Is Neutrino Dirac or Majorana Particle?

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The discovery of neutrino oscillations provides unambiguous evidence that neutrinos have non-zero and non-degenerate masses, which constitutes one of the most solid observational signatures of physics beyond the Standard Model. However, the fundamental nature of neutrinos—whether they are Dirac or Majorana fermions—remains one of the most profound open questions in modern particle physics.

In this paper, we systematically elaborate the theoretical distinction between Dirac and Majorana fermions from the perspective of relativistic quantum field theory. We review the mainstream theoretical frameworks for neutrino mass generation under both hypotheses: for Majorana neutrinos, we analyze the Type-I, Type-II and Type-III seesaw mechanisms as well as the leptogenesis scenario that explains the cosmic matter-antimatter asymmetry; for Dirac neutrinos, we introduce alternative schemes including the Dirac seesaw, modular symmetry and non-seesaw frameworks that naturally generate tiny neutrino masses without lepton number violation.

We focus on neutrinoless double beta decay ($0\nu\beta\beta$) as a golden probe to discriminate between the two scenarios, and present its physical principle, current experimental status and prospects of next-generation detectors. We also discuss complementary probes including cosmological constraints, direct neutrino mass measurement via tritium beta decay, and the emerging gravitational wave detection approach. We further discuss the core difficulties in current research, notably the untestability of the canonical high-scale seesaw mechanism and the revived motivation for Dirac neutrino scenarios. Resolving the nature of neutrinos will have far-reaching implications for our understanding of fundamental symmetries, particle physics and cosmic evolution.

Keywords: Neutrino mass; Majorana neutrino; Dirac neutrino; Neutrinoless double beta decay; Seesaw mechanism; Leptogenesis.

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I. INTRODUCTION

The discovery of neutrino oscillation has confirmed that neutrinos possess non-zero and unequal masses, which is one of the most transformative breakthroughs in modern particle physics. This observation contradicts the original Standard Model, which predicted neutrinos to be massless, and gives a way for us to explore new physics beyond Standard Model. However, despite the phenomenon of neutrino oscillation is now firmly established, the fundamental intrinsic property of neutrino itself remain one of the most crucial unsolved mysteries in physics.

At the heart of this mystery is a simple yet profound question: is the neutrino a Dirac particle or a Majorana particle? In 1928, Paul Dirac formulated the relativistic wave equation for fermions, predicting that every particle has an independent antiparticle. For Dirac neutrinos, the neutrino (ν) and antineutrino ($\bar{\nu}$) are distinct particles, with lepton number strictly conserved. However, in 1937, Ettore Majorana proposed a revolutionary theory: electrically neutral fermions can be their own antiparticles. For Majorana neutrinos, the neutrino is identical to its antineutrino ($\nu = \bar{\nu}$). This property not only can naturally explain why neutrino masses are extremely tiny through the seesaw mechanism[1] but also leads to a breaking of lepton number conservation by two units.

The distinction between Dirac and Majorana neutrinos is not merely a theoretical curiosity; it has profound implications for both particle physics and cosmology. If neutrinos are Majorana particles, the seesaw mechanism provides an explanation for why neutrino masses are at least a million times smaller than the electron mass, by introducing heavy right-handed sterile neutrinos at the grand unification scale.[2][3] Most importantly, Majorana neutrinos combined with CP violation in the lepton sector could drive the process of leptogenesis in the early universe[4][5], naturally generating the observed matter-antimatter asymmetry—a cosmic puzzle that cannot be explained by the small CP violation observed in the quark sector alone.

The only practical experimental method to verify the Majorana nature of neutrinos is the search for neutrinoless double beta decay ($0\nu\beta\beta$), a nucleus undergoes double beta decay emitting two electrons and no antineutrinos. This process can only occur when neutrinos are Majorana particles, as the virtual antineutrino emitted by one neutron decay must be absorbed as a neutrino by a second neutron decay, requiring $\nu = \bar{\nu}$.[6] The observation of neutrinoless double beta decay would not only confirm the Majorana nature of neutrinos but also prove that lepton number is not a fundamental symmetry of nature, with revolutionary implications for our understanding of the early universe.

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In this essay, we will systematically explore the theoretical distinction between Dirac and Majorana neutrinos, the experimental challenges and current status of the search for neutrinoless double beta decay, and the profound implications of a Majorana discovery for physics beyond the Standard Model and the origin of the matter-dominated universe.

