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Discovery of neutrino and oscillation phenomenon

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Abstract. As an intersection of particle physics, nuclear physics and geophysics, neutrinos are currently a hot research direction in the physics field, and it plays an important role in the study of the origin and evolution of the universe and the formation and evolution of celestial bodies. The Standard Model of particle physics has achieved great success in describing experimental phenomena in particle physics and correctly classifying known particles. In 2015, Takaaki Kajita and Arthur B. McDonald won the Nobel Prize in Physics for their discovery of neutrino oscillations, which brought neutrino research to a climax. In recent years, major breakthroughs have been made in the study of neutrinos, with the discovery that neutrinos have mass and that different neutrinos can be transformed into each other in a way known as neutrino oscillations, or neutrino mixing. Neutrino oscillations are the only physical phenomenon so far that cannot be explained by the Standard Model. Because neutrinos play an important role in both the most microscopic particle physics and the most macroscopic formation and evolution of the universe, the study of neutrinos is increasingly becoming a popular research direction. In this paper, the neutrino oscillation experiment is comprehensively studied and interpreted from the perspective of historical development. Designed to verify the existence of neutrino oscillations and thus prove that neutrinos have mass.

Keywords: Neutrino, Quality, Neutrino oscillation

1. Introduction

Neutrinos, also known as neutrinos, are named after the Arabic word for neutrino, which is essentially a tiny particle that is electrically neutral [1]. In the early 20th century, when humans observed α, β, and γ, only discrete α and γ ray energy spectra were observed, but the spectrum of β rays was continuous. Since nuclear decay is a transition between different quantum energy levels of the nucleus, the energy level separation of the quantum system inevitably leads to the energy released by nuclear decay is also discrete. In understanding the production mechanism of beta rays, Danish physicist Bohr has proposed

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[2]: “In the current atomic theory, neither empirically nor theoretically there is no reason to insist that energy must be conserved in the process of beta decay.” This shows how puzzled physicists at the time were about the continuous spectrum of beta rays. The neutrino hypothesis was first proposed by Austrian physicist Pauli in 1930, in order to ensure the conservation of energy-momentum and angular momentum in the process of beta decay. He believed that the neutron, as a massive neutral particle, became a proton, an electron, and a small neutral particle in the process of beta decay, and it was this small mass particle that carried away the energy. The energy-stealing “thief” Pauli predicted was the neutrino. Neutrinos interact very little with other matter, with a cross section of about 10-40cm2. In other words, a neutrino could penetrate a light-year thick lead brick unimpeded. The sun, cosmic rays, nuclear power plants, and even the Earth’s interior all produce large amounts of neutrinos in nature. A typical nuclear power plant reactor with a thermal power of 3 millions KW can produce about 6*1020 antielectron neutrinos per second.

On October 16, 2015, the Royal Swedish Academy of Sciences announced that the 2015 Nobel Prize in Physics was awarded to Takaaki Kajita and Arthur B. MacDonald , for their work in discovering that neutrinos have mass, known as neutrino oscillations. They have experimentally demonstrated that neutrinos can change their form, and this change assumes that neutrinos have mass. This discovery is of vital importance to the scientific community, not only changing our understanding of the deeper aspects of matter, but also playing a key role in further understanding of the universe. Therefore, from the perspective of historical development, this article attempts to further explore the standard model and neutrino mass by elaborating on the properties of neutrinos, and draws conclusions about neutrino mass and ordering from neutrino oscillations and experiments, aiming to provide some reference basis for comprehensive research and interpretation of neutrino oscillation experiments.

