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Status of Θ_{13}

FAIZA AKBAR

Department of Physics, Aligarh Muslim University, Aligarh – 202002, India

Email: akbar.faiza@ymail.com

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Abstract: The Neutrino mixing angle θ_{13} is at the focus of current neutrino research. Till 2010 the value of θ_{13} was assumed to be zero. Thanks to a number of consistent experimental efforts now we have a definitive value of θ_{13}. Its measured value is $\sin^2 2\theta_{13} \approx 0.1$. This has promising implications for the determination of the two remaining unknown parameters, sign of the Δm^2_{31} and CP violating phase δ_{CP} from the present and proposed accelerator neutrino experiments in the foreseeable future.

Keywords: Neutrino, Neutrino oscillation parameters, Neutrino experiments, CP violation, Neutrino mass hierarchy

1. INTRODUCTION

Neutrinos are one of the fundamental and least interacting particles in the standard model of particle physics. This particle was proposed by Pauli in 1930 to explain the continuous nature of β - spectrum and restore the energy, linear and angular momenta conservation laws. Pauli called it neutron which was later rechristened by Fermi as neutrino. In 1956, Reines and Cowan at the Savannah River Nuclear Power Plant observed for the first time an antineutrino ($\bar{\nu}$) inferring the basic reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Since then neutrinos have travelled a long distance and got prime importance in the field of particle physics for several reasons.

Neutrinos are neutral and follow Fermi-Dirac statistics i.e. they are fermions with spin ½. There are three flavors of neutrinos: ν_e, ν_μ, ν_τ and their antiparticles. Each flavour of neutrino is related to a charged lepton (e, μ, τ) and placed in a doublet with same lepton number. In the Standard Model of particle physics, neutrinos are kept massless and therefore have definite helicity. All neutrinos are left handed while all antineutrinos are right handed. Neutrinos are produced both by natural as well as man-made sources. Large numbers of neutrinos are coming on us from all directions.

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2. NEUTRINO OSCILLATIONS

Sun is shining due to nuclear reactions taking place inside its core and these reactions produce a huge flux of low energy electron neutrinos that can be detected at the surface of the earth. These are known as solar neutrinos and were first observed at Homestake Gold Mines by Davis and co-workers in an experiment that began in 1968, where they tried to detect a few solar neutrinos per year. After 20 years of data they confirmed that Sun emits three times less neutrinos than predicted by the Standard Solar Model. This is known as Solar Neutrino Problem. Similarly there is another anomaly that is associated with the atmospheric neutrinos. When primary cosmic rays (mainly protons and alpha particles) interact with the earth's atmospheric, secondary cosmic rays are produced. Secondary cosmic rays mainly consist of pions and kaons. Pions decay into muons as

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}\left(\bar{\nu}_{\mu}\right)$$

and then muon decays as

$$\mu^{\pm} \rightarrow \mathrm{e}^{\pm} + \nu_{\mathrm{e}}\left(\bar{\nu}_{\mathrm{e}}\right) + \nu_{\mu}\left(\bar{\nu}_{\mu}\right),$$

in this process two muon type and one electron type neutrinos are produced. As neutrinos are weakly interacting particles so they will reach to the earth. When these neutrinos are observed through the experiments performed on the earth then observed flux is in the ratio of 1:1 which should be otherwise 2:1 (two muon type and one electron type). It was the Kamiokande, IMB and some other atmospheric neutrino experiments which gave a clear evidence of a deficit in the atmospheric muon neutrino flux. This deficit was later confirmed with high statistics in the Super-Kamiokande experiment. It is now well established that atmospheric neutrinos do oscillate. It was the SNO (Sudbury Neutrino Observatory) experiment which on the 18th June 2001, published their results for the solar neutrino deficit through a clean experiment where they observed charged and neutral current induced neutrino interactions with the deuterium target and showed convincingly that some of the ν_{e} coming from the sun towards the earth do change their flavors.