II. DIRAC AND MAJORANA PARTICLES

A. Mathematical Description

The difference between Dirac and Majorana fermions originates from their relativistic quantum field descriptions[7]. We start from the Lagrangian density of a free spin-1/2 particle:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \tag{1}$$

where $\bar{\psi} = \psi^\dagger \gamma^0$ denotes the Dirac adjoint, γ^μ are the gamma matrices, and m is the fermion mass. Applying the Euler–Lagrange equation to Eq. (1) yields the celebrated Dirac equation:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0. \tag{2}$$

Here, ψ is a four-component Dirac spinor, which describes two independent physical degrees of freedom: the particle and its distinct antiparticle, each with two spin polarization states.

For charged fermions such as electrons and quarks, the particle and its antiparticle carry opposite electric charge and can never be identified. Hence charged fermions must be described as Dirac particles. In the Dirac framework, lepton number is an exactly conserved quantum number: creating a neutrino increases lepton number by $+1$, while creating an antineutrino decreases it by -1, and the two processes are physically distinguishable.

In the Weyl representation, the Dirac spinor can be decomposed into left-handed and right-handed chiral components:

$$\psi = \begin{pmatrix} \psi_R \\ \psi_L \end{pmatrix}, \tag{3}$$

where ψ_L and ψ_R are two-component Weyl spinors. Substituting this decomposition into the Dirac mass term gives:

$$m\bar{\psi}\psi = m(\bar{\psi}_L + \bar{\psi}_R)(\psi_L + \psi_R) = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L). \tag{4}$$

Equation (4) shows that the Dirac mass term acts as a coupling between the two chiral components, continuously converting a left-handed state into a right-handed state and vice versa.

By projecting the Dirac equation (2) onto the two chiral sectors:

$$i\gamma^\mu \partial_\mu \psi_L = m\psi_R, \quad i\gamma^\mu \partial_\mu \psi_R = m\psi_L. \tag{5}$$

In the massless limit $m \to 0$, the two equations decouple and reduce to the Weyl equations:

$$i\gamma^\mu \partial_\mu \psi_L = 0, \quad i\gamma^\mu \partial_\mu \psi_R = 0, \tag{6}$$

describing purely left-handed and purely right-handed massless fermions.

For electrically neutral fermions such as neutrinos, an additional constraint becomes mathematically and physically consistent: the Majorana condition. To formulate it, we first define the charge conjugation matrix C, which satisfies

$$C\gamma^{\mu T} C^{-1} = -\gamma^\mu, \quad C^T = -C. \tag{7}$$

Taking the charge conjugate of the second equation in Eq. (5), multiplying by γ^0 on the right and by C on the left, one arrives at:

$$i\gamma^\mu \partial_\mu \, C\bar{\psi}_R^T = m \, C\bar{\psi}_L^T. \tag{8}$$

If we impose the condition

$$\psi_R = C\bar{\psi}_L^T, \tag{9}$$

then Eq. (8) becomes identical in structure to the first equation of Eq. (5). This means the entire Dirac equation can be rewritten purely in terms of the left-handed Weyl field. The full Majorana spinor therefore takes the form:

$$\psi = \psi_L + \psi_L^c = \left(\psi_L + \psi_L^c\right)^c = \psi^c, \tag{10}$$

where $\psi^c = C\bar{\psi}^T$ denotes the charge-conjugated spinor.

Equation (10) is the covariant form of the Majorana condition: $\psi = \psi^c$. Physically, charge conjugation maps a particle state into its antiparticle state by flipping the sign of all relevant internal quantum numbers. The Majorana condition therefore states that the neutral fermion is identical to its own antiparticle. As a consequence, a Majorana fermion possesses only two physical degrees of freedom — the two spin orientations — half the number of a Dirac fermion.

Most critically, Majorana mass terms explicitly violate lepton number conservation by two units ($\Delta L = 2$). Such lepton-number-violating terms are strictly forbidden in the original Standard Model. Therefore, any experimental confirmation that neutrinos are Majorana particles would constitute direct evidence for physics beyond the Standard Model.

B. If Neutrino is Majorana Particle(More mainstream)

The Majorana neutrino hypothesis has become the more mainstream theoretical expectation, primarily because it naturally explains the extreme smallness of neutrino masses and provides a mechanism for the cosmic matter-antimatter asymmetry.

