Introduction to Neutrino Physics 1

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Outline of these lectures

1
- 1) Introduction: Motivation, highlights of neutrino history
- 2) Majorana or Dirac ?

2
- 3) Neutrino oscillations: phenomenology and experiments (solar neutrinos)

3
- 4) Recent progress in neutrino oscillations (accelerator-reactors)

4
- Measurement of absolute neutrino mass
- Leptogenesis (optional)

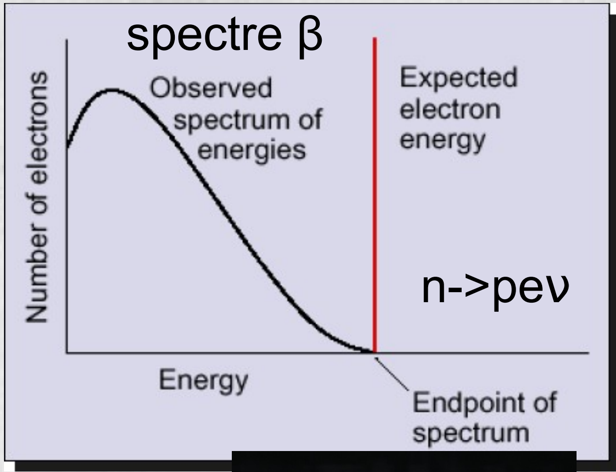
References

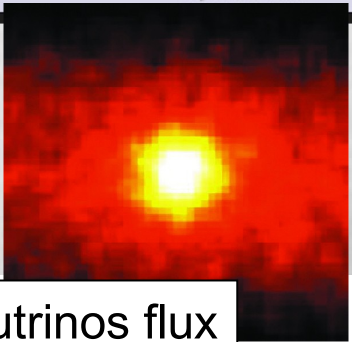
- B. Kayser The physics of massive neutrinos 1989
- E. Akhmedov Neutrino Physics hep-ph/0001264
- A. Strumia F. Vissani “Neutrino masses and mixing and …” hep-ph/0606054
- A very good reference for Diracology: L. Landau Relativistic Quantum Theory
- And I used material from talks by: J. Bouchez, H. Murayama, B. Kayser …

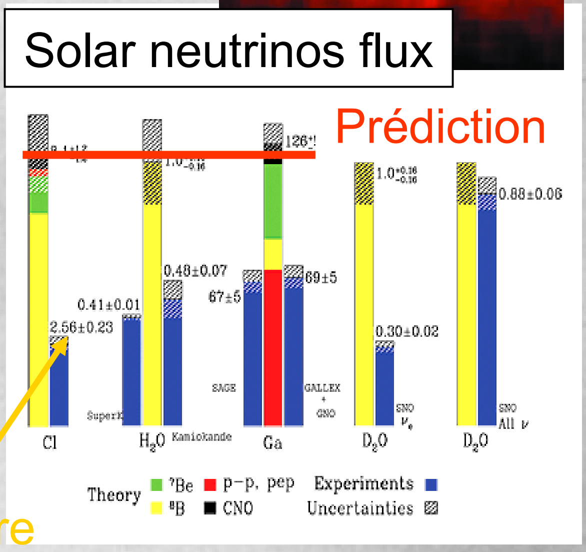
- Thanks to Michele Frigerio for useful discussions

Neutrino physics: a century of discoveries

- 1895 : H. Becquerel discovers radioactivity
- 1930 : Pauli formulates the hypothesis of a neutral weakly interacting particle: the concept of the neutrino is born
- 1956 : observation of neutrino at a nuclear reactor
- 1968 ->solar neutrino deficit, atmospheric neutrino anomaly, 30 years of experiments
- 1996-2002 : measurement of neutrino oscillations => **neutrinos are massive and they mix**
- 2011 Measurement of θ_{13} mixing angle
- **Why are neutrinos so special ?**







Beyond the Standard Model with neutrinos

- Standard Model = Gauge symmetry group (SU(3)xSU(2)xU(1)) +Lorentz+renormalizability
- Give up the renormalizability
- Effects of physics beyond the SM as effective operators
- Can be classified systematically (Weinberg)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

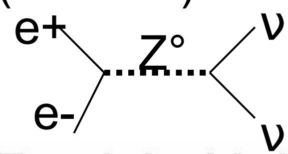
Lowest order effect of physics at short distances !

$$\mathcal{L}_5 = (LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

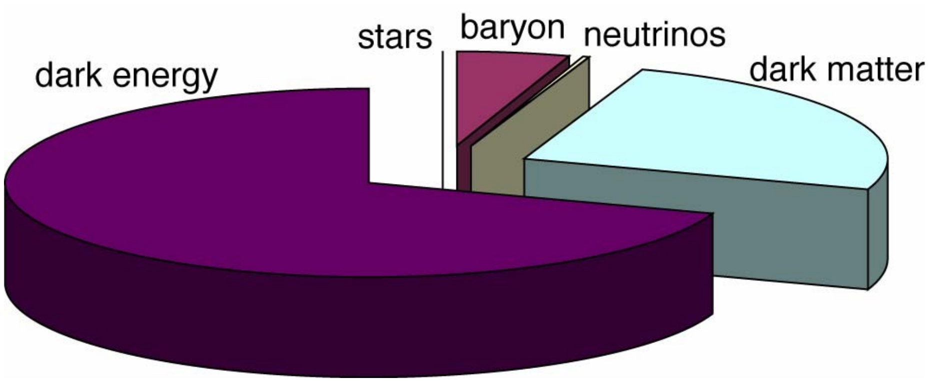
$$\begin{aligned}\mathcal{L}_6 \quad = \quad & QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}He, \\ & W_\nu^\mu W_\lambda^\nu B_\mu^\lambda, (H^\dagger D_\mu H)(H^\dagger D^\mu H), \cdots\end{aligned}$$

