SOME PHENOMENOLOGICAL ASPECTS OF NEUTRINO PHYSICS

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I concentrate on two topics. One is techniques to distinguish amongst various oscillation scenarios from atmospheric neutrino data; and the other is the Borexino solar neutrino detector and its capabilities.

The current high level of interest in neutrino properties is well justified. Neutrino properties (such as masses, mixings, magnetic moments etc.) are of interest for a variety of reasons: (i) in their own right as fundamental parameters and (ii) as harbingers of new physics beyond the standard model (if e.g. $m_i \neq 0, \theta_i \neq 0, \mu_i \neq 0$ etc.).

I will not review here the kinematic limits on masses but concentrate on the current evidence for mixing and oscillations. First we summarize some salient features of neutrino oscillations. For two flavor mixing (say $\nu_e$ and $\nu_\mu$), the standard forms for survival probability and conversion probability are given by

$$P_{ee}(L) = 1 - \sin^2 2\theta \sin^2 \left(\frac{\delta m^2 L}{4E}\right)$$

$$P_{e\mu}(L) = \sin^2 2\theta \sin^2 \left(\frac{\delta m^2 L}{4E}\right)$$

for a neutrino starting out as $\nu_e$. Here $\theta$ is the mixing angle, $\delta m^2 = m_2^2 - m_1^2$, $L=ct$ and the ultra-relativistic limit $E_i \approx p + \frac{m_{i}^{2}}{2p}$ has been taken. Although these formulae are usually derived in plane wave approximation with $p_1 = p_2$, it has been shown that a careful wave-packet treatment yields the same formulae. When the argument of the oscillating term $\left(\frac{2\delta m^2 L}{4E}\right)$ is too small, no oscillations can be observed. When it is much larger than one, then due to

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the spread of \( E \) at the source or finite energy resolution of the detector, the oscillating term effectively averages out to \( 1/2 \).

There are some obvious conditions to be met for oscillations to take place. As the beam travels, the wave packet spreads and the mass eigenstates separate. If the width \( \Delta x \) remains greater than the separation, then oscillations will occur; but if the separation is greater then two separate pulses of \( \nu_1 \) (mass \( m_1 \)) and \( \nu_2 \) (mass \( m_2 \)) register in the detector with intensities \( \cos^2 \theta \) and \( \sin^2 \theta \) separated by \( \Delta t = (\delta m^2/2E^2)(L/c) \). In principle, the intensities as well as oscillation expressions should reflect the slightly different decay widths for different mass eigenstates but this is of no practical importance. The same expressions remain valid if the mixing is with a sterile neutrino with no weak interactions. With 3 flavors mixing, the mixing matrix can have a phase (à la Kobayashi and Maskawa) and the oscillations have a CP non-conserving term leading to

\[
P_{\alpha\beta}(L) \neq P_{\beta\alpha}(L), \quad P_{\alpha\beta}(L) \neq P_{\bar{\alpha}\beta}(L)
\]

etc. Some possibilities for observing CP violating effects in Long Baseline experiments were discussed here by Dr. Koike and by Dr. Sato. An old observation which has become relevant recently is the following: it is possible for neutrinos to be massless but not be orthogonal. For example, with three neutrino mixing we have

\[
\begin{align*}
\nu_e &= U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3 \\
\nu_\mu &= U_{\mu1}\nu_1 + U_{\mu2}\nu_2 + U_{\mu3}\nu_3
\end{align*}
\]

Suppose \( m_1 = m_2 = 0 \) but \( m_3 \) is non-zero and \( m_3 > Q \) where \( Q \) is the energy released in \( \beta^- \)-decay or \( \pi^- \)-decay producing \( \nu_e \) and \( \nu_\mu \) beams. Then \( \nu_e \) and \( \nu_\mu \) will have zero masses but will not be orthogonal:

\[
< \nu_e | \nu_\mu > = -U_{e3}^*U_{\mu3} \neq 0 \quad (4)
\]

(Scenarios similar to this are realized in combined fits to solar and LSND neutrino anomalies). Incidentally, the “\( \nu_e \)” and “\( \nu_\mu \)” produced in \( Z \) decay will not be massless and will be nearly orthogonal! This example illustrates the fact that neutrino flavor is not a precise concept and is process dependent.