2. Standard Model and neutrino mass

In the theory of particle physics, matter is made up of elementary particles such as quarks, electrons and neutrinos. In the Standard Model, which describes elementary particle interactions, neutrinos come in three types, or flavors, including electron neutrinos, mu-neutrinos, and tau-neutrinos. Leptons have six “flavors”, namely electron number, muon number, tao-muon number, electron neutrino number, mu-neutrino number and tao-neutrino number [3]. So far, it has been confirmed by positron collisions that no fourth type of neutrino involved in gauge interactions has been found below the mass limit of 45GeV/c2. A revolutionary experiment in 1957 found that parity is not conserved in weak interactions, and showed that neutrinos involved in weak interactions are purely left-handed (neutrinos whose spin direction and momentum direction satisfy the left-handed rule) and have no right-handed neutrinos. In the same year, Lee, along with Yang, Landau, and Salam independently proposed the two-component neutrino theory, which means that neutrinos have only left-handed components and zero mass. In the mass term of the Standard Model interaction Laplace quantity, if there is no right-handed neutrino, then the mass term of the neutrino will not exist, that is, the neutrino has zero mass, so the neutrino is strictly massless in the Standard Model. Any experimental evidence that neutrinos have mass would indicate new physics beyond the standard Model [4].

3. Neutrino oscillation

If a neutrino has mass, even if it is very small, its matter wave travels in a strange way: the neutrino changes from one type to another, and the neutrino’s taste changes [5]. This phenomenon, called neutrino oscillation, was first proposed by Italian physicist Pontecorvo in 1957. In 1962, the Japanese physicist Maki improved the neutrino oscillation theory on this basis, so that the mass eigenstate of the neutrino is transformed into the taste eigenstate of the neutrino through the neutrino mixing matrix. Since neutrinos only participate in the weak interaction, their production and detection are embodied by the “taste” eigenstates, namely electron - (e), μ- and τ- neutrinos. However, in the equations of motion that describe neutrino propagation, the form of the neutrino’s Hamiltonian depends on its energy and is therefore related to the neutrino mass. In the simple two neutrino flavor mixing modes, the mass eigenstate and the flavor eigenstate can be linked by a rotational change [6]. Such as:

$$\binom{v_e}{v_u} = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \binom{v_1}{v_2}$$

The result of mixing is to produce a neutrino with a given taste through a weak interaction. With the evolution of time, the wave function of the flavor eigenstate, in the above equation, the time-dependent wave function of the μ-neutrino is expressed as:

$$v_\mu(t) = -\sin\theta\, e^{-iE_1}t|v_1 + \cos\theta\, e^{-iE_2}t\,|v_2$$
$$= \cos^2\theta\, e^{-iE_1}t + \sin^2\theta\, e^{-iE_2}t|v_\mu + \sin\theta\cos\theta(e^{-iE_3}t - e^{-iE_1}t|v_e)$$

In this way, the neutrinos with a given taste will have a certain probability of converting into neutrinos with other tastes, that is, the oscillation effect will occur. At this point, the probability of neutrinos with no change in flavor (such as electron neutrinos) is:

$$P^{2V(V_e \to V_U)} = 1 - \left| < \mathrm{V_e} \middle| \mathrm{V_u} > \right|^{2=} 1 - \sin\theta^2\, 2\theta\big(1.267 \triangleright \mathrm{M}^2\, \mathrm{L/E}\big)$$

Further, if the neutrino mass is not zero, and the eigenvalues of the three generations of neutrino mass eigenstates are not equal, then any neutrino given a taste eigenstate will be transformed into other taste eigenstates by oscillation during the propagation process. In experimental measurements, if the experimental apparatus is not sensitive to other flavor eigenstates, then the so-called neutrino "loss" phenomenon, also known as neutrino oscillation.

4. Neutrino oscillation experiment

Although neutrinos were introduced as a concept to explain the continuous energy spectrum of beta particles in the beta decay of atomic nuclei, their existence was proved only 26 years later. American physicists Cowen and Reines et al. used anti-electron neutrinos from the reactor to react with protons in the target material to produce detectable positrons and neutrons, and found evidence of neutrinos for the first time from the Sa-vannahRiver experiment. On June 14, 1956, Cowen and Reines sent a telegram to Pauli at the University of Zurich in Switzerland: "I am pleased to inform you that by observing the antibeta decay of protons, we have definitely detected neutrinos from fission products." The observed cross sections agree very well with the expected 6*10-40cm2." Forty years later, Reines was awarded the 1995 Nobel Prize in Physics. The experimental detection of neutrinos is achieved by reacting with matter. The most common way to do this is to make neutrinos interact with electrons or nucleons (protons and neutrons), producing electrically charged leptons (such as positrons or μs) that can be detected. Some experiments can also be combined with the detection of recoil nucleons to determine the positive and antineutrino types [7]. From a kinematic point of view, if the energy of the neutrino is much greater than the rest mass of the charged lepton produced, these charged leptons tend to carry information about the direction of the original incident microons. In this way, the momentum of the incident neutrino can be reconstructed experimentally, so as to achieve the purpose of studying neutrinos. The number of cases of neutrinos expected to be detected experimentally can be simply estimated as follows:

