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SOLAR NEUTRINO PUZZLE

K V L Sarma
Tata Institute of Fundamental Research
Homi Bhabha Road
Bombay 400 005, India

The solar neutrino puzzle is one of the major problems of modern physics which has been with us nearly for the past two decades Stated simply, the solar neutrino flux measured on Earth is smaller than what is expected by about a factor 3 4 The puzzle is how to understand this deficit in the observed number of neutrinos from the Sun.

Why should we be interested? The Sun is powered by nuclear fusion reactions taking place in the hot regions of the interior wherein the hydrogen nuclei combine or fuse to manufacture successively heavier elements such as He C N, The scheme according to which the various reactions proceed was proposed by Bethe in the 1930 s But what is the experimental evidence for this scenario in the Sun? Unfortunately we have to telescope to 'look directly into the Sun interior However there is an indirect way for this and that is to exploit neutrinos

The fusion reactions lead to nuclei some of which are unstable and undergo beta or gamma decay The photons from the latter are quickly absorbed by the surrounding material in the Sun's interior, and low energy photons are subsequently emitted It takes millions of years for the electromagnetic energy released in the core to reach the Sun s surface In contrast, the neutrinos coming from beta decay interact only weakly with matter and hence they go right through the entire material of the Sun with essentially no absorption Thus we can look for neutrinos arriving at Earth directly from the Sun s intrior, and hence our interest in the neutrinos from the Sun

How does one look for the solar neutrinos? The method adopted is to initiate an inverse beta decay reaction and identify the daughter nucleus Since 1967 R Davis and coworkers have been detecting neutrinos by using ^{37}Cl

$$\text{Solar } \nu_e + {}^{37}_{17}\text{Cl} \to e + {}^{37}_{18}\text{Ar} \tag{1}$$

The detector consists of 615 metric tons of C_2Cl_4 (containing 2 19 x 10^{30} atoms of ^{37}Cl) in a tank placed in the Homestake Gold Mine, South Dakota, USA (strange that one goes into the Earth to extract information on the solar interior! This is to reduce the background processes producing Argon particularly from processes involving cosmic ray muons) The number of Argon atoms is counted by the 35 day half life of ^{37}Ar, which is extracted by radio chemical methods The observed neutrino capture rate measured in SNU (solar neutrino unit defined as 10^{36} neutrino captures per target atom per second) as reported by R Davis et al [1] in the 1987 cosmic ray conference at Moscow is

$$2\ 07 \pm 0\ 25 \text{ SNU} \tag{2}$$

The result of the chlorine experiment can be compared with the theoretically expected rate based on the standard solar model Table I lists the reactions responsible for yielding neutrinos in the Sun, the corresponding energy range of neutrinos, the capture rates expressed in SNU for the chlorine detector (threshold energy is 0 814 MeV) and

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Talk given at the II National Workshop on Solar Physics at Kodaikanal during September 24 29 1987 also for the Gallium detector (threshold energy is 0 236 MeV) according to the 1985 calculations of Bahcall et al [2] The total capture rate for chlorine according to the calculations is

$$5 9 \pm 2 2 \text{ SNU}, \tag{3}$$

where the theoretical error 2 2 is an 'effective' 3 standard deviation value It seems recently there is an upward revision of this theoretical value to 8 5 ± 2 5 SNU In any case the discrepancy between the observed and expected rates is a factor 3 4

Other Experiments

Among the many experimental proposals, perhaps the most important is the one using Gallium as the detector element The advantage here is the low threshold to initiate the inverse beta decay reaction (≃ 0 236 MeV) and the consequent detectability of the large neutrino flux from the pp reaction (E_ν = 0 0 42 MeV) estimated to be 70 2 SNU An experiment using ^{71}Ga is under way in Baksan Valley in USSR

$$\nu_e + {}^{71}_{31}\mathrm{Ga} \rightarrow e + {}^{71}_{32}\mathrm{Ge}\ , \tag{4}$$

and the results could be expected in a couple of years time

How are we sure that the detected neutrinos are coming from the Sun? Recently the group at Kamioka in Japan operating a 3,000 ton water Cerenkov detector reported a limit on the solar neutrino flux by looking at the reaction

