Neutrino: Dirac or Majorana particle?

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Abstract: Dirac particles have distinct antiparticles with opposite charges, whereas Majorana particles are their own neutral antiparticles. Are neutrinos Majorana or Dirac particles? In this paper, we briefly discuss this question and present the theoretical analyses and experimental explorations conducted to solve this question. The Majorana condition is simpler than the Dirac condition and could successfully explain the violation of lepton numbers and the reason why neutrino masses are so small.

Keywords: Neutrino, Majorana Particle, Double Beta Decay

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Contents

1 Introduction

In the Standard Model, there exist three generations of neutrinos: electron neutrinos (ν_e), muon neutrinos (ν_μ), and tau neutrinos (ν_τ). Neutrinos are unique among fermions in that they participate only in weak interactions. Neutrinos are also particles with many interesting properties. Currently, we still have many basic unsolved problems, including the mass ordering, the value of the CP phase δ, the existence of a 4th flavor of neutrino, and whether neutrinos are Majorana or Dirac particles.

In this paper, we will discuss the possibilities of whether neutrinos are Majorana or Dirac particles. In particle physics, Dirac particles have distinct antiparticles with opposite charges, while Majorana particles are their own antiparticles, being neutral. There is a general belief that neutrinos are Majorana particles [1]. The famous two-component Weyl theory of a massless neutrino was proposed in 1957 by Landau [2], Lee and Yang [3], and Salam [4], and was confirmed in the classical Goldhaber et al. experiment on the measurement of neutrino helicity [5].While we now know that neutrinos have very small masses, the simplest possibility to illustrate the origin of neutrino masses is to assume neutrinos are Majorana particles. Dirac particles require both left-handed and right-handed components, implying the need for right-handed neutrinos if neutrinos are Dirac particles, which complicates the Standard Model. Conversely, Majorana particles can be described using only left-handed components, simplifying the model. The distinction between these particles affects lepton number conservation and the nature of neutrino mass, with Majorana particles allowing lepton number violation, which is significant in theories explaining the matter-antimatter asymmetry in the universe.And the most sensitive experiments, which allow us to probe the Majorana nature, are experiments on the search for neutrinoless double beta decay.

This paper is organized as follows: in Section II we will introduce the basic knowledge of Majorana and Dirac fermions, and show the discussions of whether neutrinos are Majorana or Dirac fermions. Section III discusses experimental principles and techniques used to explore the nature of neutrinos and presents some recent experimental results. And we will give a summary in Section IV.

2 Majorana and Dirac Fermions

2.1 Mathematical Descriptions

First, let's introduce some basic knowledge [6].

The Lagrangian of free spin 1/2 particle reads

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \tag{2.1}$$

and its solution is Dirac equation

$$(i\gamma^\mu \partial_\mu - m)\psi = 0.$$

Here, ψ is a four-component Dirac spinor.

In the Standard Model, mass is included through the Dirac mass term

$$m\bar{\psi}\psi.$$

In Weyl representation, we could decompose the Dirac spinor into it's left- and right-chiral component

$$\psi = \begin{pmatrix} \psi_R \\ \psi_L \end{pmatrix},$$

where ψ_R and ψ_L are two-component Weyl spinors.

So the mass term is

$$m\bar{\psi}\psi = m(\bar{\psi}_L + \bar{\psi}_R)(\psi_L + \psi_R) = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L), \tag{2.2}$$

and the Dirac mass can be viewed as being the coupling constant between the two chiral components.

By spliting the Dirac Equations (2.1), we could get

$$\gamma^\mu \partial_\mu \psi_L = m\psi_R,\ i\gamma^\mu \partial_\mu \psi_R = m\psi_L. \tag{2.3}$$

