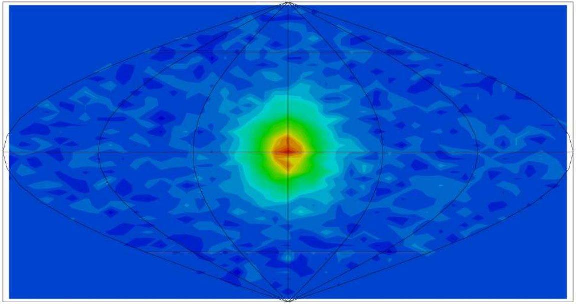
Neutrino Mysteries, Surprises and Promises

Carlo Giunti
INFN, Sezione di Torino, and Dipartimento di Fisica Teorica, Università di Torino

ESOF, Torino, 4 July 2010

Shedding Light on Neutrinos

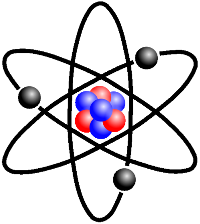


Organiser: Francesca Di Lodovico

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 nuclear model of the atom



$^{7}_{3}$Li

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

Z atomic number (number of protons)

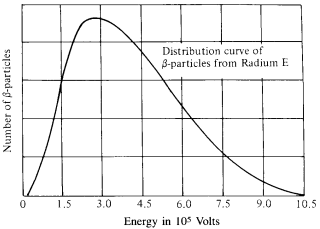
A mass number (number of protons + neutrons)

number of electrons = number of protons

- A radioactive nucleus can decay by emitting:
  - α : a Helium-4 nucleus (2 protons + 2 neutrons: $^{4}_{2}$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]



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

Bi = Bismuth (Radium E)

Po = Polonium

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

- Niels Bohr proposed that energy may be conserved statistically, but energy conservation may be violated in individual decays

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 continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant.

- Radium E decay: $^{210}_{83}\text{Bi} \to ^{210}_{84}\text{Po} + e^- +$ "neutron"

- What we call neutron was discovered by Chadwick in 1932

Neutrino Naming and Interactions: Fermi

- 1933: Enrico Fermi proposes the name neutrino (italian: small neutron) at the Solvay Congress in Brussels.

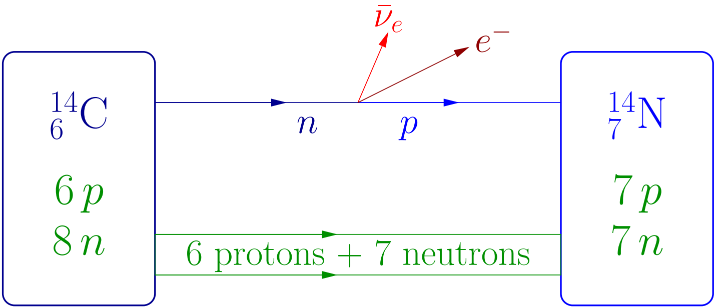
- 1934: Enrico Fermi formulates A Theory of Beta Radiation which is the theory of Weak Interactions

- Neutrinos interact only with Weak Interactions $\Longrightarrow$ Very difficult to detect (maybe impossible; H. Bethe and R. Peierls, 1934)

- The neutrino mass much be much smaller than the electron mass. Maybe the neutrino is massless

- 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"

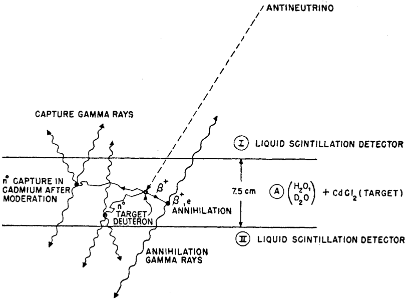
- Basic β decay: $n \to p + e^- + \bar{\nu}_e$
- Nuclear β decay example: ${}^{14}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + e^- + \bar{\nu}_e$



