Search for Neutrinoless Double-Beta Decay

Physics Beyond Standard Model

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Abstract

Are neutrinos their own antiparticles ? What is the mass of neutrinos and what are their origin ? Why is there more matter than antimatter ? The search for neutrinoless double-beta decay process could answer all these questions. There are many experiments to explore this decay. This article gives a brief theoretical and experimental overview of this worldwide exploration for neutrinoless double-beta decay.

Keywords — Majorana neutrino, neutrinoless double-beta decay, lepton number violation, matter-antimatter asymmetry

Introduction

Henry Becquerel, Marie Curie, and Ernest Rutherford set the foundation of radioactivity more than a century ago. Since then radioactivity has been extensively studied and applied to many areas of human existence: medicine (cancer treatment), nuclear power plants (electricity generation), archaeology (carbon dating) etc.

The Standard Model of particle physics is a theory that successfully describes the physics of all elementary particles except neutrinos [1]. The "Higgs Boson" particle, discovered in 2012, was the final missing piece of the Standard Model. It was proven the Higgs mechanism is responsible for providing mass to all elementary particles other than neutrinos.

Neutrinos are the massive elementary particles produced by, for example the Big Bang, a core collapse supernova, the Sun, the Earth, radioactive decay, a nuclear reactor, or a particle accelerator etc. Neutrinos do not follow the rules of the Standard Model of particle physics.

Thus, theories beyond Standard Model must be needed to explain various unsolved mysteries of neutrino science. One of the remedies is the search for an extremely rare radioactive process, called neutrinoless double-beta decay. This radioactive decay has not yet been observed. However, several experiments are currently running and more are in planning to search for this rarest of nuclear decays.

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1 Single β-decay & Double β-decay

Enrico Fermi developed the theory of β-decay in 1934 [2]. β-decay is a spontaneous radioactive nuclear reaction that occurs when a neutron transforms into proton, and ejects relativistic electron and antineutrino, as shown in figure 1. The decay is governed by weak interaction.

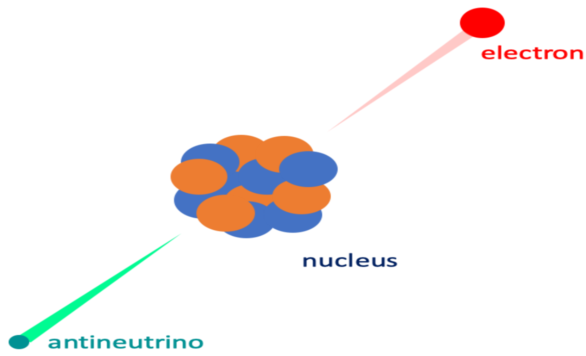

Figure 1: An example of a typical nuclear β-decay, newly produced electron and antineutrino moving opposite to each other to conserve the momentum.

$$\beta\text{-decay} : (A, Z) \rightarrow (A, Z + 1) + \mathrm{e}^- + \overline{\nu_e} \tag{1}$$

Where, A: the mass number = the sum of neutrons and protons, Z: the atomic number = the number of protons in an atomic nucleus. Electron (e^-) and electron antineutrino ($\overline{\nu_e}$) share the nuclear decay energy, Q-value; this gives a continuous distribution of energy as shown in figure 2. Franz Kurie developed the procedure to analyze the shape of the β-spectrum known as Kurie plot.

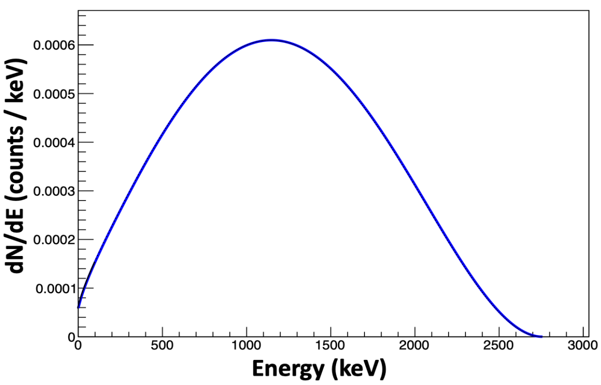

Figure 2: Experimental β-spectrum of Oxygen-20: ${}^{20}_{8}\mathrm{O} \rightarrow {}^{20}_{9}\mathrm{F} + {}_{-1}\beta^0 + \overline{\nu_e}$. Data is taken from [3].

