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NEUTRINO PROPERTIES¹

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Abstract

Neutrinos have reached the status of being probes to study the structure of other systems. We have not, however, definite answers to the questions associated with its intrinsic properties. The selected topics are organized according to a "Decameron", which covers both aspects of neutrino physics. One comes to the conclusion that we are entering an exciting period in this field, with experiments able to establish new phenomena and/or put better limits to some intrinsic properties.

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ABSTRACT

Neutrinos have reached the status of being probes to study the structure of other systems. We have not, however, definite answers to the questions associated with its intrinsic properties. The selected topics are organized according to a "Decameron", which covers both aspects of neutrino physics. One comes to the conclusion that we are entering an exciting period in this field, with experiments able to establish new phenomena and/or put better limits to some intrinsic properties.

1. INTRODUCTION

Neutrinos, with its over 60 years of having been postulated¹ by Pauli to explain the β -decay continuous spectrum and after 35 years of its discovery² by Cowan and Reines in their celebrated reactor experiment, have been and are being used, by means of their weak interaction, as a probe of the structure of complex systems, such as nucleons, stars or the Universe. However, still today we have not definite answers to the question of the intrinsic properties of this particle. To organize the discussion about the different topics involved in neutrino properties, some choice is necessary and this is here presented as a "Decameron" of questions:

- i) How many Neutrino Families?
- ii) Neutrino Masses and Mixings?
- iii) 17 - KeV Neutrino?
- iv) Solar Neutrino Anomaly?
- v) Neutrino-Oscillations?
- vi) Theoretical Ideas for Neutrino Mass
- vii) Does $\bar{\nu} = \nu$? $3\beta_{\nu\nu}$ -Decay
- viii) Neutrino Dipole Moments?
- ix) Neutrino as Probe of other's Structure
- x) Neutrinos as Mediators of Long Range Force

Of course, these different problems are not independent and connections between the lines could be established; for example, points iii) and iv) can be considered as hints of the evidence for neutrino masses and mixings, or the neutrinoless double beta decay process as source of information on Majorana masses.

2. HOW MANY NEUTRINO FAMILIES?

For active left-handed neutrinos with the family structure of the standard theory, and provided that the neutrino mass is below $\frac{m_Z}{2}$, the Z total width is a measure of the number of neutrino families N_ν .

From the different channels associated with the partial widths of the $Z \rightarrow f\bar{f}$

one can build a "nearly" model independent method to extract N_ν . One has

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_e} = \frac{1}{\Gamma_e} (\Gamma_{inv} - \Gamma_h - 3\Gamma_l) = \frac{\Gamma_e}{\Gamma_e} \left[\left(\frac{12\pi R_{had}}{\sigma_h^0 m_Z^2} - R_{had} - 3 \right) \right] \quad (1)$$

where Γ_{inv} , Γ_h , Γ_l , Γ_e and Γ_l are the invisible, neutrino, total, hadronic and charged lepton widths of the Z. The bracket of the right hand side of Eq.(1) contains only the measured quantities: the branching ratio $R_{had} = \frac{\Gamma_h}{\Gamma_e}$ of hadronic to leptonic widths, the hadronic cross section σ_h^0 at the peak and the Z-mass m_Z . In this way the standard model has to be used only for the ratio $\left(\frac{\Gamma_e}{\Gamma_e} \right)$, which is independent of hard (power) mass terms, due to the top-quark, in its electroweak radiative corrections. The present result from the four experiments of LEP gives³ the number

$$N_\nu = 2.99 \pm 0.05 \quad (2)$$

One of the great achievements of LEP has been the precise mapping of the Z - LINE SHAPE as measured with hadronic events. The comparison of the measured hadronic cross section with the prediction at different values of N_ν shows that $N_\nu = 3$ is clearly demonstrated.

Primordial Nucleo-synthesis can be also used as a source of information about the value of N_ν . This is reviewed in the lecture by G.Steigman in this Workshop, showing that for light neutrinos (masses much smaller than MeV) one gets¹ $N_\nu \leq 3.4$. The constraints imposed on the particle contents and their couplings to the Z by this method are quite complementary to those imposed by (2) on extensions beyond the standard theory. Nucleosynthesis constrains the number of light degrees of freedom in thermal equilibrium at a temperature of 1 MeV, whereas the width of the Z determines the number of species that couple to the Z with mass less than $m_{Z/2}$. This is, for example, illustrated by the scalars of Majoron models.

3. NEUTRINO MASS

The neutrino property of greatest interest is the mass. In the Standard Model, one has imposed "by hand" a massless neutrino. In fact, it is the particle contents of the theory the one responsible for:

i) Absence of a $\bar{\nu}_L(x) \nu_L(x)$ Majorana-type mass term. As the left-handed field $\nu_L(x)$ is member of a doublet under the standard $SU(2)_L$ group, a mass term like the Majorana one would need a triplet of scalar fields to generate the mass term from the Yukawa couplings by spontaneous symmetry breaking. However, only the doublet scalar field is present in the theory.

ii) Absence of a $\bar{\nu}(x) \nu_R(x)$ Dirac-type mass term. This is a consequence of the postulated existence of the $\nu_L(x)$ field only.