Neutrinos are Real

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

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

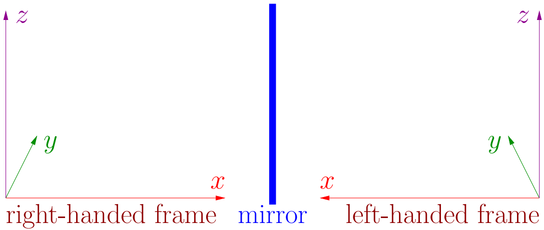


[Cowan, Reines, Physical Review 107 (1957) 1609]

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

Parity Violation

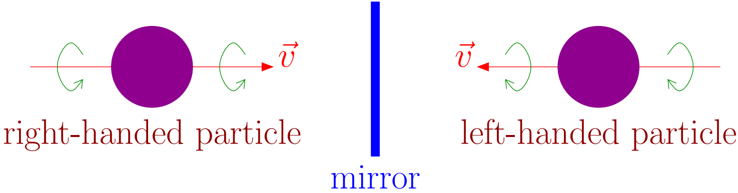
- Parity is the symmetry of space inversion (mirror transformation)



- 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

Left-Handed Neutrinos

- 1957: Landau, Lee & Yang, Salam propose that neutrinos are massless and are only left-handed or right-handed



- 1958: Goldhaber, Grodzins and Sunyar measure neutrino helicity:

LEFT-HANDED

Standard Model

- Glashow (1961), Weinberg (1967) and Salam (1968) formulate the Standard Model of ElectroWeak Interactions (1979 Physics Nobel Prize)
- Neutrinos are left-handed: ν_L
- Antineutrinos are right-handed: $\bar{\nu}_R$
- Parity is violated: $\nu_L \xrightarrow{\text{P}} \not{\nu}_R$ $\bar{\nu}_R \xrightarrow{\text{P}} \not{\bar{\nu}}_L$
- Particle-Antiparticle symmetry (Charge Conjugation) is violated:
  $\nu_L \xrightarrow{\text{C}} \not{\bar{\nu}}_L$ $\bar{\nu}_R \xrightarrow{\text{C}} \not{\nu}_R$
- Neutrinos are massless! (Experimentally allowed until 1998)

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 (ν_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) $\Longrightarrow$ there is a new neutrino type: ν_μ (1988 Physics Nobel Prize)

Two Generations

- Known elementary particles in 1970:

	1[st] Generation	2[nd] 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:

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

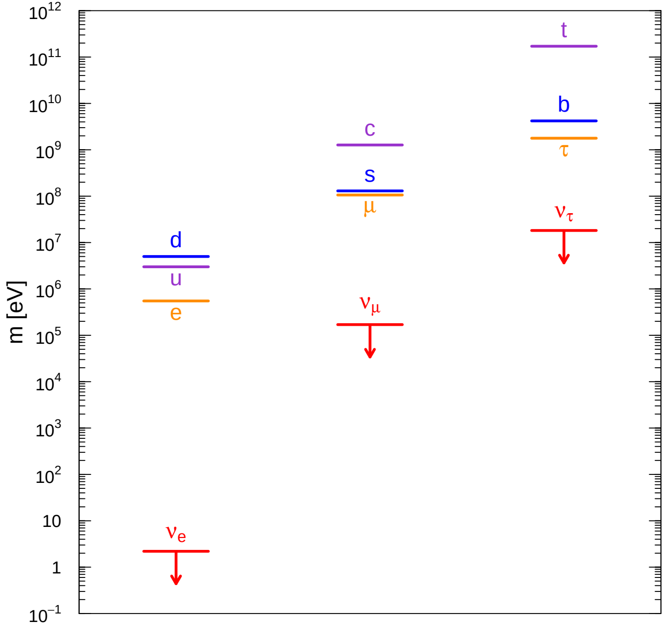
- 1974: charm quark discovered at BNL and SLAC: $J/\psi = c\bar{c}$

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)



