no practically possible way of observing the neutrino.

Never Say Never

- 1951: Clyde Cowan and Frederick Reines start to plan to detect neutrinos with the reaction

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

  with a large detector ($\sim 1\,\mathrm{m}^3$) filled with liquid scintillator viewed by many photomultipliers: El Monstro

- At that time the largest detectors had a volume of about a liter!

- Liquid scintillator just discovered in 1949-50.

- They planned to see the emitted e^+.

- But how to find an intense source of neutrinos?

What about an Atomic Bomb?

- Reines worked in Los Alamos at atomic bomb tests after World War II.
- He started to think about neutrino detection because he knew that the fission products emitted a huge neutrino flux. [Reines, Nobel Lecture 1995]

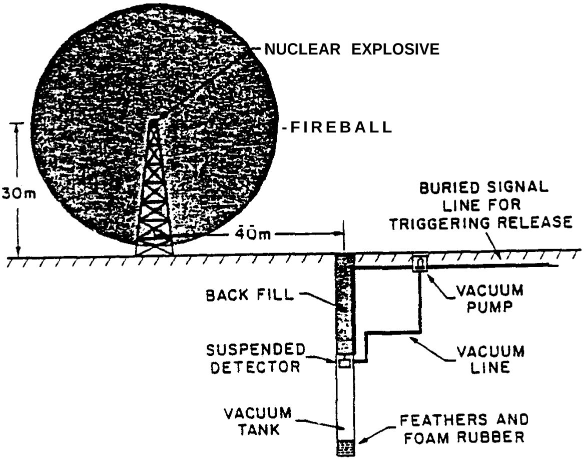


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrinc using a nuclear bomb. This experiment was approved by the authorities at Los Alamos bu was superceded by the approach which used a fission reactor.

- Cowan and Reines were thinking also about the more practical possibility to detect neutrinos from nuclear reactors.

- Nuclear reactors had neutrino fluxes thousands of times smaller than an atomic bomb explosion but experiment can be made for a much longer time.

- Background is the problem: cosmic rays, neutrons, gamma, etc.

- 1952: Cowan and Reines discover that neutron detection in

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

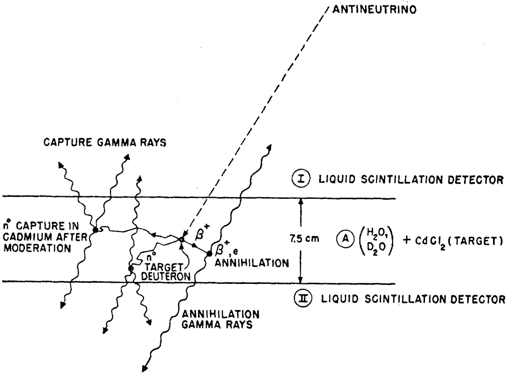
  Allow to reduce drastically the background using the delayed coincidence between the positron and neutron signals.

- They understood that the detection of reactor neutrinos is feasible and much easier than making atomic bomb experiments!

Neutrinos are Real

- 1956: Clyde Cowan and Frederick Reines detect antineutrinos ($\bar{\nu}$) produced by the Savannah River nuclear plant

$$\bar{\nu} + {}^2_1\text{H} \to n + n + e^+ \qquad (\bar{\nu} + p \to n + e^+)$$



[Cowan, Reines, Physical Review 107 (1957) 1609]

- Reines received the 1995 Physics Nobel Prize. Cowan died in 1974.

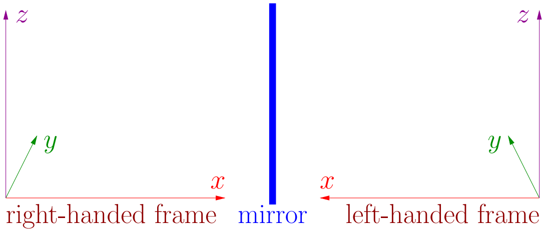
- 1934 conclusion of Bethe and Peierls: one can conclude that there is no practically possible way of observing the neutrino

I confronted Bethe with this pronouncement some 20 years later and with his characteristic good humor he said, "Well, you shouldn't believe everything you read in the papers".

