Neutrino mass:from Pauli to neutrino oscillations and seesaw

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December 6, 2010

On December 4th 1930 W.Pauli wrote his famous letter in which he postulated existence of neutrino

At that time protons and electrons were considered as elementary particles

Nuclei are bound states of p's and e^-'s

Two problems in the framework of this assumptions

I. β-decay: $(A, Z) \to (A, Z+1) + e^-$ (no other particles to emit)

Two particle decay. Monochromatic electron must be produced. In experiment continuous β-spectrum was observed

II. Spins of some nuclei. ${}^7N_{14} = (14p + 7e) \to \mathrm{half\ integer\ spin}$

From molecular spectra : ${}^7N_{14}$ satisfy Bose-Einstein statistics; spin must be integer

Pauli came to idea that a new particle is needed

Pauli assumed that exist a neutral, spin 1/2, particle. Interaction of this particle is much weaker that the interaction of photon. It is not observed in the β-decay experiments. Pauli called new particle neutron

Further Pauli assumed

- Nuclei are bound states of p's, e^-'s and "n"'s. No problem of spin of $^7N_{14}$ and other nuclei
- β-decay: $(A, Z) \to (A, Z+1) + e^- +$ "n". Three-body decay, continuous spectrum of electrons

Pauli considered a new particle as a constituent. Non zero mass.

From Pauli letter

"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 of the proton mass".

In 1932 neutron, a neutral particle with a mass approximately equal to the proton mass, was discovered by Chadwick

Neutron is constituent of nuclei (from experiment)

Heisenberg, Majorana, Ivanenko : nuclei are bound states of p's and n's

Confirmed by all nuclear data

No problem of spin. For example, ${}^{7}N_{14} = (7p + 7n)$, integral spin

What about β-decay and continues spectrum?

Can not be solved if we will not assume that the β-decay is three-body decay

F. Fermi accepted Pauli hypothesis of the existence of a new light particle (much lighter than neutron) which E. Fermi proposed to call neutrino (from Italian, *neutral, small*)

Fermi (1934) assumed that (e, ν) pair is produced in the quantum transition of neutron to proton

$$n \rightarrow p + e + \nu$$

Fermi proposed the first Hamiltonian which provides this transition

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

Neutrino mass in Fermi theory? Unknown parameter.

Fermi and Perrin proposed a method of measuring of the neutrino mass via investigation of the β-spectrum

$$Q = E + E_{\nu}$$

(E is electron kinetic energy, Q is energy release)

The region $(Q - E) \simeq m_{\nu}$ is sensitive to m_{ν}

Convenient decay for measuring of neutrino mass

$$^{3}H \rightarrow ^{3}He + e^{-} + \bar{\nu}$$

($Q \simeq 18.6 \ \mathrm{KeV}$, superallowed (NME is a constant],
$t_{1/2} \simeq 12.3 \ \mathrm{years}$ etc)

β-spectrum is given by the phase space

$$\frac{d\Gamma}{dE} = C|M|^2 p(E+m_e)(Q-E)\sqrt{(Q-E)^2 - m_\beta^2}\; F(E)$$

The first tritium experiment was performed by Hanna and Pontecorvo and S. Curran et al (1949) It was found the upper bound

$$m_\beta \leq 500\ \mathrm{eV}$$

In 1957 violation of parity P (and C) was discovered in β-decay and other weak processes

Hamiltonian is a sum of scalar and pseudoscalar

β-decay of polarized nucleus (Wu et al experiment)

$w_{\vec{P}}(\vec{p}) = w_0(1+\alpha\ \vec{P}\cdot\vec{k}) = w_0(1+\alpha P\cos\theta)$, $\quad \vec{k} = \frac{\vec{p}}{p}$, α is the asymmetry parameter

The pseudoscalar $\alpha\ \vec{P}\cdot\vec{k}$ is due to interference of P-conserving and P-violating parts of the matrix element

From Wu et al experiment $\alpha \simeq -0.7$

P-conserving and P-violating parts of the Hamiltonian are comparable. Large violation of parity

Two-component neutrino theory

Landau, Lee and Yang, Salam (1957)

Large violation of parity is connected with neutrino mass

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

Left-handed (right-handed) component $\nu_{L,R}(x) = \frac{1\mp\gamma_5}{2}\nu(x)$

$$i\gamma^{\alpha}\partial_{\alpha}\nu_L(x) - m\,\nu_R(x) = 0, \quad i\gamma^{\alpha}\partial_{\alpha}\nu_R(x) - m\,\nu_L(x) = 0$$