1 Atmospheric Neutrinos

The cosmic ray primaries produce pions which on decays produce \( \nu_\mu \)'s and \( \nu_\tau \)'s by the chain \( \pi \rightarrow \mu \nu_\mu, \mu \rightarrow e \nu_e \nu_\mu \). Hence, one expects a \( \nu_\mu/\nu_e \) ratio of 2:1. As energies increase the \( \mu \)'s do not have enough time (decay length
becomes greater than 15-20 km) and the $\nu_\mu/\nu_e$ ratio increases. Also at low energies the $\nu$ flux is almost independent of zenith angle; at high energies due to competition between $\pi$-decay and $\pi$-interaction the famous “sec ($\theta$)” effect takes over. Since the absolute flux predictions are beset with uncertainties of about 20%, it is better to compare predictions of the ratio (which may have only a 5% uncertainty) $\nu_\mu/\nu_e$ to data in the form of the famous double ratio $R = (\nu_\mu/\nu_e)_{\text{data}}/(\nu_\mu/\nu_e)_{\text{mc}}$.

For the so-called “contained” events which for Kamiokande and IMB correspond to visible energies below about 1.5 GeV, the weighted world average (before SuperKamiokande) is $R = 0.64 \pm 0.06$. This includes all the data from IMB, Kamiokande, Frejus, Nusex and Soudan. As we heard from Dr. Nakahata, the new SuperK results are completely consistent with this. It may be worthwhile to recall all the doubts and concerns which have been raised about this anomaly (i.e. deviation of $R$ from 1) in the past and their resolution. (i) Since initially the anomaly was only seen in Water Cerenkov detectors, the question was raised whether the anomaly was specific to water Cerenkov detectors. Since then, it has been seen in a tracking detector i.e. SOUDAN II. (ii) Related to the above was the concern whether $e/\mu$ identification and separation was really as good as claimed by Kamiokande and IMB. The beam tests at KEK established that this was not a problem. (iii) The $\nu_e$ and $\nu_\mu$ cross-sections at low energies are not well known; however $e - \mu$ universality should hold apart from known kinematic effects. (iv) If more $\pi^+\prime$s than $\pi^-\prime$s are produced, then even though the ratio of 2/1 is preserved there is an asymmetry in $\bar{\nu}_e/\nu_e$ versus $\bar{\nu}_\mu/\nu_\mu$. Since $\nu$ cross-sections are larger than $\bar{\nu}$ cross-sections, the double ratio $R$ would become smaller than 1. However, to explain the observed $R$, $\pi^+\prime$s would have to dominate over $\pi^-\prime$s by 10 to 1, which is extremely unlikely and there is no evidence for such an effect. (v) Cosmic ray muons passing thru near (but outside) the detector could create neutrals (especially neutrons) which enter the tank unobserved and then create $\pi^0\prime$s faking “e” like events. Again this effect reduces $R$. However, Kamiokande plotted their events versus distance from wall and did not find any evidence for more “e” events near the walls. (vi) Finally, the measurement of $\mu$ flux at heights of 10-15 km to tag the parent particles as suggested by Perkins was performed by the MASS collaboration. This should help decrease the uncertainty in the expected $(\nu_\mu/\nu_e)$ flux ratio even further. It seems that the anomaly is real and does not have any mundane explanation. The new data from SuperK that we just hear about extends the anomaly to higher energies than before and shows a clear zenith angle dependence as well. This rules out most explanations offered except for the ones based on neutrino oscillations.

