The Surprising History of Sterile Neutrinos

Carlo Giunti

INFN, Sezione di Torino

giunti@to.infn.it

Ghost Hunters: The Search for New Types of Neutrinos

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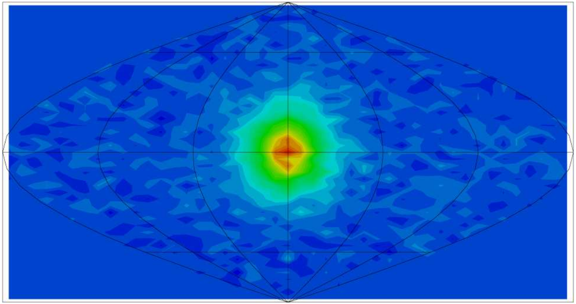
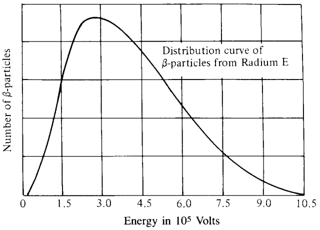


The sun observed through neutrinos by Super-Kamiokande

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]



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

Bi = Bismuth (Radium E)

Po = Polonium

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

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: $^{210}_{83}\text{Bi} \to {}^{210}_{84}\text{Po} + e^- +$ "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 $\sim 10^{-10}\,\text{cm}$ can be contained in a nucleus with dimensions $\sim 10^{-13}\,\text{cm}$).

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

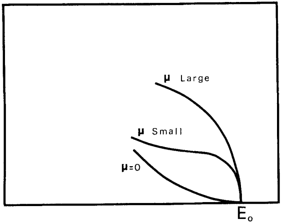
  Theory of the emission of β rays by radioactive substances, based on the hypothesis that the electrons emitted by nuclei do not exist before the disintegration but are formed, together with a neutrino, in a way which is analogous to the formation of a quantum of light which accompany a quantum jump of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

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.

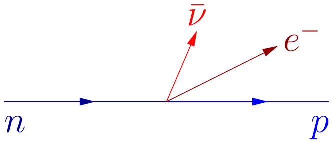


The closer similarity with the experimental curves is achieved for $\mu = 0$. Therefore we reach the conclusion that the neutrino mass is zero or, in any case, small in comparison to the electron mass.

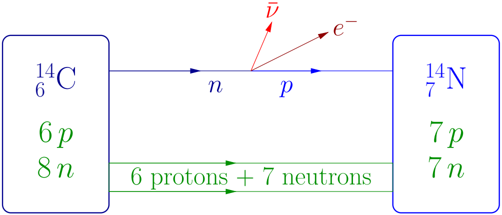
Neutrino Interactions

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

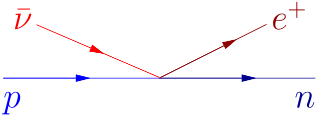
- Neutron decay: $n \to p + e^- + \bar{\nu}$



- Nuclear β decay:



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



Neutrino Detection?

- From the beginning it was clear that since neutrinos interact only with Weak Interactions they are 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.

  …one can conclude that there is no practically possible way of observing the neutrino.

- We have this wonderful new particle and we cannot see it? Too bad!

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 (The Monster).
- But how to find a source of neutrinos enough intense?
- The first artificial nuclear reactor was constructed at the University of Chicago by a team led by Enrico Fermi in late 1942.
- The first nuclear power plants started in the early 50's.
- A nuclear power plants emit a flux of about 2×10^{20} neutrinos per second per GigaWatt of thermal power.

Neutrinos are Real

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

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

- What about the 1934 conclusion of Bethe and Peierls that 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]*

- Note however that we never see directly the neutrino: we can only see the electrons and neutrons produced by the neutrinos.

- Neutrinos are real ghost particles!

