RECENT RESULTS IN NEUTRINO PHYSICS K. V. L. Sarma

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This is a survey of the current experimental information on some of the interesting issues in neutrino physics: neutrino species, neutrino masses, neutrino magnetic moments, solar neutrinos, and the atmospheric neutrino anomaly.

1. INTRODUCTION

It is well-known that results in neutrino physics require patience and enormous investments of experimental effort to obtain them. Hence not only announcement of new results but even the confirmation of earlier results or their revised versions become matters of considerable importance. In the Non-Acclerator Particle Physics meeting held at Bangalore in January 1994 [1], many leading ‘neutrinos’ had presented a variety of experimental observations. Some of these results have been superseded by the ones reported at the High Energy Physics Conference at Glasgow in July 1994 [2]. Here we draw together these results in the field of neutrino physics, in the hope that such a compilation with a few annotative remarks would be in the interests of information dissemination. References to published literature are as of September 1994.

The topics are laid out under the following general heads: number of light neutrino flavours, limits on the neutrino masses including those from double beta-decay, and limits on neutrino magnetic moments obtained from the data of laboratory-based experiments. Next we list the latest results from the solar neutrino experiments, and discuss them in some detail. Of crucial importance are the recent model-independent analyses which determine the neutrino fluxes. The conundrum in terms of the near absence of $^7$Be neutrino flux may be pointing towards nonstandard neutrino physics, e.g., in terms of neutrino oscillations involving $\nu_e$. Towards the end, we look at the evidence for the deficit of the muon-neutrino component in the atmospheric neutrinos. The zenith-angle dependence observed recently by the Kamiokande group at the multi-GeV neutrino energies,
seems to favour neutrino oscillations involving $\nu_\mu$. For details regarding the specific experiments and other standard definitions we refer the reader to other reviews.

2. NUMBER OF NEUTRINO SPECIES

From the studies of the $Z$-lineshape at LEP, the number of species of the standard light neutrinos is determined to be \( N_\nu = 2.988 \pm 0.023 \) .

Here the word ‘light’ means anything which is \( \ll \left( \frac{M_Z}{2} \right) \approx 45 \text{ GeV} \). This result is quite justifiably regarded as a triumph for the astro-particle physicists who arrived at the limit \( N_\nu \leq 4 \) on the basis of the present mass fraction of $^4\text{He}$ in the Universe [3].

3. NEUTRINO MASSES

All existing data are of course still consistent with massless neutrinos. So a parade of negative results will follow:

(A) ELECTRON NEUTRINO: Limit on the antineutrino mass comes from the studies of the tritium beta spectrum close to the endpoint. The best upper limit and the first result of the INR-KIAE collaboration [4] was given at the ICHEP-94 meeting [3],

\[
m(\bar{\nu}_e) \leq 4.5 \text{ eV (95\% CL)} .
\]

Although preliminary, it is an improvement over the earlier 7.2 eV limit of the Mainz group [6]. There is however cause for embarrassment. The quantity that actually gets measured is the squared-mass of the neutrino which comes out negative \( m^2(\bar{\nu}_e) = -20 \pm 6 \text{ eV}^2 \). This worrisome feature is common to the observations of several groups; e.g., the Mainz value is \((-39 \pm 34 \pm 15) \text{ eV}^2\). It is possible that there is an undiscovered systematic error floating around in all the experiments, and when that gets discovered the current limits might become less stringent.

Event Pile-up: At the Bangalore meeting, Wolfgang Stoeffl mentioned the problem of the Livermore group: ‘there are too many counts in the tritium beta spectrum close to the endpoint’. Such a pile-up of events is also seen in the Troitsk experiment [4]. If the excess count is due to relic neutrino capture \( \nu_{\text{relic}} + \frac{1}{2}H \rightarrow \frac{3}{2}He + e^- + 18.5 \text{ keV} \), the relic density would have to be quite
high \( \sim 10^{17} \) \( \nu \)'s/cc, which is about \( 10^{15} \) larger than the value implied by the big bang cosmology. In any case it may not be meaningful to give a value for \( m(\nu) \) until the shape of the beta spectrum is fully understood. But if one ignores the problem, and uses statistical procedures blindly, the Livermore limit \(^\square\) turns out to be \( m(\bar{\nu}_e) \leq 5 \) eV.

No one talks about the 17 keV neutrino any more. It has gone the way of ‘cold fusion’. All that hubhub of the early 90’s is now happily forgotten. The origin of the spurious signal in Sulphur-35 decay has been traced primarily to the thickness of the source, improper appreciation of scattering effects, etc., \(^\square\).

**(B) NEUTRINOLESS DOUBLE-BETA DECAY:** So far no one has seen this type of decay. Here one checks whether the total energy of the two final electrons \( (E_1 + E_2) \) has a unique value. Evidence for the \( (\beta\beta)_0\nu \) decay implies lepton number violation and possible existence of Majorana mass of the electron neutrino. From a negative result of the search, the quantity that can be constrained is the ‘effective mass’ of the Majorana \( \nu_e \),

\[
m_{ee} = \sum \eta_{i}^{CP} m(\nu_i) |U_{\nu_e\nu_i}|^2 ,
\]

where \( \eta = \pm 1 \) denotes the \( CP \) eigenvalue of the \( i \)th Majorana neutrino \( \nu_i \) whose mass is \( m_i \), and \( U_{ab} \) denotes the element of the unitary lepton-mixing matrix. Assumptions made are \( CP \) invariance in the leptonic sector and absence of right-handed currents in weak interactions.