Equation are coupled because of mass m

In 1957 from tritium experiments $m_{\nu} < 200\ \mathrm{eV} \ll m_e$

Neutrino is much lighter than electron, the lightest charged particle (Pauli guess)

Landau, Lee and Yang, Salam assumed $m_{\nu} = 0$

In this case equations are decoupled

$$i\gamma^{\alpha}\partial_{\alpha}\nu_{L,R}(x) = 0$$

For the neutrino field $\nu_L(x)$ $(\mathrm{or}\ \ \nu_R(x))$ can be chosen. This is the two-component neutrino theory of Landau and others

The equation for left-handed (right-handed) component of a massless particle was discussed by Pauli in his book on Quantum Mechanics (1933). He wrote;"because this equation is not invariant under P it is not applicable to physical reality"

The general β-decay Hamiltonian

$$\mathcal{H}_I = \sum_i G_i\, \bar{p}\ O_i n\ \bar{e}\ O^i \tfrac{1}{2}(1 \mp \gamma_5)\nu + \mathrm{h.c.}$$

$$O \to 1,\ \gamma_\alpha,\ \sigma_{\alpha\beta},\ \gamma_\alpha\gamma_5,\ \gamma_5$$

Large violation of parity (in agreement with the Wu et al experiment)

Important prediction of the two-component theory

If neutrino field is $\nu_L(x)$, neutrino is left-handed $(h=-1)$ and antineutrino is right-handed $(h=+1)$. In the case of $\nu_R(x)$ neutrino is right-handed $h=1$ and antineutrino is left-handed $h=-1$

In fact, for massless neutrino $\gamma_5\, u^h(p) = h\ u^h(p)$, $\frac{1-\gamma_5}{2}$ is projection operator

$$\frac{1-\gamma_5}{2}\, u^{-1}(p) = u^{-1}(p), \quad \frac{1-\gamma_5}{2}\, u^{1}(p) = 0$$

$$\nu_L(x) = \int N_p \left(u^{-1}(p)\ c_{-1}(p)\ e^{-ipx} + u^{1}(-p)\ d_1^{\dagger}(p)\, e^{ipx} \right)\, d^3 p$$

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

$$\begin{array}{l} e^- +^{152}\mathrm{Eu} \to \nu + \quad {}^{152}\mathrm{Sm}^* \\ \qquad\qquad\qquad\qquad\quad\;\; \downarrow \\ \qquad\qquad\qquad\qquad\quad {}^{152}\mathrm{Sm} \quad + \gamma \end{array}$$

Spins of ${}^{152}\mathrm{Eu}$ and ${}^{152}\mathrm{Sm}$ are equal to zero and ${}^{152}Sm^*$ is equal to one

Measurement of the circular polarization of γ allows to determine neutrino helicity

From Goldhaber et al experiment: neutrino has negative helicity

Two-component neutrino theory with neutrino field $\nu_L(x)$ was confirmed

Universal, $V-A$ theory of weak interaction (1958)

Feynman and Gell-Mann, Marshak and Sudarshan

Assumed that into Hamiltonian of the weak interaction enter not only $\nu_L(x)$ but left-handed components of all other massive fields

General Hamiltonian of the β-decay takes a simplest $V-A$ form

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

Feynman and Gell-Mann introduced 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 that the Hamiltonian has current × current form

$$\mathcal{H}_I = \frac{G_F}{\sqrt{2}}\,j^\alpha\,j^+_\alpha$$

This Hamiltonian describes not only β-decay, but also μ-decay, μ-capture and many other processes. Good agreement with experiments

Neutrino mass?

A parameter. No special role in the current × current theory.

F-G, M-S accepted two-component theory of massless neutrino

The first physicist who started to think about possible small neutrino masses after the two-component neutrino theory was B. Pontecorvo (1957-58)

He believed in analogy between weak interaction of hadrons and leptons: To every weak hadronic process corresponds leptonic process

BP looked for analogy of a fascinating phenomenon $K^0 \leftrightarrows \bar{K}^0$ oscillations which was discovered at that time

K^0 $(\bar{s}\ d) \to \bar{K}^0$ $(s\ \bar{d})$ corresponds to $(\bar{\mu}\ e) \to (\mu\ \bar{e})$ transition (muonium -antimuonium)

In the paper on muonium -antimuonium oscillations B.P. wrote for the first time about possibility of neutrino oscillations

"If the two-component neutrino theory turn out to be incorrect (which at present seems to be rather improbable) and if the conservation law of neutrino charge would not apply, then in principle neutrino $\rightleftharpoons$ antineutrino transitions could take place in vacuum."

