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Review Article

Theoretical and Experimental Challenges in the Measurement of Neutrino Mass

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Neutrino masses are yet unknown. We discuss the present state of effective electron antineutrino mass from β decay experiments; effective Majorana neutrino mass from neutrinoless doubele-beta decay experiments; neutrino mass squared differences from neutrino oscillation: solar, atmospheric, reactor, and accelerator-based experiments; sum of neutrino masses from cosmological observations. Current experimental challenges in the determination of neutrino masses are briefly discussed. The main focus is devoted to contemporary experiments.

1. Introduction

Neutrinos are the second most abundant known particles in the Universe. Despite of their abundance in the nature, their hypothetical presence was first announced by Pauli in 1930, when trying to protect the law of conservation of energy in beta radioactivity [1]. This particle got its name "Neutrino" by Enrico Fermi in 1934. The neutrinos were introduced as the neutral and massless fermions [2]. These neutrinos interact only via weak interaction and their cross-section of interaction is very small [3].

The standard model (SM) of particle physics is based on the gauge group $(\mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times U(1)_Y)$ [4, 5]. The electroweak group is represented by $\mathrm{SU}(2)_\mathrm{L} \times U(1)_Y$. SM describes the interaction between fundamental matter particles, i.e., quarks and leptons which are fermions, three fields, i.e., electromagnetic, weak and strong field, and their associated gauge bosons along with a scalar Higgs boson. All the charged fermions in the SM are Dirac, leaving neutrinos. Neutrinos are Dirac ($\nu \neq \bar{\nu}$), or Majorana ($\nu = \bar{\nu}$) is yet to be established [6–8]. In SM, neutrinos are considered as massless fermion.

The discovery of neutrino oscillations by neutrino experiments came up with the rejection of the idea of massless neutrino. The neutrino oscillation was confirmed by Super-Kamiokande [9] and Sudbury Neutrino Observatory [10]; this remarkable discovery led to the Nobel Prize in Physics in 2015 [11, 12]. This discovery was the first experimentally confirmed dent in the SM and it opened the door for physics beyond standard model (BSM).

2. Neutrino Mass

Generally, the neutrino mass can be determined using, (i) cosmological data: sets a most stringent bound on the sum of neutrino masses (Σm_ν); (ii) beta decay: sets a most stringent bound on effective electron antineutrino mass (m_{ν_e}) by observing the kinematics of weak interaction; (iii) neutrinoless double-beta decay: sets a most stringent bound on effective Majorana neutrino mass ($m_{\beta\beta}$) by observing the monoenergetic peak (if observed) at the decay Q value. These approaches are discussed below.

2.1. Sum of Neutrino Masses: Cosmological Bounds. Sum of neutrino mass is defined as $\sum m_\nu = m_1 + m_2 + m_3$, where m_1, m_2, and m_3 are three neutrino mass eigenstates. Cosmological observations carry imprints of neutrinos, and there-

Table 1: Cosmological bounds on sum of neutrino masses based on ΛCDM+Σm_ν model, where TT: temperature power spectra; TE: temperature-polarization power spectra; EE: polarization power spectra; low-E: low-l polarization; RSD: redshift-space distortions; DES: dark energy survey; Pantheon: combined sample of supernova Type Ia.

Data	Σm_ν (eV) (95% C.L.)	Ref.
Planck (TT + low-E)	<0.54	[30]
Planck (TT,TE,EE + low-E)	<0.26	[30]
Planck (TT + low-E) + BAO	<0.13	[31]
Planck (TT + low-E + lensing)	<0.44	[30]
Planck (TT,TE,EE + low-E + lensing)	<0.24	[30]
Planck (TT,TE,EE + low-E) + BAO + RSD	<0.10	[31]
Planck (TT + low-E + lensing) + BAO + Lyman-α	<0.087	[32]
Planck (TT,TE,EE + low-E) + BAO + RSD + Pantheon+DES	<0.13	[33]

fore, it can be used to extract and constrain the neutrino properties. Cosmology is sensitive to the following neutrino properties: (i) number of active neutrinos, (ii) neutrino density, (iii) sum of neutrino masses.

Generally accepted cosmological model, standard model of cosmology, explains the large-scale structures and their dynamics and answers unresolved puzzles associated with the evolution and fate of the Universe. The Λ-CDM (cold dark matter) model best describes the present parameters, such as density parameter of baryons ($\Omega_b \simeq 0.05$) which refers to observable objects in the Universe, density parameter of CDM ($\Omega_c \simeq 0.25$) which refers to nonbaryonic and nonrelativistic matter, density parameter of cosmological constant ($\Omega_\Lambda \simeq 0.70$) which refers to vacuum, also called the dark energy, and the Hubble constant ($h \simeq 70\, km\, s^{-1}\, Mpc^{-1}$) which refers to the present rate of expansion of the Universe.

The precise estimation of neutrino to photon number density ratio (n_ν/n_γ) is important for the determination of the sum of neutrino masses (Σm_ν), and this ratio is fixed in SM including many extensions of SM. The ratio related to Σm_ν as $\Omega_\nu = \rho_\nu^0/\rho_{\rm crit}^0 = \Sigma m_\nu/(93.14\, h^2 eV)$, where Ω_ν is the present total neutrino density in terms of critical density $\rho_{\rm crit}^0$. The expression of Ω_ν reported in the text assumes the "standard" (n_ν/n_γ). This ratio is connected to the physics of neutrino decoupling.

The neutrino to photon energy density ratio (ρ_ν/ρ_γ) between the e^-e^+ annihilation time and nonrelativistic transition time of neutrino can be given by the expression $\rho_\nu/\rho_\gamma = (7/8)\, N_{\rm eff} (4/11)^{4/3}$, where $N_{\rm eff}$ is the effective number of neutrinos estimated as 3.044 from a detailed calculations of the process of neutrino decoupling with at least 10^{-4} numerical precision [13–16]. The direct measurement of the invisible width of Z-boson limits the number of active left-handed neutrino states to three, $N_\nu = 2.9963 \pm 0.0074$, and they are ν_e, ν_μ, ν_τ [17].

