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Neutrino Physics from Natural and Reactor Beams

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Natural and reactor neutrino investigations have been among the most active and successful fields of particle physics research over the past decades, accumulating important and sometimes unexpected achievements. Unquestionably, they have contributed to the history of physics through the unveiling of the neutrino oscillation phenomenon. In this work, the characteristics of these area of studies are reviewed, together with their bright perspectives for the next ambitious round of experimental efforts.

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1. Introduction

Natural neutrino beams measured so far are Solar Neutrinos, Atmospheric Neutrinos, Supernova Neutrinos from SN1987A, Geoneutrinos and Astrophysical Neutrinos. On the other hand, beams from reactors have acted as incident neutrino sources for many detectors, since the Savannah River experiment [1], which provided the first proof of (anti)neutrinos existence.

The current understanding of the neutrino mass-mixing properties (angles in the PNMS matrix [2][3][4] and mass-squared differences) stems from three of these beams (obviously, plus the outputs of the accelerator based neutrino experiments, not covered by this work): Solar and Atmospheric Neutrinos, as well as reactor beams.

There is a common “fil rouge” throughout this collective story, which is constituted by the sequence of initial experimental anomalies that in turn triggered further studies, eventually leading to the great discovery of neutrino oscillations. This breakthrough has then been followed by a broad program of precision measurements, still enduring, on which are based the exciting present enterprises and the bright future perspectives of the field. How this saga evolved in the three areas of Solar, Atmospheric and reactor studies and which are its future perspectives is the core of this work.

2. Solar Neutrinos

The nuclear hypothesis as energy-generating mechanism able to sustain the Sun over its 4.5 billion of years of existence was elaborated in its modern form in 1938, when Von Weizsacker postulated the CNO cycle and Bethe the p-p chain as the two possible sources powering our star.

In both cases, the nuclear production mechanism can be summarized through the overall equation

$$4^1H \rightarrow 4He + 2e^+ + 2\nu_e + energy.$$

How can it be proved experimentally? Well, neutrinos coming from the putative nuclear reactions are the smoking gun! They pass undisturbed through the solar matter and if detected at Earth they would prove unambiguously the nuclear hypothesis. This argument was put forward as a concrete possibility during the debate about neutrino detection just after the World War II, among other also by Pontecorvo.

From this prologue, the Solar Neutrino experimental investigation emerged, whose fascinating evolution over almost 50 years represents one of the pillars of the modern understanding of the neutrino properties.

2.1 The global Solar Neutrino scenario

On the experimental side, Solar Neutrino experiments constitute a successful 50 years long plot, commenced with the pioneering radiochemical detectors, i.e Homestake [5], Gallex/GNO [6] and Sage [7], continued with the Cerenkov detectors Kamiokande/Super-Kamiokande [8][9] in Japan, and SNO [10] in Canada, and with the last player which entered the scene, Borexino [11] at the Gran Sasso Laboratory, which introduced in this field the liquid scintillation detection approach. A common and distinctive features of all these set-ups has been the extreme radiopurity attained in the detecting medium as essential prerequisite for the rare event search of the extremely tiny Solar Neutrino flux.

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For more than 30 years, the persisting discrepancy between the experimental results and the theoretical predictions of the Solar Model formed the basis of the so-called Solar Neutrino Problem (SNP), which in the end culminated with a crystal clear proof of the occurrence of the neutrino oscillation phenomenon. Moreover, the other striking achievement has been the definite and conclusive quantitative assessment of the pp burning mechanism fueling the Sun.

On the theoretical side, it has been ascertained that at the temperatures characteristic of the core of the Sun both chains reactions postulated in 1938 could occur, being however the pp chain overwhelming with respect to the CNO cycle: the former indeed produces the vast majority of the energy (>99%) of the Sun, while the CNO contribution is estimated to less than 1 %.

Starting from this cornerstone, the effort to produce a solar model able to reproduce fairly accurately the solar physical characteristics, as well as the spectra and fluxes of the several produced neutrino components (named after the elements involved in the producing reactions), was led for more than forty years by John Bahcall [12]. This effort was crowned with the synthesis of the so-called Standard Solar Model (SSM), which represents a true triumph of the physics of XXth century, leading to extraordinary agreements between predictions and observables, in particular for the helioseismology characteristics (like the sound speed) of the Sun. Such a beautiful concordance, however, has been somehow recently spoiled, as a consequence of the controversy arisen regarding the surface metallic content of the Sun, stemming from a more accurate 3D modeling of the Sun photosphere. Therefore, there are now two versions of the SSM, according to the adoption of the old (high) or revised (low) metallicity of the surface [13]. The paradox here is that the more recent evaluation of the (low) metallicity, supposed to be more accurate, leads to a clear disagreement with the helioseismology data, while the older estimate pointing to a higher metallicity continues to represent the optimal interpretation of the acoustic wave propagation in the Sun.