$$\nu_e + e \rightarrow \nu_e + e \tag{5}$$

The recoiling electron "remembers the direction of the incident neutrino and thus enables one to check that the incident neutrino is indeed coming from the direction where the Sun is located The Kamioka group has an angular resolution of ± 28° for 10 MeV neutrino (trigger threshold is 7 5 MeV) On the basis of observations for 128 days a preliminary limit (90% CL) given by Koshiba et al [3] (E > 10 5 MeV) on the solar neutrino flux is

$$\phi_\nu \leq 3 2 \times 10^6 \nu_e \text{ cm}^{2} \text{ sec}^{1},$$

which may be compared with the theoretical expectation of $(6 0 \pm 2 0) \times 10^6 \nu_e \text{cm}^{2} \text{sec}^{1}$ Another way of stating this preliminary result is that the Kamioka rate is les than 4 SNU

Explanations of the Solar Neutrino Puzzle

There have been many suggestions to resolve the solar neutrino puzzle ensuing from the chlorine experiment (1) suggest a way to reduce the central temperature of the Sun thereby inhibiting the production of ^{8}B (whose neutrinos should be contributing about 75% of the expected rate, see Table I), (2) during the flight between the solar interior and the terrestrial detector, the beta decay neutrino may have been transformed into another kind of neutrino which cannot initiate the Cl Ar reaction

We shall not discuss the suggestions under the first category which involve taking into account mixing, diffusion, postulation of WIMPs (weakly interacting massive particles m≃a few GeV), etc The WIMP Solution seems to be interesting as it can also help explain the recent observations of Helioseismology But unfortunately there is as yet no experimental evidence for WIMPs at the accelerators

Last year there has been resurgence of interest in the neutrino flavour oscillations due to a suggestion of Mikheyev and Smirnov [4] according to which the electron type neutrinos ν_e could be converted to muon type ν_μ or tau type ν_τ neutrinos in their passage through the dense interior of the Sun The conversion $\nu_e \rightarrow \nu_x$ where x μ or τ, is a resonant kind of phenomenon resulting from a difference in the respective forward scattering amplitudes on atomic electrons of the medium The conversion depends sensitively on the difference in masses between the neutrinos and on the mixing angle θ

So far people have discovered 3 kinds of ν ν_e, ν_μ and ν_τ. In the technical jargon, so far three "neutrino flavours" have been identified They are all distinct, in particular, an incident ν_μ or ν_τ in relation (1) cannot lead to a final state containing an electron (ν_μ needs an energy >106 MeV to produce a final μ, and ν_τ need an energy > 1784 MeV to produce a τ, together with the Ar nucleus) There may be more than 3 flavours of neutrinos in Nature

Regarding the neutrino masses, there is no clear evidence whether any of the three has any mass Available experimental limits are $m(\nu_e) < 18$ eV $m(\nu_\mu) < 0\ 25$ MeV $m(\nu_\tau) < 50$ MeV

Neutrino Oscillation

This is a fascinating possibility based on the interference of waves Oscillations occur because different components of a neutrino wavefunction can have different phase factors

To illustrate this in the simple case of ν_e ν_μ oscillations we shall start by assuming that there are two states ν_1 and ν_2 with masses m_1 and m_2, respectively Assume that the ν_e and ν_μ states are linear combinations of the mass states ν_1 and ν_2

$$\begin{aligned} \nu_e &= \cos\theta\,\nu_1 + \sin\theta\,\nu_2 \\ \nu_\mu &= \sin\theta\,\nu_1 + \cos\,\nu_2 \end{aligned} \qquad (0 < \theta < \frac{\pi}{4}) \tag{6}$$

where θ is called the mixing angle

If we start at time $t = 0$ with a pure ν_e state then after a time t it evolves to a state which is a mixture of ν_e and ν_μ writing c for cos θ and s for sin θ, we have

$$\nu_e = c\,\nu_1 + s\,\nu_2 \xrightarrow[\text{time } t]{} c\,e^{iE_1t}\,\nu_1 + s\,e^{iE_2t}\,\nu_2$$