[Reines, Nobel Lecture 1995]

Parity Violation

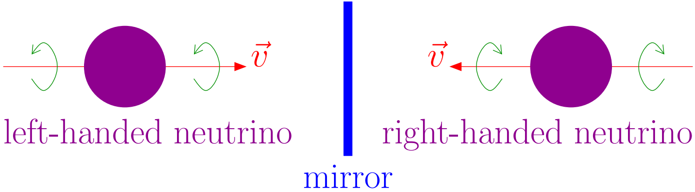
- Parity is the symmetry of space inversion (mirror transformation)



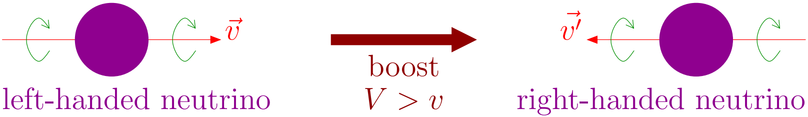
- Parity was considered to be an exact symmetry of nature
- 1956: Lee and Yang understand that Parity can be violated in Weak Interactions (1957 Physics Nobel Prize)
- 1957: Wu et al. discover Parity violation in β-decay of ^{60}Co

Massless Chiral Neutrinos

- 1957: Landau, Lee & Yang, Salam propose that neutrinos are massless and are only left-handed (ν_L) or right-handed (ν_R)
- It is possible only if Parity is violated, because $\nu_L \overset{\text{P}}{\rightleftharpoons} \nu_R$:

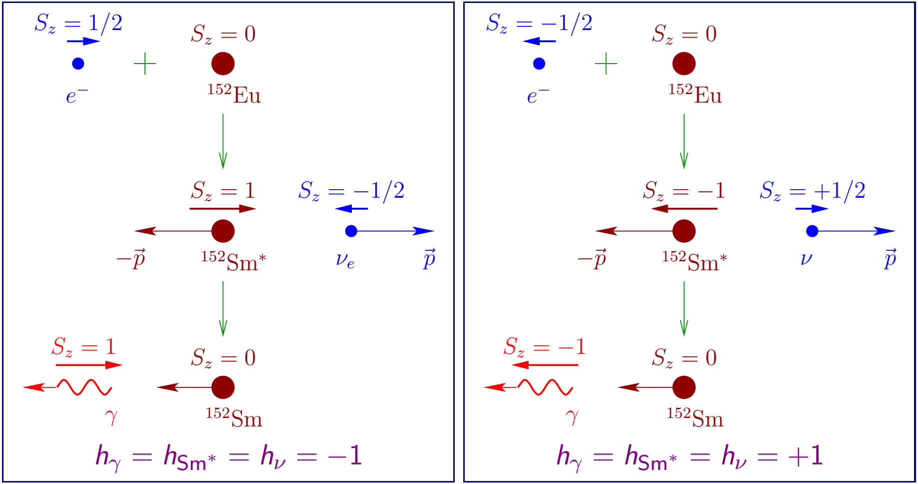


- It is possible only if neutrinos are massless, because a Lorentz boost can change ν_L into ν_R:



Left-Handed Neutrinos

- 1958: Goldhaber, Grodzins and Sunyar measure neutrino helicity



$h_\gamma = -0.91 \pm 0.19 \Longrightarrow$ NEUTRINOS ARE LEFT-HANDED: ν_L

$V - A$ Weak Interactions

[Feynman, Gell-Mann, PR 109 (1958) 193; Sudarshan, Marshak, PR 109 (1958) 1860; Sakurai, NC 7 (1958) 649]

- The Fermi Hamiltonian (1934) $\quad H_\beta = g\,(\overline{p}\gamma^\alpha n)\,(\overline{e}\gamma^\alpha \nu) + \text{H.c.}$ explained only nuclear decays with $\Delta J = 0$.
- 1936: Gamow and Teller extension to describe observed nuclear decays with $|\Delta J| = 1$: [PR 49 (1936) 895]

$$H_\beta = \sum_{j=1}^{5} \left[g_j\,(\overline{p}\,\Omega^j\,n)\,(\overline{e}\,\Omega_j\,\nu_e) + g'_j\,(\overline{p}\,\Omega^j\,n)\,(\overline{e}\,\Omega_j\,\gamma_5\,\nu_e) \right] + \text{H.c.}$$

with $\quad \Omega^1 = 1,\ \Omega^2 = \gamma^\alpha,\ \Omega^3 = \sigma^{\alpha\beta},\ \Omega^4 = \gamma^\alpha\gamma^5,\ \Omega^5 = \gamma^5$