If the atmospheric neutrino anomaly is indeed due to neutrino oscillations
as seems more and more likely; one would like to establish just what the nature of oscillations is. There have been several proposals recently. One is to define an up-down asymmetry for $\mu'$s as well as $e'$s as follows:

$$A_\alpha = (N^d_\alpha - N^u_\alpha)/(N^d_\alpha + N^u_\alpha)$$  \hspace{1cm} (5)$$

where $\alpha = e$ or $\mu$, $d$ and $u$ stand for downcoming ($\theta_Z = 0$ to $\pi/2$) and upgoing ($\theta_Z = \pi/2$ to $\pi$) respectively. $A_\alpha$ is a function of $E_\nu$. The comparison of $A_\alpha(E_\nu)$ to data can distinguish various scenarios for $\nu$-oscillations rather easily. This asymmetry has the advantage that absolute flux cancels out and that statistics can be large. It can be calculated numerically or analytically with some simple assumptions. One can plot $A_e$ versus $A_\mu$ for a variety of scenarios: (i) $\nu_\mu - \nu_\tau$ (or $\nu_\mu - \nu$ sterile) mixing, (ii) $\nu_\mu - \nu_e$ mixing, (iii) three neutrino mixing (iv) massless $\nu$ mixing etc. Oscillations of massless neutrinos can occur in models of flavor violating couplings to gravity and Lorentz invariance. However, in both these cases the dependence of oscillations on the distance is very different from the conventional oscillation: $\frac{\delta m^2 L}{4E}$ is replaced by $\frac{\delta f \phi E L}{2}$ or by $\frac{1}{2} \delta v E L$. Here $\delta f = 2\delta \gamma = 2(\gamma_2 - \gamma_1)$ is the small number parameterizing the flavor violating coupling to gravity, $\phi$ the gravitational potential and $\delta v = v_2 - v_1$ is the difference between the two maximum speeds of the velocity eigenstates when Lorentz invariance is violated. The general features of the asymmetry plot are easy to understand. For $\nu_\mu - \nu_\tau$ (or $\nu_\mu - \nu_{\text{st}}$) case, $A_\mu$ increases with energy, and $A_e$ remains 0; for $\nu_\mu - \nu_e$ mixing, $A_e$ and $A_\mu$ have opposite signs; the three neutrino cases interpolate between the above two; for the massless case the energy dependence is opposite and the asymmetries decrease as $E_\nu$ is increased; when both $\nu_\mu$ and $\nu_e$ mix with sterile $\nu'$s, both $A_\mu$ and $A_e$ are positive etc. With enough statistics, it should be relatively straightforward to determine which is the correct one. As we heard, preliminary indications point to $\nu_\mu - \nu_\tau$ as the culprit. There is also another suggestion which can in principle distinguish $\nu_\mu - \nu_\tau$ from $\nu_\mu - \nu_{\text{st}}$ mixing. If one considers the total neutral current event rate divided by the total charged current event rate; the ratio is essentially the n.c. cross section divided by the c.c. cross section. With $\nu_\mu - \nu_{\text{st}}$ oscillations the ratio remains unchanged since $\nu_{\text{st}}$ has neither n.c. nor c.c. interactions and the numerator and denominator change equally ($\nu_\mu - \nu_e$ case is even simpler: nothing changes); however, in $\nu_\mu - \nu_\tau$ case the denominator decreases and the ratio is expected to increase by $(1 + r \frac{P}{P + r}) \approx 1.5$, (here $r = N_{\nu_\mu}^0/N_{\nu_\mu}^0 \approx 1/2$ and $P = 1/2 = \nu_\mu$ survival probability). Of course, it is difficult to isolate neutral current events; but it is proposed to select $\nu N \rightarrow \nu \pi^0 N$ and $\nu N \rightarrow \ell \pi^0 N$ events and the Kamiokande data seem to favor $\nu_\mu - \nu_\tau$ over $\nu_\mu - \nu_{\text{st}}$ or $\nu_\mu - \nu_e$
If we scale \( L \) and \( E \) each by the same amount, say \( \sim 100 \), we should again see large effects. Hence, upcoming thrugoing \( \mu' \)s which correspond to \( E \sim 100 \) GeV on the average, with path lengths of \( L \gtrsim 2000 \) km should be depleted. There are data from Kolar Gold Fields, Baksan, Kamiokande, IMB, MACRO, SOUDAN and now SuperK. It is difficult to test the event rate for \( \nu_\mu \) depletion since there are no \( \nu'_e \)s to take flux ratios and the absolute flux predictions have 20% uncertainties. However, there should be distortions of the zenith angle distribution and there seems to be some evidence for this.