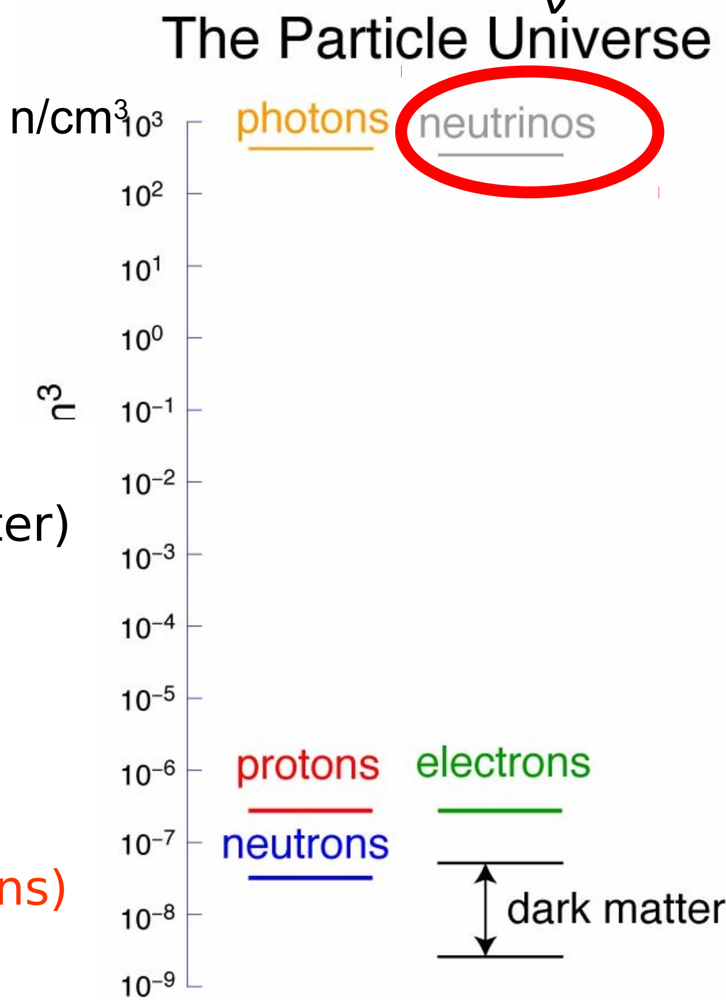
Ubiquitous relic neutrinos

Every particle was in equilibrium in the primordial plasma : traces (« relic ») in the actual universe (cf. CMB)



Universe energy density





We float in a neutrino gas : ~300/cm^3

Neutrinos are the most copious fermionic (matter) particles (10^9 more than protons and neutrons)

Mass comparable to all the stars ! Important <u>consequences on the structures</u> (galaxies, clusters)

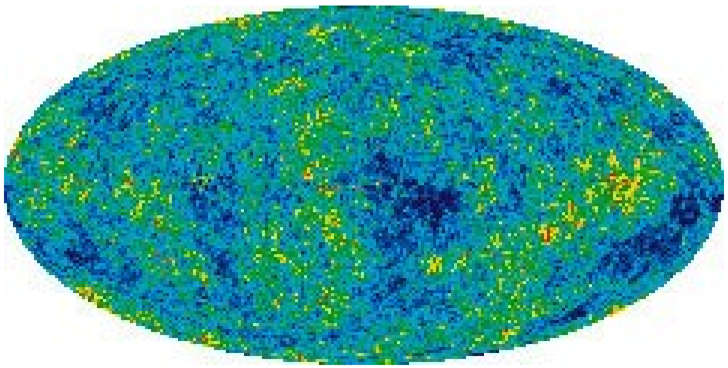
However very difficult to detect ....

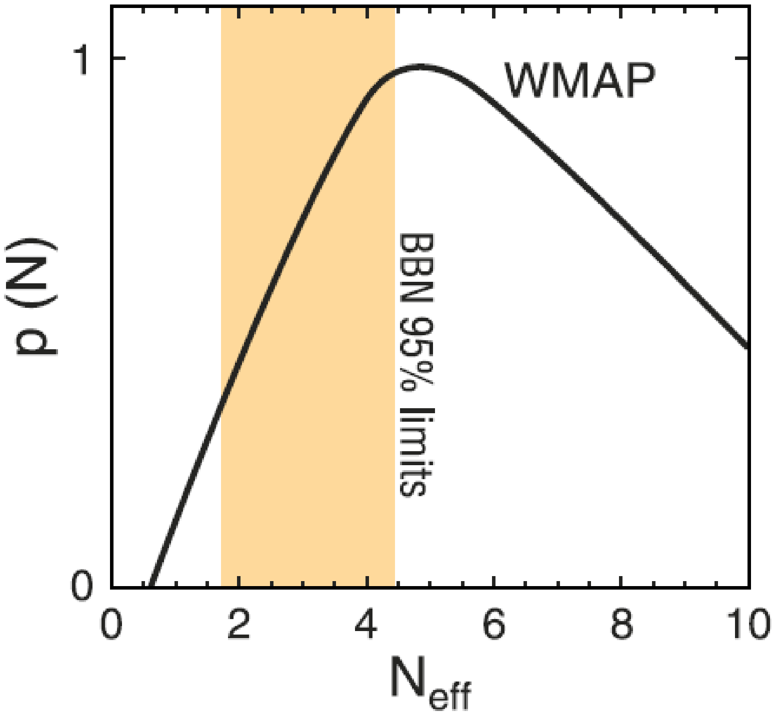
We need to know neutrinos (masses, interactions) to understand the universe

Results confirmed by the PLANCK data

Cosmic Microwave Background probes Neutrinos

WMAP 5-year data





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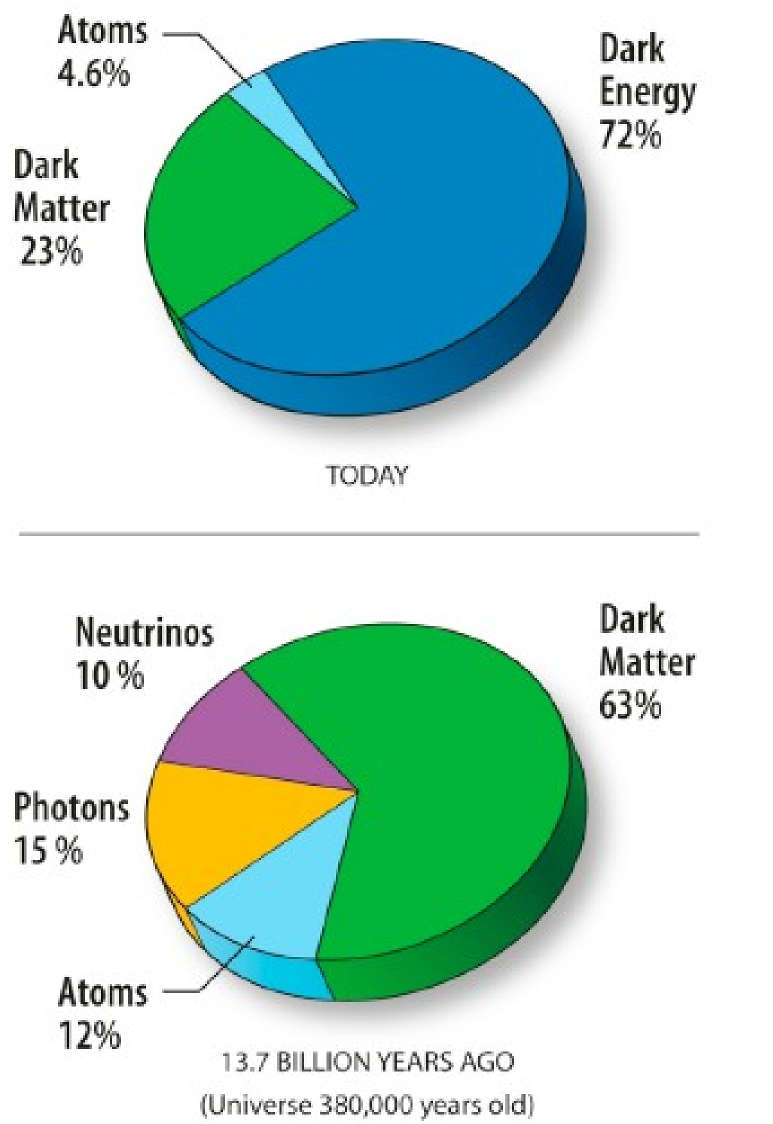


Neutrino and the origin of matter

Andrei Sakharov

The universe today contains very little antibaryons ($N_{Bar} >> N_{\overline{Bar}}$) while the initial state is supposed to be symmetric ($N_{Bar} = N_{\overline{Bar}}$).