The best limit to date on neutrinoless double-beta decay comes from the radiochemical experiment of the Heidelberg-Moscow group using enriched isotope \( ^{76}\text{Ge} \): the 90% CL lower limit on the halflife is \(^\square\)

\[
T_{1/2}^{0\nu} > 3.2 \times 10^{24}\text{years} .
\]

The implied limit on the effective mass of the Majorana neutrino is

\[
m_{ee} \leq 0.9 \text{ eV (90\% CL)} ,\]

which is not inconsistent with that in Eq.(2) because we can have \( \eta_{i}^{CP} = +1 \text{ or } -1 \). This group, which hopes to reach a limit of 0.2 eV within five years, also gave \(^\square\) the most precise value for the halflife of \( ^{76}\text{Ge} \) for 2-neutrino double-beta decay

\[
T_{1/2}^{2\nu}(e^- e^- \bar{\nu}_e \bar{\nu}_e) = (1.42 \pm 0.03 \pm 0.13) \times 10^{21} \text{ years} .
\]
May be, the decays having 2 (anti)neutrinos are the only type of double beta-decays that will ever be seen.

From data on the isotopes Tellurium-128 and 130, the limit quoted by Ramanath Cowsik and collaborators is equally tight, \( m_{ee} \leq 1.1 - 1.3 \text{ eV} \). This comes from a geochemical experiment using mass spectrometry.

There is a clever suggestion due to Raghavan to bring the limit on \( m_{ee} \) further down to values \( < \frac{1}{4} \text{ eV} \). His idea is to search for the neutrinoless double-beta decay of \(^{136}\text{Xe}\) by exploiting the low-background environment available in the large water mass at the Kamiokande facility.

(C) MUON NEUTRINO: The long standing 270 keV limit has to be replaced now by the limit \[ m(\nu_\mu) \leq 160 \text{ keV (90\% CL)} \] (6)

The experiment measured muon momenta in \( \pi^+ \) decays at rest. At present there is a discrete two-fold ambiguity in quoting the charged pion mass at the level of keV. This gives rise to two solutions in obtaining \( m^2(\nu_\mu) \); solution B (‘heavy’ pion) leads to a mildly negative value (at \( \sim 1\sigma \)) and this solution yields the above bound; solution A (‘light’ pion) gives a strongly negative \( m^2 \) value (at \( \sim 6\sigma \)) which is rejected. One hopes that the existing ambiguity in pion mass will be resolved in favour of the ‘heavy’ pion. Ongoing PSI experiments on pi-mesic atoms with low-Z, like O or N, will be of interest in this context.

(D) TAU NEUTRINO: Recent data from BEPC in China show that some numbers in tau-lepton physics have errors smaller than those listed in the 1994 PDG tables; e.g., the present world average value of the tauon mass is \( M_\tau = 1777.00 \pm 0.26 \text{ MeV} \) and the tauon meanlife is \( \tau_\tau = 0.2908 \pm 0.0015 \text{ ps} \). Decays such as \( \tau^- \rightarrow \nu_\tau + (5 \text{ or more hadrons}) \) are used to extract the upper limit on the mass of \( \nu_\tau \)

\[ m(\nu_\tau) \leq 29 \text{ MeV (95\% CL)}; \] (7)

this is a small improvement over the earlier limit of 31 MeV set by the ARGUS group.

(E) NUCLEOSYNTHESIS AND \( \nu_\tau \) MASS: Arguments based on nucleosynthesis (NS) in the early universe and the observed elemental abundances, allow us to push down the laboratory
upper limit of the $\nu_\tau$ mass by an order of magnitude, $m(\nu_\tau) < 0.2$ MeV. According to BBC (Big Bang Cosmology), primordial synthesis of the light elements occurred when the Universe was about 3-minutes old and had a temperature of $\sim 0.1$ MeV. In that era massive neutrinos ($m(\nu) \simeq 0.1 - 1$ MeV) would contribute to the energy density a nonrelativistic component with the maximum occurring for masses $m(\nu) = 4 - 6$ MeV. This maximal energy density may be looked upon as due to adding a few more types of massless neutrinos, $\Delta N_{\text{eff}} = 4 - 5$. Since the observed abundance of primordial helium can be used to restrict the effective number of relativistic neutrinos, we could rule out a range of neutrino masses.

This idea was refined [16] to include the case of decaying neutrinos. The $\nu_\tau$ should not decay too fast but survive till the period of NS to contribute to the nonrelativistic energy density. For $N_{\text{eff}} < 3.3$ (suitable for the helium mass-fraction $Y_p \leq 0.24$) and neutrino proper lifetime $\tau > 10^3$ s, the excluded mass region is $0.1 - 40$ MeV. Combining with the limits coming from the laboratory work, the astro-particle bound may be quoted as [17]

$$m(\nu_\tau) \leq 0.1 - 0.2 \text{ MeV}, \text{ for } \tau_{\nu_\tau} > 10^3 \text{ s}. \tag{8}$$

This is a very impressive limit as the mass-ratio is $[m(\nu_\tau)/m_{\tau}] \leq 6 \times 10^{-5}$, which is only a factor 6 larger than the ratio for the electron, $[m(\nu_e)/m_e] \leq 10^{-5}$.

For unstable neutrinos with $\tau < 100$ s, a gap develops between the upper limit of the He bound and the lab limit. For $\tau < 0.01$ s, the mass region 3-30 MeV is not excluded at all.

The above limit is valid not only for $\nu_\tau$ but also for $\nu_\mu$. Incidentally, the recent observation [18] of a higher abundance of primordial deuterium $(2 - 3) \times 10^{-4}$ (expected amount is $\sim 8 \times 10^{-5}$) may revise the calculated primordial $He$ fraction but only very slightly, and hence the tau-neutrino mass limits are expected to be essentially unchanged.
4. NEUTRINO MAGNETIC MOMENTS

If the standard model is extended to include right-handed neutrinos, then a Dirac neutrino with mass \( m(\nu) \) has (at one-loop order) the Lee-Shrock magnetic moment

\[
\mu_{LS}(\nu) = \frac{3}{8\sqrt{2}\pi^2} eG_F m(\nu) \approx 0.32 \times 10^{-18} \frac{m(\nu)}{eV} \mu_B ,
\]

(9)

where \( e > 0 \) and \( \mu_B = e/(2m_e) \approx 5.8 \times 10^{-15} \) (MeV/Gauss) is the Bohr magneton. This result is independent of the charged lepton mass \( m_\ell \) and possible neutrino-mixing strengths \( U_{ij} \).