The estimated sum of neutrino masses from composite samples (such as Planck, BAO, and RSD) based on ΛCDM $+ \Sigma m_\nu$ model is mentioned in Table 1. There are several challenges in measuring the sum of neutrino masses which needs to be mentioned for imposing more stringent constraints on Σm_ν. Detailed overview of the cosmological constraints on the neutrino properties can be found in [18–21].

2.1.1. Main Challenges in the Measurement of Sum of Neutrino Masses

(i) Measurement of cosmological parameters with utmost accuracy

(ii) Dependency on cosmological model

(iii) Making scaling to current detectors

(iv) Removal of false B-mode signal in the CMB (cosmic microwave background) measurement

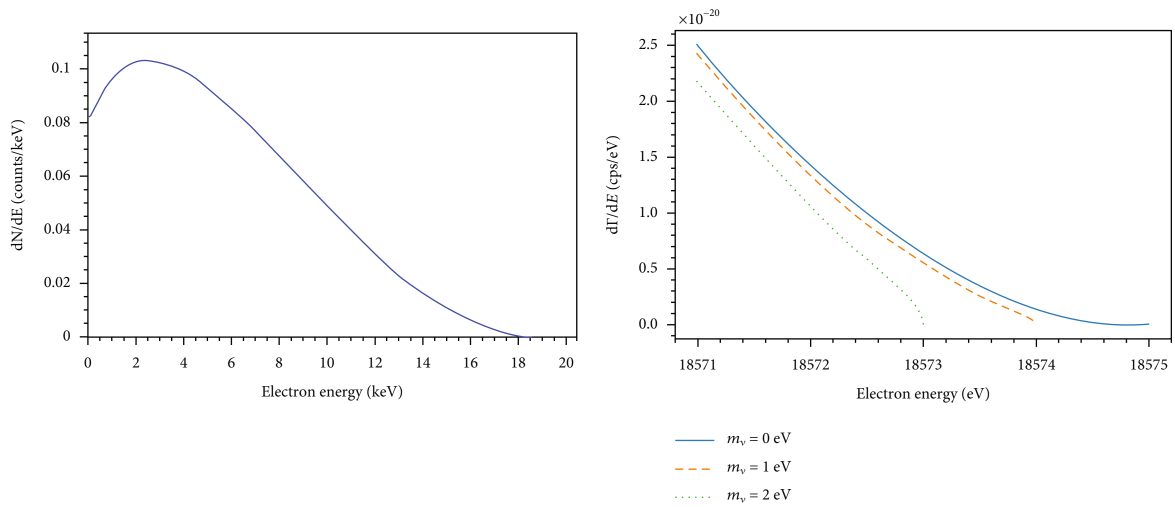
(v) Subpercent level precision in BAO (baryon acoustic oscillation) measurements of the distance scale

(vi) Sum of neutrino mass calculated by different models using composite dataset has to be minimized, because we know, if the neutrino mass variation is in the range 0.025 eV-1 eV, then the error of the order of 5% will be generated on the matter power spectrum in comparison to the current matter power spectrum

Next-generation cosmological experiments will address the abovementioned issues and provide better constraints on Σm_ν; few upcoming experiments are DESI [22], Euclid [23], LSST [24], SPHEREx [25], SKA [26], Simon Observatory [27], CMB-S4 [28], and LiteBird [29].

2.2. Effective Electron Antineutrino Mass: β Decay Bounds.

Effective electron antineutrino mass is defined as follows: $m_{\nu_e} \equiv \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$, where U_{e1}, U_{e2}, and U_{e3} are components of neutrino mixing matrix. Determination of m_{ν_e} is of urgent importance for cosmology and particle physics. This information will help in understanding the role of neutrinos in the structure formation of the Universe after the Big Bang [34]. In addition, the value of effective electron antineutrino mass will help us in identifying the right theories for the prediction of BSM physics [35, 36].



(a) (b)

Figure 1: (a) The beta spectrum of ^{3}H. Data is taken from [37]. (b) Shape distortion produced by effective electron antineutrino mass (m_ν) in ^{3}H beta spectrum. Image credit [38].

The β decay experiments are designed in a way to explore effective electron antineutrino mass. The weak interaction process of β decay can be expressed as $n \longrightarrow p + e^- + \bar{\nu}_e$, a careful study of the given reaction can quantitate the effective electron antineutrino mass. β-decay experiment measures a distortion in the spectral shape near the endpoint of β decaying isotope. The phase space of an electron emitted in a β decay process can be expressed as $P(E) \propto E(E - E_0)p\sqrt{(E_0 - E)^2 - m_{\nu_e}^2}$, where p is the momentum of outgoing electron possessing energy E, m_{ν_e} is the effective electron antineutrino mass, and E_0 is the end point energy of the spectrum. The β decay spectrum of $^3\mathrm{H}(Q_\beta = 18.6\,\mathrm{keV})$ is shown in Figure 1(a), and distortion produced by effective electron antineutrino mass in ^{3}H energy spectrum is shown in Figure 1(b).

One of the most promising experiments designed to probe the effective electron antineutrino mass by studying the kinematics of β decay is KATRIN (KArlsruhe TRItium Neutrino) experiment by looking at the decay of tritium (^{3}H) as $^3\mathrm{H} \longrightarrow {}^3\mathrm{H}e + e^- + \bar{\nu}_e$. KATRIN put a constrain on $m_{\nu_e} < 0.8\,\mathrm{eV}$ at the 90% C.L [39] and have potential to impose constrain on $m_{\nu_e} < 0.2\,\mathrm{eV}$.

