An angle to tackle the neutrinos

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A brief history of the discovery of neutrino oscillations and neutrino mass is presented highlighting the recent breakthrough in the determination of a crucial neutrino parameter by the Daya Bay and RENO reactor experiments. The importance of this parameter in the context of one of the goals of the India-based Neutrino Observatory (INO) project and also in advancing the frontier of neutrino physics is explained.

Recently, an important discovery was made by two neutrino experiments, one in China, called Daya Bay[1] and the other in Korea, called RENO[2]. Both measured the flux of the antineutrinos at some distance from a complex of powerful nuclear reactors in their respective countries. The measurements showed that the antineutrinos oscillated, thus allowing the determination of a fundamental parameter of neutrino physics, the reactor angle. One must also mention that, a little earlier, the Double CHOOZ experiment in France had also measured this angle, but with larger errors[3].

To appreciate the importance of this experimental discovery one must go back a little in time.

Early history and the India-based Neutrino Observatory

India was a pioneer in neutrino physics. The very first detection of atmospheric neutrinos was made in the Kolar Gold Field (KGF) mines in South India in 1965. These are the neutrinos produced in the upper atmosphere by cosmic rays and hence are called atmospheric neutrinos. The KGF laboratory was closed in the 90s because of the closure of the KGF mines.

It is the further study of these cosmic ray-produced neutrinos that led the Japanese physicists to discover neutrino oscillations and their leader M. Koshiba to win the Nobel Prize in 2002. We in India missed the boat. Can we recover the lost initiative? We can and we must. The India-based Neutrino Observatory (INO) has been conceived with this objective in view[4].

The INO Laboratory and INO Centre will come up in Theni District and near Madurai city respectively, both in the southern part of India. In the underground (more correctly, under-mountain) laboratory, a gigantic 50 kton magnetized particle detector will be erected to study atmospheric neutrinos.

The Japanese group led by Koshiba discovered oscillations of atmospheric neutrinos. But, before that, R. Davis (USA) had already got evidence for neutrino oscillations in his pioneering experiments on neutrinos from the Sun. However, the oscillations of the solar neutrinos got the clinching evidence only from the subsequent experiment done with the heavy-water detector in the Sudbury Neutrino Observatory in Canada. Davis shared the Nobel Prize with Koshiba.

Although neutrino oscillation follows directly from quantum mechanics, it leads to a result of profound consequence for physics and astrophysics – that neutrinos have mass. That is the importance of the discovery of neutrino oscillations. Neutrino mass is the only concrete evidence that we have for physics beyond the Standard Model (SM) of high energy physics and hence is expected to take us beyond the known SM.

The three angles

Neutrino oscillations occur among three types of neutrinos that are known to exist. The mixing among these three types is governed by a 3×3 unitary matrix which can be specified by three angles (like the three Eulerian angles required to specify the 3×3 orthogonal matrix that describes the rotation of a rigid body) and a certain number of phases.

The three angles can be called atmospheric, solar and reactor angles since they respectively control the oscillations of atmospheric, solar and reactor neutrinos. The atmospheric and solar neutrino studies had determined the atmospheric and solar angles as about 45° and 30° respectively, more than 10 years ago. Now the Daya Bay and RENO experiments have determined the reactor angle to be about 9°.

Again let us go back a little in history. During the exciting period in the 90s when neutrino oscillations were discovered, our group at the Institute of Mathematical Sciences, Chennai was one of the earliest to initiate a comprehensive study of both solar and atmospheric neutrino oscillations using the full mixing among the three types of neutrinos[5,6]. Others were using toy-models of mixing among two types of neutrinos only to describe solar and atmospheric neutrinos separately.

Since we were working with the complete three-neutrino framework, we were the first to analyse the reactor neutrino data that came in 1997 from the CHOOZ experiment in France. Analysing the data within this framework, we[7] showed that the reactor angle was smaller than 12°, and also showed that as a consequence the solar and atmospheric oscillations became approximately decoupled. This decoupling played a major role in all the subsequent analyses of atmospheric and solar data helping to pin down the parameters in these two sectors more easily.

The upper limit remained as our only information on the crucial reactor angle for the last 15 years until it was determined this year to be 9°, not far away from the upper limit. Now we are ready to explain the importance of this measurement. There are two points: one in the context of INO and the other in the context of matter–antimatter asymmetry.

Neutrino masses and INO

Although oscillations establish that the neutrinos are massive, their actual mass cannot be determined by oscillation experiments; only the mass differences (actually differences of squares of masses) are determined. Calling the three neutrinos as 1, 2 and 3, the 2 – 1 mass difference is determined by the solar neutrino oscillations, whereas the 3 – 2 mass difference is determined by the atmospheric sector.

