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Eighty Years of Neutrino Physics

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Abstract

This is a pedagogical overview of neutrino physics from the invention of neutrino by Pauli in 1930 to the precise measurement of neutrino mass and mixing parameters via neutrino oscillation experiments in recent years. I have tried to pitch it at the level of undergraduate students, occasionally cutting corners to avoid the use of advanced mathematical tools. I hope it will be useful in introducing this exciting field to a broad group of young physicists.

1. Introduction

Neutrino physics originated from the study of radioactive beta decay,

$$N(A,Z) \rightarrow N'(A,Z \pm 1) + e^{\mp}. \quad (1)$$

Thanks to Becquerel and the Curies, several radioactive decays of this type had been investigated by the 1920s. Denoting the momenta of the decay products in the rest frame of the parent nucleus as ±p, one sees that the kinetic energy of N' and the total energy of electron are

$$E_{N'} = p^2/2M_{N'} \ \& \ E_e = \sqrt{p^2 + m_e^2}, \quad (2)$$

where p ~ MeV in natural units (ħ = c = 1). Thus $E_{N'} << E_e$, i.e. the recoil energy of the daughter nucleus is negligible relative to the electron energy. Thus by energy conservation one would expect the outgoing electron energy to equal the difference between the parent and daughter nuclear masses (known as the reaction energy release Q), i.e.

$$E_e \approx M_N - M_{N'} = Q. \quad (3)$$

So one expected a monoenergetic line spectrum for the electron. Instead it showed up as a typical continuum spectrum spanning the range m_e – Q, as illustrated in fig.1. This figure is adopted from ref.[1], which we closely follow in this section. To explain this discrepancy Pauli suggested the RHS of the decay (1) to contain a neutral particle, i.e.

$$N(A,Z) \rightarrow N'(A,Z \pm 1) + e^{\mp} + \bar{\nu}(\nu), \quad (4)$$

where the bar on top indicates antiparticle.

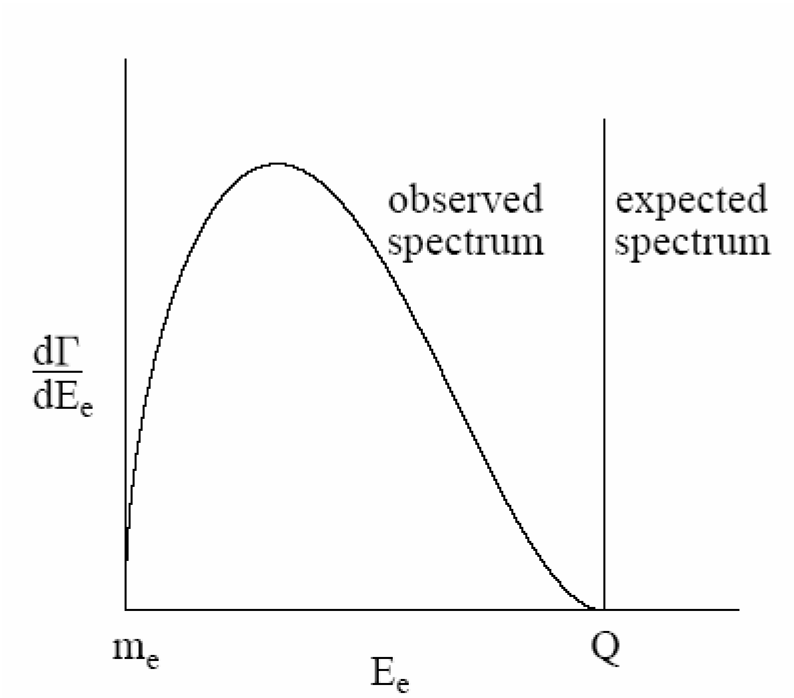

Fig1. The electron energy spectrum in nuclear beta decay [1].

