On the study of neutrino properties

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We review the discovery of the neutrino and outline the history of neutrino physics. Many interesting phenomena involving the neutrino are exhibited. We also discuss the long-standing solar neutrino puzzle and the properties of the neutrino which lead to various important results. We present a possible experimental test of the neutrino property. In addition, neutrino oscillation and neutrino spin precession are also demonstrated.

I. INTRODUCTION

The elusive neutrino\(^1\) has played an important role in our understanding of physics in many ways: from the parity violation\(^2\) of beta decay to the solar neutrino puzzle; from the formulation of the four Fermion weak interaction theory to the unification of electromagnetic and weak interactions into the electroweak interaction.\(^3\) There are various open questions about neutrinos that need both theoretical and experimental exploration. As the most intriguing and fascinating fundamental particle, the neutrino is so important that neutrino physics has become one of the most significant branches of modern physics.

On December 4, 1930, W. Pauli proposed the neutrino as a desperate-remedy to the observed continuous spectrum of energy for the outgoing electrons of beta decay. In accurate measurements on beta decay process before 1930, physicists found the emitted electron with a continuous energy spectrum, unlike alpha decay and gamma decay in which the emitted particles carried away the well-defined energy which is equal to the total energy difference of the initial and final states. It meant that a particular nucleus emitted an electron bearing unpredictable energy in a particular transition. This experimental result apparently violated the conservation laws of energy and momentum. In order to solve this serious problem Pauli proposed an entirely new particle in his open letter\(^2\) to the group of radioactives at the meeting of the regional society in Tubingen:

"...This is the possibility that there might exist in the nuclei electrically neutral particles, which I shall call neutrinos, which have spin 1/2, obey the exclusion principle and moreover differ from light quanta in not travelling with the velocity of light."

"... I admit that my remedy may perhaps appear unlikely from the start, since one probably would long ago have seen the neutrons if they existed. But ‘nothing venture, nothing win’, and the gravity of the situation with regard to the continuous beta spectrum is illuminated by a pronouncement of my respected predecessor in office, Herr Debye, who recently said to me in Brussels ‘Oh, it’s best not to think about it at all-like the new taxes’. One ought to discuss seriously every avenue of rescue.”

In his letter, Pauli called his new proposed particle-the "neutron" which is now called neutrino due to Enrico Fermi. Pauli proposed that this new speculative neutral particle might resolve the nonconservation of energy. If the proposed neutrino and the electron were emitted simultaneously, the continuous spectrum of energy might be explained by the sharing of energy and momentum of emitted particles in beta decay. The neutrino was first experimentally detected by Fred Reines and Clyde Cowan in 1956\(^3\) using a liquid scintillation device. Their experiment involved detecting the reaction \(p + \nu_e \rightarrow n + e^+\) exploiting antineutrinos from the Savannah river nuclear reactor. This important discovery won the 1995 Nobel prize in physics. It is worth mentioning that long before the neutrino was experimentally detected, Enrico Fermi\(^4\) incorporated Pauli’s proposal in his brilliant model for beta decay in the framework of quantum electrodynamics in 1934. He showed clearly with his beta decay theory that the neutron decayed into a proton, an electron and a neutrino simultaneously. In 1957, B. Pontecorvo\(^5\) suggested that neutrino flavor eigenstates are superpositions of its mass eigenstates, thus as the neutrino propagate it would undergo oscillation, which is just similar to the \(K\) meson system. The little neutrino has found its application to a number of different research areas in physics, such as in particle physics, nuclear physics, cosmology and astrophysics. Thanks to the conjecture of the neutrino by Pauli which rescues the fundamental conservation laws of energy and momentum. Although his proposal contradicted the well-accepted knowledge at the time on beta decay process, his new beta decay process involving the neutrino was not completely impossible experimentally.

