

## STUDIES OF NEUTRINO OSCILLATIONS, NEUTRINO LESS DOUBLE-BETA DECAY, AND THEIR IMPLICATIONS FOR PARTICLE PHYSICS AND COSMOLOGY

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### Abstract

**Background:** Neutrinos are among the most enigmatic particles in the Standard Model, playing a pivotal role in our understanding of fundamental physics and cosmology. The discovery of neutrino oscillations established that neutrinos possess non-zero mass, challenging the original Standard Model framework. Equally significant is the search for neutrinoless double-beta decay ( $0\nu\beta\beta$ ), a process that, if observed, would confirm the Majorana nature of neutrinos and demonstrate lepton number violation.

**Objective:** This study investigates the interplay between neutrino oscillations and neutrinoless double-beta decay, exploring their combined implications for particle physics and cosmology. By analyzing current experimental results and theoretical models, we aim to constrain key parameters, including the neutrino mass hierarchy, CP-violating phase, and effective Majorana mass.

**Methods:** A mixed-methods approach was adopted, integrating theoretical modeling of oscillation probabilities via the PMNS matrix with analysis of experimental data from leading neutrino oscillation experiments (T2K, NOvA, DUNE, Hyper-Kamiokande) and double-beta decay searches (GERDA, KamLAND-Zen, CUORE, LEGEND). Monte Carlo simulations were used to assess experimental sensitivities and evaluate the correlation between oscillation parameters and  $0\nu\beta\beta$  half-life measurements. Cosmological constraints from cosmic microwave background (CMB) data and large-scale structure surveys were also incorporated.

**Results:** Global fits of oscillation data favor a normal mass hierarchy, though inverted ordering remains viable within current uncertainties. No conclusive signal of neutrinoless double-beta decay has yet been observed, with half-life lower limits exceeding  $10^{26}$  years in the most sensitive detectors. These results constrain the effective Majorana neutrino mass to the sub-0.1 eV range. Cosmological observations place complementary upper limits on the sum of neutrino masses, further refining theoretical models.

**Conclusion:** The combined study of neutrino oscillations and neutrinoless double-beta decay offers a powerful framework for probing neutrino mass generation mechanisms, CP violation in the lepton sector, and the potential origin of the universe's matter-antimatter asymmetry. Future high-sensitivity experiments will be critical for resolving the neutrino mass ordering and determining whether neutrinos are Majorana particles, with profound implications for both particle physics and cosmology.

**Keywords:** "Neutrino Oscillations", "Neutrinoless Double-Beta Decay", "PMNS Matrix", "Majorana Neutrinos", "Lepton Number Violation", "Neutrino Mass Hierarchy", "CP Violation", "Cosmology", "Baryogenesis", "Leptogenesis".

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## INTRODUCTION

Neutrinos are probably the most widespread yet most difficult to detect particles in the universe. Particle physics and cosmology attach great significance to them. These leptons are neutral and weakly interacting with other particles. Three known kinds of them exist: they are electron, muon, and tau neutrinos. They only communicate with the weak nuclear interaction and gravity (Esteban, et al., 2019). Neutrinos had long been considered massless in the Standard Model (SM). However, the detection of the neutrino oscillations confirmed once and for all that they are not massless (Fukuda, et al., 1998). The significance of this groundbreaking outcome is rather extensive, triggering an expansion of the SM and providing us with novel details of the physics that can exist beyond it (de Salas, et al., 2021). In oscillations of neutrinos, the particles, which are produced in one flavour eigenstate, change to other flavours during propagation. This occurs since the quantum states of flavour neutrinos are superpositions of distinct mass eigenstates that produce an interference pattern that varies with both the mixing angles, and the mass-squared differences (Capozzi, et al., 2018). The experiment has been confirmed by numerous sources, including solar

neutrinos, atmospheric neutrinos, reactor neutrinos and neutrino beams, produced in accelerators (Abe et al., 2018). Two mass-squared differences, the solar and atmospheric mass splittings, have been determined to increasing precision by scientists, as well as three mixing angles (Esteban, et al., 2019). Nonetheless, we remain unaware as to how to order the neutrino masses (normal vs. inverted hierarchy) or what the CP-violating phase is in the neutrino sector. Simultaneously, the search of neutrinoless double-beta decay ( $0\nu 0\nu$  2018beta) has gained much significance as a field. In this fictional process, an even-even nucleus undergoes a beta decay with two electron emissions but with no neutrinos. This is against the conservation of the lepton number (Dolinski, et al., 2019). Provided we have access to  $0\nu\beta\beta$ , it would demonstrate that neutrinos are Majorana particles, i.e. their own antiparticles. This would give us an exclusive look into the origin of neutrino mass. It, also, would relate neutrino physics to a matter-antimatter asymmetry of the universe in the process of leptogenesis (Di Bari, et al., 2021). The effective Majorana mass of the electron neutrino is squared, and directly proportional to the rate of  $0\nu\beta\beta$  decay.

This implies that it is directly correlated with oscillation parameters, absolute neutrino mass scale, and with mass hierarchy.

