Journal of Scientific Research
Banaras Hindu University, Varanasi

Vol. 63, 2019 : 265-272
ISSN : 0447-9483

EXPERIMENTS AND CHALLENGES IN NEUTRINOLESS DOUBLE BETA DECAY OBSERVATION

D. Singh[1], A. Pandey[1], A. Kumar[1], A. Brahmaxatriya[1, 2], M. K. Singh[1, 3], P. Kumar[1], D. Grover[1], N. Marimuthu[1], M. K. Singh[1#], V. Singh[1]
1. Department of Physics, Institute of Science, Banaras Hindu University, Varanasi – 221005, India
2. Department of Physics, Central University of Haryana, Haryana – 123031, India
3. Institute of Physics, Academia Sinica, Taipei – 11529, Taiwan
Present Address: Department of Physics, Institute of Applied Sciences & Humanities, G. L. A. University, Mathura - 281406, India
Email ID: venkaz@yahoo.com

Abstract:

The observation of neutrinoless double beta decay would show that lepton number is violated ($\Delta L = 2$) and result reveals that neutrinos are the Majorana particles and provide the information about the absolute neutrino mass. A discovery potential experiment covering the neutrino inverted ordering region, with neutrino masses of 15−50 meV, will require ton-scale detectors with excellent energy resolution and extremely low backgrounds, at the level of ~ 0.1 count / (FWHM-t-yr) in the region of interest.

Keywords: Neutrinoless double beta decay, Neutrino absolute mass, Germanium detectors.

1. Introduction and Physics Motivation

Neutrinos are the fundamental fermions – particles that follow the Fermi-Dirac statistics, without electric charge within the Standard Model (SM) of particle physics, observed in the phenomenon of beta decay, and double-beta decay in the case of even (p) - even (n) nuclei, that were firstly observed in $^{124}Sn_{50}$ isotope. In case of double beta decay, neutrino and antineutrino are not identical, so neutrino is a Dirac particle in standard model of particle physics. In standard model of particle physics, lepton number is nuclear quantum number associated with leptons. In any given process, this number is expected to be conserved. However, there is no experimental evidence that it should always be conserved. There might be a process in which the lepton number violation is possible.

Now, if neutrino is an antiparticle of itself, which will show its Majorana nature, then there will be no emission of neutrinos in double beta decay as they will annihilate each other, which is called Neutrinoless Double Beta Decay (NDBD). In other words, the simultaneous beta decay of two neutrons in a nucleus without the emission of neutrinos is called neutrinoless double beta decay as shown in **figure 1.** Figure 1 shows that two neutrons are simultaneously changing into two protons through exchange of $W^{\square}$ bosons, which leads to annihilation of two neutrinos, and it is a lepton number violating process ($\Delta L = 2$). This process is not allowed in the Standard Model of particle physics ($\Delta L = 0$) **[1]**.

Here only two electrons are emitted along with the daughter nuclei. The transition in which an even (p) – even (n) nucleus (A, Z) decays into its (A, Z+2) isobar can be observed for isotopes whose single beta decay is forbidden **[2-4]**.

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} \tag{1}$$

In the Standard Model (SM) of particle physics, this process is allowed with the simultaneous emission of two electrons and two anti-neutrinos, and it has been observed experimentally in more than ten isotopes with half-lives of the order of $10^{18} - 10^{21}$ year. There are various hypothesized mechanisms for neutrinoless double beta decay. In the standard interpretation, neutrinoless double beta decay is mediated by the virtual exchange of massive Majorana neutrinos **[5].** On the other hand, there exists a number of other proposed lepton number violating mechanisms that can contribute to the neutrinoless double beta decay rate.

The present experimental physics motivation to study the neutrinoless double beta decay is that it will provide the absolute mass of the neutrinos as well as shed light on the neutrino oscillations parameters along with the long-standing puzzle of matter-antimatter problem.

2. Signature of neutrinoless double beta decay

The experimental signature for $0\nu\beta\beta$ decay is a line having the energy equal to the sum of the kinetic energies of the two electrons, and it is equal to the Q-value of the double beta decay isotope **[6].** The line peak of the signal will appear at the end-point energy of the background spectra i.e. spectra belongs to the single and double beta decay as shown in **figure 2 [7]**.

