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High-energy astrophysical neutrinos

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Summary. — A brief overview of the topics covered in my lectures on high-energy astrophysical neutrinos at the 2023 MAYORANA School is provided

Neutrinos appeared in physics by taking away part of the energy available to the electrons emitted in beta decays. To account for this missing energy Pauli hypothesized the existence of these light neutral particles and Fermi wrote down the first weak-interaction Hamiltonian. Due to their very feeble interactions, it only became possible to observe them much later, by producing huge amounts of neutrinos in nuclear reactors and detecting the particles (neutrons and positrons) produced when few of them hitted a target containing protons. Neutrinos got also produced in accelerators, mostly through pion decays, in which case they come in association with a muon rather than with an electron. These two types of neutrinos were found to be different, since muon neutrinos, unlike electron neutrinos, do not produce electrons when they interact. The third flavor of neutrino is that associated with the third generation tau lepton, and it was observed more recently in accelerator experiments that produced heavier mesons which can decay into those particles. Their characteristic property is that they would create a tau lepton when interacting through charged currents.

Neutrinos are also copiously produced in the cosmos. They were indeed in thermal equilibrium in the dense early universe when the temperature was higher than an MeV, and after decoupling from the plasma those cosmic neutrinos survive today as a background with an effective temperature of 1.9K and a density comparable to that of CMB photons. Neutrinos are produced in the hot interior of the stars, both by beta processes associated to the nuclear fusion reactions which give rise to the stellar energy generation and via thermal production, which becomes increasingly important the larger is the mass of a star. The neutrino emission is the dominant process associated to the core collapse of very massive stars in supernova events, as was indeed confirmed by the observation of a burst of neutrinos with energies of tens of MeV in association with the SN1987A which took place in the nearby Large Magellanic Cloud galaxy. The energetic cosmic rays (CRs) accelerated in the supernova explosions or in other violent astrophysical processes can also lead to the production of neutrinos when the CRs interact with gas or

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with radiation. This happens in particular when the CRs arriving to the Earth hit the atomic nuclei of the upper atmosphere, producing in this way the so-called atmospheric neutrinos which have energies ranging from MeVs up to beyond the PeV. CRs may also interact at or around their sources, producing high-energy neutrinos which are referred to as astrophysical neutrinos. Yet another possibility is that the CRs interact in the intergalactic space with the radiation backgrounds they encounter during their trip from the sources, leading to the so-called cosmogenic neutrinos, which should have energies between 1 PeV and 10 EeV given that the CRs producing them should have ultra-high energies in order to be able to photoproduce pions when interacting with low-energy photons.

The detection of neutrinos from the Sun and from the atmosphere were fundamental to establish the phenomenon of neutrino oscillations, which leads to the observed reduction of the flux of solar electron neutrinos and of that of atmospheric muon neutrinos. We understand now that this is due to the massiveness of the neutrino states, which implies that the mass eigenstates present in the flavor states interfere quantum mechanically as they propagate. In this way, the flavor content of the neutrino fluxes change with the distance to their sources and in particular the electron neutrinos that are produced in the Sun arrive to the Earth as a superposition of the three neutrino flavors, while the muon neutrinos of GeV energies produced in the atmosphere can be largely converted to tau neutrinos after travelling thousands of km. The oscillating nature of the neutrino flavor conversion was also explored in detail with long-baseline experiments involving reactor and accelerator experiments, and the determination of some of the mixing angles and of the mass squared differences involved has achieved by now the percent level precision. Still several important unknowns remain in the parameters of the neutrino sector, such as the neutrino mass ordering (*i.e.*, the sign of Δm^2_{32}), the absolute neutrino mass scale, the octant of the atmospheric mixing angle θ_{23} and its precise value as well as the value of the leptonic CP violating phase that could lead to different probabilities for oscillations in vacuum of neutrinos and of antineutrinos. The need to make progress in answering those questions is the main driving force of the present and next generation neutrino experiments being carried out, which involve the more precise measurement of the oscillations of atmospheric neutrinos (Icecube DeepCore, ORCA, HyperKamiokande, ...), of solar and reactor neutrinos with more sensitive detectors (JUNO), of very long-baseline accelerator experiments (T2K, NOνA, DUNE, ...), of neutrinoless double-beta decay experiments (KamLAND-Zen, CUORE, NEXT, SNO+, ...), of precise studies of the large-scale galaxy distribution (EUCLID, ...), which together with the CMB anisotropy determinations can help to understand the dynamical effects that massive neutrinos had on the large-scale structure formation and hence inform about the absolute value of the neutrino masses, and eventually also by the direct detection of the cosmic background neutrinos (PTOLEMY).

