Neutrinos: From their Birth to the 2015 Nobel Prize and Beyond

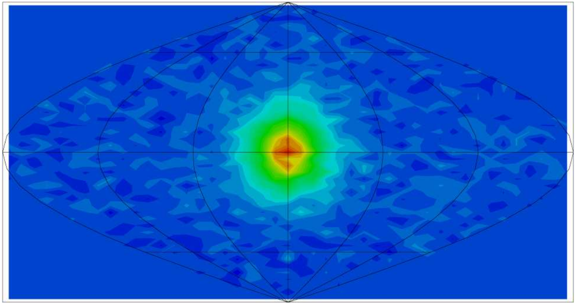
Carlo Giunti

INFN, Sezione di Torino

giunti@to.infn.it

Scuola di Fisica 2016

Torino – 21-23 March 2016

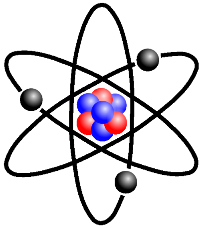


The sun observed through neutrinos by Super-Kamiokande

Neutrino Prehistory: Radioactivity

- 1896: Henri Becquerel discovers radioactivity of Uranium ("uranic rays") (1903 Physics Nobel Prize)
- 1898: Marie Curie discovers radioactivity of Thorium and proposes the name radioactivity. Pierre and Marie Curie discover two new substances, Radium and Polonium, which are much more radioactive than Uranium. (1903 Physics Nobel Prize - Marie Curie: 1911 Chemistry Nobel Prize)
- 1899: Ernest Rutherford discovers that there are two types of radiation: alpha and beta. (1908 Chemistry Nobel Prize)
- 1900: Paul Villard discovers a third type of radiation coming from radium: gamma rays.
- 1902: Ernest Rutherford and Frederick Soddy (1921 Chemistry Nobel Prize) formulate the atomic transformation theory of radioactivity: radioactive bodies contain unstable atoms which decay into a different atom emitting radiation: elements are not immutable!

- 1911: Ernest Rutherford formulates the first nuclear model of the atom.
- Current nuclear model of the atom:



$^{7}_{3}\mathrm{Li}$

Nuclear notation: $^{A}_{Z}\mathrm{Element}$

Z atomic number (number of protons)

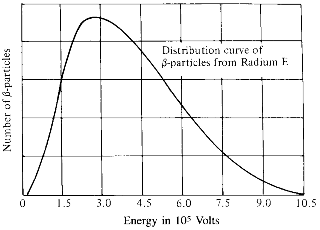
A mass number (number of protons + neutrons)

number of electrons = number of protons

- A radioactive nucleus can decay by emitting:
  - α : a Helium-4 nucleus (2 protons + 2 neutrons: $^{4}_{2}\mathrm{He}$)
  - β : an electron (e)
  - γ : a high-energy photon (γ)

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

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 ...

  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. ...

  Unfortunately, I cannot personally appear in Tübingen, since I am indispensable here on account of a ball taking place in Zürich in the night from 6 to 7 of December ...

- 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.

- Its mass must be much smaller than the mass of the proton because the atomic mass is not changed in the decay.

Neutrino Naming and Interactions: Fermi

- The 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.

TENTATIVO DI UNA TEORIA DELL'EMISSIONE DEI RAGGI "BETA"

[E. Fermi, Ricerca Scientifica 4 (1933) 491]

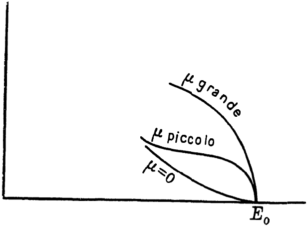
Riassunto. – Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Neutrino Mass?

TENTATIVO DI UNA TEORIA DEI RAGGI β

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

La dipendenza della forma della curva di distribuzione dell'energia da μ è marcata specialmente in vicinanza della energia massima E_0 dei raggi β.

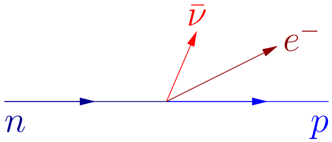


La maggiore somiglianza con le curve sperimentali si ha per la curva teorica corrispondente a $\mu = 0$. Arriviamo così a concludere che la massa del neutrino è uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone.

