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Editorial

Editorial for the Special Issue "Recent Advances in Neutrino Physics: From Theory to Experiments"

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Among all the known particles in our Universe, neutrinos are definitely the most elusive and mysterious. Electrically neutral and much lighter than their charged leptonic partners, they barely interact with ordinary matter, providing severe challenges for both theoretical and experimental physicists. Yet, since their prediction in 1930, neutrinos have been playing a central rôle in particle physics, as they act as unique cosmic messengers complementary to photons and possible candidates for exotic forms of energy/matter. Remarkably, they have caught even more attention after the discovery of neutrino mass and mixing, offering promises in the hunt for new physics beyond the Standard Model. Despite the enduring effort, several questions remain open, such as the intimate nature of neutrinos (Dirac or Majorana) or the origin of their small masses. All of that makes neutrino physics an unparalleled arena where to concentrate efforts toward disclosing new future horizons in particle physics, astronomy and cosmology.

Starting from the above premises, the present Special Issue is intended to summarize recent advances and explore new developments in the field of neutrino physics. Along with theoretical aspects, several phenomenological achievements are examined, giving a broad overview of the present status of neutrino physics, the experimental progress needed to overcome the current technical limits and the upcoming round of projects to be launched in next years.

The contributions to this Special Issue cover different areas of physics, ranging from quantum theory, to gravitational and cosmological contexts. Three original manuscripts addressing neutrino dynamics in a quantum-corrected spacetime [1], non-unitarity in neutrino mixing from Noνa experiment [2] and shore shadow effects in Baikal [3], respectively, are complemented by as many reviews dealing with general Quantum Field Theory (QFT) of mixing and oscillations [4,5] and cosmological implications of neutrino decoupling from the early Universe to the current epoch [6]. The latter contribution, in particular, opens up intriguing perspectives in the future study of neutrinos, since it involves applications to the Cosmic Neutrino Background (CνB)—the frontier field of research in neutrino physics.

Paper [1] highlights the profound versatility of neutrino physics, as it explores the possibility to probe quantum gravity (QG) signatures in neutrino oscillations and decoherence. Specifically, the propagation of neutrino wave-packets is studied in a quantum-corrected Schwarzschild spacetime, showing that QG might significantly affect both oscillation and coherence lengths. Though being still below the current experimental sensitivity, the ensuing corrections are potentially measurable in the next generation of neutrino experiments, thus indicating the guidelines for an alternative search of non-classical features of gravity (further discussion along this line can be found in the recent review [7]).

It is commonly found that QG models fail to yield unitarily implementable dynamics. The problem of non-unitary neutrino mixing is the main subject of the contribution [2]. The analysis of this work is motivated by the fact that, should the mixing matrix for three

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active neutrinos be unitary, the oscillation between muon and electron neutrinos $\nu_\mu \to \nu_e$ over short baseline ($\lesssim$1 km) would then occur hardly. On the other hand, the probability for this process is not negligible in case of non-unitary mixing ("zero-distance" effect). This phenomenon is tested using Noνa near detector data, which allow to constrain the non-unitary parameters as $\alpha_{00} > 0.911$, $|\alpha_{10}| < 0.020$ and $\alpha_{11} > 0.952$ at 90% confidence level, in agreement with the limits obtained from short baseline neutrino measurements. This result is however in tension with far detector data of Noνa alone, which do not rule out the possibility of non-unitary mixing.

Staying in the phenomenological realm, in [3] Baikal-GVD neutrino telescope experiment is taken as a reference to estimate the underwater atmospheric muon flux based on GEANT-4 simulation. This study is crucial, since the measurement of individual charged particles (in particular muons) coming from primary cosmic rays enables to infer relevant distinguishing parameters to identify the chemical composition of the cosmic primary particles. Results of [3] show consistency with the shore shadow observed in the measurements in NT-96. Additionally, the advantage of the strategy in [3] over other approaches is that it can also be exploited to propagate the muons through long distances in matter like water, ice or earth, thus having a broader of applicability.

On the theory side, the contributions [4,5] contain a review of the quantum field theoretical formalism of neutrino mixing and oscillations. In more detail, the analysis of [4] deals with the rôle of canonical transformations in QFT of mixing and the ensuing inequivalence between the Fock spaces of energy and flavor eigenstates. Moreover, the dynamics of the mixed (interacting) fields is explicitly solved, leading to corrected oscillation formulas consistent with the definition of flavor vacuum in QFT.

The study of the inherent properties of flavor vacuum for mixed fields is deepened in [5]. It is shown that neutrino mixing phenomenon is associated with a non-trivial gauge structure and that flavor oscillations are related to multi-mode entanglement of single-particle states. In particular, flavor vacuum is found to be an entangled generalized coherent state of SU(2). Furthermore, a discussion of flavor-energy uncertainty relations is proposed along with the derivation of a lower bound on the precision of neutrino energy measurements.

Finally, contribution [6] presents a thorough investigation of relic neutrinos and their relevance in holding clues about the evolution of the Universe. Due to the interactions with electron and positron background, these neutrinos exhibit characteristic spectral distortions. Such effects are estimated in neutrino decoupling on the number and energy densities of $C\nu$B in the current Universe. Furthermore, the implications of spectral distortions on the capture rates are examined in direct detection of the $C\nu$B on tritium, with focus on PTOLEMY experiment. This analysis allows to infer the value $N_{eff} = 3.044$ for the effective number of neutrinos, consistently with predictions from particle physics.

To summarize, we emphasize that this Special Issue provides an introductory analysis of selected topics in current neutrino physics. Furthermore, it gives an overview of challenges on which prospective research should focus. Needless to say that some other fundamental aspects on neutrinos are not mentioned here. For a comprehensive analysis of these issues, we invite the reader to consult the pertinent literature.

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Abbreviations

The following abbreviations are used in this manuscript:

QFT	Quantum Field Theory
CνB	Cosmic Neutrino Background
QG	Quantum Gravity

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