Neutrino physics – An expanding realm

Shankar Nath Mukherjee

We describe how the ethereal neutrino gradually assumed a tangible form and played a pivotal role in our quest to understand intrinsic particle properties. In the road map for the exploration of neutrino mass, new experiments and new facilities are planned to find the nature of the neutrino mass, the possible cosmological relevance of neutrino as hot dark matter and the origin of all matter in the universe.

Keywords: Cosmology, detection, mass, neutrino, source.

IN 1930, Wolfgang Pauli suggested that the neutrino (invisible then and remained so for another 25 years) is emitted along with an electron in nuclear beta decay, where the elementary processes are: $p \rightarrow n + e^+ + \nu_e$, $n \rightarrow p + e^- + \bar{\nu}_e$. Pauli's neutrino (or antineutrino) is a neutral, massless, spin-half particle and its presence rescues apparent violation of both energy and angular momentum conservation in the beta decay process.

Subsequently it was found by particle physicists that the neutrino comes in three flavours: ν_e, ν_μ and ν_τ. Schewartz, Steinberger and Lederman shared the Nobel Prize in 1988 for the discovery of the muon neutrino by the neutrino beam method. Experimental confirmation of the neutrino required many years of effort but the discovery antineutrino ($\bar{\nu}_e$) in reverse beta decay: $\bar{\nu}_e + p \rightarrow n + e^-$ by Reines and Cowan[1], led to a Nobel Prize for them in 1995. Martin Perl also shared the Nobel Prize for his discovery of the τ lepton. The 2002 Nobel Prize was awarded to Raymond Davis Jr[2] and Koshiba[3] for their painstaking experiments of increasing size and number, which proved that neutrinos have mass. The recent 2006 Nobel Prize was shared by John Mather and George Smoot for their discovery of the blackbody form and anisotropy of cosmic ray microwave background (CMB) radiation. Their precision cosmological measurements may indicate that the presently observed distribution of matter (through high resolution galaxy surveys) and the distribution of CMB radiation would both be affected by the presence of massive neutrino in the early universe.

Experiments carried out established beyond any doubt that neutrinos coming from the sun due to nucleosynthesis or from the upper atmosphere due to cosmic ray high energy proton–proton collision (Figure 1) do not behave as theoretically predicted. Neutrinos detected on earth are less than those predicted. This is known as the missing neutrino problem. The usual practice is to present the atmospheric neutrino flux data as a ratio of ratios:

$$R = \frac{[(\text{flux } \nu_\mu + \text{flux } \bar{\nu}_\mu)/(\text{flux } \nu_e + \text{ flux } \bar{\nu}_e)]_{\text{observed}}}{[(\text{flux } \nu_\mu + \text{flux } \bar{\nu}_\mu)/(\text{flux } \nu_e + \text{ flux } \bar{\nu}_e)]_{\text{predicted}}}.$$

For the solar neutrinos this ratio is usually defined in terms of the measured and calculated electron neutrino flux. Another ratio is that of the total, flavour-independent neutrino flux and the calculated electron neutrino flux. The predicted solar flux ratio is based on the standard solar model.

Table 1 gives the results of different types of solar neutrino experiments. If neutrinos are not lost during their journey, R is expected to be 1.

In addition to the solar and atmospheric neutrino sources, there are other sources such as accelerator, reactor, geo and supernovae. There are some tentative estimates of geoneutrinos (33–110) per year, to be confirmed by more experiments for validating the hypothesis of geoneutrinos[4].

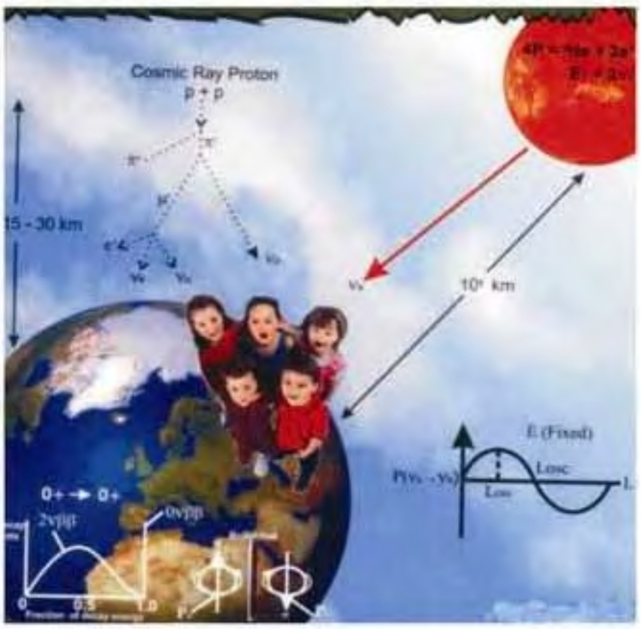

Figure 1. Solar and atmospheric neutrinos reaching earth.