II. THE PROPERTIES OF THE NEUTRINO

The solar neutrino problem is a famous puzzle on the neutrino. The sun shines mainly because of the hydrogen burning. The nuclear fusion reaction may be written as,

\[ 4p \rightarrow \He + 2e^+ + 2\nu_e \quad (2.1) \]

The positions produced in the above nuclear fusion reaction was annihilated with electrons while the emitted
neutrinos hardly and weakly interact with matter therefore the sun may be regarded as a well-defined neutrino source shown in FIG.1. Thanks to the sun. So we may have the great opportunity to study the properties of the neutrino. The pioneering work of detecting the solar neutrino was carried out by R. Davis\cite{(11)}. His Homestake chlorine experiment was based upon the following reaction,

\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- \]  

(2.2)

When detecting the neutrino emitted from the sun, Davis consistently observed fewer solar neutrino capture rate than the calculated capture rate predicted by J. Bahcall\cite{(12)} in chlorine using detailed computer models of the solar interior in 1968. Later the missing neutrino mystery was also observed by other groups using different materials. This is the long-standing solar neutrino puzzle.

The SNO experiment \cite{(13)} detected the solar neutrino which showed the flavor change of the neutrino. They measured only the high energy \(^{8}\text{B}\) solar neutrinos through the reactions,

\[ \nu_e + d \rightarrow p + p + e^- \quad \text{(CC)} \]
\[ \nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)} \]
\[ \nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)} \]

In their measurement of the \(^{8}\text{B}\) neutrino fluxes, they assumed the standard spectrum shape\cite{(14)} and obtained,

\[ \phi_{\text{SNO}}^{\text{CC}}(\nu_e) = 1.75 \pm 0.07 \, \text{(stat.)}^{+0.12}_{-0.11} \, \text{(sys.)} \pm 0.05 \, \text{(theor.)} \times 10^6 \, \text{cm}^{-2}\text{s}^{-1} \]
\[ \phi_{\text{SNO}}^{\text{ES}}(\nu_x) = 2.39 \pm 0.34 \, \text{(stat.)}^{+0.16}_{-0.14} \, \text{(sys.)} \times 10^6 \, \text{cm}^{-2}\text{s}^{-1} \]

Their total flux of active \(^{8}\text{B}\) neutrinos is,

\[ \phi(\nu_x) = 5.44 \pm 0.99 \times 10^6 \, \text{cm}^{-2}\text{s}^{-1} \]  

(2.3)

which agrees with the predictions made from the standard solar models\cite{(12),(14)}.

Although SNO uses heavy water to detect the neutrino, as far as the charge current reaction is concerned, SNO experiments are very similar to the ones carried out at Super-Kamiokande\cite{(15),(17)}, which also show that the neutrino flavor change. They are both real time experiments sensitive to \(^{8}\text{B}\) solar neutrinos only with the Cherenkov detector. When comparing their measured flux via charge current reaction with the flux obtained by Super-Kamiokande Collaboration of the \(^{8}\text{B}\) flux using the elastic scattering reaction, they found the difference was \(0.57 \pm 0.17 \times 10^6 \, \text{cm}^{-2}\text{s}^{-1}\), which was about 3.3\sigma. This gives the direct evidence of the flavor change of the neutrino. As a consequence of the flavor change, the neutrinos should have mass. The neutrino flavor change was also justified by the KamiLAND reactor neutrino experiment with liquid scintillator detector located at the old Kamiokande site\cite{(15)}.

A great number of explanations were proposed to solve the solar neutrino puzzle. The most popular one is the neutrino oscillation. Next we will show the three flavor neutrino oscillation with the plane wave approximation. A definite neutrino flavor field \(\nu_f\) with flavor \(f\) is a linear combination of the neutrino mass fields \(\nu_m\) with the definite mass \(M_m\) and definite energy \(E_m\), so

\[ \nu_f = \sum_{m=1}^{3} U_{fm}\nu_m \]  

(2.4)

where \(f = e, \mu, \tau\), \(U_{fm}\) are the entries of a unitary matrix.