- 1958: Using simplicity arguments, Feynman and Gell-Mann, Sudarshan and Marshak, Sakurai propose the universal theory of parity-violating $V - A$ Weak Interactions:

$$H_W = \frac{G_F}{\sqrt{2}} \Big\{ \left[\overline{p}\gamma^\alpha\left(1-\gamma^5\right) n\right] \left[\overline{e}\gamma^\alpha\left(1-\gamma^5\right)\nu\right] + \left[\overline{\nu}\gamma^\alpha\left(1-\gamma^5\right)\mu\right] \left[\overline{e}\gamma^\alpha\left(1-\gamma^5\right)\nu\right] \Big\} + \text{H.c.}$$

in agreement with $\nu_L = \dfrac{1-\gamma^5}{2}\nu$

Theory of the Fermi interaction

[Feynman and Gell-Mann, PR 109 (1958) 193]

These theoretical arguments seem to the authors to be strong enough to suggest that the disagreement with the ^{6}He recoil experiment and with some other less accurate experiments indicates that

these experiments are wrong

. . . After all, the theory also has a number of successes . . .

Standard Model

- Glashow (1961), Weinberg (1967) and Salam (1968) formulate the Standard Model of ElectroWeak Interactions (1979 Physics Nobel Prize)

  assuming that

  neutrinos are massless and left-handed

- $V - A$ Weak Interactions

- Quantum Field Theory: if neutrinos are left-handed (ν_L) then antineutrinos are right-handed ($\bar{\nu}_R$)

- Parity is violated: $\nu_L \xrightarrow{P} \cancel{\nu_R}$ $\quad$ $\bar{\nu}_R \xrightarrow{P} \cancel{\bar{\nu}_L}$

- Particle-Antiparticle symmetry (Charge Conjugation) is violated:

  $\nu_L \xrightarrow{C} \cancel{\bar{\nu}_L}$ $\quad$ $\bar{\nu}_R \xrightarrow{C} \cancel{\nu_R}$

Neutrino Proliferation

- 1960: Bruno Pontecorvo suggests that the neutrino produced in

$$\pi^+ \to \mu^+ + \nu$$

may be different from a neutrino produced in β^+ decay:

$$N_{A,Z} \to N_{A,Z-1} + e^+ + \nu_e$$

- It was known that $\nu_e + n \to p + e^-$

- Pontecorvo proposed to check if

$$\underbrace{\pi^+ \to \mu^+ + \nu}_{\text{source}} \xrightarrow{\text{propagation}} \underbrace{\nu + n \to p + e^-}_{\text{detector}}$$

- 1962: Lederman, Schwartz and Steinberger perform the experiment at Brookhaven National Laboratory (BNL): no electrons above background $\Longrightarrow$ there is a new neutrino type: ν_μ (1988 Physics Nobel Prize)

Two Generations

- Known elementary particles in 1970:

	1st Generation	2nd Generation
Quarks:	u (up)	
	d (down)	s (strange)
Leptons:	ν_e (electron neutrino)	ν_μ (muon neutrino)
	e (electron)	μ (muon)

- 1970: Glashow, Iliopoulos and Maiani predict existence of charm quark (c) which completes the two-generations quark-lepton symmetry:

	1st Generation	2nd Generation	Charge
Quarks:	u	c	$+2/3$
	d	s	$-1/3$
Leptons:	ν_e	ν_μ	0
	e	μ	-1

- 1974: charm quark discovered at BNL and SLAC: $J/\psi = c\bar{c}$ (Richter and Ting: 1976 Physics Nobel Prize)

CP Violation and Three Generations

- 1964: Christenson, Cronin, Fitch and Turlay discover unexpected violation of CP symmetry (Cronin and Fitch: 1980 Physics Nobel Prize)