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:

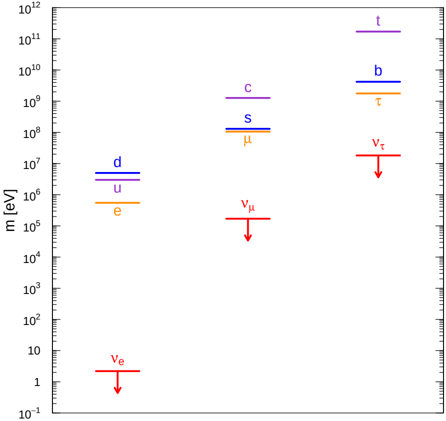
$$n \to p + e^- + \bar{\nu}_e$$

- 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)

Three Generations



- In the Standard Model formulated in the 60's neutrinos are assumed to be massless.
- Most physicists believed it, but neutrino physicists argued that there is no fundamental reason for neutrinos to be massless.
- But if neutrinos have tiny masses how is it possible to reveal them?

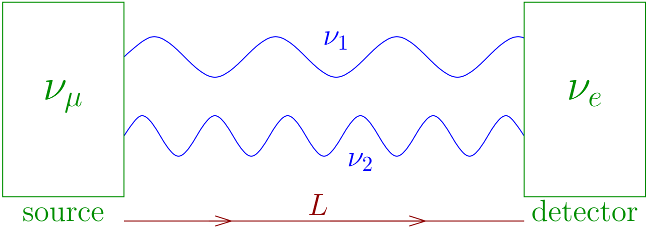
Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed the first idea 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 and the theory of neutrino oscillations as flavor transitions which oscillate with distance.
- Flavor Neutrinos: ν_e, ν_μ produced in Weak Interactions
- Massive Neutrinos: ν_1, ν_2 propagate from Source to Detector
- A Flavor Neutrino is a quantum-mechanical superposition of Massive Neutrinos

$$\nu_e = \cos\vartheta\,\nu_1 + \sin\vartheta\,\nu_2$$
$$\nu_\mu = -\sin\vartheta\,\nu_1 + \cos\vartheta\,\nu_2$$

- ϑ is the Mixing Angle

$$\nu(L=0) = \nu_\mu = -\sin\vartheta\,\nu_1 + \cos\vartheta\,\nu_2$$



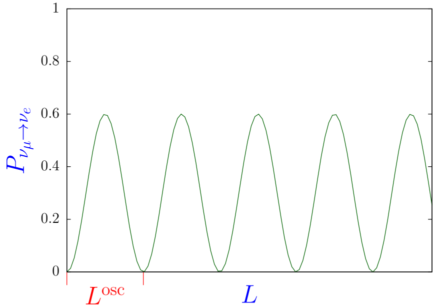
$$\nu(L>0) = -\sin\vartheta\,\cos\left(\frac{m_1^2 L}{2E}\right)\nu_1 + \cos\vartheta\,\cos\left(\frac{m_2^2 L}{2E}\right)\nu_2 \neq \nu_\mu$$

$$P_{\nu_\mu\to\nu_e} = \sin^2 2\vartheta\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

The transition probability depends on ϑ and $\Delta m^2 \equiv m_2^2 - m_1^2$

If neutrinos oscillate they are massive!

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \implies \boxed{L^{\text{osc}} = \frac{4\pi E}{\Delta m^2}}$$



Tiny neutrino masses lead to observable macroscopic oscillation distances!

$$L \sim \begin{cases} 10 - 100\,\text{m} & \text{short-baseline experiments} & \Delta m^2_{\text{sens}} \sim 0.1\,\text{eV}^2 \\ 1 - 13000\,\text{km} & \text{long-baseline experiments} & \Delta m^2_{\text{sens}} \sim 10^{-4}\,\text{eV}^2 \\ 150 \times 10^6\,\text{km} & \text{solar neutrino experiments} & \Delta m^2_{\text{sens}} \sim 10^{-11}\,\text{eV}^2 \end{cases}$$

Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Discovery of Neutrino Oscillations

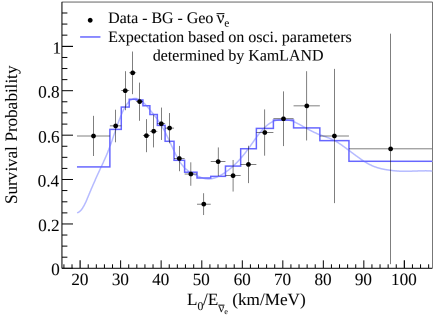
1998: Oscillations of atmospheric neutrinos observed by the Super-Kamiokande experiment

Takaaki Kajita
2015 Physics Nobel Prize

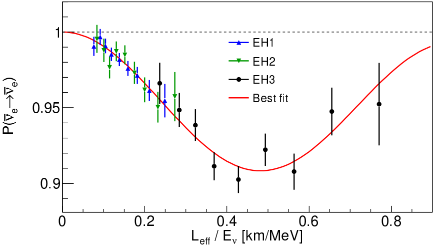
2002: Oscillations of solar neutrinos observed by the SNO experiment

Arthur B. McDonald
2015 Physics Nobel Prize

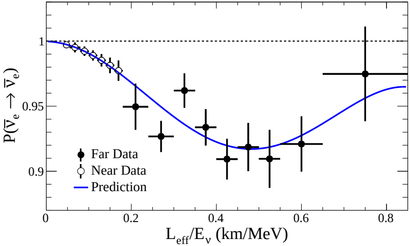
Explicit Observations of Neutrino Oscillations



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



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



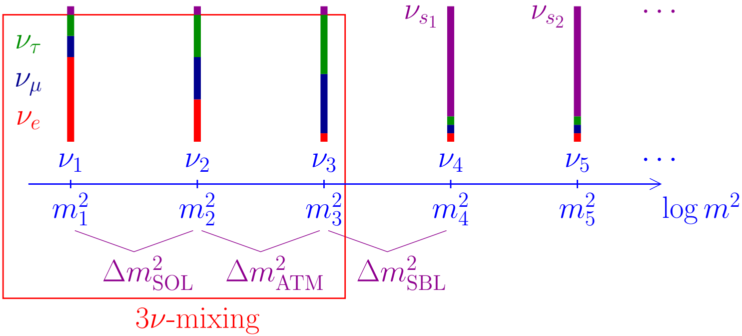
[RENO, arXiv:1511.05849]

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 $\nu_1 \neq \bar{\nu}_1,\, \nu_2 \neq \bar{\nu}_2,\, \nu_3 \neq \bar{\nu}_3$ and neutrino masses can be accommodated in the framework of an Extended Standard Model.
- 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 $\nu_1 = \bar{\nu}_1,\, \nu_2 = \bar{\nu}_2,\, \nu_3 = \bar{\nu}_3$ and neutrino masses are due to Physics Beyond the Standard Model.

More Neutrinos?: Sterile Neutrinos

- Another powerful link with the Physics Beyond the Standard Model is the Number of Neutrinos.
- We know that there are three active flavor neutrinos: ν_e, ν_μ, ν_τ.
- We do not know how many massive neutrino there are: ν_1, ν_2, ν_3, ... ?

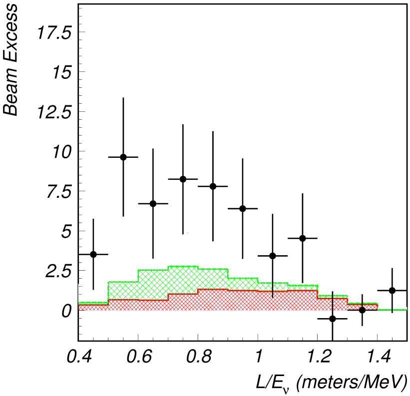


- If there are more than three massive neutrinos, in the flavor basis the additional neutrinos correspond to non-interacting sterile neutrinos.
- If normal active neutrinos are ghost particles, sterile neutrinos are super-ghost particles! And they are most likely Majorana particles.