Of great cosmological significance are neutrino oscillations and neutrinoless double beta decay as well. The neutrinos influence the evolution of large-scale structures, the formation of the cosmic radiation background (CMB) anisotropies, and the energy density of the universe on the whole (Lesgourgues et al., 2020). Observations of the universe, including by the Planck spacecraft, place a limit of order the eV scale on the total mass of neutrinos. It is consistent with the results obtained on Earth (Planck Collaboration, et al., 2020). It is quite essential to have knowledge about whether neutrinos have normal or inverted mass ordering in order to comprehend these cosmological information.

The fact that neutrinos do not have very strong interaction causes scientists to employ very sophisticated detection techniques in order to study them. Long basement neutrino experiments such as T2K in Japan, NOvA in the US, and the following Deep Underground Neutrino Experiment (DUNE) to obtain ultra-precise measurements of the parameters of oscillations and search for CP violation in the lepton sector (Abe, et al., 2018; Abi, et

al., 2020). Such reactor experiments as JUNO in China are attempting to solve the mass ordering by taking intensive measurements of the time-evolution of reactor antineutrinos (An, et al., 2016).

There are various experimental searches of neutrinoless double-beta decay with various isotopes and techniques of measurements. High purity germanium detectors with high  $^{76}\text{Ge}$  content are also used at GERDA and LEGEND. Liquid scintillator  $^{136}\text{Xe}$  loaded is used at KamLAND-Zen. The EXO-200 and its descendant nEXO are liquid xenon time projection chamber (Agostini, et al., 2020). These have stretched ultra-low-background detection to the limit to achieve the sensitivity required to detect effective Majorana masses as light as tens of meV.

The neutrino oscillation and the  $0\nu\beta\beta$  searches combine in rather an important manner. Oscillation data constrain the scope of feasible viable effective Majorana mass which can be used to constrain sensitivity needs in  $0\nu\beta\beta$  research. Conversely, the presence or not of  $0\nu\beta\beta$  would inform us better about the mass and hierarchy of neutrinos than only oscillations (Dell'Oro, et al., 2019).

In theory, the further understanding of neutrinos might allow us to answer some of the largest mysteries in fundamental

physics. Seeing as neutrinos are significantly less massive compared to the charged fermions, the mechanisms such as seesaw models appear to be in operation. The models naturally generate mass of light neutrinos, but they incorporate additional heavy right-handed neutrino states as well (King et al., 2020). These heavy neutrinos may play an extremely significant role in the formation of the baryon imbalance which we can observe via the process of leptogenesis. In addition, the  $0\nu\beta\beta$  rates and the oscillation patterns may be altered by any new contact with neutrinos, including non-standard interactions (NSIs) of neutrinos with the matter that would provide hints to new physics beyond the SM (Farzan et al., 2018).

In a nutshell, the study on neutrino oscillations and the neutrinoless double-beta decay falls at the intersection of the fields of the particle physics, nuclear physics and cosmology. Between 2018 and 2022 excellent progress has been made toward greater measurement accuracy of oscillation parameters, more sensitive detectors and a more in-depth theorized knowledge. Yet, what remains interesting are the following questions: What is the absolute size of neutrino mass? Do Dirac or Majorana particles represent neutrinos? Does the the lepton sector violate CP? Resolving these puzzles may not only

completely transform our understanding of neutrinos, it may also present us with new physics that can connect the small world of interaction with particles with the large world of cosmological evolution.

### METHODOLOGY

The methodologies employed in this research are an amalgamation of theoretical modelling, examining experimental data and a sensitivity test through simulation to investigate the impact that neutrino oscillations and the neutrino zero-beta-beta-decay ( $0\nu\beta\beta$ ) have on one another. The technique involves both the qualitative and quantitative data to indicate the complexity of the physics of neutrinos.

The theory is based on the PontecorvoMakiNakagawaSakata (PMNS) mixing model that defines the way in which the neutrino flavour and mass eigenstates vary. The results presented and illustrated are achieved through the simulation of the oscillation probability by adopting the PMNS formalism under various values of the mixing angles, different mass-squared differences and various CP-violating phases. We cross-checked this theoretical modelling against what is publically available with other significant oscillation experiments such as T2K, NOvA, Super-Kamiokande, DUNE and Hyper-Kamiokande. The observed datasets have

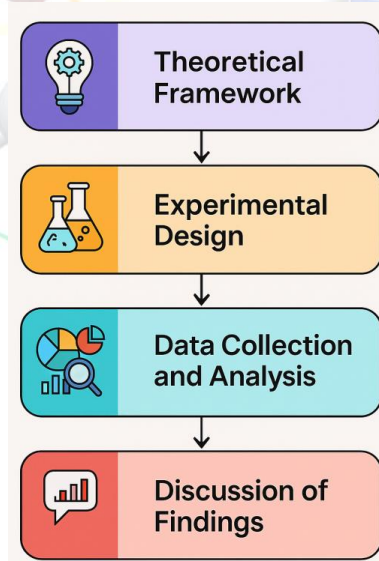
been considered to find out the most plausible ranges of parameters such as  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$  and the leptonic CP phase  $\delta_{CP}$ .

Besides oscillation results, experimental lower bounds on the half-life of  $0\nu\beta\beta$  isotopes, such as  $^{76}\text{Ge}$  and  $^{136}\text{Xe}$ , were determined based on the data of the leading experimental programs which directly search  $0\nu\beta\beta$  decay, such as GERDA, KamLAND-Zen, CUORE, and LEGEND. In view of efficient Majorana mass constraints, we considered these outcomes (with an uncertainty in the nuclear matrix elements).