K^0 and $\bar K^0$, particles with definite strangeness, are produced and absorbed in hadronic processes

Weak interaction does not conserve the strangeness

Neglecting small effect of the CP violation

$$|K^0\rangle = \frac{1}{\sqrt{2}}(|K^0_1\rangle + |K^0_2\rangle), \quad |\bar K^0\rangle = \frac{1}{\sqrt{2}}(|K^0_1\rangle - |K^0_2\rangle)$$

$|K^0_{1,2}\rangle$ are states of particles with definite masses and (widths), eigenstates of the total Hamiltonian

If a beam of K^0 is produced at $t = 0$

$$|K^0\rangle_t = \frac{1}{\sqrt{2}}(e^{-i\lambda_1 t}|K_1^0\rangle + e^{-i\lambda_2 t}|K_2^0\rangle)$$

$$\lambda_{1,2} = m_{1,2} - \frac{i}{2}\Gamma$$

Oscillations take place if phases are different ($m_1 \neq m_2$)

BP assumed by analogy

$$|\nu_L\rangle = \frac{1}{\sqrt{2}}(|\nu_{1L}\rangle + |\nu_{2L}\rangle), \quad |\bar{\nu}_L\rangle = \frac{1}{\sqrt{2}}(|\nu_{1L}\rangle - |\nu_{2L}\rangle)$$

where ν_1 and ν_2 are Majorana neutrino with different masses m_1 and m_2

"neutrino and antineutrino are *mixed particles*, i.e., a symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2"

"the cross section of the production of neutrons and positrons in the process of the absorption of antineutrinos from a reactor by protons would be smaller than the expected cross section....It would be extremely interesting to perform the Reins-Cowan experiment at different distances from reactor"

What was Pontecorvo argument for nonzero neutrino masses in 1958?

There is no principle (like gauge invariance in the case of the photon) which require neutrino to be massless. So why not small nonzero masses?

Pontecorvo discussed the problem of neutrino mass with Landau. Landau agreed that after success of $V-A$ theory there were no reasons for neutrino to be massless

There were no observational reasons in favor of massless neutrino

Neutrino helicity?. If neutrino is massive longitudinal polarization

$$P_{\parallel} = -\beta \simeq -(1 - \frac{m^2}{2E^2})$$

The correction is too small (even for $m \simeq 100$ eV, $\frac{m^2}{2E^2} \simeq 10^{-8}$). No chance to see effect of neutrino mass in the Goldhaber et al experiment

No possibility to see effects of small neutrino mass in β-decay and other weak processes: from special tritium experiments only upper bounds for the neutrino mass was obtained

In 1962 Maki, Nakagawa and Sakata also came to an idea of massive neutrino

They used Nagoya model in which proton was considered as a bound state of neutrino and some vector boson B^+, "a new sort of matter". For MNS neutrino was a constituent and, correspondingly, massive (like neutrino Pauli). Following idea of Gell-Mann and Levy they assumed mixing

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

In connection with the (first accelerator) Brookhaven experiment (1962) they qualitatively discussed "virtual transition $\nu_\mu \rightleftarrows \nu_e$" They concluded that if in the Brookaven experiment no ν_e was observed we can conclude that $\Delta m \lesssim 1$ eV

Neutrino mass in the Standard Model (1967)

SM is based on $SU(2)_L \times U_Y(1)$ local gauge symmetry with left-handed doublets

$$\left(\begin{array}{c} \nu_{eL} \\ e_L \end{array}\right) \quad \left(\begin{array}{c} \nu_{\mu L} \\ \mu_L \end{array}\right) \quad \left(\begin{array}{c} \nu_{\tau L} \\ \tau_L \end{array}\right), \ldots$$

and right-handed singlets e_R, μ_R,...Before symmetry is broken all masses are equal to zero. After spontaneous violation of the symmetry vector $W^{\pm}$ and Z^0 become massive, their masses can be predicted

In order to generate masses of fermions we need to assume Yukawa interaction. Fermion masses $m_f = g_f v$, $v = (\frac{1}{\sqrt{2}G_F})^{1/2} \simeq 256~\mathrm{GeV}$, characterize the scale of EW symmetry breaking (vev), g_f are parameters (can not be predicted by the SM)

For quarks and leptons we need to introduce masses

Neutrino mass?

