Sci. Bull. (2015) 60(23):2077–2079
DOI 10.1007/s11434-015-0940-7

www.scibull.com
www.springer.com/scp

News & Views

Massive neutrinos: where we are standing and where we are going

Shun Zhou

Neutrinos are the most elusive particles that we have ever discovered in nature. They are fermions of spin one-half and have no electric charges. Since they interact with matter rather weakly, it is extremely difficult to catch them even in huge detectors. Thanks to the tremendous experimental efforts made in past 85 years, we have successfully detected neutrinos and learned much about their fundamental properties [1].

First, we know there are three flavors of neutrinos ν_α (for $\alpha = e, \mu, \tau$), which are always produced together with the corresponding charged leptons e, μ and τ in the charged-current weak interaction. As quarks and charged leptons have their antiparticles, we also have three flavors of antineutrinos $\overline{\nu}_\alpha$.

Second, as indicated by a great number of elegant neutrino oscillation experiments, now we know that neutrinos have masses and lepton flavors are mixed. Three neutrino mass eigenstates $|\nu_i\rangle$ of masses m_i for $i = 1, 2, 3$ are related to three flavor eigenstates $|\nu_\alpha\rangle$ for $\alpha = e, \mu, \tau$ via the flavor mixing matrix U, i.e., $|\nu_\alpha\rangle = U^*_{\alpha i}|\nu_i\rangle$. Conventionally, the unitary matrix U is parametrized in terms of three mixing angles (θ_{12}, θ_{13}, θ_{23}) and one Dirac CP-violating phase δ. Given distinct masses, neutrino mass eigenstates develop different quantum phases and interfere with each other, when traveling from the sources to the detectors. As a consequence, neutrinos can transform from one flavor to another if the flavor mixing matrix is nontrivial. This phenomenon, known as neutrino oscillation, has been observed in solar, atmospheric, accelerator and reactor neutrino experiments, and used to determine neutrino mixing and mass parameters:

(1) The SNO experiment has offered a robust evidence for oscillations of solar neutrinos ν_e into the other two flavors ν_μ and ν_τ, and the KamLAND reactor neutrino experiment singles out the large-mixing-angle solution with Mikheyev–Smirnov–Wolfenstein (MSW) matter effects. Hence, we have $\theta_{12} \approx 34^\circ$ and $\Delta m^2_{21} \equiv m^2_2 - m^2_1 \approx 7.5 \times 10^{-5}\,\mathrm{eV}^2$.

(2) The Super-Kamiokande experiment demonstrates a substantial oscillation of atmospheric neutrinos $\nu_\mu \to \nu_\tau$, showing $\theta_{23} \approx 45^\circ$ and $|\Delta m^2_{32}| \equiv |m^2_3 - m^2_2| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$, which are further verified in the accelerator experiments K2K and MINOS.

(3) The Daya Bay experiment is the first to discover reactor neutrino oscillations at a short baseline of about 2 km and measure precisely the smallest mixing angle, i.e., $\theta_{13} \approx 9^\circ$, which has been confirmed by the results from both the RENO and Double Chooz experiments.

It is worth mentioning that the latest results from T2K and NOνA accelerator experiments observing $\nu_\mu \to \nu_e$ oscillations point to a maximal CP-violating phase $\delta \approx 270^\circ$. However, this observation is not statistically significant and needs to be confirmed by more data.

Despite recent exciting progress, a lot of burning questions in neutrino physics remain to be answered. Here is an incomplete list:

Is neutrino mass ordering normal or inverted? With the help of MSW effects in the Sun, we obtain $m_1 < m_2$ from solar neutrino experiments, but it remains to be determined whether $m_1 < m_2 < m_3$ (normal) or $m_3 < m_1 < m_2$ (inverted) is realized in nature. As both quarks and charged

S. Zhou (✉)
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
e-mail: zhoush@ihep.ac.cn

S. Zhou
Center for High Energy Physics, Peking University, Beijing 100871, China

leptons take on a normal mass ordering, the determination of neutrino mass ordering is crucially important for understanding the symmetry between leptons and quarks and exploring the origin of neutrino masses [2]. Two complementary methods will be implemented to resolve the problem of neutrino mass ordering. The first one is to precisely measure the energy-spectrum distortion of reactor neutrinos induced by three-flavor oscillations at a medium baseline of 60 km, such as JUNO and RENO-50 experiments. The second one is to utilize the Earth matter effects, which affect the oscillations of accelerator neutrinos and atmospheric neutrinos at a long baseline. The relative sign between Δm^2_{32} and the matter potential of neutrinos traversing the Earth is responsible for significant changes in the oscillation probabilities. The long-baseline accelerator experiments include T2K, NOνA and LBNF/DUNE, while future atmospheric experiments contain PINGU, ORCA, INO and Hyper-Kamiokande.

Is there leptonic CP violation? The joint symmetry of charge conjugate and space inversion has already been found to be violated in the weak interactions of quarks, such as in the mixing and decays of neutral K and B mesons. It is unclear whether CP symmetry is violated in the lepton sector. If so, for instance, the oscillation probabilities of neutrinos should be different from those of antineutrinos. This difference can be observed in the long-baseline accelerator experiments, which can be operated in both neutrino and antineutrino channels. Those non-reactor oscillation experiments sensitive to neutrino mass ordering can probe the CP-violating phase δ as well. In addition, the future super-beam experiments with an intensive neutrino beam, like ESSνSB and MOMENT, and a neutrino factory are able to ultimately measure δ to the precision of a few degrees.