2 Solar Neutrinos

The data from four solar neutrino detectors (Homestake, Kamiokande, SAGE and Gallex) have been discussed extensively. The SuperK data are consistent with those from Kamiokande but increase the statistics by an order of magnitude in one year. To analyze these data one makes the following assumptions: (i) the sun is powered mainly by the pp cycle, (ii) the sun is in a steady state, (iii) neutrino masses are zero and (iv) the \( \beta\)-decay spectra have the standard Fermi shapes. Then it is relatively straightforward to show using these data with the solar luminosity that the neutrinos from \( ^7\text{Be} \) are absent or at least two experiments are wrong. \( ^7\text{Be} \) is necessary to produce \( ^8\text{B} \) and the decay of \( ^8\text{B} \) has been observed; and the rate for \( ^7\text{Be} + e^- \rightarrow \nu + Li \) is orders of magnitude greater than \( ^7\text{Be} + \gamma \rightarrow ^8\text{B} + p \) and hence it is almost impossible to find a “conventional” explanation for this lack of \( ^7\text{Be} \) neutrinos. The simplest explanation is neutrino oscillations.

Assuming that neutrino oscillations are responsible for the solar neutrino anomaly; there are several distinct possibilities. There are several different regions in \( \delta m^2 - \sin^2 2\theta \) plane that are viable: (i) “Just-so” with \( \delta m^2 \sim 10^{-10}eV^2 \) and \( \sin^2 2\theta \sim 1/16 \), (ii) MSW small angle with \( \delta m^2 \sim 10^{-5}eV^2 \) and \( \sin^2 2\theta \sim 10^{-2} \) and (iii) MSW large angle with \( \delta m^2 \sim 10^{-7}eV^2 \) (or \( \delta m^2 \sim 10^{-5}eV^2 \)) and \( \sin^2 2\theta \sim 1 \). The “just-so” is characterized by strong distortion of \( ^8\text{B} \) spectrum and large real-time variation of flux, especially for the \( ^7\text{Be} \) line; MSW small angle also predicts distortion of the \( ^8\text{B} \) spectrum and a very small \( ^7\text{Be} \nu \) flux and MSW large angle predicts day-night variations. These predictions (especially spectrum distortion) will be tested in the SuperK as well as SNO detectors. In particular SNO, in addition to the spectrum, will be able to measure \( NC/CC \) ratio thus acting as a flux monitor and reducing the dependence on solar models.

The only way to directly confirm the absence of \( ^7\text{Be} \) neutrinos is by trying to detect them with a detector with a threshold low enough in energy. One such detector under construction is Borexino, which I describe below.
Borexino is a liquid scintillator detector with a fiducial volume of 300T; with energy threshold for 0.25MeV, energy resolution of 45 KeV and spatial resolution of $\sim 20$cm at 0.5 MeV. The PMT pulse shape can distinguish between $\alpha'$s and $\beta'$s. Time correlation between adjacent events of upto 0.3 nsec is possible. With these features, it is possible to reduce backgrounds to a low enough level to be able to extract a signal from $^7$Be $\nu_e'$s via $\nu - e$ scattering. Radioactive impurities such as $^{238}U$, $^{232}Th$ and $^{14}C$ have to be lower than $10^{-15}$, $10^{-16}$g/g and $10^{-18}(14C/12C)$ respectively. In the test tank CTF (Counting Test Facility) containing 6T of LS, data were taken in 1995-96 and these reductions of background were achieved. As of last summer, funds for the construction of full Borexino have been approved in Italy (INFN), Germany (DFG) and the U.S. (NSF); and construction should begin soon. The Borexino collaboration includes institutions from Italy, Germany, Hungary, Russia and the U.S.