The detailed study of the astrophysical high-energy neutrinos was the main topic covered in the lectures I gave at the 2023 MAYORANA School (see [1] for a detailed account and for a list of references to the many works mentioned here). This subject underwent a revolutionary change after the detection in 2012 by the IceCube observatory in the South Pole of a neutrino flux of non-atmospheric origin at energies above tens of TeV. These searches exploit the fact that the atmospheric neutrino spectrum is quite steep, scaling approximately as $E^{-3.7}$, and hence the harder astrophysical spectrum may eventually surface out at high enough energies. Up to hundreds of TeV energies the main channel exploited was that of upgoing muons produced by muon neutrinos, since these are not affected by the large background of atmospheric muons which rain down to the detector. Moreover, given that the muon range can be of several km at energies larger than a TeV, the muons can be produced in the ice and rock around the detector and still reach it, significantly enlarging the effective detection volume. However, given the growth of the neutrino cross section with energy, above 100 TeV the Earth becomes quite opaque to the neutrinos and hence one needs to look for those coming from above or from near the horizon. In order to get rid of the background of atmospheric muons it becomes necessary to veto them by looking for tracks starting inside a fiducial detector volume, with no tracks in the surrounding veto region, or to look for cascade events inside the detector which can be produced by all neutrino flavors through neutral currents and also by electron or tau neutrino flavors through charged currents. The cascades lead to more spherical signals due to the localised energy deposit of the showers, and have hence a reduced angular resolution. These last signals were actually the first to provide positive detections of astrophysical neutrinos of PeV energies, but the threshold was progressively reduced and the search extended to the different channels as the analyses improved and more data were gathered. Also the surface IceTop array can be used to discriminate the neutrinos of atmospheric origin coming from above, since those get produced in association with large air showers that should produce simultaneous signals in the surface detectors, unlike what would happen if the neutrinos observed underground were of astrophysical origin.

The measurement of the astrophysical neutrinos with energies from several tens of TeV up to several PeV allowed to determine the flux overall normalization and its slope, and in particular fitting it to a power law $E^{-\gamma}$ led to values of γ in the range from 2.2 to 2.8, depending on the type of events and analysis considered. Although some tension is present between the different slope determinations, this may be due to the fact that the spectrum may not be a perfect power-law and different energy ranges are considered in the different analyses. They also get polluted in different amounts by other contributions, such as those from prompt atmospheric neutrinos from charmed meson decays, by astrophysical neutrinos of Galactic origin that would affect differently the fluxes from above (where the central part of the Galaxy lies) than those from below, etc. The study of the attenuation of the neutrino fluxes due to the interactions while crossing the Earth allowed to estimate the neutrino nucleon cross section at energies larger than about 10 TeV, which are well beyond the previous determinations at colliders which extended only up to few hundred GeV. New experiments at the LHC (FASERν) should allow to measure this cross section also in the intermediate energy regime, providing an interesting test of the Standard Model.

A major breakthrough was the detection of a muon track associated to a 300 TeV muon neutrino coming from the direction of the Blazar TXS 0506, what provided the first identification of an extragalactic source of high-energy neutrinos, which was also found to have had some years before an enhanced emission of neutrinos of several TeV. A blazar is an active galactic nucleus with a powerful jet pointing towards the observer, but also more recently a different type of AGN, the Seyfert NGC 1068, was found to have a steady emission of neutrinos up to tens of TeV probably associated to the core corona region. Some hints also exist of emission from the direction of some tidal disruption events, which would be related to the disruption of a star in the neighbourhood of a super-massive black hole with the subsequent production of a jet. Hence, it seems that different types of sources are contributing to the astrophysical neutrino fluxes, and understanding the mechanism producing them is one of the main open questions one seeks to answer.

Other remarkable results have also been obtained. One was the observation of some candidate tau neutrino events, characterized by a double bang signal arising from the two showers produced, the first from the recoil of the target nucleus in the charged current interaction producing the tau lepton, and the second from the decay of this last after it has travelled several meters. Another is the observation of a cascade shower with an energy of about 6 PeV, which is the energy at which an electron antineutrino could interact with an atomic electron to produce an on-shell W boson, so that the cross section for this process has a huge enhancement (Glashow resonance). By comparing the rates of observed tracks, cascades, double bangs and Glashow resonance events, one can constrain the flavor composition of the astrophysical flux at Earth, and hence restrict the original flavor mix at the sources, which can give information about the mechanism producing them. For instance, pion decays produce twice as many muon type neutrinos than electron ones, unless strong magnetic fields dump the muons before they can decay, in which case mostly muon type neutrinos get produced, while neutron decays (as could be the case if strong disintegrations of nuclei take place) would lead to mostly electron antineutrinos at the sources. Those flavors will be affected by oscillations on their way to us, but anyway the averaged fluxes detected at the Earth should allow to distinguish the different scenarios with the large statistics that is expected to be gathered in the future. Finally, there was the recent observation of a flux of energetic neutrinos from the Galactic plane direction, a region where a diffuse flux of GeV gamma rays has been observed long ago, expected to be associated with the interactions of CRs with the gas present in the Galactic plane, and also many TeV gamma sources have been observed with Cherenkov Telescopes such as HESS and ground arrays such as LHAASO, which even found some gamma sources extending up to the PeV. An associated neutrino emission is clearly expected if the mechanism producing those photons is hadronic (*i.e.*, from π^0 decays), with the neutrinos resulting from the associated charged meson decays. The observation of this Galactic neutrino flux was made possible by extending the search of cascades from above (where the Galactic center lies) to lower energies, using machine learning techniques and several improvements in the analysis, but the limited angular resolution of these events is not yet powerful enough to clearly identify the individual sources and to establish if they are point-like or of a more diffuse nature.

Many other experiments are contributing to these searches, such as the GVD Observatory in the lake Baikal, the ARCA observatory being built near Sicily, the Auger observatory searching for the still elusive cosmogenic neutrinos, radio detectors such as ANITA, AERA or the future AugerPrime and GRAND detectors, the IceCube Gen2 extension, etc., which should help to identify and characterize the ultra-high energy neutrino sources and shed light into the most energetic processes taking place in our Universe.

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REFERENCES

[1] Roulet E., *"High-Energy Astrophysical Neutrinos", Lectures at the 2023 MAYORANA School*, `https://agenda.infn.it/event/33174/`.