Then we obtain,

\[ |\nu_f \rangle = \sum_{m=1}^{3} U_{f m}^*|\nu_m \rangle \]  

(2.5)

namely the neutrino flavor state is the superposition of the neutrino mass eigenstates. Next, considering the neutrino mass state at time \(t\), \(|\nu_m \rangle_t\), using the Schrödinger equation yields,

\[ |\nu_m \rangle_t = e^{-iE_m t}|\nu_m \rangle \]  

(2.6)

where \(|\nu_m \rangle\) represents the neutrino mass state at time 0 in its rest frame. Combining with Eq.\ref{2.5}, we immediately obtain the neutrino flavor state at time \(t\),

\[ |\nu_f \rangle_t = \sum_{m=1}^{3} U_{f m}^* e^{-iE_m t}|\nu_m \rangle \]
\[ = \sum_{f'} \left( \sum_{m=1}^{3} U_{f m}^* e^{-iE_m t} U_{f' m} \right) |\nu_{f'} \rangle \]
\[ = \sum_{f'} M(\nu_f \rightarrow \nu_{f'}) |\nu_{f'} \rangle \]  

(2.7)

where \(f' = e, \mu, \tau\) and \(M(\nu_f \rightarrow \nu_{f'})\) represents the amplitude of neutrino flavor transition at time \(t\). That the neutrino initially with flavor \(f\) turns into a superposition of different neutrino flavors after traveling time \(t\) is clearly shown in Eq.\ref{2.7}. Therefore we immediately obtain the probability of the neutrino flavor transition in vacuum from \(\nu_f\) to \(\nu_{f'}\),

\[ P = |M(\nu_f \rightarrow \nu_{f'})|^2 \]
\[ = \left| \sum_{m=1}^{3} U_{f m}^* e^{-iE_m t} U_{f' m} \right|^2 \]
\[ = \sum_{m,m'} U_{f m}^* U_{f' m}^* U_{f m} U_{f' m} e^{-i(E_m - E_{m'}) t} \]  

(2.8)
where \( m, m' = 1, 2, 3 \) representing the neutrino mass eigenstates. Next exploit the mass-energy relation due to Einstein,

\[
E_m = \sqrt{p_m^2 + m^2} \approx p + \frac{m^2}{2p}
\]  

(2.9)

where we have assumed that all neutrino mass eigenstates have the same momentum \( p \) and employed the relation \( p \gg m \), because of the high energy neutrinos observed. When plugging Eq. (2.9) into Eq. (2.8), yields the probability of the neutrino flavor transition in vacuum from \( \nu_f \) to \( \nu_{f'} \),

\[
P = \sum_{m, m'} U_{f'm}^* U_{f'm} e^{-i(m^2 - m'^2) \frac{t}{2m_e^2}}
\]

\[
= U_{f'm}^* U_{f'm} e^{-i \frac{\Delta m^2}{2m_e^2} t}
\]  

(2.10)

where \( E \) is the neutrino energy in the massless limit which is approximately equal to its momentum \( p \) due to the extremely small mass of the neutrino and we have defined,

\[
\Delta m^2_{mm'} = m^2 - m'^2
\]  

(2.11)