$$= (c^2 e^{iE_1t} + s^2 e^{iE_2t})\,\nu_e - c\,(e^{iE_1t} - e^{iE_2t})\nu_\mu$$

where $E_k = (p^2 + m_k^2)^{\frac{1}{2}} \approx p + (m_k^2/2p)$ at high energies Replacing $t - x/v$, by x we have the probability of detecting a ν_μ obtained by squaring the amplitude,

$$P(\nu_e \rightarrow \nu_\mu, x) = \sin^2(2\theta)\,\sin^2\left[\frac{\pi x}{\ell_v}\right] \tag{7}$$

$$\text{Oscillation length (in vacuum)} \quad \ell_v \equiv \frac{4\pi p}{|\,m_2^2 \quad m_1^2\,|} \tag{8}$$

we note that $\nu_e \rightarrow \nu_\mu$ oscillations are negligible if the mixing is small ($\theta \sim 0$ implies $P \sim \theta^2$), or if the mass difference $\Delta = (m_2^2 - m_1^2)$ is small ($\Delta \sim 0$ implies $P \sim \Delta^2$)

Many experimental groups have been looking for the oscillations at nuclear power reactors and particle accelerators, without any success The general feeling is either θ is too small or Δ is too small One may therefore have to turn to non laboratory sources of neutrinos to look for the consequences of flavour oscillations (among neutrinos in cosmic rays from Sun, from Supernova bursts)

Neutrino Oscillations in Matter

The ν_e ν_μ oscillation probability when the neutrinos are passing through matter was first discussed by Wolfenstein [5] in 1978 The point here is that although neutrinos interact weakly with matter it is important to consider the <u>coherent</u> scattering of the neutrino on the electrons of the atom of the medium, the ν_e experiences an additional scattering potential due to the W exchange while the ν_μ does not The ν gets scattered in the forward direction with no recoil to the electron, and the amplitude for this is proportional to the number of elelctrons N_e per unit volume of the medium The eigenstates propagating in matter are denoted by ν_{1m} and ν_{2m} (distinct from the earlier ν_1 and ν_2) with masses μ_1 and μ_2

We shall skip the details and quote only the relevant results in terms of the mixing angle θ_m in matter,

$$\begin{aligned} \nu_e &= \cos\theta_m \ \nu_{1m} + \sin\theta_m \ \nu_{2m} , \\ \nu_\mu & \quad \sin\theta_m \ \nu_{1m} + \cos\theta_m \ \nu_{2m} \end{aligned} \tag{9}$$

$$\underset{(1)}{\mu_2^2} = \tfrac{1}{2}(m_2^2 + m_1^2 V\Delta) \underset{(-)}{+} \tfrac{1}{2}\Delta[(V \quad \cos 2\theta)^2 + \sin(2\theta)]^{\frac{1}{2}} \tag{10}$$

$$V = 2\sqrt{2}\ E\, G_F\, N_e / \Delta \tag{11}$$

$$\Delta \quad m_2^2 \quad m_1^2 \tag{12}$$

For antineutrino propagation the corresponding V is negative of what is given in Eq (11) The probability for finding ν_μ after travelling a distance x in matter has a formula analogous to Eq (7)

$$P_m(\nu_e \to \nu_\mu , x) \qquad \sin^2(2\theta_m)\sin^2[\frac{\pi x}{\ell_m}] \tag{13}$$

$$\text{where } \sin^2(2\theta_m) = \frac{\sin^2(2\theta)}{(V \quad \cos 2\theta)^2 + \sin^2(2\theta)} \tag{14}$$

$$\ell_m = \frac{4\pi p}{|\mu_2^2 \quad \mu_1^2|} \tag{15}$$

The important observation made by Mikheyev and Smirnov [4] (MS) is that the oscilltion probability given by Eq (13) is maximal when the medium has a density such that

$$V = \cos(2\theta) \tag{16}$$

This is the MS resonance condition For this to be realized a necessary condition is that Δ should be positive i e , <u>ν_e must be lighter than ν_μ</u> When the MS resonance condition is met we will have $\sin^2(2\theta_m) = 1$ for any non vanishing mixing angle θ however small The expression in Eq (13) will therefore exhibit a Breit Wigner type resonance with width' given by

$$\Gamma = 2\sin(2\theta) \tag{17}$$

Note that the MS resonance condition (16) is a condition on the density ρ of the medium,