Shankar Nath Mukherjee is in the Department of Physics, Banaras Hindu University, Varanasi 221 005, India.
e-mail: snthmukherjee@rediffmail.com

In the KamLand experiment a large liquid scintillator detector was built to measure the deficit of $\bar{\nu}_e$ from nuclear reactors. Seventeen reactors in the Japan landscape were used for this experiment. A substantial deficit event rate was observed (Figure 2). It is intriguing that neutrinos coming from various sources fall in line, if neutrinos of one flavour say ν_e are assumed to oscillate to those of another flavour say ν_μ. This $\nu_e \leftrightarrow \nu_\mu$ oscillation mechanism is possible only if neutrinos have mass and are non-degenerate[5,6].

Thus evidence of neutrino mass brought a crack in the Standard Model (SM) of particle physics, which is the most comprehensive theory of electro-weak unification and elementary particle interactions.

It is extremely successful in particle physics phenomenology without serious discrepancy with almost all existing data; only one exception at present might be an evidence of massive neutrino established with recent observation of neutrino oscillation. Therefore, evidence of neutrino mass will show that the SM, based on massless neutrino, is not the ultimate theory and it will lead to 'new physics' beyond the SM[5,6].

There is a general consensus that to search for evidences for physics beyond the SM is the most urgent issue in particle physics of the 21st century.

Neutrino detection and experiments

We begin with the pioneering experiment of Davis[2], at Homestake Gold Mine, USA, in which the following reaction (inverse β-decay) was used: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$, with detector threshold at $E_{\nu_e} = 0.82$ MeV. No ^{37}Ar was detected with the $\bar{\nu}_e$ beam, proving that the neutrino is distinctly different from the antineutrino. The interaction between an antineutrino and a proton in an absorption experiment: $\bar{\nu}_e + p \rightarrow n + e^+$ produces a neutron and a positron. Soon after its formation, the positron is annihilated which results in the emission of two photons, each of energy 0.51 MeV. These photons produce scintillation within the scintillating liquid (Figure 3) resulting into two electrical pulses within two photomultiplier tubes, the output of which was fed to the coincidence circuit.

In the experiment by Davis, the detector contained approximately 4×10^5 l of C_2Cl_4 (tetrachloroethelene), having a density = 1.5 g ml^{-1} and ^{37}Cl abundance of 25%. The number of Cl nuclei

$$n = \frac{4 \times 6 \times 10^8 \times 6.02 \times 10^{23}}{4 \times 164} \approx 2.2 \times 10^{30}.$$

The nucleo synthesis

The reaction $4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 26.8$ MeV (Figure 1) taking place in the sun gives one neutrino per 13.4×10^6 eV energy, whereas the energy received by the earth's surface from the sun = $0.134 \times 6 \times 10^{18}$ eV cm^{-2} s^{-1}. Therefore, the solar neutrino flux received by the earth

$$f_\nu = \frac{0.81 \times 10^{18} \text{ eV cm}^{-2} \text{ s}^{-1}}{13.4 \times 10^6 \text{ eV}} = 6 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}.$$

Usually one takes $\bar{f}_\nu = 8.8 \times 10^8$ cm^{-2} s^{-1}, resulting from all the reactions taking place in the sun. The interaction cross-section of neutrinos with matter is a function of energy. The average cross-section for $E_\nu > 0.82$ MeV is $\bar{\sigma} = 10^{-45}$ cm^2/Cl, where $E_\nu = (M_{Ar} - M_{Cl})c^2 = 0.82$ MeV. Therefore, the number of neutrinos detected per day (=number of ^{37}Ar atoms produced per day) is

$$N_\nu = n \bar{f}_\nu \bar{\sigma} t = 0.17 \text{ day}^{-1}.$$

In the radiochemical experiment ^{71}Ga was used as a target for measuring primarily pp neutrinos, while ^{115}In-based detector was used to measure low energy solar neutrinos in real time.

Table 1. Results for different types of solar neutrino experiments

R	Homestake	Super K	SNO	GALLEX
	0.335 ± 0.029	0.459 ± 0.017	0.473 ± 0.074	0.550 ± 0.05

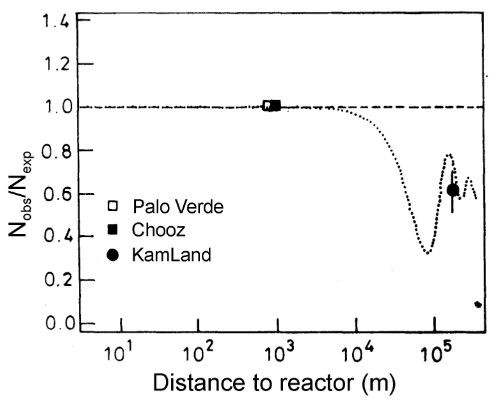

Figure 2. The KamLand experiment.

