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SOLAR NEUTRINOS - AN OVERVIEW[#1]

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ABSTRACT

The results reported by the four solar neutrino experiments, the Chlorine experiment at Homestake, the Cerenkov light water experiment at Kamiokande, the Soviet American Gallium experiment at Baksan and the European Gallium experiment at Grand Sasso, confirm that the Sun produces its energy by fusion of protons into Helium nuclei. The event rates observed in the four experiments are significantly below those predicted by the Standard Solar Model. This can be due to inacurate input parameters and/or inaccurate treatment of plasma physics effects in the model. The solar neutrino flux inferred from the Homestake experiment, however, is significantly smaller than that measured by Kamiokande. If that is not due to a statistical fluctuation and/or a systematic error, it implies new physics beyond the standard model of particle physics. In particular, matter enhanced neutrino oscillations can explain simultaneously the results of all four experiments if the ν_e is mixed with the ν_μ or the ν_τ with mixing parameters $\Delta m^2 \sim 10^{-5} eV^2$ and $sin^2 2\theta \sim 4 \times 10^{-3}$. This solution will be tested in the new generation of solar neutrino experiments which will be able to detect both the distortion of the spectrum of ^{8}B solar ν_e's and the anticipated flux of solar ν_μ's or ν_τ's. Evidence may also be obtained from the neutronization burst from a nearby supernova explosion. The above solution combined with a seesaw mechanism for generating neutrino masses further suggests $m_{\nu_e} \sim 3 \times 10^{-8} eV$, $m_{\nu_\mu} \sim 3 \times 10^{-3} eV$, $m_{\nu_\tau} \sim$ 25 eV. A tau neutrino with $m_{\nu_\tau} \sim 25$ eV can account for most of the dark matter in the Universe and may help explain the formation of the large scale structure in the Universe. Such a mass may be detected in neutrino oscillation experiments at accelerators and in the thermal burst of neutrinos from nearby supernova explosions.

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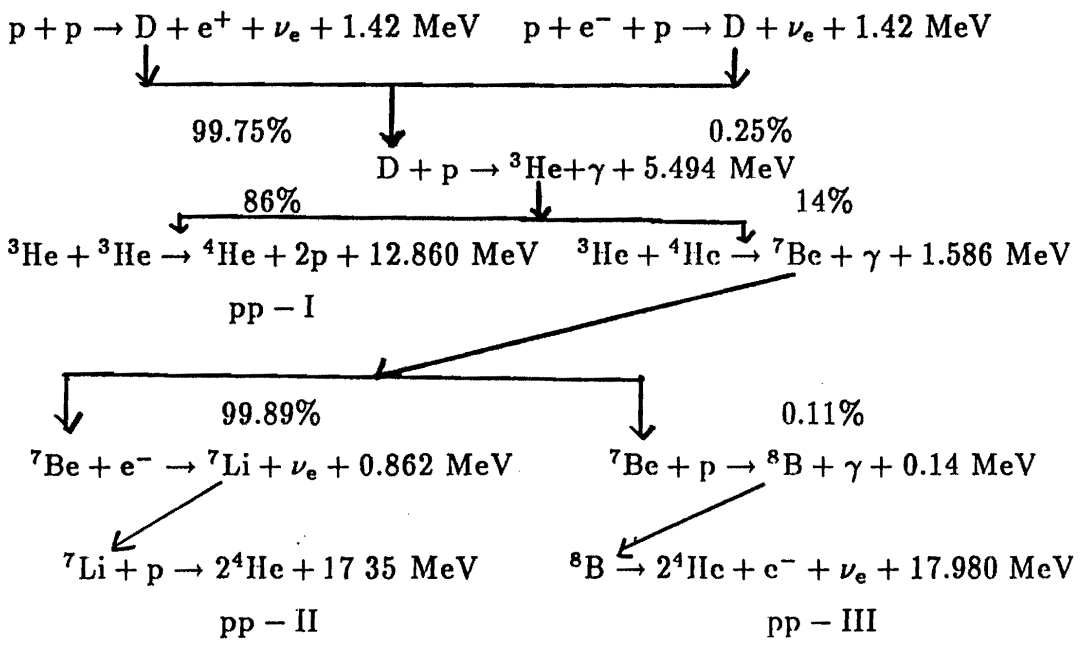
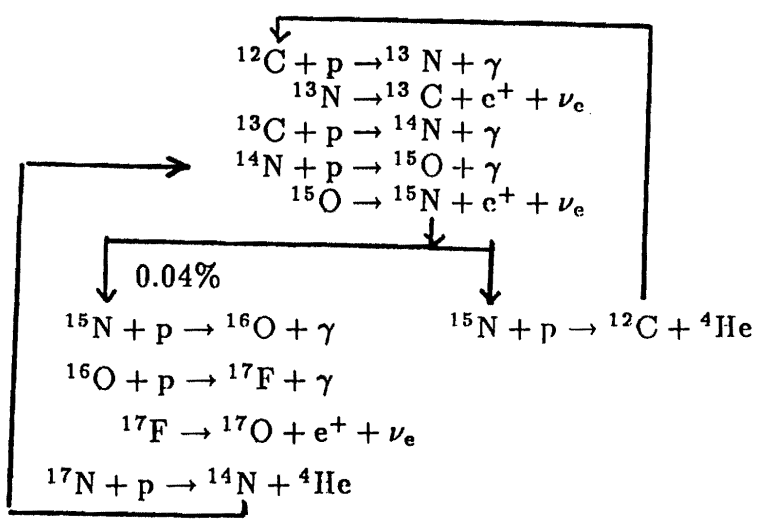
1. THE STANDARD SOLAR MODEL

The sun is a typical main sequence star that is believed to generate its energy by fusion of protons into Helium nuclei in a sequence of nuclear reactions that was first outlined by Bethe (1939) and is summarized below (for a general review see for instance Bahcall 1989):

The pp Cycle



The CNO Cycle



The rates of the various nuclear reactions depend on the conditions within the sun. These are obtained from calculating the evolution of a cloud of gas with a solar mass, $M_\odot \approx 1.9889 \times 10^{33} g$, and an estimated presolar chemical composition, which gravitationally contracts into a main sequence star that slowly burns its nuclear fuel. The presolar chemical composition is estimated from the measured composition of the heliosphere, the old meteorites, the surface of the sun and of the planets. However, the presolar helium abundance is known only very approximately and it is treated as a free parameter. It is adjusted by requiring that the calculations of the evolution of the sun yield for the present age of the sun, $t_\odot \approx 4.56\ GY$, the observed radius, $R_\odot \approx 6.959 \times 10^{10}\ cm$, photon luminosity, $L_\odot \approx 3.826 \times 10^{33}\ erg \cdot s^{-1}$, and an internal solar structure consistent with helioseismology data (see for instance Christensen -Dalsgaard and Dappen 1992 and references therein). Deviations from spherical symmetry, rotation and internal magnetic fields are assumed not to play any significant role in determining the internal properties of the sun which affect the nuclear reaction rates near its center, and are neglected in the calculations. The above scheme with the best available input physics (equations of state, opacities, nuclear cross sections and plasma physics effects) is called The Standard Solar Model (SSM). The first calculation of the neutrino fluxes obtained from a detailed model of the Sun was published by Bahcall, Fowler, Iben and Sears in 1963. Since 1963 these calculations have been improved and updated continuously by Bahcall and his collaborators (see for instance Bahcall and Ulrich 1988, Bahcall 1989 and references therein) and more recently by additional groups (Turck-Chieze et al. 1988, Cox, Guzik and Kidman 1989, Guenther, Jaffe and Demarque 1989, Sackman, Boothroyd and Fowler 1990). Table I summarizes the neutrino fluxes at Earth from the neutrino producing reactions in the Sun as obtained from the most updated published versions of the SSM calculations of Bahcall and Pinsonneault 1992 (BP) and of Turck-Chieze and Lopes 1993 (TL), and the corresponding capture rates in ^{37}Cl and ^{71}Ga (in Solar Neutrino Units = 10^{-36} captures per second per nucleus). The difference between the two calculations is mainly due to the use of different extrapolated low energy cross sections, screening factors and solar opacities in the two calculations. These differences may serve as a reasonable estimate of the theoretical "1σ" uncertainties in the calculated values.

