PROCEEDINGS OF SCIENCE

PoS(NOW2024)066

Summary of Session 3: Neutrino masses, states and interactions

Luca Pattavina[a,b] **and Noemi Rocco**[c]

[a] *Dipartimento di Fisica, Università di Milano - Bicocca,*
Piazza della Scienza 3, I-20126

[b] *INFN Sezione Milano - Bicocca,*
Piazza della Scienza 3, I-20126 Milano, Italy

[c] *Fermi National Accelerator Laboratory,*
Theoretical Physics Department, P.O. Box 500, Batavia, IL 60410, USA

E-mail: luca.pattavina@unimib.it, nrocco@fnal.gov

12th Neutrino Oscillation Workshop (NOW2024)
2-8, September 2024
Otranto, Lecce, Italy

1. Advances in Neutrino Physics and Beta Decay Measurements

The session at NOW2024 represented a comprehensive review of the latest developments in neutrino physics and nuclear beta decay research. These topics lie at the heart of contemporary efforts to extend our understanding of the universe beyond the Standard Model (SM) of particle physics. Central to the discussions were the unifying power of effective field theory (EFT), the precision and diversity of experimental techniques, and the growing synergies between theoretical models and experimental data. By combining these elements, the session showcased the progress in elucidating neutrino properties, exploring the fundamental nature of mass, and testing new physics scenarios.

The underlying themes of the session included the role of neutrino mass measurements, searches for lepton number violation (LNV), and the study of rare nuclear decays. These efforts provide unique insights into the properties of neutrinos and their role in the evolution of the universe, such as in the generation of the matter-antimatter asymmetry.

2. Highlights of Theoretical and Experimental Progress

2.1 Effective Field Theory (EFT) and Neutrino Decays

One of the key themes of the session was the application of EFT to beta and neutrinoless double-beta ($0\nu\beta\beta$) decays. EFT provides a systematic and hierarchical approach to connecting high-energy BSM theories with low-energy nuclear processes. This approach enables a unified interpretation of diverse experimental observations, reducing uncertainties in nuclear matrix elements (NMEs) and facilitating the exploration of lepton number violation.

In particular, the presentations highlighted how EFT frameworks incorporate a wide range of theoretical inputs, from hadronic structure to nuclear potentials. By bridging scales from TeV to MeV, these frameworks allow to address questions about the fundamental nature of neutrinos, including whether they are Majorana particles. Such insights have profound implications for our understanding of the baryon asymmetry of the universe and the mechanisms that generate neutrino masses [1].

2.2 Probing Neutrino Mass through Beta Decay

Direct measurements of the neutrino mass remain one of the most compelling challenges in physics. KATRIN's precise tritium beta decay experiments were showcased as a landmark achievement in reducing the upper limit on the effective electron neutrino mass (m_ν) to the sub-eV scale. The innovative combination of spectroscopic techniques, advanced detector technologies, and rigorous data analysis ensures KATRIN's role as a leading experiment in the field [2].

Complementing KATRIN, cryogenic detectors and calorimetric approaches, particularly those utilizing ^{163}Ho, present alternative methods for studying neutrino masses. These approaches leverage their ability to measure the entire decay spectrum with exceptional energy resolution, offering unique sensitivities to neutrino properties. Together, these complementary techniques represent a robust framework for unraveling the mystery of neutrino mass [3, 4].

2.3 Advances in Neutrinoless Double-Beta Decay Searches

The search for $0\nu\beta\beta$ decay continues to be a cornerstone of neutrino physics, with experiments like LEGEND and CUORE leading the way. These experiments use state-of-the-art techniques to achieve unprecedented levels of sensitivity to this rare process, which, if observed, would confirm the Majorana nature of neutrinos and demonstrate lepton number violation. LEGEND's use of enriched ^{76}Ge and CUORE's deployment of ^{130}Te within cryogenic calorimeters exemplify the strategic diversity in isotopic selection and detector design [5, 6].

Key achievements discussed include significant reductions in background contamination, improvements in energy resolution, and increased detector exposure. These advancements ensure that current-generation experiments are well-positioned to test theoretical predictions for $m_{\beta\beta}$ and inform the design of next-generation detectors capable of exploring even smaller mass scales.