Table I

Reaction	ν_e energy (MeV)	^{37}Cl(>0.81 MeV)	^{71}Ga(>0.236 MeV)
$pp \to De^+ \nu_e$	0 - 0.42	0	70.2
$ppe \to D\nu_e$	1.44	0.2	2.5
$e\ ^7Be \to\ ^7Li\ \nu_e$	0.861 x 0.9 + 0.383 x .1	1.0	27.0
$^8B \to\ ^8Be\ e^+ \nu_e$	0 - 14.06	4.3	16.0
$^{13}N \to\ ^{13}C\ e^+ \nu_e$	0 - 1.2	0.1	2.6
$^{15}O \to\ ^{15}N\ e^+ \nu_e$	0 - 1.73	0.3	3.5
		5.9 SNU	121.8 SNU

Table II

Eigen state	High Density ($V \gg \cos 2\theta$)	Reson Density ($V = \cos 2\theta$)	Low Density ($V \ll \cos 2\theta$)
ν_{1m}	$\nu_\mu + o[1/V]\nu_e$	$1/\sqrt{2}(\nu_e - \nu_\mu)$	$\cos\theta\, \nu_e - \sin\theta\, \nu_\mu$
ν_{2m}	$\nu_e + o[1/V]\nu_\mu$	$1/\sqrt{2}(\nu_e + \nu_\mu)$	$\sin\theta\, \nu_e + \cos\theta\, \nu_\mu$

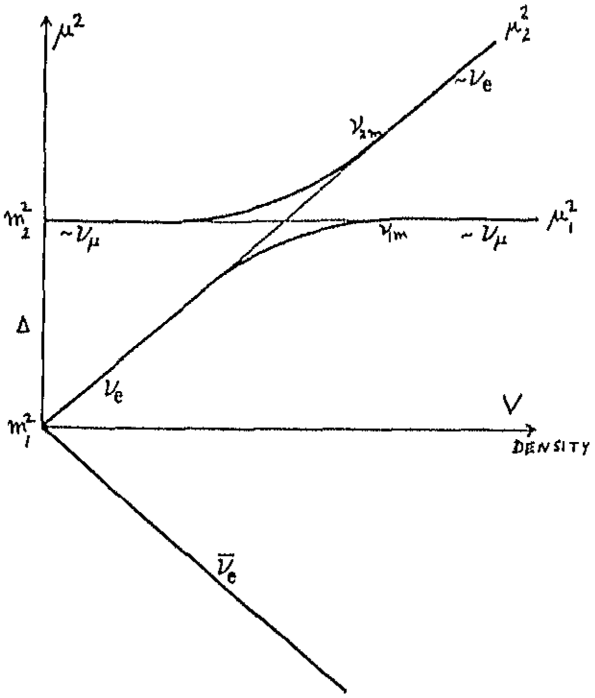

Fig.1 Effective mass squared μ^2 of the neutrino state propagating in the medium versus $V (\equiv 2\sqrt{2}\, G_F N_e E/\Delta)$. Large (small) values of V correspond to densities in solar core (solar edge) for fixed values of E/Δ

$$[\frac{E}{MeV}] \, [\frac{\rho}{gm \; cm^{\;3}}] = 0 \; 7 \times 10^{7} \cos(2\theta) \, [\frac{\Delta}{ev^{2}}] \qquad (16a)$$

In the Sun we start with a large central density ($\sim$ 150 gm cm ^{3}) and the density decreases to zero as we go towards the edge of the Sun Thus if the neutrino during its passage encounters layers of right density the oscillation probability is enhanced and the ν_e will be converted into ν_μ or ν_τ

The eigen states in matter are listed in Table II for three interesting cases of limiting densities (high density resonant density and low density approximating the case of vacuum) In the solar core the beta decay neutrino ν_e will propagate radially outwards according to the high density solution which is approximately ν_{2m} until it meets the resonant density somewhere in the body of the Sun In the resonant layer of the density, due to the MS mechanism, $\nu_e \rightarrow \nu_\mu$ oscillations are enhanced As the ν passes further towards the edge of the Sun and travels in the intervening space of Sun and Earth, the low density solution is operative and there will be negligible oscillations if the mixing angle θ is small