C:	PARTICLE ⇆ ANTIPARTICLE	$\nu_L \leftrightarrows \bar{\nu}_L$
P:	LEFT ⇆ RIGHT	$\nu_L \leftrightarrows \nu_R$
CP:	LEFT-HANDED P ⇆ RIGHT-HANDED $\bar{\text{P}}$	$\nu_L \leftrightarrows \bar{\nu}_R$

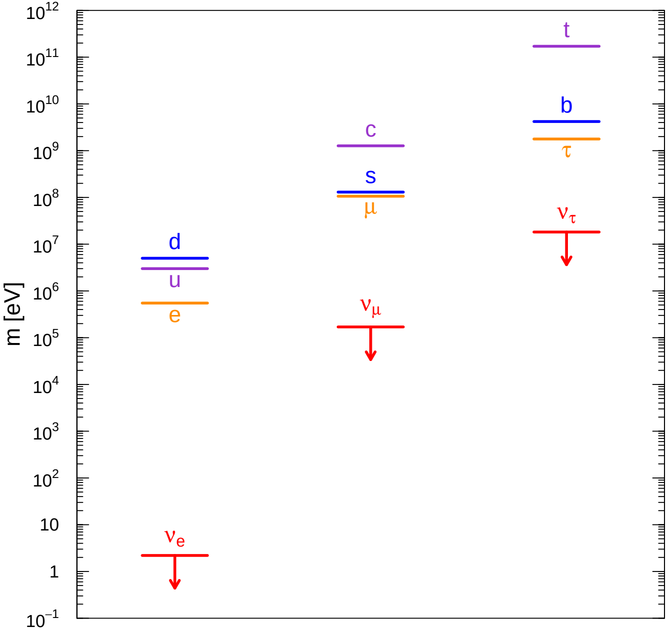
- 1973: Kobayashi and Maskawa understand that CP violation requires existence of third generation (2008 Physics Nobel Prize)

- 1975: τ discovery by Perl (1995 Physics Nobel Prize)

- 1977: b quark discovered at Fermilab

- 1995: t quark observed at Fermilab

- 2000: ν_τ observed at Fermilab (DONUT)



m [eV]
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^−1
t
b
τ
ν_τ
c
s
μ
ν_μ
d
u
e
ν_e

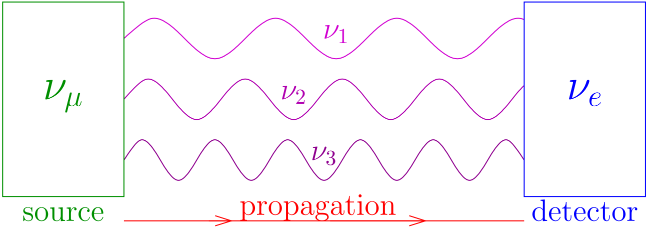
Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed a form of neutrino oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955).
- Theoretical and experimental developments led to neutrino mixing [Maki, Nakagawa, Sakata, Prog. Theor. Phys. 28 (1962) 870] and the theory of neutrino oscillations as flavor transitions which oscillate with distance [Pontecorvo, Sov. Phys. JETP 26 (1968) 984; Gribov, Pontecorvo, PLB 28 (1969); Bilenky, Pontecorvo, Sov. J. Nucl. Phys. 24 (1976) 316, PLB 61 (1976) 248; Fritzsch, Minkowski, Phys. Lett. B62 (1976) 72; Eliezer, Swift, Nucl. Phys. B105 (1976) 45] .
- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector
- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu1}\,|\nu_1\rangle + U_{\mu2}\,|\nu_2\rangle + U_{\mu3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau1}\,|\nu_1\rangle + U_{\tau2}\,|\nu_2\rangle + U_{\tau3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_\mu\rangle = U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{\mu 1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{\mu 2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{\mu 3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_\mu\rangle$$

$$E_k^2 = p^2 + m_k^2 \qquad\qquad t \simeq L$$

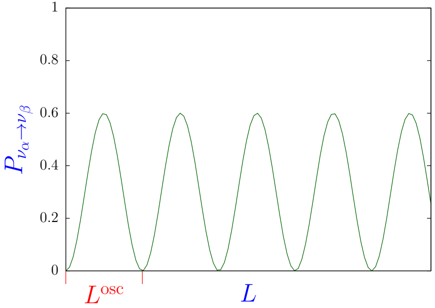
$$P_{\nu_\mu\to\nu_e}(t>0) = |\langle\nu_e|\nu(t>0)\rangle|^2 \sim \sum_{k>j} \mathrm{Re}\left[U_{ek}\,U_{\mu k}^*\,U_{ej}^*\,U_{\mu j}\right] \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right)$$

transition probabilities depend on U and $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$