2.4 Forbidden Beta Decays and Spectral Shapes

Forbidden beta decays, such as those involving ^{115}In, offer a unique window into nuclear physics and the detailed structure of weak interactions. These decays, which occur through higher-order processes, provide valuable benchmarks for refining nuclear models and improving predictions for rare event searches. The spectral shapes of these decays were analyzed in detail, revealing how deviations from theoretical expectations can offer insights into fundamental constants and parameters [7].

These studies not only contribute to a better understanding of nuclear processes but also play a crucial role in characterizing backgrounds for experiments like CUORE and LEGEND. By combining theoretical models with precise spectral measurements, researchers can further constrain uncertainties and enhance the sensitivity of searches for exotic phenomena.

2.5 Neutrino production and detection at accelerators

The intersection of accelerator-based neutrino experiments and high-energy physics is exemplified by initiatives like ENUBET and FASER. ENUBET's pioneering monitored neutrino beam concept offers unprecedented precision in neutrino flux measurements, addressing one of the dominant uncertainties in neutrino cross-section studies. This innovation is poised to benefit long-baseline neutrino experiments and improve our understanding of neutrino interactions [8].

Similarly, FASER's unique location within the LHC allows it to detect high-energy neutrinos produced in proton-proton collisions. This capability extends the neutrino physics program into energy regimes inaccessible to traditional experiments, bridging the gap between fixed-target and cosmic-ray studies. Together, these efforts highlight the potential of accelerators to advance both standard model measurements and searches for light long-lived BSM particles [9].

3. Neutrino interactions and beam physics: theoretical and experimental perspectives

The Neutrino Oscillation Workshop 2024 (NOW2024) highlighted the intricate interplay of theory and experiment in advancing our understanding of neutrino interactions. The session brought together cutting-edge developments in neutrino-nucleus scattering, cross-section measurements, and neutrino beam physics. These studies are foundational for addressing critical questions in neutrino oscillations, mass hierarchy, and the potential for beyond-Standard Model (BSM) physics.

The recurring theme throughout the session was the dual challenge of precision and complexity. On one hand, accurate modeling of neutrino interactions at the nuclear level is essential for interpreting experimental results. On the other, modern detector technologies demand innovative approaches to handle the intricate interplay of final-state interactions, nuclear effects, and beam systematics. Together, these efforts represent a transformative step in neutrino physics, paving the way for future discoveries.

4. Modeling neutrino-nucleus interactions

4.1 Theoretical Frameworks and Advances

The theoretical modeling of neutrino-nucleus interactions remains a cornerstone of neutrino physics. Recent advancements in EFTs, coupled with sophisticated nuclear models, have significantly enhanced our ability to predict cross-sections across different interaction channels. SuperScaling models, such as SuSAv2, extend traditional scaling approaches to incorporate meson exchange currents (MEC) and relativistic mean-field effects. These models accurately describe quasielastic (QE) scattering and provide insights into multinucleon excitations, enabling a detailed understanding of nuclear dynamics.

A notable area of focus was the role of final-state interactions (FSI) in reshaping outgoing particle kinematics. Advanced modeling techniques, including relativistic optical potentials (ROP) and intranuclear cascade (INC) models, offer powerful tools to simulate these effects. These approaches refine energy reconstruction algorithms, reducing biases that arise from complex nuclear environments. Additionally, modern semi-inclusive analyses, such as one-muon-one-proton ($1\mu 1p$) measurements, emphasize the importance of exclusive channels in unraveling the structure of neutrino-nucleus interactions.

4.2 Ab-Initio approaches and Monte Carlo simulations

Ab-initio methods, such as Green's Function Monte Carlo (GFMC) and Auxiliary Field Diffusion Monte Carlo (AFDMC), provide a first-principles approach to studying neutrino interactions with nuclei. These techniques achieve remarkable precision by incorporating realistic nuclear wavefunctions and two-body currents, offering virtually exact predictions for light nuclei. However, their application to heavier nuclei is limited by computational challenges, necessitating hybrid methods [10].

