Neutrino. History of a unique particle

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December is special month for neutrino

In December 1930 Pauli letter

During 81 years many events occurred

Three Nobel Prizes

1988 Lederman, Schwartz, Steinberger (ν_μ)

1995 Reines (neutrino)

2002 Davis, Koshiba (solar and SN ν's)

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Brief history of neutrino

Why neutrinos are special?

- Because ν's are the only fundamental fermions with $Q=0$

1. No direct EM interaction. Neutrinos interact with heavy $W^{\pm}$ and Z^{0}

Processes in which W and Z are virtual (decays, neutrino reactions) are weak processes determined by Fermi constant

$$G_F = \sqrt{2}\frac{g^2}{8m_W^2} \simeq 10^{-5}\frac{1}{M_p^2}$$

2. Neutrinos can be truly neutral Majorana particles ($\nu \equiv \bar{\nu}$) not poccessing any charges

This could explain recent discovery of small neutrino masses by a new L-violating interaction of SM particles with very heavy ($\simeq 10^{14}$-10^{15} GeV) Majorana fermions

Pauli idea of neutrino (neutron)

1930

- p, e^- are only elementary particles
- nuclei are bound states of p and e^-

two problems

1. Continuous β-spectra
2. Spins of some nuclei

β-decay $(A, Z) \to (A, Z+1) + e^-$

From energy-momentum conservation

$$T_e \simeq m_{A,Z} - m_{A,Z+1} - m_e = Q$$

In experiments

$$0 \leq T_e \leq Q$$

Only two possibilities

I Energy-momentum is not conserved

II Exist neutral elementary particle emitted in β-decay together with e^- has weak interaction "absorption length is 10 times larger than absorption length of the γ-quantum" not detected in experiment

$$(A, Z) \to (A, Z+1) + e^- + \text{"}n\text{"}$$

three-particle decay, continuous β-spectrum

The problem of spin

${}^{7}N_{14} = (14p + 7e^-)$ half-integer spin

From measurement of molecular spectra

${}^{7}N_{14}$ satisfy Bose-Einstein statistics

From spin-statistics theorem

the spin of ${}^{14}N_{7}$ is integer

Pauli assumed that "n" has spin $\frac{1}{2}$

and also is a constituent of nuclei

Soon it was clear that last idea is not correct

In 1932 neutron was discovered

Nuclei are bound states of p and n
(Heisenberg, Majorana, Ivanenko)

Problem of the spin of $^{14}N_7$ and other nuclei disappeared

$^{14}N_7 = (7p + 7n)$ integer spin

Fermi built first theory of the β-decay (1934)

He gave the Pauli particle the name neutrino (neutral, small)

For Fermi it was a problem to understand how e^- and ν are produced by nuclei (bound states of p, n)

By analogy with emision of the photon

Fermi assumed that e and ν are produced in quantum transition

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

By analogy with EM interaction

$$\mathcal{H}_I^{EM} = e\bar{p}\gamma^\alpha p A_\alpha \qquad p \to p + \gamma$$

Fermi assumed

$$\mathcal{H}_I^\beta = G_F \bar{p}\gamma^\alpha n \,\bar{e}\gamma_\alpha \nu + h.c.$$

Fermi Hamiltonian describes decays in which

$$\Delta J = 0 \quad \pi_i = \pi_f \quad (\Delta J = J_f - J_i)$$

e^- and $\bar{\nu}$ are emitted in $S=0$ (singlet) state

If e^- and $\bar{\nu}$ are emitted in $S=1$ (triplet) state

$$\Delta J = \pm 1, 0 \quad \pi_i = \pi_f$$

(Gamow-Teller transition)

Both Fermi and G-T decays were observed

Total β-decay Hamiltonian must include additional terms

The most general Hamiltonian

$$\mathcal{H}^{\beta} = \sum_{i=S,V,T,A,P} G_i \, \bar{p} O^i n \, \bar{e} O_i \nu + h.c.$$

$$O^i \Rightarrow 1, \gamma^\alpha, \sigma^{\alpha\beta}, \gamma^\alpha \gamma_5, \gamma^5$$

Five interaction constants

Search for dominant terms

During many years the situation remained uncertain (S, T or V, A)

In 1934 Bethe and Peierls estimated cross section of the interaction of ν with matter