$\nu_e \to \nu_\mu \qquad \nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_e \qquad \nu_\mu \to \nu_\tau$

$\bar{\nu}_e \to \bar{\nu}_\mu \qquad \bar{\nu}_e \to \bar{\nu}_\tau \qquad \bar{\nu}_\mu \to \bar{\nu}_e \qquad \bar{\nu}_\mu \to \bar{\nu}_\tau$

- Neutrino Oscillations are due to interference of different phases of massive neutrinos: pure quantum-mechanical effect!
- Phases of massive neutrinos depend on distance $\Longrightarrow$ Oscillations depend on distance L

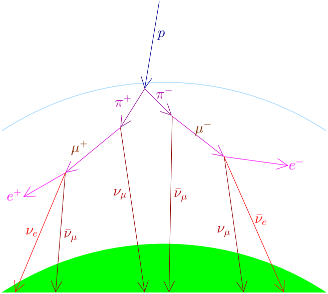


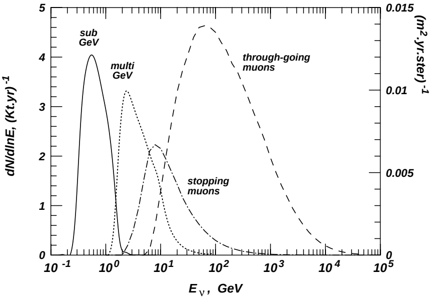
Oscillations seen without doubt for the first time in the

Super-Kamiokande experiment in 1998

Takaaki Kajita: 2015 Physics Nobel Prize

Atmospheric Neutrinos





$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \simeq 2 \quad \text{at } E \lesssim 1\,\text{GeV}$$

uncertainty on ratios: $\sim 5\%$

uncertainty on fluxes: $\sim 30\%$

ratio of ratios

$$R \equiv \frac{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{data}}}{[N(\nu_\mu + \bar{\nu}_\mu)/N(\nu_e + \bar{\nu}_e)]_{\text{MC}}}$$

$$R^{\text{K}}_{\text{sub-GeV}} = 0.60 \pm 0.07 \pm 0.05$$

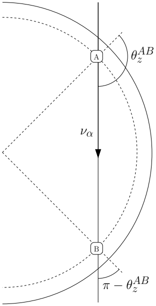
[Kamiokande, PLB 280 (1992) 146]

$$R^{\text{K}}_{\text{multi-GeV}} = 0.57 \pm 0.08 \pm 0.07$$

[Kamiokande, PLB 335 (1994) 237]

Super-Kamiokande Up-Down Asymmetry

Presented for the first time by Takaaki Kajita at Neutrino 1998



$E_\nu \gtrsim 1\,\text{GeV} \Rightarrow$ isotropic flux of cosmic rays

$$\phi^{(A)}_{\nu_\alpha}(\theta_z^{AB}) = \phi^{(B)}_{\nu_\alpha}(\pi - \theta_z^{AB}) \qquad \phi^{(A)}_{\nu_\alpha}(\theta_z^{AB}) = \phi^{(B)}_{\nu_\alpha}(\theta_z^{AB})$$

$$\Downarrow$$

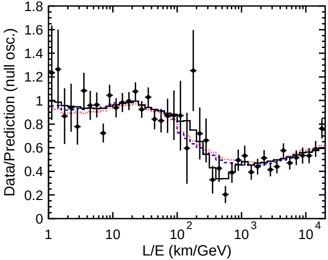
$$\phi^{(A)}_{\nu_\alpha}(\theta_z) = \phi^{(A)}_{\nu_\alpha}(\pi - \theta_z)$$

$$A^{\text{up-down}}_{\nu_\mu}(\text{SK}) = \left(\frac{N^{\text{up}}_{\nu_\mu} - N^{\text{down}}_{\nu_\mu}}{N^{\text{up}}_{\nu_\mu} + N^{\text{down}}_{\nu_\mu}} \right) = -0.296 \pm 0.048 \pm 0.01$$