As seen, there is no principle which requires neutrinos to be massless and, from the stand-point of grand unified theories, this would be quite unnatural. Many intensive searches for possible neutrino masses have produced no uncontested positive evidence for such masses.

If neutrinos are massless, and hence degenerate, there is no difference in the standard theory between the weak eigenstates, as those with definite transformation properties under the electroweak gauge group, and the mass eigenstates. In models beyond the standard theory, in which neutral currents are not universal, the neutral current couplings of neutrinos can play the role to distinguish these states from the weak eigenstates. In these exotic models, Mixing can become physical even if neutrinos are massless². We shall limit the discussion, however, to the scenario of nondegenerate massive neutrinos with conventional weak interaction properties. The flavour states (index f) can be written by means of the unitary matrix in terms of the mass eigenstates (index j) as

$$\nu_f = \sum_{j=1}^3 U_{fj} \nu_j \quad (U^\dagger U = 1) \quad (3)$$

Then the charged current process in which a neutrino is produced, such as tritium beta decay ${}^3\text{H} \rightarrow {}^3\text{He} + e^- + \bar{\nu}$, $\nu = (f = e)$, is actually an INCOHERENT SUM of the separate decay modes

$$^3H \rightarrow ^3He + e^- + \bar{\nu}_j, (j = 1, 2, 3) \quad (4)$$

The leptonic charged current weak interaction determines the couplings to the different mass eigenstates $j = 1, 2, 3$. One has

$$L_{\text{cc}}(x) = \frac{g}{\sqrt{2}} W^\mu(x) \sum_{j=1}^3 \bar{l}_{fL} \gamma_\mu U_{fj} \nu_{jL} + \text{h.c.} \quad (5)$$

with amplitudes for $j = 1, 3$ as shown by the diagrams

Assuming hierarchical leptonic mixing, in which the diagonal matrix elements are much larger than the off-diagonal ones,

$$|U_{ij}|^2 \gg |U_{ik}|^2, j \neq k \quad (6)$$

the conventional limits on neutrino masses of " ν_e, ν_μ, ν_τ " can be reinterpreted in terms of m_1, m_2, m_3 , respectively.

The first class of tests for " $m(\nu_e) \approx m_1$ " corresponds to the shape of the electron spectrum in β -decay near its end point. In presence of a non-vanishing neutrino mass m_ν , the Kurie plot deviates from a straight line, with

$$K(E) \propto Q - E^{1/2} (Q - E)^{1/2} - m_\nu^2 E^{-1/2} \quad (7)$$

where Q is the Q -value of the process (energy release to the leptonic system) and E the energy of the detected electron.

The highest sensitivity is obtained from ^3H β -decay, with the results as shown in the Table

Group	ITEP ⁽⁷⁾	Tokyo ⁽⁸⁾	Zurich ⁽⁹⁾	LANL ⁽¹⁰⁾
Source	Valine	Mono-layer	Mono-layer	Free T_2 Gas
$m_\nu^2 (eV^2)$		-82	-158	-147
$St (eV^2)$		87	150	68
$Sys (eV^2)$	$17 < m < 40$		103	41
Limit (eV)		29	15.4	9.3

The columns include the central value for m_ν^2 , the statistical and the systematic errors. All m_ν -limits, given in the last column, are 95% C.L. The reason why $m_\nu^2 < 0$ is preferred is unknown. Perhaps bremsstrahlung emission accompanying the tritium β -decay, which produces an apparent negative m^2 effect in the end-point spectrum, could be responsible for this unpleasant feature.

A second class of tests for non-vanishing neutrino masses corresponds to the measurements made of the time-of-flight of neutrinos arriving from SN1987A. If the neutrinos are emitted "simultaneously" (within a small fraction of a second), the dispersion in arrival times of the neutrinos as a function of their energy depends on the neutrino mass according to

$$\Delta t \approx 0.26 (d/50 Kpc) \left(\frac{m_\nu}{1 eV} \right)^2 (10 MeV E_\nu)^{-1} \quad (8)$$

Using the IMB⁽¹¹⁾ and Kamiokaide⁽¹²⁾ data, with a total of 20 events, one can get from the time duration of the neutrino pulse (12 seconds) a value of the neutrino mass. However, one has to consider the intrinsic time scale of the supernova, which is model dependent. An analysis⁽¹³⁾ of these effects gives a limit on the electron neutrino mass of about 20 eV.

For the muon neutrino mass, its limit comes from the measurement of the momentum of the muon emitted in pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$. Kinematics of the process determines the neutrino mass as

$$m_\nu^2 = m_\pi^2 + m_\mu^2 - 2m_\pi \sqrt{m_\mu^2 + p_\mu^2} \quad (9)$$

The value reported at present comes from the following ingredients: the pion mass from the measurements⁽¹⁴⁾ of the

pionic X-rays in 1986 and the muon momentum from the experiment¹⁵ of Abela et al. in 1984. This gives

$$m_{\nu\mu}^2 = -0.097 \pm 0.072 \text{ MeV}^2; m_{\nu\mu} < 0.27 \text{ MeV} (90\% \text{ C.L.}) \quad (10)$$

Recently, new measurements¹⁶ of p_μ give some improvement in the accuracy: near to one part in 10^5 . However, the value of m_π has been questioned¹⁷ at a significant level, so that this problem has to be settled before giving any new numbers for $m_{\nu\mu}$.