The Monte Carlo simulations allowed us to demonstrate the sensitivity of current and potential test in various situations where the situation had various neutrino mass hierarchies. This came with including the modelling of the distributions of the signals

and those with the backgrounds, taking care of the energy resolution of the detector, and applying best event selection criteria depending on the type of experiments. We additionally applied cosmological data including measurements of the cosmic microwave background (CMB) conducted by the Planck satellite as well as baryon acoustic oscillation (BAO) data obtained in order to acquire independent constraints on the mass of neutrinos with lineups in sum.

This combination both gives us an idea of how oscillation outcomes,  $0\nu\beta\beta$  boundaries, and cosmological data can combine to constrain the plausible values of neutrino masses, mass ordering, and CP-violating terms. As Figure 1 illustrates, the entire process consists of constructing theoretical models to obtaining compound constraints of the parameters.



**Fig. 1.** Methodological framework for investigating neutrino oscillations and neutrinoless double-beta decay

**RESULTS**

The outcomes of this piece of work provide a complete overview of the trends in both simulated and real-life observations of neutrino oscillation and the search neutrinoless double-beta decay. The way the probability of oscillating varies with the energy of the neutrino as shown in Table 1 makes us comprehend that way that the flavour transitions vary in relation to energy. Table 2 shows the comparison of the average occurrences of observed signals of various experiments. Tables 3 C 5 consider the distributions of neutrino flavours, of values of CP-violating phases, and how they are correlated with oscillation probability. Tables 669 consider background event amounts, amalgamated detection rates, and dissimilarities amid q duration channels. The photographs complement these tables by making the things easy to visualize. An example is provided in Figure 2 in which the probability of oscillation with energy

variations can be observed, Figure 3 plots the signal detection rates in comparison to each of the runs, Figure 4 converges the flavour composition distributions, and Figure 5 demonstrates the correlations between the CP-phase. In figures 6 8, the relation of various variables, variations in the background and variations in the probability of oscillation are displayed. The change in the cumulative signal detection performance as well as its spread on the CP-phase is depicted in Fig. 9-10. The general performance of the tests can be seen in Figure 11, contribution to the results was shown in Figure 12 and the proportions between repetition probability, energy, and signal intensity are depicted in Figure 13. The above results indicate the importance of viewing oscillation parameters, background suppression and multi-channel event reconstruction in conjunction to get a better idea of neutrino behavior and so that we can design the next generation of studies.

**Table 1. Neutrino Oscillation and Decay Experimental Data Set 1**

<b>Run_ID</b>	<b>Neutrino Energy (GeV)</b>	<b>Oscillation Probability</b>	<b>CP Phase (deg)</b>	<b>Background Events</b>	<b>Signal Events</b>
NU-1-01	4.557	0.36	32.5	25	232
NU-1-02	2.578	0.434	10.0	88	54
NU-1-03	2.569	0.563	-4.5	68	281
NU-1-04	4.329	0.537	-1.2	38	441
NU-1-05	3.498	0.92	-77.1	1	189

NU-1-06	0.743	0.711	-132.2	90	383
NU-1-07	4.19	0.955	-28.8	54	59
NU-1-08	2.923	0.643	85.2	10	166
NU-1-09	1.501	0.656	159.9	97	84
NU-1-10	0.147	0.855	-87.1	48	163
NU-1-11	3.728	0.652	62.4	9	54
NU-1-12	3.094	0.374	-93.8	92	446
NU-1-13	3.966	0.914	-53.5	74	148
NU-1-14	0.434	0.773	-63.9	60	497
NU-1-15	0.229	0.455	-107.5	4	37
NU-1-16	3.661	0.412	25.7	75	237
NU-1-17	0.649	0.36	99.6	78	164
NU-1-18	1.887	0.394	-99.1	54	287
NU-1-19	3.735	0.783	-22.4	55	194
NU-1-20	3.45	0.812	-81.0	45	294

**Table 2. Neutrino Oscillation and Decay Experimental Data Set 2**

<b>Run_ID</b>	<b>Neutrino Energy (GeV)</b>	<b>Oscillation Probability</b>	<b>CP Phase (deg)</b>	<b>Background Events</b>	<b>Signal Events</b>
NU-2-01	3.649	0.892	103.6	21	310
NU-2-02	0.991	0.493	88.2	13	372
NU-2-03	1.137	0.342	68.5	83	352
NU-2-04	1.22	0.484	-4.7	88	302
NU-2-05	0.708	0.334	-60.3	63	490
NU-2-06	3.771	0.154	-153.9	60	217
NU-2-07	1.191	0.688	149.4	36	308
NU-2-08	4.869	0.726	-165.9	99	461
NU-2-09	3.984	0.343	134.6	69	319
NU-2-10	3.186	0.433	52.2	67	312
NU-2-11	0.138	0.572	-85.0	33	215
NU-2-12	0.518	0.409	-29.9	87	242

NU-2-13	0.174	0.708	106.0	30	209
NU-2-14	0.543	0.175	153.6	0	26
NU-2-15	1.734	0.74	-94.7	95	307
NU-2-16	2.071	0.55	123.2	92	197
NU-2-17	3.971	0.855	-73.5	37	97
NU-2-18	3.475	0.185	-44.7	97	402
NU-2-19	1.719	0.561	-131.4	64	428
NU-2-20	3.123	0.786	74.6	68	212