But the matter density $\rho(r)$ in the Sun is a function of the radial distance r from the centre Bethe [6] argued that if we assume that the density $\rho(r)$ is gently decreasing in the resonant layer (of width Γ) the state ν_{2m} will continue to evolve as ν_{2m} and will not develop the ν_{1m} component (see Fig 1) This is called the adiabatic approximation which states that the resonant oscillation length t_m^{res} in the medium is much smaller than the thickness δx of the resonant layer

$$t_m^{res} \qquad \frac{1}{2\pi} \; \frac{\ell_v}{\sin 2\theta} \quad << \; \delta x \qquad \frac{2 \tan(2\theta)}{[\frac{1}{\rho} \frac{d\rho}{dr}]} \qquad (18)$$

In this approximation the levels do not cross (no level crossing) and there is complete conversion of ν_e to ν_μ

Bethe's explanation to resolve the solar neutrino puzzle roughly proceeds as follows The resonance condition (16a) describes a hyperbolic curve in E versus ρ plot Solar neutrino energies are limited by $E \lesssim$ 14 MeV and the solar densities by $\rho \lesssim$ 150 gm cm ^{3} Therefore one can define a 'critical energy E_c so that for $E > E_c$ the resonance condition is satisfied somewhere inside the Sun, and for neutrinos having $E < E_c$ the MS resonance condition is not satisfied anywhere in the Sun To get the required depletion in the observed ν_e capture rate in the Davis experiment Bethe suggests

$$E_c \qquad 6 \text{ MeV} \qquad (19)$$

This implies that Davis should have observed only those neutrinos having $E <$ 6 MeV, whereas the high energy solar neutrinos (with $E >$ 6 MeV) went undetected by him as they were all converted into ν_μ in the resonant layer adiabatically Subsequent oscillations in vacuum during the flight from solar surface to the chlorine detector can be ignored by choosing $\theta \sim 0$ According to this adiabatic solution to solar neutrino puzzle we require

$$\text{Cos}(2\theta) \; \Delta \quad 0 \; 6 \times 10^{\;4} \, (ev)^{2} \, , \qquad (20)$$

and to satisfy the adiabatic condition we require

$$\tan^{2}(2\theta) \;\; \underline{>} \;\; 1 \; 6 \times 10^{\;4} \; , \text{ i e } \;\; \theta \; \underline{>} \; 0 \; 4^{o} \qquad (21)$$

Taking $\theta \sim 0$, $m_1 \sim 0$ in Eq (20), one requires $m_2 \sim 0\,008$ eV which is too small a mass to be measurable in the laboratory

Tests of Adiabatic Solution

(1) Since the low enelrgy neutrinos (below 6 MeV) escape the MS resonance and since the bulk of the capture rate in the low threshold Ga Ge experiment comes from the abundant low energy solar ν_e (from pp reaction) there should only be a small deficit in the expected capture rate in the Gallium experiment, that is the Ga rate should yield $\sim$ 108 SNU instead of the standard value $\sim$122 SNU given in Table I

(2) There should be significant distortions in the neutrino energy spectra which can be measured by employing suitable elements for target materials Deuterium [7] Boron [8] etc

It should be mentioned that when the density variation is not gentle the adiabatic approximation fails and there will only be a <u>partial</u> conversion of ν_e to ν_μ in the resonant layer This situation when levels cross has been examined by many authors in great detail [9] For the simple case of linear variation of density with radial distance (in the resonant layer) the formula for level crossing possibility P_x was first derived by Landau and by Zener in 1932 [10],

$$P_x = P(\nu_e \rightarrow \nu_e, x) = \exp\left[\frac{\pi}{4}\, t\, \frac{\delta x}{\underset{m}{res}}\right] \qquad (22)$$

where the notation is as in relation (18) According to the nonadiabatic solution at high energies there will be level crossing and at low energies $P_x \approx 0$, thus mostly low energy ν_e's convert into ν_μ's and the high energy ν_e's emerge from the Sun as ν_e's only