KATRIN reduce the statistical uncertainty by a factor of three and systematic uncertainty by a factor of two relative to its earlier campaign. In a first campaign, KATRIN (2019) reached a sensitivity of 1.1 eV at 90% C.L, and in its second campaign, KATRIN (2021) achieved sensitivity of 0.7 eV at 90% C.L. KATRIN would be dominated by systematics, although results of KATRIN first and second campaign are dominated by statistical uncertainties. KATRIN continue reducing its systematic uncertainty to achieve a designed sensitivity of 0.2 eV at 90% C.L on m_{ν_e}. The constrain imposed on the upper limit of effective electron antineutrino mass by KATRIN experiment is shown in Table 2. To pin down the effective electron antineutrino mass from β decay experiments, many potential challenges need to be addressed carefully.

Table 2: Current bounds on effective electron antineutrino mass from β decay kinematics.

Experiments	Isotope	m_{ν_e} (eV) (90% C.L.)	Ref.
KATRIN (2019)	^{3}H	<1.1	[46]
KATRIN (2021)	^{3}H	<0.9	[39]
KATRIN (combined)	^{3}H	<0.8	[39]

2.2.1. Main Challenges in the Measurement of Effective Electron Antineutrino Mass

(i) Spectrometer with good counting rate or high efficiency

(ii) Spectrometer with better end-point energy resolution

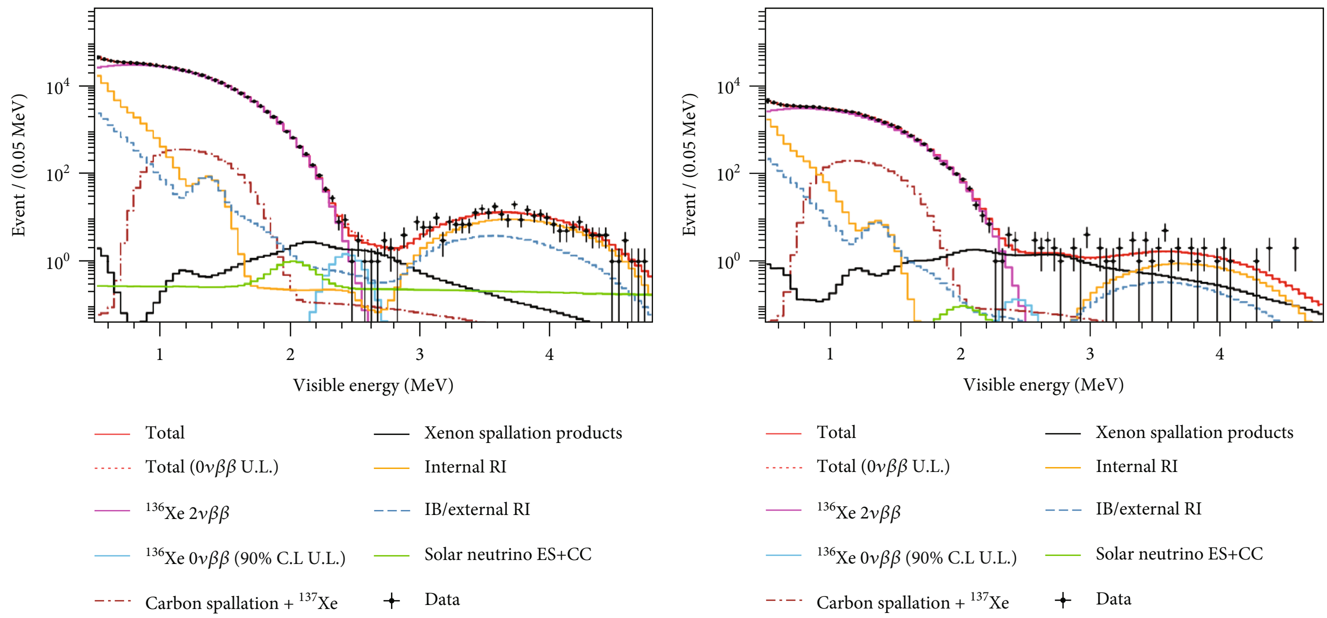
(iii) Intense source of tritium and Holmium-163: high Becquerel activity is recommended

(iv) Energy loss of β in the source, [8, 40].

(v) Removal of background produced by radon decays inside spectrometer

Many other promising upcoming experiments which are designed to impose better constrain on m_{ν_e} are PTOLEMY (^{3}H) [41], Project8 (^{3}H) [42], EcHo (^{163}Ho) [43], HOLMES (^{163}Ho) [44], and NuMECS (^{163}Ho) [45].

The advantage of using ^{163}Ho isotope having 100% decay via electron capture process and very small total nuclear decay energy (< 3 keV).



(a) (b)

Figure 2: Energy distribution measured by KamLAND-Zen experiment. (a) Events from short-lived backgrounds. (b) Events from long-lived backgrounds. Fit to the $0\nu\beta\beta$ decay signal $Q_{\beta\beta}$ at 2.458 MeV is shown in cyan. Image credit [59].

2.3. Effective Majorana Neutrino Mass: $0\nu\beta\beta$ Decay Bounds. Effective Majorana neutrino mass is defined as $m_{\beta\beta} \equiv |U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3|$. Neutrinoless double-beta ($0\nu\beta\beta$) decay is a hypothetical nuclear transition and is expressed as $(A, Z) \longrightarrow (A, Z+2) + 2e^-$. This lepton number violating [47] phenomenon if observed, will assign neutrinos Majorana characteristics of particle. $0\nu\beta\beta$ decay could provide effective Majorana neutrino mass assuming the decay is mediated by light Majorana neutrino. Experiments measuring $0\nu\beta\beta$ decay measure small peak generated by the sum of energy of energy of two electrons.

Different isotopes used by experiments searching for the signatures of $0\nu\beta\beta$ decay are, ^{76}Ge [48, 49], ^{82}Se [50], ^{100}Mo [51], ^{130}Te [52], ^{136}Xe [53, 54], ^{48}Ca [55], ^{96}Zr [56], ^{116}Cd [57], and ^{150}Nd [58]. The half-life sensitivity of an experiment is estimated using the expression, $T_{1/2}^{0\nu} \propto a\varepsilon \sqrt{\mathscr{E}/(B.\Delta E)}$ (with background) and $T_{1/2}^{0\nu} \propto a\varepsilon\mathscr{E}$ (background free), where a is the isotopic abundance, ε is the efficiency of the detection of $0\nu\beta\beta$ signal at the region of interest (ROI), B is the background index, ΔE is the energy resolution of the detector, and the exposure ($\mathscr{E}$) is given by the product of the mass of the isotope and run time.