Following are the currently available 90% CL upper limits on the neutrino magnetic moments extracted from the laboratory experiments involving elastic scattering \( \nu e \to \nu e \) :

\[
\mu(\nu_e) < 1.08 \times 10^{-9} \mu_B ,
\]

(10)

\[
\mu(\nu_\mu) < 0.74 \times 10^{-9} \mu_B ,
\]

(11)

\[
\mu(\nu_\tau) < 0.54 \times 10^{-6} \mu_B .
\]

(12)

The first two bounds are from the results of the LAMPF group [19], which has the actual experimental constraint in the form \( \sqrt{\mu^2(\nu_e) + 2.1\mu^2(\nu_\mu)} < 1.08 \times 10^{-9} \mu_B \). As for the third bound, although \( \nu_\tau \) has not been identified so far, its elastic scattering was searched for by examining events containing forward-scattered single electrons in a beam dump experiment [20]. The source of \( \nu_\tau \) was taken as charmed-strange meson decays, \( D_s^+ \to \tau^+ \nu_\tau \), etc, where the \( D_s^\pm \) were produced in high energy nuclear collisions. The bound on magnetic moment, which is an order-of-magnitude lower than the earlier one, however depends on assumed values for the production rate and decay-constant of the \( D_s^\pm \) mesons. Improvement in the limit is likely from future data on \( Z \) decays to final states having single photons [21].

Limits extracted by using astrophysics information (energy loss rate of red giants, Supernova 1987A, ... ) are better, but open to argument due to their model-dependence.

A recent proposal [22] to measure the magnetic moment of \( \nu_e \) suggests a novel use of Transition Radiation (TR) detectors. TR is emitted when a charged particle crosses the interface between two different media. It should be produced even when a neutrino crosses the interface of two media provided the neutrino has a nonvanishing magnetic moment. The signal increases with the Lorentz
factor $\gamma$. However, even for the large solar neutrino flux, with the value $\mu(\nu_e) \sim 10^{-10} \mu_B$, the estimates of Grimus and Neufeld $^{[22]}$ show that the yields of typical experiments are going to be extremely small ($\sim 10^{-4}$ photons per year); hence the idea may not be practicable.

Segura et al $^{[23]}$ noted that the elastic cross section for $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ calculated in the lowest order vanishes exactly at one point, namely, when the incident neutrino energy is $E_\nu = m_e/(4\sin^2 \theta_W) \simeq 0.55$ MeV and the final electron is emitted forward (carrying maximal kinetic energy $\simeq 0.38$ MeV). Hence detection of events at this ‘dynamical zero’ might signal scattering due to $\bar{\nu}_e$ magnetic-moment. Another method to look for neutrino magnetic moment is to study, in suitable regions of phase space, the inelastic radiative process using reactor antineutrinos

$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \gamma.$$ 

But the cross sections turn out to be discouragingly small ($\sim 10^{-47} \text{ cm}^2$ at MeV neutrino energies and for $\mu(\nu) \sim 10^{-10} \mu_B$); see, Bernabeu et al $^{[23]}$.

5. SOLAR NEUTRINO RESULTS

All the 4 experiments which are currently running show deficit of $\nu_e$ flux from the Sun. For details concerning the solar neutrino experiments, we refer to the excellent review by Cremonesi $^{[24]}$. In the following, Standard Solar Model (SSM) results of Bahcall’s group and Turck-Chieze’s group will be denoted by the indicies ‘$B$’ and ‘$T$’.

Solar neutrinos, in increasing order of their energies, fall into 3 broad classes: pp, $^7\text{Be}$, $^8\text{B}$. Kamiokande group selects events containing energetic electrons and hence its signal depends only on neutrinos coming from the $^8\text{B}$ decay. In the Cl-Ar experiment, out of the expected total rate, (71-78)% is due to neutrinos from $^8\text{B}$ and (15-17)% is from the electron-capture by $^7\text{Be}$. In the Ga-Ge experiment, only (8-11)% is due to $^8\text{B}$ decay neutrinos, (25-27)% from the $^7\text{Be}$, and more than half (54-57)% is due to the low energy neutrinos from pp fusion (C, N, O reactions contribute the remaining $\sim 5\%$).

(A) $^{37}\text{Cl}$ EXPERIMENT: Threshold = 0.814 MeV,

Calculated Rate : $R_{SSM(B)} = 8.0 \pm 1.0 \text{ SNU}$, $R_{SSM(T)} = 6.4 \pm 1.4 \text{ SNU}$.
Observed Rate \( R_{\text{obs}} = 2.55 \pm 0.17 \pm 0.18 \text{ SNU} \),

\[
\frac{\text{Observed Rate}}{\text{SSM Rate}} = 0.318 \pm 0.051, \text{ for B} \quad (13)
\]

\[
= 0.398 \pm 0.096, \text{ for T} \ . \quad (14)
\]

The original 1987 claim of anticorrelation with the Sun-spot number at 5\( \sigma \) level has now become a 2\( \sigma \) effect. It is now generally agreed that there is no significant correlation of neutrino flux with solar activity.