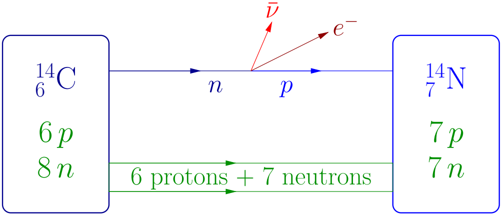
Neutrino Interactions

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

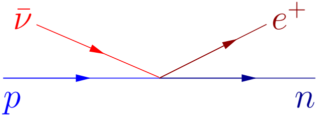
- Neutron decay: $n \to p + e^- + \bar{\nu}$



- 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 ... 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.

- 10^{16} km $\approx 10^{3}$ light years ≈ 10 times the diameter of our galaxy.

- We have this mysterious new particle and we cannot detect it? Very depressing!

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]

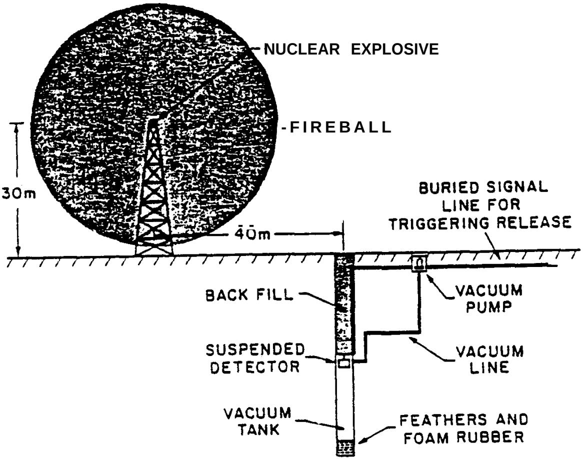


Figure 1. Sketch of the originally proposed experimental setup to detect the neutrino using a nuclear bomb. This experiment was approved by the authorities at Los Alamos but was superceded by the approach which used a fission reactor.

- Cowan and Reines were thinking also about the more practical possibility to detect neutrinos from nuclear reactors.
- 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.
- Background is the problem: cosmic rays, neutrons, gamma, etc.
- 1952: Cowan and Reines discover that neutron detection in

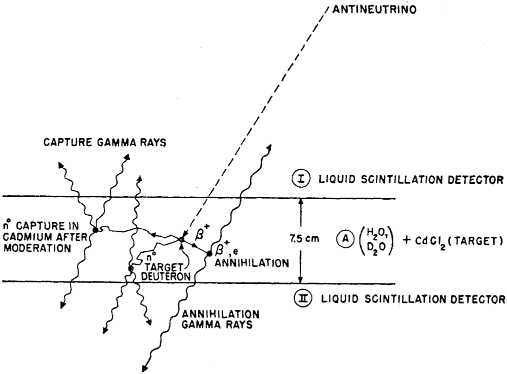
  $$\bar{\nu} + p \to n + e^{+}$$

  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

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



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

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

- 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 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:

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

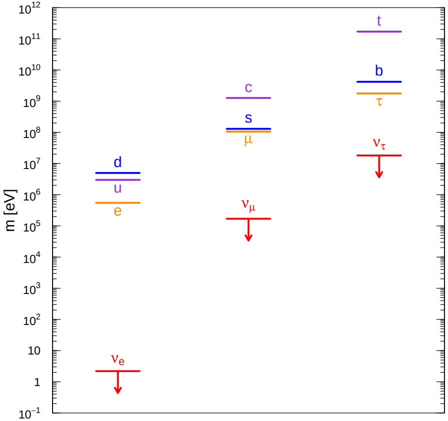
- It was known that $\nu_e + n \to p + e^-$

- 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?

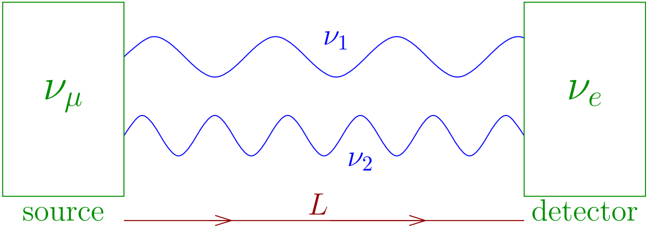
Neutrino Oscillations

- 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

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



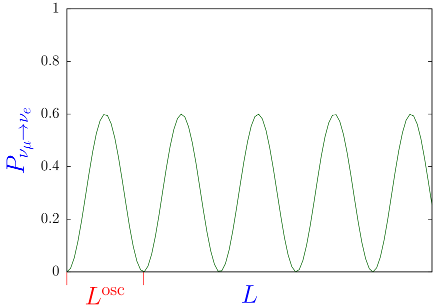
$$\nu(L>0) = -\sin\vartheta\,\cos\left(\frac{m_1^2 L}{2E}\right)\nu_1 + \cos\vartheta\,\cos\left(\frac{m_2^2 L}{2E}\right)\nu_2 \neq \nu_\mu$$

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

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

If neutrinos oscillate they are massive!