KamLAND-Zen sets the strongest limit on the half-life of any $0\nu\beta\beta$ decay isotope to date, for ^{136}Xe as $T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ yr [59]. Energy spectrum of ^{136}Xe measured by KamLAND-Zen experiment (currently running) is shown in Figure 2. Energy spectrum of ^{76}Ge measured by GERDA experiment (final results) is shown in Figure 3.

By considering neutrinos to be a Majorana particle, its $m_{\beta\beta}$ is estimated for experimentally measured isotopic half-life using relation, $(T_{1/2}^{0\nu})^{-1} = G_{0\nu} g_A^4 |M_{0\nu}|^2 (m_{\beta\beta}^2/m_e^2)$. Here, $M_{0\nu}$ is the nuclear matrix element, $G_{0\nu}$ is the phase space factor, g_A is the axial coupling constant, m_e is the mass of electron. The tightest bounds imposed on the $T_{1/2}^{0\nu}$ of different isotopes by various experiments and estimated $m_{\beta\beta}$ values are mentioned in Table 3.

2.3.1. Main Challenges in the Measurement of Effective Majorana Neutrino Mass

(i) Enhanced energy resolution of detectors is to distinctly visualize the monoenergetic signal from the prominent two neutrino double-beta ($2\nu\beta\beta$) decay continuum and to reduce the background since sharper signal sits on less background

(ii) Mitigation of background is extremely challenging, and experiments are investigating various techniques to minimize the background at the ROI [60–62]

(iii) Requirement of large mass of the enriched $\beta\beta$ isotope is to enhance the statistics

(iv) Uncertainty in nuclear matrix element (model-dependent) leads to the uncertainty in $m_{\beta\beta}$ estimation

LEGEND-200 (^{76}Ge) [63] experiment is currently taking data. Next-generation experiments are planned to address some of the above challenges. Few upcoming experiments are AMoRE-II (^{100}Mo) [64], nEXO (^{136}Xe) [65], SNO+(^{130}Te) [66], SuperNEMO (^{82}Se) [67], LEGEND-1000 (^{76}Ge) [63], KamLAND-Zen 800 (^{136}Xe) [68], and NEXT-100 (^{136}Xe) [69] (isotopes corresponding to each experiment are shown in bracket).

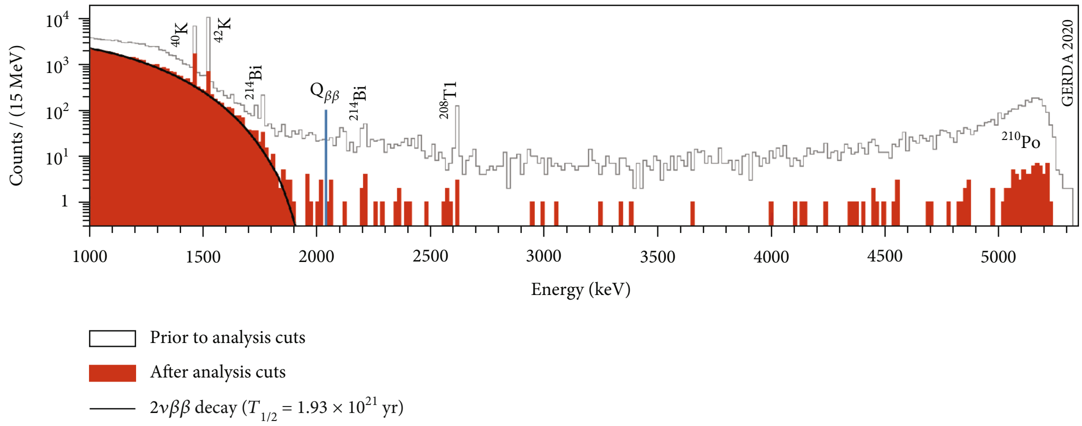


FIGURE 3: Energy distributed measured by GERDA experiment, expected $0\nu\beta\beta$ decay peak $Q_{\beta\beta}$ at 2039 keV is shown in blue. Image credit [49].

TABLE 3: Current bounds on $0\nu\beta\beta$ decay half-life and effective Majorana neutrino mass.

Experiment	Isotope	$T_{1/2}^{0\nu}$ (10^{26} yr)	$m_{\beta\beta}$ (eV)	Ref.
KamLAND-Zen	^{136}Xe	>2.3	<0.036-0.156	[59]
GERDA	^{76}Ge	>1.8	<0.08-0.18	[49]
Majorana demonstrator	^{76}Ge	>0.83	<0.113-0.269	[70]
EXO-200	^{136}Xe	>0.35	<0.09-0.29	[65]
CUORE	^{130}Te	>0.22	<0.09-0.31	[52]
CUPID-0	^{82}Se	>0.046	<0.263-0.545	[50]
CUPID-Mo	^{100}Mo	>0.015	<0.31-0.54	[51]

2.4. Neutrino Mass Squared Differences. In the old theory of electroweak interactions, formulated by Glashow, Weinberg, and Salam, lepton flavor was conserved and neutrinos were assumed as massless fermions. This simply means that leptons produced in a particular flavor state will remain in that state forever.

As soon the theory of two-component neutrino was developed, Pontecorvo proposed the idea of neutrino oscillation in 1957-1958 [71, 72]. Later, neutrino oscillation or conversion of the neutrino flavor was observed in the solar [10] and atmospheric [9] neutrino experiments. Therefore, solar and atmospheric neutrino anomaly was resolved by assigning oscillation phenomenon to neutrino. In 2015, the Nobel prize in physics was awarded to Kajita and McDonald for their landmark discovery of neutrino oscillation. These results of neutrino oscillation were subsequently confirmed by reactor experiment, such as KamLAND [73, 74] and long baseline experiment, such as NOvA [75]. Neutrino oscillation experiment measure the appearance or disappearance channel.