If the particle is massless, we could get the decoupled Weyl equations:

$$i\gamma^\mu \partial_\mu \psi_L = 0, i\gamma^\mu \partial_\mu \psi_R = 0.$$

We could define a charge conjugation matrix C, satisfying

$$C\gamma^{\mu T}C^{-1} = -\gamma^{\mu}; C^T = -C.$$

Then, by taking conjugate of the second equation of (2.3) , multiplying on the right by γ_0 and left by C, we get

$$i\gamma^{\mu}\partial_{\mu}C\bar{\psi}_R^T = mC\bar{\psi}_L^T. \tag{2.4}$$

If we have the condition

$$\psi_R = C\bar{\psi}_L^T, \tag{2.5}$$

then we could see (2.3) has the same structure with the first equation in (2.3). So we can rewrite the Dirac equation in terms of the left-handed field. The Majorana field becomes

$$\psi = \psi_L + \psi_L^C = (\psi_L + \psi_L^C)^C = \psi^C. \tag{2.6}$$

The charge conjugate matrix in (2.5) actually means to turn a particle state into an antiparticle state, by flipping the sign of all the relevant quantum numbers. So the Majorana condition (2.6) means a neutral particle that is identical to its antiparticle.

2.2 Mass Origin of Neutrinos

In the Standard Model, neutrinos are considered massless Dirac particles, while other particles gain mass through the Higgs mechanism.

Briefly speaking, the Higgs mechanism is the only method for fundamental particles to obtain mass in the Standard Model. It couples the left-handed and right-handed components of a particle's wave function (see (2.2))via Yukawa coupling with the Higgs field. However, there are only left-handed neutrinos in SM, meaning there are no right-handed neutrinos to couple with. Consequently, this coupling cannot occur for neutrinos, preventing them from gaining mass through the Higgs mechanism. So neutrinos were initially assumed to be massless.

In 2015, Takaaki Kajita from the University of Tokyo and Arthur B. McDonald from Queen's University in Canada were jointly awarded the Nobel Prize in Physics for their leadership in the discovery of neutrino oscillations, which demonstrated that neutrinos have mass. This significant discovery also indicated that the Standard Model of particle physics is incomplete. Thus, we must go beyond the Standard Model of particle physics.

2.2.1 Assuming Neutrinos are Dirac Fermions

One choice is to assume neutrinos are Dirac fermions and consider the standard Higgs mechanism for the generation of fermion masses. To do so, we need to introduce right-handed neutrino fields, imitate the Higgs mechanism of the mass generation for other fermions, and assume that into the total Lagrangian includes the $SU_L(2) \times U_Y(1)$ invariant Yukawa interation [1]

$$\mathcal{L}^{\nu}{}_Y(x) = -\sqrt{2}\sum_{l_1,l_2}\bar{\psi}_{l_1 L}(x)Y^{\nu}{}_{l_1 l_2}\nu'_{l_2 R}(x)\tilde{\phi}(x) + \text{h.c.},$$

where $\tilde{\phi} = i\tau_2\phi^*$ is the conjugated Higgs doublet, Y is the Yukawa coupling constant matrix, h.c. represents the hermitian conjugate, and right-handed fields ν'_{lR} are singlets. After the spontaneous breaking of the Standard Model gauge symmetry, neutrinos acquire Dirac masses.

Although Dirac neutrino masses can be introduced in the Standard Model, this possibility looks extremely implausible because of the tiny neutrino masses. The neutrino masses are many orders of magnitude smaller then masses of leptons and quarks, see figure 1 from [7].

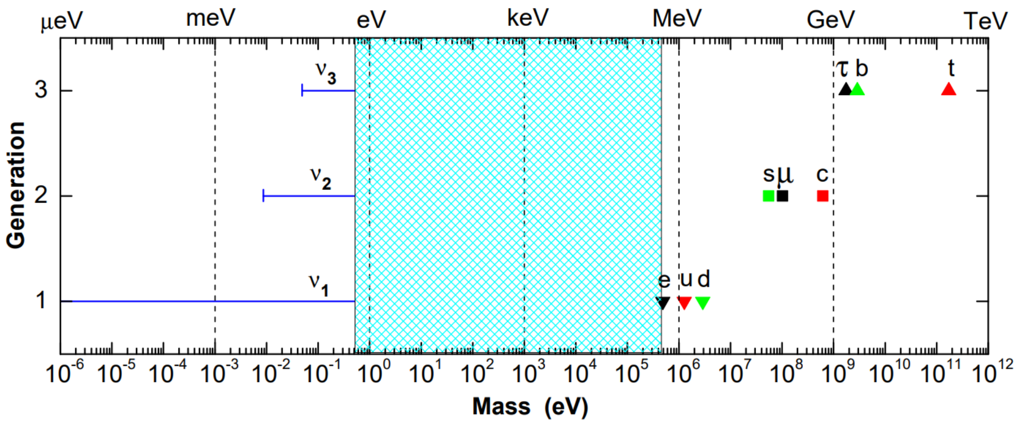

Figure 1: A schematic illustration of flavor "hierarchy" and "desert" problems in the SM fermion mass spectrum at the energy scale MZ.