Remarkably, solar neutrinos are endowed with the intrinsic capability to shed light on this astrophysical conundrum, since the high or low metallicity variants of the SSM originate different predictions for the neutrino fluxes, which become very significant for the neutrinos stemming from the CNO cycle.

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2.2 Solar Neutrino experiments

The outputs of the pioneer radiochemical experiment Homestake and Cerenkov detector Kamiokande gave origin to the Solar Neutrino Problem, e.g. the already highlighted discrepancy between the experimental determined neutrino flux and the corresponding theoretical prediction from the SSM.

In a radiochemical experiment to detect solar neutrinos the principle is very simple and elegant: the detection medium is a material, which, upon absorption of a neutrino, is converted into a radioactive element whose decay is afterwards revealed and counted. Homestake used a chlorine solution as a target for the inverse β^- interaction

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

characterized by a threshold of 0.814 MeV.

On the other hand, by observing the Cherenkov light in a large water detector surrounded by an array of photomultipliers, and in particular how the light cone is mapped into a very characteristic ring, the properties of the incoming particles can be inferred rather precisely. This is the way in which Kamiokande measured solar neutrinos, though with a threshold of several MeV (about 7 MeV) because of limitations from the radioactivity traces in water.

The existence of the Solar Neutrino Problem was later further confirmed at the beginning of the 90's by other two radiochemical experiments, i.e. Gallex/GNO and Sage which adopted gallium as neutrino target, with the advantage of a much lower threshold of 233 keV, low enough to detect neutrinos from the initial proton fusion chain. Therefore, Gallex and Sage were the first to prove experimentally the nuclear hypothesis for the Sun by revealing such low energy neutrinos, which are somehow the debris of the solar engine and thus the smoking gun of the occurring nuclear reactions.

The second round of Solar Neutrino experiments, from the middle of the 90's till now, solved the Solar Neutrino Problem by unraveling the underlying mechanism of neutrino oscillations which was at its root. The experiments of this second phase of the Solar Neutrino investigation are the SNO heavy water detector, now dismissed, the Super-Kamiokande water Cerenkov detector and the scintillator based Borexino detector, both instead still operational.

The basic idea beyond the choice of heavy water in SNO (1 kton in total) was to perform two independent Solar Neutrino measurements based on the deuterium target: the first is aimed to detect specifically the electron neutrino component, while the second is sensitive to the all flavor flux. Thus, the comparison of the two results can permit to discern clearly if neutrinos, generated only as electron neutrinos in the core of the Sun, undergo flavor conversion during the path Sun-Earth. The first, flavor-specific reaction is the charged current reaction sensitive only to electron neutrinos. The second, flavor-independent reaction is the so-called neutral current reaction, equally sensitive to all neutrino types.

There is also a third reaction occurring in the detector, flavor-independent as well, which is the electron scattering, and this is the one exploited by the other two experiments Super-Kamiokande (and before Kamiokande) and Borexino.

Super-Kamiokande is a classic water Cerenkov detector, whose distinctive feature is the large dimensions, containing about 50 ktons of water. It was conceived as the immediate successor of Kamiokande, with the aim to greatly enhance the statistic of accumulated data as the major key to unveil the characteristics of the detected neutrino flux. Further improvements throughout the years led also to a substantial reduction of the threshold, to the level of 3.5 MeV.

Borexino, still taking data at the Gran Sasso Laboratory, being a scintillator detector employs as active detection medium about 300 tons of pseudocumene-based scintillator. Main features of the experiments are the intrinsic high luminosity, and hence the low detection threshold of about 150 keV, as well as the extremely limited radioactive contamination of the scintillator, at unprecedented ultralow levels.