- How can we explain dynamically the observed baryon number B ?
- Sakharov conditions (1967):

Fukugita and Yanagida PLB174 45 (1986)

Leptogenesis = Baryons from neutrinos

- Processes out of thermal equilibrium otherwise
NBar = N$\overline{\text{Bar}}$ = $\int d^3p(\exp(-\sqrt{p_B^2+m_B^2})+1)^{-1}$
mB= m$\overline{\text{B}}$ par CPT

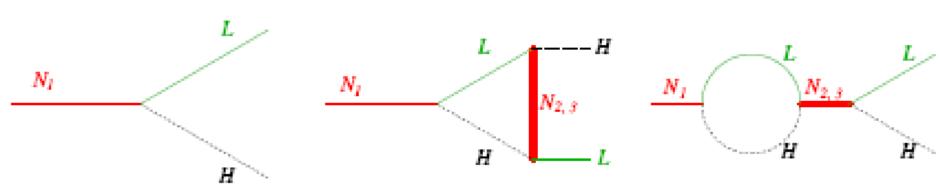
- Violation of C and CP : 1/3 B = $q_L + q_R - \bar{q}_L - \bar{q}_R$: $(B)^{CP} = (B)^C = -B$

C

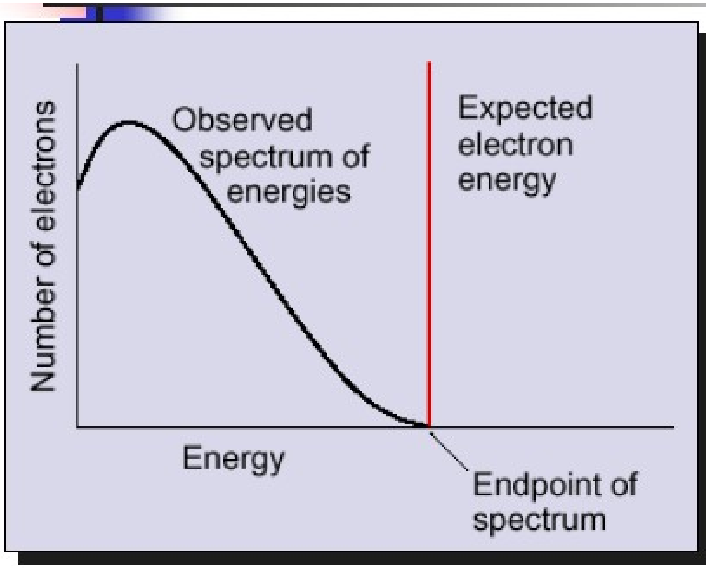
CP

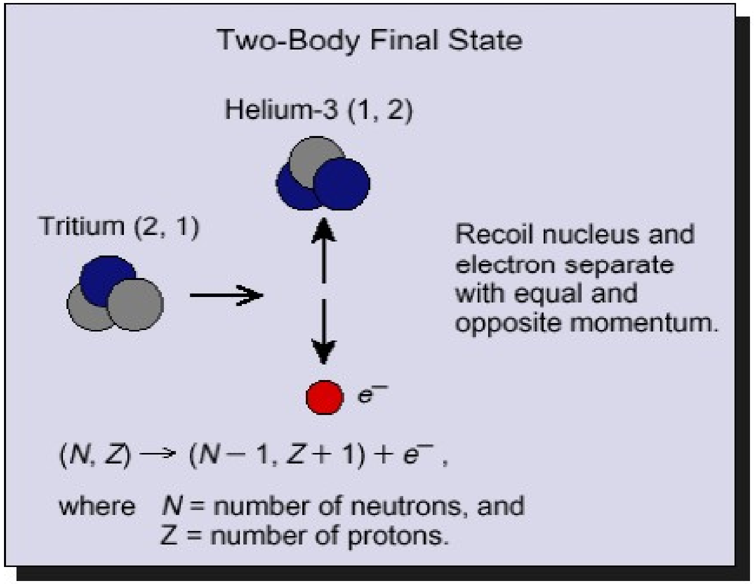
- B violating process to have B=0 $\rightarrow$ B$\neq$0

- Decay out of equilibrium of superheavy neutrino (m~GUT scale)
- CP violating decays of N to leptons
- Processes violating B+L convert the lepton asymmetry into B asymmetry



The Beta spectrum





Is energy conserved in this process ?

Neutrino: ein verzweifelter Ausweg!

Wolfgang Pauli

Offener Brief an die Gruppe der Radioaktiven bei der Gauverein-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen dürfte von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Unpublished!!

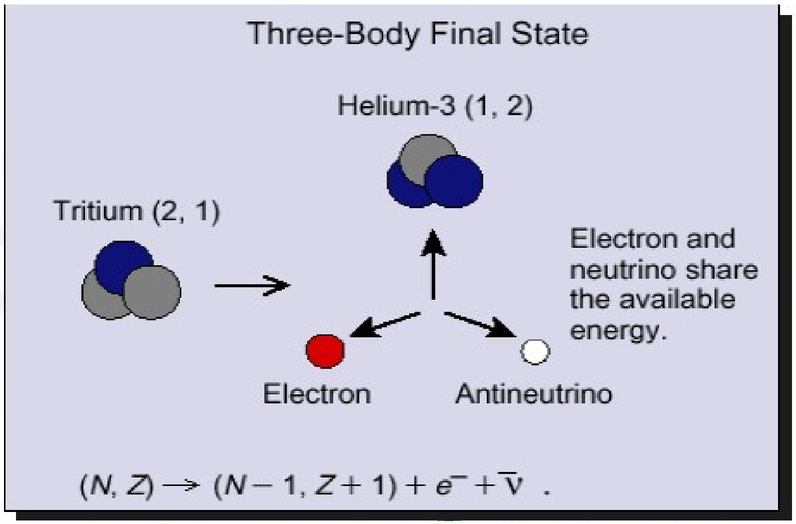
Neutrino: a desperate solution!

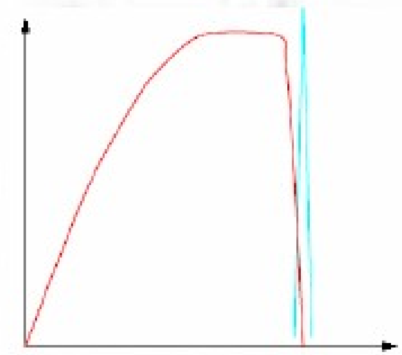
4th December 1930
Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and 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 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...
From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tübingen personally, because I am indispensable here due to a ball which will take place in Zürich during the night from December 6 to 7….
Your humble servant,
W. Pauli

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do."