In the Fermi Hamiltonian quantum fields enter

It describes not only

$$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}$$

but also

$$\bar{\nu} + (A,Z+1) \to e^+ + (A,Z), \ldots$$

$\Gamma = \frac{1}{T_{1/2}}$ and σ are proportional to $|M|^2$

$\sigma \simeq \frac{A}{T_{1/2}}$ A has dimension $L^2 \cdot T$

Longest length and time involved

$\frac{\hbar}{m_e c}$ and $\frac{\hbar}{m_e c^2}$ $\sigma \leq \frac{\hbar^3}{m_e^3 c^4 T_{1/2}}$

B − P bound $\sigma \le 10^{-44}\,\text{cm}^2$

$L_a \gtrsim 10^{14}$ km

(modern calculation for $\bar{\nu} + p \to e^+ + n$

$\sigma \simeq 2{,}6 \cdot 10^{-43}\,\text{cm}^2$, $L_a \simeq 6 \cdot 10^{14}$ km in water, $E \simeq 3$ MeV)

In the B−P paper ("Neutrino")

"there is no practically possible way of observing the neutrino"

Pauli "I have done a terrible thing: I have postulated a particle that can not be detected"

This general oppinion was

challenged by B. Pontecorvo (1946)

He proposed the first radiochemical method of neutrino detection

Reaction

$$\nu + {}^{37}Cl \rightarrow e^{-} + {}^{37}Ar$$

he considered as very perspective

after one-two months irradiation of a large volume a few ${}^{37}Ar$ atoms will be produced

Radioactive ${}^{37}Ar$ atoms can be extracted from the target and their decay can be observed in a proportional counter

Pontecorvo pointed out intensive sources of neutrinos

1. Sun, the flux $\simeq 6 \cdot 10^{10} \frac{\nu}{cm^2 sec}$
2. Reactor, the total flux $\simeq 2 \cdot 10^{20} \frac{\bar{\nu}}{sec}$ per $(GW)_{ther}$
3. Radiactive source, can be produced in reactor

The first direct proof of the existence of neutrino was obtained in the Reines and Cowan experiment (1953 - 1959)

R – C built large ($\sim 1\,m^3$) detector exploiting phenomenon of scintilation of organic liquids discovered at that time

They, however, prepared an experiment to detect antineutrinos from atomic bomb explosion

Later they understood that an experiment with reactor $\bar{\nu}$ is more simple and feasible

Reines "I have wandered since why it took so long for us to come to this now obvious conclusion and how it escaped others around us with whom we talked"

R - C detected reactor $\bar{\nu}$ via observation

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

Signature of neutrino event
two γ-quanta from e^{+}-e^{-} annihilation and delayed γ's from capture of the neutron by Cd

The γ-quanta were detected by 110 photomultipliers

The measured cross section

$$\sigma = (11 \pm 2.6) 10^{-44} \text{cm}^{2}$$

In agreement with prediction

$$\sigma = 9.5 \cdot 10^{-44} \text{cm}^{2}$$

In 1956 R. Davis searched for

$$\bar{\nu} + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

at Savannah River reactor

Pontecorvo radiochemical method was used

No events were found (rumor)

$$\sigma < 0.9 \cdot 10^{-45}\ cm^2$$

$\bar{\nu}$ from reactor produce e^+ (R-C)

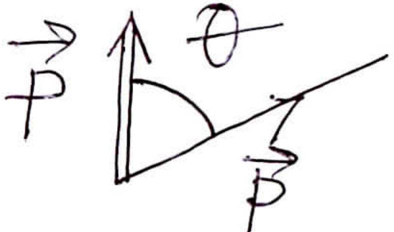
and do not produce e^- (D)

Conserved lepton number

	e^- ν	e^+ $\bar{\nu}$
L	1	-1

Understanding of neutrino drastically changed after parity violation in the β-decay and other weak processes was discovered (1957)

β-decay of polarized ^{60}Co (Wu et al experiment)



From invariance under rotations

$$w_{\vec{p}}(\vec{p}) = w_0(\vec{p}^2)(1+\alpha\vec{P}\cdot\vec{k}) = w_0(1+\alpha P\cos\theta)$$

$$\vec{k} = \frac{\vec{p}}{|\vec{p}|}$$

Polarization is pseudovector and momentum $\vec{p}$ is a vector, under inversion

$$\vec{P}' = +\vec{P}, \quad \vec{p}' = -\vec{p}$$

The sign of the scalar product $\vec{P}\cdot\vec{p}$ depend on the choice of the system