To produce neutrino masses below 1 eV, the Yukawa coupling between neutrinos and the Higgs field must be less than 10^{-12}. On the other hand, the top quark, which is also a Dirac particle, has a mass of 172 GeV, corresponding to a Yukawa coupling of approximately 1, which is 12 orders of magnitude larger than the neutrino's coupling. Thus understanding such a small neutrino Yukawa coupling is a problem that the Dirac neutrino mass model must address.

Note also that in this assumption, the total lepton number L is conserved under a global transformation, and $\nu_i(x)$ is the Dirac field of neutrinos ($L = 1$) and antineutrinos ($L = -1$). In practice, if a fermion and its antiparticle can be distinguished by different quantum numbers (such as lepton number), then such particles are referred to as Dirac particles. If there is no conserved quantum number that distinguishes a neutrino from an antineutrino, then it is a Majorana particle. However, while lepton number and baryon number reflect the symmetry of the Standard Model Lagrangian at the classical level, quantum anomaly effects actually lead to the violation of baryon and lepton numbers [8].

In conclusion, Dirac neutrinos face the severe hierarchy problem of Yukawa couplings and the self-consistency issue arising from the mandatory requirement of lepton number conservation.

2.2.2 Assuming Neutrinos are Majorana Fermions

As discussed above, the assumption that neutrinos gain mass through the Higgs mechanism is unatural and suffered from some problems. In the 1960s, Gribov and Pontecorvo showed that it is possible to introduce neutrino masses using only left-handed neutrino fields and no right-handed sterile fields. In that case, neutrinos are Majorana and the lepton number L is not conserved [9].

We could construct the right handed conjugated field as [10]

$$\nu^c{}_{lL} = C\bar{\nu}_{lL}^T,$$

where C is the charge conjugated matrix which we discussed in section 2.1. Thus we could build the Majorana mass term

$$\mathcal{L}^M = -\frac{1}{2}\sum_{l,l'} \bar{\nu}_{l'L} M^M{}_{l'l} \nu^c{}_{lL} + h.c.$$

There are no right-handed neutrino fields in the Lagrangian, so the number of neutrino degrees of freedom is minimal.

Weinberg then proposed a beyond-the-Standard-Model mechanism of neutrino mass generation, which leads to the Majorana mass term and allows us to explain the smallness of neutrino masses [11]. Then a wide class of neutrino mass models was proposed, such as three types of see-saw mechanism. The general conclusion is small neutrino masses are generated by a L-violating, beyond SM interactions.

Compared to the four distinct types of Dirac particles: left- and right-handed particles, and left- and right-handed antiparticles, the Majorana condition uses just a single left-handed field to describe massive neutrinos, so we only have left-handed neutrinos or right-handed antineutrinos.

2.3 Lepton Number violating

The main difference between Dirac and Majorana condition is whether lepton number is conserved. Dirac neutrinos have lepton number $L = +1$, and antineutrinos have lepton number $L = -1$. Since Majorana neutrinos are the same as their antiparticle, it is impossible to assign such an object a conserved lepton number. Indeed, interactions involving Majorana neutrinos generally violate lepton number conservation by $\Delta L = \pm 2$ [6].

If neutrinos are Majorana, we would expect to find evidence of matter-antimatter non-conservation. This is because, under the Majorana condition, lepton number non-conservation gives rise to another intriguing idea called leptogenesis, which is intrinsically linked to the question of matter-antimatter asymmetry. If the probability of one of the heavy neutrinos from the see-saw mechanism decaying into a left-handed neutrino is slightly different from the probability of decaying into a right-handed antineutrino, then there would be a greater probability of creating quarks than antiquarks, leading the universe to be matter-dominated. This would explain why there is more matter than antimatter in the universe.