Source	Flux (BP) $(cm^{-2}s^{-1})$	$<\phi\sigma>_{Cl}$ (SNU)	$<\phi\sigma>_{Ga}$ (SNU)	Flux (TL) $(cm^{-2}s^{-1})$	$<\phi\sigma>_{Cl}$ (SNU)	$<\phi\sigma>_{Ga}$ (SNU)
pp	$5.95E10$	0	70.7	$6.02E10$	0	71.1
pep	$1.41E8$	0.23	3.07	$1.39E8$	0.22	2.99
^{7}Be	$4.75E9$	1.17	32.9	$4.34E9$	1.10	30.9
^{8}B	$5.24E6$	5.53	12.31	$4.63E6$	4.63	10.77
^{13}N	$4.39E8$	0.072	2.68	$3.83E8$	0.063	2.36
^{15}O	$3.75E8$	0.24	4.28	$3.18E8$	0.21	3.66
^{17}F	$4.72E6$	0.003	0.04		0.003	
Sum	$6.52E10$	7.4	128	$6.54E10$	6.4	123

2. SOLAR NEUTRINO OBSERVATIONS

In 1946 Pontecorvo (Pontecorvo 1946) suggested that neutrinos could convert ^{37}Cl to ^{37}Ar whose radioactive decay could be measured. This possibility was later studied independently by Alvarez (1949) and in the early 1950s Davis began to develop a radiochemical ^{37}Cl detector for neutrinos which finally led to the construction of the Chlorine neutrino detector at the Homestake gold mine in the early and mid 1960s (Davis et al 1968, for details see Bahcall and Davis 1982).

Homestake: The observed production rate of ^{37}Ar by solar neutrinos in the Cl experiment averaged over 20 years of observations (Davis et al. 1990, Lande 1992) is

$$< \phi\sigma >_{Cl} = 2.23 \pm 0.22 \; SNU, \tag{1}$$

for neutrinos above the 0.81 MeV threshold energy for capture by ^{37}Cl. This average production rate is much smaller than that predicted by the Standard Solar Models. The ratio between the observed and predicted production rates by solar neutrinos is

$$R_{Cl} \equiv \frac{< \phi\sigma >_{exp}}{< \phi\sigma >_{theor}} \approx \begin{cases} 0.30 \pm 0.05 & \text{Bahcall SSM} \\ 0.35 \pm 0.08 & \text{Turck-Chieze et al. SSM} \end{cases} \tag{2}$$

Even if the Cl detector sees only ^{8}B neutrinos, the corresponding ratios are

$$R_{Cl} \equiv \frac{< \phi\sigma >_{exp}}{< \phi\sigma >_{theor}} \approx \begin{cases} 0.40 \pm 0.07 & \text{Bahcall SSM} \\ 0.48 \pm 0.09 & \text{Turck-Chieze et al. SSM} \end{cases} \tag{3}$$

This discrepancy has become known as "The Solar Neutrino Problem" (Bahcall and Davis 1978, Bahcall 1989). It is still unresolved. It led to the construction of new solar neutrino experiments that might shed light on its origin. [This discrepancy, however, should not shadow the achievement of R. Davis which should be considered as an historical triumph for both theoretical and experimental physics: In a heroic underground experiment, R. Davis and his colaborators succeeded in detecting a neutrino flux at energy above the 0.81 MeV threshold of the Cl detector, consistent within a factor three or so with the theoretically anticipated flux of solar neutrinos from the nuclear reactions in the core of the Sun that are believed to power the Sun. Despite the fact that the flux of the energetic neutrinos depends strongly on the conditions near the center of the Sun, e.g., $\sigma \sim T^{18}$, the measured flux agreed with theory (see for instance Bahcall, Bahcall and Shaviv 1968) within a factor three or so.]

The radiochemical Cl experiment has no directional resolution and a rather poor time resolution and it can not locate in the sky the source of the captured neutrinos. (Detection of annual variations in the neutrino flux due to the change in distance to the Sun requires enormous statistics). The first real time and directional observation of solar neutrinos from the nuclear fusion reactions in the core of the Sun was made in 1987 with the Kamiokande light water Cerenkov telescope:

Kamiokande II has detected electron recoils from scattering of neutrinos from the direction of the Sun since 1987 with energies above 9.3 MeV during 450 days of detector live time and above 7.5 MeV during another 590 days of detector live time (Fig. 1). After replacing 10% of their photomultipliers, further purifying their water from Rn tracers and increasing their light collection efficiency by 20% by installing new mirrors, Kamiokande III reported results from observations during another 395 days of detector live time. Both Kamiokande II and III found a recoil spectrum consistent with that expected from ^{8}B neutrinos (Fig. 2) and event rate based on 1435 days of observation corresponding to a total flux of (see for instance Nakamura 1993, Totsuka 1993)

$$\phi_{\nu_e}(^8\mathrm{B}) = (2.67 \pm 0.25\ ) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}, \tag{4}$$

where the quoted error (one standard deviation) was obtained by adding in quadrature the reported statistical and systematic errors. The ratio between the observed ^{8}B solar neutrino flux and those predicted by the SSM is

$$R_{H_2O} \equiv \frac{<\phi\sigma>_{exp}}{<\phi\sigma>_{theor}} \approx \begin{cases} 0.51 \pm 0.10 & \text{Bahcall SSM} \\ 0.61 \pm 0.15 & \text{Turck-Chieze et al. SSM} \end{cases} \tag{5}$$

Kamiokande provided the first solid proof that the Sun emits neutrinos with energies above 7.5 MeV and a spectrum consistent with that of ^{8}B. The observed flux is smaller by about a factor of two than that predicted by the SSM, supporting the existence of a solar neutrino problem.
In view of the solar neutrino problem it became very important to detect the bulk of the solar neutrinos, namely, the pp neutrinos, and to check whether their flux is significantly different from that estimated directly from the solar luminosity. Two Gallium experiments were designed to meet this difficult challenge. They use Gallium for the detection of solar neutrinos, as was first suggested by Kuzmin (1966) and Pomansky (1974) because of its low energy threshold, 0.23 MeV, for neutrino capture. These two experiments, GALLEX first and now also SAGE, apparently have succeeded in detecting the solar neutrinos from the major pp reaction in the Sun:
GALLEX, the European Gallium experiment at the Grand Sasso underground laboratory, observed the solar neutrino flux from 14 May 1991 to 29 April 1992 (GALLEX I) and from 19 August 1992 to 3 February 1993 (GALLEX II), through neutrino capture by ^{71}Ga to form ^{71}Ge. With counting data considered until 29 April 1993 , the capture rate based on all the 21 runs during these periods is (Anselman et al. 1993):

$$<\phi\sigma>_{Ga} = 87 \pm 16\ SNU\ , \tag{6}$$

with statistical and systematic errors added in quadrature. The corresponding

ratios between the observed and predicted capture rates in Gallium are

$$R_{Ga} \equiv \frac{< \phi\sigma >_{exp}}{< \phi\sigma >_{theor}} \approx \begin{cases} 0.70 \pm 0.19 & \text{Bahcall SSM} \\ 0.72 \pm 0.19 & \text{Turck-Chieze et al. SSM} \end{cases} \tag{7}$$

SAGE, the Soviet-American Gallium Experiment in the Baksan underground laboratory began its observations of the solar neutrino flux in 1990. The initial results of SAGE indicated a large discrepancy with the SSM predictions (Abazov et al. 1991). However, the capture rate observed by SAGE in 1991 (Gavrin 1992, 1993), $85^{+22}_{-32}[stat.] \pm 20[syst.]$ *SNU*, is now in excellent agreement with that observed by GALLEX, $87 \pm 14[stat.] \pm 7[syst.]$ *SNU*.