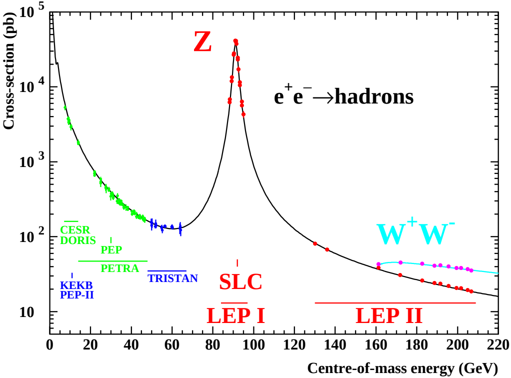
m [eV]
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^−1
t
b
τ
ν_τ
c
s
μ
ν_μ
d
u
e
ν_e

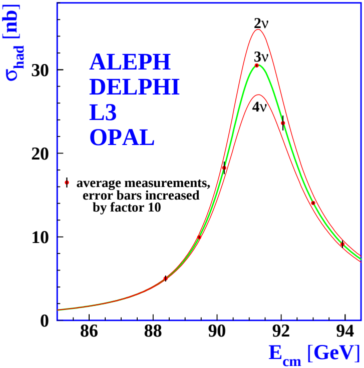
	1st Generation	2nd Generation	3rd Generation
Quarks:	u	c	t
	d	s	b
Leptons:	ν_e	ν_μ	ν_τ
	e	μ	τ
quark and charged lepton mass scale	10^{6-7} eV	10^{8-9} eV	10^{9-11} eV

$$10^6\,\text{eV} = 1.8 \times 10^{-27}\,\text{g}$$

- Mystery: Why neutrino mass in each generation is much smaller than other masses?
- Mystery: Why more than one generation with same properties and heavier masses?
- Mystery: Why three generations?

Three Neutrinos $\Longrightarrow$ Three Generations





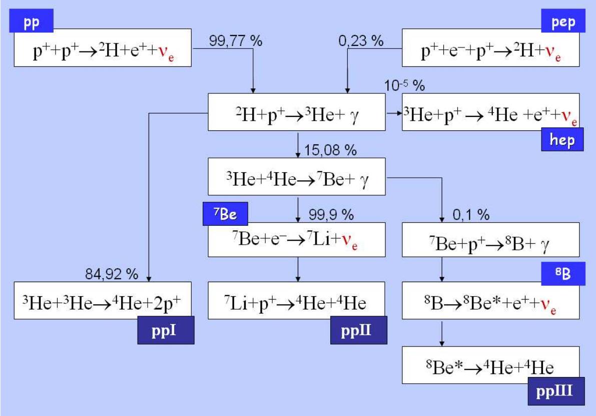
[LEP, Phys. Rept. 427 (2006) 257, arXiv:hep-ex/0509008]

$$\Gamma_Z = \sum_{\ell=e,\mu,\tau} \Gamma_{Z\to\ell\bar{\ell}} + \sum_{q\neq t} \Gamma_{Z\to q\bar{q}} + \Gamma_{\text{inv}} \qquad \Gamma_{\text{inv}} = N_\nu \, \Gamma_{Z\to\nu\bar{\nu}}$$

$$N_\nu = 2.9840 \pm 0.0082$$

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 $\quad 4\,p + 2\,e^- \to {}^4_2\text{He} + 2\,\nu_e + 26.7\,\text{MeV}$



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

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 (1996-2010), SNO (1999-2008), Borexino (2007-2010).

Solar Neutrino Problem

- Solar neutrino experiments found that the flux of ν_e arriving on Earth is about 1/3 of that produced in the core of the Sun

- 2002: The SNO experiment found that the flux of ν_e, ν_μ and ν_τ arriving on Earth is the same as the flux of ν_e produced in the core of the Sun

- It is a proof of Neutrino Oscillations:

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

- Neutrino Oscillations is a new phenomenon beyond the Standard Model: neutrino flavor transitions due to neutrino masses

- Oscillations is a phenomenon peculiar to neutrinos: charged leptons do not oscillate.