2.4 Summary of Section II

In summary, in this part, we introduced Dirac fermions and Majorana fermions, whose antiparticles are themselves. Then we illustrate why, in the Standard Model, neutrinos are massless. As we discovered that neutrinos indeed have masses, we need a mass generation mechanism beyond the Standard Model. The assumption that neutrinos are Dirac fermions faces these three problems:

- Requiring additional right-handed neutrino fields, which are contrary to the economy and simplicity of the Standard Model.
- The Yukawa coupling of the heaviest neutrino is more than ten orders of magnitude smaller than the Yukawa couplings of other particles in the third family. So it's unusual to insist that neutrinos have the same mass generation mechanism as other fermions.
- Quantum anomaly effects lead to the violation of baryon and lepton numbers, so Dirac neutrinos face the self-consistency issue arising from the mandatory requirement of lepton number conservation.

So we then consider the possibility of constructing the neutrino mass term using only left-handed neutrinos, and in that case, the neutrino could only be Majorana. This approach is more economical and simpler compared to Dirac conditions, so most people believe neutrinos are Majorana. This may also explain why there is more matter than antimatter in the universe.

3 Neutrinoless Double Beta Decay

To discover the Majorana nature of neutrinos, the neutrinoless double β-decay of some even-even nuclei ($0\nu\beta\beta$-decay) is under enthusiastic investigation. In this part we will briefly introduce its experimental principle and techniques, then show some recent experiment results.

3.1 Experimental Principle

Double-beta decay is a nuclear physics process in which the nuclear charge is changed by two units [12]:

$$(Z, A) \to (Z+2, A) + 2e^- + 2\overline{\nu}_e.$$

Majorana proposed another possible progress:

$$(Z, A) \to (Z+2, A) + 2e^-,$$

which clearly violates lepton number conservation. The first neutron decays, emitting a chirally right-handed $\overline{\nu}_e$. If and only if neutrinos are Majorana (thus it equals to its antiparticle), the right-handed neutrino could be absorbed by a second neutron as chirally left-handed ν_e, see figure 2 from [13].

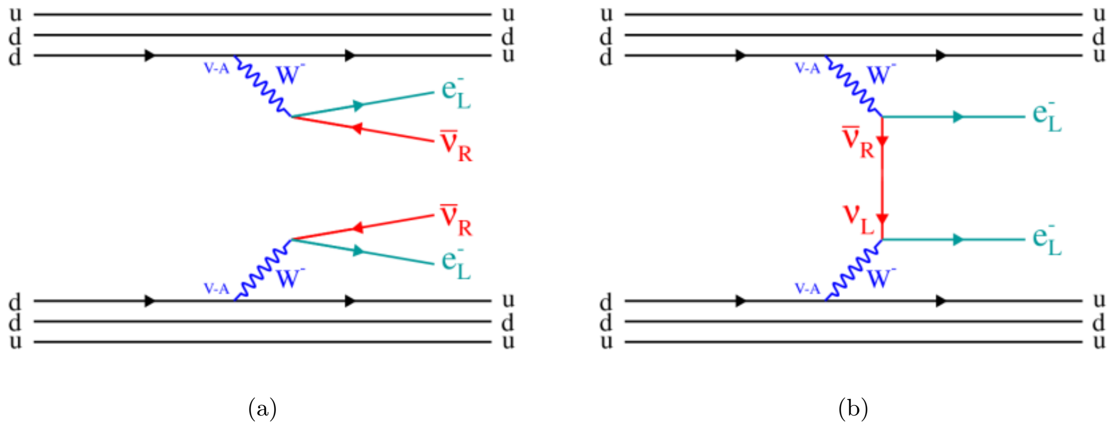

Figure 2: Right: representation of the two neutrino double beta decay. Left: an example of the neutrinoless double beta decay via a virtual exchange of a light Majorana neutrino.