3. DO SOLAR NEUTRINO OBSERVATIONS IMPLY NEW PHYSICS ?

The general success of stellar evolution theory indicates that the Sun does derive its energy from fusion of Hydrogen into Helium by the pp and CNO cycles. Conservation of baryon number, charge and lepton flavour then requires that the net reaction is

$$4\mathrm{p} + 2\mathrm{e}^- \rightarrow {}^4\mathrm{He} + 2\nu_\mathrm{e} + \mathrm{Q} \ , \tag{8}$$

and energy conservation requires that $Q \approx 26.73$ *MeV*. Eq.8 tells us that two neutrinos are produced in the sun per 26.73 MeV release of nuclear energy. Thus, if the Sun derives its energy from fusion of Hydrogen into Helium and if the Sun is in a steady state where its energy production rate equals its luminosity, then the total solar neutrino flux at Earth is given by

$$\phi_\nu = \frac{2L_\odot}{Q - 2\bar{E}_\nu} \frac{1}{4\pi D^2} \geq 6.35 \times 10^{10} \ cm^{-2}s^{-1} \ , \tag{9}$$

where $L_\odot \approx 3.826 \times 10^{33}$ $erg\ s^{-1}$ is the solar luminosity, $\bar{E}_\nu$ is the average neutrino energy and $D \approx 1.496 \times 10^{13}$ cm is the distance to the Sun. Of all the neutrinos produced in the Sun the *pp* neutrinos have the smallest average energy. The Kamiokande and ^{37}Cl experiments observe much smaller fluxes of the more energetic neutrinos. Consequently, $\bar{E}_\nu \approx \bar{E}_\nu(pp)$ and

$$\phi_\nu = \frac{2L_\odot}{Q - 2\bar{E}_\nu} \frac{1}{4\pi D^2} \approx 6.48 \times 10^{10} \ cm^{-2}s^{-1} \ , \tag{10}$$

in very good agreement with the total solar neutrino flux $\phi_\nu \approx 6.50 \times 10^{10}$ $cm^{-2}s^{-1}$, predicted by the SSM detailed calculations.

Of all the neutrinos produced in the Sun, the pp neutrinos have the smallest average capture cross section. Therefore, the minimal capture rate of solar neutrinos in Gallium, which is consistent with standard physics, must be larger than that obtained by assuming that all solar neutrinos are pp neutrinos, i.e., $< \phi\sigma >_{Ga} \geq 76\ SNU$. A signal smaller than that could provide evidence for new physics. However, GALLEX, and by now also SAGE, have reported capture rates of solar neutrinos in Gallium larger than this minimal rate. *Thus, GALLEX and SAGE do not provide any evidence for physics beyond the Standard Electroweak Model such as flavour change or significant helicity flip of solar neutrinos in the Sun or on their way to Earth.*
Moreover, if the flux of solar neutrinos other than the pp neutrinos is suppressed by an energy independent factor S, then it follows from the Cl experiment that $S \equiv (2.23 \pm 0.22)SNU/(7.4 \pm 0.85)SNU = 0.29 \pm 0.04$ and the predicted capture rate in the Gallium experiment is

$$< \phi\sigma >_{Ga} \approx 70 + (1 - S)6 + S(58 \pm 19)\ SNU = 91 \pm 6\ SNU. \qquad (11)$$

(The first two terms are due to pp neutrinos and the last term is due to all other neutrinos.) If, on the other hand, the flux of ^{7}Be solar neutrinos is suppressed much more strongly than the flux of ^{8}B neutrinos, as suggested by the joint results of the *Cl* and the Kamiokande experiments, then,

$$< \phi\sigma >_{Ga} \approx 76 + 0.51 \times (12.7 \pm 1.8)\ SNU = 83 \pm 6\ SNU. \qquad (12)$$

(The first term is due to the pp neutrinos and the second term is due to the ^{8}B neutrinos.) Both predictions are practically unaltered if we use the SSM of Turck-Chieze and Lopes (1993). Both are in good agreement with the capture rates reported by GALLEX and SAGE. Thus, any solution to the solar neutrino problem that can explain the reduced solar neutrino fluxes observed by the *Cl* and the Kamiokande experiments, but does not modify significantly the pp solar neutrino flux, can also explain the capture rates observed by GALLEX and SAGE.
The claim by Bahcall and Bethe (1991) that the solution of the solar neutrino problem requires new physics beyond the Standard Electroweak Model is based entirely on the difference between the values of the ^{8}B solar neutrino flux extracted from the Cl and the Kamiokande experiments: Since the energies of the pep, ^{7}Be and the CNO neutrinos are above the energy threshold of the *Cl* detector but below that of Kamiokande detector, they contribute to the signal in the Cl detector but not to that observed by Kamiokande. Even if the signal in the Cl detector is completely due to ^{8}B neutrinos, their measured flux, averaged over 20 years, is only

$$\phi_{\nu_e}(^8\mathrm{B}) = (2.10 \pm 0.25\ ) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \qquad (13)$$

Such a flux is smaller, by about two standard deviations, than the flux measured by Kamiokande II, $(2.67 \pm 0.21) \times 10^6\ cm^{-2}s^{-1}$, instead of being larger. However, after the installment of new pumps, the average capture rate measured by the Cl

detector since 1988 is 2.53 ± 0.32 SNU. If this signal is entirely due to ^{8}B neutrinos, then

$$\phi_{\nu_e}(^8\mathrm{B}) \leq (2.39 \pm 0.30\ ) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{14}$$

This flux is not significantly different from that measured by Kamiokande during the same period (see Fig. 3). Thus, the evidence for new physics, argued by Bahcall and Bethe (1991), is not very compelling. However, consistency between the Homestake and Kamiokande results exists only if the ^{7}Be solar neutrino flux is also much smaller than that predicted by the SSM.

4. A STANDARD PHYSICS SOLUTION ?

The uncertainties in the SSM predictions are mainly due to uncertain plasma physics effects and uncertain values for some low energy nuclear cross sections. Can they be responsible for the discrepancy between the SSM predictions and the Kamiokande measurments ?