1. Seesaw Mechanism

The observed extreme smallness of neutrino masses strongly suggests the existence of new physics at a high energy scale. The seesaw mechanism provides a natural and elegant explanation for $m_\nu \ll v$ (where v is the electroweak vacuum expectation value) by introducing heavy degrees of freedom that couple to active neutrinos. Among its various realizations, the Type-I seesaw is the simplest and most widely studied paradigm.

In the Type-I seesaw mechanism, one introduces gauge-singlet right-handed neutrinos N_i with large Majorana masses M_i. The relevant Lagrangian contains the Yukawa coupling terms and the Majorana mass terms for the heavy singlets:

$$\mathcal{L} \supset -y_{\alpha i}\, \bar{L}_\alpha \tilde{H} N_i - \frac{1}{2} M_i \overline{N_i^c} N_i + \text{h.c.}, \tag{11}$$

where L_α denotes the left-handed lepton doublet, $\tilde{H} = i\sigma_2 H^*$ is the conjugate Higgs doublet, and $y_{\alpha i}$ are the Yukawa coupling matrices.

After electroweak symmetry breaking, the Higgs field acquires its vacuum expectation value $v/\sqrt{2}$, generating a Dirac mass matrix $(m_D)_{\alpha i} = y_{\alpha i} v/\sqrt{2}$ that connects the left-handed active neutrinos ν_L to the heavy right-handed neutrinos. In the (ν_L, N^c) basis, the full neutrino mass matrix takes the block form:

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}, \tag{12}$$

where $M = \text{diag}(M_1, M_2, M_3)$ is the diagonal Majorana mass matrix of the heavy singlet neutrinos.

In the hierarchical limit $M \gg m_D$, diagonalizing Eq. (12) yields two sets of Majorana mass eigenstates: three light active neutrinos with masses approximately given by

$$m_\nu \approx -m_D M^{-1} m_D^T, \tag{13}$$

and three heavy states with masses close to M. This is the characteristic "seesaw" relation: the larger the heavy neutrino mass scale M, the smaller the light neutrino mass.

For illustration, taking a Dirac mass $m_D \sim 100$ GeV (comparable to the electroweak scale) and a heavy Majorana mass $M_R \sim 10^{14}$ GeV (near the grand unification scale), one obtains a light neutrino mass $m_\nu \sim 0.1$ eV, in excellent agreement with experimental constraints. Even if the Yukawa couplings are of order unity, a large M at the grand unification scale naturally suppresses the active neutrino mass to the observed sub-eV range. This mechanism was first independently proposed by Minkowski (1977)[1], Yanagida (1980)[2], and Gell-Mann *et al.*[3].

Beyond the Type-I scenario, the Type-II seesaw mechanism generates Majorana neutrino masses without introducing gauge-singlet fermions[8]. Instead, it adds an

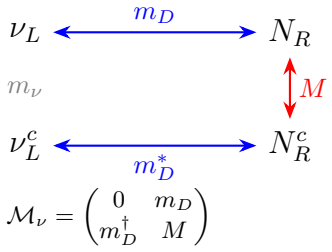


Figure 1. Schematic of the Type-I seesaw mechanism in the (ν_L, N_R^c) basis. The left-handed active neutrino ν_L couples to the heavy right-handed neutrino N_R via the Dirac mass m_D, while the heavy singlet carries a large Majorana mass M. Diagonalization yields light Majorana neutrino masses scaling as $m_\nu \sim m_D^2/M$.

SU(2)_L scalar triplet Δ with hypercharge $Y = +1$, which couples directly to lepton doublets via

$$\mathcal{L} \supset -\frac{1}{2} Y_{\alpha\beta}\, L_\alpha^T C(i\sigma_2) \Delta L_\beta + \text{h.c.}. \tag{14}$$

When the neutral component of the triplet acquires a small vacuum expectation value v_Δ, neutrinos obtain Majorana masses $m_{\alpha\beta} = Y_{\alpha\beta} v_\Delta$. The smallness of v_Δ is naturally achieved if the triplet has a large mass M_Δ: through a trilinear coupling $\mu H H \Delta$, the induced VEV scales as $v_\Delta \sim \mu v^2/M_\Delta^2$, so that $m_\nu \ll v$ when M_Δ is large. Early implementations of the Type-II seesaw appeared in left-right symmetric models and other Standard Model extensions.