The mass-square differences so determined turn out to be very tiny: 0.00007 and 0.002 in units of electron volt (eV) squared for 2 – 1 and 3 – 2 respectively. The sign of the 2 – 1 mass difference is determined to be positive, but the sign of the other is not determined. So although neutrino 2 is heavier than 1, we do not know whether 3 is heavier than the 2 – 1 doublet or lighter.

A major discovery item in the agenda of the big magnetized particle detector at INO is to resolve this ambiguity in the sign of the 3-2 mass difference and thus determine the actual mass-ordering of the neutrinos. A non-zero value for the reactor angle is crucial for this discovery and that is the importance of the reactor angle for INO. The rather large measured value of this angle has enhanced the optimism of the INO Collaboration. However, in order to achieve this discovery, the Collaboration and its managers have to execute all the components of the project according to strict time schedules. There is no time to lose.

Matter–antimatter asymmetry

This is about the phases of the 3 × 3 unitary mixing matrix for the neutrinos. Earlier we mentioned the three angles of this unitary matrix. In contrast to the orthogonal rotation matrix which is made of real numbers, the unitary matrix is made of complex numbers and one can show that these complex numbers lead to matter–antimatter asymmetry in elementary particle interactions. Matter–antimatter asymmetry (also called CP violation) was discovered experimentally in 1964 and is an important topic in high energy physics.

A complex number can be written as a real number multiplied by a phase factor and this phase is therefore the signal for matter–antimatter asymmetry. And it is this asymmetry which is presumed to be responsible for the evolution of a original matter–antimatter symmetric universe into the present-day asymmetric universe that contains only matter and no antimatter. So that is the cosmological importance of the phases in the unitary mixing matrix.

The question is: apart from the three angles, how many phases exist?

It was the simple remark of Kobayashi and Maskawa that the dimension of the unitary matrix has to be at least 3 for a phase to exist, which won a Nobel Prize for them in 2008. That was in the context of quarks and so for the 3 × 3 unitary mixing matrix for quarks there exists precisely one phase. For the neutrino case, there is some difference. Ignoring this difference for the moment, there is one phase in the case of neutrino mixing too.

However, if the reactor angle were zero, then as already mentioned the three-neutrino problem would be reduced to two uncoupled two-neutrino problems described by two 2 × 2 matrices which will not have any matter–antimatter symmetry violating phase. Hence the importance of the non-zero reactor angle that couples the solar and atmospheric sector into one three-neutrino problem. Now that the angle has been measured and found to be 9°, the door is open for measuring the CP-violating phase. That will, however, require long baseline neutrino experiments, in which neutrinos produced by accelerators in Japan, Europe or USA will travel through thousands of kilometres inside the Earth and be detected and analysed. In the second phase of the INO experiment, the magnetized detector will play the role of this end-detector.

This will lead to an understanding of the contribution of the matter–antimatter asymmetry in the neutino sector to cosmological evolution.

Two more brief points must be added to make the neutrino picture more complete.

Towards a complete picture

1. Although neutrinos are now known to be massive from the existence of neutrino oscillations, we do not know the value of the masses since only the differences in neutrino mass squares can be determined from the oscillation phenomena. Nuclear beta-decay experiments (in particular decay of tritium) can give the absolute masses. So far it has only led to an upper limit of 2.2 eV. Since the mass differences are very small as already mentioned above, we see that all the three neutrino masses are clustered around a mass level below 2.2 eV. This is almost a million times smaller than the mass of the lightest massive elementary particle known until the discovery of neutrino mass, namely electron of mass 0.5 MeV.

2. It must be pointed out that the fundamental nature of the neutrino is still not known, namely whether the neutrino is its own antiparticle or not. If the neutrino is its own antiparticle, then the Kobayashi–Maskawa counting of the number of phases is not valid for the neutrino sector. It has to be augmented by two more phases. The question whether the neutrino is its own antiparticle can be answered only by the neutrinoless double beta-decay experiment, which is therefore the most important experiment in all of neutrino physics. This experiment also is a part of the INO project.

Summary

The reactor angle whose upper bound was found 15 years ago in Chennai was determined only this year by Daya Bay and RENO. The rather large value of this angle gives strong impetus to INO to pursue without delay its original goal of determining the neutrino mass ordering and also to participate in the long baseline neutrino programmes aiming to fix the matter–antimatter symmetry violating phase which is of cosmological importance.

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