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Editorial

Neutrino Physics in the Frontiers of Intensities and Very High Sensitivities 2016

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Neutrinos are the messengers of our universe about phenomena from astrophysical and Earth-bound laboratory processes alike. Despite the amazing progress in experimental, phenomenological, and theoretical neutrino physics, a remarkable number of questions associated with neutrino properties and interactions still remain unanswered. We collected articles in this volume that address topics of the current searches on these mysteries: validation that neutrinos are massive after we measure their absolute mass scale; particle-antiparticle conjugation properties of neutrinos related to the distinction (Dirac neutrinos) or no distinction (Majorana neutrinos); neutrino's moments, or at least the existence of electric dipole moment, magnetic moment, charge radius, and so forth; roles of neutrinos in astrophysics and cosmology; cosmic background neutrinos, and whether they contribute to dark matter's influence of the large-scale structure formation; high energy neutrinos associated with black-hole X-ray binary systems, active galactic nuclei, and so forth. Before delving in the particular articles we have for our readers some news and ideas on these open questions from the current research in our field of Intensity and High Sensitivity Frontier.

The finite neutrino mass may have already played a fundamental role in the appearance of little matter in our universe. Initially there were approximately equal amounts of matter and antimatter particles. A more reasonable progression should be that all matter would have been annihilated with all the antimatter. This is one of the most prominent unknown mysteries of the universe and it has inspired a great number of extensions of the standard model. Some of these are mentioned in the articles in this special issue. For example, the mass of neutrinos implies that they may have magnetic moment. In turn, this allows for electromagnetic interactions among neutrinos and other standard model fermions as in neutrino-electron scattering. In addition to the weak interaction contribution mediated by W-boson exchange, there will be a photon exchange contribution to the interaction. Hence, the measured neutrino scattering cross sections provide an upper bound on the neutrino magnetic moment. On a grander scale, the remarkable developments of neutrino and gamma-ray astronomy have to show new telescopes and detector facilities like the ground-based observatory for gamma-ray astronomy named Cherenkov Telescope Array (CTA), the Ice-Cube neutrino observatory at the South Pole, and the KM3NeT at the Mediterranean Sea. These state-of-the-art technologies are used to detect neutrinos in a wide energy range and much higher than the energies of man-made accelerator beams. Such neutrinos are produced from very interesting galactic and extragalactic sources. Their distributions are closely related to the evolution of the various structures of our universe. The dynamical mechanisms producing astrophysical neutrinos strongly affect the neutrino emissivity and require an interdisciplinary approach.

Furthermore, one of the most interesting mysteries in neutrino physics is the number of neutrino species. Many recent experimental measurements are consistent with only three types of neutrinos coupled to the W- and Z-bosons. Therefore, if other (also called sterile) neutrino species exist

in nature, they must interact either much weaker with the W and Z or not at all. A great number of ongoing and future, high sensitivity experiments aim to determine if there exist any sterile neutrinos, how many species there are, and how strong their coupling is. We cover all of these examples of neutrino mysteries in our special issue.

In the world of High Sensitivity Frontier, extensive experimental programs and related theoretical works are going on to study the fundamental neutrino properties and weak interactions beyond Standard Electroweak Model (SM). Neutrinoless double beta decay (DBD) beyond SM is a high sensitivity unique probe for studying the Majorana nature of neutrinos (ν), the absolute ν-mass scales, the mass hierarchy, the right-handed weak interactions, and others beyond SM. Nuclear matrix elements (NMEs) $M^{0\nu}$ for $0\nu\beta\beta$ decay are crucial for extracting neutrino properties from DBD experiments. The NMEs are connected with the light mass mechanism in that they contribute multipole states in intermediate nuclei as calculated in the pn-QRPA model. For example, the magnetic hexadecapole ($M4$) γ-decay NMEs are relevant to high multipole DBD NMEs. The cumulative sums of the NMEs define the energy region of the intermediate states. Also, experimental NMEs are compared with those of the quasi-particle model (QPM) and microscopic quasi-particle phonon model (MQPM). The fact that the experimental NMEs are reduced with respect to the QPM and MQPM NMEs suggests the existence of the nuclear and nonnuclear reduction effects on the high multipole NMEs. Our special issue includes articles on the $M4$ γ-decay NMEs relevant to DBD NMEs and analyses of the intermediate state contributions to these matrix elements.

The articles in our special issue discuss venues to disentangle the mixed right-handed and left-handed mechanisms (λ and η) from the neutrino mass mechanism in the left-right symmetry. It is mostly shell model calculations that are carried out for the angular and energy distributions of the two beta rays for medium heavy nuclei. These calculations are used to identify the individual mechanisms, the mass mechanism, the λ dominance in competition with the mass mechanism, and the η dominance in competition with the mass mechanism.

The NMEs for the standard model process of the two neutrino DBDs obtained with the microscopic approach offered by the deformed self-consistent mean field are useful for the analysis of $0\nu\beta\beta$ decay. The same nuclear Hamiltonian is entering to the two processes while the calculated NMEs are directly compared with experimental lifetimes. The phase space factors (PSFs) in the neutrino producing processes of single $\beta^{\pm}$-decay, and bound electron-capture, require accurate electron and positron wave functions obtained by modeling the solution of the Dirac equation with realistic nuclear potential. In this volume we include theoretical papers on $2\nu\beta\beta$ decay NMEs, and on the relevant phase space.