Wolfgang Pauli

To save the conservation of energy





The Energy of the "β"

- If the above picture is complete, conservation of energy in this two body decay predicts monochromatic β
  - but a continuous spectrum had been observed (since 1914)
- Pauli suggests "neutron" takes away energy!
- *"The exchange theorem of statistics", by the way, refers to the fact that a spin½ neutron can't decay to an spin½ proton + spin½ electron*

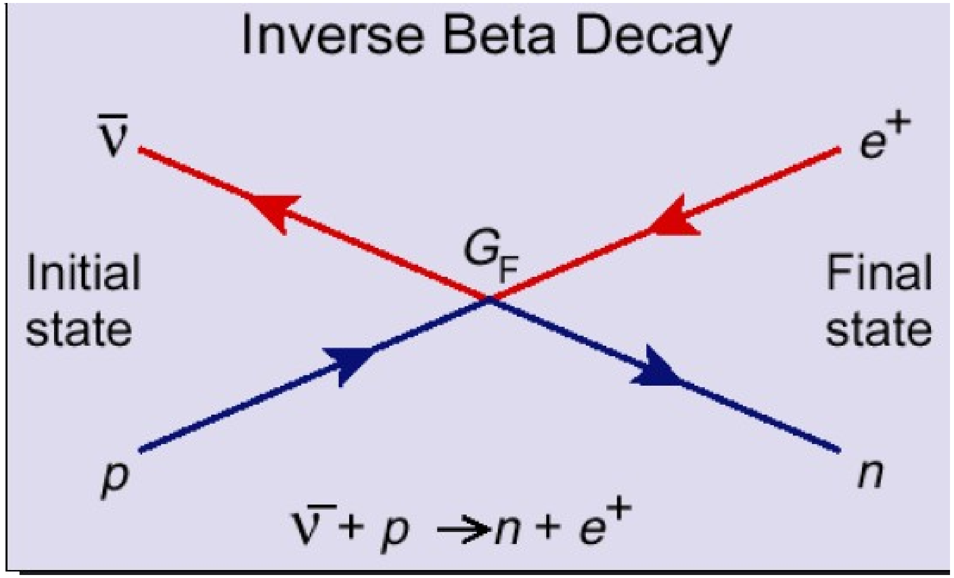
First theory of beta decays

- Fermi 1934 Z.f. Physik 88, 161
- Paper rejected by Nature: “it contains speculations too remote from reality to be of interested for the reader” …
- Fermi was so shocked that he turned after this to experimental physics !
- Four fermions contact interaction (no propagator) of the form

$$H_W = G_F / \sqrt{2}\, \bar{\psi}_p \psi_n \bar{\varphi}_\nu \varphi_e$$

- n->p e- nubar
- Allows to predict other processes like inverse beta decay (p nu bar → e+n), electron capture
- Correct order of magnitude for the neutrino cross section (10-44
-

Fermi 4 fermion interaction



$$L_{weak} = G_F(\bar{\psi}_p \gamma_\mu \psi_n)(\bar{\psi}_e \gamma_\mu \psi_\upsilon)$$

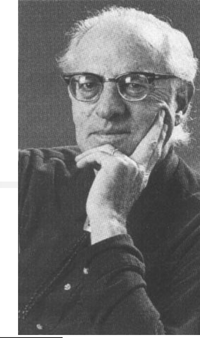
$$L_{QED} = -e(\bar{\psi}_e \gamma_\mu \psi_e)A^\mu$$

How weak are weak interactions?

- $\sigma(\nu p) \sim 10^{-44}$ cm^2 to be compared to typical (γp) cross-section of 10^{-24} cm^2
- Mean free path in steel of a 1 MeV neutrino is 10 light years !
- We need a VERY strong neutrino source to detect a signal

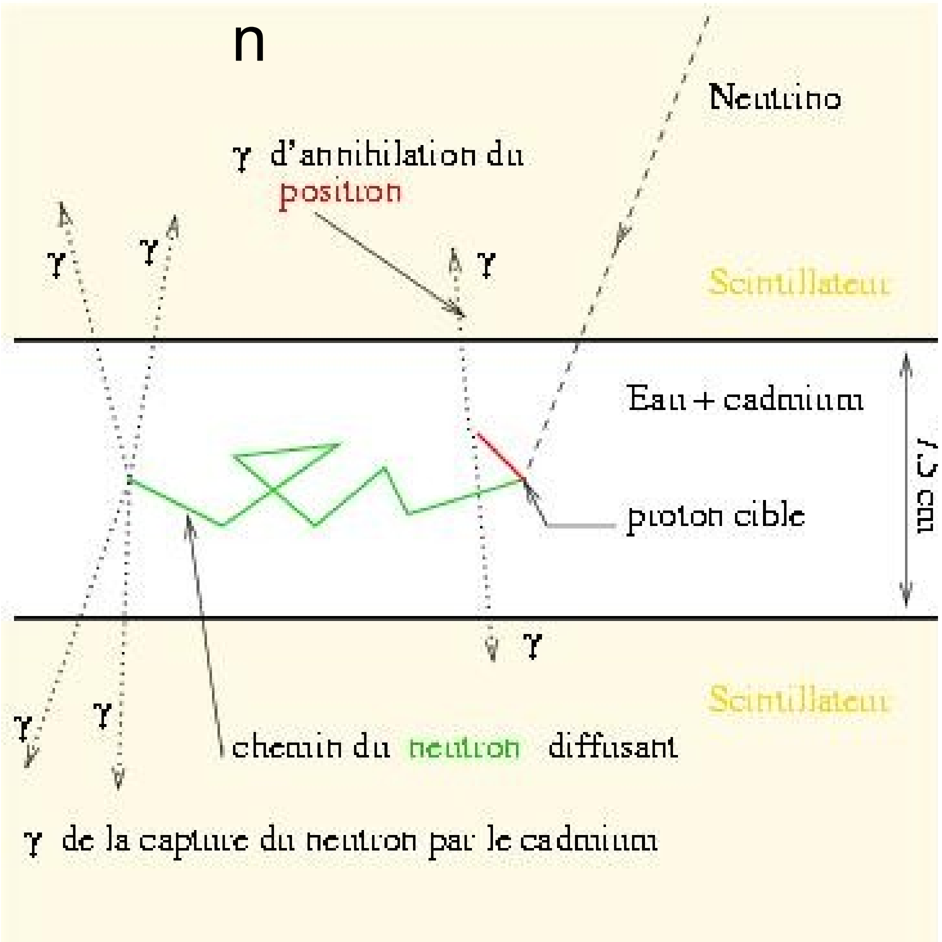
- Typical reactor thermal energy: 900 MW (electric) ->2800 MW (thermal)
- Typical energy release in a fission process: 200 MeV
- Average number of beta decays per fission: 6
- Neutrino/s = $6\ 2800\ 10^6 / (200\ 10^6\ 1.6\ 10^{-19}) \sim 5\ 10^{20}$ ν/s

Neutrino discovery Reines and Cowan (1955)