With a FV of 300T, the events rate from $^7$Be $\nu_e'$s is about 50 per day with SSM, and if $\nu_e'$s convert completely to $\nu_\alpha(\alpha = \mu/\tau)$ then the rate is reduced by a factor $\sigma_{\nu_{\mu}e}/\sigma_{\nu_{ee}} \sim 0.2$ to about 10 per day, which is still detectable. Since the events in a liquid scintillator have no directionality, one has to rely on the time variation due to the $1/r^2$ effect to verify the solar origin of the events. If the solution of the solar neutrinos is due to “just so” oscillations with $\delta m^2 \sim 10^{-10}eV^2$, then the event rate from $^7$Be $\nu_e'$s shows dramatic variations with periods of months.

Borexino has excellent capability to detect low energy $\bar{\nu}_e'$s by the Reines-Cowan technique: $\bar{\nu}_e + p \rightarrow e^+ + n, n + p \rightarrow d + \gamma$ with 0.2 msec separating the $e^+$ and $\gamma$. This leads to possible detection of terrestrial and solar $\bar{\nu}_e'$s. The terrestrial $\bar{\nu}_e'$s can come from nearby reactors and from $^{238}U$ and $^{232}Th$ underground. The Geo-thermal $\bar{\nu}_e'$s have a different spectrum and are relatively easy to distinguish above reactor backgrounds. Thus one can begin to distinguish amongst various geophysical models for the $U/Th$ distribution in the crust and mantle. Solar $\bar{\nu}_e'$s can arise via conversion of $\nu_e$ to $\bar{\nu}_\mu$ inside the sun when $\nu_e$ passes thru a magnetic field region in the sun (for a Majorana magnetic moment) and then $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ by the large mixing enroute to the earth.$^{19}$

3 Three Neutrino Mixing.

In addition to the atmospheric and solar neutrino anomalies, there is also the LSND observations (as we heard from Dr. Kim)$^{20}$ which require $\nu_e\nu_\mu$ mixing with $\delta m^2 \sim 0(1)eV^2$ and $\sin^22\theta \sim (0)(10^{-3})$. With the atmospheric anomaly requiring $\nu_\mu$ mixing with a $\delta m^2 \sim 5.10^{-3}eV^2$ and solar neutrinos a $\delta m^2$ in the range $10^{-5} - 10^{-7}eV^2$ (or $10^{-10}eV^2$) for $\nu_e$ mixing; it is clear that one needs 4
neutrino states to mix in order to account for the three separate $\delta m^2$'s. There have been two proposals to account for the three effects with just three flavors. One was by Acker and Pakvasa which uses the same $\delta m^2 \sim 5 \times 10^{-3}$ with large $\nu_e - \nu_\mu$ mixing to account for both solar and atmospheric neutrinos; and a small mixing with $\nu_\tau (\delta m^2 \sim 1 eV^2)$ to account for the LSND. The other, by Cardall and Fuller employs a $\delta m^2$ of $\sim 0.3 eV^2$ to account for both atmospheric and LSND with solar neutrinos driven by either MSW ($\delta m^2 \sim 10^{-5} eV^2$) or “just so” ($\delta m^2 \sim 10^{-10} eV^2$). At the moment, both of these are disfavored: by the CHOOZ results which saw no $\nu_e - \nu_\mu$ oscillations at a $\delta m^2$ of $5 \times 10^{-3} eV^2$ with large mixing and by the SuperK data which requires a $\delta m^2$ of $5 \times 10^{-3} eV^2$. It thus seems inescapable that the three anomalies together require four light neutrino states; and thus at least one sterile neutrino.

4 Conclusion

The only conclusion I can draw is that we have seen possible evidence for neutrino oscillations and within the next 3-4 years, data (from SuperKamiokande, SNO, Borexino; the Long, Short and Intermediate Baseline Experiments, CHOOZ and Palos Verde; LSND and Karmen); will tell us more precisely the parameters of the neutrino mass matrix.

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