SNO with its flavor specific and flavor independent measurements proved unambiguously that the SNP was due to the neutrino flavor conversion effect; moreover, its results together with that from the reactor experiment KamLAND [14] pinpointed the MSW phenomenon [15][16] as the oscillation mechanism at origin of the flavor conversion. The corresponding mixing parameters were found in the so called LMA (large mixing angle) region. Nowadays, taking together all the updated solar neutrino results and the KamLAND results, the "solar" oscillation parameters $\sin^2\theta_{12}$ and Δm^2_{21} are, respectively, 0.307 ± 0.013 and $7.53\pm0.18 \times 10^{-5}$ eV^2 [17].

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It is worth to briefly remind that the PNMS matrix connecting the flavor and mass eigenstates, and thus governing the neutrino oscillation phenomenon, is factorized in three terms, one (12) related to the solar oscillations, one (23) to the oscillations in the atmospheric sector, with the third (13) relating the first two terms. The term (12) is accessible through the solar experiments and KamLAND, the second through the atmospheric and accelerator experiments, and the third via reactor and accelerator experiments. The angles in the PNMS matrix, together with the three so-called mass squared splitting (only two independent)

$$\Delta m_{31}^2 - \Delta m_{32}^2 = \Delta m_{21}^2$$

allow writing the appearance and disappearance probabilities, describing the oscillation effects in all possible experimental scenarios.

In Fig. 1 [18] the MSW predicted Pee (electron neutrino survival probability) is shown, together with several experimental points, all from the Borexino spectroscopic detection of the low and medium energy fluxes from the whole pp chain. ^{7}Be and pep neutrinos are mono-energetic, while the pp and ^{8}B components are emitted over a broad energy span, so that their reported experimental values refer to the actual range contributing to the measurement. The violet band of the Pee corresponds to the prediction of the MSW-LMA solution. It is calculated for the ^{8}B solar neutrinos, considering their production region in the Sun, and represents rather accurately the other components, as well.

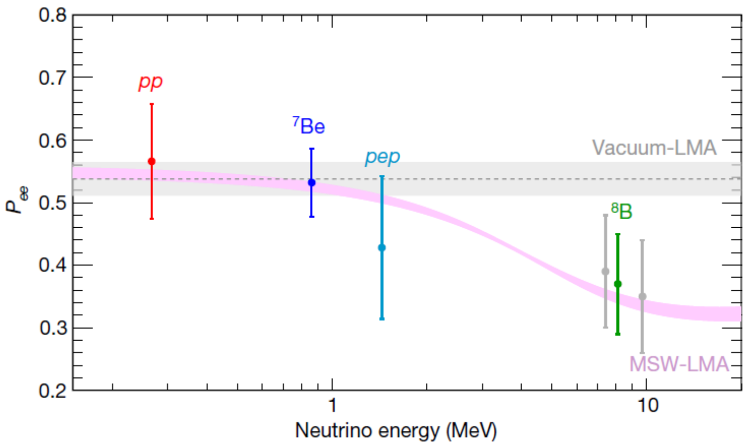

Fig. 1 - Electron neutrino survival probability Pee as a function of neutrino energy

The vertical error bars of each data point amount to the 1σ interval.

Altogether, from this figure we can conclude that the solar data accumulated by Borexino so far, spectacularly confirm over the entire energy range of interest the MSW-LMA solar neutrino oscillation scenario, providing the clear evidence of the transition from the high energy, more suppressed "matter" regime, to the low energy, less suppressed "vacuum" regime.

In this beautiful and well-understood overall scenario, there are however some emerging anomalies whose status is still unclear, whether they are originated by statistical fluctuations or point to some intrinsic, profound effect.

One is the absence of up-turn in the ^{8}B spectrum of Super-Kamiokande, as would be predicted by the MSW-LMA solution. The other is the persistent 2σ discrepancy between the Δm^2_{21} stemming from KamLAND alone and that from the solar experiments. While this difference

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is compatible with being a pure fluctuation, the occurrence that it is now stably present while more and more data are accumulated, may suggest also some true intrinsic physics effect of unknown nature. Connected to this anomaly, there is also the puzzling circumstance that the day-night effect detected in the ^{8}B flux by Super-Kamiokande is more aligned with the Δm^2_{21} from the solar experiments only, and less consistent with that of KamLAND alone.