Before 1957 it was postulated that such quantities can not enter into observables (parity is conserved)

In this case $\alpha = 0$ and the probability does not depend on θ

Strong dependence on θ was observed in Wu et al experiment $|\alpha| \geq 0.7$

Practically at the same time large effect of parity violation was observed in $\mu^+ \to e^+ + \nu + \bar{\nu}$

Hamiltonian of the β-decay (and other weak processes) is a sum of scalar plus pseudoscalar

The most general Hamiltonian of the β-decay

$$\mathcal{H}^{\beta} = \sum_{i=S,V,T,A,P} \bar{p} O^{i} n \, \bar{e} O_{i} (G_{i} + G_{i}' \gamma_{5}) \nu + h.c$$

additional five (pseudoscalar) terms and five interaction constants

Landau, Lee and Yang, Salam (1957) possible connection of the large violation of the parity and neutrino

Two-component neutrino

The Dirac equation

$$(i\gamma^{\alpha}\partial_{\alpha} - m)\nu = 0$$

$\nu = \nu_L + \nu_R$, $\nu_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\nu$

$\nu_{L,R}$ is left-handed (right-handed) component

Coupled equations

$$i\gamma^\alpha \partial_\alpha \nu_L - m\nu_R = 0 \qquad i\gamma^\alpha \partial_\alpha \nu_R - m\nu_L = 0$$

if $m=0$ the equations are decoupled

$$i\gamma^\alpha \partial_\alpha \nu_{LR} = 0$$

Neutrino field

$\nu_L(x)$ or $\nu_R(x)$

This is two-component neutrino theory of Landau, L-Y, S

neutrino mass

$m < 200\,eV \simeq 4 \cdot 10^{-4} m_e$ "Natural" to assume $m=0$

Can be valid if parity is violated

$$\nu'(x') = \eta\gamma^0\nu(x)$$

$$\nu'_{L,R}(x') = \eta\gamma^0\nu_{R,L}(x)$$

under inversion L(R) is transformed into R(L)

Major consequences

① $G'_i = -G_i$ if $\nu_L(x)$

$G'_i = +G_i$ if $\nu_R(x)$

$$\mathcal{H}^\beta = \sum_{i=S,V,T,A,P} G_i\, \bar{p} O^i n\, \bar{e} O_i (1 \mp \gamma_5)\nu + h.c.$$

Scalar and pseudoscalar terms with the same coefficients

Large violation of parity

② neutrino helicity

$$\not{p}\, u^r(p) = 0 \qquad (\vec{\Sigma}\cdot\vec{K})\, u^r(p) = r\, u^r(p)$$

$$\gamma_5\, u^r(p) = r\, u^r(p)$$

$$\frac{1 \pm \gamma_5}{2}\, u^r(p) = \frac{1 \pm r}{2}\, u^r(p)$$

$$\begin{array}{cccc} \underset{\nu}{\overset{\Longleftarrow}{\longrightarrow}} & \underset{\bar{\nu}}{\overset{\Longrightarrow}{\longrightarrow}} & \text{if} & \nu_L(x) \\ \underset{\nu}{\overset{\Longrightarrow}{\longrightarrow}} & \underset{\bar{\nu}}{\overset{\Longleftarrow}{\longrightarrow}} & \text{if} & \nu_R(x) \end{array}$$

Neutrino helicity was measured in famous Goldhaber et al experiment (1958)

$$e^- + {}^{152}Eu \to \nu + {}^{152}Sm^*$$
$$\hookrightarrow {}^{152}Sm + \gamma$$

Spins of ${}^{152}Eu$ and ${}^{152}Sm$ are equal to zero

Spin of ${}^{152}Sm^*$ is equal to one

From conservation of the projection of the total momentum: Measurement of the circular polarization of γ allows to determine neutrino helicity

"result is compatible with 100% negative helicity of neutrino"

Confirmed two-component theory

Neutrino field is $\nu_L(x)$

Remark

The equation $i\gamma^{\alpha}\partial_{\alpha}\nu_{L,R}=0$ for massless particle was proposed by Weil in 1929.