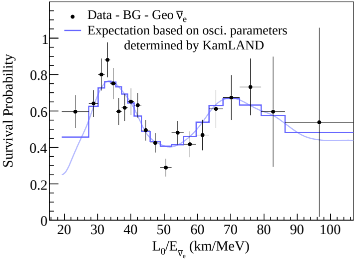
[Super-Kamiokande, Phys. Rev. Lett. 81 (1998) 1562, hep-ex/9807003]

6σ model independent evidence of ν_μ disappearance due to oscillations!

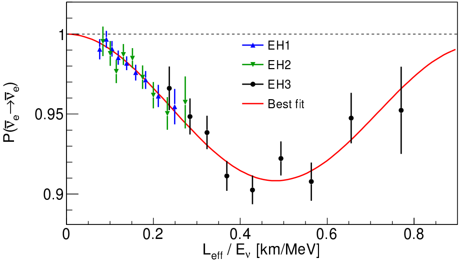
Explicit Observations of Neutrino Oscillations



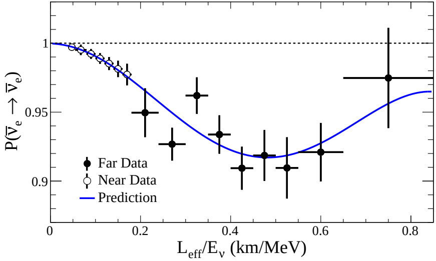
[Super-Kamiokande, PRL 93 (2004) 101801, hep-ex/0404034]



[KamLAND, PRL 100 (2008) 221803, arXiv:0801.4589]



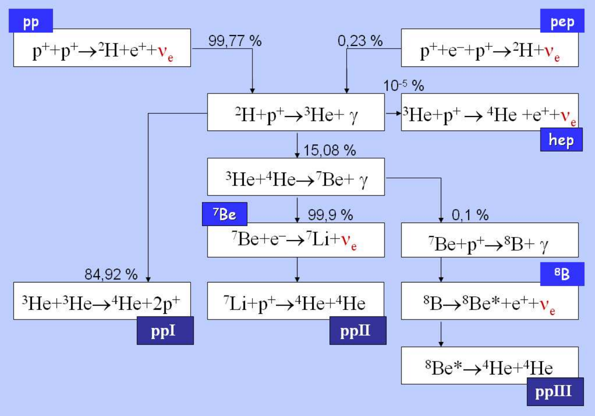
[Daya Bay, PRL, 112 (2014) 061801, arXiv:1310.6732]



[RENO, arXiv:1511.05849]

Solar Neutrinos

- Solar energy is generated by thermonuclear fusion reactions in the hot solar core (about 1.5×10^7 K)
- Main reactions: *pp* chain $\quad 4\,p + 2\,e^- \to {}^4_2\mathrm{He} + 2\,\nu_e + 26.7\,\mathrm{MeV}$



- Solar neutrinos are the only direct messengers from the core of the Sun!
- Flux on Earth is about $6 \times 10^{10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$!

Solar Neutrino Detection

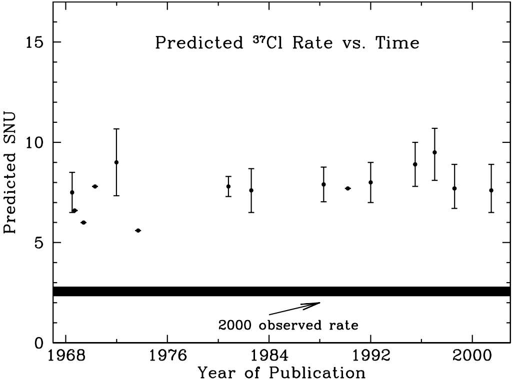
- 1957: Bruno Pontecorvo suggests to detect Solar Neutrinos using a large underground tank with Chlorine: $\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$
- 1964: John N. Bahcall finds that the cross-section of the Cl-Ar reaction is about 20 times larger than previous calculations
- 1964: Raymond Davis proposes the Homestake experiment (built in 1965–1967)
- 1970: Davis and collaborators observe the first solar neutrino interactions in the Homestake detector (2002 Physics Nobel Prize)
- Solar neutrinos have been detected by the experiments: Homestake (1970-1994), Kamiokande (1987-1995) SAGE (1990-2010), GALLEX/GNO (1991-2000), Super-Kamiokande (1996-2015), SNO (1999-2008), Borexino (2007-2015).