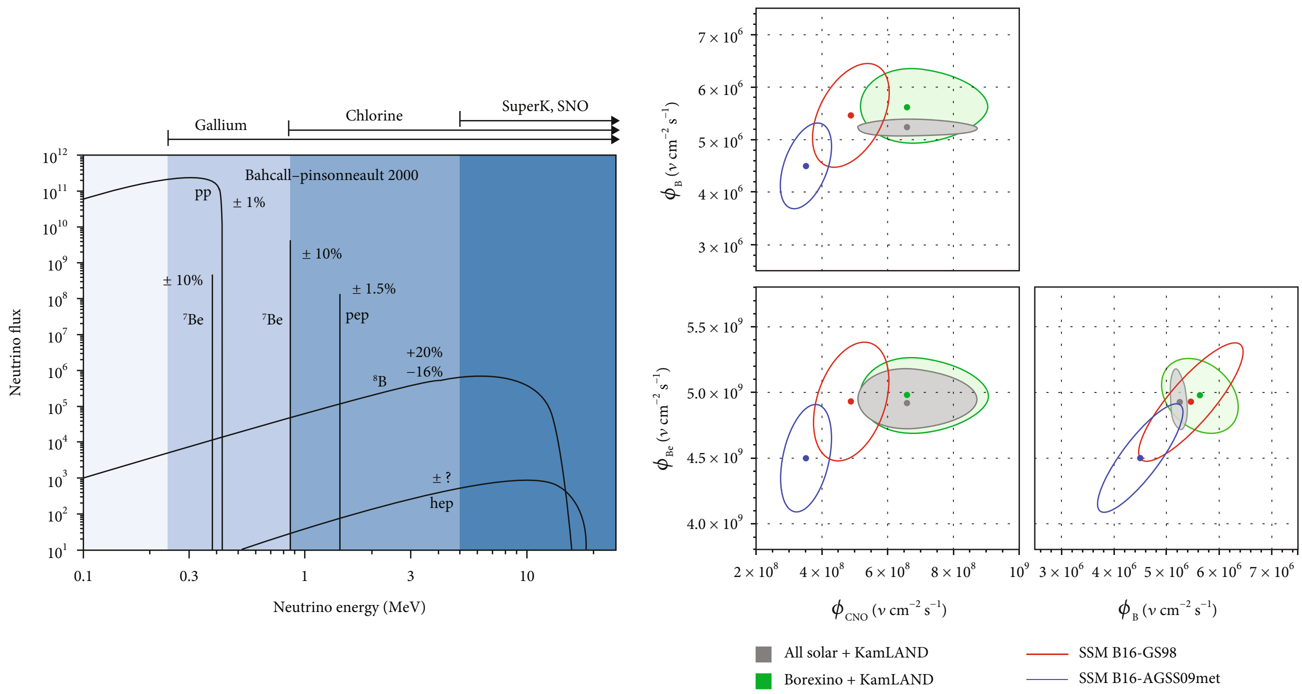
Due to quantum mechanical nature of neutrino, during propagation, neutrinos are represented as superposition of three mass eigenstates $|\nu_i>$, $(i=1,2,3)$ and detected as neutrino flavor state $|\nu_\alpha>$, $(\alpha=e,\mu,\tau)$ are related as $|\nu_\alpha> = \sum_{i=1}^{3} U_{\alpha i}|\nu_i>$, where $U_{\alpha i}$ is the mixing matrix or Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, [8, 76, 77]. The neutrino oscillations can be analytically expressed using PMNS matrix and two mass-squared differences of active neutrino; this makes minimum six parameters, solar mixing angle θ_{12}, atmospheric mixing angle θ_{23}, reactor mixing angle θ_{13}, solar mass-squared difference Δm_{21}^2, atmospheric mass-squared difference Δm_{31}^2, and Dirac CP-violating phase δ_{CP}. In a PMNS matrix, δ_{CP} informs about the difference in neutrino and antineutrino oscillations. For baseline (L), neutrino energy (E) and $\delta_{CP}=0$, in three flavor neutrino oscillation probability equations can be expressed as follows:

For small values of L/E,

$$P(\nu_e \longrightarrow \nu_\mu) = \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m_{23}^2 \frac{L}{E}\right). \tag{1}$$

For large values of L/E,

$$P(\nu_e \longrightarrow \nu_{\mu,\tau}) = \cos^2(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(1.27\Delta m_{12}^2 \frac{L}{E}\right) + \frac{1}{2}\sin^2 2\theta_{13}. \tag{2}$$



(a) (b)

Figure 4: (a) Predicted neutrino flux from solar standard model, image credit [83, 84]. (b) Estimated 1σ allowed region of solar neutrino flux by experiments and SSM, image credit [85].

Among the abovementioned six parameters, $\theta_{12}, \theta_{13}, \theta_{23}$, Δm^2_{21}, and $|\Delta m^2_{31}|$ are known with good precision, but sign of $|\Delta m^2_{31}|$, value of δ_{CP}, and octant of θ_{23} are still in the research phase. Sign of $|\Delta m^2_{31}|$ is unknown therefore the mass of active neutrinos can be represented by two hierarchies: normal hierarchy ($\Delta m^2_{31} > 0$) and inverted hierarchy ($\Delta m^2_{31} < 0$), where mass state distribution in this hierarchy indicates normal hierarchy: $m_3 > m_2 > m_1$ and inverted hierarchy: $m_2 > m_1 > m_3$. Several groups working on global fits to neutrino oscillation data [78–80].

2.4.1. Solar Neutrino Experiment. Sun is an abundant source of neutrino and produces electron neutrino in the process of fusion. The total solar neutrino flux comes from different fusion reactions as shown in Figure 4(a). Among these, the dominant contribution to solar neutrino flux comes from pp reaction (99.6%).