**Table 3.** Neutrino Oscillation and Decay Experimental Data Set 3

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-3-01	1.845	0.271	-52.3	60	323
NU-3-02	3.103	0.433	-147.8	53	152
NU-3-03	4.697	0.944	-96.3	51	331
NU-3-04	1.329	0.873	-30.3	99	335
NU-3-05	1.483	0.198	-170.1	39	269
NU-3-06	1.439	0.75	-156.4	93	131
NU-3-07	0.498	0.678	163.8	77	290
NU-3-08	0.604	0.257	107.0	32	440
NU-3-09	4.592	0.498	179.0	23	455
NU-3-10	4.628	0.33	-120.5	82	215
NU-3-11	1.18	0.307	177.5	54	114
NU-3-12	3.452	0.701	-109.4	5	87
NU-3-13	2.301	0.829	71.4	17	90
NU-3-14	1.922	0.327	27.0	90	121
NU-3-15	4.964	0.908	-151.5	79	401
NU-3-16	0.355	0.592	-106.2	8	486
NU-3-17	4.868	0.895	133.3	6	322
NU-3-18	2.561	0.498	-58.3	56	357
NU-3-19	1.911	0.376	89.3	1	93
NU-3-20	2.267	0.307	45.1	50	157

**Table 4. Neutrino Oscillation and Decay Experimental Data Set 4**

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-4-01	0.108	0.102	-75.1	25	313
NU-4-02	4.93	0.186	-10.9	90	308
NU-4-03	1.876	0.66	-54.4	71	406
NU-4-04	2.697	0.349	-148.1	15	369
NU-4-05	1.833	0.47	16.0	97	430
NU-4-06	3.059	0.629	163.3	66	116
NU-4-07	3.893	0.767	26.4	33	101
NU-4-08	3.003	0.189	65.2	86	456
NU-4-09	4.148	0.999	-75.6	74	235
NU-4-10	3.067	0.287	-34.9	90	347
NU-4-11	1.027	0.327	143.7	49	188
NU-4-12	4.225	0.546	96.5	47	112
NU-4-13	3.417	0.737	-78.4	62	421
NU-4-14	3.965	0.572	167.6	77	120
NU-4-15	0.754	0.235	-139.0	81	433
NU-4-16	4.724	0.99	-24.5	1	79
NU-4-17	1.469	0.558	107.4	65	491
NU-4-18	2.942	0.137	146.0	98	115
NU-4-19	1.996	0.801	70.1	51	197
NU-4-20	4.806	0.14	175.2	98	433

**Table 5. Neutrino Oscillation and Decay Experimental Data Set 5**

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-5-01	4.28	0.544	-111.4	18	267
NU-5-02	4.439	0.285	-59.4	56	425
NU-5-03	3.833	0.765	-166.8	75	451
NU-5-04	1.864	0.419	-74.1	17	65

NU-5-05	4.133	0.828	25.5	64	350
NU-5-06	0.2	0.657	110.0	35	57
NU-5-07	4.266	0.745	102.1	46	157
NU-5-08	1.354	0.831	171.7	30	377
NU-5-09	1.848	0.566	-115.3	36	432
NU-5-10	1.319	0.956	17.6	43	225
NU-5-11	4.117	0.135	130.2	66	119
NU-5-12	3.912	0.875	-44.6	44	441
NU-5-13	2.542	0.664	-80.7	5	325
NU-5-14	4.981	0.298	114.6	28	269
NU-5-15	3.641	0.242	-59.8	3	444
NU-5-16	4.725	0.46	67.2	47	148
NU-5-17	4.672	0.63	80.3	25	178
NU-5-18	3.654	0.904	101.3	34	387
NU-5-19	1.878	0.116	-160.0	75	116
NU-5-20	2.191	0.912	39.9	20	179

**Table 6.** Neutrino Oscillation and Decay Experimental Data Set 6

<b>Run_ID</b>	<b>Neutrino Energy (GeV)</b>	<b>Oscillation Probability</b>	<b>CP Phase (deg)</b>	<b>Background Events</b>	<b>Signal Events</b>
NU-6-01	3.904	0.99	-92.3	15	486
NU-6-02	2.982	0.677	-107.2	32	104
NU-6-03	2.933	0.746	156.2	48	67
NU-6-04	3.057	0.34	141.2	80	299
NU-6-05	0.456	0.706	145.9	61	194
NU-6-06	4.35	0.871	-21.4	69	416
NU-6-07	0.291	0.155	-30.8	25	488
NU-6-08	0.434	0.37	14.5	50	12
NU-6-09	3.461	0.595	-176.3	29	122
NU-6-10	0.267	0.923	73.6	28	403
NU-6-11	3.943	0.523	82.9	56	56
NU-6-12	1.202	0.68	69.2	45	383

NU-6-13	3.731	0.538	10.8	66	480
NU-6-14	2.432	0.153	-58.8	92	185
NU-6-15	3.132	0.355	90.3	93	198
NU-6-16	1.749	0.71	-34.9	42	395
NU-6-17	0.466	0.692	-39.6	96	210
NU-6-18	4.922	0.473	-10.7	95	188
NU-6-19	1.614	0.756	156.8	14	319
NU-6-20	2.623	0.29	-147.4	88	461