This method could also be used in obtaining an estimate of the absolute neutrino mass. The half-life of neutrinoless double beta decay could be expressed as

$$T^{-1}{}_{0\nu} = G^{0\nu}|M^{0\nu}|^2|m_{ee}|^2,$$

where $G^{0\nu}$ is a known phase-space factor which determines how many electrons have the right energies and momenta to participate in this process, $M^{0\nu}$ is a nuclear matrix element which describes the actual decays in the nuclear environment, and m_{ee} is a linear combination of the neutrino mass states

$$|m_{ee}| = |\sum_i U^2{}_{ei} m_i|$$

with U_{ei} being the relevant elements of the PMNS mixing matrix (see the writeup on neutrino oscillations), and m_i is the mass of the mass eigenstates.

3.2 Experiment techniques

To realize a $0\nu\beta\beta$-decay experiment, a technology has to be chosen taking into account the candidate isotopes. Table 1 from [14] summarizes properties for the most important isotopes considered for $0\nu\beta\beta$ searches.

The signal for neutrinoless double beta decay is a spike in the spectrum of the sum of the emittedelectrons at a specific energy (the Q-value of the transition). Conversely, for 2ν double beta decay,this spectrum will be continuous from 0 up to the Q-value (see figure 3 from [13]).

Neutrinoless double beta decay detectors are of two types: counting experiments, which measure the sum energy of the electrons with high background, and tracking experiments, which detect electrons independently to minimize background but have limited source mass.

There are two counting experiments: semiconductor experiments and cryogenic experiments. Semiconductor experiments detect double beta decay using semiconductors, where

Isotope	**Natural abundance (%)**	$\mathbf{Q_{\beta\beta}}$ **(MeV)**
^{48}Ca	0.187	4.263
^{76}Ge	7.8	2.039
^{82}Se	8.7	2.998
^{96}Zr	2.8	3.348
^{100}Mo	9.8	3.035
^{116}Cd	7.5	2.813
^{130}Te	34.08	2.527
^{136}Xe	8.9	2.459
^{150}Nd	5.6	3.371

Table 1: Characteristics of commonly used $\beta\beta$-decay isotopes.

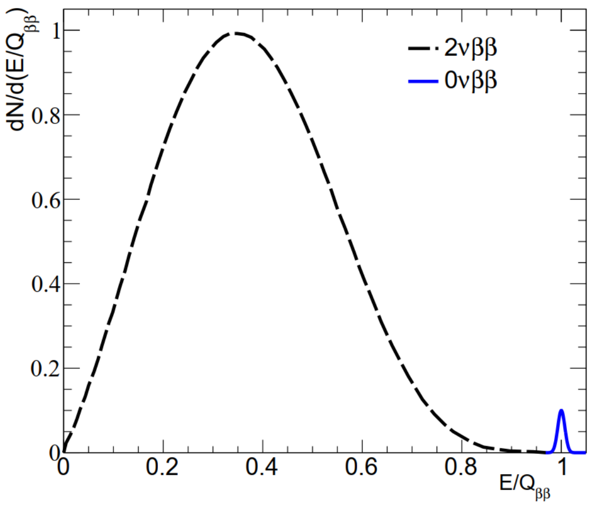

Figure 3: Typical spectrum of a double beta decay (dashed black) and of the neutrinoless double beta decay (blue).

emitted electrons ionize the material, producing measurable voltage pulses. These detectors offer high energy resolution but typically measure only the total electron energy, with background from other radioactive processes. Cryogenic experiments measure electron emissions by detecting slight temperature increases in materials kept at very low temperatures, offering another method to study double beta decay.

3.3 Recent Experiment Results

In this section, we will present the recent experimental results on the search for neutrinoless double beta decay.

In the expression

$$({T^{0\nu}}_{1/2})^{-1} = G^{0\nu} {g^4}_A |M^{0\nu}|^2 \frac{< m_{\beta\beta} >^2}{{m^2}_e}$$

the phase space $G_{0\nu}$ has been accurately calculated, see figure 4 from [15]; the nuclear matrix element is of significant theory uncertainty, see figure 5 from [16].