The existence of the tau neutrino has been inferred indirectly from the tau decay data and from the measurement of the number of neutrino families N_ν . The decay of taus into five charged pions and a neutrino $\tau \rightarrow 5\pi^+ \nu_\tau$ provides the most sensitive test of the tau neutrino mass, as the phase space left after producing five pions is small and quite sensitive to neutrino mass. The measurement of the tau neutrino mass is predominantly limited by statistics, and the ARGUS-value¹⁸ in 1988 is

$$m_{\nu\tau} < 35 \text{ MeV} (95\% \text{ C.L.}) \quad (11)$$

with only 12 events. It is expected that as accelerators with higher luminosities, in particular a τ -e Factory, come on line that this limit will be improved.

The familiar constraint from Primordial Nucleo-synthesis on the number of Neutrino Families $N_\nu = 3.1$ applies to massless (mass $\ll$ MeV) neutrino species. If the τ -neutrino mass were greater than order 1 MeV, the limit on N_ν would not apply. This traces to the temperature of the Universe when the weak interactions freeze out: $T_f \approx 1 \text{ MeV}$. After a massive neutrino species decouples and becomes nonrelativistic, its energy density is comparable to or even greater than a massless species. An MeV-mass neutrino species can thus have a significant effect on ^4He production. Kolb et al.¹⁹ have studied the impact of a massive neutrino on nucleosynthesis, obtaining that the masses allowed for the τ -neutrino are

$$m_{\nu\tau} < 0.5 \text{ MeV} \quad \text{or} \quad m_{\nu\tau} > 25 \text{ MeV} \quad (12)$$

This is not strongly sensitive to the Dirac or Majorana character of the τ -neutrino.

If neutrinos have a non-vanishing mass of the Dirac type $\bar{\nu}_L(x)\nu_R(x)$, the presence of this term in the weak Lagrangian leads to the conclusion that right-handed neutrinos are produced in the hot Supernova core. Once produced, they scatter off the stellar matter via the helicity flip mechanism. The energetics of the Supernova constrains any additional energy drain beyond that observed from SN1987A going into left-handed ordinary neutrinos. The limit

$$Q(\text{exotic}) \leq 2 \times 10^{51} \text{ erg/s} \quad (13)$$

provides a forbidden band of neutrino masses from the emission rate of right-handed neutrinos in the free-streaming regime. This regime is the one that applies when the light particles are so weakly interacting that they leave the star without scattering. The production of right-handed neutrinos is dominated by the scattering of standard neutrinos off nucleons and by nucleon-nucleon bremsstrahlung of right-handed neutrinos. One obtains a forbidden range of Dirac neutrino masses²⁰

$$m_\nu \leq 20 \text{ KeV} \quad \text{or} \quad m_\nu \geq 30 \text{ MeV} \quad (14)$$

The consequences of these limits depend on the type of neutrino considered. Taking into account the laboratory bounds, one can conclude that

$$m(\nu_\mu), m(\nu_\tau) \leq 20 \text{ KeV} \quad (15)$$

for Dirac neutrinos. The limits (15) are indicative, and their reliability is probably within a factor of two.

4. 17-KeV NEUTRINO?

This is one of the present hints (2) for non-vanishing neutrino mass. In 1985 Simpson reported²¹ evidence for a small ($|U_{\tau 4}|^2 \approx 1\%$) component of a heavy (mass $m_4 \approx 17 \text{ KeV}$) neutrino in the electron neutrino.

This is manifested as a local kink in the nuclear β -decay spectrum. Subsequent measurements allowed β -decay spectra have produced results that both support and contradict this claim. The positive evidence is presented in the Table and there is consistency in the reported masses and mixing parameters, including the eight standard-deviation result of Hime and Jelley²¹. The evidence from internal bremsstrahlung in electron capture (IBEC) comes again from a kink in the corresponding spectrum, as a consequence of an incoherent sum over the two definite mass channels

$$\frac{dW(k)}{dk} = \frac{dW(k, m_1)}{dk} |U_{e1}|^2 + \frac{dW(k, m_2)}{dk} |U_{e2}|^2 \quad (16)$$

where k is the photon energy.

Table

Year/Ref.	Element	Number decays/keV	Mass (keV)	Mixing
1985 ²¹⁾	³ H	$2 \cdot 10^7$	17	$< 1\%$
1989 ²²⁾	³ H	$8 \cdot 10^7$	17	$1-1\%$
1989 ²³⁾	³⁵ S	$5 \cdot 10^7$	17	0.8%
1991 ²⁴⁾	³⁵ S	$2 \cdot 10^7$	17	0.8%
1991 ²⁵⁾	¹¹ C		17	0.8%
1991 ²⁶⁾	⁷⁶ Ge		17	0.6%

as revised in 1989

The EVIDENCE for the small kink is not apparent in a visual inspection of the spectrum. One has to normalize the spectrum to the one for $m_1 = 0$ and then one gets typically

These experiments are accompanied by several other experiments²⁷ from 1985 to 1991¹ searching for a heavy neutrino by measuring the spectra of electrons originating in the β decays of ¹⁵S, ⁶³Ni and ³H, with negative results. The combined information seems to indicate a mixing parameter $|U_{e1}|^2 \sim 0.3\%$,

with a 99% C.L., of the 17-KeV neutrino into the electron neutrino.