Screening of the repulsive Coulomb interaction between the approaching nuclei by their joint electronic cloud is known to enhance significantly laboratory nuclear cross sections at very low energies (see for instance Engstler et al 1987) although complete theoretical understanding of the effect is still lacking (see for instance Shoppa et al. 1993). Screening corrections to nuclear reaction rates in stellar interiors have been first estimated by Salpeter (1954) and since then are included in standard stellar evolution codes. Traditionally, the Debye-Huckel approximation is used to calculate the screened potential which must be penetrated by the approaching nuclei in order to undergo a nuclear reaction. However, the Debye-Huckel approximation is valid only when $e\Phi \ll kT$, where Φ is the screened Coulomb potential. The Coulomb barrier is of the order of 1 MeV while $kT \sim 1keV$ near the center of the Sun. The reactions proceed there at effective energies much larger than kT. At the classical turning point $e\Phi = E$. Thus, inside the barrier, $e\Phi \gg kT$. Consequently, the use of the Debye-Huckel screened potential at distances shorter than the classical turning point for calculating the barrier penetration factor is completely unjustified. (The Debye-Huckel solution also requires that the inter-ion spacing is much shorter than the Debye length, and that there are many electrons within a Debye sphere. Both conditions are not satisfied in the core of the Sun). It is intersting to note that when the conditions for the validity of the Debye-Huckel approximation are badly violated in laboratory plasma the Debye-Huckel approximation for the screened potential fails dramatically (Goldsmith, Griem and Cohen 1984). We estimate (Dar and Shaviv, to be published) that if the electronic charge distribution in the plasma does not change significantly when two fast nuclei with c.m. energy around the effective energy approach each other, then the screening correction vanishes.

In the SSM the screening correction based on the Deby-Huckel potential increases the thermonuclear reaction rates of pp, ^{3}He^{3}He, ^{3}He^{4}He and p^{7}Be near the center of the Sun by a factor of 1.05, 1.21, 1.21 and 1.21, respectively. Since Bahcall found (Bahcall 1989) that

$$\phi(^8\mathrm{B}) \sim \sigma_{11}^{-2.6}\sigma_{33}^{-0.4}\sigma_{34}^{0.8}\sigma_{17}^{1}, \tag{15}$$

therefore the omission of the screening corrections reduces the predicted ^{8}B solar neutrino flux by about 13%.

Moreover, the reaction rates between various nuclei in the Sun is assumed to be given by $n_1 n_2 < \sigma v >$. This classical formula is valid only for an ideal gas where most of the time the colliding particles are outside the range of interaction. That is not the case in the dense plasma near the center of the Sun where the Coulomb energy is not negligible compared with the thermal energy. For instance, the average velocity between subsequent Coulomb collisions is smaller than the asymptotic velocity. We estimate that the reduced average velocity decreases the ^{8}B solar neutrino flux by about 5% (Dar and Shaviv, to be published).
Most of the nuclear cross sections that play important role in the Sun drop steeply at energies far below the Coulomb barrier. These cross sections at solar conditions are either calculated theoretically (e.g. for the pp and pep reactions and electron capture) or extrapolated from measurements at much higher energies. To eliminate from the extrapolation the strong energy dependence due to barrier penetration, the cross sections are normally parametrized as

$$\sigma(E) = S(E)E^{-1}exp(-2\pi\eta), \tag{16}$$

where $2\pi\eta = 31.29 Z_1 Z_2 \sqrt{\mu/E}$ is the Sommerfeld parameter, Z_1 and Z_2 being the charge numbers of the colliding nuclei, μ their reduced mass in atomic mass units and E their center-of-mass energy in keV. The factor S(E) is expected to vary slowly with energy and is determined by fitting the measured cross section at relatively high energies. However, the above formula neglects the contribution of higher partial waves than s wave to the cross sections at the high energies where the cross sections have been measured and where the contribution of p and d waves is not negligible (e.g., Clayton 1968, Robertson 1972). Moreover, the approximate expression for the WKB penetration factor in Eq. 16 is accurate only at very low energies and the exact WKB form, or even better, the exact quantum mechanical penetration factor for finite size nuclei should be used instead. (Some authors, e.g., Kajino, Toki and Austin 1987, Typel et al. 1991 Johnson et al 1992, used instead an extrapolation based on the energy dependence that follows from their specific model for the reaction). Using the precise WKB expression for the penetration factor we find that the most recent published experimental data on the reaction ^{7}Be(p, γ)^{8}B that also extends to the lowest measured energies (Fillipone et al. 1983, Filippone 1986) yields $S_{17}(0) = 17 \pm 2\ eV \cdot b$ (Dar and Shaviv , to be published). This value was also found by Barker and Spear 1986. It is smaller by about 25% than the value $S_{17}(0) = 22.4\ eV \cdot b$ proposed by Johnson et al. (1992) and used by Bahcall and Pinsonneault 1992. We also find that $S_{34}(0) = 0.45 \pm 0.03$ keV $\cdot$ b, using the world data on the reaction ^{3}He(α, γ)^{7}Be. This value is smaller by about 20% than the value $S_{34}(0) = 0.56$ keV $\cdot$ b, used by Bahcall and Pinsonneault 1992.
The joint effect of the above four modifications is to reduce the ^{8}B solar neutrino flux that was predicted by Bahcall and Pinsonneault (1992) by about 50%, to the value $\phi(^8\mathrm{B}) \approx 2.64 \times 10^6$ cm^{-2}s^{-1}, which is in a good agreement with the flux measured by Kamiokande II and III (assuming that all the interactions are due to ν_e's.)
Note however, that this solution does not explain the difference between the results of the Cl experiment and the Kamiokande H2O experiment.

5. PARTICLE PHYSICS SOLUTIONS

If the SSM calculations of Bahcall and Pinsonneault (1992) correctly describe the production rates of solar neutrinos then all four solar neutrino experiments indicate that the solar neutrino flux which reaches Earth is different from that produced in the core of the Sun. That could be due to decay in flight, and/or helicity flip, and/or flavour change of the solar neutrinos, or because of another unknown reason. The neutrino decay solution has been ruled out (Bahcall, Dar and Piran, 1987) by the arrival of neutrinos from SN1987A at a distance of about 165000 light years. Helicity flip via neutrino magnetic interaction (Voloshin et al. 1986) which could explain the reduced capture rate, requires a large neutrino magnetic moment which is inconsistent with the upper bounds that were derived from the cooling rate of He stars (Raffelt and Dearborn 1988) and of SN1987A, and from Big-Bang nucleosynthesis (Fukugita and Yazaki 1987). It is also inconsistent with the absence of significant annual variation in the solar neutrino flux that has been measured by Kamiokande. The Mikheyev-Smirnov-Wolfenstein (MSW) solution (Mikheyev and Smirnov 1986, Wolfenstein 1978, Wolfenstein 1979), namely matter amplification of neutrino flavour oscillations, is at the moment the most attractive particle physics solution to the solar neutrino problem.

THE MSW SOLUTION: Fig. 5. displays the counting rates that are predicted by the SSM and the MSW effect for the solar neutrino experiments for different choices of neutrino mixing parameters, $\Delta m^2 \equiv m^2_{\nu_\mu} - m^2_{\nu_e}$ and $sin^2 2\theta$, θ being the vacuum mixing angle of the neutrino mass eigenstates. From Fig. 5 it can be seen that the experimental results of all four solar neutrino experiments can be well explained by the SSM modified by the MSW effect provided that

$$\Delta m^2 \sim 10^{-5}\ eV^2 \quad \text{and} \quad sin^2 2\theta \sim 4 \times 10^{-3}\ . \tag{17}$$