Complementing these efforts, advanced Monte Carlo generators play a pivotal role in bridging theory and experiment. By integrating ab-initio inputs with phenomenological models, these generators address the challenges of scale and complexity. Recent developments emphasize the inclusion of two-particle-two-hole (2p2h) contributions, resonant and deep inelastic scattering processes, and their interplay with nuclear medium effects. These enhancements ensure that Monte Carlo tools remain indispensable for interpreting data from current and next-generation experiments [11].

5. Experimental advances in neutrino cross-Section measurements

5.1 Liquid Argon Time Projection Chambers (LArTPCs)

The precision of liquid argon time projection chambers (LArTPCs) has revolutionized neutrino interaction studies. These detectors provide unparalleled spatial and calorimetric resolution, enabling detailed reconstruction of both leptonic and hadronic final states. Experiments utilizing LArTPCs, such as those in the Short Baseline Neutrino (SBN) program, have demonstrated their capability to disentangle complex final-state topologies. From charged-current quasielastic (CCQE) scattering to pion production and multinucleon events, LArTPCs are setting new standards for cross-section measurements [13].

A significant focus has been placed on understanding nuclear effects through novel observables, such as transverse kinematic imbalance (TKI). These variables isolate nuclear effects more effectively than traditional measurements, revealing the impact of nuclear ground-state distributions and hadronic reinteractions. By probing such effects in heavy nuclei like argon, these analyses refine our understanding of detector response and neutrino energy reconstruction [14].

5.2 Hadron production and beam physics

The physics of neutrino beams plays a central role in the precision of cross-section measurements. Modern experiments rely on detailed knowledge of hadron production to constrain beam flux uncertainties. Dedicated programs, such as NA61/SHINE, have systematically measured hadron yields from thin and replica targets, spanning the phase space of primary and secondary interactions [12]. These datasets are critical for reweighting Monte Carlo simulations, ensuring accurate flux predictions for experiments like T2K, DUNE, and Hyper-Kamiokande.

The interplay between hadron production data and neutrino flux simulations highlights the importance of comprehensive beam monitoring systems. Techniques such as secondary muon monitoring and near-detector flux measurements are essential for reducing systematic uncertainties.

6. Future directions

6.1 Synergy between theory and experiment

The session underscored the critical interplay between theoretical frameworks and experimental methodologies. Advances in modeling, from scaling approaches to ab-initio calculations, are directly informing the design and interpretation of experiments. Conversely, precise measurements from modern detectors provide valuable feedback for refining theoretical models. This synergy is particularly evident in the development of exclusive cross-section measurements, which bridge the gap between inclusive data and detailed nuclear dynamics.

6.2 Innovations in detector technology

The continued evolution of detector technology is expanding the frontiers of neutrino physics. From the high granularity of LArTPCs to the sophisticated calorimetry in water Cherenkov detectors, these innovations are enabling new levels of precision. Emerging techniques, such as high-pressure time projection chambers (HP-TPCs) and advanced scintillators, promise further improvements in particle identification and energy resolution.

6.3 Global Collaboration and Future Experiments

Looking ahead, the next generation of neutrino experiments will benefit from the collaborative efforts highlighted at NOW2024. Large-scale initiatives like DUNE and Hyper-Kamiokande will leverage the insights gained from current programs, integrating advanced modeling, cutting-edge technology, and comprehensive beam physics. These experiments are poised to address fundamental questions, from CP violation in the lepton sector to the nature of neutrino mass.

7. Advancing Neutrino Interaction Physics

The Neutrino Oscillation Workshop 2024 (NOW2024) highlighted the interplay of theoretical advancements and experimental precision in understanding neutrino interactions. Central themes included coherent elastic neutrino-nucleus scattering (CEνNS), the role of radiative corrections, and systematic improvements in cross-section measurements.

7.1 Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

CEνNS remains a crucial probe for weak interactions, offering insights into the neutron-number dependence of cross-sections and the Standard Model (SM). Recent results from CsI [15], argon [16], and germanium detectors [17] show consistency with SM predictions, with systematic uncertainties significantly reduced. Radiative corrections, including neutrino charge radius (NCR) effects, are now essential for precise interpretations, introducing flavor-dependent deviations and momentum-dependent terms that refine weak mixing angle measurements [18].