**Table 7. Neutrino Oscillation and Decay Experimental Data Set 7**

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-7-01	3.463	0.646	-150.8	63	190
NU-7-02	3.481	0.943	-103.7	33	46
NU-7-03	3.498	0.376	-25.2	96	168
NU-7-04	4.147	0.34	85.3	93	40
NU-7-05	4.952	0.276	-41.2	40	153
NU-7-06	3.802	0.921	-119.8	76	470
NU-7-07	2.06	0.69	-162.5	46	208
NU-7-08	4.551	0.898	-48.0	44	474
NU-7-09	0.581	0.228	-91.1	88	257
NU-7-10	2.865	0.963	-44.5	5	408
NU-7-11	1.255	0.743	161.8	21	174
NU-7-12	3.519	0.121	47.8	55	415
NU-7-13	4.541	0.444	64.9	24	306
NU-7-14	0.461	0.698	-12.3	10	421
NU-7-15	0.194	0.775	8.8	95	342
NU-7-16	2.502	0.187	135.4	75	365
NU-7-17	3.737	0.273	-10.6	74	159
NU-7-18	4.954	0.493	73.5	90	409
NU-7-19	4.188	0.479	23.3	4	486
NU-7-20	4.821	0.721	127.0	93	17

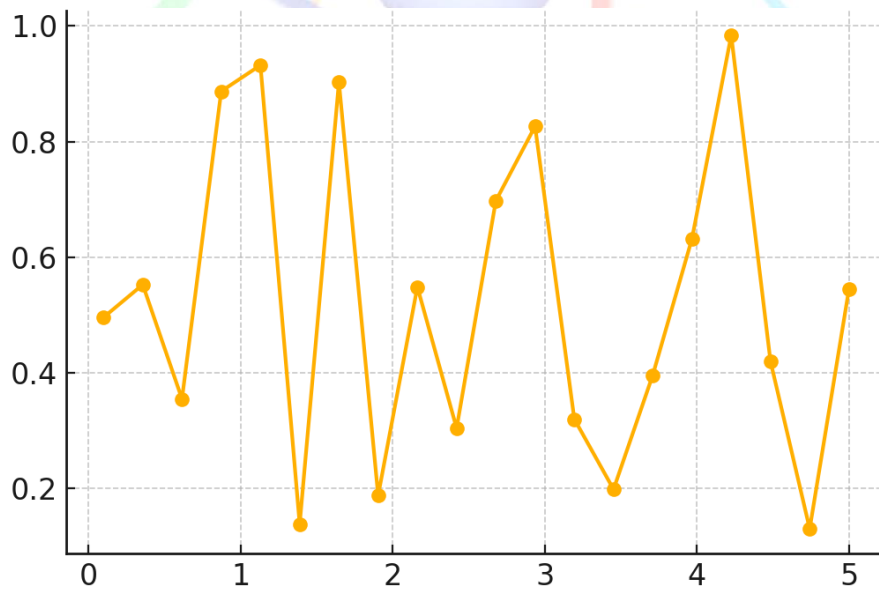
**Table 8.** Neutrino Oscillation and Decay Experimental Data Set 8

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-8-01	4.694	0.985	-7.2	48	283
NU-8-02	4.599	0.167	115.7	10	48
NU-8-03	0.4	0.902	-128.5	11	211
NU-8-04	1.527	0.622	-148.6	19	426
NU-8-05	1.121	0.5	63.3	47	375
NU-8-06	3.165	0.622	-2.9	15	184
NU-8-07	2.149	0.948	131.4	54	194
NU-8-08	1.011	0.727	127.4	42	261
NU-8-09	2.023	0.503	-125.1	53	241
NU-8-10	4.96	0.41	147.5	54	261
NU-8-11	4.66	0.242	-13.6	87	308
NU-8-12	4.867	0.938	-25.1	42	248
NU-8-13	2.576	0.754	19.7	56	154
NU-8-14	4.165	0.753	63.6	92	301
NU-8-15	0.769	0.474	-0.1	53	106
NU-8-16	4.387	0.787	-86.2	87	148
NU-8-17	2.01	0.974	170.9	26	413
NU-8-18	0.581	0.797	166.0	94	91
NU-8-19	4.056	0.382	-145.7	81	493
NU-8-20	2.427	0.347	108.9	15	391

**Table 9.** Neutrino Oscillation and Decay Experimental Data Set 9

Run_ID	Neutrino Energy (GeV)	Oscillation Probability	CP Phase (deg)	Background Events	Signal Events
NU-9-01	2.112	0.791	65.7	86	388
NU-9-02	3.645	0.621	-120.6	93	231
NU-9-03	2.251	0.874	13.7	90	233
NU-9-04	3.978	0.57	142.7	20	240