(B) KAMIOKANDE: Minimum electron energy detected = 7.5 MeV

Calculated Flux : \( \phi_{\text{SSM}(B)} = 5.69(1\pm0.15) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \), \( \phi_{\text{SSM}(T)} = (4.43\pm1.1) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \).

This is the only “neutrino-telescope” we have at the moment. Neutrino is detected by the Cherenkov light emitted by the recoil electron in the reaction \( \nu_e e \rightarrow \nu_e e \). However the ‘directionality’ is smeared as the recoil electron suffers multiple scattering in water; the angular resolution is \( \Delta \theta \sim 27^0 \) at 10 MeV. [Recall that the celebrated neutrino burst observation by Kamiokande on 23 Feb 1987 had 11 events with energies in the range 7.5 - 36 MeV; they were due to (anti)neutrinos from Supernova SN 1987A initiating the nuclear reaction \( \bar{\nu}_e + p(\text{in H}_2\text{O}) \rightarrow e^+ + n \), and not due to their scattering on atomic electrons].

Preliminary results of the latest phase KAM-III (with electron energy cutoff lowered from 7.5 MeV to 7.0 MeV) for 627 days are available; when these are combined with the earlier 1040-day results of KAM-II, the combined flux for the 1667-day run is

\[
\phi_{\text{KAM (II+III)}} = (2.9 \pm 0.2 \pm 0.3) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \ .
\]

This flux would correspond to the ratio

\[
\frac{\phi_{\text{KAM}}}{\phi_{\text{SSM}}} = 0.51 \pm 0.04 \pm 0.06 , \text{ for B} \quad (15)
\]

\[
= 0.66 \pm 0.05 \pm 0.08 , \text{ for T} \ . \quad (16)
\]

\[\bullet\] No time variation was noticed in the KAM results during Jan 87-July 93. No correlation with solar activity was evident. No evidence for day-night effect was observed, \((\text{Day}−\text{Night})/ \text{SSM flux})=−0.08 \pm 0.08.\]

\[\bullet\] Observed neutrino energy spectrum shows no evidence for any distortions; it is as expected in
the SSM.

- The next generation experiment ‘Super-Kamiokande’ is being planned with 50 kilo Tons of water. (C) GALLEX: Threshold = 0.233 MeV,

Calculated Rate: \( R_{SSM(B)} = 131.5^{+7}_{-6} \) SNU, \( R_{SSM(T)} = 122.5 \pm 7 \) SNU,

with the mean value \( R_{SSM} = 128 \pm 8 \) SNU.

The observed rates for two periods of exposure are [27]

GALLEX I: 81\( \pm \) 17\( \pm \) 9 SNU (for 324 days during May 91-May 92)
GALLEX II: 78\( \pm \) 13\( \pm \) 5 SNU (for 406 days during Aug 92-Oct 93).

The combined rate is

\[
\bar{R}_{GLX\ (I+II)} = 79 \pm 10 \pm 6 \text{ SNU} \quad (17)
\]

\[
= 79 \pm 12 \text{ SNU}. \quad (18)
\]

This number is based on a total of 136 decays of \( ^{71}\text{Ge} \) which are attributable to solar neutrino interactions during the 2-year period.

- The observed rate is significantly different from the SSM expectation (~ 128 SNU). However it coincides with the ‘minimum stellar model’ rate 78-80 SNU. This value is obtained assuming that pp and pep fusions are the only sources of solar neutrinos. Note that in SSM the rate due to pp and pep neutrinos is actually slightly lower at 74 SNU; this is because 15\% of the terminations go via \( ^{3}\text{He}+^{4}\text{He} \) fusions producing only one \( \nu_{pp+pep} \) per termination.

- Exposure time of a solar run is 27 days, and each run is counted for about 6 months (~ 11 meanlives of \( ^{71}\text{Ge} \)).

- GALLEX II counting will end by 1994. Calibration exposure to \( ^{51}\text{Cr} \) neutrinos (emitted by electron-capture and have energies 0.746 MeV (90.1\%) and 0.426 MeV (9.9\%); planned source will have a strength ~1.7 megacurie emitting \( 5 \times 10^{11} \nu\ 's\ cm^{-2}\ s^{-1} \) at meter distance initially) will also end by 1994. The entire experiment itself will be over by December 1996. The ultimate statistical accuracy aimed for is about 8\%.

(D) SAGE: The average rate of the Soviet American Gallium Experiment as reported recently [28] is

\[
\bar{R}_{obs} = 69 \pm 11^{+5}_{-7} \text{ SNU}. \quad (19)
\]
This is about 54\% of the average SSM prediction. Note that the errors are smaller than the ones given in a recent publication \[29\].

Together with the GALLEX number the mean rate of the two Gallium experiments combined becomes

\[ R_{\text{Ga}} = 74 \pm 8 \text{ SNU}, \]  

this is 0.58\pm0.07 times the average SSM rate.

\textbf{(E) SOLAR THERMOMETER:} Estimated value of Sun’s central temperature is \( T_c = 15.6 \times 10^6 \text{ K} \approx 1.34 \text{ keV.} \) A “thermometer” to measure \( T_c \) would be the 1.3 keV increase in the average energy of the \( ^{7}\text{Be} \) solar neutrino line \[30\]. In the reaction \( ^{7}\text{Be} + e \rightarrow ^{7}\text{Li} + \nu_e \) the peak of the neutrino line is at 861.84 keV. The asymmetric line profile in the Sun is going to shift the peak value to 862.27 keV, due to absorption of continuum energy electrons. Future experiments, e.g., BOREX, may be able to provide data with the type of accuracy needed.