Assuming that neutrino mixing takes place indeed and

$$\nu_{\alpha L}(x) = \sum_{i=1}^n U_{\alpha i} \nu_{iL}(x) \quad (17)$$

the LEP-results for the number of flavour-neutrinos ($N_\nu = 3$) indicate that there should exist at least three (two-component neutrinos with definite mass: $n \geq 3$). The massive neutrinos can be Dirac or Majorana particles. From the limits on oscillations $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$, one reaches the conclusion²⁸ from $|U_{\mu n}|^2 \sim 0.01$ that

$$|U_{\tau n}|^2 \simeq 0.99 \quad (18)$$

In this case ν_τ practically coincides with the heavy neutrino ν_n "seen" in the β -decay experiments. This is why we have identified $n = 3$ in the above discussion. The most stringent direct constraint on the nature of the heavy neutrino follows from the data on the neutrinoless double β -decay. This process has not been observed and, from $1 < m_\nu < 10$ few eV, one could think in a solution of "standard" Dirac neutrinos with $m_1 \simeq 17$ KeV $\rightarrow m_1, m_2$. However, one cannot satisfy the cosmological constraints on the heavy neutrino properties, unless the neutrino decay early enough to allow for a consistent period of matter domination. This requirement yields the bound²⁹

$$\tau_\nu \sim 3 \cdot 10^7 \text{ sec} \sim 1 \text{ yr} \quad (19)$$

These considerations seem to point in favour of solutions where Majorons are present. Models³⁰ reconciling the 17 KeV anomaly with the Solar Neutrino Deficit include a Sterile Neutrino.

5. SOLAR NEUTRINO DEFICIT

The Sun is an intense source of low energy ($E_\nu \leq 15$ MeV) electron neutrinos. They are products of the nuclear processes in its higher temperature central region which provide the solar energy. The dominant chain of reactions in the Sun provide a net balance

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu + 25\text{MeV} \quad (20)$$

with a total luminosity $L_{\odot} = 4 \times 10^{33}$ erg/s.

This balance tells us that the produced number of neutrinos per second is given by $2L_{\odot}/(25\text{MeV})$, which at Earth implies

$$\text{Flux} \simeq 6 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \quad (21)$$

Most of this flux is due to the primary fusion reaction in the Sun

The solar neutrino spectrum³¹ and the corresponding initial states of the reactions producing neutrinos are presented in the Figure.

The active experiments at present are

i) The ^{37}Cl experiment

For more than two decades, Davis and co-workers have been detecting solar neutrinos deep under a mine in South Dakota, USA. Their detector contains 2.2×10^{31} atoms in the form of liquid C_2Cl_4 .

The threshold energy is 0.814 MeV, so the experiment cannot detect any pp neutrino. Since the absorption cross section rises sharply with energy, the ${}^3\text{B}$ neutrinos contribute most to the capture rate.

The data obtained by Davis' group can be normalized to the theoretical result obtained with the Standard Solar Model (SSM). Of the different evolutionary model calculations, two are outstanding: 1) Bahcall and co-workers³²; 2) The French-Belgian collaboration of Turck-Chieze et al.³³. The two theoretical results agree very well, although the predicted ^{37}Cl neutrino rates are somewhat different, due to different input values of the ${}^8\text{B}$ production cross section and the opacity,

$$\left. \begin{aligned} \Phi_{\text{Bahcall}} &= (7.1 \pm 0.9) \text{ SNU} \\ \Phi_{\text{Turck-Chieze}} &= (5.8 \pm 1.3) \text{ SNU} \end{aligned} \right\} \quad (23)$$

The unit SNU is defined to be 1 capture per 10^{31} target atoms per second. The error bars in the number are 1σ . Using Φ_{Bahcall} for the normalization, one has for Davis' data³¹

$$P_{\text{Davis}} = \frac{\Phi_{\text{Davis}}}{\Phi_{\text{Bahcall}}} = 0.27 \pm 0.04 \quad (24)$$

The solar neutrino problem is the statement that $P_{\text{Davis}} \ll 1$.

ii) The Kamiokande experiment

The Kamiokande II detector has been operational since 1986. The energy response for the capture rate is peaked at high energies. Since it detects neutrinos by electron scattering, a high threshold has to be set to allow an event. In the recent runs, the threshold was brought down to 7.5 MeV. The integrated result³⁵ from the runs analyzed so far gives

$$P_{\text{Kami}} = \frac{\Phi_{\text{Kami}}}{\Phi_{\text{Bahcall}}} = 0.16 \pm 0.07(\text{stat}) \pm 0.06(\text{syst}) \quad (25)$$

Thus, the solar neutrino problem is present in this experiment independent of the Davis result. The present situation of the Kamiokande experiment is reviewed by Totsuka in this Workshop.

iii) The ^{71}Ga experiments

The low threshold of Gallium makes the SAGE and GALLEX detectors very important, since they can capture many of the neutrinos from the pp reaction. The expected

rate is very high, predicted to be 132 SNU by Bahcall and co-workers¹² and 125 SNU by Turck-Chieze et al.¹³. The SAGE group has presented the results in terms of a bound¹⁶

$$P_{sage} \equiv \frac{\Phi_{sage}}{\Phi_{th}} < 0.60 \quad (90\% C.L.) \quad (26)$$

The present situation of SAGE is reviewed by Gavrin and that of GALLEX¹⁷ by Kirsten in this Workshop.