Before abandoning the Solar Neutrino beam, it is worth to remind that, besides Borexino and Super-Kamioande still taking data, in the future there will be a number of new experiments capable to detect solar neutrinos. The three gigantic detectors of next generation DUNE (liquid argon) [19], Hyper-Kamiokande (water) [20] and JUNO (liquid scintillator) [21] have a vast solar neutrino program in their respective science reach. Furthermore, there are the two novel proposals, the Theia Water Based liquid scintillator [22] and the Jinping Neutrino Experiment [23] with slow scintillator, which in principle are also sensitive to solar neutrinos, without forgetting that future large mass cryogenic (Xenon and Argon based) Dark Matter detectors could also catch low energy solar neutrinos.

3. Atmospheric Neutrinos

Atmospheric Neutrinos are produced by cosmic-ray interactions with the air nuclei in the atmosphere. The typical height of the neutrino production is 15 km above ground. In the cascade of particles stemming from such interactions, ν_e and ν_μ and their antiparticles are produced with a specific ration, i.e.

$$\nu_\mu + \bar{\nu}_\mu / \nu_e + \bar{\nu}_e \cong 2$$

in the GeV energy range.

Kamiokande [24] and IMB [25] found the above ratio lower, originating the atmospheric neutrino anomaly. Actually, beyond this crude estimate, careful comparisons between data and several accurate model predictions confirmed the anomaly (more recent atmospheric flux calculations can be found in [26] [27] [28]).

The major players in the Atmospheric Neutrino saga have been the two water Cerenkov experiments Kamiokande and Super-Kamiokande already encountered in the Solar Neutrino context. The advantages of the Cerenkov technique for the detection of atmospheric neutrinos are many. On one hand, the water allows the detection of multiple interaction channels ((quasi-)elastic scattering, single meson production, meson deep inelastic interaction, and coherent pion production), and on the other the characteristic topology of the emerging Cerenkov light enables the identification of a plurality of pattern configurations. In particular, the events can be categorized as fully or partially contained, of single or multi ring type (allowing to distinguish between e-like and μ-like signals), and finally as downward or upward going.

These multiple features were the key for Kamiokande to understand the existence of the anomaly and for Super-Kamiokande to uncover its origin. Indeed Super-Kamiokande, profiting of its high statistic of accumulated data, selected a large enough number of up-going and down-going events, further distinguishing in this selection between the e-like and μ-like events. By comparing the selected samples, Super-Kamiokande clarified that the anomaly discovered by Kamiokande and IMB was due to a depletion of μ-like up-going events. The interpretation of this result is straightforward: the up-going ν_μ's travel a path long enough through the Earth to allow the development of the oscillation phenomenon, which therefore subtract muon-like events from

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the detection in the detector. The later discovery in the detector of some ν_τ signals, which are the products of the oscillation, unquestionably nailed down this interpretation.

The Super-Kamiokande results announced in 1998 [29] are considered the discovery of the neutrino oscillation mechanism, with consistent indications coming at that time also from Soudan 2 [30] and Macro [31].

Nowadays, the enormous amount of data amassed by Super-Kamiokande [32] allows a very high precision analysis of the oscillation parameters governing the (23) term of the PNMS matrix and the corresponding mass splitting. Furthermore, the great precision achieved enables to gauge in the data the existence of sub leading, matter induced effects in the oscillation mechanism, which in turn are the key towards additional mass-mixing features and parameters.

In particular, Super-Kamiokande is giving interesting clues for the yet unknown neutrino mass hierarchy (whether the third mass eigenstate is heavier, Normal Hierarchy, or lighter, Inverse Hierarchy, than the other two) which is accessible through the resonance in the multi-GeV ν_e (NH) or anti-ν_e (IH) fluxes. Moreover, the magnitude of the resonance is able to provide the indication of the octant (above or below 45°) of the θ_{23} angle, while the interference between two Δm^2 driven oscillations enables to shed some light also on the δ_{cp} phase (the cp violating phase in the PNMS matrix).

Numerically, the precise determination of the (23) mixing parameters of Super-Kamiokande profits also of the θ_{13} input from the ongoing reactor experiments: in [32] the best estimate of $\sin^2\theta_{23}$ is $0.588^{+0.031}_{-0.064}$ (NH) or $0.575^{+0.036}_{-0.073}$ (IH), while the mass splitting evaluation amounts to $\Delta m^2_{32}=2.50^{+0.13}_{-0.20}$ for NH or $\Delta m^2_{31}=2.50^{+0.08}_{-0.37}$ for IH, in units of 10^{-3} eV^2. Finally, in the same paper the hint of the experiment in favor of the NH is reported at the level of about 2σ.