Solar Neutrino Problem

- Since the Homestake experiment started in 1970 all solar neutrino experiments measured a flux of ν_e arriving on Earth about 1/3 of that predicted by the Standard Solar Model
- 1968: Bruno Pontecorvo predicted that solar ν_e can disappear because of Neutrino Oscillations: [Sov. Phys. JETP 26 (1968) 984]

$$\nu_e \to \nu_\mu \qquad \text{and} \qquad \nu_e \to \nu_\tau$$

- 1968-2005: John Bahcall was the champion of the Standard Solar Model



In 2002 the SNO (Sudbury Neutrino Observatory) experiment

proved without doubt the oscillations of solar neutrinos

Arthur B. McDonald: 2015 Physics Nobel Prize

SNO: Sudbury Neutrino Observatory

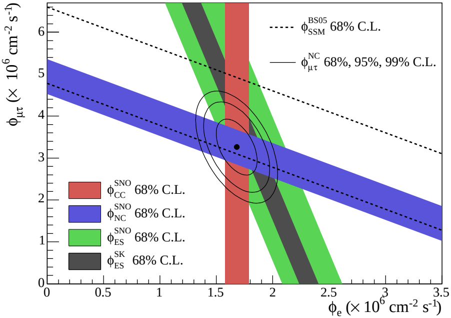
1 kton of D_2O

CC: $\nu_e + d \to p + p + e^-$

NC: $\nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau}$

$\Phi^{SNO}_{\nu_e} = 1.76 \pm 0.11 \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$

$\Phi^{SNO}_{\nu_\mu,\nu_\tau} = 5.41 \pm 0.66 \times 10^6 \, \text{cm}^{-2} \, \text{s}^{-1}$



[SNO, PRL 89 (2002) 011301, nucl-ex/0204008]

- SNO proved in a model independent way that the Solar Neutrino Problem is a manifestation of Neutrino Oscillations: $\nu_e \to \nu_\mu, \nu_\tau$

Open Question: Dirac or Majorana Neutrinos?

- 1928: Paul Dirac formulates "The Quantum Theory of the Electron" which predicted that each fermion has a corresponding antifermion. (1933 Physics Nobel Prize)

- Particle and antiparticle have opposite charges $\Longrightarrow$ for charged particles particle and antiparticle are different $\Longrightarrow$ charged fermions (quarks, e, μ, τ) must be Dirac particles

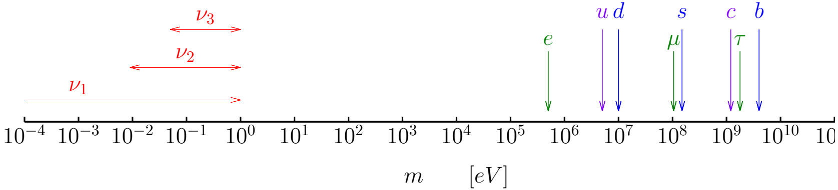
- If neutrinos are Dirac particles $\quad \nu_1 \neq \bar{\nu}_1, \nu_2 \neq \bar{\nu}_2, \nu_3 \neq \bar{\nu}_3$

- 1937: Ettore Majorana formulates the "Teoria simmetrica dell'elettrone e del positrone" (Symmetrical theory of the electron and positron)

- According to the Majorana theory for a neutral fermion particle and antiparticle can be equal

- If neutrinos are Majorana particles $\quad \nu_1 = \bar{\nu}_1, \nu_2 = \bar{\nu}_2, \nu_3 = \bar{\nu}_3$