3. Experiments

In the recent years, new operational neutrinoless double beta decay experiments have reported the half-life lower limits of occurrence of such event. In July 2013, the Germanium Detector Array (GERDA) collaboration published its first result on the neutrinoless double beta decay using ^{76}Ge isotope. However, no signal has been observed and a lower limit is derived for the half-life of neutrinoless double beta decay of ^{76}Ge, $T^{0\nu}_{1/2} > 2.1\times10^{25}$ yr (90% C.L.) **[8].** GERDA experiment is using p-type point contact high purity (PPC HPGe detector) Ge detector. Phase 1 and Phase 2 have been conducted by the GERDA and set a half-life sensitivity of 10^{26} yr (90% C.L.) within 3 years of data collection **[9].**

MAJORANA DEMONSTRATOR are also using PPC HPGe detector and they have built two modules of HPGe arrays from ultra-low background components. They achieved very high energy resolution of 2.5 keV FWHM at $Q_{\beta\beta}$. The MAJORANA DEMONSTRATOR experiment also achieved a very low background with 9.95 kg-yr of enriched Ge exposure with no evidence of signal. Therefore, the experiment derived a lower limit on the half-life of 1.9×10^{25} yr at 90% C.L. (Confidence Level). This result constrains the effective Majorana neutrino mass to below 240–520 meV, depending on the matrix elements used. The MAJORANA DEMONSTRATOR experiment is planning to reach a background level of 2.5 counts / (FWHM-t-yr) and projected to approach a sensitivity of $T^{0\nu}_{1/2} > 10^{26}$ year **[10]**.

EXO (Enriched Xenon Observatory) Collaboration is searching for Neutrinoless Double Beta Decay in ^{136}Xe with the EXO-200 detector i.e. Time-Projection-Chamber (TPC) and found no evidence of this event so they set a limit on half-life sensitivity $T^{0\nu}_{1/2} > 1.6 \times 10^{25}$ year at 90% C.L. **[11, 12]**.

KamLAND-Zen collaboration is also searching for Neutrinoless Double Beta Decay in ^{136}Xe by using liquid scintillator. It has set the limit on half-life sensitivity $T_{1/2} > 2.6 \times 10^{25}$ at 90% C.L. **[13]**.

At the same time, the experiments KamLAND-Zen and EXO both reported half-life lower limits on the neutrinoless double beta decay of ^{136}Xe of 1.9×10^{25} year at 90% C.L **[14]**, and 1.1×10^{25} y at 90% C.L. **[6]**, respectively. The combined analysis of KamLAND-Zen and EXO results yields a half-life lower limit $T^{0\nu}_{1/2} > 3.4\times10^{25}$ year (90% C.L.) **[8]**.

No experimental evidence for neutrinoless double beta decay has been observed so far. For the completeness, we are tabulating the ongoing experiments along with the possible isotopes of neutrinoless double beta decay and their half-life, abundance and Q-value in **Table 1 [15]**.

4. Other isotopes and approaches

^{48}Ca has the highest Q value of neutrinoless double beta decaying isotopes, which makes it experimentally very attractive as a candidate isotope **[16]**. However, its natural abundance is very low (0.187%), thus new enrichment techniques are needed in order to perform a successful experiment. The CANDLES experiment is using scintillating CaF_2 crystals. These crystals are submerged in liquid scintillator and only 0.3 kg of ^{48}Ca has been deployed, which limits its sensitivity **[5]**. The abundance of ^{124}Sn is 5.8% and Q value is quite high (2.288 KeV) **[17]**, which makes it a good candidate for the experiment. The TIN-TIN detector is a Sn cryogenic bolometer for the study of Neutrinoless Double Beta Decay in ^{124}Sn and is currently in the R&D stage at TIFR, Mumbai, which has been planned to be installed in the India-based Neutrino Observatory (INO) **[17]**.

5. Main considerations for the next generation experiments

To achieve desired sensitivity of the neutrinoless double beta decay experiments, future experiments should make following considerations.

The enriched isotope should be of the ton scale with very high enrichment. The background level should be zero i.e. zero background experiment. These experiments will be very expensive at the scale that even few countries jointly will not be able to run the whole experiment. The isotope enrichment technology should be simple and popular. Finally, selection of the best technology and isotope(s) will be a big challenge that needs to consider Nuclear Matrix Element (NME) calculations, Q - values of isotopes, backgrounds in the Region of Interest (ROI), energy resolution, enrichment and cost.

6. Background Consideration

As the Neutrinoless Double Beta Decay signal is very rare, so in order to observe this signal we have to reduce the background as much as possible because background can mimic the desired signal. Thus, the reduction in background is very important **[5]**.