For an example of the calculations in the general context (both adiabatic and non adiabatic) to explain the solar neutrino puzzle using the MS mechanism, and the regions of the required values of Δ and θ, one may consult the paper of Parke and Walker [11] (see Figure 2)

$$\Delta \sim 10^{7} \quad 10^{4}\,(ev)^2, \text{ and } \sin^2 2\theta \sim 10^{3} \quad 10^{1} \qquad (23)$$

Influence of Earth's Medium

Matter effects on ν_μ ν_e oscillations when the atmospheric neutrinos propagate through Earth (assuming uniform density) have been studied earlier These effects are important when $V \approx 1$ where V is defined in Equation (11) [12]

For the case of solar neutrinos, for some narrow range of values of the parameters it is possible to have the MS conversion in the Earth's material also [13] The density profile in the Earth is a complicated function of the radial distance If the solar ν_e is converted to ν_μ or ν_τ in the solar material, it may be reconverted into the original ν_e in the Earth's material

$$\nu_e \xrightarrow[\text{Sun}]{} \nu_\mu \text{ (or } \nu_\tau) \quad \xrightarrow[\text{Earth}]{} \nu_e \qquad (24)$$

The point here is that the first conversion should happen in the Sun at the densities equal to the terrestrial densities (5 12 gm cm ^{3}) This leads to the spectacular <u>Day Night Effect</u> according to which there will be more ν_e during the night (when the neutrino has to pass through the Earth) than during the day time Thus the Sun shines "brighter' during night from the view point of the Gallium detector The required values of the parameters are in the ranges

$$\Delta = 10^{6} \quad 10^{4}\,(ev)^2 \text{ and } \sin\theta = 0\ 086 \quad 0\ 52 \qquad (25)$$

The influence of the Earth's medium not only gives rise to diurnal variations but also seasonal variations in the observed solar ν_e flux [13] The Ga Ge experiment in

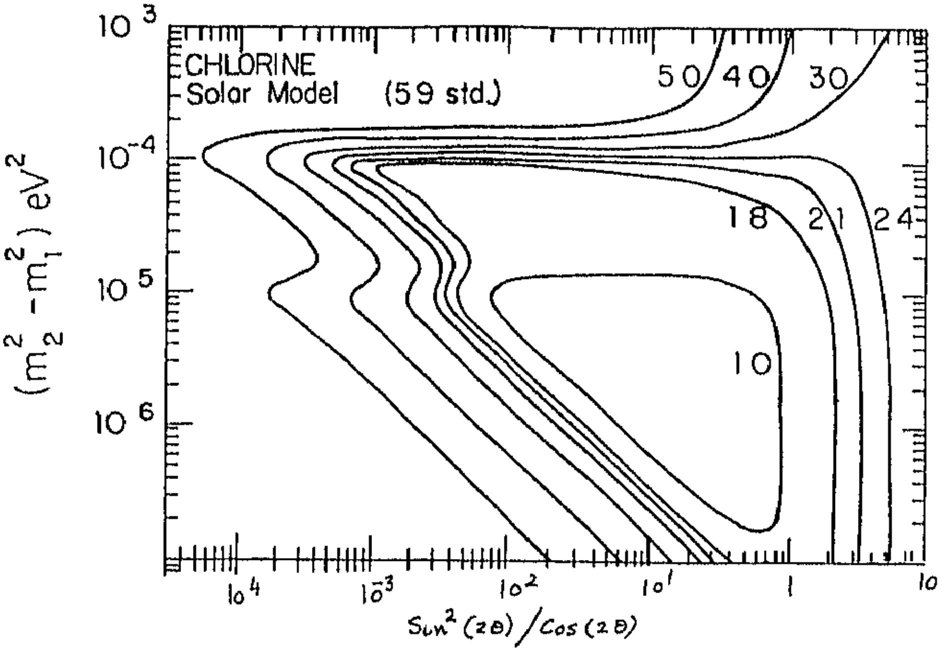

Fig 2(a)