  Example: $e^- \to \mu^-$ is forbidden

Neutrino Oscillations

- 1957: Bruno Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955)

- Flavor Neutrinos: ν_e, ν_μ, ν_τ produced in Weak Interactions

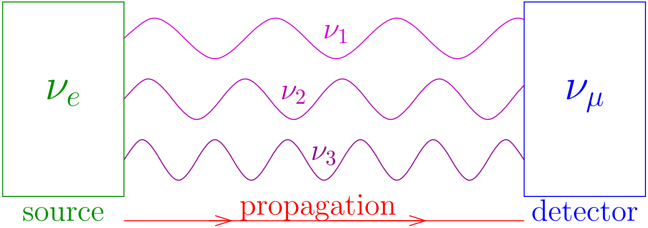
- Massive Neutrinos: ν_1, ν_2, ν_3 propagate from Source to Detector

- A Flavor Neutrino is a superposition of Massive Neutrinos

$$
\begin{aligned}
|\nu_e\rangle &= U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle \\
|\nu_\mu\rangle &= U_{\mu 1}\,|\nu_1\rangle + U_{\mu 2}\,|\nu_2\rangle + U_{\mu 3}\,|\nu_3\rangle \\
|\nu_\tau\rangle &= U_{\tau 1}\,|\nu_1\rangle + U_{\tau 2}\,|\nu_2\rangle + U_{\tau 3}\,|\nu_3\rangle
\end{aligned}
$$

- U is the 3×3 Neutrino Mixing Matrix

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$



$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

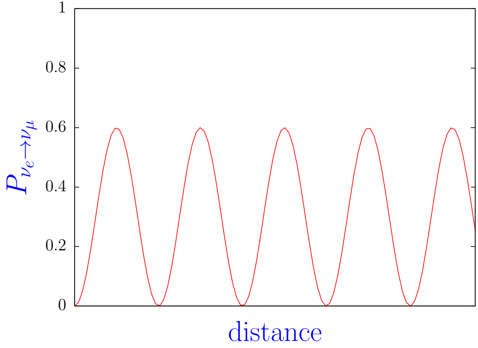
Neutrino Oscillations are Flavor Transitions

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

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

- Neutrino Oscillations are due to interference of different phases of massive neutrinos

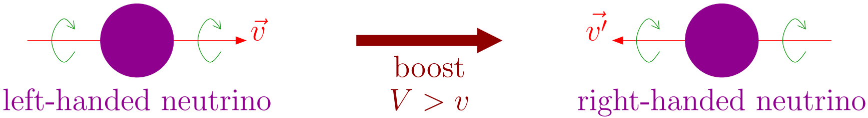
- Phases of massive neutrinos depend on distance $\Longrightarrow$ Oscillations depend on distance



- Oscillations seen without doubt for the first time in the Super-Kamiokande experiment in 1998

Massive Neutrinos

- A left-handed massive neutrino has a velocity $v < c$
- It is possible to boost to a reference frame with $V > v$
- In the new reference frame the neutrino has velocity v' in opposite direction and spin in same direction $\Longrightarrow$ the neutrino is seen as right-handed



- Since neutrinos are massive, there are both left-handed (ν_L) and right-handed (ν_R) neutrinos
- In Standard Model neutrinos are only left-handed $\Longrightarrow$ they are massless
- Neutrino Oscillations $\Leftrightarrow$ Massive Neutrinos $\Longrightarrow$ Standard Model must be extended: add ν_R (Dirac neutrinos) or Majorana neutrinos

Dirac or Majorana Neutrinos?

- Dirac neutrinos are similar to quarks and charged leptons: for each particle there is a corresponding antiparticle connected by Charge Conjugation:

$$\begin{array}{lcccccc} & u \xrightarrow{C} \bar{u} & & d \xrightarrow{C} \bar{d} & & e \xrightarrow{C} \bar{e} & \\ & d \xrightarrow{C} \bar{d} & & s \xrightarrow{C} \bar{s} & & \mu \xrightarrow{C} \bar{\mu} & \\ & t \xrightarrow{C} \bar{t} & & b \xrightarrow{C} \bar{b} & & \tau \xrightarrow{C} \bar{\tau} & \end{array}$$

$$\text{charge} \qquad +\frac{2}{3} \qquad -\frac{2}{3} \qquad -\frac{1}{3} \qquad +\frac{1}{3} \qquad -1 \qquad +1$$

- Particle and antiparticle have opposite charges $\Longrightarrow$ for charged particles particle and antiparticle are different (Dirac)

- For neutral particles particle and antiparticle can be different (Dirac) or equal (Majorana): only neutrinos can be Majorana!