Pauli made this suggestion in an informal letter dated December 1930, where he called it 'neutron'. But by the time he published it in 1933 [2], the neutron had been discovered by Chadwick as the neutral partner of the proton. So it was renamed by Fermi as 'neutrino', meaning the little neutron. Pauli also suggested correctly that the neutrino carried spin ½ to satisfy angular momentum conservation.

Pauli discussed his suggestion in many lectures given during 1931-33, which was closely followed by Fermi. Fermi also discussed this idea in depth with Pauli. This led him to publish his theory of weak interaction in 1934 [3]. This was based in analogy with Dirac's theory of electromagnetic (EM) interaction. But this was an effective theory, based on contact interaction, as illustrated in fig. 2. We know now that this contact interaction represents the modern gauge theory of weak interaction in the low energy limit, $Q^2 \ll m_W^2$, where

$$G_F = \frac{\sqrt{2}}{8}\left(\frac{g^2}{m_W^2}\right) \simeq 10^{-5} GeV^{-2} \tag{5}$$

is called the Fermi coupling. It represents the contact amplitude for weak decay processes like

$$\mu^- \to \nu_\mu e^- \bar{\nu}_e \;\&\; d \to u e^- \bar{\nu}_e, \tag{6}$$

where we have distinguished the neutrinos having charged current interaction with electron and muon by the corresponding subscripts in anticipation of the next section.

The second process describes the decay of ‘down’ to ‘up’ quark, which underlies neutron beta decay

$$n(udd) \to p(uud)e^{-}\bar{\nu}_e, \tag{7}$$

which in turn underlies all other nuclear beta decays of eq. (4).

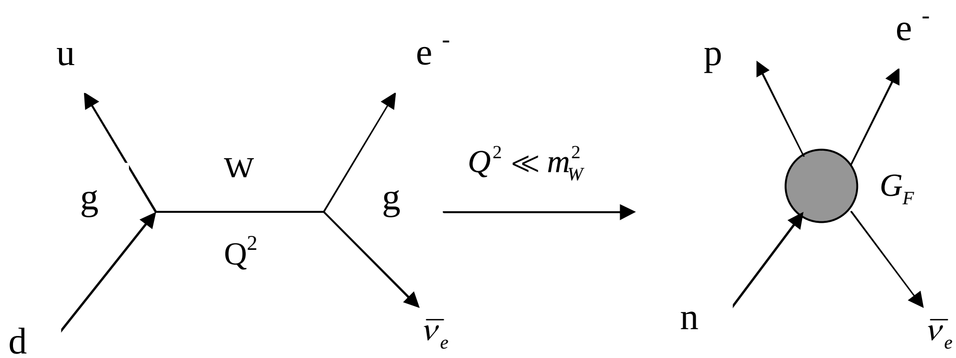

Fig. 2. Fermi’s theory of weak interaction (Four fermion contact interaction) as the low energy effective theory of charged current gauge interaction, mediated by the exchange of the massive W boson, with gauge coupling g to quarks and leptons.

One can easily compute the differential and total decay rates of neutron (eq. 7) or any radioactive nucleus (eq. 4) by using Fermi’s golden rule – i.e. squaring the decay amplitude of fig.2 and integrating over the phase space of final state particles. Thus

$$\begin{aligned} d\Gamma &\simeq G_F^2 \frac{d^3 p_e}{(2\pi)^3} \frac{d^3 p_\nu}{(2\pi)^3} (2\pi)\delta(Q - E_e - E_\nu)\left|M_W\right|^2, \\ d\Gamma / dE_e &\simeq G_F^2 \frac{(4\pi)^2}{(2\pi)^5} E_e p_e \underbrace{\sqrt{(Q-E_e)^2 - m_\nu^2}}_{p_\nu} \underbrace{(Q-E_e)}_{E\nu} \left|M_W\right|^2, \end{aligned} \tag{8}$$

where $\left|M_W\right|^2 \sim 6$ is the nuclear matrix element, connecting the nucleons to the underlying quarks [1]. In the last step we have $(4\pi)^2$ from the angular integrations of p_e and p_ν , while we have used the δ-function to integrate over E_ν. Taking $m_\nu = 0$, we find

$$d\Gamma / dE_e \propto p_e E_e (Q - E_e)^2 \propto \sqrt{E_e^2 - m_e^2}.E_e (Q - E_e)^2. \tag{9}$$