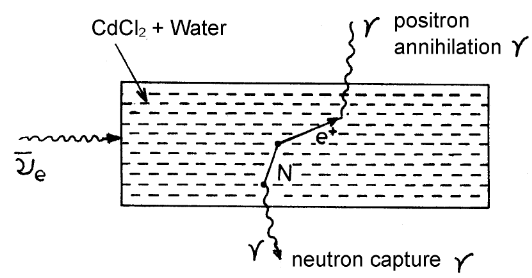

Figure 3. Neutrino absorption experiment.

Another quantity of interest is the up-down asymmetry,

$$A = \left(\frac{N_{up} - N_{down}}{N_{up} + N_{down}} \right)_{\mu\text{-like}},$$

where 'up' neutrinos are those travelling from the bottom and reaching the detector placed on the surface of the earth covering a distance = 4.8×10^4 km, and 'down' neutrinos are those travelling from the upper atmosphere and reaching the detector on the earth's surface covering a distance of 15–30 km.

Neutrino oscillations and masses

Precise measurements of neutrino fluxes coupled with amazing flavour transformation properties of neutrinos provide positive evidence for neutrino mass. Neutrino oscillation is viewed as a quantum mechanical interference phenomenon in which neutrinos of a given flavour transform to another.

Let us consider only two neutrino flavour states as the physical states and ν_1 and ν_2 as the corresponding mass eigen states. We write the neutrino flavour eigen states at $t = 0$ as linear superposition of the mass eigen states in a matrix form:

$$\begin{pmatrix} |\nu_e(0)\rangle \\ |\nu_\mu(0)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}, \quad (1)$$

where the transformation matrix is real and unitary, and θ is the mixing angle. In non-relativistic quantum mechanics, we employ the time-dependent Schrödinger equation to study the time evolution of the state $\nu_e(t)$ as

$$|\nu_e(t)\rangle = c_\theta e^{-iE_1t}|\nu_1\rangle + s_\theta e^{-iE_2t}|\nu_2\rangle, \quad (2)$$

where $s_\theta = \sin\theta$ and $s_\theta = \cos\theta$, and in the natural units: $\hbar = c = 1$; $E_i \cong p + (m_i^2/2p)$ with p as common momentum ($P >> m_i$). The flavour composition of the mass eigen states gives:

$$|\nu_e(t)\rangle = (c_\theta^2 e^{-i(m_1^1/2p)} + s_\theta^2 e^{-i(m_2^2/2p)})|\nu_e(0)\rangle$$
$$+ (c_\theta s_\theta e^{-im_2^2t/2p} - c_\theta s_\theta e^{-im_1^2t/2p})|\nu_\mu(0)\rangle. \quad (3)$$

The probability that a muon neutrino which starts evolving at time $t = 0$ is transformed into an electron neutrino at time t is

$$P(\nu_\mu(0) \to \nu_e(t)) = |\langle \nu_e(t)\, |\nu_\mu(0)\rangle|^2$$
$$= \sin^2 2\theta \, \sin^2\left[\frac{1.27\, \Delta m_\nu^2(\text{eV}^2) L_\nu(\text{km})}{E_\nu(\text{GeV})}\right],$$
$$\text{since } \langle \nu_\mu(0)|\nu_e(0)\rangle = 0. \quad (4)$$

In eq. (4), $\Delta m_\nu^2 = |m_2^2 - m_1^2|$, L_ν is the distance travelled by the neutrino in question and E_ν is its average kinetic energy. The variation of flavour transition probability with respect to L_ν for fixed E_ν is shown in Figure 1 (right bottom). The oscillation is characterized by an oscillation length $L_{osc} = 2.48\, E_\nu(\text{GeV})/\Delta m_\nu^2(\text{eV}^2)$ and $\sin^2 2\theta$. The survival probability $P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e)$, due to the conservation of probability. The survival probability $P(\nu_\mu \to \nu_\mu)$ data of super kamiokonde (super K) experiments for atmospheric neutrinos for maximum mixing angle $\theta = \pi/4$ yields $\Delta m_\nu^2 = 5 \times 10^{-3}$ eV^2.