No information. Only upper bound.

In 1967 it was natural to assume that neutrino is two-component massless particles.

This is not a prediction of the Standard Model

In 1970 first experimental (model dependent) indication in favor $m_\nu \neq 0$ was obtained

R. Davis obtained first solar neutrino data

Upper bound of the solar neutrino flux was 2-3 times smaller than SSM predicted flux (solar neutrino puzzle)

In 1967 B. Pontecorvo considered flavor neutrino oscillations

$$\nu_e \rightleftarrows \nu_\mu$$

In 1967 paper (before R. Davis published his first result) BP pointed out

"..due to neutrino oscillations the observed flux of solar neutrinos could be two times smaller than the expected flux"

In seventies the explanation of the solar neutrino puzzle by neutrino masses and oscillations was the dominant one

At that time GUT models appear and idea of neutrino mass became theoretically motivated

In GUT models quarks and leptons enter into the same multiplets.

In some models ($SO(10)$ etc) generation of masses of quarks and leptons is accompanied by the generation of neutrino masses

The seesaw mechanism of neutrino masses was invented

The idea of neutrino masses as a signature of the beyond the SM physics became more and more popular

In eighties special experiments on the search for neutrino oscillations (reactor, accelerator) started

Large water Cerenkov detectors (Kamiokande, IMB) were build.

Atmospheric neutrino and solar neutrino (Kamiokande) experiments started

Existence of the solar neutrino puzzle was confirmed.

Atmospheric neutrino anomaly was discovered (the ratio of the numbers of ν_μ's and ν_e's was about two times smaller than the predicted ratio)

No indications in favor of oscillations in reactor and accelerator experiments at that time

Tritium experiments

In ITEP (Moscow) high resolution spectrometer was build (Tretyakov)

In the seventieth the ITEP group announced measurement of neutrino mass

$$17 \leq m_\nu \leq 40 \text{ eV}$$

This claim triggered many new tritium experiments (Zurich, Los Alamos, Livermore, MAINZ, Troitsk).

ITEP result was not confirmed

Latest MAINZ and Troitsk result:

$$m_\beta \leq 2.3 \text{ eV}$$

GOLDEN YEARS OF PHYSICS OF MASSIVE AND MIXED NEUTRINOS

1998 Super-Kamiokande discovery of neutrino oscillations in atmospheric experiment (zenith angle dependence of the number of ν_μ's)

2001 SNO Model independent proof of the transition of solar ν_e into ν_μ and ν_τ (ratio of the flux of ν_e 's to the total flux of ν_e, ν_μ and ν_τ is about 1/3)

2002 KamLAND reactor experiment (significant distortion of the spectrum of reactor $\bar{\nu}_e$'s)

Neutrino oscillations were discovered. Neutrino are massive and mixed. First evidence in the particle physics for a new beyond the Standard Model physics was obtained

Briefly on the status of neutrino oscillations

Basic assumptions

I. Standard Model interaction

$$\mathcal{L}_{\mathcal{I}}^{\mathcal{CC}}(x) = -\frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} \bar{\nu}_{lL}(x)\, \gamma_\alpha\, l_L(x)\ W^\alpha(x) + \mathrm{h.c.}$$

II. Mixed flavor fields

$$\nu_{lL}(x) = \sum_i U_{li}\, \nu_{iL}(x).$$

$\nu_i(x)$ is the field of neutrinos with mass m_i, $U^\dagger U = 1$

III. States of the flavor neutrinos ν_e, ν_μ and ν_τ

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li}^*\ |\nu_i\rangle$$

$|\nu_i\rangle$ is the state of neutrino with mass m_i

IV. Transition probability in vacuum

$$\mathrm{P}(\nu_l \to \nu_{l'}) = |\sum_i U_{l'i}\, e^{-i\frac{\Delta m^2_{2i} L}{2E}}\, U^*_{li}|^2 = |\sum_{i \neq 2} U_{l'i}\, (e^{-i\frac{\Delta m^2_{2i} L}{2E}} - 1)\, U^*_{li} + \delta_{l'l}|^2.$$

$$\Delta m^2_{ki} = m^2_i - m^2_k$$

All data (with the exception of the data of LSND and MiniBooNE ($\bar{\nu}_\mu$) experiments which are required confirmation) are in agreement with the minimal assumption that the number of massive neutrinos is equal to the number of the flavor neutrinos (three, LEP). No sterile neutrinos