This can also be seen directly from simple analytical considerations (Dar and Nussinov 1991):
The MSW effect takes place if a solar ν_e produced in the core of the Sun encounters the resonant electron density,

$$n_e = \frac{\Delta m^2 cos 2\theta}{2\sqrt{2} G_F E_\nu}\ , \tag{18}$$

on its way out of the Sun. The probability that the ν_e flips its flavour is then given by the Landau-Zenner formula (Haxton 1986, Parke 1986, Dar et al. 1987)

$$P(\nu_e \rightarrow \nu_\mu) \approx 1 - e^{-\epsilon/E_\nu}, \quad \text{where} \quad \epsilon = \frac{\pi H \Delta m^2 sin^2\theta}{4 cos 2\theta} \tag{19}$$

and $H \equiv -n_e/(dn_e/dr)$ is the local solar scale height at the resonant density. If the mixing angle is small, vacuum oscillations are unimportant and the solar neutrino

flux at Earth is given by

$$\phi_\nu = \phi_{\nu_e} + \phi_{\nu_\mu};\ \phi_{\nu_e} \approx (1-P)\phi_\nu;\ \phi_{\nu_\mu} \approx P\phi_\nu, \tag{20}$$

where ϕ_ν is the solar neutrino flux in the absence of neutrino flavour oscillations. The Cl detector is blind to ϕ_{ν_μ}. If only ^{8}B neutrinos contribute to the capture rate in the Cl detector then $< P > \approx 1 - 2.23/5.56 = 0.60$, where 2.23 SNU is the observed capture rate in the Cl detector and 5.56 SNU is the capture rate predicted by the SSM of Bahcall and Pinsonneault (1992). In that case the event rate in the Kamiokande detector, which detects both ν_e's and ν_μ's (with a relative cross section $\sigma(\nu_\mu e) \approx (1/6)\sigma(\nu_e e)$), should be $40\% + (1/6) \times 60\% = 50\%$ of the rate predicted by the SSM, in complete agreement with the rate reported by Kamiokande II and III.
Since $\phi\sigma$, the capture rate of ^{8}B neutrinos in ^{37}Cl , peaks sharply around $10MeV$, it follows from Eq. 3 that $P \approx 0.6$ around $10MeV$ and therefore $\epsilon \approx 9.2$. Consequently,

$$\Delta m^2 sin^2 2\theta \approx 3.5 \times 10^{-9}(R_\odot/H)\ eV^2 \approx 3.7 \times 10^{-8}\ eV^2\ , \tag{21}$$

where $R_\odot/H \approx 10.5$ near the center of the Sun. Essentially this MSW solution to the Cl solar neutrino problem was first discovered numerically by Rosen and Gelb (1986, 1989).
We have already pointed out that the observed capture rates in Gallium and in ^{37}Cl and the event rate in Kamiokande are consistent only if the ^{7}Be solar ν_e flux is strongly suppressed while the pp solar ν_e flux is approximately that expected from the solar luminosity. This is possible only if the resonance condition is not satisfied in the Sun by the pp neutrinos, i.e., for neutrino energies $E_\nu \leq 0.43\ MeV$, but it is satisfied by the ^7Be neutrinos with $E_\nu = 0.86\ MeV$. Eq. 18 then yields the condition

$$0.65 \times 10^{-6} eV^2 \lesssim \Delta m^2 \lesssim 1.30 \times 10^{-5} eV^2 \tag{22}$$

and Eq. 21 yields, correspondingly,

$$5.8 \times 10^{-3} \gtrsim \sin^2 2\theta \gtrsim 2.9 \times 10^{-3}\ . \tag{23}$$

6. IMPLICATIONS OF THE MSW SOLUTION

Testable implications of the above MSW solution (Dar and Nussinov 1991) include:
Distortion of the B^8 spectrum. The MSW solution predicts that the solar neutrino spectrum is distorted by approximately the Landau-Zenner factor $1 - P(E) \approx exp(-\varepsilon/E)$ with $\varepsilon \approx 9.2\ MeV$. Such a distortion (see Fig. 1b) of the B^8 spectrum can be detected by high statistics electronic experiments such as the SNO and Super Kamiokande experiments. Its detection will provide clear evidence that the solar neutrino problem is a particle physics problem which can be solved by the MSW effect.

Appearance of the missing solar ν_e flux as a ν_μ (or ν_τ) flux. If this ν_μ flux will be detected by the new generation of solar neutrino detectors which are sensitive also to the neutral current interactions of the ^{8}B neutrinos (e.g., the SNO heavy water Cerenkov detector, the Super Kamiokande light water Cerenkov detector, ICARUS, or HELLAZ) it will provide another convincing proof for the MSW solution.
A short ν_μ neutronization burst from Type II supernova explosions. Because of the relatively large scale height in the stellar envelope of a giant star, $H \gtrsim H_\odot$, the MSW flavour change at the resonant density in the giant star envelope is more/as efficient than/as in the sun. Thus, most of the ν_e's from the expected short (few milliseconds) neutronization burst from a Type II Supernova explosion (Mayle, Wilson and Schramm 1987) whose typical energies are below 10 MeV, will be converted via the MSW effect in the stellar envelope into a ν_μ's (or ν_τ's). Such a short ν_μ neutronization burst from a nearby Type II supernovae explosion might be detected by the new generation of neutrino telescopes such as the SNO heavy water Cerenkov detector, Superkamiokande, ICARUS and HELLAZ). *Such a short neutronization burst of ν_μ's can be used to measure m_{ν_μ} or to limit it to below ~ 0.1 eV if the burst lasts for a few milliseconds.*
Non detectable $\nu_e \leftrightarrow \nu_\mu$ oscillations of accelerator, reactor or atmospheric neutrinos. The tiny Δm^2 and the small mixing precludes seeing any $\nu_e \leftrightarrow \nu_\mu$ oscillations of accelerator, reactor or atmospheric neutrinos.

7. THE SEESAW MECHANISM AND THE MSW SOLUTION

Let us now consider the implications of the MSW solution combined with the seesaw mechanism (Yanagida 1978, Gell-Mann et al. 1979) which is the only scheme presently known for naturally generating small, non-vanishing, neutrino masses. The Dirac masses of the quarks and leptons in the i'th generation and a heavy right handed ν_R of a mass M_R fix the mass of the ordinary ν_i via $m_{\nu_i} \approx m_{F_i}^2/M_R$.
We implicitly assumed a generation independent M_R usually associated with a new scale of left-right or grand unified symmetry breaking (see for instance Langacker 1982). While the actual value of M_R is unknown (and ranges between 10-100 M_W and M_{Planck}) it has been emphasized (Harari and Nir 1986) that the pattern of ν_i mass ratios is extremely useful. To fix these ratios we assume that the Dirac masses of the upper members of the lepton and quark doublets in each generation are proportional, and then

$$m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \approx m_u^2 : m_c^2 : m_t^2 \approx 0.005^2 : 1.5^2 : 135^2 \ , \tag{24}$$

where we used the recent estimates for the mass of the top quark $m_t = 135 \pm 20$ GeV. Adopting the value $\Delta m^2 \approx 10^{-5}$ eV^2, suggested by the MSW solution to the solar neutrino problem, we then find

$$m_{\nu_e} \sim 3 \times 10^{-8} eV \ ; \ \ m_{\nu_\mu} \sim 3 \times 10^{-3} eV \ ; \ \ m_{\nu_\tau} \sim \ 25 \ eV \ , \tag{25}$$

which implies a rather high, $M_R \sim 10^{12}$ GeV, right handed mass scale.

8. IMPLICATIONS OF THE SEESAW MECHANISM

Below we point out some additional implications for particle physics, astrophysics and cosmology of the above suggested neutrino masses and mixings.

The neutrino lifetimes are extremely long: Simple dimensional arguments based on the small neutrino masses (small phase space for decay products), the small neutrino mixings and the strength of the weak interaction show that neutrino lifetimes are extremely long compared with the age of the Universe and have no observational consequences for astrophysics and cosmology.