The two neutrino models described earlier have been generalized to three neutrino flavours. The mixing matrix eq. (1) was parametrized with respect to three mixing angles θ_{12}, θ_{13}, θ_{23} and a phase δ. In this parametrization without δ, the mass spectrum constraint, $\Delta m_{atom}^2 \sim 10^{-3}$ eV^2 >> $\Delta m_{sol}^2 \sim 10^{-5}$ eV^2 permits the identification $\theta_{12}(\theta_{23})$ = solar (atmospheric) mixing angle in a two-flavour picture. The Sudbury Neutrino Observatory (SNO) data yield: $\Delta m_{12}^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2 and $\theta_{12} = 32.50^{+2.4}_{-2.3}$. Liquid Scintillator Neutrino Detector (LSND) data yield $\Delta m_{12}^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2 and $\sin^2 2\theta = 0.001$–0.01 which cannot be accommodated in a three-generation picture. It has been widely realized that the remedy for this situation might be the introduction of a fourth neutrino usually called the sterile neutrino[7].

Mikheyev–Smirnov–Wolfenstein (MSW)[8] made the important suggestion that the solar neutrino might convey resonant effect on matter-induced neutrino mixing in the sun. The MSW effect could convert a large fraction of ν_e produced in the solar core to another type. The new mixing angle in matter θ_N depends on the vacuum mixing angle θ and on vacuum and matter oscillation lengths respectively, L_{osc} and L_0, such that the effective oscillation length in matter L_N is given by

$$\frac{L_N}{L_{osc}} = \frac{\sin 2\theta_N}{\sin 2\theta} = \left[1 + \left(\frac{L_{osc}}{L_0}\right)^2 - \frac{2L_{osc}}{L_0}\cos 2\theta\right]^{-1/2},$$

where

$$\frac{L_{osc}}{L_0} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2} \text{ and } L_0 = \frac{\sqrt{2}\pi}{G_F N_e}. \quad (5)$$

In eq. (5), N_e is the number density of electrons in matter and G_F is the Fermi coupling constant ($=1.16 \times 10^{-5}$ GeV^{-2}). We can express L_0 as $L_0 = 1.7 \times 10^4$ km/ρ_e(g/cm^3)Y_e with $Y_e = 1/2$ for an equal number of neutrons and protons in matter. In rocks, $\rho_e = 4$ g/cm^3, so that $L_0 = 10^4$ km. At the centre of the sun, $L_0 = 200$ km.

The propagation of flavour eigen states in matter is given by

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \frac{2\pi}{L_{osc}}\begin{pmatrix} -\cos 2\theta + \frac{L_{osc}}{L_0} & \frac{\sin 2\theta}{2} \\ \frac{\sin 2\theta}{2} & 0 \end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}. \quad (6)$$

From eq. (6), one can see that in matter, unlike in vacuum, the oscillation pattern depends on whether the mixing angle θ is larger or smaller than $\pi/4$. For $L_{osc} = L_0$, the matter effect is enhanced. In particular, for $(L_{osc}/L_0) = \cos 2\theta$, eq. (5) yields:

$$\sin 2\theta_N = \sin 2\theta\,[1 + \cos^2 2\theta - 2\cos^2 2\theta]^{-1/2} = 1.$$

i.e. maximum mixing even for a small vacuum mixing angle θ. When neutrinos propagate in matter of varying density, the equations of motion (eq. (6)) must be solved. In the general case there is a finite probability P_x for jumping from one eigen state to another. The average survival probability is[9]

$$\overline{P}(\nu_e \to \nu_e) = \frac{1}{2}\,[1 + (1 - 2P_x)\cos 2\theta_m(\rho_{max})\cos 2\theta].$$

Usually $\cos 2\theta_m(\rho_{max}) \approx -1$ and thus $\overline{P}(\nu_e \to \nu_e) \cong \sin^2\theta + P_x \cos 2\theta$.

The transition point between the regime of vacuum and matter oscillation was determined by the ratio L_{osc}/L_0. If $(L_{osc}/L_0) > 1$, the matter oscillations dominate, and when $L_{osc}/L_0 < \cos 2\theta$, the vacuum oscillations dominate.

In the SNO, situated 2070 m underground in a nickel mine in Canada, the charged current reaction of deuteron: $\nu_e + D \to e^- + p + p$ was used. The detector used was 1 K ton heavy water in a 5 cm thick, transparent acrylic vessel of diameter 12 m, surrounded by 10,000 photomultiplier tubes on 7000 tons of water to absorb γ-rays and neutron resulting from radioactivity in the rocks. The measured up–down ratio for $\nu_\mu \to \nu_\tau$ oscillation in this experiment is:

$$\left(\frac{N_{up} - N_{down}}{N_{up} + N_{down}}\right)_{\mu\text{-like}} = 0.288.$$

In the above experiment the neutrino travel distance for up neutrino was 12,800 km and neutrino travel distance for down neutrino was 15 km. For $\sin^2 2\theta = 1$, the two-neutrino oscillation model gives $\Delta m_\nu^2 = 2 \times 10^{-3}$ eV for $\chi^2 = 1$. The KamLand reactor experiment (Figure 2) gives

$$\frac{N(\overline{\nu}_e)_{observed}}{N(\overline{\nu}_e)_{expected}} = 0.6111 \pm 0.085,$$

which when fitted by the oscillation formula with $\sin^2 2\theta = 0.83$ gives $\Delta m_\nu^2 = 5.5 \times 10^{-5}$ eV^2.