Weil theory was discussed by Pauli in his book on Quantum Mechanics (1933)

"... because the equation for $\nu_L(x)$ ($\nu_R(x)$) is not invariant under space reflection it is not applicable to the physical reality."

after discovery of the parity violation the situation with the Hamiltonian of the β-decay was uncerain

From e−ν angular correlation in the decay $^{6}He \to {}^{6}Li + e^{-} + \bar{\nu}$ followed S, T

From e−ν angular correlation in $^{35}Ar \to {}^{35}Cl + e^{-} + \bar{\nu}$ followed V, A

In 1958 two fundamental papers Feynman - Gell-Mann, Marshak - Sudarshan proposed a principle it was a generalization of the two-component neutrino theory in the Hamiltonian of the weak interaction enter not only ν_L but left-handed components of all fields

$$\mathcal{H}^{\beta}_{I} = \sum_{i} G_i \, \bar{p}_L O^{i} n_L \, \bar{e}_L O_i \nu_L + h.c.$$

$$\bar{e}_L O_i \nu_L = \bar{e} \frac{1+\gamma_5}{2} O_i \frac{1-\gamma_5}{2} \nu$$

$$\frac{1+\gamma_5}{2}(1, \sigma^{\alpha\beta}, \gamma_5)\frac{1-\gamma_5}{2} = 0$$

S, T, P can not enter into $\mathcal{H}_I^\beta$

$$\frac{1+\gamma_5}{2}\gamma^\alpha\gamma_5\frac{1-\gamma_5}{2} = -\frac{1+\gamma_5}{2}\gamma^\alpha\frac{1-\gamma_5}{2}$$

A and V are equal

$$\underline{\mathcal{H}_I^\beta} = \frac{G_F}{\sqrt{2}}4\bar{p}_L\gamma^\alpha n_L\,\bar{e}_L\gamma_\alpha\nu_L + h.c. =$$

$$= \frac{G_F}{\sqrt{2}}\bar{p}\gamma^\alpha(1-\gamma_5)n\,\bar{e}\gamma_\alpha(1-\gamma_5)\nu + c.c$$

only one constant G_F
(like in the Fermi Hamiltonian, but with G-T transition (A) and parity violation)

F - G, M - S

implemented idea of μ-e universality

The idea was first proposed by

B. Pontecorvo (1947)

He compared

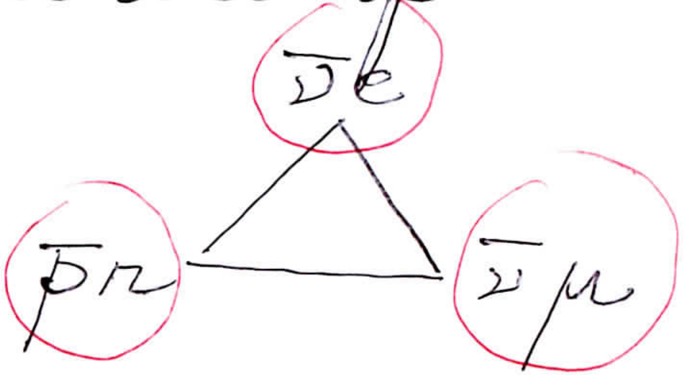
$\mu^- + (A,Z) \to \nu + (A,Z-1)$ and

$e^- + (A,Z) \to \nu + (A,Z-1)$

characterized by the same constant

Puppi (1948) generalized this idea

Different parts of the Hamiltonian are product of verteces of the triangle



F-G indroduced μ-e universal weak charged current

$$j^{\alpha}=2(\bar{p}_L\gamma^{\alpha}n_L+\bar{\nu}_L\gamma^{\alpha}e_L+\bar{\nu}_L\gamma^{\alpha}\mu_L)$$

and assumed

$$\mathcal{H}_I=\frac{G_F}{\sqrt{2}}j^{\alpha}j_{\alpha}^{+}\ ;\ j^{\alpha}_{had}=\bar{p}\gamma^{\alpha}n-\bar{p}\gamma^{\alpha}\gamma_5 n\quad (V-A)$$

What about ^6He and other data?
F-G suggested that they a wrong.