The Type-III seesaw mechanism is structurally analogous to Type-I, but replaces the gauge-singlet right-handed neutrinos with fermionic SU(2)_L triplets Σ_i with hypercharge $Y = 0$. The Yukawa couplings $\bar{L}\Sigma\tilde{H}$ and the Majorana mass M_Σ for the heavy triplet fermions produce a block mass matrix identical in form to the Type-I case. Integrating out the heavy fermionic triplets yields the same effective light neutrino mass relation $m_\nu = -m_D M_\Sigma^{-1} m_D^T$. The minimal Type-III seesaw models were first proposed by Foot *et al.* in 1989[9].

Despite their different field content, all three canonical seesaw realizations reduce to the same dimension-5 Weinberg effective operator[10][11]

$$\mathcal{O}_5 = \frac{(LH)(LH)}{\Lambda} + \text{h.c.} \tag{15}$$

when the heavy degrees of freedom are integrated out. Suppressed by the new physics scale Λ, this operator generates small Majorana neutrino masses $m_\nu \sim v^2/\Lambda$ after electroweak symmetry breaking, providing a unified effective description of the seesaw paradigm.

2. The Process of Leptogenesis

Heavy Majorana neutrinos from the seesaw framework also provide a compelling and widely studied mechanism

for generating the cosmic matter-antimatter asymmetry, known as leptogenesis, first proposed by Fukugita and Yanagida in 1986[4]. This framework naturally satisfies the three Sakharov conditions required for any viable baryogenesis scenario: baryon number violation, C and CP violation, and departure from thermal equilibrium[5].

In the extremely hot early universe, heavy right-handed Majorana neutrinos are abundantly produced via thermal interactions and remain in full chemical equilibrium with the primordial particle plasma. As the universe expands and cools below the mass scale of the heavy neutrinos, their production rate drops below the cosmic Hubble expansion rate. They can no longer maintain thermal equilibrium and begin to decay out of equilibrium. If CP symmetry is violated in the lepton sector, the partial decay rates into leptons and antileptons will differ, generating a net lepton number asymmetry. Subsequently, non-perturbative electroweak sphaleron processes, which violate both baryon number and lepton number while preserving the combination $B - L$, convert a fixed fraction of this lepton asymmetry into a baryon asymmetry, ultimately giving rise to the matter-dominated universe we observe today.

At the microscopic level, the lightest of the three heavy right-handed neutrinos, conventionally denoted N_1, dominates the generation of the surviving lepton asymmetry. Asymmetries produced by heavier heavy neutrino states are generally washed out by subsequent thermal interactions in the early plasma, and only the asymmetry from the latest-decaying N_1 persists. The N_1 state has two principal decay channels:

$$N_1 \to l_\alpha + \phi, \quad N_1 \to \bar{l}_\alpha + \bar{\phi}, \tag{16}$$

where ϕ denotes the Higgs field and l_α represents a charged lepton of flavor α.

The CP asymmetry between the two decay channels does not arise from tree-level processes alone. Instead, it originates from the quantum interference between the tree-level decay amplitude and one-loop vertex and self-energy diagrams involving the heavier heavy neutrino states N_2 and N_3. The complex CP-violating phases contained in the neutrino Yukawa coupling matrix lead to unequal partial widths for the lepton and antilepton final states, which constitutes the fundamental microscopic origin of the net lepton number excess.

In this physical picture, all three Sakharov conditions are naturally fulfilled. First, lepton number violation is inherent to the Majorana nature of the heavy neutrinos, with $\Delta L = 2$. Second, CP violation is encoded in the complex Yukawa phases and manifests itself through the tree-loop interference in the decay amplitudes. Third, the out-of-equilibrium condition is satisfied when the cosmic Hubble expansion rate exceeds the N_1 decay rate, preventing inverse decay processes from erasing the generated asymmetry.

For canonical thermal leptogenesis, successful reproduction of the observed baryon-to-photon ratio typically requires the mass of the lightest heavy neutrino to satisfy $M_{N_1} \gtrsim 10^9$ GeV. However, if the heavy neutrino masses are nearly degenerate, resonant enhancement of the CP asymmetry can significantly lower the required mass scale, potentially down to the TeV range.

3. *The implications if Neutrino is Majorana Particle*

The confirmation of Majorana neutrinos would have far-reaching consequences. First, it would prove that lepton number is not a fundamental symmetry of nature, representing a clear breakdown of the Standard Model. Second, it would provide strong experimental support for the seesaw mechanism and grand unified theories. Third, combined with leptonic CP violation, it would strongly support the leptogenesis scenario as the origin of cosmic baryon asymmetry. In short, discovering Majorana neutrinos would revolutionize our understanding of particle physics and cosmology.