Recently, ANTARES neutrino detector deployed in the Mediterranean sea searched for high energy neutrinos of extraterrestrial origin[10]. If one concentrates on the detection of muon produced in a charged current interaction, then the large range of muon in matter would allow for large effective volumes. Direction of the muon is closely related to the direction of the neutrino. If the detection medium is water or transparent ice, then the muon can be tracked through its emission of Cherenkov radiation. The sea and the rock below the seabed provide the interaction volume, and water provides the detection medium. Because of its large scattering length for Cherenkov light, the sea water allows excellent timing and consequently good directional accuracy can be obtained.

These high-energy neutrinos may have been produced in the high energy events in the cosmos, travelling towards us. If their direction can be determined then their origin in the universe can be identified. High energy neutrinos would be an indicator of certain types of dark matter.

The flavour oscillation of neutrinos, confirmed at atmospheric, solar, accelerator and reactor sources provide us with mass square differences Δm^2. However, direct measurement of mass, discussed in the next section can provide precision limits on the mass and nature of the neutrinos.

Direct measurement of neutrino mass

Conceptually the simplest way to explore neutrino mass is by kinematical mass measurement. For example, near the end of the β-spectrum of ^{3}H decay ($^3H \to {}^3He + \beta^- + \overline{\nu}_e$), which has a very low Q-value (=18.6 keV), a massive neutrino has little kinetic energy and the effect of finite neutrino mass becomes visible. The end-point shifts and the rate of beta emission near the end point is depressed (Figure 4). Recent measurements[11] put an upper limit of electron antineutrino mass $m_{\overline{\nu}_e} = 2.2$ eV. The Katrin Collaboration[12] tries to bring it down to 0.2 eV.

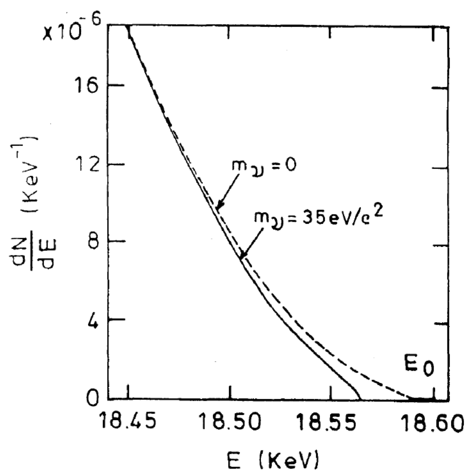

Figure 4. Tritium beta spectrum.

There are experiments now under way at CERN and other laboratories to measure the beta decay end-point energy using ion traps. For example, in the precise measurement of the half-life of free neutron decay, experimentalists detect not the electron final decay product but the protons. Because the protons, as decay products, are relatively slow moving and have charge +e, they can be trapped in a device called a Penning trap, where the combination of electric and magnetic fields holds them in this 'electromagnetic bottle' to be counted.

Historically, rare decays in nuclear/particle physics have lead to new developments. One such example is the laboratory experiments to discover the actual way in which the double beta decay processes occur.

Direct evidence of neutrino mass also comes from double beta decay, which is a rare transition between two nuclei with same mass number A, involving change of nuclear charge by two units. There are two modes of double beta decay: (i) two-neutrino decay ($2\nu\beta\beta$) and (ii) neutrinoless decay ($0\nu\beta\beta$). The $0\nu\beta\beta$ mode differs from the $2\nu\beta\beta$ mode by the fact that the emitted neutrino is reabsorbed (Figure 1, bottom left). Therefore, $0\nu\beta\beta$ violates lepton number conservation. Within certain forms of the Grand Unified Theory (GUT), there is no strict conservation law for leptons and so neutrinoless beta decay could be possible. It also indicates that the neutrino is identical to its antiparticle, i.e. $C|\nu_e\rangle \equiv |\tilde{\nu}_e\rangle = |\nu_e\rangle$, where C is a charge conjugation operator. Such a neutrino is called a Majorana neutrino. For the Dirac neutrino: $C|\nu_e\rangle = |\tilde{\nu}_e\rangle \neq |\nu_e\rangle$. Wu's experiment confirming parity non-conservation (Figure 1, bottom) showed that the neutrino is left-handed. Indeed it is so for a massless spin 1/2 particle obeying the Dirac equation. Thus, parity non-conservation proved that right-handed $\bar{\nu}_e$ could never match the left-handed ν_e: $n \rightarrow p + e^- + \tilde{\nu}_e(R)$ and $\nu_e(L)$ + $n \rightarrow p + e^-$.