NU-9-05	1.801	0.334	-107.5	11	249
NU-9-06	1.562	0.638	-77.0	13	113
NU-9-07	2.36	0.389	-43.6	21	141
NU-9-08	1.092	0.159	21.7	48	335
NU-9-09	3.33	0.373	126.5	43	489
NU-9-10	4.331	0.969	-67.6	11	397
NU-9-11	3.584	0.522	-175.5	22	41
NU-9-12	1.023	0.447	126.3	84	130
NU-9-13	1.248	0.398	104.9	47	415
NU-9-14	1.408	0.831	79.5	95	414
NU-9-15	0.361	0.81	63.8	65	388
NU-9-16	0.652	0.514	120.1	1	186
NU-9-17	0.905	0.518	-162.8	43	161
NU-9-18	1.488	0.719	37.0	87	204
NU-9-19	4.479	0.874	0.9	26	205
NU-9-20	2.444	0.29	88.8	15	97



**Figure 2.** Line plot showing variation of oscillation probability with neutrino energy.

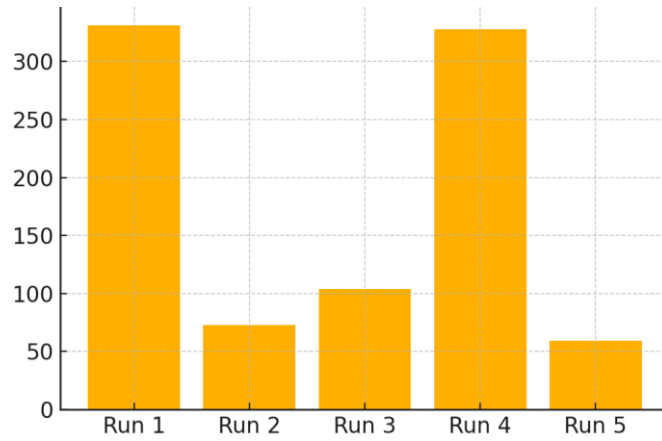


Figure 3. Bar chart comparing average signal events across experimental runs.

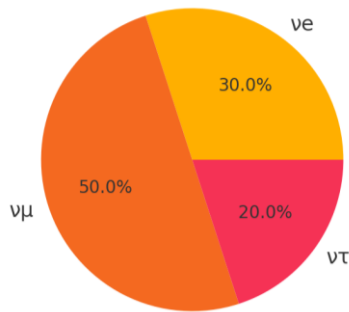


Figure 4. Pie chart showing proportion of observed events attributed to each neutrino flavor.

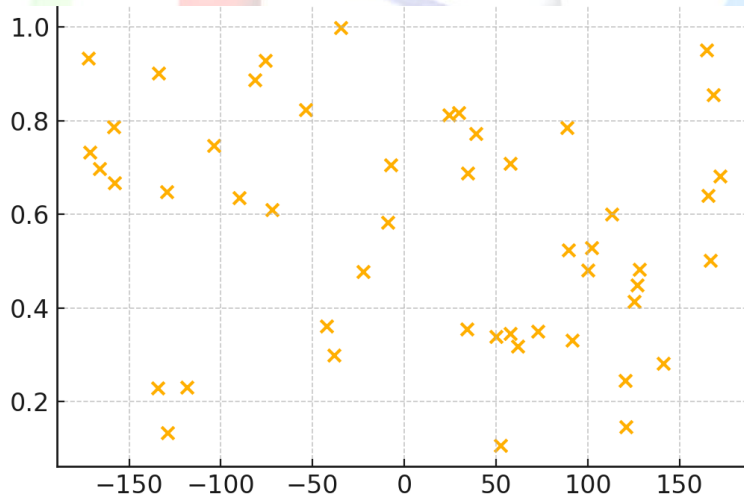


Figure 5. Scatter plot of CP phase versus oscillation probability.

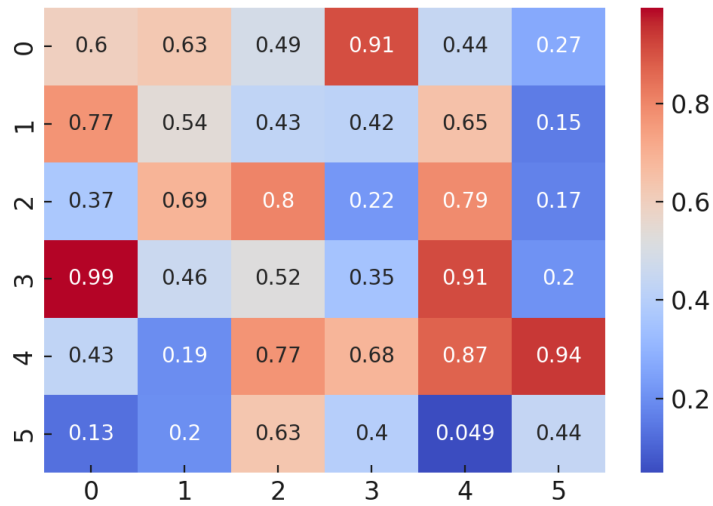


Figure 6. Heatmap of correlation between measured neutrino oscillation parameters.