C. If Neutrino is Dirac Particle

If neutrinos are Dirac particles, the neutrino and its antineutrino are fundamentally distinct states, and lepton number remains an exact, unbroken symmetry of nature. Historically, the Dirac scenario was regarded as less theoretically natural, since a minimal tree-level Dirac mass term from the Standard Model Higgs mechanism offers no inherent explanation for why neutrino masses are orders of magnitude smaller than the masses of charged leptons and quarks. However, multiple well-motivated theoretical frameworks have been developed to naturally generate tiny Dirac neutrino masses without invoking lepton number violation or Majorana fermions, as outlined below.

1. *Dirac Seesaw Mechanism[12]*

The Dirac seesaw framework introduces additional right-handed neutrino states together with protective symmetries (such as discrete flavor symmetries or gauged $B - L$ symmetry), which strictly forbid both tree-level Dirac mass terms and Majorana mass terms. Instead, extremely small effective Yukawa couplings are generated through higher-dimensional operators mediated by heavy virtual states. Analogous to the Majorana seesaw, the light neutrino masses are naturally suppressed by the high scale of new physics, yielding sub-eV Dirac masses without fine-tuning, while preserving exact lepton number conservation throughout.

2. *Modular Symmetry Framework[13][14]*

Modular symmetry has emerged as a rapidly developing, high-profile direction in neutrino flavor physics in

recent years. This framework is built upon finite modular groups Γ_N (most commonly the A_4 group for level $N = 3$), in which Yukawa couplings are not free parameters but are expressed as modular forms of a complex modulus τ. A key advantage is that it does not require extending the Standard Model scalar sector with additional flavon fields, providing a minimal and highly predictive scheme. It can naturally reproduce the observed lepton flavor structure and mass hierarchies, and can be consistently formulated to accommodate purely Dirac neutrino masses without relying on a seesaw mechanism.

3. Non-Seesaw Dirac Framework[15][16]

Non-seesaw Dirac scenarios explain tiny neutrino masses without introducing heavy mediator fields for a seesaw mechanism. Instead, discrete symmetries are imposed to directly forbid tree-level Yukawa couplings for neutrinos entirely. The light neutrino masses then arise from even higher-dimensional effective operators, which are naturally suppressed by powers of the high new physics scale. This construction circumvents the naturalness problem of unnaturally small tree-level Yukawa couplings, offering an economical and theoretically consistent alternative to the Majorana seesaw paradigm.

III. EXPERIMENTAL EXPLORATION

A. Neutrinoless Double Beta Decay

Neutrinoless double beta decay ($0\nu\beta\beta$) is the most direct experimental probe that can directly distinguish between Dirac and Majorana neutrinos.

In ordinary double beta decay ($2\nu\beta\beta$), two neutrons in a nucleus transform into two protons, emitting two electrons and two electron antineutrinos. In contrast, $0\nu\beta\beta$ is a hypothetical lepton-number-violating process of the form

$$(A, Z) \to (A, Z + 2) + 2e^-, \tag{17}$$

in which no neutrinos appear in the final state, and lepton number is violated by two units.

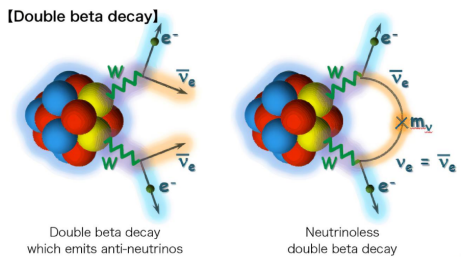


Figure 2. $2\nu\beta\beta$ vs $0\nu\beta\beta$

As a result, the sum of the kinetic energies of the two electrons equals the total decay energy $Q_{\beta\beta}$, producing a sharp monoenergetic peak in the electron energy spectrum — the characteristic experimental signature of the process.

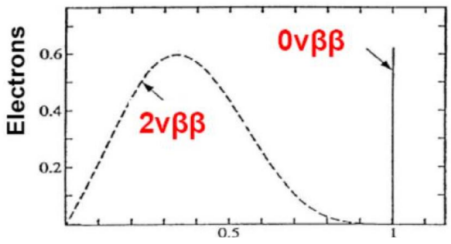


Figure 3. Experimental signature in electron energy spectrum

As first demonstrated by Furry in 1939[6], $0\nu\beta\beta$ can only occur if neutrinos are Majorana particles. The process proceeds via the exchange of a virtual neutrino between the two neutron decay vertices: the virtual antineutrino emitted at one vertex must be absorbed as a neutrino at the other, which requires $\nu = \bar{\nu}$, the defining property of a Majorana fermion. Observation of $0\nu\beta\beta$ would therefore unambiguously establish that neutrinos are Majorana fermions and that lepton number is not a fundamental symmetry of nature.