The Majorana mass of the ν_e is far too small to manifest in neutrinoless double β decay experiments (see for instance Rosen 1988, Fiorini 1988).

Appearance $\nu_\mu \to \nu_\tau$ experiments are feasible: The relatively large value, $\Delta m^2 \sim 625\ eV^2$ which the MSW solution and the seesaw mechanism suggest for the $\nu_\mu \nu_\tau$ mixing, imply that $\nu_\mu \to \nu_\tau$ appearance experiments at accelerators have a good chance of seeing the ν_τ's.

Supernova neutrinos may be used to determine m_{ν_τ} : Future neutrino telescopes such as SNO and Super Kamiokande will be sensitive enough to detect ν_μ's and ν_τ's from galactic Type II supernova explosions. A mass of the tau neutrino of the order $m_{\nu_\tau} \approx 25\ eV$ may yield a detectable time delay between the mean arrival times of the ν_τ's and of the ν_e's and ν_μ's from the thermal neutrino burst of a nearby Type II supernova explosion, which may be used to measure (Dar 1987) m_{ν_τ}.

Neutrinos can account for most of the cosmological dark matter in the Universe: A stable ν_τ with a mass around 25 eV contributes a cosmological energy density (see for instance Weinberg 1972) $\rho_\nu \approx n_{\nu_\tau} m_{\nu_\tau} \approx (3/11) n_\gamma m_{\nu_\tau} \approx 114 m_{\nu_\tau}\ cm^{-3} \approx 3\ keV\ cm^{-3}$ similar to the closure density, $\rho_c \approx 10.6 h^2\ keV\ cm^{-3}$, where $0.5 \lesssim h \lesssim 1$, h being the Hubble constant in units of 100 $km\ Mpc^{-1} s^{-1}$.

Neutrinos with a mass around 25 eV can help explain the large scale structure formation in the Universe: Models based on the simultaneous existence of cold and hot dark matter (see for instance Kolb and Turner 1990) find it easier to explain the observed large scale structure in the Universe and the fluctuations in the microwave background radiation seen by the Cosmic Background Explorer (COBE) satellite (see for instance the articles by Frieman and by Stebbins in this proceedings), in particular if the mass of the tau neutrinos (the hot dark matter particles) is around 25 eV.

If $m_{\nu_\tau} \lesssim 25\ eV$ then baryons are more likely to form the dark matter in galactic halos than neutrinos: Light neutrinos ($m_\nu \sim 25\ eV$) are unlikely to form galactic halos (Tremaine and Gunn 1979) of dwarf and spiral galaxies. Within the standard particle physics model the remaining candidates for dark matter particles are baryons. Thus, in the above particular scenario the dark matter in galactic halos is likely to be hadronic, probably brown dwarfs (over production of neutron stars and stellar black holes would pollute the galaxy with high Z materials which is not observed). Interestingly, the cosmological baryonic mass density that best fits Big-Bang nucleosynthesis (Dar, Goldberg and Rudzsky 1992) $n_b \approx 1.6 \times 10^{-10} n_\gamma \approx 6.6 \times 10^{-8}\ cm^{-3}$ yields $\Omega_b \sim 0.59 \times 10^{-2} h^{-2}$. This baryonic density, although being about 1% of the closure energy density, is indeed consistent with the amount of luminous plus dark matter in galaxies: The measured luminosity density in the Universe (see for instance Kolb and Turner 1990) is $L \approx 2.4 \times 10^8 h L_\odot / Mpc^3$. The masses of spiral and elliptical galaxies deduced

from rotational curves, velocity dispersions, escape velocities and X-ray luminosities, and recently also from gravitational lensing (see for instance Langston et al. 1990) yield average mass to light ratio of $< M/L > \approx (8 \pm 2) h M_\odot / L_\odot$. Consequently, $\Omega_G \approx < M/L >_G L/\rho_c \approx (0.7 \pm 2) \times 10^{-2}$, in good agreement with the nucleosynthesis value, especially if one uses the recent estimate, $h = 0.87 \pm 0.12$ (Jacoby 1990, Fukugita 1992).

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FIGURE CAPTIONS

Fig. 1 The average rate of electron recoil events as function of the angle between the electron direction and the direction from the Sun as observed by Kamiokande II in 1040 live detector days between January 1987 - April 1990 (Kihara 1992).

Fig. 2 (a) The energy spectrum of the recoil electrons along the direction from the Sun as measured by Kamiokande II (full dots) relative to that expected from the ^{8}B solar neutrinos flux calculated from the SSM of Bahcall and Ulrich (1988) (full line histogram). The broken line histogram is obtained by adjusting the normalization of ^{8}B solar neutrino flux to fit the data (Kiara 1992).
(b) The ratio between the electron recoil energy spectrum measured by Kamiokande II and that predicted by the SSM of Bahcall and Ulrich (1988), as function of energy (full dots). The line is the ratio predicted by the MSW solution described in the text.
Fig. 3 Comparison between the observed rates of events induced by solar neutrinos in the Cl and the Kamiokande II experiments divided by the rates predicted by the SSM of Bahcall and Ulrich (1988) as function of time during the period January 1987 through April 1990. The round circles are the Cl data points, the square boxes are the Kamiokande II data points and the cross hatched boxes are the weighted average of several ^{37}Cl runs corresponding in time to the Kamiokande II data points (Kihara 1992).
Fig. 4 The allowed regions of the neutrino mixing parameters which can explain through the MSW effect the results of the Cl experiments (full line), of the Kamiokande II experiment (dashed line) and of both experiments (dotted area), at 90% C.L. The cross-hached area is excluded at 90% C.L. by the observational limit on the day- night effect obtained by Kamiokande II (Kihara 1992).
Fig. 5 Iso-SNU contours for the Ga detectors (dotted lines) superimposed on Fig. 4. The black area is the region of neutrino mixing parameters at 90% C.L. which can explain simultaneously the results of the four solar neutrino experiments.