References

[1] V. Cirigliano, Z. Davoudi, J. Engel, R. J. Furnstahl, G. Hagen, U. Heinz, H. Hergert, M. Horoi, C. W. Johnson and A. Lovato, *et al.* J. Phys. G **49**, no.12, 120502 (2022) doi:10.1088/1361-6471/aca03e [arXiv:2207.01085 [nucl-th]].

[2] M. Aker *et al.* [KATRIN], Nature Phys. **18**, no.2, 160-166 (2022) doi:10.1038/s41567-021-01463-1 [arXiv:2105.08533 [hep-ex]].

[3] B. Alpert, M. Balata, D. Bennett, M. Biasotti, C. Boragno, C. Brofferio, V. Ceriale, D. Corsini, P. K. Day and M. Gerone, *et al.* Eur. Phys. J. C **75**, no.3, 112 (2015) doi:10.1140/epjc/s10052-015-3329-5 [arXiv:1412.5060 [physics.ins-det]].

[4] L. Gastaldo, J. Low Temp. Phys. **209**, no.5-6, 804-814 (2022) doi:10.1007/s10909-022-02780-2 [arXiv:2203.01395 [physics.ins-det]].

[5] S. Calgaro [LEGEND], Nuovo Cim. C **47**, no.3, 69 (2024) doi:10.1393/ncc/i2024-24069-0.

[6] D. Q. Adams *et al.* [CUORE], Nature **604**, no.7904, 53-58 (2022) doi:10.1038/s41586-022-04497-4

[7] L. Pagnanini, G. Benato, P. Carniti, E. Celi, D. Chiesa, J. Corbett, I. Dafinei, S. Di Domizio, P. Di Stefano and S. Ghislandi, *et al.* Phys. Rev. Lett. **133**, no.12, 122501 (2024) doi:10.1103/PhysRevLett.133.122501 [arXiv:2401.16059 [nucl-ex]].

[8] F. Bramati, F. Acerbi, I. Angelis, L. Bomben, M. Bonesini, A. Branca, C. Brizzolari, G. Brunetti, M. Calviani and S. Capelli, *et al.* Nuovo Cim. C **47**, no.3, 68 (2024) doi:10.1393/ncc/i2024-24068-1

[9] T. Inada [FASER], Nucl. Instrum. Meth. A **1065**, 169547 (2024) doi:10.1016/j.nima.2024.169547.

[10] N. Rocco, Front. in Phys. **8**, 116 (2020) doi:10.3389/fphy.2020.00116.

[11] L. Alvarez-Ruso *et al.* [NuSTEC], Prog. Part. Nucl. Phys. **100**, 1-68 (2018) doi:10.1016/j.ppnp.2018.01.006 [arXiv:1706.03621 [hep-ph]].

[12] H. Adhikary *et al.* [NA61/SHINE], [arXiv:2410.23098 [hep-ex]].

[13] P. Abratenko *et al.* [ICARUS], Eur. Phys. J. C **83**, no.6, 467 (2023) doi:10.1140/epjc/s10052-023-11610-y [arXiv:2301.08634 [hep-ex]].

[14] K. Abe *et al.* [T2K], Phys. Rev. D **103**, no.11, 112009 (2021) doi:10.1103/PhysRevD.103.112009 [arXiv:2102.03346 [hep-ex]].

[15] D. Akimov *et al.* [COHERENT], Phys. Rev. Lett. **129**, no.8, 081801 (2022) doi:10.1103/PhysRevLett.129.081801 [arXiv:2110.07730 [hep-ex]].

[16] D. Akimov *et al.* [COHERENT], Phys. Rev. Lett. **126**, no.1, 012002 (2021) doi:10.1103/PhysRevLett.126.012002 [arXiv:2003.10630 [nucl-ex]].

[17] S. Adamski, M. Ahn, P. S. Barbeau, V. Belov, I. Bernardi, C. Bock, A. Bolozdynya, R. Bouabid, J. Browning and B. Cabrera-Palmer, *et al.* [arXiv:2406.13806 [hep-ex]].

[18] M. Atzori Corona, M. Cadeddu, N. Cargioli, F. Dordei and C. Giunti, JHEP **05**, 271 (2024) doi:10.1007/JHEP05(2024)271 [arXiv:2402.16709 [hep-ph]].