Theorists favor Majorana neutrinos because it may explain smallness of neutrino masses with the seesaw mechanism

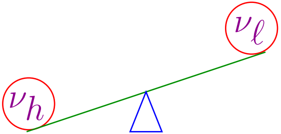


$$\mathcal{L}^{\mathrm{D+M}} = -\frac{1}{2} \begin{pmatrix} \overline{\nu_L^c} & \overline{\nu_R} \end{pmatrix} \begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} + \mathrm{H.c.}$$

m_R can be arbitrarily large (not protected by SM symmetries)

$m_R \sim$ scale of new physics beyond Standard Model $\Rightarrow m_R \gg m_{\mathrm{D}}$

diagonalization of $\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}} & m_R \end{pmatrix} \Longrightarrow m_\ell \simeq \frac{m_{\mathrm{D}}^2}{m_R} \qquad m_h \simeq m_R$



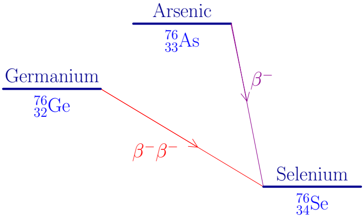
[Minkowski, PLB 67 (1977) 42; Yanagida (1979); Gell-Mann, Ramond, Slansky (1979); Mohapatra, Senjanovic, PRL 44 (1980) 912]

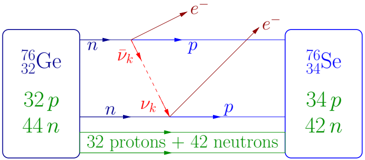
Neutrinoless Double-Beta Decay

Many experiments are searching for Majorana neutrinos through

Neutrinoless Double-β Decay

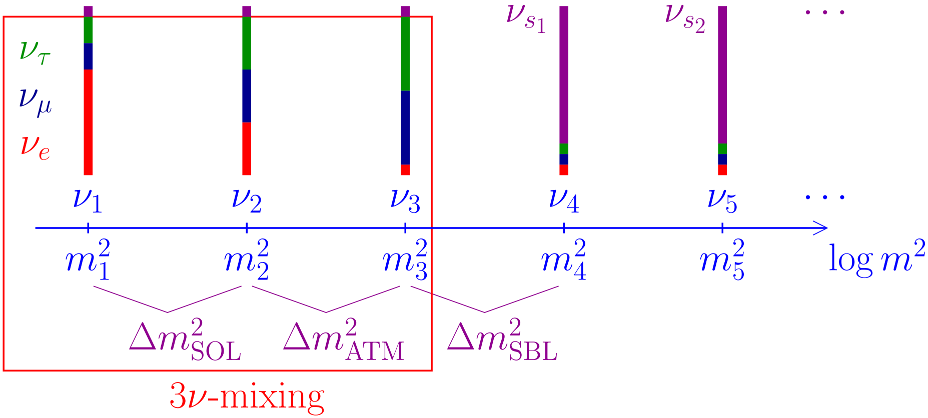
Example: $\,^{76}_{32}\text{Ge} \to \,^{76}_{34}\text{Se} + e^- + e^-$





Possible only if $\bar{\nu}_k = \nu_k \Longrightarrow$ Majorana!

More Neutrinos?: Sterile Neutrinos



Summary and Perspectives

- Neutrino properties are fundamental ingredients of the Standard Model
- Neutrino properties (Dirac or Majorana mass, sterile, electromagnetic, non-standard interactions, ...) are powerful windows on the physics beyond the Standard Model
- Neutrinos led to the Standard Model and now neutrinos are leading us beyond the Standard Model
- Past and present neutrino Nobel prizes:
  - 1988: L. Lederman, M. Schwartz and J. Steinberger, for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino
  - 1995: F. Reines, or the detection of the neutrino
  - 2002: R. Davis and M. Koshiba, for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos
  - 2015: T. Kajita and A. McDonald, for the discovery of neutrino oscillations, which shows that neutrinos have mass
- Future neutrino Nobel prizes?:
  - ?: ?, for the discovery that neutrinos are Majorana particles?
  - ?: ?, for the discovery of sterile neutrinos?
  - ?: ?, ?