The total flux of all neutrino flavors measured by SNO agrees well with the theoretical prediction of the Standard Solar Model of J.N. Bahcall. Further measurements carried out by SNO have since confirmed and improved the precision of the original result. Thus a neutrino created with a specific lepton flavor (electron, muon or tau), may later transforms its flavor. This phenomenon is known as ***Neutrino Oscillation***. This phenomenon was first predicted by Pontecorvo in 1957. This idea formed the basis for the quantitative theory of neutrino flavor oscillation, which was developed by Maki, Nakagawa, and Sakata in 1962 and further elaborated by Pontecorvo in 1967. It is purely a quantum-mechanical phenomenon. This is based on the assumption that the neutrino flavor states v_e, v_μ and v_τ, that couple to electron, muon and tau, respectively, and mass eigen states m1, m2 and m3 are related via a unitary mixing matrix U, parameterized in terms of three rotation angles θ_{12}, θ_{23}, θ_{13} and one possible CP-violating phase δ_{CP} in standard notation. This unitary matrix is given by:

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{r1} & U_{r2} & U_{r3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{bmatrix} \begin{bmatrix} C_{13} & 0 & S_{13}e-i\delta \\ 0 & 1 & 0 \\ 0 & 0 & C_{13} \end{bmatrix} \begin{bmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix}$$

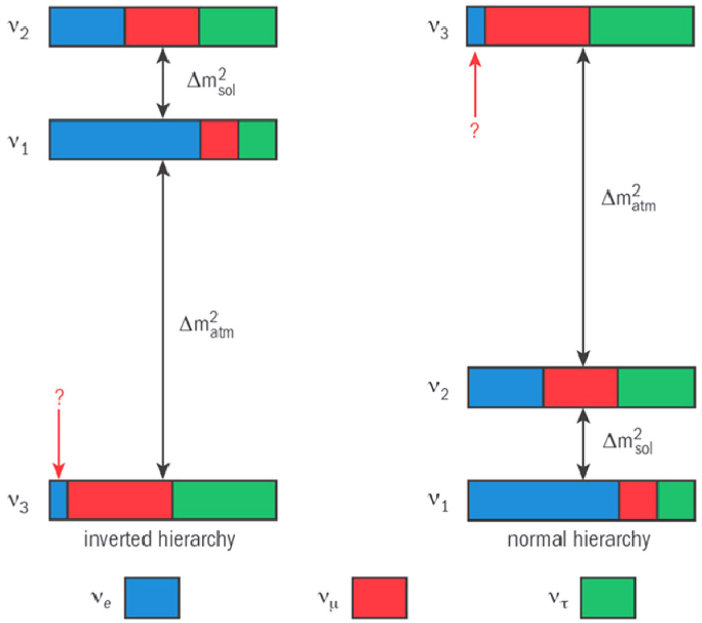
CP Violation and mass hierarchy in neutrino oscillations

Neutrino oscillates from one flavor to the other. The probability relation for neutrino transition from one flavor to other is given by $P(\alpha \rightarrow \beta)(t)$ and the probability relation for their respective anti-neutrinos is given as $P(\alpha \rightarrow \beta)(t)$. According to the CPT theorem both of the probabilities must be equal i.e. $P(\alpha \rightarrow \beta)(t) = P(\alpha \rightarrow \beta)(t)$. CP violation manifests itself if the oscillation probabilities of $\nu_\alpha \rightarrow \nu_\beta$ are different from its CP conjugate process $\nu_\alpha \rightarrow \nu_\beta$. So an observable would be

$$\Delta P^{CP}{}_{\alpha\beta} = P\left(\nu_\alpha \rightarrow \nu_\beta\right) - P\left(\nu_\alpha \rightarrow \nu_\beta\right) \neq 0 \quad \alpha \neq \beta.$$

For CP violation effects to be present, all the angles must be non-zero and, therefore, three-flavour mixing is essential.