Six parameters:$\Delta m^2_{12}, \Delta m^2_{23}, \theta_{12}, \theta_{23}, \theta_{13}, \delta$

From experimental data

$\Delta m^2_{12} \simeq \frac{1}{30}\Delta m^2_{23}, \quad \sin^2\theta_{13} \leq 4\cdot 10^{-2}$

In atmospheric, accelerator region of $\frac{L}{E}$ $(\frac{\Delta m^2_{23} L}{2E} \gtrsim 1)$ dominant transition is $\nu_\mu \to \nu_\tau$ and probability

$$\mathrm{P}(\nu_\mu \to \nu_\mu) \simeq 1 - \frac{1}{2}\ \sin^2 2\theta_{23}\ (1 - \cos\Delta m^2_{23}\frac{L}{2E})$$

In the reactor KamLAND region of $\frac{L}{E}$ $(\frac{\Delta m^2_{12} L}{2E} \gtrsim 1)$ dominant transitions are $\bar\nu_e \to \bar\nu_{\mu,\tau}$ and probability

$$\mathrm{P}(\bar\nu_e \to \bar\nu_e) \simeq 1 - \frac{1}{2}\ \sin^2 2\theta_{12}\ (1 - \cos\Delta m^2_{12}\frac{L}{2E}).$$

From the latest analysis of the Super-Kamiokande atmospheric data

$$1.9\cdot 10^{-3} \leq \Delta m^2_{23} \leq 2.6\cdot 10^{-3}\ \mathrm{eV}^2, \quad 0.407 \leq \sin^2\theta_{23} \leq 0.583$$

$$\sin^2\theta_{13} \leq 4\cdot 10^{-2}$$

Confirmed by the accelerator long-baseline experiments. From the analysis of the MINOS data

$$\Delta m^2_{23} = (2.43 \pm 0.13) \cdot 10^{-3}\ \mathrm{eV}^2, \quad \sin^2 2\theta_{23} > 0.90$$

From the latest global analysis of the reactor KamLAND and solar data

$$\Delta m^2_{12} = (7.50^{+0.19}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2, \quad \tan^2\theta_{12} = 0.452^{+0.035}_{-0.032}$$

$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.018}$$

Two possible three-neutrino mass spectra are compatible with experiments

- I.Normal mass spectrum
  $m_1 < m_2 < m_3; \quad \Delta m^2_{12} \ll \Delta m^2_{23}$
- II Inverted mass spectrum
  $m_3 < m_1 < m_2; \quad \Delta m^2_{12} \ll |\Delta m^2_{13}|$

The determination of the character of the neutrino mass spectrum is a big experimental challenge

Another open problem: nature of the neutrino mass

Two possible neutrino mass terms

I. Dirac mass term

$$\mathcal{L}^{\mathrm{D}} = -\sum_i m_i(\bar{\nu}_{iL}\nu_{iR} + \bar{\nu}_{iR}\nu_{iL}) = -\sum_i m_i\bar{\nu}_i\nu_i$$

Lepton number is conserved. ν and $\bar{\nu}$ are different

$$L(\nu_i) = 1, \quad L(\bar{\nu}_i) = -1$$

II. Majorana mass term

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2}\sum_i m_i(\bar{\nu}_{iL}(\nu_{iL})^c + \overline{(\nu_{iL})^c}\nu_{iL}) = -\frac{1}{2}\sum_i m_i\bar{\nu}_i\nu_i$$

No conserved lepton numbers. $\nu_i = (\nu_i)^c$ (Majorana field)

$$\nu \equiv \bar{\nu}$$

In order to resolve the problem of the nature of neutrino mass
Dirac or Majorana ? necessary to investigate very rare neutrinoless
double beta decay $(A, Z) \to (A, Z+2) + e^- + e^-$

Before the Standard model appeared masses of particles were considered as parameters After the SM we started to generate masses. We would like to explain masses (at least quantitatively)

The Standard Model does not predict any fermion masses

Neutrino masses can be generated by the standard Higgs mechanism. We can conclude, however, that small neutrino masses are not (or not only) of the Standard model origin