The following remarks can be made:

- The Kamiokande experiment sees only, and ³⁷Cl sees mostly, neutrinos from the decay of ⁸B.
- The production of ⁸B in the solar cycle varies as T¹⁸, where T is the temperature of the solar core.
- Suppose that the low Kamiokande flux is due to a T lower than that of the SSM, i.e., Kamiokande measures T. With T known, the predicted rate for ³⁷Cl from Bahcall and co-workers would be 3.8 ± 0.5 SNU. But the Davis experiment gives 2.1 ± 0.3 SNU for the observed ³⁷Cl capture rate.
- This suggests that the Solar Neutrino Deficit is due to the neutrino properties and not to solar physics. This argument is due to Bahcall and Bethe¹⁹.

The future Solar Neutrino Detectors include the ones sensitive to neutral current detection of the incoming neutrinos, BOREX at the Gran Sasso Underground Laboratory²⁰ and SNO at the Sudbury mine²¹. BOREX will use the following reactions

$$\left. \begin{aligned} \nu_e + {}^7\text{Be} &\rightarrow \nu_e + {}^7\text{Be} \\ \nu_e + {}^7\text{Be} &\rightarrow \nu_e + {}^7\text{Be} \\ (E_\nu \geq 2\text{MeV}) \\ \nu_e + {}^7\text{Li} &\rightarrow \nu_e + {}^7\text{Li} \end{aligned} \right\} \quad (27)$$

A small version of this detector, BOREXINO, with a threshold $E_\nu = 250$ KeV, will be sensitive²² to monoenergetic neutrinos from the ⁷Be line (energy of 0.86 MeV and spread of 1.3 KeV). The SNO detector²³ will use deuterium as target, and the neutrino signal from the following reactions

$$\left. \begin{aligned} \nu_e + d &\rightarrow \nu_e + n + p \quad (E_\nu \geq 2.22\text{MeV}) \\ \nu_e + d &\rightarrow \nu_e + p + p \quad (E_\nu \geq E_d = 1.11\text{MeV}) \\ \nu_e + d &\rightarrow \nu_e + e \end{aligned} \right\}$$

Assuming that the observed Solar Neutrino Deficit is a signal of neutrino mass, the mechanism of resonant flavour conversion of neutrinos in matter, due to¹² Mikheyev, Smirnov and Wolfenstein, can explain the results for definite regions of the neutrino parameters Δm^2 and $\sin^2 2\theta$.

One has in this plane^{15,18}

The region is that allowed by the Davis Homestake experiment, whereas is that selected by the Kamiokande experiment. Qualitatively, the non adiabatic and the "vacuum" lines are compatible with both experiments. If the SAGE limit (26) for the Ga detector is used, the energy dependence of the MSW mechanism would favour¹⁴ the non-adiabatic line for the solution of the Solar Neutrino Problem.

6. NEUTRINO OSCILLATIONS

This phenomenon, originally discussed¹¹ by Pontecorvo, uses the ingredients of neutrino mixing plus the different time evolution of the different mass-eigenstate neutrinos.

If at time $t_0 = 0$ one produces a neutrino with definite flavour ν_i and momentum p_i , the probability amplitude that at time t the neutrino will have a flavour ν_f , is

$$A(\nu_f \rightarrow \nu_f; j, t) = \sum_j U_{ff'} e^{-iE_j t} U_{f'j}^* \quad (29)$$

For two families involved in the mixing, the relevant parameters are the mixing angle and the oscillation time (or length)

$$E_1 - E_2 \approx \frac{m_1^2 - m_2^2}{2p} \propto \frac{1}{T_{osc}} \propto \frac{1}{L_{osc}} \quad (30)$$

One can summarize the present situation stating that no positive oscillation-signal has been observed yet. There is a hint from atmospheric neutrinos, for which a depletion of atmospheric muon neutrino events is seen in the Kamiokande and to some extent in the IMB experiments¹⁵; the NUSEX and Frejus experiments¹⁶ exhibit no such effect, however.

The oscillation experiments can be classified into two main types:

i)- **Appearance Experiments**, in which one measures the probability $P(\nu_f \rightarrow \nu_{f'}) = |A(\nu_f \rightarrow \nu_{f'}; t)|^2$. The limits coming from accelerator experiments $\nu_\mu \rightarrow \nu_\tau$ [1 - ϵ , τ are more sensitive to small mixing. The typical values for $\nu_\mu \rightarrow \nu_\tau$ are¹⁷

$$\sin^2 2\theta < 3 \cdot 10^{-3}; \Delta m^2 < 10^{-3} \text{ eV}^2 \quad (31)$$

In the near future, the KARMEN experiment will improve these limits and the LSND collaboration at LAMPF will collect a high statistics for $\nu_\mu \rightarrow \nu_e$. This will settle¹⁸ the question of atmospheric neutrinos if the anomaly is thought to be explained by values near the present limits. New techniques are foreseen at Fermi Lab and CERN for $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments, and the search for $\nu_e \rightarrow \nu_\tau$ oscillations has been advocated¹⁸ in connection with the 17 KeV-neutrino.

ii)- **Disappearance Experiments**, from reactors, in which one measures $\sum_i P(\bar{\nu}_i \rightarrow X)$. The limits extracted from these reactor experiments are more sensitive to small Δm^2 , with typical values¹⁷

$$\sin^2 2\theta < 10^{-3}; \Delta m^2 < 8 \cdot 10^{-3} \text{ eV}^2 \quad (32)$$

In the near future, the Rugey collaboration will improve somewhat the limits and there is a long baseline CALTECH

proposal to lower substantially the Δm^2 - limit to connect with the solar indications from the MSW mechanism.