The problem of the pion decay. In the universal current×current theory

$$R=\frac{\Gamma(\pi^+\to e^+\nu)}{\Gamma(\pi^+\to\mu^+\nu)}=\frac{m_e^2}{m_\mu^2}\frac{(1-\frac{m_e^2}{m_\pi^2})^2}{(1-\frac{m_\mu^2}{m_\pi^2})^2}\simeq 1{,}2\cdot 10^{-4}$$

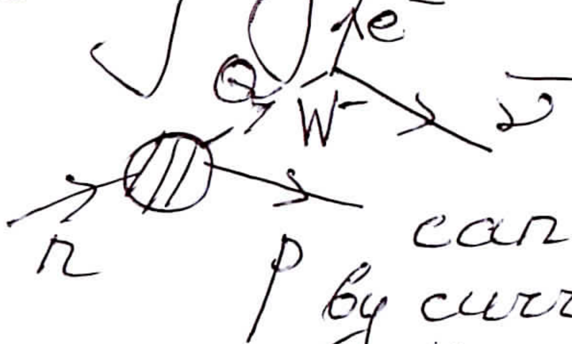
In experiment $R<10^{-5}$

Current×current Hamiltonian can be induced by the interaction with charged, vector $W^\pm$ bosons

If we assume

$$\mathcal{L}_I = -\frac{g}{2\sqrt{2}} j^\alpha W_\alpha + h.c$$

the β-decay of neutron



If $Q^2 \ll m_W^2$ can be described by current×current Hamiltonian

with

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 m_W^2}$$

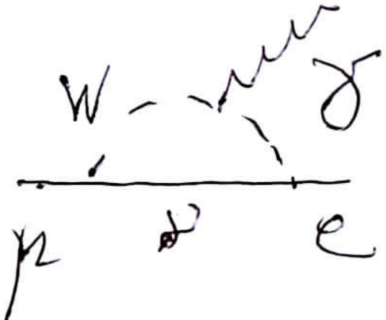
Hypothesis of W-Boson with $\mathcal{L}_I$

1. can explain the current×current structure
2. dimension of G_F

The idea of W-boson belong to O. Klein (1938)
Fermi analogy with EM is more complete if vector $W^{(\pm)}$ (analog of γ) exists

Are neutrinos produced together with e and μ the same or different particles?

The first indication that they are different comes from $\mu \to e\gamma$
Calculated in the theory with W by Feinberg (1958)



$$R = \frac{\Gamma(\mu^+ \to e^+ \gamma)}{\Gamma(\mu^+ \to e^+ \nu \bar{\nu})} \simeq \frac{\alpha}{24\pi} \simeq 10^{-4} \text{ (cut-off } \Lambda \simeq m_W)$$

From experiment $R < 10^{-8}$

First direct proof $\nu_\mu \neq \nu_e$

Brookhaven experiment (1962)

Proposed by B. Pontecorvo in 1959

If $\nu_\mu \neq \nu_e$ F-G charged current

$$j^\alpha = 2(\bar{p}_L \gamma^\alpha n_L + \underline{\bar{\nu}_{eL}} \gamma^\alpha e_L + \underline{\bar{\nu}_{\mu L}} \gamma^\alpha \mu_L)$$

$\pi^+ \to \mu^+ \nu_\mu$ is dominant channel

decays of pions is the source of ν_μ's

if $\nu_\mu \neq \nu_e$ $\nu_\mu + N \to \mu^- + X$ (μ^- will be observed)

if $\nu_\mu \equiv \nu_e$ $\nu_\mu + N \to \mu^- + X$ (μ^- and e^- will be observed)

$\nu_\mu + N \to e^- + X$

In the BNL experiment

29 μ-events were detected

6 e^--events could be explained by a background

$$\boxed{\nu_\mu \neq \nu_e}$$

Two conserved lepton numbers must be introduced

	$\nu_e \; e^-$	$\nu_\mu \; \mu^-$
L_e	1	0
L_μ	0	1

$$\underline{\sum_i L_e^{(i)} = \text{const} \qquad \sum_i L_\mu^{(i)} = \text{const}}$$

strange particles were included in the current×current theory by N. Cabibbo (1963)

From the study of the decays
$K^+ \to \mu^+ \nu_\mu$, $\Lambda \to p + e^- + \bar{\nu}_e$, $\Xi^- \to \Lambda + \mu^- + \bar{\nu}_\mu$, etc.
three phenomenological rules

① $|\Delta S| = 1$ $\Delta S = S_f - S_i$

② $\Delta Q = \Delta S$

③ decays of strange particles are suppressed

Rule ② can be explained if we assume that weak interaction is interaction of quarks and leptons

From u, d, s quark fields only two F-G charged currents can be built

$$2\bar{u}_L\gamma^\alpha d_L \quad \text{and} \quad \underline{2\bar{u}_L\gamma^\alpha s_L}$$

This last current gives $\underline{\Delta S = 1}$ and $\underline{\Delta Q = \Delta S}$