Solar neutrino experiments designed to study solar neutrino flux can be largely divided into two groups, (i) radiochemical: (a) gallium based experiment (GALLEX-GNO; SAGE) and (b) chlorine based experiment (Homestake); (ii) real time: (a) (heavy) water detectors (Kamiokande; Super-Kamiokande; SNO) and (b) liquid scintillator detectors (Borexino; KamLAND).

The solar neutrino fluxes predicted by standard solar model (SSM) at one astronomical unit are shown in Figure 4(a), where continuum sources are in units of cm^{-2} $s^{-1}MeV^{-1}$, and the line fluxes are in units of $cm^{-2}s^{-1}$.

Along with the SSM predictions, Figure 4(b) gives the current picture of the experimentally estimated flux of B, Be with respect to CNO (carbon–nitrogen–oxygen) and Be with respect to B. These estimated solar neutrino fluxes are compared with solar models, SSM B16-GS98 [81] and SSM B16-AGSS09met [81].

Allowed regions for Δm^2_{21} as a function of $\sin^2\theta_{12}$ from all solar neutrino data is shown in Figure 5. From accelerator and short-baseline reactor neutrino experiments, a combined three-flavor analysis of solar and KamLAND data gives fit values for the oscillation parameter, $\Delta m^2_{12} = (7.53 \pm 0.18) \times 10^{-5} eV^2$ [17, 82]. Solar neutrino experiments are listed in Table 4.

Main Challenges in the Measurement of Mass-Squared Difference from Solar Neutrinos.

(i) Good energy resolution of detectors

(ii) Large fiducial mass of detector to reduce the statistical error

(iii) Suppression of U, Th, and ^{14}C and radon-daughter contamination inside the detector volume

(iv) Detector needs to be shielded by overburden of the Earth to reduce the cosmic background

(v) Accurate measurement of pp, pep, ^7Be fluxes in constraining Δm^2_{21} better

(vi) Oscillation tomography of the Earth will need solar neutrinos to be studied to get a better picture of oscillated neutrino flux

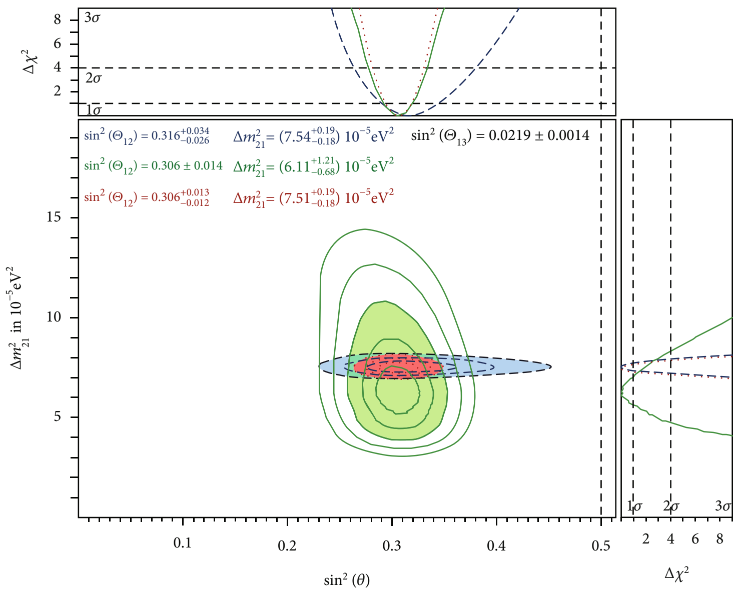


Figure 5: Dependency of Δm^2_{21} on $\sin^2\theta_{12}$ from all solar neutrino data for allowed 1σ, 2σ, 3σ regions where green represents SK+SNO, blue represents KamLAND, and red represents for combined result. Image credit [91, 92].

Table 4: Solar neutrino experiments (LS: liquid scintillator, $x = e, \mu, \tau$).

Experiment	Material	Reaction	Threshold (MeV)	Ref.
SNO	D_2O	$\nu_e + d \longrightarrow e^- + p + p$	3.5	[93]
		$\nu_x + d \longrightarrow \nu_x + p + n$		
		$\nu_x + e^- \longrightarrow \nu_x + e^-$		
SK	H_2O	$\nu_x + e^- \longrightarrow \nu_x + e^-$	3.5	[94]
KamLAND	LS		0.5/5.5	[95]
Homestake	C_2Cl_4	$\nu_e + {}^{37}Cl \longrightarrow e^- + {}^{37}Ar$	0.814	
Borexino	LS	$\nu_x + e^- \longrightarrow \nu_x + e^-$	0.19	[96–98]
SAGE	^{71}Ga	$\nu_e + {}^{71}\text{Ga} \longrightarrow {}^{71}\text{Ge} + e^-$	0.233	[99]
GALLEX-GNO	$GaCl_3$	$\nu_e + {}^{71}\text{Ga} \longrightarrow {}^{71}\text{Ge} + e^-$	0.233	[99]

(vii) Minimization of uncertainties in the fiducial volume due to the vertex shift and uncertainty in energy scale due to water transparency in the Cherenkov signals

(viii) Detection of neutrinos from hep reaction since their contribution to neutrino flux is very small

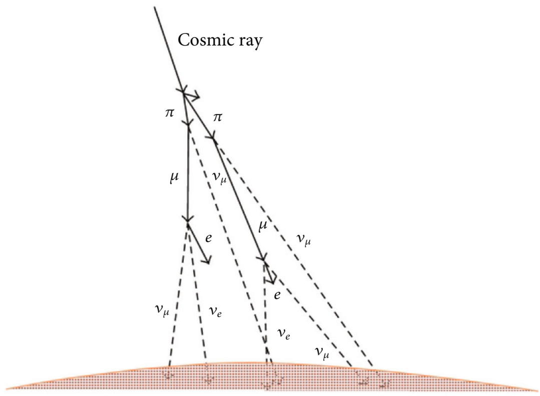
(ix) Precision in the measurements of neutrinos produced from CNO cycle

(x) Uncertainties in solar models affect the predictions of solar neutrino fluxes