The decay half-life is inversely proportional to the square of the effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$, following the relation:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = g(Z)\,|M_{0\nu}|^2\,\langle m_{\beta\beta}\rangle^2\,, \tag{18}$$

where $g(Z)$ is a phase-space factor dependent on the nuclear charge Z, and $M_{0\nu}$ is the nuclear matrix element. The effective Majorana mass is a coherent sum over all neutrino mass eigenstates:

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|, \tag{19}$$

where m_i are the neutrino mass eigenvalues and U_{ei} are the electron-flavor elements of the PMNS lepton mixing matrix.

Observing $0\nu\beta\beta$ is experimentally extremely challenging, as the process has an extremely long predicted half-life, exceeding 10^{25} years. Experiments require large quantities of enriched double-beta-decay isotopes, ultra-low-background environments deep underground to shield from cosmic rays, and excellent energy resolution to identify the characteristic peak. To date, no confirmed observation of $0\nu\beta\beta$ has been reported, and successive generations of experiments have only set increasingly stringent lower limits on the half-life.

Recent leading experiments include GERDA (using ^{76}Ge), KamLAND-Zen (using ^{136}Xe), and CUORE. GERDA set a lower limit of $T^{0\nu}_{1/2} > 1.8\times10^{26}$ yr[17], while

KamLAND-Zen reported the strongest current limit of $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr at 90% confidence level[18]. Depending on the adopted nuclear matrix element calculations, these results correspond to upper bounds on the effective Majorana mass in the range $m_{\beta\beta} \lesssim 0.03$–$0.2$ eV, already probing the parameter space predicted by many mainstream neutrino mass models.

Next-generation experiments such as nEXO, LEGEND-1000, and CUPID aim to improve the half-life sensitivity by roughly an order of magnitude, pushing the effective mass sensitivity deep into the parameter space of the inverted neutrino mass ordering, and bringing a potential discovery within experimental reach.

B. Other Ways

Besides neutrinoless double beta decay, multiple experimental and observational approaches can probe neutrino masses, though none can directly distinguish between Dirac and Majorana nature on their own. They provide complementary constraints on the absolute mass scale and mass hierarchy, serving as important benchmarks for understanding neutrino properties.

1. Cosmological Constraints

Cosmological observations, including measurements of the cosmic microwave background (CMB), baryon acoustic oscillations (BAO), and Type Ia supernovae (SN), place stringent limits on the sum of the masses of the three active neutrino species. The combined analysis of Planck satellite CMB data, BAO surveys and SN observations yields an upper bound on the total neutrino mass at 95% confidence level[19]:

$$\sum m_i < 0.12 \text{ eV}.$$

Cosmological probes are sensitive to the neutrino mass ordering (normal vs inverted hierarchy), and provide constraints that are highly complementary to laboratory searches such as $0\nu\beta\beta$. However, they cannot differentiate between Dirac and Majorana neutrinos, as both scenarios produce identical effects on cosmic structure formation.

2. KATRIN Tritium Beta Decay Experiment

The KATRIN experiment performs a direct, model-independent measurement of the effective electron antineutrino mass by precisely analyzing the endpoint region of the tritium beta decay energy spectrum. It is currently the most sensitive direct neutrino mass measurement experiment in operation.

The latest combined result sets an upper limit on the effective electron neutrino mass of

$$m_\nu < 0.8 \text{ eV}$$

at 90% confidence level. The experiment has a final design target sensitivity of 0.2 eV[20]. While KATRIN is insensitive to the Dirac or Majorana nature of neutrinos, it provides a robust absolute mass scale benchmark that is essential for interpreting results from neutrinoless double beta decay and other searches.

3. Gravitational Wave Probes

As an emerging frontier direction that has become a research hotspot in 2025, gravitational wave astronomy provides a novel indirect probe to differentiate between Dirac and Majorana neutrinos through early universe physics. The intrinsic nature of neutrinos is tightly linked to the energy scale and type of symmetry-breaking phase transitions in the primordial universe, which leave distinct characteristic imprints on the stochastic gravitational wave background. Each neutrino scenario predicts a uniquely identifiable gravitational wave spectrum[21]:

- **Majorana neutrinos with high-scale symmetry breaking ($\sim 10^{14}$ GeV)**: The grand-unification-scale symmetry breaking associated with the canonical Majorana seesaw mechanism generates cosmic string topological defects. The persistent oscillation and decay of cosmic strings produce a nearly flat, broadband gravitational wave spectrum that spans a wide frequency range.