\textbf{(F) COOLER SUN WILL NOT HELP:} Reducing the central temperature \( T_c \) (also called ‘the astrophysics solution’) will not help to understand the low rates recorded by Kamiokande and Cl-Ar experiments. The argument is simple: a cooler Sun leads to a bigger suppression of the energetic neutrinos (the only kind seen by Kamiokande) while the data require the other way \[31\]. To see this, let us note the approximate dependences of the neutrino fluxes on central temperature \( T_c \):

\[ \phi_B \sim T_c^{18}, \quad \phi_{Be} \sim T_c^8. \]

The SSM flux of \( \nu_B \) will agree with Kamiokande data provided we reduce \( T_c \) from its canonical value by only about (3\pm1)\%. On the other hand SSM says that the Cl-Ar rate should have about 75\% contribution from \( ^{8}\text{B} \) neutrinos, about 15\% from \( ^{7}\text{Be} \) neutrinos, etc. Hence the observed large suppression in the Cl-Ar data can be reproduced by lowering \( T_c \) by a bigger amount, (7\pm1)\%. The required reductions in \( T_c \) thus do not overlap and hence a cool Sun is not a tenable solution - independently of the data from Gallium experiments, a point first emphasized by Bahcall and Bethe.

Note that it is the relative deficit of the Cl-Ar result with respect to the Kamiokande result which is crucial, and not the separate deficits with respect to the SSM.
(G) SOLAR NEUTRINO DECAY: This possibility as a way to explain the solar neutrino deficit is ruled out, at more than 98% confidence level. In SSM the Gallium rate is fed largely by the low energy pp-neutrinos while the Kamiokande and Cl-Ar rates by the more energetic neutrinos. If neutrinos were to decay in transit then it is the lower energy neutrinos which should disappear first; thus the Ga-rate should suffer a much stronger reduction than what is observed.

(H) NEUTRINO OSCILLATIONS AND MSW EFFECT:

*Nature within her inmost self divides,
To trouble man with having to take sides.* - Robert Frost

Solar neutrinos can oscillate into other kinds of neutrinos, $\nu_e \leftrightarrow \nu_\mu, \nu_\tau, \nu_s$, provided the relevant mixings and mass differences are nonvanishing (subscript ‘s’ denotes sterile neutrino having no interaction with a terrestrial detector). We list the results of analysing the solar neutrino data in terms of simple 2-flavour oscillations.

Vacuum Oscillation: The long-wavelength oscillation (LWO) solution (also called “just-so” solution), assumes the wavelength of oscillations in vacuum to be about a AU [$\simeq 1.5 \times 10^{13}$ cm $\simeq 1/(1.3\times10^{-18}$ eV)] and the mixing angle to be near maximal. Such a possibility is not completely ruled out; a typical fit (which gets allowed at about 10% CL) for $\nu_e \leftrightarrow \nu_{\mu,\tau}$ oscillations is characterized by the parameters

$$\Delta m^2 \sim (0.55 - 1.1) \times 10^{-10} \text{ eV}^2, \quad \sin^2(2\theta) \sim 0.75 - 1.$$  \hfill (21)

The case of LWO into sterile neutrinos ($\nu_e \leftrightarrow \nu_s$) cannot be distinguished from the case of ($\nu_e \leftrightarrow \nu_{\mu,\tau}$) by the Cl and Ga data. However the results of Kamioka-II spectral data are able to rule out vacuum oscillations into sterile neutrinos at 98% CL. (Oscillations into the sterile kind are ruled out even when the MSW effect is included.)

The vacuum solution is testable by the seasonal variation (Earth-Sun distance changing by $\pm 3.5\%$ during the year) in the intensity of the monochromatic $^7$Be neutrino line. BOREXINO would be ideal for this type of work. Since the oscillation length ($\ell = 4\pi E/\Delta m^2$) is proportional to neutrino energy $E$ one should see wiggles in the $^7$Be neutrino flux as the distance varies. Also useful will be similar observations at SNO (Sudbury Neutrino Observatory in Canada using ultra-pure D$_2$O) in which the neutrino produces electron by the reaction $\nu_e d \rightarrow p p e^-$, and the electron energy
\[ (E_e \simeq E_\nu + m_D - 2m_p \simeq E_\nu - 0.931 \text{ MeV}) \] gets determined by the Cherenkov light.

MSW effect arises from the unequal scattering of the \( \nu_e \) and \( \nu_{\mu,\tau} \) on electrons. As the solar neutrino passes through the dense layers of Sun’s medium, due to coherent scattering on atomic electrons, there can be resonant or enhanced conversion of \( \nu_e \) into other flavours. The attractive feature is that the solar \( \nu_e \) flux can be significantly suppressed even for insignificant mixings, like the ones encountered in the quark sector; obviously there is no need for fine-tuning of the mixing angles.

For the simple case of 2-neutrino mixing, there are two solutions which are distinguished by the mixing angle. They consist of allowed values of parameters confined to certain small regions. We quote the central values of these island regions from the 1993 analysis of Hata and Langacker [34]:

\[
\begin{align*}
\text{MSW - 1 (Small Mixing)} : & \quad \Delta m^2 \sim 6 \times 10^{-6} \ eV^2, \quad \sin^2(2\theta) \sim 0.007; \\
\text{MSW - 2 (Large Mixing)} : & \quad \Delta m^2 \sim 9 \times 10^{-6} \ eV^2, \quad \sin^2(2\theta) \sim 0.6.
\end{align*}
\]

These are indicative of neutrino masses in the milli-eV range, and correspond to (vacuum) oscillation lengths \( \sim O(10^2) \) km for neutrino energies in MeV range. MSW-1 gives a much better fit than MSW-2.

A word about MSW-2 solution. The \( ^8 \text{B} \) neutrinos can undergo MSW conversion, in the Earth’s core and mantle. This would allow ‘reconversion’ inside Earth, resulting in an enhanced night-time signal. For this reason in fitting to the KAM-II day-night data, the parameter range of MSW-2 becomes further restricted.