In addition to normal β-decay, there are other rare types of β-radioactivity were predicted. In 1935 Maria Goeppert Mayer predicted a rare beta-decay process, called double beta-decay, in which two β-decays occurs simultaneously. This was first observed in 1950 and later seen in a few nuclei.

Double beta-decay or two neutrino double-beta ($2\nu\beta\beta$) decay is a rare nuclear process in which two neutrons simultaneously converts into two protons and creates two electrons and two electron antineutrinos [2] as shown in figure 3. The nuclear decay Q-value is shared by four particles ($2e^-$ and $2\overline{\nu_e}$) which leads to an energy continuum as shown in figure 4.

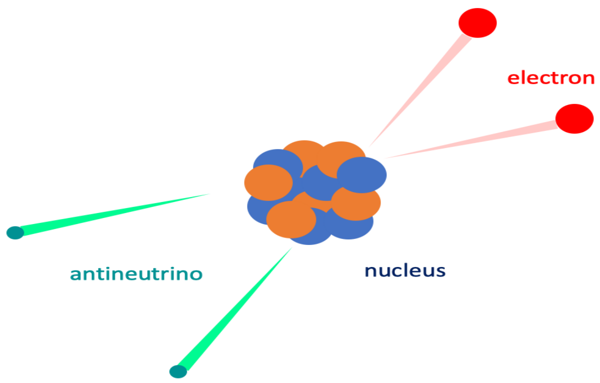

Figure 3: Double beta-decay. Two electrons moves in one direction and two electron antineutrinos move in the direction in order to conserve the momentum. This radioactive decay has been experimentally confirmed.

$$2\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + \mathrm{e}^- + \mathrm{e}^- + \overline{\nu_e} + \overline{\nu_e} \tag{2}$$

GERmanium **D**etector **A**rray (GERDA) experiment in Italy observed double-beta process in Germanium-76 isotope as :

$$^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{34}\mathrm{Se} + \mathrm{e}^- + \mathrm{e}^- + \overline{\nu_e} + \overline{\nu_e} \tag{3}$$

Double-beta decay half-life of Ge-76 measured by GERDA is 2×10^{21} year.

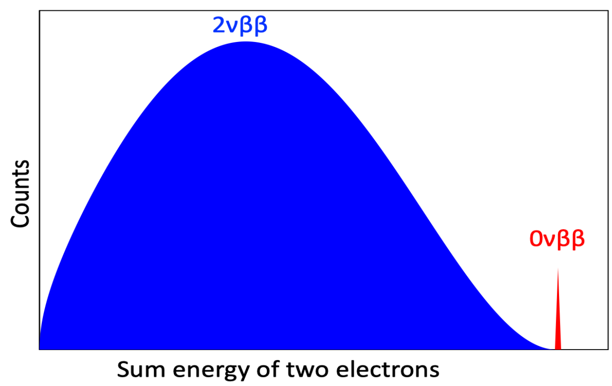

Figure 4: Typical example of the energy spectrum of $2\nu\beta\beta$ decay continuum (observed) and $0\nu\beta\beta$ decay signal a small peak (yet to be observed).

Other experiments including, NEMO-3 in France, CUORE in Italy, EXO in United States, and KamLAND-Zen in Japan also observed double-beta decay in a small number of nuclei.

2 Neutrinoless Double-Beta Decay

Neutrinoless double-beta ($0\nu\beta\beta$) decay is a hypothetical nuclear process theorized by W. H. Furry in 1939 [4]. $0\nu\beta\beta$ decay is a matter-creation process that does not create antimatter. Therefore this decay is not allowed by the Standard Model of particle physics. $0\nu\beta\beta$ decay predicted to occur when two neutrons in a radioactive nucleus simultaneously convert into two protons and thereby create only two electrons as shown in figure 5. No neutrinos are produced in this process.