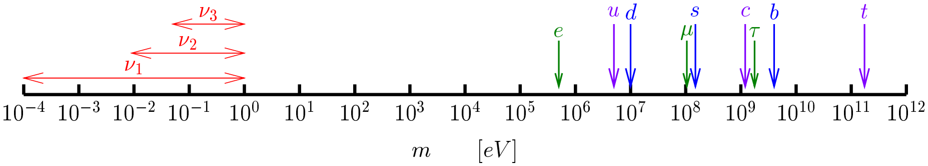
- 1928: Paul Dirac formulates "The Quantum Theory of the Electron" (1933 Physics Nobel Prize)
- A Dirac neutrino is different from the corresponding antineutrino:

$$\nu \neq \bar{\nu}$$

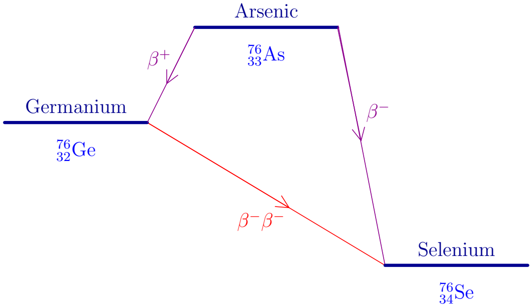
- 1937: Ettore Majorana formulates the "Teoria simmetrica dell'elettrone e del positrone" (Symmetrical theory of the electron and positron)
- A Majorana neutrino coincides with the corresponding antineutrino:

$$\nu = \bar{\nu}$$

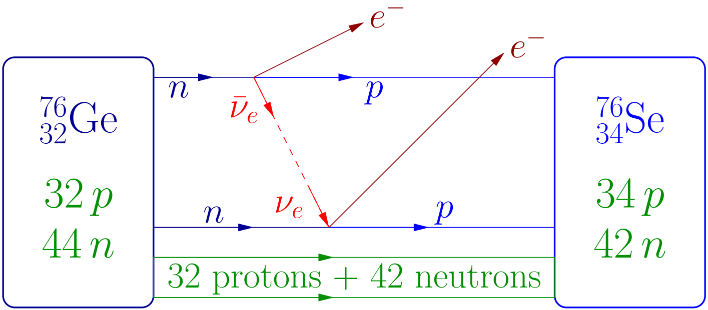
- Theorists favor Majorana neutrinos because it may explain smallness of neutrino masses:



- Many experiments are searching for Majorana neutrinos through Neutrinoless Double-β Decay. Example: ${}^{76}_{32}\text{Ge} \to {}^{76}_{34}\text{Se} + e^- + e^-$



Neutrinoless Double-Beta Decay



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

- Possible only if $\bar{\nu}_e = \nu_e \Longrightarrow$ Majorana!
- Many underground experiments are searching for Neutrinoless Double-β Decay

Conclusions

- Neutrino Mysteries:
  - Neutrino was invented by Pauli to solve the mystery of continuous energy spectrum in β decay (the mystery lasted 16 years, from 1914 to 1930)
  - Existence of neutrino was a mystery for 26 years, from 1930 to 1956, due to weak interactions
  - Existence of neutrino masses was a mystery until 1998
  - For us it is a mystery if neutrinos coincide with antineutrinos or not (Majorana or Dirac)
- Neutrino Surprises:
  - In 1956-1958 Parity violation and neutrino left-handedness was a big surprise
  - In 1970 Solar Neutrino Problem was a surprise to everybody except Bruno Pontecorvo, who predicted the effect due to Neutrino Oscillations in 1967
  - In 1998 the experimental proof of Neutrino Oscillations and the existence of neutrino masses was a surprise to most physicists, who believed the Standard Model
- Neutrino Promises:
  - The physics of massive neutrinos is a promising window on the physics beyond the Standard Model
  - More promises in the following talks