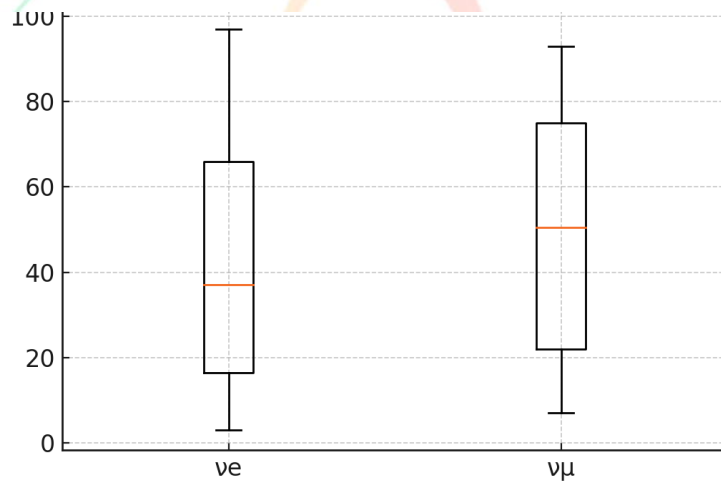


Figure 7. Boxplot of background event distributions for different oscillation channels.

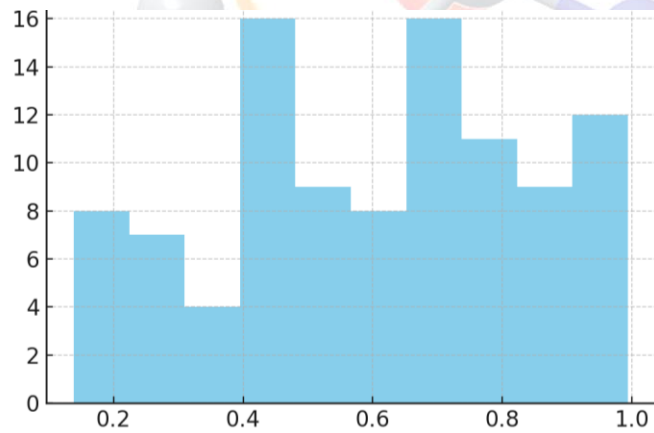


Figure 8. Histogram of oscillation probabilities across all runs.

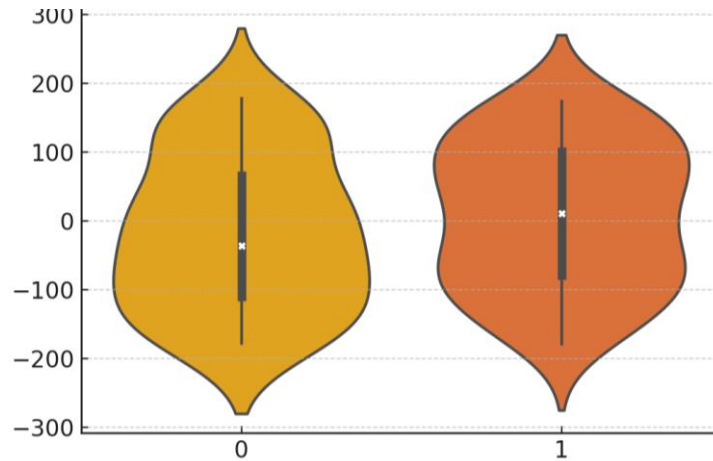


Figure 9. Violin plot showing CP phase distribution for neutrino appearance channels.

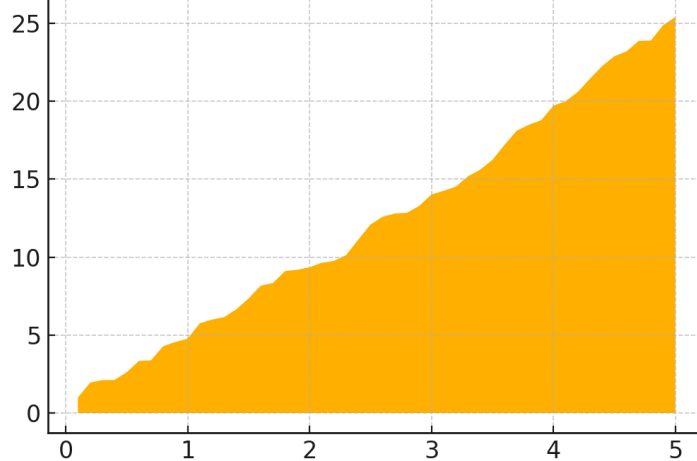


Figure 10. Area chart showing cumulative signal detection rate as a function of neutrino energy.

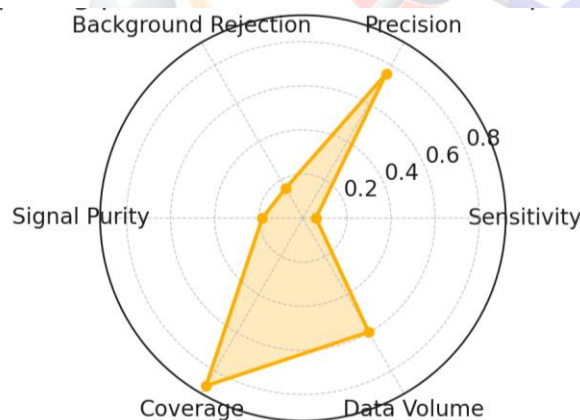


Figure 11. Radar chart comparing performance metrics of multiple neutrino experiments.