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



Tiny neutrino masses lead to observable macroscopic oscillation distances!

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

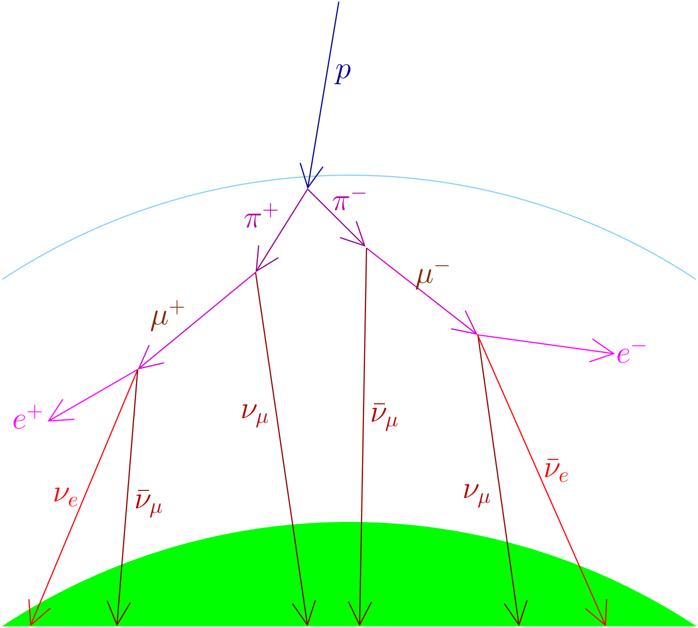
Neutrino oscillations are the optimal tool to reveal tiny neutrino masses!

Discovery of Neutrino Oscillations

Super-Kamiokande experiment in 1998

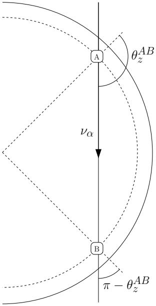
Takaaki Kajita: 2015 Physics Nobel Prize

Atmospheric Neutrinos



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

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

$$\Downarrow$$

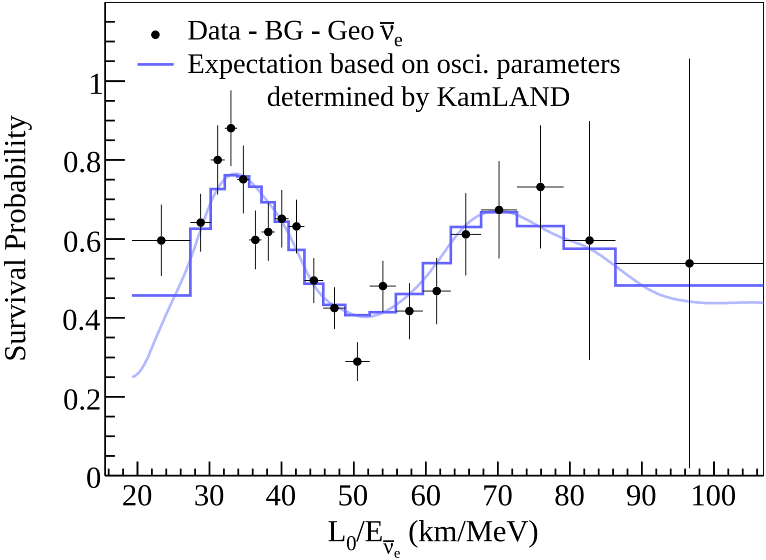
$$\phi^{(A)}_{\nu_\alpha}(\theta_z) = \phi^{(A)}_{\nu_\alpha}(\pi - \theta_z)$$