We can easily compute this and see that it gives a very good approximation to the shape of the electron energy spectrum for neutron or any other nuclear beta decay. The small remaining difference comes from the EM interaction of the electron (positron) with the recoiling nucleus. Finally, we can compute the total neutron decay width from (8), i.e.

$$\begin{aligned}\Gamma_n &\simeq G_F^2 \int \frac{d^3 p_e}{(2\pi)^3} \frac{d^3 p_\nu}{(2\pi)^3} (2\pi) \delta\left(m_n - m_p - E_e - E_\nu\right) |M_W|^2 \\ &\simeq G_F^2 \frac{(4\pi)^2}{(2\pi)^5} \int_{m_e}^{m_n - m_p} dE_e E_e p_e \left(m_n - m_p - E_e\right)^2 |M_W|^2 .\end{aligned} \tag{10}$$

With $G_F \sim 10^{-5} GeV^{-2}$ & $|M_W|^2 \sim 6$, one finds $\Gamma_n = \hbar/\tau_n \approx 10^{-28}$ GeV, corresponding to neutron decay lifetime $\tau_n \approx 887$ s.

2. Neutrino scattering and detection

The Fermi theory of fig.2 describes not only neutron beta decay but also the neutrino scattering processes

$$\nu_e n \to p e^- \;\&\; \bar{\nu}_e p \to n e^+, \tag{11}$$

since in quantum field theory the absorption of a particle is equivalent to the emission of its antiparticle. These are the reactions, responsible for neutrino detection. We can easily compute the corresponding cross-section by squaring the amplitude and integrating over the 2-body phase space, i.e.

$$\begin{aligned}\sigma &\simeq G_F^2 \int \frac{d^3 p_e}{(2\pi)^3} (2\pi) \delta\left(m_p + E_\nu - m_n - E_e\right) |M_W|^2 \\ &\simeq \frac{G_F^2}{\pi} p_e E_e |M_W|^2 .\end{aligned} \tag{12}$$

For incident neutrino energy significantly larger than m_e we get

$$\sigma \sim G_F^2 E_\nu^2 |M_W|^2 / \pi \sim 10^{-44} cm^2 (\, for E_\nu \sim 1 MeV). \tag{13}$$

The above equation shows how small is the neutrino scattering cross-section. The scattering rate is given by the product of this cross-section with the incident neutrino flux times the number of target nucleons. Thus for rock, with density $\rho \sim 6$ gm/cc $\sim 10^{24}$ nucleons/cc, we see that a single neutrino in the MeV energy range will pass through 10^{20} cm = 10^{15} km of rock before any interaction. This is a hundred billion times the diameter of earth ($\approx 10^4$ km)! This shows how weak is the neutrino interaction and how hard it is to detect them.

Note that we now understand the reason for the weakness of neutrino interaction to be its short range – i.e. the heavy mass of the exchanged W boson. The range is $\hbar c/m_W \sim 0.002$ fm for the observed W boson mass of 80 GeV; while the position uncertainty of a 1 MeV neutrino is $\hbar c/1$ MeV ~ 200 fm. So the scattering amplitude is suppressed by the overlap fraction of the two areas ~ $(1\ \mathrm{MeV}/M_W)^2 \sim 10^{-10}$. And the corresponding cross-section is suppressed by a factor of 10^{-20} with respect to the long range EM interaction. The electron has a cross-section of $\sim 10^{-24}\ \mathrm{cm}^2$, and gets absorbed by a few cm thick matter, in contrast with the 10^{20} cm for neutrino. Indeed Pauli had commented in the early 1930s that he has invented such a particle, which will never be detected experimentally.