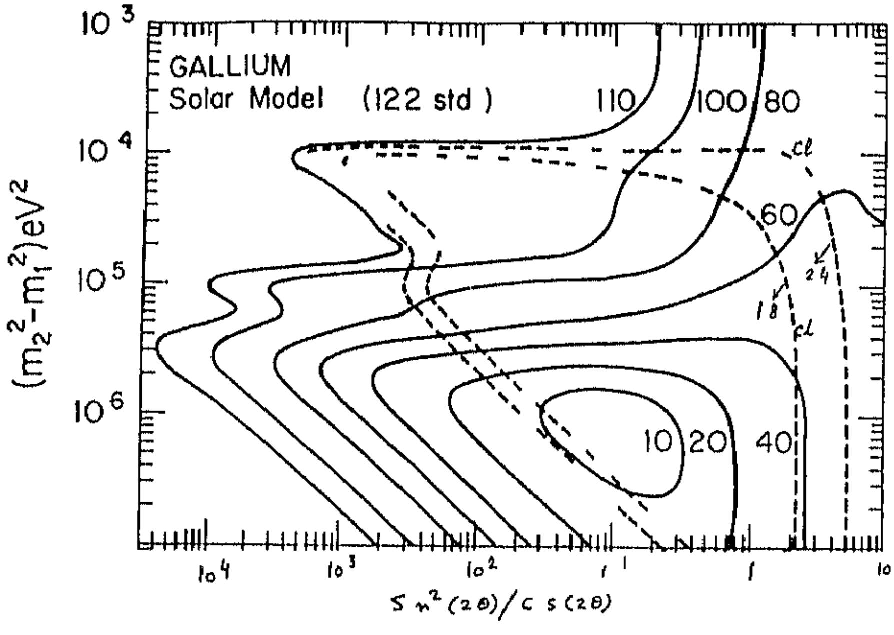

Fig 2(b)

Fig.2. Allowed regions in the parameter space Δ and θ according to the calculations of Parke and Walker (Ref 11) The numbers along the curves indicate the experimental capture rates in SNU for the detector elements (a) Chlorine (b) Gallium The total capture rates expected on the standard solar model are 5 9 SNU and 122 SNU In Fig (b) the dashed contours refer to the Chlorine detector for 1 8 SNU and 2 4 SNU

progress expects to observe the day-night effect by collecting the daughter radioactive atoms twice daily.

It may also be mentioned that the Mikheyev-Smirnov resonance enhancement of neutrino oscillations has been studied including 3-level mixing between ν_e, ν_μ, ν_τ by assuming some hierarchy of masses [14].

Sun Spots and Solar Activity

There have been a number of analyses suggesting that the neutrino rates observed in the Davis experiment show systematic time variations. The neutrino capture rates during 1977-85 seem to show a strong anti-correlation with the solar activity cycle and increased rates during large solar flares [1,15] (see Figure 3).

Voloshin-Vysotski and Okun (V^2O) [16] have recently suggested that the neutrino may have a large magnetic moment

$$\mu(\nu_e) \simeq (\frac{1}{3} - 1) \times 10^{-10}\, \mu_{Bohr} \tag{26}$$

When the solar activity is maximum (as evidenced by the increased number of Sun spots) the neutrino in passing through the solar magnetic fields ($\sim 10^3 - 10^4$ Gauss) could flip its spin

$$\nu \text{ (Left handed) } \xrightarrow[\text{spin flip}]{} \nu \text{ (Right handed)}$$

This renders the neutrino emerging from the Sun sterile to initiate the Cl-Ar reaction. It is estimated that during the period of active Sun the magnetic fields present are an order of magnitude larger than the fields in the quite Sun. In this way the maximum of Sun spot number will be anticorrelated to the solar neutrino capture rate as seen in Figure 3.

The current experimental limits on the neutrino magnetic moments coming from ν_e scattering at the reactor [17], and the $\nu_\mu e$ scattering at the accelerator [18] are

$$\mu(\nu_e) < 1.5 \times 10^{-10}\, \mu_B$$

$$\mu(\nu_\mu) < 9.5 \times 10^{-10}\, \mu_B$$

These limits are at the same level as the value suggested by V^2O. Moreover, the astrophysical bound [19] ($\mu < 0.7 \times 10^{-10}\, \mu_B$) obtained from the cooling rate of young white dwarfs by the decay of plasmons ($\gamma^* \to \nu\nu$) is also consistent with the value in Eq (26).