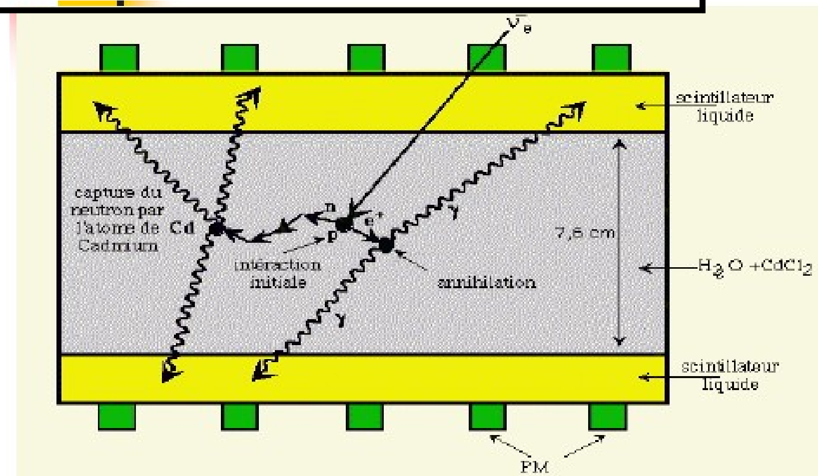


Experiment at Savannah River nuclear reactor 10^{20} nu/s

$\bar{\nu} + p \text{ ------> } e^+ + n$



reactor off	1 evt/h
reactor on	4 evt/h
SIGNAL = 3 neutrinos/hour !	



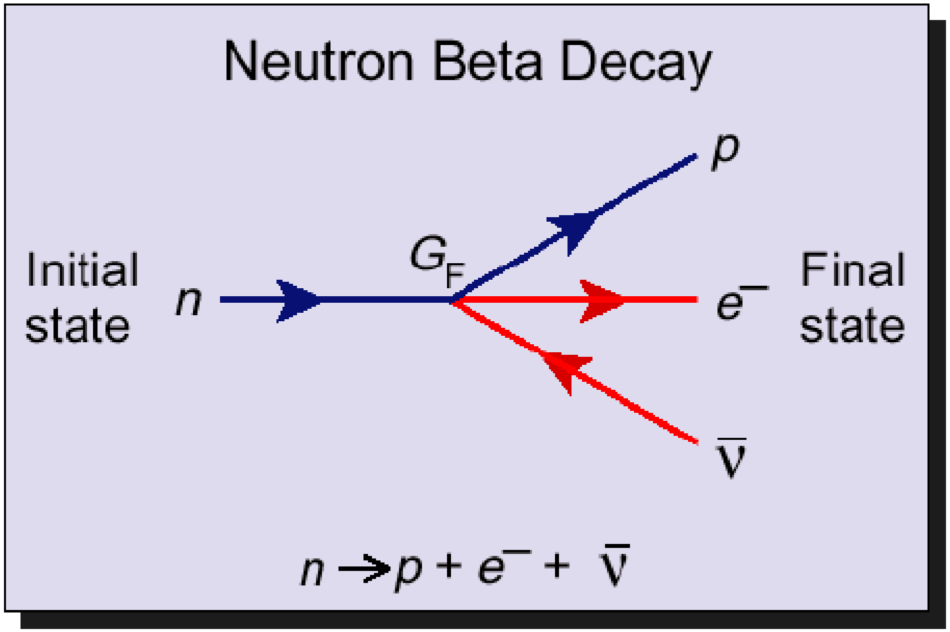
Expérience de Reines et Cowan (1953)

$\nu_e + p \longrightarrow n + e^+$

$n + Cd \xrightarrow{capture} 3\gamma$

$e^+ + e^- \xrightarrow{annihilation} 2\gamma$

Weak interactions (Feynman & Gell Mann,1958)



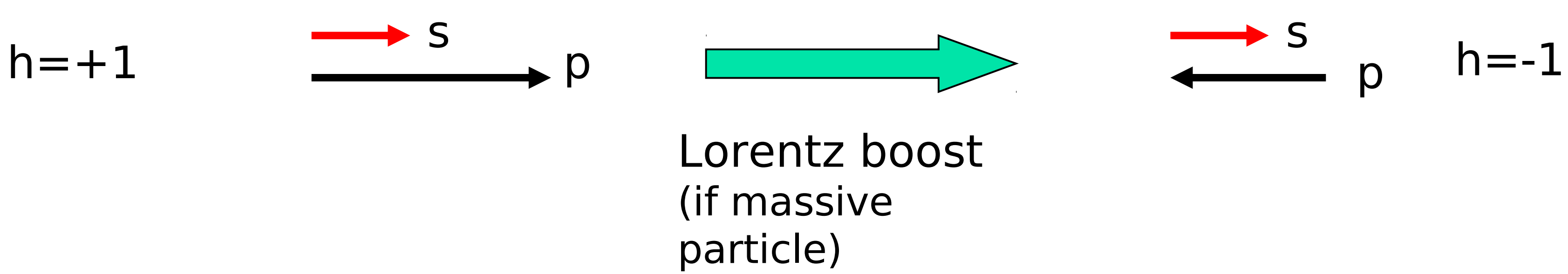
- Weak interactions are maximally Parity violating
- Only Left-handed fermions participating in these interactions

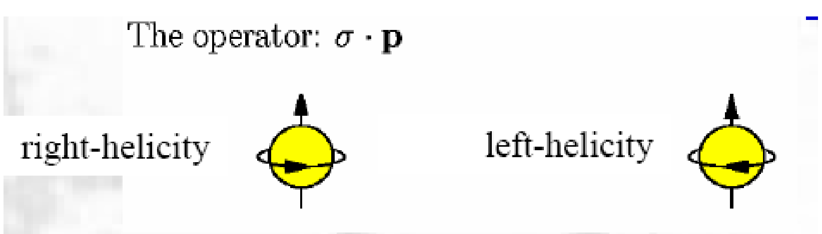
$$L_{weak} = \frac{G_F}{\sqrt{2}} (\bar{\psi}_p \gamma_\mu (1-\gamma_5) \psi_n)(\bar{\psi}_e \gamma^\mu (1-\gamma_5) \psi_\nu)$$