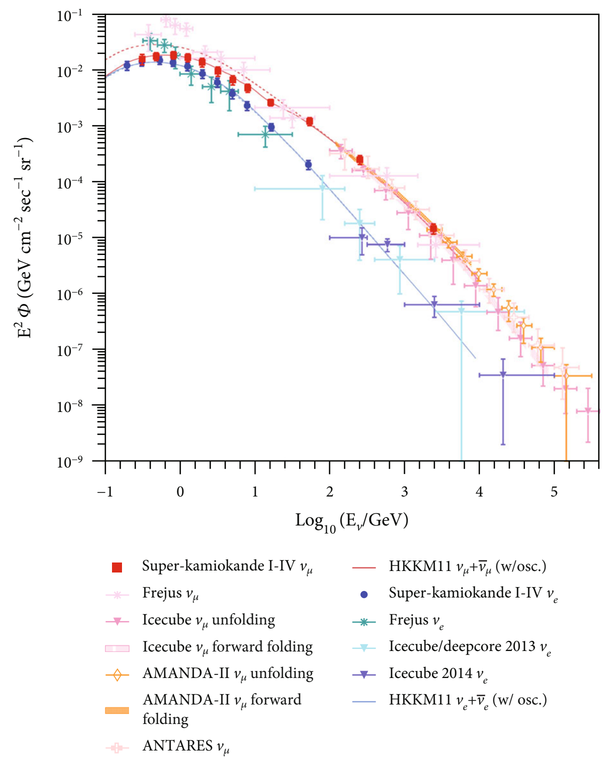
Upcoming experiments addressing the above challenges are SNO+ (liquid scintillator) [66, 86], JUNO (linear alkylbenzene) [87], Hyper-Kamiokande (water Cherenkov) [88], DUNE (liquid argon) [89], and DARWIN (liquid xenon) [90].

2.4.2. Atmospheric Neutrino Experiment. Cosmic ray particles are mostly protons, these protons after entering the Earth's atmosphere interacts with atmospheric nuclei present at high altitude. These high-energy nuclear interactions produce many pi mesons and less abundantly produced kaons. These mesons are unstable and decay into other particles. The π^+ meson decays into a μ^+ and a ν_μ. This produced μ^+ are also unstable particles which further decay into an e^+, ν_e, and $\bar{\nu}_\mu$ as shown in Figure 6(a). Similar decay process takes place for unstable π^- meson and kaons. The neutrino produced in these processes are known as atmospheric neutrinos. The atmospheric flux consists of both neutrinos and antineutrinos.

Atmospheric neutrino flux as a function of neutrino energy is shown in Figure 6(b). The energy of these atmospheric neutrinos varies from few MeV to few PeV range and their path lengths are suitable to probe many of the prevailing neutrino puzzles. When these neutrinos



(a)



(b)

FIGURE 6: (a) Production of atmospheric neutrinos. Image credit [104]. (b) Atmospheric neutrino flux. Image credit [105].

TABLE 5: Atmospheric neutrino experiments.

Experiment	Material	Δm^2_{32} (10^{-3}) eV^2	Ref.
Super-Kamiokande	H_2O	$2.50^{+0.13}_{-0.20}$ (NO)	[108]
IceCube	Ice	$2.31^{+0.11}_{-0.13}$ (NO)	[109]
ANTARES	H_2O	$2.0^{+0.4}_{-0.3}$	[110]
Kamiokande	H_2O		[111]
Soudan2	Fe		[112]
IMB	H_2O		[113]

TABLE 6: Reactor neutrino experiments.

Experiment	Material	Δm^2_{32} (10^{-3}) eV^2	Ref.
Daya Bay	Liquid scintillator	$2.471^{+0.068}_{-0.070}$ (NO) $-2.73^{+0.14}_{-0.14}$ (IO)	[118]
RENO	Liquid scintillator	$2.63^{+0.14}_{-0.14}$ (NO) $-2.73^{+0.14}_{-0.14}$ (IO)	[121]
Double Chooz	Liquid scintillator	θ_{13}	[122]
KamLAND	Liquid scintillator	θ_{12}, Δm^2_{21}	[82]

(antineutrinos) pass via Earth, the matter effects [100] influence the oscillation probability as the oscillation parameters $\sin^2\theta_{13}$ and Δm^2_{32} are replaced by their matter equivalents. Matter effects play a significant role in distinguishing neutrino mass hierarchy since atmospheric neutrino flux has L/E dependency. Current atmospheric neutrino experiments are listed in Table 5.

Upcoming experiments sensitive to neutrino mass ordering are Hyper-Kamiokande (4.0 σ for runtime of 10 years) [91, 101], DUNE (3.0 σ for runtime of 10 years) [89, 91], KM3NeT/ORCA (4.4 σ for normal ordering and 2.3 σ for inverted ordering for runtime of 3 years) [91, 102], and IceCube Upgrade (3.8 σ for normal ordering and 1.8 σ for inverted ordering for runtime of 6 years) [91, 103].

Main Challenges in the Measurement of Mass-Squared Difference from Atmospheric Neutrinos.

(i) Large fiducial mass of detector to reduce the statistical error

(ii) Underground deployment of detector to reduce the cosmic muon flux

(iii) Uncertainty in atmospheric neutrino flux since flavor changes with neutrino energy

(iv) Smearing in neutrino energy and neutrino direction measurement

(v) Neutrino flavor identification

Table 7: Accelerator neutrino experiments.

Experiment	Material	Δm^2_{32} (10^{-3}) eV^2	Ref.
NOvA	Liquid scintillator	$2.48^{+0.11}_{-0.06}$ (NO) $-2.54^{+0.11}_{-0.06}$ (IO)	[75]
T2K	Water Cherenkov	$2.45^{+0.07}_{-0.07}$ (NO) $-2.43^{+0.07}_{-0.07}$ (IO)	[126]
MINOS+	Steel scintillator	$2.40^{+0.08}_{-0.09}$ (NO) $-2.45^{+0.07}_{-0.8}$ (IO)	[135]
ICARUS T600	Liquid argon	$\nu_\mu \longrightarrow \nu_e$	[124]
SND@LHC	Tungsten	ν_μ	[136]
FASERν	Tungsten	ν_μ, $\bar{\nu}_\mu$	[137]

(vi) Reconstruction of the direction of neutrino energy

(vii) Degeneracy due to uncertainty in neutrino parameters [106].