The experiment by Davis also made clear-cut difference between ν_e and $\bar{\nu}_e$. If the neutrino is massive, then it has both left- and right-handed components. Thus, $0\nu\beta\beta$ will manifest itself with finite neutrino mass. The search for $0\nu\beta\beta$ by various international groups doing large-scale experiment is in progress[13,14]. $0\nu\beta\beta$ can only proceed via exchange of Majorana neutrino. This possibility led to development in the gauge theoretical model beyond the SM, namely Majorana models of GUT. The lower limits of $T_{1/2}^{0\nu}$, the half-life of neutrinoless beta decay at 90% confidence limit for two candidates are shown in Table 2.

The next generation of $0\nu\beta\beta$ experiments predict $\langle m_\nu\rangle = 10^{-2}$ eV. The $0\nu\beta\beta$ experiment is of great importance for testing the SM of particle physics, which treats neutrinos as massless and left-handed particles to account for the parity violation in weak interactions.

Cosmology and neutrino mass

Stars and galaxies are the main building blocks of the universe. A tenuous interstellar gas cloud composed largely of hydrogen and helium can become gravitationally unstable and condense to form a star, which is constantly battling against the force of gravity. A supernova arises when the core of the star collapses under its own gravitational attraction releasing energy, which causes the outer envelope to explode. Thus, the inner part of the star undergoes an implosion while the outerpart undergoes an explosion[15].

As the gravitational pressure in the supernova relic increased, electrons and protons fused through the weak interaction to neutrons and neutrinos: $e^- + p \rightarrow n + \nu_e$. As the neutrino escapes, a neutron star with mass $M_{ns} \geq 1.4\ M_0$ and radius $R_{ns} \geq 15$ km is formed. The neutron pressure then prevents the star to become a black hole, i.e. it does not shrink so much that the light from the star cannot get out of its strong gravitational inward pull.

The gravitational binding energy as the star radius shrinks is $E_b = (3/5)(GM_{ns}^2/R_{ns})$, where $G = 10^{-38}$ GeV^{-2}, $M_{ns} = 1.4 \times 10^{57}$ GeV, mass of the sun $M_0 = 10^{57}$ GeV and $R_{ns} = 15$ km $= 75 \times 10^{18}$ GeV^{-1}. Therefore, $E_b = 78 \times 10^{58}$ MeV. The star cools through the emission neutrinos and each neutrino (or antineutrino) carries 13×10^{58} MeV energy. Invoking the virial theorem, we get the average kinetic energy for a nucleon on the surface of the neutron star as:

$$\langle E_k\rangle = \frac{1}{2}\frac{GM_{ns}m_N}{R_{ns}} = 93 \text{ MeV}. \tag{7}$$

The number of neutrinos produced equals the number of neutrons. Therefore, neutrinos in thermal equilibrium with their environment ($T = 2/3\langle E_k\rangle = 62$ MeV) will have similar energies. Thus, the number of neutrinos produced in a supernova explosion

$$(N_\nu)_{\text{supernova}} = \frac{73}{68} \times 10^{58} \approx 10^{58}.$$

Table 2. Results of neutrinoless double beta decays[13,14]

	Experiment		Theory	
Nucleus	$T_{1/2}^{0\nu}$ (year)	$\langle m_\nu\rangle$ (eV)	$T_{1/2}^{0\nu}$ (year)	$\langle m_\nu\rangle$ (eV)
^{76}Ge	1.4×10^{25}	1.8–2.5	1.4×10^{22}	16
^{130}Ge	6.6×10^{23}*	1.8–2.5	2.5×10^{22}	130
	1.8×10^{24t}**	0.2–1.1	–	–

In the present universe, the number densities of neutrinos n_ν is comparable to the photon number density n_γ. The baryon energy density $n_B = \eta m_N n_\gamma$ where $\eta = n_B n_\gamma$. Neutrinos will dominate the mass density of the universe if $m_\nu > \eta m_N$. The theory of Big Bang Nucleosynthesis (BBN) and abundances of ^{4}He, ^{7}Li, ^{2}H and three neutrino species require $\eta = 7 \times 10^{-10}$. Hence, $m_\nu > 0.7$ eV. One of the early limits on neutrino mass was deduced from cosmological arguments by Cowsik and McClelland[16].