Projects on left-handed states

Helicity

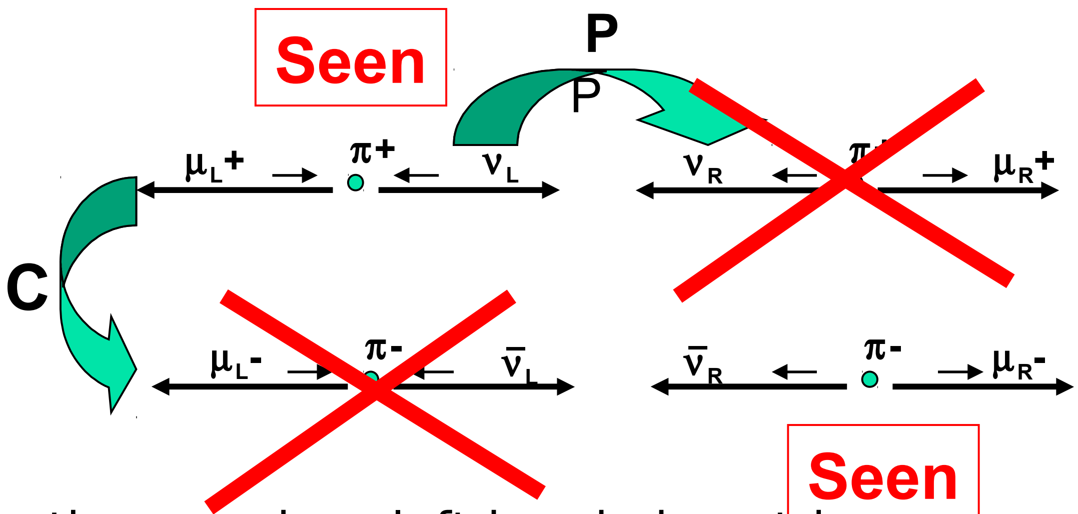
- A spin ½ fermion is characterized by its momentum p and its spin s
- We can label the states by the projection of the spin along the momentum: this is called helicity ($h=\vec{s}\cdot\vec{p}$)
- h=+1 (-1) right (left)-handed





Discrete symmetries and weak interactions

- Parity P : P(**r**) = -**r**, P(**p**) = -**p**, P(**l**) = **l**
- Charge conjugation C : transforms a particle in an antiparticle (reverses all the charges)
- Time inversion T : T(t)=-t



Weak interactions produce left-handed neutrinos (and right handed antineutrinos)

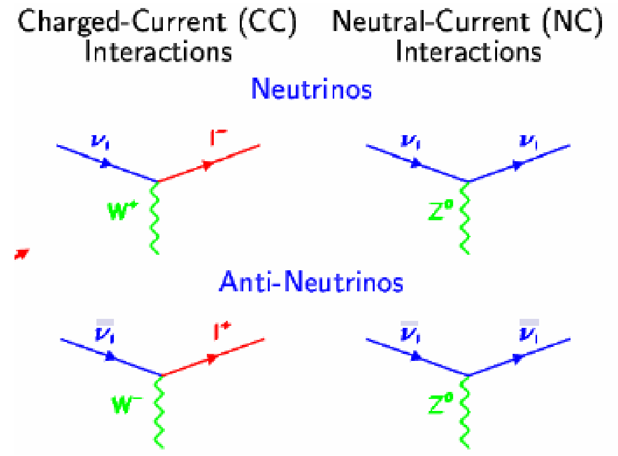
NB For weak interactions, the left-handed states are defined by chirality which corresponds to helicity only for massless particles, otherwise a left-handed state corresponds to helicity h=-1 up to terms of order o(m/E)

Neutrinos in the Standard Model

Gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)$

$I_L=1/2$, $I_3=-1/2$ $q=0$ $\quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R$ $\quad I_L=0$ $q=-1$

$$\mathrm{L}_W = \frac{1}{\sqrt{2}} g\,(\overline{e_L}\gamma_\mu \nu_L)\,W^{+\mu} + \frac{1}{2}\frac{g}{\cos\theta_W}(\overline{\nu_L}\gamma_\mu \nu_L)\,Z^\mu$$



The mass of the neutrino

Two possibilities for a massive neutrino

- Let us start from a massive left-handed neutrino which we have observed

ν_L

Two possibilities for a massive neutrino

- Let us start from a massive left-handed neutrino which we have observed, then apply CPT

$$(\nu_{-}\ ,\ \overline{\nu}_{+})$$

$$\nu_{-} \xrightarrow{\text{CPT}} \overline{\nu}_{+}$$

Two possibilities for a massive neutrino

- Let us start from a massive left-handed neutrino which we have observed

Lorentz boost

$$(\nu_- \,,\ \overline{\nu}_+) \qquad\qquad (\quad ,\ \nu_+)$$

CPT

Two possibilities for a massive neutrino

- Let us start from a massive left-handed neutrino which we have observed

Lorentz boost

$$(\nu_- \, , \, \bar{\nu}_+) \qquad\qquad (\quad , \nu_+)$$

CPT

Is this a new state ?

Two possibilities for a massive neutrino

- Let us start from a left-handed neutrino which we have observed

Lorentz boost

$(\nu_- \, , \, \bar{\nu}_+) \qquad (\quad , \nu_+)$

CPT

Is this a new state ?

Lorentz boost

$(\nu_- \, , \, \bar{\nu}_+) \qquad (\bar{\nu}_- , \nu_+)$

CPT CPT

Lorentz boost

$(\nu_- \, , \, \nu_+)$

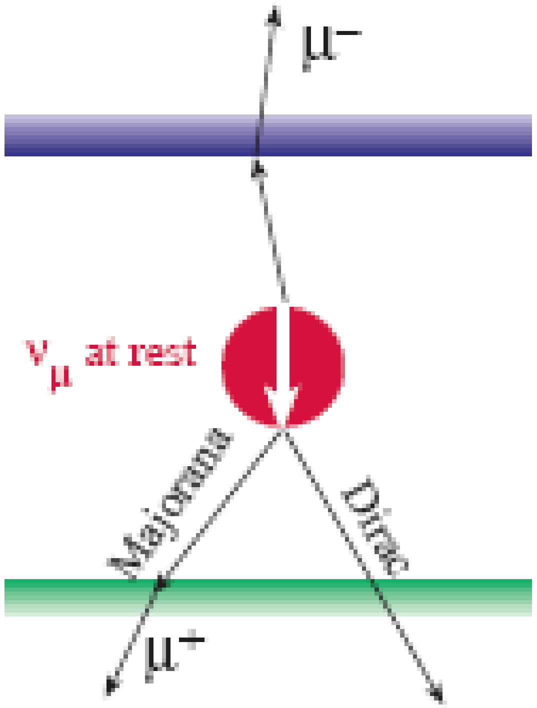
CPT

Yes. Dirac neutrino
4 states: particle-antiparticle,
2 helicities

No. Majorana neutrino
2 states: particle=antiparticle,
2 helicities

Physical meaning of Dirac vs Majorana

Strumia-Vissani



- Suppose we have a ν_μ at rest with spin down
- Imagine (not very simple to realize …) that we can accelerate it upwards to relativistic energy
- Then by charged current it will interact on the ceiling producing a mu-
- Accelerating it downward it will
  - Produce a mu+ if Majorana (it will interact in the same way as what we call “antineutrino”)
  - Have no interaction if Dirac

Dirac vs Majorana neutrino in terms of Quantum Field Theory

- To understand the Dirac versus Majorana neutrino difference we need to
  1. go back to the Dirac equation
  2. Define the chirality projectors
  3. define the charge conjugation operator
  4. Check what happens to chirality under charge conjugation
  5. See if we can define a massive spin ½ field using only one chiral projection (=Weyl field)
  6. Study possible mass terms for this field