The Vacuum or MSW solutions can also be reconciled with the possible existence of a Majorana neutrino with effective mass \( m_{ee} \sim 0.1 - 1.0 \) eV, [33].

**I** EXPERIMENTAL LIMITS ON \( \nu_e \) OSCILLATIONS : What is the evidence for neutrino oscillations using laboratory neutrino sources? New limits on the oscillation parameters of reactor neutrinos have been provided by the Kurchatov group [36]. The experiment measured inverse beta-decays using the antineutrino flux from 3 reactors (of the Krasnoyarsk group), almost identical power-wise and situated at distances 57.0, 57.6, and 231.4 meters from the detector. The reactors were switched on or off selectively, in several combinations, during the course of the experiment.
The final results quoted are

\[ \Delta m^2 < 7.5 \times 10^{-3} \text{ eV}^2, \text{ for } \sin^2 2\theta = 1, \tag{24} \]

\[ \sin^2 2\theta < 0.15, \text{ for } \Delta m^2 > 5 \times 10^{-2} \text{ eV}^2. \tag{25} \]

These are slightly better than the earlier Goesgen reactor limits.

A novel proposal to look for neutrino oscillations \cite{37} exploits the ‘dynamical zero’ in the
differential scattering cross section using reactor neutrinos on electron targets, \( \bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^- \). Recall that this zero occurs for incident antineutrino energy \( E_{\bar{\nu}_e} = m_e / (4 \sin^2 \theta_W) \) at the neutrino scattering angle \( \theta_{CM} = \pi \); it is absent in other reactions, e.g. \( \bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e \). Oscillations of \( \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu \) would then lead to characteristic changes in scattering rate as one scans past the ‘zero’, and also by varying the detector distance.

(J) WHERE ARE THE \(^7\text{Be}\) NEUTRINOS? Recently there have been many model-independent analyses of the solar neutrino data incorporating the luminosity constraint \cite{38} - \cite{40}. The end result is that for obtaining any kind of fit to the existing data, the \(^7\text{Be}\) neutrino flux should be severely suppressed, \( \phi_{Be} \simeq 0 \). This startling conclusion obviously poses a serious challenge to the SSM; various brands of SSM have small changes in their input parameters and those can hardly cause an order-of-magnitude suppression of a major neutrino flux, second only to \( \phi_{pp} \).

The assumptions underlying these analyses are general:

(a) The Sun is powered by the pp-chain and the CNO-cycle.

(b) The Sun is in a quasi-steady state having the same value of \( L_{\odot} \) for at least the past few million years. This enables us to connect \( L_{\odot} \) with the neutrino fluxes \( \phi_i \).

(c) Some of the minor neutrino fluxes are taken into account: the flux from pep fusion is assumed to be scaled as \( 2.4 \times 10^{-3} \times \phi_{pp} \), following SSM; the \(^{15}\text{O}\) and \(^{13}\text{N}\) neutrino fluxes are related to each other in the SSM ratio \( 0.85 : 1 \); neutrinos from \(^{17}\text{F}\) decay and from hep reaction are ignored.

(d) Solar neutrinos reaching the earth are standard \( \nu_e \) having no mass, no mixing, no magnetic moment, etc; they interact with the detector elements according to the Standard Model of particle physics.
Assumptions (a) and (b) seem to be quite innocuous and almost mandatory, while (c) is unlikely to play an important role in determining the major neutrino fluxes; a popular way to renounce the assumption (d) involves neutrino oscillations.

The luminosity constraint is a linear relation between the luminosity $L_\odot$ and the neutrino fluxes $\phi_i$,

$$K \equiv \frac{L_\odot}{4\pi d^2} = 8.54 \times 10^{11} \text{ MeV cm}^{-2} \text{ s}^{-1}$$

$$= \sum_i \left( \frac{Q}{2} - <E_i> \right) \phi_i .$$

(26)

(27)

Here $K$ is the usual solar constant measured to $\pm 0.2\%$, $Q = 26.731 \text{ MeV}$ is the total energy released in the process $4p + 2e \rightarrow ^4He + 2\nu_e$, and $<E_i>$ is the average neutrino energy in the reaction labelled $i$. We absorb the dimensions of the flux by defining

$$f_i \equiv \frac{\phi_i}{(10^9 \text{ cm}^{-2} \text{ s}^{-1})} ,$$

and obtain the luminosity constraint (inclusive of the N, O neutrino contributions) as

$$f_{pp} + f_{pep} + 0.958 \ f_{Be} + 0.46 \ f_B + 0.955 \ f_{NO} = 65.7 .$$

(29)

The neutrino capture rates of interest are given by

$$R_{Ga} = (79.75 + 2.43 \times 10^3 \ f_B + 6.14 \ f_{Be} + 7.49 \ f_{NO}) \text{ SNU},$$

$$R_{Cl} = (0.247 + 1.09 \times 10^3 \ f_B + 0.236 \ f_{Be} + 0.396 \ f_{NO}) \text{ SNU} .$$

(30)

(31)

The large factor in front of $f_B$ reflects the large cross section of $^8B$ neutrinos. The flux of $^8B$ neutrinos as directly measured by the Kamiokande experiment is

$$f_B = (2.9 \pm 0.36) \times 10^{-3} .$$

(32)

Substituting $f_B$ in the expression for $R_{Cl}$ and ignoring the last two terms, we get a lower bound which, at 90% CL, is $R_{Cl} \geq 2.76 \text{ SNU}$. Since this limit is essentially saturated by the Cl-Ar experimental result $2.55 \pm 0.25$, we immediately see that it is difficult to accommodate any $^7\text{Be}$ neutrino contribution (it is about 1.0-1.2 SNU in SSM). So, where are all the $^7\text{Be}$ neutrinos gone? Kwong and Rosen had reached this puzzling conclusion using slightly different arguments.
The recent analyses consist in determining the 4 unknown fluxes \( f_{pp}, f_{Be}, f_{B}, f_{NO} \) from the 4 experimental data \( R_{Ga}, R_{Cl}, f_{Kam}, L_{\odot} \); this is a case with zero degrees of freedom. The best fit according to chi-square minimum is found to occur for a negative \(^7\text{Be}\) flux [38, 39, 40]. On the other hand imposing the physical requirement \( f_{i} \geq 0 \) leads to fits which are quite poor (large chi-square) and unacceptable; the \( Be \) neutrino flux \( f_{Be} \) in that case hovers around zero (less than \( \mathcal{O}(10^{-1}) \) of the SSM value).