The exclusion plot Δm^2 versus $\sin^2 2\theta$ is shown in the Figure,

where the present accelerator and reactor limits (continuous lines), the proposed aims (dotted lines) and the region of solar MSW (dashed lines) are given.

7. THEORETICAL IDEAS FOR NEUTRINO MASS.

To incorporate neutrino masses and mixings requires new neutrino interactions, obtained by enlarging the lepton and/or Higgs sectors of the Standard Model. Neutrino masses can be kept small by the introduction of new neutrinos, a new symmetry or both.

With three new right handed Majorana neutrinos, N_R , one can obtain a dynamical (seesaw) mechanism¹⁹ to explain small masses m_ν for the three left handed neutrinos. Allowing the Majorana mass term $M_N N_R^T N_R$ as well as the Dirac mass term $m_D \nu_L N_R$, with M_N a non-singular 3×3 matrix, the diagonalization of the 6×6 chirality - flavour mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D & m_N \end{pmatrix} \quad (33)$$

leads to three light Majorana neutrinos with mass matrix $m_\nu = m_D M_N^{-1} m_D^T$ and three heavy Majorana neutrinos with mass matrix M_N . In natural models one can thus obtain a seesaw hierarchy of small neutrino masses, proportional to the squares of charged lepton or quark masses²⁰.

For an example of a new symmetry, confined to the usual ν_L , that keeps one of the neutrino masses zero, one has the ZKM symmetry⁵¹ that allows flavour changes preserving $L_e = L_\mu + L_\tau$. If M_N is a rank two matrix, then a singular seesaw model⁵² with this symmetry is possible. Then two neutrinos can be organized to form a Dirac or pseudo-Dirac neutrino of intermediate mass $m_D \sim 17 \text{ keV}$ and, by virtue of the 4×4 seesaw mechanism, two neutrinos are light. Both MSW solar neutrino oscillations and a 17 KeV could then be accommodated.

Majorana neutrino masses can be added to the Standard Model even if no extra fermions are introduced, provided there are new scalar Higgs fields. In the isotriplet Higgs model⁵³, with lepton number symmetry spontaneously broken, two of the three neutral scalars must be very light: the Majoron J and the light scalar ρ . They couple to the Z_μ with a strength determined by the weak hypercharge of the Majoron, leading then to the decay $Z \rightarrow \rho + J$. This would contribute an equivalent of two new families of light neutrinos to the invisible decay width. The result (2) shows that this particular model is ruled out by the LEP experiments. One way to avoid the coupling of the Majoron to the Z consists in having the Majoron predominantly as an electroweak singlet in such a way that the Majoron carries essentially no hypercharge⁵⁴.

8. DIRAC OR MAJORANA?

This question corresponds to the statement of whether $\bar{\nu} = \nu$. The identity of the neutrino ν with its antiparticle $\bar{\nu}$ means that both ν and $\bar{\nu}$ interact with matter in the same way. Do they? It is very difficult to answer in practice. The reason is that the available neutrinos and so-called antineutrinos have opposite polarization: the neutrinos are left-handed, the "antineutrinos" right-handed. These two species interact with matter quite differently: for example the inclusive neutrino-nucleon and antineutrino-nucleon cross sections are shown⁵⁵ in the Figure

However, it is not known whether this difference is due merely to the different polarizations of the particles or reflects a difference between neutrinos and antineutrinos. We should find out whether neutrinos and antineutrinos of the SAME helicity interact in the same way. Challenging! ...

The best way to test the Dirac or Majorana character of the neutrinos is to search for neutrinoless double beta decay. The process $\beta\beta_{nn}$ is the lepton-number violating nuclear decay

$$(A, Z) \rightarrow (A, Z+2) + 2e^- \quad (31)$$

and can be produced by the diagram

The amplitude is non-vanishing if ν_j is a Majorana particle. This is required in gauge theories even if right-handed currents exist.⁵⁶ For only left-handed currents, there is the effect of helicity suppression due to the selection imposed by the charged current vertices. One has

$$\text{Amp}[\beta\beta_{nn}] \propto m_\nu \times (\text{Phase Space})(\text{Nucl. Phys.}) \quad (35)$$

If there are no right-handed currents, for ν_j with definite CP-eigenvalue and mixing U_{ij} real, one has

$$m_\nu \propto \sum_j CP(\nu_j) U_{ij}^2 m_j \quad (36)$$

The present experimental lower limits to the half-lives $T_{1/2}$ for $\beta\beta_{nn}$ -processes are discussed in the lecture⁵⁷ by A. Morales in this Workshop. Results are available for ^{76}Ge , ^{82}Se , ^{136}Xe , ^{100}Mo , ^{116}Cd and for ^{130}Te using the TiO_2 bolometer. The most sensitive limit is that obtained for ^{76}Ge by the Moscow-Yerevan collaboration⁵⁸: $T_{1/2} > 1.3 \times 10^{25}$ years and by the UCSB-LBL collaboration⁵⁹: $T_{1/2} > 2.1 \times 10^{25}$ years. The comparison with the theoretical prediction gives

$$\langle m_\nu \rangle \leq 2 \text{ eV} \quad (37)$$

This result, interpreted in terms of definite mass neutrinos by means of Eq. (36), provides a fundamental constraint on the suggested 17 KeV neutrino.