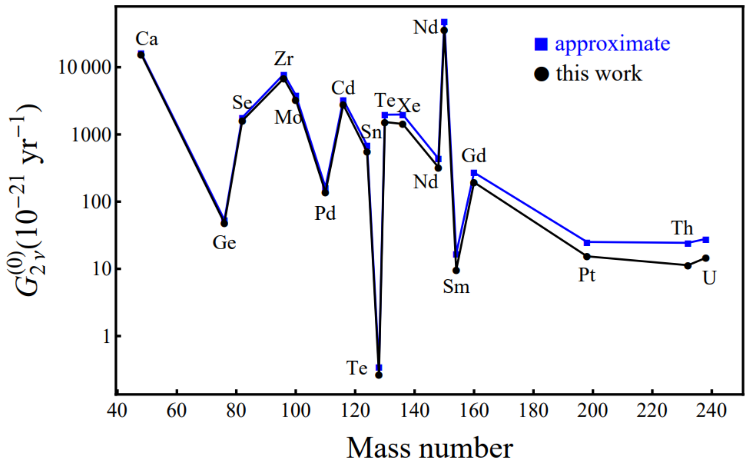

Figure 4: Phase space factors $G^{(0)}_{2\nu}$ in units $(10^{-21}y^{-1})$. The label "approximate" refers to the results obtained by the use of approximate electron wave functions. The figure is in semilogarithmic scale.

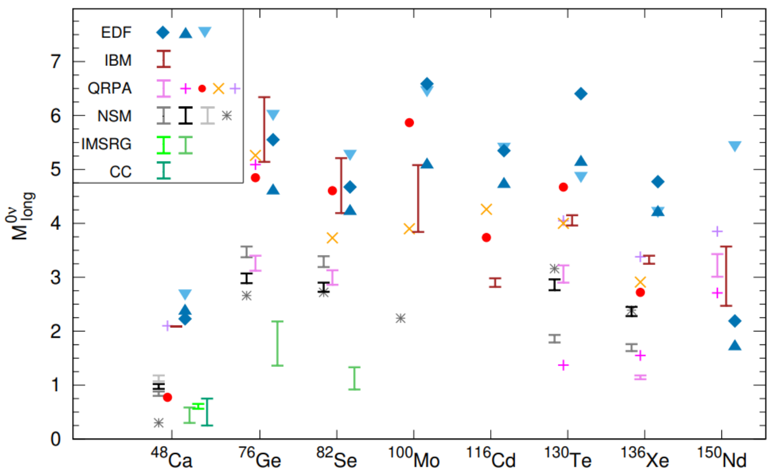

Figure 5: Nuclear matrix elements $M^{0\nu}$ for light-neutrino exchange from different many-body methods.

Examples of a few of the projects focused on neutrinoless double beta decay are the Majorana Demonstrator and EXO in the United States and CUORE and GERDA in Italy.

In 2023, the Majorana Collaboration, a consortium of researchers from universities worldwide, has been trying to observe neutrinoless double-beta decay [17]. They used the Majorana Demonstrator, a detector located at the Sanford Underground Research Facility in South Dakota. The Majorana Demonstrator searched for neutrinoless double-β decay $(0\nu\beta\beta)$ of ^{76}Ge using modular arrays of high-purity detectors in vacuum cryostats within a low-background shield. Operating with up to 40.4 kg of detectors (27.2 kg enriched to ∼88% in ^{76}Ge), it accumulated 64.5 kg yr of enriched active exposure. With a world-leading energy resolution of 2.52 keV FWHM at 2039 keV Q$\beta\beta$ (0.12%), it set a half-life limit of $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.L.), providing upper limits on $m_{\beta\beta}$ of (113–269) meV (90% C.L.), depending on the choice of nuclear matrix element, see figure 6 from [17]. While they did not yet detect $0\nu\beta\beta$ decay, the Majorana collaboration's efforts demonstrate the feasibility of deploying their approach on a much larger scale to search for this elusive form of radioactive decay.