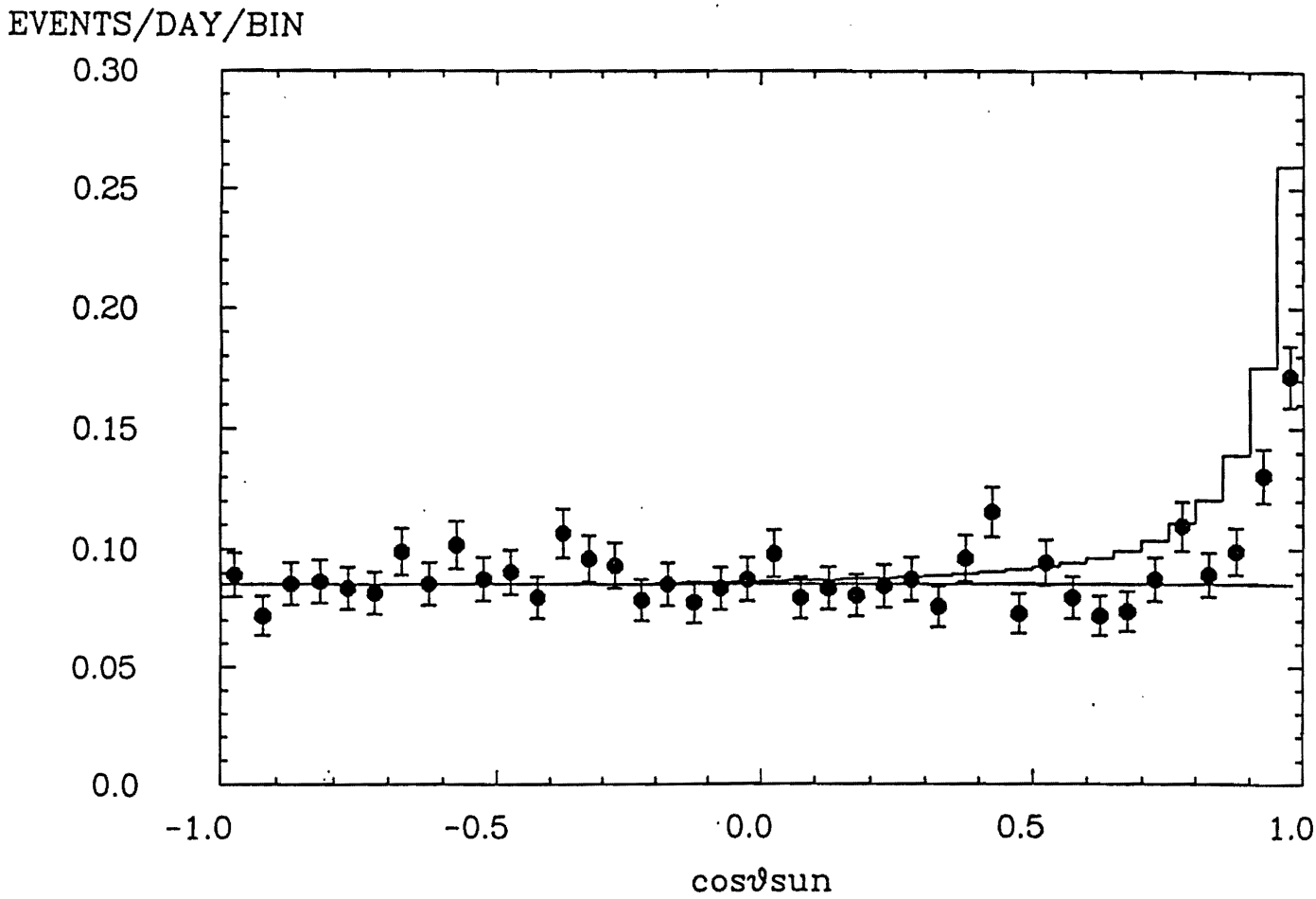
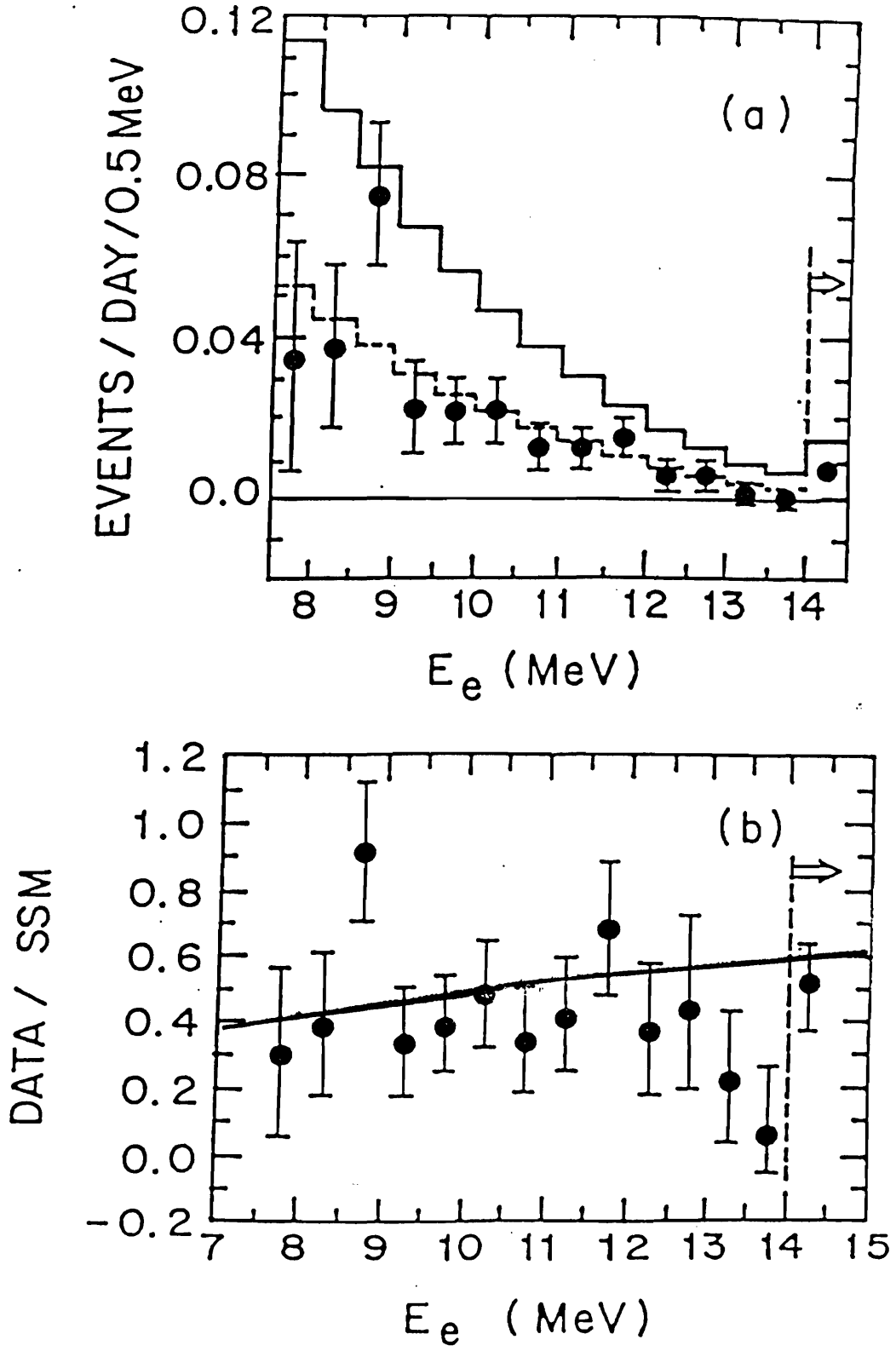


Fig. 1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0.08
0.04
0.0
EVENTS / DAY / 0.5 MeV
(a)
8
9
10
11
12
13
14
E_e (MeV)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
DATA / SSM
(b)
7
8
9
10
11
12
13
14
15
E_e (MeV)