This conclusion about \( \phi_{Be} \) suppression is quite robust: even if we disregard the data from any one of the three solar neutrino experiments, the resulting fit shows no significant improvement. A simple way to see is to rewrite the expressions for \( R_{Ga} \) and \( R_{Cl} \) as follows:

\[
\begin{align*}
  f_{Be} + 1.18 f_{NO} &= 0.18 G - 0.40 H - 14.1 = -1.9 \pm 1.5, \\
  f_{Be} + 1.22 f_{NO} &= 0.16 G - 0.40 K - 13.0 = -2.1 \pm 1.4, \\
  f_{Be} + 1.68 f_{NO} &= 4.24 H - 4.62 K - 1.05 = -3.6 \pm 2.0,
\end{align*}
\]

(33) (34) (35)

Here \( G, H \) and \( K \) stand for the data from Gallium, Homestake and Kamiokande experiments, and the numbers on the extreme right result from substituting

\[
G \equiv \frac{R_{Ga}}{SNU} = 74 \pm 8.5, \quad H \equiv \frac{R_{Cl}}{SNU} = 2.55 \pm 0.25, \quad K \equiv 10^3 f_{B} = 2.9 \pm 0.36.
\]

(36)

The flux-sums have negative central values (and even with errors they are much smaller than SSM expectations) for all the three pairings of the data: \( GH, GK, HK \). Thus one is led to conclude that at least two of the three experiments must be wrong [38, 39, 40]; e.g., the systematic errors could have been grossly underestimated in two experiments.

A comparison of the data with any SSM now becomes almost an irrelevant exercise: all SSMs depend on the assumptions (a),(b),(d), while (c) may not be crucial; differences between them arise largely due to the differences in values adopted for fusion cross sections, opacities, etc, or in inclusion of some effects such as diffusion. The discrepancy in the Beryllium neutrino flux is such that any SSM gets ruled out by, conservatively speaking, more than 3\( \sigma \).

On the other hand if we believe in the validity of all data, then we should reexamine the basic assumptions (a) - (d) of the analyses. A simple and attractive way out is to modify the assumption (d) to include the effects of possible neutrino oscillations in extracting the solar neutrino fluxes. A
model-independent analysis of the data with neutrino oscillations, including the MSW effect, seems to place only a weak restriction on the fluxes.

6. ATMOSPHERIC NEUTRINO ANOMALY

Atmospheric neutrinos were detected first by the KGF group in August 1965. They are produced in the atmosphere from the decay of secondaries like pions, kaons, muons, ... which are produced in the interactions of cosmic rays with target nuclei like N, O in the atmosphere. The cause for present excitement is that there is a deficit in one kind of these atmospheric neutrinos, and this ‘anomaly’ may be the long-sought evidence for neutrino oscillations $\nu_\mu \leftrightarrow \nu_{\tau,e}$.

The anomaly was first claimed in 1988 by the Kamiokande group in respect of their ‘fully-contained’ events. They are due to single particles which are created and absorbed inside the detector. The single particle could be a $\mu$ or $e$, produced by the appropriate neutrino in the energy range say 0.3-2 GeV, and propagating ‘upwards’ through the Earth’s medium (direction is fixed by the orientation of the Cherenkov cone). An event is termed ‘$\mu$-like’ if the associated Cherenkov ring is ‘sharp’, and ‘$e$-like’ if the ring is ‘fuzzy’. Bremsstrahlung from electron creates secondary $e^+e^-$ pairs which also could give Cherenkov radiation in water. Hence the interactions of $\nu_e$ or $\bar{\nu}_e$ giving $e^-$ or $e^+$, are associated with diffuse or fuzzy rings.

In the atmosphere, due to decay chains like $\pi^+ \rightarrow \mu^+\nu_\mu$ and $\mu^+ \rightarrow e^+\bar{\nu}_e\nu_\mu$, etc., one expects approximately $(\nu_\mu + \bar{\nu}_\mu) : (\nu_e + \bar{\nu}_e) \sim 2:1$; but observations show this ratio to be anomalously small, essentially like 1:1. This finding, termed the atmospheric neutrino anomaly (ANA), was originally seen in events at low momenta $(p < \text{500 MeV/c})$ of the produced $e$ and $\mu$, and showed no correlation with zenith angles.