$$N_v = \sigma_v^* N_{target^*} \Phi_{v^*} T$$

Since the neutrino reaction cross section σv is about 10-40cm2, the number of target atoms Ntarget contained in a ton of target matter is about 1030. Therefore, in order to obtain sufficient statistics from the experiment, the current intensity Φν of the incident neutrino should not be too low, and the data collection time T should be long enough. For some neutrino sources with low current intensity to be studied (such as solar neutrinos, Earth neutrinos and supernova neutrinos), the target volume must be increased, which constitutes the unique characteristics of neutrino experiments that require hundreds or even tens of thousands of tons of target volume, and the accumulation of data over several years or even more than ten or twenty years.

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5. Neutrino mass and sequencing

Although the establishment of neutrino oscillation clearly indicates that neutrinos have mass, the experimental study of oscillation can only give the absolute value of the mass squared variance between the mass eigenstates of neutrinos, and cannot give the absolute mass of neutrinos and the order of the mass sizes of the three types of neutrinos, as expressed in the probability formula of neutrino oscillation [8]. The so-called positive and inverse ordering problem of the three types of neutrino mass is generated. Moreover, the oscillation experiment could not answer the question of the nature of the neutrino: whether it is the left-handed Dirac neutrino or the Majorana neutrino, which is not divided between the left and right hands. Laboratories around the world are planning new experiments, hoping to find possible evidence of neutrino-free double beta decay in the decay spectra of isotopes with double beta decay, to determine whether it is a Dirac or Majorana neutrino. Neutrinos have mass, which is not only of great significance to particle physics, but also of profound significance to cosmology. It is generally believed that in the Big Bang that gave birth to the universe, equal amounts of matter and antimatter were produced, but the properties of the two are completely different, and almost all of the antimatter disappeared, leaving only positive matter to form the present universe. This is despite the fact that Makoto Kobayashi and Toshihide Maskawa, winners of the 2008 Nobel Prize in Physics, discovered the origin of at least three generations of quark breaking symmetries predicted to exist in nature. However, the charge-parity breaking strength observed in the quark mix still does not explain the formation of the universe. The current general view is that this may have something to do with the properties of neutrinos. The current popular theoretical scheme believes that the mystery of the disappearance of cosmic antimatter is related to the possible existence of supermassive right-handed neutrinos and the charge conjugation-parity destruction they contain, because in the evolution of the universe, with the decrease of temperature, the decay process of right-handed neutrinos is irreversible, so that the positive and negative matter differences are left over. In the orthodox seespeg mechanism, the supermass of the right-handed neutrino is inversely proportional to the tiny mass of the normal left-handed neutrino, which also explains why the neutrino mass is so small. Although neutrinos are currently thought to make up less than 1% of the matter in the universe, they are an important part of models of the universe. Of all the hypotheses about the mysterious dark matter, neutrinos are the only particles that have so far been able to prove that dark matter actually exists. The current mass limit of antielectron neutrinos directly measured by beta spectroscopy is 2.3eV/c2 (95% confidence level). Using data from the cosmic microwave background, combined with data from supernovae and the structure of the Milky Way, studies have shown that the mass of various types of neutrinos is no greater than 0.66eV/c2 (95% confidence level) [9]. It can be seen that small neutrinos may indeed warp the vast universe, as suggested by the “seespeg mechanism.”