Cabibbo introduced a parameter θ_C and assumed

$$j^{\alpha\,Cab} = 2(\cos\theta_C\,\bar{u}_L\gamma^\alpha d_L + \sin\theta_C\,\bar{u}_L\gamma^\alpha s_L)$$

from analysis of data

$$\underline{\sin\theta_C \simeq 0.2 \quad \text{(suppression)}}$$

The Cabibbo current can be rewritten

$$j^{\alpha\,Cab} = 2\bar{u}_L \gamma^\alpha d_L^m$$

$$d_L^m = \cos\theta_c\, d_L + \sin\theta_c\, s_L .$$

In the framework of gauge theories the Cabibbo current generate NC which change S and induce processes like

$$K^+ \to \pi^+ + \nu + \bar{\nu}$$

which where not observed

The problem was solved by GIM in 1970

They introduced charmed quark c
and additional charged weak current

$$j^{\alpha\,GIM} = 2\bar{c}_L \gamma^\alpha s_L^m$$

$$s_L^m = -\sin\theta_c\, d_L + \cos\theta_c\, s_L$$

orthogonal to Cabibbo combination of d_L and s_L

In 1975-77 τ and b-quark were discovered and CC took the form

$$j^\alpha = 2(\bar{u}_L \gamma^\alpha d_L^{mix} + \bar{c}_L \gamma^\alpha s_L^{mix} + \bar{t}_L \gamma^\alpha b_L^{mix})$$

$$d_L^{mix} = \sum_{q=d,s,b} V_{uq}\, q_L,\quad s_L^{mix} = \sum_q V_{cq}\, q_L,\quad b_L^{mix} = \sum_q V_{tq}\, q_L$$

$V^{+}V = 1$, V is 3×3

Cabibbo-Kobayashi-Maskawa mixing matrix

In 1967-1968 Weinberg and Salam proposed SM. In 1961 Glashow proposed the gauge part of the SM weak and EM interactions were unified

The SM is based on

① Phenomenological V-A theory

② Local gauge $SU(2) \times U(1)$ invariance which requires existence of $W^{\pm}, Z^{0}$

3. Spontaneous symmetry breaking (Higgs)

4. as for neutrinos it was assumed that neutrinos are massless 2-component particles

(natural assumption at that time, no evidence for neutrino masses)

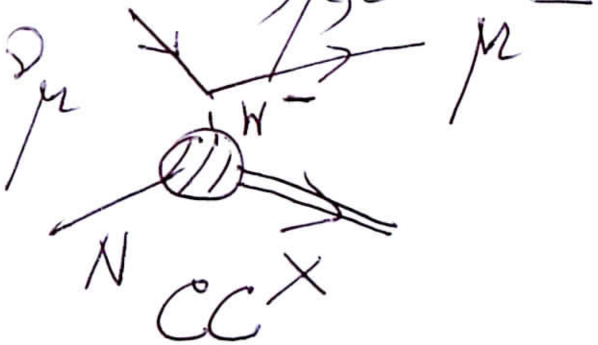
Unification of the weak and EM interaction on the basis of local $SU(2) \times U(1)$ group requires existence of Z^0 and NC interaction

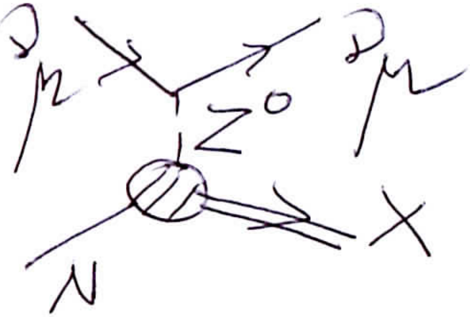
First evidence of NC was obtained in neutrino experiments

$$\mathcal{L}_I^{NC} = -\frac{g}{2\cos\theta_W} j_\alpha^{NC} Z^\alpha$$

$$j_\alpha^{NC} = 2 j_\alpha^{3} - 2\sin^2\theta_W \, j_\alpha^{EM}$$

$$2 j_\alpha^{3} = \sum_{l=e,\mu,\tau} \bar{\nu}_l \gamma_\alpha \nu_l + \dots$$





NC events were discovered in Gargamelle (CERN) in 1973

$R_\nu = 0,21 \pm 0,03$, $R_{\bar{\nu}} = 0,45 \pm 0,09$

Neutrino masses, mixing and oscillations

Earliest ideas

Pontecorvo 1958

analogy between weak interaction of lepton and hadrons

Looked for analogy of $K^0 \rightleftarrows \bar{K}^0$ oscillations in the lepton world