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

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

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

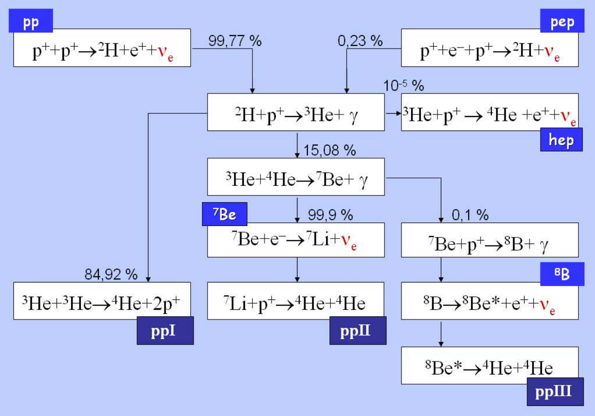
Explicit Observation of Neutrino Oscillations



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

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

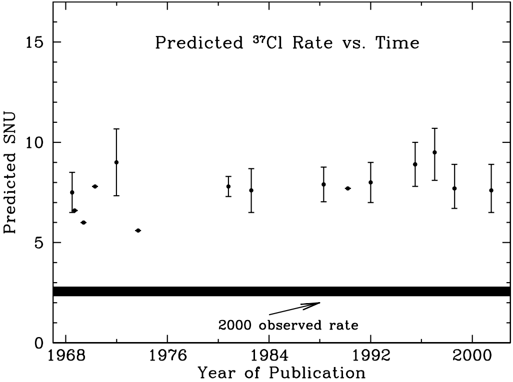
- 1957: Bruno Pontecorvo suggests to detect Solar Neutrinos using a large underground tank with Chlorine: $\nu_e + {}^{37}\text{Cl} \to {}^{37}\text{Ar} + e^-$
- 1964: John N. Bahcall finds that the cross-section of the Cl-Ar reaction is about 20 times larger than previous calculations
- 1964: Raymond 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

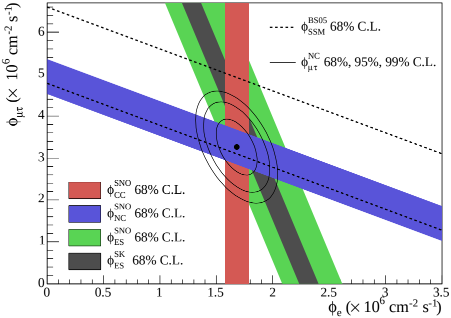
1 kton of D_2O

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

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

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

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



[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?

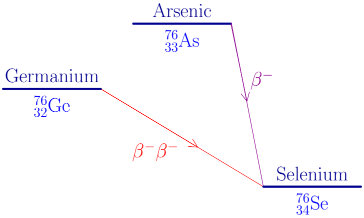
- 1928: Paul Dirac formulates "The Quantum Theory of the Electron" which predicted that each fermion has a corresponding antifermion. (1933 Physics Nobel Prize)
- Particle and antiparticle have opposite charges $\Longrightarrow$ for charged particles particle and antiparticle are different $\Longrightarrow$ charged fermions (quarks, e, μ, τ) must be Dirac particles.
- If neutrinos are Dirac particles $\nu_1 \neq \bar{\nu}_1, \nu_2 \neq \bar{\nu}_2, \nu_3 \neq \bar{\nu}_3$ 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.

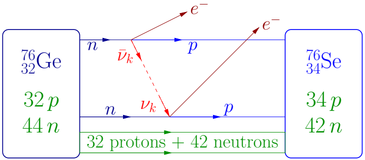
Neutrinoless Double-Beta Decay

Many experiments are searching for Majorana neutrinos through

Neutrinoless Double-β Decay

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

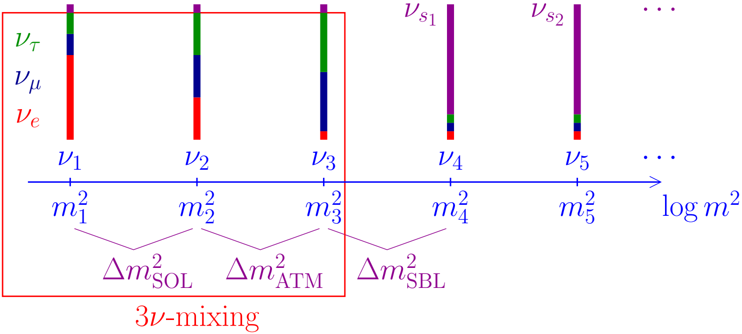




Possible only if $\bar{\nu}_k = \nu_k \implies$ Majorana!

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.

Conclusions

- Neutrino physics is a very active field of theoretical and experimental research.
- 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?
  - ?: ?, ?