- **Dirac neutrinos with low-scale symmetry breaking ($\sim 10^7$ GeV)**: For Dirac neutrino models protected by discrete symmetries, the corresponding symmetry breaking proceeds via a first-order phase transition at a much lower energy scale. This process generates a distinct peak-shaped gravitational wave spectrum centered at the frequency corresponding to the phase transition scale.

- **Pseudo-Dirac neutrinos**: In pseudo-Dirac scenarios, the tiny mass splitting between the two nearly degenerate Majorana components leads to the formation of domain wall topological defects. The annihilation of these domain walls in the early universe produces a characteristic kink-like feature in the gravitational wave spectrum, which serves as a unique observational signature.

This cosmic gravitational wave probe offers a complementary approach to direct laboratory searches, opening a new observational window to probe the fundamental nature of neutrinos.

IV. DIFFICULTIES IN RESEARCH

A. The Untestability of the Canonical Seesaw Mechanism

Despite its theoretical elegance and strong physical motivation, the canonical Type-I seesaw mechanism faces a fundamental experimental limitation. The heavy right-handed Majorana neutrinos it introduces are predicted to have masses near the grand unification scale, of order $\sim 10^{14}$ GeV. This energy scale is many orders of magnitude beyond the reach of any current or planned particle accelerator: the Large Hadron Collider (LHC) operates at a center-of-mass energy of 14 TeV, and even the proposed Future Circular Collider (FCC) will only reach approximately 100 TeV. As a result, these heavy singlet neutrinos cannot be directly produced or detected in collider experiments.

Our only experimental handles on the seesaw paradigm are indirect. The observation of neutrinoless double beta decay would confirm the Majorana nature of neutrinos and provide circumstantial support for the seesaw framework, but it would not allow a direct measurement of the heavy neutrino mass scale. Similarly, the success of leptogenesis as an explanation for the cosmic baryon asymmetry would be indirect evidence for heavy Majorana neutrinos, but would not constitute a direct test. This intrinsic untestability at collider energies is one of the primary criticisms of the minimal high-scale seesaw scenario.

B. Alternatives

To address the untestability of the canonical high-scale seesaw, theorists have proposed a variety of low-scale variants and alternative mass generation mechanisms. The inverse seesaw lowers heavy neutral leptons to the TeV range via tiny lepton-number-violating mass terms, enabling direct collider searches[22]. Radiative frameworks such as the scotogenic model generate neutrino masses only at the loop level, naturally suppressing masses through loop factors and often accommodating dark matter candidates[23]. Extra-dimensional models can also explain tiny neutrino masses through the small wavefunction overlap between left- and right-handed states across extra dimensions[24]. Many of these alternatives can be formulated for both Majorana and Dirac neutrinos, demonstrating that the Majorana hypothesis is not the only path to naturally light neutrinos, and keeping the Dirac scenario theoretically well-motivated.

C. Why Dirac Neutrinos Are Regaining Attention

In recent years, the Dirac neutrino scenario has undergone a significant revival and attracted renewed research attention, driven by both experimental null results and theoretical developments.

First, after decades of increasingly sensitive searches, neutrinoless double beta decay has still not been observed. Successive generations of experiments have continuously tightened the upper bound on the effective Majorana mass, with no confirmed signal to date. This persistent null result has led the community to re-examine the possibility that neutrinos might be purely Dirac particles, and that lepton number is an exact, unbroken symmetry of nature.

Second, new theoretical frameworks such as modular symmetry have emerged, providing elegant and highly predictive mechanisms to naturally generate tiny Dirac neutrino masses without fine-tuning[13]. These constructions address the long-standing naturalness objection to Dirac neutrinos, showing that small Dirac masses can arise from fundamental symmetry principles rather than ad-hoc tiny Yukawa couplings.

Third, the development of Dirac leptogenesis scenarios has shown that Dirac neutrinos can also successfully explain the observed cosmic baryon asymmetry of the universe (BAU), without requiring lepton number violation[25]. This removes one of the key theoretical arguments historically favoring Majorana neutrinos, providing a fully consistent cosmological framework for pure Dirac neutrinos.