^{4}He abundances

In the standard hot BBN, the neutron number gets frozen at a temperature T, when the inverse reactions $\bar{\nu}_e$ + p → e^+ + n gets suppressed and (n/p) ratio is fixed at $\mathrm{n/p} = e^{-(m_n - m_p)/T}$.

The temperature T is governed by the expansion rate yielding $T = 0.66$ MeV. The fractional number of ^{4}He nuclei is

$$x = \frac{N\,(^4\mathrm{He})}{\mathrm{p-n}} = \frac{\mathrm{n/2}}{\mathrm{p-n}} = \frac{1}{2}\,\frac{1}{(\mathrm{p/n}\ -1)}. \quad (8)$$

With $T = 0.66$ MeV and $(m_n - m_p) = 1.29$ MeV, eq. (8) gives $\mathrm{p/n} = e^{1.94} \approx 7.0$. Hence, $x = 1/2$. The mass-fraction

$$Y = \frac{M\,(^4\mathrm{He})}{M\,(^1\mathrm{H}_1) + M\,(^4\mathrm{He})} = 0.25.$$

By mass the universe is about 68% H, 30% ^{4}He with all other elements around 2%.

We consider now the gravitational effect of the neutrinos on the dynamics of the expanding universe.

If neutrinos were the dominant mass source in galaxies, then the virial theorem gives

$$\left\langle \frac{1}{2}\, m_\nu v^2 \right\rangle = \frac{1}{2}\frac{G m_\nu M}{R} \quad \text{or} \quad v^2 = \frac{GM}{R}, \quad (9)$$

where R is the size and M the mass of the gravitating system. Therefore, the total mass content due to the neutrino

$$M_\nu \sim m_\nu R^3 \int d^3 p = m_\nu R^3 (m_\nu v)^3 = m_\nu^4 R^3 v^3.$$

Substituting v from eq. (9), we get for $M > M_\nu$: $m_\nu \geq (G^3 M R^3)^{-1/8}$, which shows that the critical neutrino mass decreases with size and mass of the astrophysical system and for galatic halo $m_\nu \approx 20$ eV.

Massive neutrinos may affect drastically the picture of galaxy formation, because massive neutrinos can start clumping long before the photon decoupled, since neutrinos interacting so weakly can freely stream through the distribution of particles. Charged particles are prevented from clumping by photons but not neutrinos. If $M_{H\nu}$ denotes the amount of neutrino masses within the horizon at a temperature $T \cong m_\nu$, then $M_{H\nu} = n_\nu m_\nu$ (horizon size)^3, where the horizon size is $\sim M_{p\ell}/T^2$ in the radiation era and $M_{p\ell}$ ($=10^{19}$ GeV) is the Planck's length. For relativistic particles such as neutrinos we have $n_\nu = T^3$ and $T = m_\nu$. Hence,

$$M_{H\nu} = \frac{M_{p\ell}^3}{m_\nu^2} = \left(\frac{1\ \mathrm{eV}}{m_\nu}\right)^2 \times 10^{18} M_0,$$

where M_0 = mass of the sun = 10^{57} GeV.

For $M_{H\nu}$ to be of the order of a typical galatic mass $\sim M_{\mathrm{galaxy}} = 10^{15} M_0$, one gets the neutrino mass from the above relation:

$$\left(\frac{1\ \mathrm{eV}}{m_\nu}\right)^2 \times 10^{18} M_0 = 10^{15} M_0,$$

which yields $m_\nu = 33$ eV.

Comparison of the power spectrum of CMB with the observed distribution of galaxies can provide information of the sum (over all flavours) of light neutrino masses. The present analysis shows that $\sum_f m_{\nu_f} < 0.7$ eV.

Future directions

In our journey to determine neutrino mass we find that there are four ways to measure or limit neutrino masses: (1) neutrino oscillations, (2) lepton number violating processes, (3) kinematical mass measurements, and (4) astrophysics and cosmology. The interface between various aspects of neutrino physics can merge different disciplines but provide an active area of research. This can be seen from the increasing trend in the number of papers in neutrino physics published per year, as shown in Figure 5.

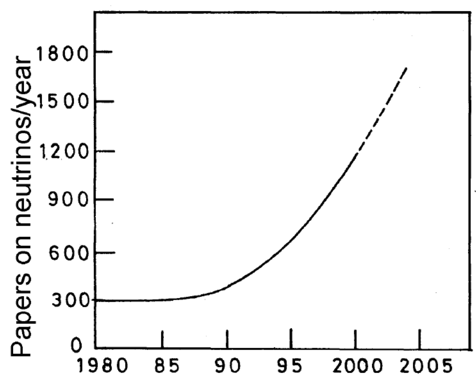

Figure 5. Growth of research in neutrino physics.