9. NEUTRINO DIPOLE MOMENTS.

It has been argued from time to time that the solar neutrino flux detected in the Chlorine experiment has shown some anticorrelation with sun spot activity. If this anticorrelation is believed to be real, perhaps the most reasonable explanation of the solar neutrino problem would involve⁶¹ a magnetic moment of the electron neutrino. Sunspot activity is related to magnetic field in the Sun. If the magnetic field is large, sunspot activity is high. If neutrinos have a magnetic moment, the vertex

$$\mu_{jj'} \sigma_{\lambda\mu} q^\mu \quad (38)$$

will induce spin precession in a magnetic field. The neutrinos produced in the nuclear reactions are left handed. As they travel through a transverse magnetic field, they can precess to a right handed neutrino which is not detected. The magnitude of the magnetic moment needed to solve the problem is a subject of debate, depending on the details of the solar magnetic field and the possibility of topological Berry phases, which can make the spin precession more efficient. To have appreciable probability of this precession, one probably needs $10^{-11} \mu_{\text{Bohr}}$ or larger.

If one also allows an electric dipole moment for the neutrinos, the vertex of Eq. (38) has an additional term

$$\sigma_{\lambda\mu} q^\mu (\mu_{jj'} + d_{jj'} \gamma_5) \quad (39)$$

When $j' \neq j$, $\mu_{jj'}$ and $d_{jj'}$ are transition dipole moments, and when $j' = j$ they are diagonal moments. If neutrinos are Majorana particles, then their diagonal moments must vanish, essentially as a consequence of CPT⁶². But one can

have transition moments which couple one neutrino mass eigenstate to another. For small mixing, the helicity-flip transition $\nu_{1L} \rightarrow \nu_{2R}$ would appear experimentally as $\nu_e \rightarrow \bar{\nu}_\mu$ for Majorana neutrinos.

There is a laboratory bound from experiments on $\bar{\nu}_e - e$ scattering at a reactor, which measure the inclusive cross section

$$\sigma(\bar{\nu}_e + e \rightarrow e + \text{"missing momentum"}) \quad (40)$$

If neutrinos have dipole moments, then this cross section can receive a contribution not only from W and Z exchange, but also from a photon exchange diagram which acts incoherently. Assuming that neutrino masses are small, the cross section (40) bounds the quantity

$$M = \left[\sum_{j=1}^3 |\mu_{1j} - d_{1j}|^2 \right]^{1/2} \quad (41)$$

which gives information on both the diagonal moment μ_{11} , d_{11} and the transition moments $\mu_{1j} - d_{1j}$, $j \neq 1$. If neutrinos are Majorana particles, μ_{1j} and d_{1j} , $j \neq 1$, are relatively imaginary, so that the sizes of each μ_{1j} and d_{1j} are bounded separately. From the reactor data⁶² of F. Reines et al., Marciano and Sirlin⁶³ have obtained

$$M \leq 4 \times 10^{-10} \mu_{\text{Bohr}} \quad (42)$$

If neutrino dipole moments exist, then the coupling of an off-shell photon γ^* in a star to one of these moments $\mu_{jj'}$ or $d_{jj'}$ can cause $\gamma^* \rightarrow \nu_{j'} + \bar{\nu}_j$ to occur. Once the neutrinos are produced, they will escape carrying away energy. From the absence of such an anomalous energy loss mechanism in red giants, one finds⁶⁴

$$|\mu_{jj'}|, |d_{jj'}| \leq 3 \times 10^{-12} \mu_{\text{Bohr}} \quad (43)$$

which holds if $m_j, m_{j'} \leq 10 \text{ keV}$, so that the process is not kinematically suppressed.

A very stringent bound⁶⁵ comes from the neutrinos from Supernova 1987 A, but this bound applies only if neutrinos are Dirac particles, in order to allow the right-handed species to escape from the supernova. One gets

$$|\mu_{JJ'}, d_{JJ'}| \leq 10^{-12} \mu_{Bohr} \quad (44)$$

It would be very interesting to improve the laboratory limit for M , Eq. (42), by dedicated νe experiments and by other possible processes.

10. NEUTRINOS AS PROBE OF PROTON STRUCTURE.

Historically, deep inelastic scattering of neutrinos on protons has provided detailed information on both the quark-parton distribution in the nucleon and the weak couplings of quarks. Here I would like to discuss the proposal to use neutrinos to extract the axial isoscalar coupling of the nucleon associated with weak neutral currents.