From the world of the accelerator driven, long baseline, Intensity Frontier, there have been new scientific results and tensions that have made the 2016 a very interesting year and will be shaping the debate of neutrino physics for the next several years. The debate that caught our attention is coming from the results presented at the biennial summer conferences Neutrino 2016 (http://neutrino2016.iopconfs.org) and 38th International Conference on High Energy Physics (http://www.ichep2016.org), the two biggest gatherings of the community.

Hosted in Japan, the T2K (Tokai to Kamioka) experiment has the world leading data set within the first three years of its run since 2010, corresponding to beam accumulation of almost 7.5×10^{20} protons-on-target. T2K had dazzled the neutrino world in 2012 reporting the first clear observation of e-like neutrino interactions in a ν_μ beam. The measurement validated the models with large values for the θ_{13} mixing angle that are used in many of the articles in this issue. This measurement has earned for T2K the 2016 Breakthrough Prize shared with K2K, KamLAND, Daya Bay, Super-Kamiokande, and SNO (https://breakthroughprize.org). After its confirmation by the reactor driven neutrino experiments (Double CHOOZ, Daya Bay, RENO, etc.), the large value for θ_{13} has opened the door to a legitimate hope of measuring the remaining, known yet unmeasured, mysteries of neutrino physics. The community is now planning to spend billions on the next generation Deep Underground Neutrino Experiment (DUNE) to search for the neutrino mass hierarchy and the CP violation in the lepton sector with its superior designed capabilities.

In the summer of 2016, T2K made yet another impression first by performing the first ever search for the CP violation in neutrino oscillations by comparing the appearance and disappearance channels in both neutrino and antineutrino beam modes. They performed this by switching the polarity of the secondary beam guiding system (horns) which changes the constitution of the tertiary beam to have more antineutrinos. Collecting another data sample with the antineutrino beam mode, again about 7.5×10^{20} protons-on-target within the last two years, T2K observed 4 e-like and 66 μ-like events at the far detector 295 km away. Compared to the 32 e-like and 135 μ-like neutrino interaction events observed during the initial measurement with the neutrino mode run, this observation is consistent with maximal disappearance. It is also the first ever indication that the CP violation may be maximal, which means that the value of δCP is probably near $-\pi/2$ for either mass orderings. The T2K measurement excludes the CP conservation case ($\delta\text{CP} = 0$) by more than 2σ as well. Such a case of a CP conservation would imply that the observed events in both modes are consistent which is no more than 17% probable at a confidence level of 90% in this size data set.

The tension to the T2K announcement (arXiv:1701.00432) which describes the assumption is used in the analysis to constrain the T2K data, of maximal coupling with a weak preference to the second octant ($\sin^2\theta_{23} > 0.5$). The tension is all on θ_{23}. The other critical constraint, the value of $\sin^2\theta_{13}$, is at no danger of being challenged. The value of θ_{13} comes from the exceptionally well defined "reactor measurement" as it has come to be known. The reactor experiments (Double CHOOZ and Daya Bay) have picked up the mantle of precision measurement experiments and have established the best ever measurements of this mixing.

The twist in the story of the 2016 summer conferences is that the NOνA experiment, hosted in the USA, made waves by announcing (arXiv:1701.05891) a new measurement with crucial deviation from the usually accepted maximal value for θ_{23}. All the previous calculations by NOνA and all other experiments in the field (SK, MINOS, T2K, etc.) use $\theta_{23} = \pi/4$. This implies for the mass mixing of the neutrino masses that there is a symmetry of the muonic and tau (τ) meson components. At a level of just 2σ, for the moment, this NOνA precision measurement excludes maximal mixing and therefore the symmetry models of muon-tau in the neutrino sector.

NOνA measured 78 μ-like interactions after the oscillation of a 2 GeV neutrino beam travelling underground for 810 km to a 14-kiloton surface detector. This corresponds to a data sample of just over 6.0×10^{20} protons-on-target after two years of world record intensity of its primary proton bean. The analysis of this observation suggests two different degenerate values for $\sin^2\theta_{23}$ of about 0.4 or 0.6 at 68% confidence level and for both mass hierarchies. This result disfavors the maximal mixing of $\sin^2\theta_{23} = 0.5$ at 2σ significance. When this result is used to constrain the data of the other NOνA observation (arXiv:1703.03328) of 33 e-like neutrino interactions in the far detector from the same beam and time period, it further disfavors the lower octant suggesting only the $\sin^2\theta_{23} \approx 0.6$ as the more probable option for the mixing. This challenges the models of the muon and tau equal mixing in the ν_3 eigenstate of neutrino and the calculations that constrain the data from T2K and all the previous experiments.

A race for a precision measurement with much more data is warranted and the host laboratory of NOνA has already initiated plans to increase the intensity of the NOνA beam. Of course, it would be most interesting if NOνA demonstrates that their reported value of the nonmaximal mixing at the high octant persists with increasing precision but the T2K never confirms it. In the meantime, with a strategic move and until the new beam intensity is established, NOνA experiment is switching its beam to antineutrino mode in an effort to catch up and test the hierarchy and CP violations reported by T2K.

As this race is heating up, more new, precision measurements, from observations from these leading experiments, with the prolific numbers of neutrino interactions, will provide new values that will shape the theory of neutrinos. If 2016 has been interesting with the new conflicting announcements during the world conferences, the next couple of years will be really intense full of new models and calculations in publications such as our special issue.

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