6. The future of neutrino shocks

Although it has been 85 years since the concept of neutrinos was proposed, and since the experiment first confirmed the oscillation phenomenon of neutrinos in 1998, revealing that neutrinos have an extremely small mass, this fact that does not meet the prediction of the standard model has puzzled physicists for many years, and the physics behind the mass of neutrinos has still not been determined. Speculation about new physics beyond the Standard Model is widely published in physics journals, and about 1,000 papers a year have “neutrinos” in their titles, which need to be tested and confirmed by experiments. As theoretical physicist Smirnov said at the 21st “Window on the Universe” Blois Conference in France in 2009: “It has been 11 years since the discovery that neutrinos have mass. Despite a great deal of theoretical and experimental work, the physics behind neutrinos’ mass remains uncertain. It should be some new physics beyond the Standard Model, either old new physics that was proposed many years ago and requires a detailed theoretical study, or new physics that is currently proposed, or something we haven’t thought of yet.” In addition to the physics of neutrino properties, the detection of neutrinos from the universe is also a study of profound significance in astrophysics. The most famous example is the study of solar neutrinos, which has theoretically understood how the sun’s interior reacts and established the standard solar model. In recent years, extremely high energy cosmic rays have been observed experimentally, and their energy has reached more than 1020eV. How can cosmic rays obtain such high energy? Where do these cosmic rays come from? Although these questions are not easy to answer, but as a cosmic messenger neutrino, due to the production of high-energy cosmic rays at the same time, will also be accompanied by the production of high-energy neutrinos, and the characteristics of neutrinos show that their flight path will not be affected by the galaxy's magnetic field, therefore, from the direction of the neutrino flight can be reversed to infer the direction of the neutrino source, and then understand the source of extremely high energy cosmic rays. Neutrinos, on the other hand, are also active participants in the evolution of the universe. They are important by-products of beta decay, which, in addition to heating the remnants of the star explosion and the interior of the planet, is an important step in the nuclear fusion reaction of the star. Neutrinos play a key role in one of two main types of supernovae that occur when massive stars implode at the end of their lives [10].

By using neutrinos to observe the supernova explosion, we can see a picture of the internal reaction in the sphere of the universal telescope error, which includes the early evolution of the key. Observations of the famous 1987 supernova neutrino burst were made by the Kamioka Neutrino Detector in Japan and the IMB (Irvine-Michigan-Brookhaven) neutrino detector in the United States. The fundamental theory of permanent star collapse has been established by the variation of the energy spectrum of microons in supernew stars with the time of the Earth. Since the above two detectors are only one-kiloton water quality phase Renkov detectors, the statistics are less, and the current detectors reach the order of ten thousand tons (such as the super-class Kamiokande probe), because of this, The high precision, large statistical measurement capability will provide accurate images of the immediate dynamics of the constant star collapse, rebound and explosion for the next supernova event. Even for the Earth on which humanity depends, neutrinos that have come from the crust, mantle, and possibly even the center of the earth through exploration can provide information not seen by conventional means in earth science research. This is because the Geoneutrino measurement can answer (1) the potassium/uranium ratio of the planet; (2) The contribution of radiative heat generation to terrestrial heat flow; (3) Distribution of radioactive heat sources in the mantle; (4) Whether there are radioactive elements in the Earth's core; (5) The shape of the boundary between Earth's core and mantle. Because of this, Earth-sphere neutrinos produced by the radioactive elements in the Earth can be used as a new type of probe to study the Earth, and push the study of ten scientific problems in the 21st century earth science research. In this regard, Japan's KamLAND experiment can be said to be a pioneer. The experiment was the first to detect geoneutrinos, published in the prestigious journal Nature in 2005, by detecting neutrinos from inside the Earth with energies below 2.6 MeV, produced by the cascade decay of uranium and thorium. The research field of mesomorphic geoplasm has been expanded [11].

7. Conclusion

No research in physics has been able to tie together particle physics, nuclear physics, geophysics, astrophysics and cosmology as tightly as neutrino research. However, due to the long-term, complex and difficult nature of neutrino detection, the relevant neutrino experimental research usually meets many technical challenges and makes slow progress. Under normal circumstances, it often takes up to 10 years for a micro experiment to start the pre-research, start the experiment to take numbers, and then publish the final physical results. The ratio of the time required to complete a neutron test to the time required to complete a study of an electromagnetic interaction is of an order of magnitude to the strength of the electromagnetic interaction and the strength of the weak interaction. This can be said to be at odds with the fast food culture that currently exists in many industries.

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