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle + |K_L\rangle) \quad |\bar{K}^0\rangle = \frac{1}{\sqrt{2}}(|K_S\rangle - |K_L\rangle)$$

K_S and K_L have different masses and widths at the time t

$$|K^0\rangle_t = g_+(t)|K^0\rangle + g_-(t)|\bar{K}^0\rangle$$

$$|\bar{K}^0\rangle_t = g_+(t)|\bar{K}^0\rangle + g_-(t)|K^0\rangle$$

$$g_\pm(t) = \frac{1}{2}\left(e^{-i\lambda_S t} \pm e^{-i\lambda_L t}\right)$$

$$\lambda_{S,L} = m_{S,L} - \frac{i}{2}\Gamma_{S,L}$$

In 1958 only one type of neutrino was known

According to the two-component theory ν_L and $\bar{\nu}_R$ in vacuum transition is not possible

Pontecorvo assumed that exist ν_R and $\bar{\nu}_L$ (sterile neutrinos)

L is not conserved
(can be revealed in special experiments)

$$|\bar{\nu}_R> = \frac{1}{\sqrt{2}}(|\nu_1> + |\nu_2>)$$

$$|\nu_R> = \frac{1}{\sqrt{2}}(|\nu_1> - |\nu_2>)$$

ν_1 and ν_2 have different masses

$$\Downarrow$$

oscillations $\nu_R \rightleftarrows \nu_R$

at the distance L

$$P(\bar{\nu}_R \to \bar{\nu}_R) = 1 - \frac{1}{2}\left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

"... the cross section of the process $\bar{\nu}_e + p \to e^+ + n$ with reactor $\bar{\nu}_c$ would be smaller than the expected cross section

It would be extremely interesting to perform Reines-Cowan experiment at

B.P. decided to publish the paper when he listen a rumor about "events" in Davis experiment ($\bar{\nu}_e + {}^{37}Cl \to e^- + {}^{37}Ar$)

In 1967 after ν_μ was discovered B.P. considered all possible transitions
$\nu_\mu \rightleftarrows \nu_e$, $\nu_\mu \rightleftarrows \bar{\nu}_{eL}$, ...

"From observational point of view the ideal object is the sun.
... the flux of observable solar neutrinos must be two times smaller that the total flux"

First Davis result in 1970
Solar neutrino puzzle was discovered

In 1969 Gribov and Pontecorvo

oscillations without sterile neutrinos

ν_{eL} and $\nu_{\mu L}$ in the Lagrangian but L_e and L_μ are not conserved

$$\nu_{eL} = \cos\theta\, \nu_{1L} + \sin\theta\, \nu_{2L}$$
$$\nu_{\mu L} = -\sin\theta\, \nu_{1L} + \cos\theta\, \nu_{2L}$$

ν_1 and ν_2 are fields of Majorana neutrinos

$$\nu_i \equiv \bar{\nu}_i$$

$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta \left(1 - \cos\frac{\Delta m^2 L}{2E}\right)$$

mixing angle θ is arbitrary parameter after Cabibbo-GIM mixing of quarks was established neutrino mixing was proposed on the basis of quark-lepton analogy (1975)

$$\nu_{eL} = \cos\theta\, \nu_{1L} + \sin\theta\, \nu_{2L}$$

$$\nu_{\mu L} = -\sin\theta\, \nu_{1L} + \cos\theta\, \nu_{2L}$$

ν_1 and ν_2 are Dirac particles

$$\nu_i \neq \bar{\nu}_i$$

but L is conserved

In 1962 MNS also came to an idea of neutrino masses and mixing

Nagoya model $\quad J_p = (B^+ \nu_1), \ldots$

MNS did not considered neutrino oscillations

However, $\nu_\mu \rightleftarrows \nu_e$ "virtual transmutations" possible effect in BNL experiment

With appearence of GUT neutrino masses is a signature of beyond the SM physics

seesaw mechanism of the generation of small neutrino masses was proposed

In the case of 3 neutrinos

$$\nu_{lL} = \sum_{i=1}^{3} U_{li} \, \nu_{iL} \qquad l = e, \mu, \tau$$

$U^{+} U = 1$, U is PMNS matrix

Many short baseline reactor and accelerator experiments on the search for neutrino experiments

No positive indications (reactors?)