The next frontier of the Atmospheric Neutrino studies surely comprises all the gigantic experiments, which will dominate the field over the next 30 years and already mentioned in the Solar Neutrino section. Moreover it, must be mentioned that to further push the matter effect hierarchy sensitivity, an innovative approach has been devised which calls for instrumenting (with photomultipliers) Mtons of ice or sea-water with fine granularity to achieve a sufficiently low detection threshold.

KM3NeT/ORCA [33], in the Mediterranean Sea, has been conceived and designed according to this novel concept, leading to the expectation that after 3 years of operation a 3σ Mass Hierarchy discovery reach for most of the parameter space is affordable. A recent proof-of-concept of the method has been realized with the IceCube DeepCore data and reported in [34]. This proof, which shows a weak preference for NH, has important implications on the best way to implement the IceCube Upgrade, maximizing the MH sensitivity.

4.Other natural beams

Before abandoning the natural beams, it is worth to mention that Super-Kamiokande just commenced the so-called phase V with Gadolinium dissolved in water. Gadolinium, with its extremely high neutron capture cross section, will give the experiment the ability to detect the anti-neutrinos composing the Diffuse Supernova Neutrino Background (DSNB from all past Supernovae), opening the way to the first detection of this yet undetected astrophysical neutrino component.

For what concern, instead, the vibrant field of Supernova burst detection, there are now many players worldwide, which can capture the neutrinos from a Supernova explosion within our

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Galaxy. Solar and Atmospheric Neutrino experiments, as well as the arrays for high energy neutrinos like IceCube, are intrinsically equipped with this capability, and are connected in the SNEWS consortium for a common early warning in case of an explosion.

Up to now, we have in the "bag" the neutrinos from SN1987A detected by Kamiokande and IMB in February 1987, but with so many active instruments if a "galactic firework" will occur, surely we will not miss it.

5.Reactor beam

5.1 General features of the reactor experiments

A reactor beam is constituted by neutrinos coming from the core of a nuclear power plant, or of a research reactor, which generates energy through the fission of heavy nuclei. Fission products are unstable and undergo beta decay, with copious anti-neutrino production.

Four main isotopes are responsible for the majority of the yield: ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu. The detection, typically with liquid scintillator detectors, happens via the Inverse Beta Decay reaction:

$$\bar{\nu}_e + p = e^+ + n$$

with the energy range of the anti-neutrinos limited to about 8 MeV.

The physics reach of the experiments done with reactor beams is multiple, depending also on the distance between the reactor and the experimental equipment. For example, KamLAND, as discussed above, with its average baseline of 180 km gave the proof of the neutrino oscillation origin of the flavor conversion between neutrinos pinpointed by SNO. In a certain sense, KamLAND closed the pioneer phase of the reactor experiments started with the Savannah river experiment; the suites of these detectors from the sixties to the nineties located at short distances never found any hint of oscillations, until KamLAND took its giant step to the distance of 180 km.

The oscillation unraveled by KamLAND is that governing the solar neutrino flux suppression, and this is why KamLAND helps determining the corresponding solar oscillation parameters.

After KamLAND, the three more recent reactor experiments Daya Bay [35], Double Chooz [36] and Reno [37] measured the θ_{13} angle, which in the PNMS matrix defines the term connecting the atmospheric and solar sectors. This breakthrough was made possible by the medium baseline of about 1 km at which the detectors were situated with respect to the source. However, the area of the short and very short baseline is far from being abandoned, since there are still ongoing several of this kind of experiments, whose purpose is to verify whether a sterile neutrino in the eV range exists, as will be better detailed below.

The future of the field is represented by the already mentioned JUNO experiment, which as reactor experiment at a baseline of 53 km will test the 3ν oscillation paradigm, through the high precision evaluation at sub percent level of the mixing parameters, as well as the neutrino mass hierarchy.

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5.2 Current status and perspectives of the reactor neutrino research

The Chinese Daya Bay, the French Double Chooz and the Korean Reno share common characteristics, as well as different features, which make them complementary in the quest of the θ_{13} angle. In particular, they all are equipped with near and far detectors, in order to cancel systematic effects by comparing the two set ups. The main difference among them is the baseline, which varies from 1050 to 1650 m, therefore allowing to sample at different points the electron neutrino survival probability curve. Other differences are the detector target volume, and the rock overburden, which impacts on the muon veto strategies to be adopted.