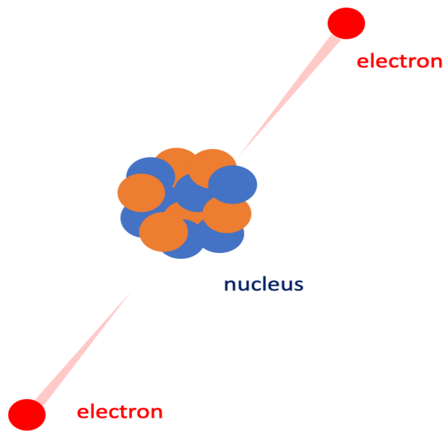

Figure 5: Neutrinoless double-beta decay. Only two electrons are produced and move opposite to each other to conserve the momentum. This radioactive decay is not yet observed.

$$0\nu\beta\beta : (A, Z) \rightarrow (A, Z + 2) + \mathrm{e}^- + \mathrm{e}^- \tag{4}$$

Observation of $2\nu\beta\beta$ decay and the massiveness of a neutrino strongly suggests the possibility of $0\nu\beta\beta$ decay. In this decay, a Q-value is given to the electrons only. This generates a discrete energy spectrum. The signal of $0\nu\beta\beta$ decay is a small peak at decay Q-value. The predicted spectrum of neutrinoless double-beta decay is shown in figure 4.

Observing such a tiny peak is an extremely challenging task. A large number of experiments have been searching $0\nu\beta\beta$ decay but as of the current state of research, no signal has been found. The global search of $0\nu\beta\beta$ decay is still ongoing and a number of large-scale experiments are planned.

The search for $0\nu\beta\beta$ decay should determine the unknown nature of neutrino, the neutrino mass and provide an explanation of the matter-antimatter asymmetry of the Universe which are described below:

Nature of neutrinos

Paul Dirac developed the theory of Dirac fermions in 1928. Ettore Majorana developed the theory of Majorana fermions in 1937. Fermions are said to be of a Dirac type when a fermion and an antifermion are separate fundamental particles. Conversely, fermions are said to be of a Majorana type when fermion and antifermion are identical particles. Electrons are Dirac fermions since electrons and positrons (anti-electrons) are different fundamental particles. But in the case of neutrinos, it is still unclear whether neutrinos and antineutrinos are different particles or identical particles since neutrinos have no electric charge.

The question is thus still open as to whether neutrinos are Dirac or Majorana fermions.

$$\begin{aligned} \nu \neq \overline{\nu} &\implies \text{Dirac neutrinos} \\ \nu = \overline{\nu} &\implies \text{Majorana neutrinos} \end{aligned} \tag{5}$$

The only practical way to prove neutrinos are Majorana particles is neutrinoless double beta decay because $0\nu\beta\beta$ decay can only occur when neutrinos are Majorana fermions. Discovery of $0\nu\beta\beta$ decay would confirm neutrinos are of the Majorana type. As of today, no Majorana fermion has been observed.

Neutrino mass

The mass of all elementary particles in the Standard Model are known precisely except neutrinos. The Higgs mechanism is responsible for providing mass to all elementary particles other than neutrinos. The Standard Model assumes neutrinos are massless. Neutrino oscillation is a mechanism that shows neutrinos have mass, but the mass of the neutrino is not yet known. $0\nu\beta\beta$ decay, if observed, would determine the mass of the neutrino[1] as:

$$\text{Neutrino mass} \propto \frac{1}{\sqrt{\text{Half-life}}} \tag{6}$$

Seesaw mechanism explains the origin of neutrino mass. However, this theory is not yet established by experiments. $0\nu\beta\beta$ decay favors the Seesaw mechanism.

Matter - Antimatter Asymmetry in the Universe

Particle reactions of the Standard Model creates matter and antimatter in equal amounts. A quantum number called the lepton number (L), for electron L=+1 and antineutrino (L=-1). In every Standard Model process, the lepton number must be balanced, $\Delta\mathrm{L} = 0$. In single β-decay electron (matter) and antineutrino (antimatter) are produced in equal amounts as shown in figure 1.

Similarly in double β-decay two electrons (matter) and two antineutrinos (antimatter) are produced in equal amounts as shown in figure 3. However in $0\nu\beta\beta$ decay only two electrons (matter) are produced, without creating antimatter as shown in figure 5.