Golden years of neutrino oscillations

1998 - 2004

Super-Kamiokande atmospheric neutrino experiment

$\nu_\mu (\bar{\nu}_\mu)$ and $\nu_e (\bar{\nu}_e)$ mainly from decays $\pi^\pm$ and $\mu^\pm$

distances from 20 km to 13 000 km

Total flux of $\nu_\mu (\bar{\nu}_\mu)$ from below $500 \leq L \leq 13000$ km is about $\frac{1}{2}$ of the total flux from above $20 \leq L \leq 500$ km

strong distortion of symmetric zenith angle dependence expected for no oscillations

SNO solar neutrino experiment

Solar neutrinos are detected via observation of

$$\nu_e + d \to e^- + p + p \quad \text{CC} \quad (\underline{\nu_e})$$

$$\nu_{e,\mu,\tau} + d \to \nu_{e,\mu,\tau} + n + p \quad \text{NC} \quad \underline{(\nu_e, \nu_\mu, \nu_\tau)}$$

$$\nu + e \to \nu + e \quad \text{ES}$$

$$\frac{\phi^{CC}_{\nu_e}}{\phi^{NC}_{\nu_e, \nu_\mu, \nu_\tau}} = 0{,}317 \pm 0{,}010 \pm 0{,}009$$

Reactor KamLAND experiment

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

55 reactors at the average distance 170 km

The total number of observed events $\simeq$ 0.6 of the expected number

Strong distortion of $\bar{\nu}_e$ spectrum

K2K and MINOS accelerator experiments

$\nu_\mu (\bar{\nu}_\mu)$ disapearance

distortion of the spectrum

all data are perfectly described by the three neutrino mixing

$$P(\nu_l \to \nu_{l'}) = \left|\sum_{i=1}^{3} U_{l'i}\, e^{-i\Delta m^2_{2i}\frac{L}{2E}}\, U^*_{li}\right|^2$$

$$\Delta m^2_{2i} = m^2_i - m^2_2$$

Six parameters

Δm^2_{23}, Δm^2_{12}, θ_{12}, θ_{23}, θ_{13}, δ

From analysis of solar and KamLAND data

$\Delta m^2_{12} = (7{,}41^{+0{,}21}_{-0{,}19})\,10^{-5}\,\mathrm{eV}$ $\quad \tan^2\theta_{12} = 0.446^{+0{,}030}_{-0{,}029}$

From MINOS data

$\Delta m^2_{23} = (2{,}32^{+0{,}12}_{-0.08})\,10^{-3}\,\mathrm{eV}$ $\quad \sin^2 2\theta_{23} > 0{,}90$

From recent T2K data

$0.03 < \sin^2 2\theta_{13} < 0.28$ (90% CL)

best fit $\sin^2 2\theta_{13} = 0.11$

Many open problems

what is the value of θ_{13}?

If relatively large as present data indicates

- CP violation in the lepton sector (phase δ)
- character of the neutrino mass spectrum

I. Normal spectrum

$m_1 \ll m_2 < m_3 \quad \Delta m^2_{12} \ll \Delta m^2_{23}$

II Inverted spectrum

$m_3 < m_1 < m_2 \quad \Delta m^2_{12} \ll |\Delta m^2_{13}|$

Are neutrinos with definite masses Dirac or Majorana particles?

Possible to answer by observation of $(0\nu\beta\beta)$ decay

$$(A,Z) \to (A, Z+2) + e^- + e^-$$

Matrix element is proportional to

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i$$

The most stringent limit for

$$^{76}Ge \to {}^{76}Se + e^- + e^-$$

$$T_{1/2} > 1.9 \cdot 10^{25} \text{ years}$$

$$|m_{\beta\beta}| < (0{,}20 - 0{,}35)\,eV$$

In future

$|m_{\beta\beta}| \sim$ a few $\cdot 10^{-2}$

What are the values of m_i ?

Mainz and Troitsk tritium experiment

$m_\beta < 2.3$ eV

$$m_\beta = \sqrt{|U_{ei}|^2 m_i^2}$$

Katrin $m_\beta \simeq 0.2$ eV

fututre cosmology $\Sigma m_i \simeq (0,05 - 0.6)$eV

How many ν_i exist in nature ?

If more than 3 sterile neutrinos

Indications

Superluminous neutrinos ?