Another possible way in explaining the solar neutrino puzzle is spin-flavor precession. It is based upon the neutrino spin precession through the strong magnetic field in the convective zone of the sun. Following their proposals, the neutrino has a magnetic moment \( \mu \approx (10^{-11} - 10^{-10}) \mu_B \) where Bohr magneton \( \mu_B = \frac{e h}{2m_e} \). The spin of the neutrino would precess from a left-handed to a right-handed helicity due to the magnetic moment as well as the electric dipole moment the neutrino has when the neutrino passes through the strong interior solar magnetic field. To be more specific, a \( \nu_{eL} \) may flip its spin and change its flavor then turn into \( \nu_{eR} \) or \( \nu_{eR} \) (where \( L \) and \( R \) represent left-handed and right-handed helicity respectively.) which would not interact with the materials used in the solar neutrino experiments. As a consequence, the neutrino spin precession leads to the measured neutrino deficit in the solar neutrino puzzle. The measured neutrino deficit may also be explained by particle interactions. Put in other word, when a neutrino interacts with an antineutrino they may produce muon neutrino and muon antineutrino pair. The cross section of this interaction would be greatly increased if the neutrino possesses any charge. We propose that the neutrino has a magnetic charge which has similarly puzzled physicists for a long time. This assumption is justified by another famous interaction in which the neutrino takes part–beta decay. As we know space inversion will not conserve in the beta decay process. Actually in all weak interactions involving neutrinos, parity violations always happen. This behavior of the neutrino is quite similar to the behavior of monopole under space inversion. As J. Jackson pointed out in his famous book on Classical Electrodynamics: “... it is a necessary consequence of the existence of a particle with both electric and magnetic charges that space inversion and time reversal are no longer valid symmetries of the laws of physics. It is a fact, of course, that these symmetry principles are not exactly valid in the realm of elementary particle physics, but present evidence is that their violation is extremely small and associated somehow with the weak interaction.” Since magnetic charge density is a pseudoscalar, the signs of a magnetic charge are opposite when observed from both the right-handed coordinate system and the left-handed coordinate system. This could result in the parity violation of the weak interaction involving the neutrino. The neutrino has the electric dipole moment \( \vec{d} \). Since the orientation of the neutrino in its rest frame is characterized only by the orientation of the internal vector — intrinsic angular momentum \( \vec{J} \), \( \vec{d} \) and \( \vec{J} \) must be either in the same direction or in the opposite direction. We obtain \( \vec{d} = L \frac{\vec{e}}{2m} \) where \( g \) is the magnetic charge a particle has, \( m \) is the mass of that particle and the parameter \( L \) is called a Lande factor. Due to the electric dipole moment of neutrino, nonconservation of time reversal of weak interactions involving neutrinos takes place. Moreover \( T \) violation induce the \( CP \) violation because of the Lüders–Pauli theorem. The electric dipole moment makes the neutrino spin precession explanation more convincing. When the neutrino moving through the strong interior solar magnetic field, the magnetic field would cause neutrino spin precession, giving rise to the surprising discrepancy between the calculated and observed capture rates of solar neutrino. Before completing this section, we give a possible experimental test based upon the Faraday induction method. Place a radioactive source at the center of an enclosed superconducting sphere. Whenever \( \beta \)-decay of the radioactive source happens, an anti-neutrino is released which would induce the supercurrents on the superconducting sphere due to the proposal. A magnetometer SQUID (superconducting quantum interference device) connected to the sphere is need to monitor the currents. To eliminate any unwanted influence of electrically charged particles, an absorbent layer would be introduced between the radioactive source and the enclosed superconducting sphere. Even though, the sensitive devices in the experiment are vulnerable to spurious signals, it is still an ideal way to detect the monopole since the method is independence of the particle’s mass and velocity. The detectors should be placed inside a magnetic shield made up of lead or mumetal to protect the detectors from external magnetic fields.

\[
\vec{G} = \vec{D} \times \vec{B}
\]  

(2.20)
III. SUMMARY AND CONCLUSION

We have reviewed the discovery and the history of neutrino physics in our paper. A number of interesting phenomena involving the neutrino have been exhibited. We have studied the long-standing solar neutrino puzzle and the properties of the neutrino which lead to various interesting results. In addition, neutrino oscillation and spin precession have also been discussed. We have presented a possible experimental test of the neutrino property. This year is the unprecedented World Year of Physics which marks the hundredth anniversary of the pioneering contributions of Albert Einstein. We dedicate this paper to Albert Einstein.

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