[1]for full equation see [5].

$$
\begin{aligned}
\text{Beta decay } \Delta L &= 0 \\
\text{Double beta decay } \Delta L &= 0 \\
\text{Neutrinoless double beta decay } \Delta L &= 2
\end{aligned}
\tag{7}
$$

The theory called leptogenesis explains the observed matter-antimatter imbalance. Observation of neutrinoless double-beta decay is a matter-creation process. This supports the leptogenesis theory and explains disappearance of antimatter in the early Universe.

Some other physics opportunities for the neutrinoless double-beta decay search are supernova neutrino, low energy solar neutrino, and baryon number violation.

Neutrino Oscillation

Neutrinos are the second most abundant particles in the Universe. Neutrinos exists in three types called "flavors": electron-neutrino (ν_e), muon-neutrino (ν_μ), and tau-neutrino (ν_τ). Neutrinos are spin $1/2$ fermions that interact only via weak interaction.

Due to the quantum mechanical nature of neutrino, during propagation neutrino mass eigenstates oscillate, which is called neutrino oscillation. Observation of neutrino oscillation confirms that neutrinos have mass. However, the Standard Model assumes only massless neutrinos. Theories beyond the Standard Model must be needed to explain the origin of neutrino mass.

The following big neutrino experiments are planned to study neutrino oscillation in more detail; Deep Underground Neutrino Experiment (DUNE) in United States, Jiangmen Underground Neutrino Observatory (JUNO) in China, Hyper Kamiokande in Japan, and Indian Neutrino Observatory (INO) in India.

3 Experiments

Several experiments are currently running and various large experiments are planned for the search for neutrinoless double-beta decay. The experiments have been located deep underground to prevent background particles reaching the detector [5]. The experiments measure the half-life of the nuclear decay. The signal of the neutrinoless double-beta decay is a small peak at the end point as shown in figure 4. The KamLAND-Zen experiment in Japan set the longest limit on half-life on neutrinoless double-beta decay. The experiments operating as of the date of writing this article are presented in table 1.

Upcoming experiments with improved technology are under research and development. A few of the planned experiments are shown in table 2.

Experiment	Location	Nuclear decay	Technology
LEGEND-200	Italy	^{76}Ge $\rightarrow$ ^{76}Se	Semiconductor
KamLAND-Zen	Japan	^{136}Xe $\rightarrow$ ^{136}Ba	Scintillator
CUORE	Italy	^{130}Te $\rightarrow$ ^{130}Xe	Bolometer
CANDLES-III	Japan	^{48}Ca $\rightarrow$ ^{48}Ti	Crystal Scintillator
AMoRE-I	Korea	^{100}Mo $\rightarrow$ ^{100}Ru	Crystal Scintillator
LUX-ZEPLIN	USA	^{136}Xe $\rightarrow$ ^{136}Ba	Time Projection Chamber
PandaX-4T	China	^{136}Xe $\rightarrow$ ^{136}Ba	Time Projection Chamber
XENONnT	Italy	^{136}Xe $\rightarrow$ ^{136}Ba	Time Projection Chamber

Table 1: Current experiments searching neutrinoless double-beta decay [6].

Experiment	Location	Nuclear decay	Technology
LEGEND-1000	Italy/Canada	^{76}Ge $\rightarrow$ ^{76}Se	Semiconductor
KamLAND-Zen2	Japan	^{136}Xe $\rightarrow$ ^{136}Ba	Scintillator
CUPID	Italy	^{100}Mo $\rightarrow$ ^{100}Ru	Bolometer
nEXO	Canada	^{136}Xe $\rightarrow$ ^{136}Ba	Time Projection Chamber
SNO+	Canada	^{130}Te $\rightarrow$ ^{130}Xe	Scintillator

Table 2: Upcoming world biggest experiments for neutrinoless double-beta decay search [6].

4 Conclusion

Neutrinoless double-beta decay search is a very active area of research today. The search would fundamentally revise our understanding of particle physics. The nature and mass of the neutrino is unknown. No signal of neutrinoless double-beta decay has been observed to date. Current experiments are running and future experiments are planned.

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Data Availability Statement

No data is generated in this article.

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