Upcoming experiments under development addressing the above challenges are KM3NeT/ORCA (water Cherenkov) [102], IceCube-Gen2 (ice Cherenkov) [103], INO (iron) [107], and Hyper-Kamiokande (water Cherenkov) [88].

2.4.3. Reactor Neutrino Experiment. Along with the energy production by nuclear fission, the nuclear reactors also produce flavor pure source of antineutrino ($\bar{\nu}_e$) flux, which is well understood, and this special feature makes reactors a "free" and copious neutrino source for the study. In reactor neutrino physics, we use inverse beta decay (IBD) where antineutrino will interact with the proton of detector target and produce a positron which annihilates an electron (prompt signal) and a neutron which is captured afterwards (delayed signal).

We can broadly categorize the reactor experiments into (i) short baseline (~1 km) and (ii) long baseline (~100-1000 km) reactor experiments. Three short baseline reactor neutrino experiments which looked for antineutrino disappearance with the main objective to measure last unknown neutrino oscillation angle θ_{13} are Double Chooz in France [114], RENO in South Korea [115], and Daya Bay in China [116]. All three experiments used detectors which included liquid scintillator target loaded with 0.1% of Gadolinium. The results of the three experiments for $\sin^2 2\theta_{13}$ are Double Chooz: 0.102 ± 0.012 [117]; Daya Bay: 0.0856 ± 0.0029 [118]; RENO: $0.0892 \pm 0.0044\,(\text{stat.}) \pm 0.0045\,(\text{sys.})$ [119]. These experiments can also add knowledge to the value of the effective combination of mass, which can be expressed as

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}. \quad (3)$$

At the same time, we can also extract information regarding the sign (+ for NO, - for IO) of a phase $\Phi_\odot$ which depends on solar parameters. The upcoming reactor experiment JUNO have the potential to determine the neutrino mass ordering at $\geq 3\sigma$ to be 31% by 2030 [120]. Current reactor neutrino experiments are shown in Table 6.

Main Challenges in the Measurement of Mass-Squared Difference from Reactor Neutrinos.

(i) Only $\bar{\nu}_e$ disappearance channel can be analyzed

(ii) Decrement of reactor neutrino flux as a function of distance because antineutrino flux is isotropic

(iii) Difficulty in computation of $\bar{\nu}_e$ spectrum, because neutrino spectrum of each decay isotope is different

(iv) About 75% of $\bar{\nu}_e$ produced by reactor remains undetected

(v) Suppression of neutron induced by cosmic-ray muons

(vi) Elimination of cosmogenic production of radioactive isotopes; ^{12}B, ^{8}Li, and ^{6}He inside the detector volume

Upcoming experiments resolving the above challenges are SNO+ (^{130}Te) [66] and JUNO (linear alkylbenzene) [87].

2.4.4. Accelerator Neutrino Experiment. The most controlled manner to neutrino production is by means of particle accelerators. The accelerators at FNAL, CERN, and J-PARC boost protons at high energies and crash into heavy target; emergent debris would primarily be the unstable pions, resulting into the beam of ν_μ and $\bar{\nu}_\mu$ as $\pi^\pm \longrightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$. Neutrino beams are then propagated towards the detectors. For short-baseline neutrino experiments, MicroBooNE [123], ICARUS [124], and SBND [125] receive unoscillated neutrino flux, whereas oscillated neutrino flux is received by long-baseline experiments, NOvA [75], T2K [126], and DUNE [89]. Current accelerator neutrino experiments are shown in Table 7.

Main Challenges in the Measurement of Mass-Squared Difference from Accelerators Neutrinos.

(i) Large fiducial mass of detector to collect high statistics of neutrino event data

(ii) Production of intense beam of neutrinos requires high power proton accelerator

(iii) Deep underground location of detector

(iv) Reduction of proton beam-related background

(v) Large distance between neutrino source and detector

(vi) Reduction of uncertainty in mixing angle (θ_{23}) and determination of its octant

(vii) Elimination of neutrons (produced from cosmogenic, $^{238}U/^{238}Th$, etc.) interacting detector volume

(viii) Neutrino energy reconstruction due to nuclear effects and nuclear properties, for example, pion produced via neutrino interaction, gives rise to fake neutrino events, [127–130].

Upcoming experiments addressing the above challenges are SBND (liquid argon) [125], MOMENT (water Cherenkov) [131], PROMPT (iron) [132], SHiP (tungsten) [133], DsTau (tungsten) [134], Hyper-Kamiokande (water Cherenkov) [88], and DUNE (liquid argon) [89].

3. Conclusion

To summarize, determination of neutrino mass is a difficult task. We have given a brief overview of current experimental challenges in a neutrino mass measurement. Current limits on effective electron antineutrino mass from β decay by KATRIN and effective Majorana neutrino mass from $0\nu\beta\beta$ decay by KamLAND-Zen, GERDA, Majorana Demonstrator, EXO-200, CUORE, CUPID-0, and CUPID-Mo are presented. Current bounds on neutrino mass-squared differences from neutrino oscillation by SNO, Super Kamiokande, KamLAND, IceCube, ANTARES, Daya Bay, RENO, NOvA, T2K, and MINOS+ are discussed. Present bounds on the sum of neutrino masses from cosmological measurements by Planck, combined with BAO, RSD, Pantheon, DES, and Lyman α, are discussed.

Given the effort of many experiments, a measurement of the absolute neutrino mass may be around the corner, especially considering cosmology. And given the interplay of all the observables, the underlying model can be tested.

Data Availability

No data is generated in this article.

Disclosure

This article is submitted to arXiv with the arXiv ID [2305.12654 [hep-ex]].

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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