What is the absolute scale of neutrino masses? Neutrino oscillation experiments are only sensitive to two independent neutrino mass-squared differences Δm^2_{21} and Δm^2_{32} but not the absolute neutrino masses. From the present tritium beta decay and neutrinoless double-beta decay experiments, one obtains useful upper bounds on the effective neutrino masses, which are combinations of absolute neutrino masses and mixing parameters. But the most restrictive bound on the sum of three neutrino masses comes from cosmological observations, i.e., $m_1 + m_2 + m_3 < 0.23$ eV at 95 % confidence level, which is derived from the precision measurements of cosmic microwave background by the Planck satellite. The absolute scale of neutrino masses is unlikely to exceed 0.1 eV, and the lightest neutrino is still allowed to be massless. The zero mass of the lightest neutrino may imply some kind of symmetry, which forbids its mass term.

Are neutrinos Majorana or Dirac particles? If neutrinos are their own antiparticles, they are Majorana particles. Otherwise, we call them Dirac particles, like quarks and charged leptons. For Dirac neutrinos, a quantum number other than electric charge should be introduced to distinguish between neutrinos and antineutrinos, such as the lepton number. Any positive signals of neutrinoless double-beta decays $N(Z,A) \rightarrow N(Z+2,A) + 2e^-$ will demonstrate that massive neutrinos are Majorana particles and lepton number is violated. So far, the experimental searches have not yet observed such a kind of decays. But the next generation of neutrinoless double-beta decays based on ^{76}Ge and ^{136}Xe could reach the edge of discovery if neutrino mass ordering is inverted. However, if the neutrino mass spectrum is normal and hierarchical, we have to wait a long time until a decisive conclusion can be made.

What is the origin of neutrino masses? Although the Higgs mechanism has been verified by the ATLAS and CMS experiments at the CERN Large Hadron Collider through a successful discovery of Higgs boson, it is not directly applicable to neutrinos. If neutrinos are assumed to be Dirac particles, they acquire tiny masses via the Higgs mechanism, just as quarks and charged leptons do. Then, one has to explain why the Yukawa couplings of neutrinos are 12 orders of magnitude smaller than that of top quark. Moreover, one has to enforce the conservation of lepton number, which is anomalously violated at the non-perturbative level in the standard model. Therefore, a simple analogue seems not to work for neutrinos. An alternative way is to assume neutrinos to be Majorana particles, for which lepton number is no longer a good quantum number. At present, the canonical seesaw mechanism with heavy right-handed Majorana neutrinos remains an attractive idea to generate tiny neutrino masses and explain the matter–antimatter asymmetry in our Universe via leptogenesis. However, the canonical seesaw model with extremely heavy neutrinos is not directly testable in any terrestrial experiments. In this sense, the origin of neutrino masses is still an open question in particle physics.

The solution to any one of the above fundamental questions will greatly improve our knowledge about neutrinos and guide us to extend the minimal standard model of elementary particles.

Finally, the role played by neutrinos in astrophysics and cosmology should also be emphasized, since astrophysical environment and the early Universe serve as an extraordinary laboratory to study neutrinos. On the other hand, the fundamental properties of neutrinos will help us explore astrophysics and cosmology.

First come supernova neutrinos. Massive stars of more than eight solar masses will end their lives in violent explosions, which are optically observed as extremely bright supernovae. How massive stars first collapse gravitationally and then explode violently remains a stunning mystery. The neutrino observation of SN 1987A essentially confirms the neutrino-driven mechanism of supernova explosions, but we cannot say more with two dozens of neutrino events. In future, a galactic supernova at a distance of 10 kpc will register about 10^4 neutrino events in the JUNO detector, which consists of 20 thousand tons of liquid scintillator and will be installed in the underground laboratory in Jiangmen, Guangdong Province, China. Such a high-statistics measurement will allow us to reconstruct neutrino energy spectra of different flavors and look deep into the supernova [3].

Next is cosmic neutrino background. Neutrinos are copiously produced in the Big Bang. They decouple from the thermal soup of other particles when our Universe is one second old. As the Universe is expanding, neutrinos cool down and survive today as a cosmic background. Nowadays, the relic density of neutrinos and antineutrinos is 336 cm^{-3} and their temperature is 1.95 K, corresponding to a kinetic energy of 10^{-4} eV. Although it is generally a big challenge to detect such low-energy neutrinos, one practical way is to capture background neutrinos by the beta-decaying nuclei, e.g., $\nu_e + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$, since there is no energy threshold in this reaction [4]. The proposed PTOLEMY experiment aims to seize background neutrinos using 100 g of tritium nuclei and will promisingly achieve a rate of a few events per year [5].

References

1. Xing ZZ, Zhou S (2011) Neutrinos in particle physics, astronomy and cosmology. Springer, Heidelberg
2. Xing ZZ (2011) Neutrino mass hierarchy and lepton flavor mixing. Chin Sci Bull 56:2594–2599
3. An FP, An GP, An Q et al (2015) Neutrino physics with JUNO. arXiv:1507.05613
4. Weinberg S (1962) Universal neutrino degeneracy. Phys Rev 128:1457–1473
5. Betts S, Blanchard WR, Carnevale RH et al (2013) Development of a relic neutrino detection experiment at PTOLEMY: princeton tritium observatory for light, early-universe, massive-neutrino yield. arXiv:1307.4738