Before the reduction in backgrounds we have to know why these backgrounds are produced. There are two types of background sources in these experiments:

1. *Ambient Backgrounds:* These backgrounds are produced from external γ-rays, which are produced by the radioactivity present in the experimental hardware and isotopes in the vicinity of the target detector.

In order to remove these backgrounds several methods can be used. For example, to remove the cosmic ray background, we use pure water. In some experiments liquid scintillators are also used as active, as well as passive shield. Oxygen-Free-High-Conductivity (OFHC) copper shielding is also used in some cases.

2. *Intrinsic background:* These backgrounds are produced due to $2\nu\beta\beta$ decay in the region of interest of $0\nu\beta\beta$ search.

These backgrounds cannot be reduced. So, we have to differentiate them either on-line during data taking or off-line during data analysis. It can also be avoided altogether by selecting an isotope with high Q-value such as ^{48}Ca and ^{150}Nd.

7. Challenges in observation

The realization of an experiment with discovery potential down to the smallest neutrino Majorana mass values is an incredible challenge in which detector technology plays a key role. So, there must be a focus on detector technologies, how to design a detector to detect such a rare event. Some requirements are radiopure background, choice and amount of material, shielding against the external radiation, high sensitivity (exposure, low background rate, isotopic abundance, and signal detection efficiency), passive detector construction. To increase the chance of observing these rare events a large amount of detector mass is advisable. So, ton scale experiments are planned for future observations.

8. Next generation requirement: The LEGEND

These experiments have achieved the best energy resolution and lowest possible backgrounds. However, the superior resolution and the lowest backgrounds leading to next generation of the ton scale neutrinoless double beta decay experiments, the

LEGEND (Large Enriched Germanium Experiment) **[18-19]** collaboration aims to increase the sensitivity for Ge - detector in two phases:

a) In the 1st phase LEGEND-200 will set a lower limit on the life time of the order of 10^{27} year **[7].**

b) In the 2nd phase LEGEND -1000 will set a lower limit on the life time of the order of 10^{28} year **[7].**

9. Summary and Outlook

Experiments looking for $0\nu\beta\beta$ decay of ^{76}Ge operate germanium diodes normally made from enriched material, i.e. the number of ^{76}Ge nuclei isotopic fraction is enlarged from 7.8% to 86% or higher in the detector crystals **[6]**.

The scientists of the GERDA and MAJORANA DEMONSTRATOR experiments along with other scientists around the globe have joined hands and formed a new collaboration called LEGEND. The Banaras Hindu University is also a participating institute from India. The recently formed LEGEND collaboration will build on these successes and purpose to probe the life time of order of 10^{28} years, neutrino mass hierarchy problem and will set the issue of neutrino's nature **[7]**. The importance of these experiments for violation of lepton number and of the Majorana nature of neutrinos is obvious. It requires beyond Standard Model Physics on one side, and may open a new era in space-time structure **[20]**.

Acknowledgement

V. Singh is thankful to the Department of Science and Technology (DST), and SPARC, Ministry of Human Resource Development (MHRD) New Delhi for constant financial support. M. K. Singh[1, 3] is thankful to the University Grant Commission (UGC), Govt. of India, and M. K. Singh[1] for the funding through UGC D. S. Kothari Post-Doctoral Fellowship (DSKPDF) scheme.

References:

[1] B. Schwingenheuer, *Annalen der Physik* **525** 269(2013), and references therein.

[2] E. Majorana, *Nuovo Cimento* **14** 171 (1937), and references therein.

[3] M. Goeppert-Mayer, *Phys. Rev.* **48** 512 (1935), and references therein.

[4] G. Racah, *Nuovo Cimento* **14** 322 (1937), and references therein.

[5] Reyo Henning, *Reviews in Physics* **1** 29 (2016), and references therein.

[6] K. H. Ackermann et al., *Eur. Phys. J. C* **73** 2330 (2013), and references therein.

[7] N. Abgrall, 1, The Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay.

[8] M. Agostini et al., *Phys. Rev. Lett.* **111** 122503 (2013), and references therein.

[9] M. Balata, *The European Physical Journal-c,* **78** 30(2018) and references therein

[10] C. E. Aalseth et al., *Phys. Rev. Lett.* **120** 7(2018) and references therein.

[11] M. Auger *et al., Phys. Rev. Lett.* **109**, 032505(2012) and references therein

[12] J. Albert et al., *Nature* **510** 229 (2014), and references therein.

[13] J. Shirai IOP Conf. Series: Journal of Physics: Conf. Series 888 (2017) 012031.

[14] A. Gando et al., *Phys. Rev. C* **85** 045504 (2012), and references therein.