However, neutrino was detected within Pauli's life time – i.e. in 1956 by Cowan and Reines [4]. This was made possible by the advent of nuclear reactors, which provided a rich flux of (anti)neutrinos ~ $10^{13}/\mathrm{cm}^2/\mathrm{s}$. Their experiment consisted of two tanks, each containing 200 liters of water with dissolved Cadmium Chloride, and sandwiched between

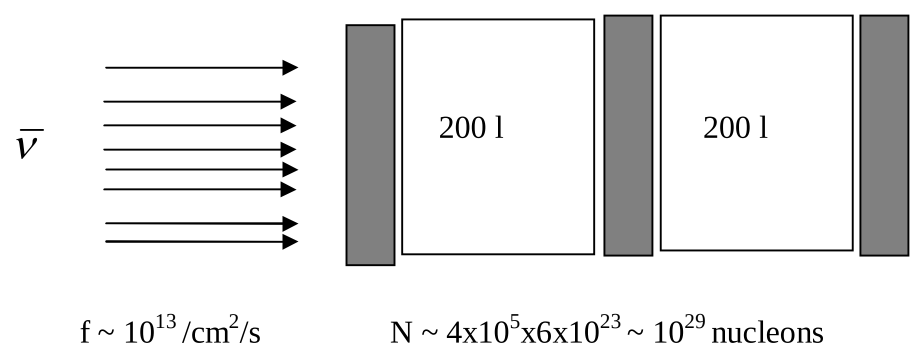

Fig.3. Schematic diagram of the neutrino discovery experiment of Cowan and Reines, showing two water tanks sandwiched between three scintillation detectors.

three scintillation detectors (Fig.3). One sees from eq. (13) that the expected interaction rate of the reactor neutrinos is

$$R \sim fN\sigma \sim 10^{-2}/s, \tag{14}$$

i.e. about 1 per 2 minutes. The proton in the water provided target for the interaction $\bar{\nu}_e p \to e^+ n$. The gamma rays from the annihilation of the produced e^+ with e^- provided the scintillation signal. This was followed closely (within a few microseconds) by gamma ray from neutron absorption in cadmium, $n\,{}^{48}\mathrm{Cd} \to \gamma\,{}^{49}\mathrm{Cd}$. The observed double gamma ray signal was further confirmed by its correlation with the reactor being in operation. (The Nobel prize came to Reines forty years later in 1996, by which time Cowan had died.)

This was followed soon by another Nobel prize winning neutrino experiment – i.e. the discovery of a second species (or flavour) of neutrino ν_μ [5]. It is related to the muon by the charged current interaction of the type shown in fig.2. It comes from muon decay process shown in eq. (6) as well as from pion decay

$$\pi^\pm \to \mu^\pm \nu_\mu (\bar{\nu}_\mu). \tag{15}$$

In fact this is the dominant decay mode of charged pions, as we shall see later. The high-energy neutrinos coming from this decay were bombarded on a nucleon target at the Brookhaven laboratory experiment [5], which detected the muons produced via

$$\nu_\mu n \to \mu^- p (\bar{\nu}_\mu p \to \mu^+ n). \tag{16}$$

That the produced particle was $\mu^\pm$ instead of $e^\pm$ demonstrated the existence of a second species of neutrino. This was closely followed by the first detection of ν_μ in a cosmic ray experiment at the Kolar gold mine [6], which was in fact the first detection of atmospheric neutrino. Finally the third neutrino species (flavour) ν_τ was discovered in 2000 at Fermilab by observing the τ leptons produced via

$$\nu_\tau n \to \tau^- p (\bar{\nu}_\tau p \to \tau^+ n) \tag{17}$$

in a nuclear emulsion experiment [7].