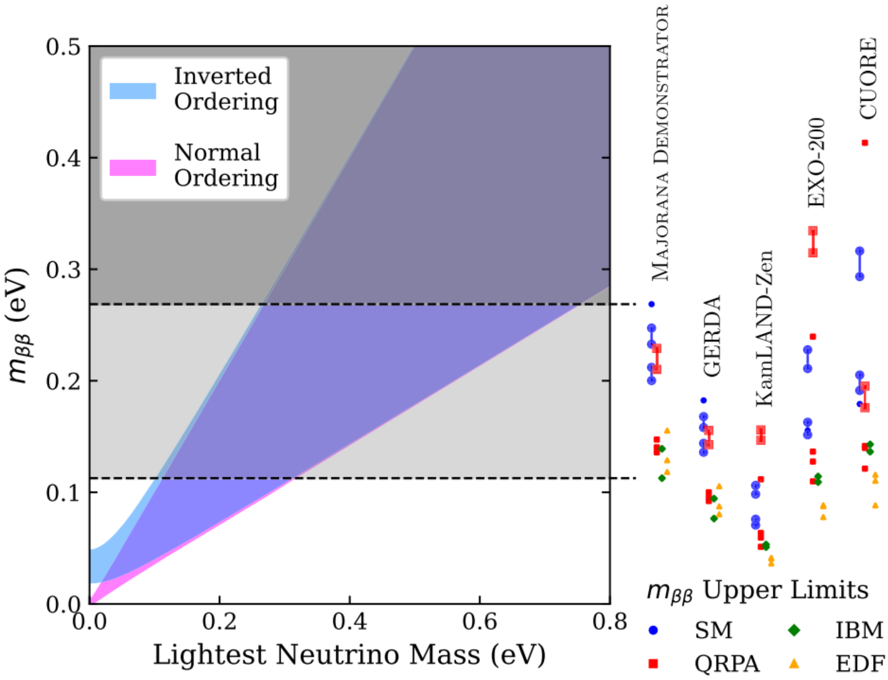

Figure 6: Allowed values of $m_{\beta\beta}$ for varying masses of the lightest neutrino eigenstate in the normal and inverted mass orderings, using the best-fit values of neutrino oscillation parameters.

3.4 Discussion For Future Experiments

In summary of recent experiments, more than 80 years since its initial proposal, upcoming experiments are now nearing the minimal masses anticipated from oscillation experiments. There is a vibrant world wide experimental effort pursuing a number of technologies at the ton scale. There is also notable theoretical advancement in accurately determining Nuclear Matrix Elements (NMEs) and Lepton Number Violation (LNV) phenomenology for neutrinoless double beta decay. If neutrinos are Majorana particles, these initiatives hold significant promise to detect this process beyond the Standard Model in the upcoming years [18].

While there is significant discovery potential in upcoming experiments, more experimental devices will be needed. For instance, extensions beyond the tonne scale may ultimately be required, see figure 7 from [19]. Achieving the necessary sensitivity to probe deeper into the properties of neutrinos and their role in the universe will likely demand even larger and more sophisticated detectors. These future experiments will necessitate extensive international collaboration, leveraging the combined expertise, resources, and technologies from scientific communities worldwide.

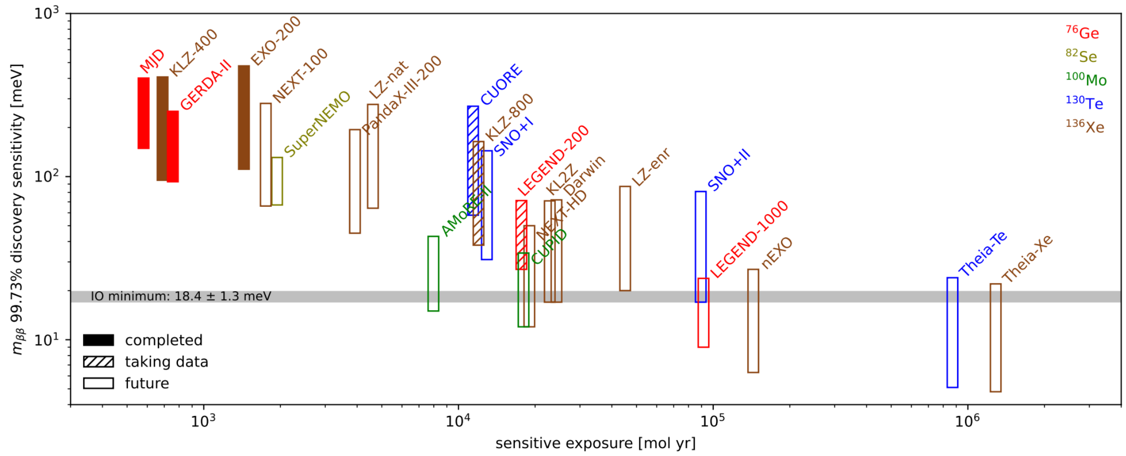

Figure 7: Discovery sensitivities of current- and next-generation $0\nu\beta\beta$-decay experiments for various mechanisms of lepton number violation, dominated by effective operators of dimension 5, i.e., light neutrino exchange.