1 The Dirac equation

$$\left(\gamma^{\mu} p_{\mu} - M\right)\psi = 0$$

The Dirac equation for a free fermion

$$u(\vec{p},s) = \begin{bmatrix} 1 \\ \dfrac{\vec{\sigma}\cdot\vec{p}}{E+M} \end{bmatrix} \chi_s \quad s = \pm\frac{1}{2}$$

$$v(\vec{p},s) = \begin{bmatrix} \dfrac{\vec{\sigma}\cdot\vec{p}}{E+M} \\ 1 \end{bmatrix} \chi_{s^C}$$

4 independent solutions for momentum p
u describes particles, v antiparticles

$$\chi_{s=1/2} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad \chi_{s=-1/2} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \chi_{s=1/2^C} = -\begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \chi_{s=-1/2^C} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

1 The gamma matrices (Pauli-Dirac representation)

$$\left(\gamma^{\mu} p_{\mu} - M\right)\psi = 0$$

$$\gamma^0 = \begin{bmatrix} I & 0 \\ 0 & -I \end{bmatrix} \quad \gamma^i = \begin{bmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{bmatrix}$$

$$\gamma^{\mu}\gamma^{\nu} + \gamma^{\nu}\gamma^{\mu} = 2g^{\mu\nu}$$

$$\gamma^{0^+} = \gamma^0 \quad \gamma^{i^+} = -\gamma^i$$

$$\gamma^5 \equiv -i\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{bmatrix} 0 & -I \\ -I & 0 \end{bmatrix} \quad \gamma^{\mu}\gamma^5 + \gamma^5\gamma^{\mu} = 0$$

$$\gamma^{5^+} = \gamma^5 \quad \gamma^{5^2} = I$$

2 Chirality and helicity

$$P_R = \frac{1-\gamma_5}{2} \quad P_L = \frac{1+\gamma_5}{2}$$ Chirality projectors

$$P_L^2 = P_L \quad P_L^2 = P_R \quad P_L P_R = P_R P_L = 0 \quad P_R + P_L = 1$$

$$P_\pm = \frac{1}{2}\left(1 \mp \frac{\vec{\sigma}\cdot\vec{p}}{p}\right)$$ Helicity projectors

In the chiral basis

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

2 Why $(1+\gamma^5)$ select left-handed states

$$\psi_L = \frac{1}{2}(1+\gamma^5)\psi$$

$$(\gamma^\mu p_\mu - m)\psi = (E\gamma^0 - \vec{p}\vec{\gamma} - m)\psi = 0$$

$$\psi = \begin{pmatrix} \varphi \\ \chi \end{pmatrix} \quad \chi = \frac{\vec{\sigma}\cdot\vec{p}}{E+m}\varphi$$

$$\psi_L = \frac{1}{2}(1+\gamma^5)\psi = \frac{1}{2}\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}\begin{pmatrix} \varphi \\ \chi \end{pmatrix} = \frac{1}{2}\begin{pmatrix} \varphi-\chi \\ \chi-\varphi \end{pmatrix}$$

$$\varphi - \chi = (1 - \frac{\vec{\sigma}\cdot\vec{p}}{E+m})\varphi$$

$\varphi - \chi = (1 - \vec{\sigma}\cdot\vec{n})\varphi$ In the limit E>>m, where n//p

$\varphi - \chi = (1-\sigma_z)\varphi = 2\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\varphi$ For z//p, then ψ has spin along -p

3 Charge conjugation

We would like to find a spinor satisfying a similar equation but for the charge conjugate particle (+e)

$$\left(\gamma^\mu p_\mu - M\right)\psi(x) = 0$$

For a charged fermion (-e)

$$\left(\gamma^\mu \left(p_\mu - ieA_\mu\right) - M\right)\psi(x) = 0$$

$$\left(\gamma^\mu \left(p_\mu + ieA_\mu\right) - M\right)\psi^C(x) = 0$$

Ψ* because this is a « negative energy » solution

$$\psi^C = \Omega\overline{\psi}^T \qquad \Omega \equiv i\gamma^2\gamma^0$$

3-4 Properties of the charge conjugation

$$C:\psi \to \psi^C = \Omega\overline{\psi}^T \quad \overline{\psi} = \psi^* \gamma^0$$

Definition of particle-antiparticle conjugation

$$\Omega = i\gamma^2\gamma^0$$

$$\Omega^+ = \Omega^T = \Omega^{-1} = -\Omega \qquad \Omega^{-1}\gamma^\mu\,\Omega = -\gamma^{\mu T}$$

Properties of the Ω matrix

$$\left(\psi^C\right)^C = \psi \quad \overline{\psi^C} = \psi^T\Omega \quad \overline{\psi_1}\,\psi_2{}^C = \overline{\psi_2{}^C}\,\psi_1$$

$$\overline{\psi_1}\,A\,\psi_2 = \overline{\psi_2{}^C}\left(\Omega^{-1}A\Omega^{-1}\right)\psi_1{}^C$$

Useful relations

$$\boxed{\left(\psi_L\right)^C = \left(\psi^C\right)_R \quad \left(\psi_R\right)^C = \left(\psi^C\right)_L}$$

C flips chirality

5 Introducing a mass term

$$-\mathcal{L}_m = m\overline{\psi}\psi = m\overline{\psi_L}\,\psi_R + m\overline{\psi_R}\,\psi_L$$

$$\psi = \psi_L + \psi_R$$

The mass term couples right and left components: a massive fermion has both!

Two solutions:

a) Dirac case, the right hand component is completely independent of the left handed

b) Majorana case: the right handed is the C conjugated of the left handed

$$\psi_R = \left(\psi_L\right)^C = \left(\psi^c\right)_R$$

or

η is a phase factor

$$\psi = \psi_L + \eta\left(\psi^c\right)_R$$

from this follows that:

$$\boxed{\psi^C = \eta^*\psi}$$

A Majorana fermion coincides with its antiparticle: a really neutral particle

5 The Dirac and Majorana fields

$$\Psi^D(x) = \sum_{\vec{p},s} N(p,s)\left[f(\vec{p},s)u(\vec{p},s)e^{ipx} + \overline{f}^+(\vec{p},s)v(\vec{p},s)e^{-ipx}\right]$$ Dirac

$$\Psi^M(x) = \sum_{\vec{p},s} N(p,s)\left[f(\vec{p},s)u(\vec{p},s)e^{ipx} + \lambda f^+(\vec{p},s)v(\vec{p},s)e^{-ipx}\right]$$ Majorana

$f(\vec{p},s)$ Annihilation operator of particle f

$\overline{f}^+(\vec{p},s)$ Creation operator of particle $\overline{f}$

6 Majorana mass term

- Let us start from a Dirac field ψ

$$-\mathcal{L}_m = m\overline{\psi}\psi = m\overline{\psi_L}\,\psi_R + m\overline{\psi_R}\,\psi_L$$

This is the usual Dirac mass term

$$\psi = \psi_L + \psi_R$$

$$\psi_L \quad \psi_R \quad \left(\psi^C\right)_L \quad \left(\psi^C\right)_R$$

What are all the Lorentz invariant terms that we can build by combining one of these terms with those ?