Fig. 2

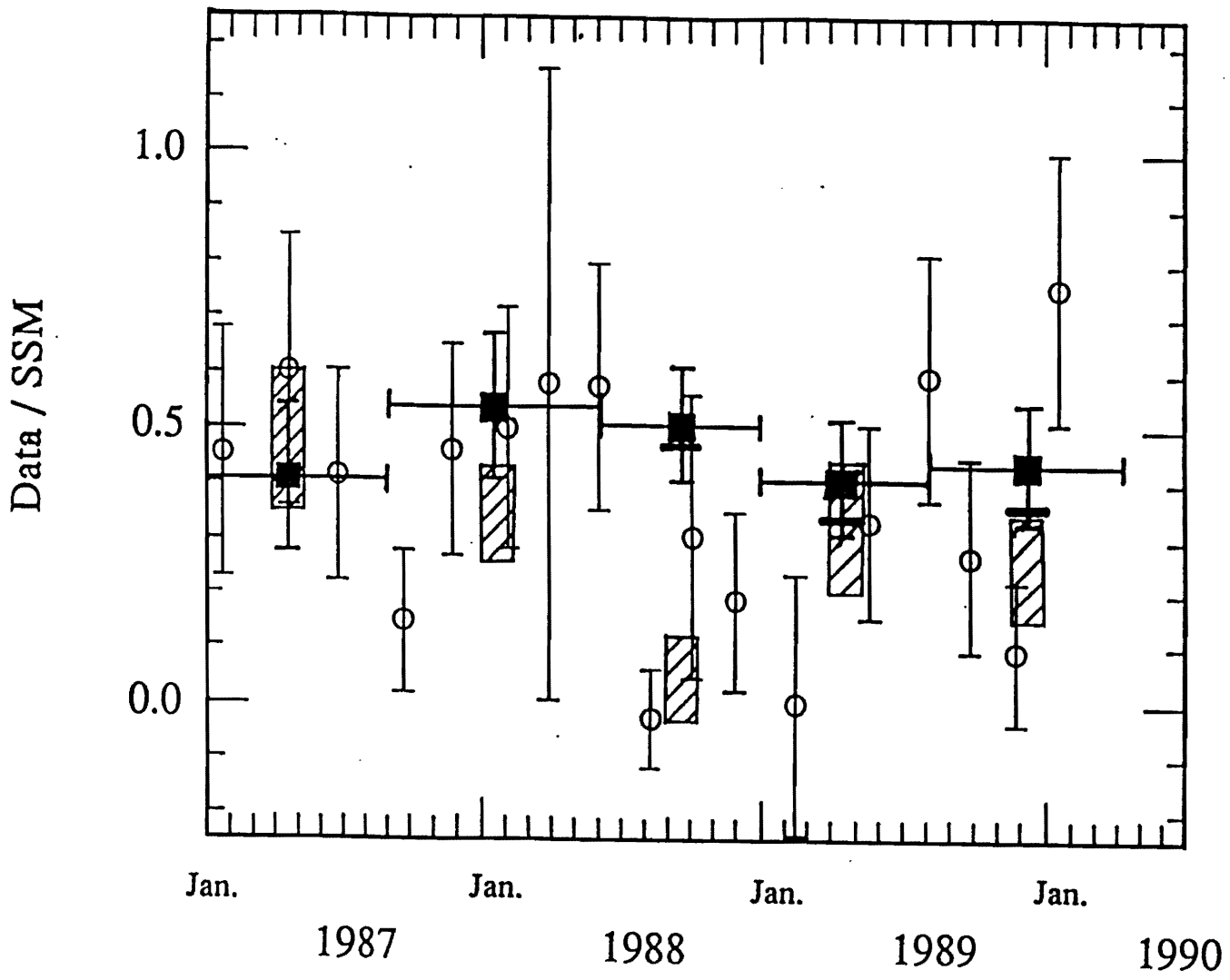
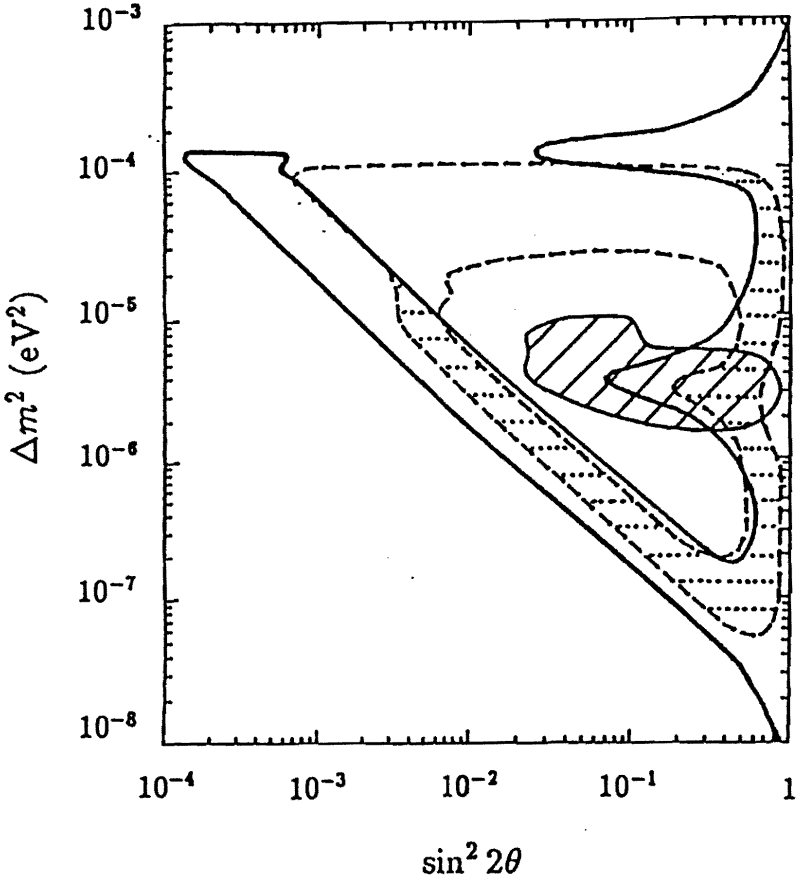


Fig. 3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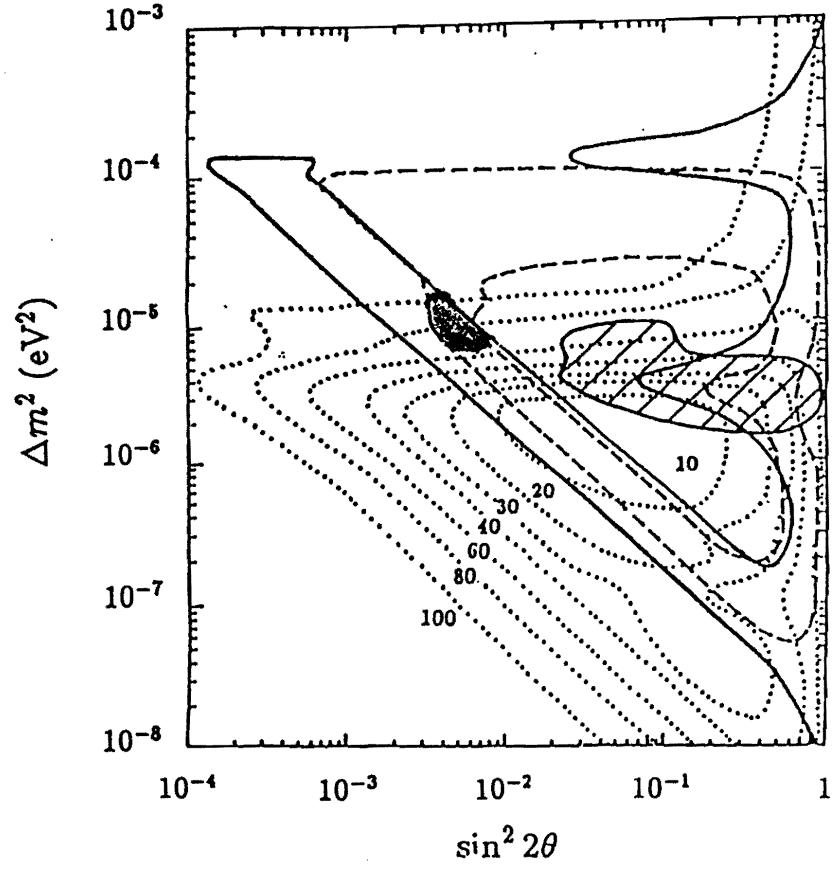
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Δm^2 (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

Fig. 4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10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Δm^2 (eV^2)
10
20
30
40
60
80
100
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$

Fig. 5