Quark and lepton masses of the third family

$$m_t \simeq 1.7 \cdot 10^2 \ \mathrm{GeV}, \quad m_b \simeq 4.7 \ \mathrm{GeV}$$

$$m_3 \leq 2.3 \ 10^{-9} \ \mathrm{GeV}, \quad m_\tau \simeq 1.8 \ \mathrm{GeV}$$

It is very unlikely that neutrino and other masses are of the same Higgs origin

Exist different explanations of the smallness of neutrino masses. All of them require beyond the SM physics

The most plausible (and popular) is seesaw mechanism

For illustration let us consider the mass term (in the case of one generation)

$$\mathcal{L} = -m_D \bar{\nu}_L \nu_R - \frac{1}{2}\ M_R \overline{(\nu_R)^c} \nu_R + \mathrm{h.c.},$$

m_D is of the order of quark or lepton mass and $M_R \gg m_D$

Mass spectrum

$$m_1 \simeq \frac{m_D^2}{M_R} \ll m_D, \quad m_2 \simeq M_R \gg m_D$$

Lepton number is violated. Both masses are Majorana. One is light (neutrino), another is very heavy. In order to explain neutrino masses we need to assume that $M_R \simeq (10^{14} - 10^{15})$ GeV

Smallness of the neutrino mass is due to violation of the lepton number at a very large scale. For three families we assume that exist heavy Majorana fermions N_i, which have the following Yukawa interaction with leptons and Higgs bosons

$$\mathcal{L}_I = -\sqrt{2} \sum_{i,l} Y_{il} \overline{L}_{lL} N_{iR} \tilde{\phi} + \mathrm{h.c.}$$

In the second order of the perturbation theory the interaction $\mathcal{L}_I$ will induce an effective Lagrangian in the case of the virtual N_i

After the spontaneous violation of the EW symmetry the Majorana mass term will be generated

$$\mathcal{L}^{\mathrm{M}} = -\frac{1}{2} \sum_{l'l} \overline{\nu}_{l'L} \; M^{L}_{l'l} \; (\nu_{lL})^{c} + \mathrm{h.c.},$$

$$M^L = Y^T \frac{v^2}{M} Y$$

is the seesaw mass matrix Large M_i in the denominator ensures smallness of neutrino masses

In a similar way the effective V-A Hamiltonian of the β-decay and other low energy processes can be obtained from SM Lagrangian in the second order of the perturbation theory with virtual W

W's were produced at accelerators and interaction of quarks and leptons with W was revealed and investigated

Heavy Majorana fermions N_i can not be produced at accelerators

However, they can be created in the early Universe. The CP violating decays of Majorana N_i's in the early Universe is widely considered as a source of the barion asymmetry of the Universe

The seesaw is not a theory. It is a very attractive idea, strategy.

This mechanism can be implemented into a future theory

It can not be tested in a direct way

However, observation of the neutrinoless double β-decay and proof that neutrinos have Majorana masses would be strong support of the seesaw idea

Matrix element of $0\nu\beta\beta$ decay is proportional to the effective Majorana mass

$$m_{\beta\beta} = |\sum_i U^2_{ei} m_i|$$

From exiting data the following (model dependent) bounds were obtained

$$m_{\beta\beta} < (0.2 - 0.7)\ \mathrm{eV}$$

It is planned that in future experiments a sensitivity

$m_{\beta\beta} \simeq \mathrm{a\ few}\ 10^{-2}$ eV will be reached

CONCLUSION

Neutrino meet his 80th in a very good shape

- Major difference between neutrinos and quarks and leptons. neutrinos have equal to zero charges
- Neutrinos have only weak interaction
- Neutrinos allow to obtain unique information (solar neutrinos probe internal region of the sun, where energy is produced) etc
- Only neutrinos can be Majorana particles
- Neutrinos could probe physics at very large scale where lepton number is violated

Challenging problems for future experiments

- Absolute values of neutrino masses (KATRIN $m_\beta \simeq 0.2$ eV, cosmology today $\sum_i m_i \lesssim 0.6$ eV; future sensitivity $\sum_i m_i \simeq 0.05$ eV)
- Character of neutrino mass spectrum (future long baseline neutrino experiments)
- Dirac or Majorana masses (future $0\nu\beta\beta$ experiments)
- How many massive neutrino? If the number of the massive neutrinos is more than three, sterile neutrinos must exist