However from the point of view of particle theorists a value such as $10^{-10}\, \mu_B$ for the magnetic moment of ν_e is rather difficult to understand. It is about 10^9 times too large compared to the magnetic moment expected on the basis of the standard model of Electro-weak unification of Glashow-Weinberg-Salam, as calculated by Fujikawa and Shrock [20],

$$\mu(\nu_e) = + \frac{3e\, G_F\, m(\nu_e)}{8\sqrt{2}\,\pi^2}$$

$$= 3.20 \times 10^{-19}\, \mu_B [\frac{m(\nu_e)}{eV/c^2}] \tag{27}$$

It has been emphasized by Bahcall et al [21] that although the apparent correlation between solar neutrino rate and the Sun spot number is intriguing, the existing data are not statistically significant and could be a coincidence. Clearly we may have to wait till the next solar maximum during 1990-95, or observe the bi-annual variation in the neutrino capture rate as predicted by V^2O.

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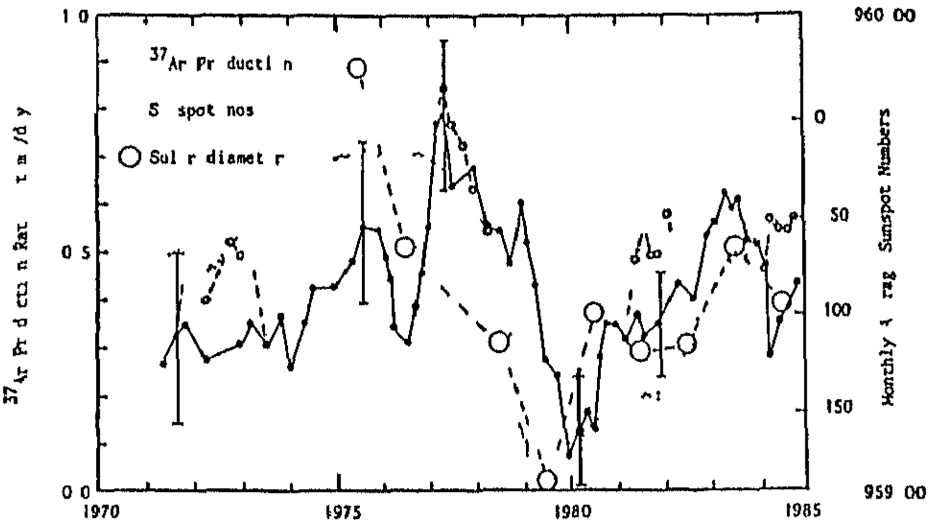

Figure Comparison of 5 point running averages of ^{37}Ar production rates with sunspot numbers and solar diameter measurements Solid points do not include runs associated with solar flares Open points include flare asso ciated runs

Fig.3 Comparison of neutrino capture rates and Sun spot numbers (from R Davis et al 1987, Ref 1)

Summary

The flux of ν_e as recorded by the ^{37}Cl detector of Davis is smaller than the expected solar ν_e flux by a factor of 3 to 4 Such a conclusion seems to be supported by the preliminary results of the only other experiment currently running at Kamioka (in Japan) using water Cerenkov detector This solar neutrino puzzle has given rise to various explanations

One of the interesting explanations which had been discussed during the past couple of years is based on the resonant enhancement of neutrino oscillations in the solar core This explanation originally due to Mikheyev and Smirnov is consistent with the standard solar model and also with all the known facts in particle physics It requires among neutrinos only very tiny mass differences (Δ) and small mixing (θ), both of which are extremely difficult to observe in the usual laboratory experiments The solar neutrinos may be the only handle we have to explore such extremely small values of these parameters Δ and θ Further from a theoretical point of view such tiny values of Δ and θ have a natural place in the Grand Unification Theories (GUTs), and hence the interest of particle theorists

A unique feature of the MS explanation is the prediction of a distorted energy spectrum of the ν_e, which can be measured It will be very exciting if the Day Night effect is also verified experimentally

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