The EMC measurement of the polarization structure function of the proton has led to the result⁶⁶

$$\int_0^1 dx g_1'(x, Q^2) = \langle p | \sum_i \frac{1}{2} q_i^2 \bar{\psi}_i \gamma_5 \gamma_\mu \psi_i | p \rangle = 0.126 \pm 0.018 \quad (45)$$

where $g_1'(x, Q^2)$ is the structure function for polarized muon-polarized proton deep inelastic scattering. This sum rule determines a combination of Axial Flavour couplings of the proton. Other two independent combinations are known from semileptonic decays of baryons. The flavour $SU(3)$ singlet current coupling is determined as

$$G_1^{(0)} = G_1^{(u)} + G_1^{(d)} - G_1^{(s)} = 0.12 \pm 0.17 \quad (46)$$

which seems to be in contradiction with constituent u, d quark models for the proton, for which (46) would be the total helicity carried by quarks in a polarized proton. This "spin crisis" of the proton can be studied from neutral current elastic scattering on the proton.

The neutral weak hadronic current contains an axial piece

$$A_\mu^Z = \bar{\psi}_u \gamma_\mu \gamma_5 \psi_u - \bar{\psi}_d \gamma_\mu \gamma_5 \psi_d - \bar{\psi}_s \gamma_\mu \gamma_5 \psi_s \quad (47)$$

so that the effective axial current coupling of the proton is

$$G_1^{(0)} = G_1^{(u)} - G_1^{(d)} - G_1^{(s)} = G_1^{(s)} = g_A + f_A \quad (48)$$

The effect of the axial isoscalar coupling f_A of the nucleon, besides the well known axial isovector coupling $g_A = 1.25$, can be searched for⁶⁷ in neutrino scattering, parity-violating electron scattering and parity violation in atomic physics. The last two observables contain, however, the small vector coupling of the electron $v_e = 1 - 4\sin^2\theta_w$ in the standard theory.

A dedicated experiment on elastic neutrino-proton scattering at low Q^2 is being carried out at LAMPF⁶⁸ in order to identify $f_A = -G_A^{(s)}$, estimated to be $\simeq 0.19$ from the EMC experiment. The axial isoscalar neutral current interaction would modify⁶⁸ the transition strengths for the neutral current detection of solar neutrinos in the planned BOREX experiment, whereas the deuterium target of the SNO detector is insensitive to such a mechanism.

11. NEUTRINOS AS MEDIATORS OF LONG-RANGE FORCE.

Between two pieces A and B of bulk macroscopic matter, two neutrino exchange induces a potential $V(r)$ given by

$$V(r) = \frac{1}{4\pi^2 r} \int_{Am_2}^\infty dt A_B s M_{AB}(t) e^{-t^{1/2} r} \quad (49)$$

The absorptive part of the elastic amplitude $A + B \rightarrow A + B$, in the t -channel, is connected with the coherent scattering of neutrinos with A and B. In fact, bulk matter has a net weak charge $Q^{(\nu)}$ as seen by neutrinos. This is induced by

so that for neutral [of electric charge] matter one has

$$Q^{(\nu_e)} = Z - \frac{N}{2}; \quad Q^{(\nu_{\mu,\tau})} = -\frac{N}{2} \quad (50)$$

where Z is the number of protons (and electrons) and N is the number of neutrons.

If $m_\nu = 0, \forall_j$, Eq. (49) gives rise to a Long-Range Repulsive Potential of the form

$$V(r) = \frac{G_F^2}{4\pi^2 r^5} Q_A Q_H \quad (51)$$

Some features of this force are the following:

i) As the ratio $(Q_A Q_H)/(M_A M_H)$ is not a pure number and depends on the type of matter, the force described by Eq. (51) induces a deviation of the equivalence principle.

ii) For relative distances $r \leq 10^{-1} \text{ cm}$, the weak force compares with the gravitational force as

$$\left| \frac{F_{\text{weak}}}{F_{\text{grav}}} \right| \geq 10^{-12} \quad (52)$$

this ratio increasing as r^{-1} when r gets smaller.

iii) The ratio between weak and gravitational forces, although dependent on the composition of matter, is independent of the density.

It would be of interest to find ways to observe the effects of this long range force induced by the coherent weak charge of bulk matter, either in laboratory experiments and/or in its astrophysical implications.

12. CONCLUSION.

The next years are going to provide precious information on the neutrino properties and its behaviour, so that we are entering an exciting period in the field of Neutrino Physics. We already know of the existence of only three [$N_\nu = 2.99 \pm 0.05$] families of left-handed light neutrinos, but their masses, mixings, dipole moments, etc. are unknown. Better and better limits are going to be obtained on these observables by on going experiments and, eventually, a positive result would be obtained.

Solar Neutrino experiments will decide whether the solar neutrino problem is due to neutrino properties or to the Standard Solar Model. New experiments on the 17 KeV neutrino will decide about its existence or, on the contrary,

its appearance as an artefact of the shape factor for the Bethe spectrum detector.

In the near future, intermediate energy neutrinos will probe the Axial Isoscalar Neutral Current for the proton thus contributing significantly to questions such as the strangeness content of the proton or the proton spin crisis. Neutrinos appear as Mediators of a Coherent Long-Range Force for matter, which should be of interest to study in its laboratory and astrophysical implications.

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