The angle θ_{13} is determined by the ratio of the measured events at the far detector over the predicted events at the same location, in turn stemming from the measure at the near detector. In particular, the results of the three experiments put in evidence a suppression of events with respect to the expectation, which is the unmistakable signature of a non-zero θ_{13}. The most precise evaluation stems from Day Bay and amounts to $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ [38].

Daya Bay and Reno can also measure the atmospheric mass splitting, with the former again providing the best result, which in the same paper [38] is reported as $\Delta m^2_{32} = 2.471^{+0.068}_{-0.070}$ for NH or $\Delta m^2_{31} = 2.575^{+0.068}_{-0.070}$ for IH, in units of 10^{-3} eV^2.

The high precision measurements provided by the three medium baseline detectors allowed also scrutinizing with exquisite accuracy the initial antineutrino spectrum from reactors. It resulted that around 5 MeV a sizeable discrepancy exists between the prediction and the data, a so-called bump, since when displayed as ration between the measure and the Monte Carlo spectrum this is how the discrepancy visually appears.

Among the attempts done to unravel the origin of this puzzle, several specific tests have been performed. Daya Bay for example has measured the evolution of the antineutrino yield as function of the composition of the reactor fuel [39], in particular following the relative abundances of ^{239}Pu and ^{235}U. Not only the antineutrino yield evolves differently with respect to the expectations, but in addition the detailed analysis of this evolution provides a clear indication that there is something not understood specifically in the ^{235}U predicted anti-neutrino yield.

Another anomaly related to the reactor flux, stemming from the joint analysis of the old and recent reactor experiments is the discrepancy between the measured and predicted value of the total anti-neutrino flux. Indeed, the measured flux throughout all the experiments is consistently 6% lower than the value stemming from the reactor model [40]. This so-called reactor anomaly generated the sterile hypothesis: under this hypothesis, the missing flux stems from the oscillation of some of the anti-nu from reactor into a sterile state of mass in the eV range. This suggestive possibility is corroborated also by other experimental hints, namely the long standing excess of events of LSND, later confirmed by Miniboone, and by the depletion of events in the calibration with the ^{51}Cr source of the Gallium experiments [40].

The situation is rather confusing, since these hints are in tension among each other. To try and clarify this obscure scenario there are many ongoing and proposed reactor experiments to test this hypothesis at short distance from reactors.

Some of them have already presented their first results, like Stereo [41], Prospect [42], Danss [43] Neos [44] and Neutrino-4 [45]. The first four did not evidence any oscillation effect linked to the putative sterile component, leading to the exclusion of a large fraction of the mixing parameter space allowed by the Reactor+Gallium anomaly. On the other hand, Neutrino-4

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observed an oscillation-like behavior of the detected flux, but corresponding to oscillation parameters with values already excluded by Daya Bay and Reno.

This collective effort is enduring and, hopefully, will lead within few years to a definite answer about the fate of this tantalizing anomaly.

Finally, regarding the future perspectives, as anticipated above over the next decades the reactor field will be dominated by the JUNO (Jiangmen Underground Neutrino Observatory) detector, a 20 kton multi-purpose underground liquid scintillator experiment, under construction in the south of China. After an intense design phase, the overall concept of the structure of the detector has been finalized, paving the way towards the ongoing construction of the several components and subsystems, which will compose it [46]. Meanwhile, the excavation of the site, which will host the experiment has been started and is rapidly progressing. The main physics target of JUNO is the determination of the neutrino mass hierarchy, which will be accessible through the measurement of the antineutrino spectrum from two high power nuclear complexes under installation 53 km away from the experimental site. In addition, its broad physics capabilities will include the high precision determination of three oscillation parameters, leading to test to better than 1% the unitarity of the PNMS matrix, as well as a rich astroparticle program, which is naturally within the reach of a giant liquid scintillator set-up like JUNO.

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6.Conclusions

In a synergic approach, natural and reactor beams contributed substantially to write one of the most beautiful pages of modern particles physics.

The discovery of neutrino oscillation has been a paradigmatic example of serendipity in physics, which has paved the way to a rich and exciting program of precision measurements exploiting complementary techniques and methods, which will endure still for many years. And the unknowns – the yet undetected fluxes and the unexplained anomalies – may perhaps still give us surprises.

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