Taken together, these developments have established the Dirac neutrino scenario as a viable and well-motivated alternative to the canonical Majorana seesaw paradigm.

D. Conclusion

The seesaw mechanism provides an elegant explanation of small neutrino masses, but it typically operates at very high scales ($M_R \sim 10^{14}$ GeV) that are far beyond direct experimental reach. This makes it challenging to test directly. Many alternative models (inverse seesaw, radiative models, extra dimensions...) have been proposed to lower the new physics scale. In the Dirac scenario, the absence of new heavy states simplifies the model, but one must still explain why the neutrino Yukawa coupling is so tiny. Additional symmetries (e.g. a conserved $B - L$) can forbid Majorana masses and keep neutrinos Dirac, but this shifts the question to a higher-level symmetry choice.

At present, neither hypothesis is confirmed. No lepton-number-violating process has been observed. If neutrinoless double-beta decay is discovered, it will confirm the Majorana nature. Conversely, if upcoming experiments reach sensitivities below the inverted-hierarchy band without a signal, attention will shift to Dirac scenarios. In either case, the resolution of this question will have profound implications for particle physics and cosmology.

V. SUMMARY

This paper presents a comprehensive review of the fundamental question in particle physics: whether neutrinos are Dirac or Majorana particles. Starting from the relativistic quantum field description of spin-1/2 fermions, we clarify the intrinsic difference between the two categories: Dirac fermions have distinct antiparticle states and strictly conserve lepton number, while Majorana fermions are identical to their own antiparticles and naturally introduce lepton number violation by two units.

On the theoretical side, the Majorana neutrino hypothesis has long been the dominant paradigm. The seesaw mechanism, with its canonical Type-I, Type-II and Type-III realizations, provides an elegant explanation for the extreme smallness of neutrino masses by relating the light neutrino mass scale to a heavy new physics scale. Furthermore, the thermal leptogenesis mechanism based on heavy right-handed Majorana neutrinos offers a compelling solution to the cosmic baryon asymmetry puzzle, building a deep connection between neutrino physics and the evolution of the early universe.

On the other hand, the Dirac neutrino scenario, once widely challenged by the naturalness problem of unnaturally tiny Yukawa couplings, has gained substantial renewed attention in recent years. Novel theoretical frameworks such as the Dirac seesaw, modular symmetry and non-seesaw higher-dimensional operator schemes demonstrate that tiny Dirac neutrino masses can also arise naturally from fundamental symmetry principles. Meanwhile, Dirac leptogenesis scenarios show that the observed matter-antimatter asymmetry can be reproduced without violating lepton number, removing a key theoretical argument that historically favored Majorana neutrinos.

Experimentally, neutrinoless double beta decay remains the only definitive probe capable of directly verifying the Majorana nature of neutrinos. Decades of experimental efforts have pushed the lower limit of the $0\nu\beta\beta$ half-life above 10^{26} years, corresponding to an upper bound on the effective Majorana mass of 0.03–0.2 eV. Next-generation experiments such as nEXO, LEGEND-1000 and CUPID are designed to fully cover the parameter space of the inverted neutrino mass ordering, bringing a potential discovery within experimental reach. Complementary probes including cosmological observations, direct tritium beta decay measurements and gravitational wave astronomy provide independent constraints on neutrino masses, and open alternative observational windows to distinguish between the two neutrino scenarios.

Despite these advances, the field still faces challenges. The canonical high-scale seesaw mechanism operates at energy scales far beyond the reach of current and planned colliders, making it difficult to test directly. This limitation has motivated a variety of low-scale seesaw variants and alternative mass generation mechanisms. The persistent null result from $0\nu\beta\beta$ searches also keeps the Dirac neutrino hypothesis as a viable and well-motivated theoretical alternative.

Looking forward, the progress of next-generation rare decay experiments, high-precision cosmological surveys and gravitational wave detectors will gradually narrow down the available parameter space. The final answer to the nature of neutrinos will not only resolve a core puzzle of particle physics, but also reshape our understanding of fundamental symmetries in nature and the origin of our matter-dominated universe.

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I made extensive use of AI in my essay writing process, mainly Doubao and ChatGPT. I used ChatGPT to outline my essay and identify the paper I need to look trough and study. This saved me a tremendous amount of time. When studying papers, I always use Doubao to assist me. It helps me quickly sort out and extract the main content of the paper, and answer my questions. Meanwhile, in fact, my English writing is poor, so it also provided great help for my writting. For example, I told it what Chinese I want to write and asked it to output English.

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