4 Summary

In this paper, we discuss the possibilities of whether neutrinos are Dirac or Majorana particles. The Majorana condition is simpler than the Dirac condition and could successfully explain the violation of lepton numbers and the reason why neutrino masses are so small. Studying Majorana neutrinos also helps us understand the matter-antimatter asymmetry in the universe. The most significant experiment to determine whether neutrinos are Dirac or Majorana particles is neutrinoless double beta decay. Although we haven't found evidence of $0\nu\beta\beta$ yet, a series of experiments are currently underway.

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References

[1] S. Bilenky, *Neutrinos: Majorana or Dirac?*, arXiv:2008.02110.

[2] L. D. Landau, *On the conservation laws for weak interactions*, *Nucl. Phys.* **3** (1957) 127.

[3] T. D. Lee and C. N. Yang, *Parity Nonconservation and a Two Component Theory of the Neutrino*, Phys. Rev. **105** (1957) 1671.

[4] A. Salam, *On parity conservation and neutrino mass*, Nuovo Cim. **5** (1957) 299.

[5] M. Goldhaber, L. Grodzins and A. W. Sunyar, *Helicity of neutrinos*, Phys. Rev. **109** (1958) 1015.

[6] S. Boyd, *Neutrino Mass and Direct Measurements*, The University of Warwick, March 24, 2015.

[7] Zhi-zhong Xing, *Flavor structures of charged fermions and massive neutrinos*, Physics Reports **854** (2020) 1-147.

[8] G. 't Hooft, *Symmetry Breaking through Bell-Jackiw Anomalies*, Phys. Rev. Lett. **37** (1976) 8.

[9] B. Pontecorvo, *Neutrino experiments and the question of leptonic-charge conservation*, Zh. Eksp. Teor. Fiz. **53** (1967) 1717.

[10] V. N. Gribov and B. Pontecorvo, *Neutrino astronomy and lepton charge*, Phys. Lett. **28B** (1969) 493.

[11] S. Weinberg, *Baryon and Lepton Nonconserving Processes*, Phys. Rev. Lett. **43** (1979) 1566.

[12] M. Goeppert-Mayer, *Double beta-disintegration*, Phys. Rev. **48** (1935) 512.

[13] T. Marrodán Undagoitia, *Neutrino physics: Theory and experiment (SS2021) Reactor neutrinos*, (2021).

[14] M. J. Dolinski, A. W. P. Poon, and W. Rodejohann, *Neutrinoless Double-Beta Decay: Status and Prospects*, Ann. Rev. Nucl. Part. Sci. **69** (2019) 219.

[15] J. Kotila and F. Iachello, *Phase-space factors for double-beta decay*, Phys. Rev. C **85**, 034316 (2012).

[16] Matteo Agostini, Giovanni Benato, Jason A. Detwiler, Javier Menéndez, and Francesco Vissani, *Toward the discovery of matter creation with neutrinoless double-beta decay*, Rev. Mod. Phys. **95**, 025002 (2023).

[17] I. J. Arnquist et al. (Majorana Collaboration), *Final Result of the Majorana Demonstrator's Search for Neutrinoless Double-Beta Decay in* ^{76}Ge, Phys. Rev. Lett. **130**, 062501 (2023).

[18] David Moore, *Double Beta Decay review (theory & experiment)*, Presented at TAUP 2023, Wright Lab, Yale University, August 29, 2023. Available at: https://indico.cern.ch/event/1199289/contributions/5262783/attachments/2704274/.

[19] C. Adams et al., *Neutrinoless Double Beta Decay*, arXiv:2212.11099.