$$\overline{\psi}_L \quad \overline{\psi}_R \quad \overline{\left(\psi^C\right)_L} \quad \overline{\left(\psi^C\right)_R}$$

$$\overline{\chi_L}\,\psi_L = 0$$

Notice that this kind of bilinears are 0 because gamma5 anticommutes with the other gammas

$$\overline{\psi_L}\,\psi_R \quad \left(\overline{\psi^C}\right)_L \psi_R \quad \left(\overline{\psi^C}\right)_R \psi_L$$

These (+hc) are all possible mass term

Majorana mass term

$$-\mathcal{L}_m = m\overline{\psi}\psi = m\overline{\psi_L}\,\psi_R + m\overline{\psi_R}\,\psi_L$$

$$\overline{\psi_L}\,\psi_R \quad \left(\overline{\psi^C}\right)_L \psi_R \quad \left(\overline{\psi^C}\right)_R \psi_L$$

Majorana mass terms

$$-L_m = M_D\left[\overline{\psi_L}\,\psi_R + hc\right] + \boxed{\frac{M_L}{2}\left[\left(\overline{\psi^C}\right)_R \psi_L\right] + \frac{M_R}{2}\left[\left(\overline{\psi^C}\right)_L \psi_R\right]}$$

This is the most general lagrangian mass term for this field

$$\overline{\psi_L}\,\psi_R$$

$$\left.\begin{aligned}\left[\left(\overline{\psi^C}\right)_R \psi_L\right] &= \overline{(\psi_L)^C}\,\psi_L = \psi_L{}^T\,\Omega\,\psi_L \\ \left[\left(\overline{\psi^C}\right)_L \psi_R\right] &= \overline{(\psi_R)^C}\,\psi_R = \psi_R{}^T\,\Omega\,\psi_R\end{aligned}\right\}$$

These terms violate a U(1) global symmetry

$$\varphi \to e^{i\alpha}\varphi$$

$\Rightarrow$ We can not assign a charge to a Majorana field

Majorana mass term and Left-Right symmetry

$$-L_m = M_D\left[\overline{\psi_L}\,\psi_R + hc\right] + \frac{M_L}{2}\left[\left(\overline{\psi^C}\right)_R \psi_L\right] + \frac{M_R}{2}\left[\left(\overline{\psi^C}\right)_L \psi_R\right]$$

$$f \equiv \frac{\psi_L + (\psi_L)^C}{\sqrt{2}} \quad F \equiv \frac{\psi_R + (\psi_R)^C}{\sqrt{2}}$$

$$-L = (\bar{f}, \bar{F})\begin{pmatrix} M_L & M_D \\ M_D & M_R \end{pmatrix}\begin{pmatrix} f \\ F \end{pmatrix}$$

Reparameterization in terms of the fields f and F: from the definition it is clear that they are Majorana fields

1 Dirac field (4 dof) -> 2 Majorana fields (2x2 dof)

$\overline{\psi_L}\,\psi_R$ — $I_L=1/2$ $I_R=1/2$

$\left[\left(\overline{\psi^C}\right)_R \psi_L\right] = \overline{(\psi_L)^C}\,\psi_L = \psi_L^T \Omega \psi_L$ — $I_L=1$ $I_R=0$

$\left[\left(\overline{\psi^C}\right)_L \psi_R\right] = \overline{(\psi_R)^C}\,\psi_R = \psi_R^T \Omega \psi_R$ — $I_L=0$ $I_R=1$

Quantum numbers under $SU(2)_L x SU(2)_R$

$m_\nu=510^{-2}$ eV =>M=~10^{15} GeV

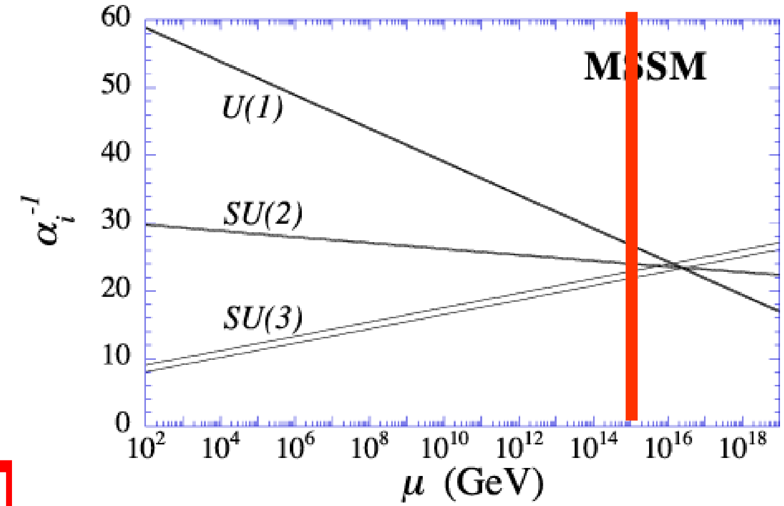
The see-saw relation

M_L term set to 0 from phenomenological constraint
Expect M_R>>M_D (electroweak symmetry breaking)

$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

$$\left.\begin{aligned} M_N &\cong M_R \\ M_{\nu'} &\cong -\frac{M_D^{\,2}}{M_R} \end{aligned}\right\}$$

Eigenvalues

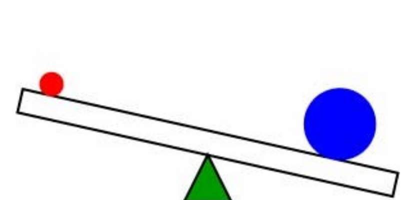


Redefining the ν' field

$$\boxed{M_\nu \cong \frac{M_D^{\,2}}{M_R}}$$

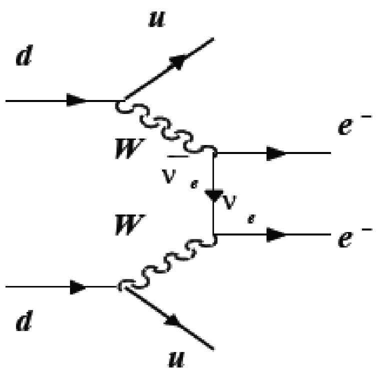
See-saw relation: the neutrino is light because there is a very heavy neutral lepton

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$



Lepton number violation

- The Standard Model is invariant under local transformations of the SU(3)C x SU(2)L x U(1) group
- In addition, it has these 4 global symmetries:
  - $U(1)_B$ $U(1)_L$ $U(1)_{Li\text{-}Lj}$
- Majorana mass terms violate Lepton number by two units!!
- New processes are possible
- Neutrinoless double beta decay
- K+ -> $\pi^- \mu^+ \mu^+$



0ν - ββ decay

What we have learned today

- Neutral massive fermions are special quantum objects
- A Majorana neutrino represents an intrinsically neutral particle
- No “charge”-like quantum number
- If it is true, then we can avoid the term “antineutrino”
- The Majorana mass term breaks the lepton number by two units
- The see-saw mechanism explains beautifully why neutrino masses are light and suggests a very high mass scale (of the order of the Grand Unification Scale)
- It is therefore very important to find out whether neutrino are Majorana or Dirac