The three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) do not have definite mass. They are superpositions of three mass eigenstates (v_1, v_2, v_3) which have definite masses m_1, m_2 and m_3, respectively. Squared mass differences



corresponding to different mass Eigen states are unknowns in three flavor neutrino matrix. Various experiments are running to measure different squared mass differences (Δm^2_{12}, Δm^2_{32}, Δm^2_{13}). If $m_1 < m_2 < m_3$ or $m_1 > m_2 > m_3$ then this corresponds to normal mass spectrum hierarchy. If $m_3 < m_1 < m_2$ then it corresponds to inverted mass spectrum hierarchy. This is represented in the following figure —

3. EXPERIMENTAL STATUS

The search for neutrino oscillations can be performed in two different ways — an appearance experiment or a disappearance experiment.

1. An appearance experiment searches for possible new flavors, which do not exists in original beam like in a ν_μ beam one is looking for ν_τ contamination, observed through charged current induced τ lepton production. The identification of the various flavors relies on the detection of the corresponding charged lepton produced in their charged current interactions, $\nu_l + N \rightarrow l^- + X$ with $l^- = e, \mu, \tau$, and N is a neutron or a proton target sitting inside a nucleus and X denotes the hadronic final state.
2. In a disappearance experiment one sees the same flavor of neutrinos and try to find out whether less than the expected number of neutrinos of a produced flavor arrive at a detector or not.

Θ_{13} — In the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix the better known quantities are mixing angles θ_{12} and θ_{23}. The mixing angle θ_{13}, the CP violation phase δ_{CP} and neutrino mass hierarchy, Δm^2 are the remaining unknowns in the standard three flavor mixing scheme of neutrinos. The mixing angle θ_{13} controls the oscillation probability of electron neutrinos (v_e). There are two possible ways in which θ_{13} could manifest it self via:

1. Appearance of electron neutrinos in a beam of muon neutrinos sent over hundred kilometers.
2. Oscillations of electron neutrinos into the other flavors over a distance of few hundred kilometers.

There is no theoretical reason for θ_{13} to be zero; however, it is known to be a bit smaller than the other two neutrino mixing angles, which are known quite precisely. Reactor experiments provide a clear measurement of θ_{13} by performing disappearance searches, looking for $v_e \rightarrow v_e$, because the energy is far below the threshold for μ, τ production. The average yield of a nuclear reactor experiment is about 6 $\bar{\nu}_e$ per fission reaction. In the past, several experiments tried to measure value of θ_{13}. The experiments performed for the determination of neutrino oscillations and to measure the value of θ_{13} were CHOOZ, Palo Verde, Borexino, KamLAND, and SNO+.

4. NEW EXPERIMENTS MEASURING Θ_{13}

Several reactor experiments have been racing to measure the value of θ_{13} more precisely:

1. T2K in Japan.
2. MINOS in the US.
3. Double CHOOZ in France.
4. RENO in South Korea.
5. Daya bay in China.

Recently, there have been a few experimental hints that the value of θ_{13} is about 10 degrees.

5. RENO

Phys. Rev. Lett. **108**, 191802 (**2012**)

The RENO (Reactor experiment for neutrino oscillations) is a short baseline reactor neutrino oscillation experiment in South Korea. The experiment was designed to either measure or set a limit on θ_{13}. The experiment has observed the disappearance of reactor electron anti-neutrinos. Antineutrinos from six 2.8 GW reactors at the Yonggwang Nuclear Power Plant in Korea, are detected by two identical detectors located at 294 m and 1383 m, respectively, from the reactor array center. It took data for 229 days between 11th August 2011 and 26th March 2012. Based on its data, it is determined that $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.})$.

6. DAYA BAY

Phys. Rev. Lett. **108**,171803 (**2012**).

It is a reactor based experiment. The experiment studies neutrino oscillations and is designed to measure the mixing angle θ_{13} using $\bar{\nu}_e$ produced by the reactors of the Daya bay nuclear power plant via inverse beta decay reaction and also to probe for CP violation neutrino section. There are two power plants at about 1.1 km apart. Reactor complex has a total power of 17.4 GW from three power plants. Detector is surrounded by mountains which acts as shield and give protection from cosmic rays that are main source of background in the experiment. Daya bay started taking data from the19th February, 2008. On March 2012, Daya bay collaboration announced that $\theta_{13} \neq 0$. $\sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)}$.

7. DOUBLE CHOOZ

Phys. Rev. D **86**, 052008 (**2012**).