LSND

[LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30\,\text{m}$ $20\,\text{MeV} \leq E \leq 60\,\text{MeV}$



- Well known source of $\bar{\nu}_\mu$:

  μ^+ decay at rest $\to e^+ + \nu_e + \bar{\nu}_\mu$

- $\bar{\nu}_\mu \xrightarrow[L\simeq 30\,\text{m}]{} \bar{\nu}_e$

- Well known detection process of $\bar{\nu}_e$:

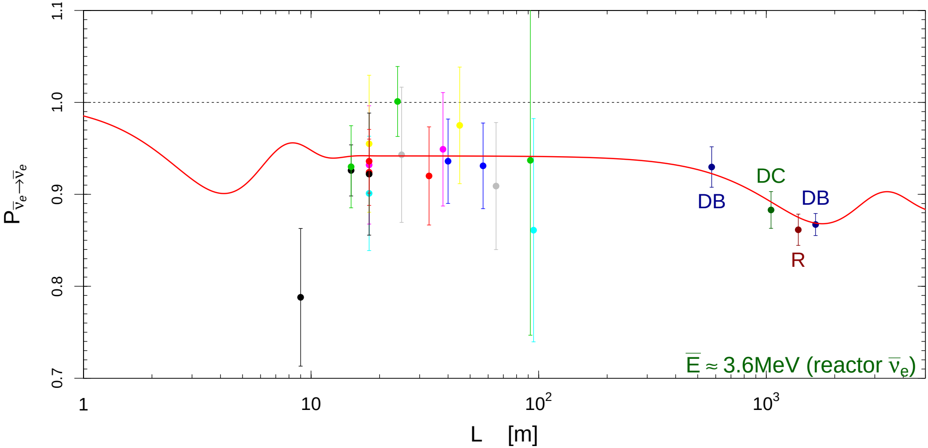
  $\bar{\nu}_e + p \to n + e^+$

$$\Delta m^2_{\text{SBL}} \gtrsim 0.2\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

Reactor Electron Antineutrino Anomaly

[Mention et al, PRD 83 (2011) 073006]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



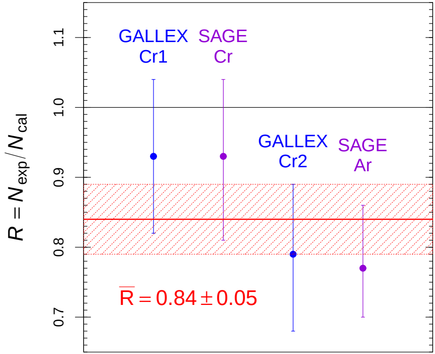
$$\Delta m^2_{SBL} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$$

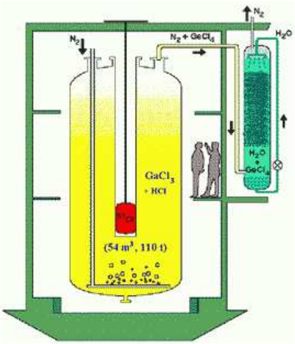
Gallium Anomaly

Gallium Radioactive Source Experiments: GALLEX and SAGE

Detection Process: $\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$

ν_e Sources: $e^- + {}^{51}\text{Cr} \to {}^{51}\text{V} + \nu_e$ $\qquad$ $e^- + {}^{37}\text{Ar} \to {}^{37}\text{Cl} + \nu_e$





$\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m} \qquad \langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

$$\Delta m^2_{\text{SBL}} \gtrsim 1\,\text{eV}^2 \gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$$

Summary and Perspectives

- Neutrino properties are powerful probes of the physics 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, for 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 of sterile neutrinos?
  - ?: ?, for the discovery that neutrinos are Majorana particles?
  - ?: ?, ?