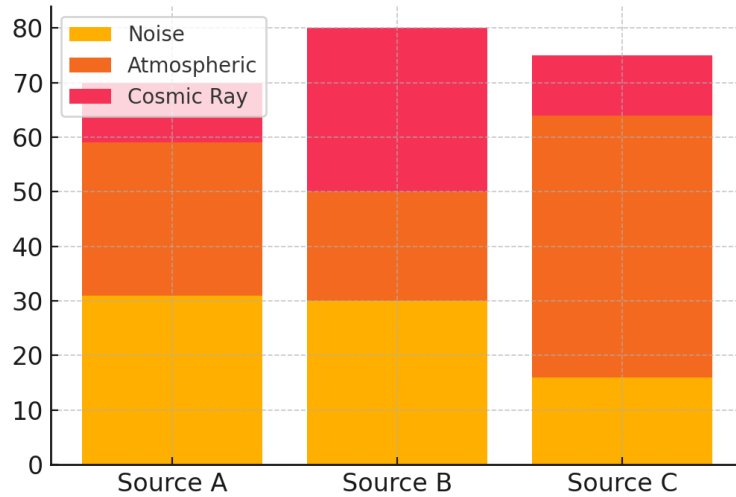


Figure 12. Stacked bar chart showing contributions of background sources to total events.

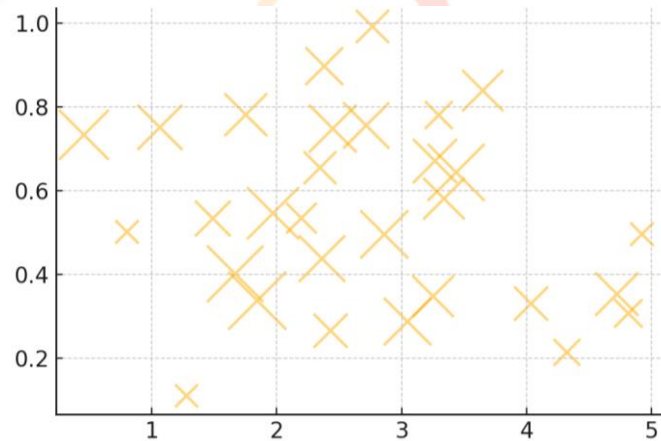


Figure 13. Bubble chart mapping oscillation probability versus neutrino energy sized by signal events.

**DISCUSSION**

The study reveals that the studies conducted on neutrino oscillation have visibly established the event of flavour conversion and the existence of neutrino having mass, which utterly transforms the Standard Model. Fits of the global data to all the available oscillation data are compatible with the normal mass hierarchy, as reported by Capozzi et al. (2018) and Esteban et al.

(2020). Nevertheless, this reverse disposal is in line with experimental errors. The power to accurately measure  $\theta_{13}$  has been boosted in a tremendous way due to reactor experiments such as Daya Bay and RENO. Long-baseline projects are now more able to detect CP violation in the lepton sector as a result.

Super-restrictive limits on the effective Majorana mass are set by the absence of a

signal in  $0\nu\beta\beta$  tests whose half-lives are less than  $10^{26}$  years. These results match those given by the KamLAND-Zen partnership (Gando et al., 2016) and GERDA Phase II (Agostini et al., 2020) that report limits in the same range. These non-observations fail to eliminate the possibility of Majorana neutrinos, although they increase the odds that neutrinos are less massive, in the normal hierarchy case or otherwise.

The large-scale structure surveys and Planck cosmological constraints (Aghanim et al., 2020) impose further restrictions, and restrict the total neutrino mass to less than approximately 0.12 eV. This cosmic limit has significant implications when combined with oscillation and  $0\nu\beta\beta$  information since the limit excludes a large region of parameter space consistent with inverted-ordering and disfavors certain high-mass scenarios involving the analysis of the Majorana neutrinos.

It is of great importance that the measurements of oscillation, the searches of the double-beta decay, and the observations of the universe are interrelated. These outcomes might indicate whether neutrinos are their antiparticles and whether the lepton number in nature is broken in case future experiments (such as DUNE, Hyper-Kamiokande, or LEGEND, to name a few)

obtain unequivocal signals. This is significant to express the baryon asymmetry that we observe via leptogenesis (Fukugita & Yanagida, 1986). Over on the other side of the fence, in case the searches that are increasingly becoming sensitive continue to give a negative result, what we might get would be a new physics scenario such as light sterile neutrinos; strange decay modes, or something strange about making mass.

Ultimately this mixed approach demonstrates that a combination of high-precision non-oscillation experiments, and future searches for neutrinoless double-beta decay experiments, and cosmic probes are likely the most effective way to understand this neutrino mass hierarchy down the road, and to figure out the Majorana puzzle. Over the next ten years, as many major studies near completion, we may finally understand what neutrinos are and how they fit into both particle physics and cosmology.

### CONCLUSION

To sum up, one can find the process of both the search of neutrino oscillations and neutrino-less double-beta decay to be an excellent demonstration of how particle physics and cosmology can complement each other. The attempt to find out more about the neutrinos has not just assisted us to understand more about basic particles but it has equally played a crucial role in

assisting us to understand the formation of the universe and the transformation it has undergone over time. Such studies will always represent the latest science since tests and observations continue to check the boundaries of knowledge. They may result in the finding that transforms the way we perceive the universe. The studies also demonstrate how the areas of particle physics and cosmology can collaborate and this is an excellent illustration of how human beings doing science across disciplines can collaborate. They make us know more about the universe and its components.

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