3. Neutrino chirality and mass:

The abovementioned quarks, charged leptons and neutrinos are all spin 1/2 particles, called matter fermions. So they can occur in right- and left-handed chirality (or helicity) states, corresponding to spin alignment along and opposite to the direction of momentum. As per the Standard Model of particle physics the three basic interactions between these particles – strong, electromagnetic and weak – are all gauge interactions. Their strengths are determined by the respective gauge charges – i.e colour charge, electric charge and weak isospin. The strong and the EM interactions are invariant under charge conjugation C and parity transformation P (i.e. space reflection). However, it was discovered in the 1950s that the weak interaction breaks C and P maximally, while preserving invariance under the combined CP transformation. This means that only the left-handed quarks and leptons (and the corresponding right-handed antiparticles) carry weak isospin (I=1/2) and take part in weak interaction. Thus we have three isospin doublets of left-handed leptons and quarks

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \& \begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L \tag{18}$$

and similarly for their right-handed antiparticles. On the other hand the right-handed quarks and charged leptons occur as isospin singlets (I=0) along with their left-handed antiparticles; and take part only in strong and EM interactions. Since the neutrinos have only weak interaction there is no need for right-handed neutrinos (or left-handed antineutrinos); and there are none in the Standard Model.

Now a fermion mass term in the Lagrangian corresponds to the combination

$$m_f \bar{\psi}_{R(L)} \psi_{L(R)} = \bar{f}_{L(R)} \xrightarrow{\Leftarrow(\Rightarrow)} \xleftarrow{\Rightarrow(\Leftarrow)} f_{L(R)}, \tag{19}$$

where $\psi_L \& \bar{\psi}_L$ are wavefunctions for left-handed fermion and its antiparticle – i.e. right-handed antifermion. (In the more rigorous language of quantum field theory $\psi_L \& \bar{\psi}_R$ are field operators for absorbing left-handed fermion and antifermion or creating right-handed antifermion and fermion respectively). The long and short arrows on the right hand side illustrate the momenta and spins of the antifermion and fermion pair in their centre of mass frame. This illustration shows that only these two combinations are allowed by angular momentum conservation, while LR and RL terms are disallowed because they carry nonzero total angular momentum, which will violate the rotational invariance of the Lagrangian. In other words, the mass term represents the absorption or creation of a fermion-antifermion pair of same chirality LL or RR (or transformation of a left-handed fermion into a right-handed one, i.e. chiral symmetry breaking).

Note that in the Standard Model a left-handed (or right-handed) fermion-antifermion pair carries total isospin 1/2; and hence breaks gauge invariance of the Lagrangian. So even the quarks and charged leptons cannot have bare mass, represented by the above mass term in the Lagrangian. Instead they get mass via their Yukawa coupling to the isospin doublet of Higgs boson, which acquires a vacuum expectation value by spontaneous breaking of the isospin gauge symmetry, i.e.

$$y \bar{\psi}_R \psi_L h \xrightarrow{sp.symm.br} \underbrace{y \langle h \rangle}_{m} \bar{\psi}_R \psi_L . \tag{20}$$

In other words their mass comes from their Yukawa interaction with the constant Higgs field <h>, present in the vacuum. This is called the Dirac mass of quarks and charged leptons, which is roughly in the range of $\sim 10^{\pm 2}$ GeV.

It is worth making a small detour on Spontaneous Symmetry Breaking, which means a symmetry is preserved by the Lagrangian but broken by the ground state. Here the Isospin symmetry of the Lagrangian is broken by the ground state (vacuum) due to the presence of the constant Higgs field, carrying nonzero isospin (I=1/2). The simplest example of SSB is a ferromagnet, where the rotational symmetry of the electro-magnetic interaction Lagrangian is broken by the ground state, as its atomic spins get aligned with one another in a particular (north-south) direction. We have a similar situation in Higgs mechanism, except that the rotational symmetry is in Isospin space instead of the ordinary space. Experimental evidence for this is expected to come from the discovery of Higgs boson at the large Hadron Collider. Incidentally, there is a spontaneous breaking of