Some key ongoing or planned experiments are:

(1) Absolute neutrino mass determination via $0\nu 2\beta$ and improved end-point measurements.
(2) Study of neutrino oscillation in new reactor experiments, superbeams and neutrino factories.
(3) Determination of neutrino mass hierarchy.
There are three possible patterns of mass eigenvalues:
Degenerate: $|m_1| \sim |m_2| \sim |m_3|$,
Hierarchical: $|m_3| >> |m_{2,1}|$,
Inverted hierarchical: $|m_1| \sim |m_2| >> |m_3|$.
(4) Search of neutrino magnetic moment. Based on reactor antineutrino flux of 6.44×10^{12} cm^2 s^{-1}, the limit on the neutrino magnetic moment μ_{ν_e} is found to be $<7.2 \times 10^{11}$ μ_B at 90% CL.
(5) Search for dark matter.

Conclusion

The priorities of particle and nuclear physics during the next 15 years are to pursue an internationally coordinated staged programme in the physics of neutrinos. Indian physicists want to make their presence felt through the proposed India Based Neutrino Observatory (INO)[18]. INO groups have focused attention in the development of various types of neutrino detectors and commissioning of data acquisition system. One indication of the importance of the study of neutrinos is the recent report on 'Facilities for the future science, A twenty-year outlook'. It lists two projects, among the 28 listed in all fields supported by the US Department of Energy, relevant to neutrino physics, the study of double beta decay in underground detectors and Super Neutrino Beam. We could be on the verge of answering the question that human beings have asked for millenia: what are the origins of mass?

1. Reines, F. and Cowan, C. L., *Phys. Rev.*, 1953, **92**, 830.
2. Davis, R., *Phys. Rev.*, 1955, **97**, 766.
Interestingly, the Homestake underground laboratory was funded by T Denny Sanford, a banker and philanthropist.
3. Ahmad, Q. R. *et al.*, *Phys. Rev. Lett.*, 2002, **89**, 011301.
4. Araki, T. *et al.*, *Nature*, 2005, **436**, 449.
5. Morii, T., Lim, C. S. and Mukherjee, S. N., In *The Physics of the Standard Model and Beyond*, World Scientific, Singapore, 2004 and references therein.
6. Mackewon, R. D. and Vogel, P., Neutrino masses and oscillations: Triumphs and challenges. *Phys. Rep.*, 2004, **394**, 315–356, and references therein.
7. Pakvasa, S. and Roy, P., *Phys. Lett. B*, 2002, **535**, 181.
8. Mikheyev, S. P. and Yu Smirnov, A., *Sov. J. Nucl. Phys.*, 1985, **42**, 913.
9. Parke, S. J., *Phys. Rev. Lett.*, 1986, **57**, 1275.
10. Giacomelli, G. and Kooijman, P., *CERN Courier*, 2006, **46**, 24.
11. Kraus, C. *et al.*, *Nucl. Phys. B*, 2003, **118**, 482; *Eur. Phys. J. C*, 2005, **40**, 447.
12. Bornscein, L., KATRIN Collaboration. *Nucl. Phys. A*, 2005, **752**, 14C.
13. Klapdor Kliengrothaus, H. V. (ed.), *Double Beta Decay and Related Topics*, World Scientific, Singapore, 1995.
14. Arnaboldi, C. *et al.*, *Phys. Rev. Lett.*, 2005, **95**, 142501.
15. Kotake, K., Sato, K. and Takahasi, K., Explosion mechanism, neutrino burst and gravitational wave in core collapse supernova. *Rep. Prog. Phys.*, 2006, **69**.
16. Cowsik, R. and McClelland, J., *Phys. Rev. Lett.*, 1972, **29**, 669; Cowsik, R., *Phys. Lett. B*, 1985, **151**, 62.
17. Singh, V., XVII DAE–BRNS High Energy Physics Symposium, Kharagpur, December 2006, p. 19.
18. India-based Neutrino Observatory Interim Project Report, vol. I, Additional material at www.imsc.res.in/~ino

ACKNOWLEDGEMENTS. I am grateful to Prof. A. Yu Smirnov and Prof. S. Parke, Abdus Salam International Centre for Theoretical Physics, Trieste, Italy for useful discussion during the summer of 2003. I am also grateful to Prof. T. V. Ramakrishnan for kind interest. Financial assistance from the Department of Science and Technology, New Delhi is acknowledged.

Received 22 January 2007; revised accepted 18 May 2007