[15] V. Alenkov *et al.,* arXiv: 1512.05957 [physics.ins-det], and references therein.

[16] I. Ogawa et al., *Nucl. Phys. A* **730** 215 (2004), and references therein.

[17] Vandana Nanal, *EPJ Web of Conferences*, **66** (2014), and references therein

[18] N. Abgrall et al., *AIP Conf. Proc*. **1894** 020027 (2017), and references therein.

[19] B. Schwingenheuer, Neutrinoless double beta decay searches with ^{76}Ge EP Seminar Jan. (2017).

[20] D. V. Ahluwalia, in Proc. of Beyond the Desert 2002, BEYOND02, Oulu, Finland, June 2002, IOP 2003, ed. H. V. Klapdor-Kleingrothaus, 143-160; D. V. Ahluwalia, M. Kirchbach, *Phys. Lett.* B 529 (2002) 124.

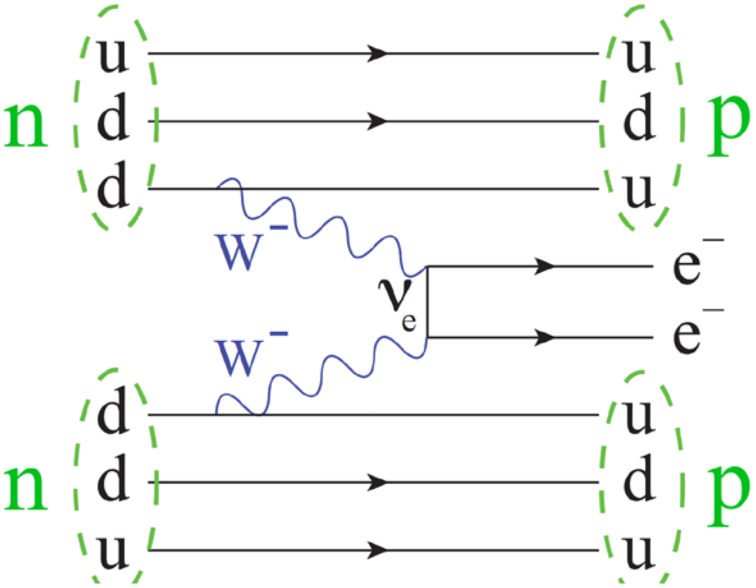

Figure 1: Feynman diagram of neutrinoless double beta decay.

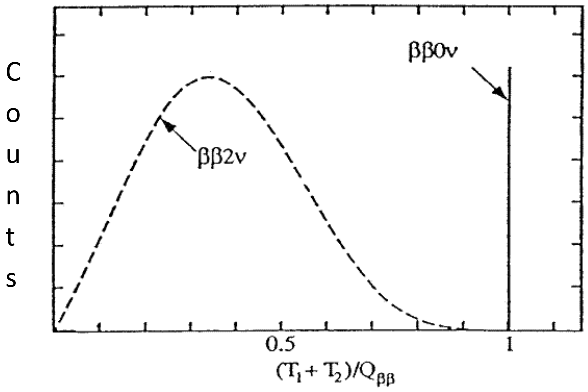

Figure 2: Expected signature of neutrinoless double beta decay.

Isotope	**Abundance (%)**	**Q-value (keV)**	**Experiment**	**Half-Life (Years)**
^{48}Ca	0.187	4267	Elegant VI CaF_2(Eu) scintillator	> 5.8×10^{22}
^{150}Nd	5.638	3371.38	NEMO-3	> 1.8×10^{22}
^{124}Sn	5.8	2288	TIN.TIN	To be discovered
^{116}Cd	7.49	2813	COBRA	Expected to be 1.0×10^{26} – 3.5×10^{26}
^{76}Ge	7.73	2039.06	GERDA	> 2.1×10^{25}
			IGEX	> 1.57×10^{25}
			LEGEND	> 5.3×10^{25} – 4.85×10^{26}
			Majorana Demonstrator	> 1.0×10^{26}
^{136}Xe	8.8573	2457.51	KamLAND-Zen	> 2.6×10^{25}
			EXO	> 1.1×10^{25}
			NEXT	> 6.0×10^{25}
			nEXO	> 1.0×10^{28}
^{82}Se	8.73	2996.4	NEMO-3	> 3.6×10^{23}
^{100}Mo	9.82	3034.37	NEMO-3	> 1.1×10^{24}
^{130}Te	34.08	2527.51	CUORE	> 4.0×10^{24}

Table 1: Known double beta decay isotopes.