Double CHOOZ is a long baseline neutrino oscillation reactor experiment in Chooz, France. Its goal is to measure or set a limit on θ_{13}. The experiment uses reactors of the CHOOZ nuclear power plant as a neutrino source. Double CHOOZ is a successor to the CHOOZ experiment. In Double CHOOZ, the near detector is approximately 400 m away from reactor cores and 40 m underground. The far detector is approximately 1.1 km away and 110 m underground. In November 2011, first result of the experiments was announced. They hinted at a non-zero value of θ_{13}. The value of $\sin^2 2\theta_{13} = 0.109 \pm 0.030 \text{ (stat)} \pm 0.025 \text{ (syst)}$.

8. TOKAI TO KAMIOKA, JAPAN

Phys. Rev. Lett. **107**, 041801(**2011**).

It is the second generation experiment follow up to the K2K experiment, a similar long baseline neutrino oscillation experiment. It is an accelerator experiment. The main goal of T2K experiment is to measure the oscillation of ν_μ to ν_e and to measure the value of θ_{13}. The previous neutrino experiments have observed the disappearance of ν_μ in a beam as they oscillate to ν_τ, but oscillations from ν_μ to ν_e has not been observed. The reason for this is that the mixing angle θ_{13}, that controls the probability for this oscillation is very small. On the June 15, 2011, the T2K collaboration announced the observation of six ν_e like events in an appearance experiment. On the basis of the data collected by T2K the value of $\sin^2 2\theta_{13} = 0.104 + 0.060 - 0.045$.

9. MINOS

Phys. Rev. Lett. **107**, 181802 (**2011**).

It is an accelerator based experiment. In MINOS i.e. Main Injector Neutrino Oscillation Search experiment, the properties of the neutrinos will be measured and compared as they leave Fermilab site one kilometer from the source, and when they arrive at the detector in Soudan. A difference between characteristics of the neutrino interactions in these two detectors will provide evidence for oscillations between types of neutrinos, and hence neutrino mass. In addition MINOS looks for the appearance of electron neutrinos in the far detector, and will either measure or set limit on the oscillation probability of muon neutrinos into electron neutrinos.

The MINOS experiment started detecting neutrinos from the NuMI beam in the February 2005. On 30th March 2006, the MINOS collaboration announced that the analysis of the initial data, collected in 2005, is consistent with neutrino oscillations. MINOS received last neutrinos from the NuMI beamline at the midnight of 30th April 2012. It is now in the process of being upgrade to MINOS+.

Conclusions

The discovery of neutrino oscillations establishes beyond doubt that neutrinos have mass and they mix. This existence of neutrino masses is in fact the first solid experimental fact requiring physics beyond the Standard Model. The angle θ_{12} was first measured with solar neutrino detectors and later more precisely with reactor anti-neutrino experiments, $\sin^2(2\theta_{12}) = 0.857 \pm 0.024$ and $\Delta m^2_{12} = (7.5 \pm 0.2) \times 10 - 2\ eV^2$. The angle θ_{23} was measured from the oscillation of neutrino produced in the upper atmosphere by cosmic rays, $\sin^2(2\theta_{23}) > 0.95$ and $\Delta m^2_{32} = 2.32 - 0.8 + 0.12 \times 10 - 3\ eV^2$. The results of T2K and Daya Bay reactor neutrino experiment provided the first direct measurement of θ_{13} followed by the RENO reactor neutrino experiment. Contrary to the naïve expectations, the value of θ_{13} turned out to be relatively large. The value of $\sin^2(2\theta_{13})$ measured at various experiments is given below:

Experiment	Measured sin2(2θ_{13})
Daya Bay	0.089 ± 0.010 (stat) ± 0.005 (syst)
RENO	0.113 ± 0.013 (stat) ± 0.019 (syst)
Double Chooz	0.109± 0.030 (stat) ± 0.025 (syst)
T2K	0.104+0.060-0.045

The most important point is that the large value of θ_{13} will help us in the determination of the mass hierarchy and possibly CP violation in the neutrino sector.

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