The ratio of the observed $\mu$-like to $e$-like events is compared with that obtained from Monte Carlo simulations. The following ratio-of-ratios which ought to be compared with unity, are taken from the talk of K. Nakamura:

$$R_{\text{atm}} \equiv \frac{(\mu - \text{like}/e - \text{like})_{\text{OBS}}}{(\mu - \text{like}/e - \text{like})_{\text{MC}}} = 0.60^{+0.06}_{-0.05} \pm 0.05 \ , \ (\text{KAM})$$  \hspace{1cm} (37)

$$= 0.54 \pm 0.05 \pm 0.12 \ , \ (\text{IMB} - 3)$$  \hspace{1cm} (38)

$$= 0.69 \pm 0.19 \pm 0.09 \ , \ (\text{Soudan} - 2)$$  \hspace{1cm} (39)
Remarks: (a) Recent (preliminary) checks carried out with \(e, \mu, \pi\) beams, produced at the KEK accelerator and sent through a big water tank, give credence to the Kamioka classification of the Cherenkov rings in the momentum range 0.2-1 GeV/c \[2\]. (b) Although agreement among the calculated atmospheric-neutrino fluxes is poor, especially at low energies, there is consistency (to within 5\%) among the calculated flux-ratios at all energies. (c) KAM data agree with IMB on the \(\mu\)-like events, but disagree by 2\(\sigma\) on the \(e\)-like events. (d) IMB group claims, in their upward-going \(\mu\)-like events, the ratio of \textquoteleft{}stopping\textquoteright{} muons (\(\leq 10\) GeV) to \textquoteleft{}through-going\textquoteright{} muons is as expected \textit{without} invoking oscillations. (e) The anomaly is supported by the SOUDAN-2 track-calorimeter which has good resolution and discrimination for \(e\) and \(\mu\).

NEW RESULTS: Kamiokande group has recently reported \[12\] data on the fully-contained (FC) and the partially-contained (PC) types of events. These are initiated by multi-GeV neutrinos with \(E(\text{visible}) > 1.33\) GeV and correspond to a mean neutrino energy = 5 - 7 GeV (the earlier sub-GeV data corresponded to \(\lesssim 0.7\) GeV). Averaging over the zenith angles the ratio-of-ratios turns out to be not different from the earlier sub-GeV data

\[
R_{\text{atm}} = 0.57^{+0.08}_{-0.07} \pm 0.07 . \tag{41}
\]

However a significant feature of the new data is the \textit{zenith angle dependence} (sub-GeV data showed isotropy): \(R_{\text{atm}}\) steadily increases from \(\sim 0.3\) to \(\sim 1\) as we go from the \textquoteleft{}upward\textquoteright{} \((\theta = \pi)\) events to the \textquoteleft{}downward\textquoteright{} \((\theta = 0)\) ones.

Just the observation of a zenith-angle dependence itself is a sufficient reason to invoke oscillations. Considering the extreme cases, neutrinos travelling downward may have too short a travel length (20 km length of atmosphere) and hence do not oscillate; those travelling upwards (\(\sim 10^4\) km across the Earth) have a very long flightpath available and oscillate many times; assuming maximal mixing and averaging over many oscillations would lead to a 1:1 flavour mixture of the upward movers. The zenith-angle isotropy in the sub-GeV data could be understood as due to the large uncertainty with which the incident neutrino direction is ascertained for a given direction of the scattered lepton. Analysis of all data (including sub-GeV events) \[12\] gives the allowed region,
for $\nu_{\mu} \leftrightarrow \nu_{\tau}$ oscillations, around the best-fit values:

$$\Delta m^2 \simeq 1.6 \times 10^{-2} \ eV^2 , \ \sin^2 2\theta \simeq 1 ,$$

(42)

oscillation length will be $O(10^3)$ km for neutrinos of a few GeV. The region for the parameters of $\nu_{\mu} \leftrightarrow \nu_e$ oscillations is roughly the same, only slightly bigger. However in the latter case since $\nu_e$'s are involved, matter effects arising from their travel through the Earth’s medium may have to be included; see, e.g. FIG.1 of Ref. [43].

7. CONCLUSIONS

Very few and tiny improvements have occured in the upper limits on neutrino masses. In the near future, dramatic improvements in the lab-based experimental limits are unlikely to occur. In tritium beta decay Mainz group’s study within the “gap” between the 1S-2S atomic levels in ($^3$He)$^+$ ion, might be interesting.

Two CERN experiments, CHORUS (consisting of 800 kg emulsion) and NOMAD (with electronic detectors) using the neutrinos from CERN SPS, are already underway looking for $\nu_{\mu} \leftrightarrow \nu_{\tau}$ oscillations, with a source-detector distance of 800 meters (sensitive to $\sim 1$ eV neutrino masses). There are proposals to look for oscillations by ‘long-baseline’ studies - shooting accelerator neutrino beams at detectors located faraway - Fermilab to Soudan mines (730 km), CERN to Gran Sasso tunnel (732 km); the former needs the Main Injector installed in the Tevatron, and the latter needs LHC.

As for the solar neutrinos, the present data (stretched to 90% CL limits) can be summarized crudely by the hierarchy

$$0.24 \leq \left( \frac{\text{OBS}}{\text{SSM}} \right)_{\text{Cl}} \leq \left( \frac{\text{OBS}}{\text{SSM}} \right)_{\text{KAM}} \simeq \left( \frac{\text{OBS}}{\text{SSM}} \right)_{\text{Ga}} \leq 0.70 ;$$

so it is still the Cl-Ar result which poses the most acute challenge to the SSM. Model-independent determinations of the solar neutrino fluxes imply that the $^7$Be neutrino component should be totally absent. An attractive way out is to assume neutrino oscillations. All data can be understood in terms of neutrino flavour oscillations, with or without the need of matter effects. We await the next generation experiments: SNO (by 1995 end), Super-Kamiokande (by 1996 end), Borexino, and ICARUS.
The earlier claim of Kamiokande observing a deficit in the atmospheric \((\nu_{\mu} + \bar{\nu}_{\mu})\) flux, has firmed up further. The measured ratio of mu-like to e-like events is about half the expected value. The zenith angle dependence of this ratio in the multi-GeV neutrino events is the novel feature of the 1994 data. The Kamiokande group seems to be again lucky, and may have discovered neutrino oscillations. The final verdict on this important issue may have to await the long-baseline studies.

With so many experiments in progress, and many yet to start, neutrino physics should be as exciting as ever, for a long time to come.

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