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THE SOLAR NEUTRINO DEFICIT — PRINCIPLE AND INTEREST (A MODERN PROBLEM)

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Sufficient data now exist that tests, independent of any solar model, can be made of whether solar neutrino experiments are consistent with the minimal Standard Model (stable, massless neutrinos). If the experimental uncertainties are correctly estimated and the sun is generating energy by light-element fusion in quasi-static equilibrium, the probability of a standard-physics solution is less than 1.2%. Even when the luminosity constraint is abandoned, the probability is not more than 5%. The sensitivity of the conclusions to input parameters is explored. New experiments nearing completion (SNO and SuperKamiokande) are expected to provide decisive evidence of neutrino oscillations, if they are indeed the explanation.

1 Introduction

The sun is believed to generate its energy by fusion reactions that can be summarized as

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.731\ \text{MeV}.$$

A number of pathways lead to ^{4}He, and a complex spectrum of neutrinos from the decays pp, pep, ^{7}Be, hep, ^{13}N, ^{15}O, ^{17}F, and ^{8}B results.[1] The spectral shape of each individual component, whether line or continuum, is determined by laboratory measurement and/or electroweak theory, but the relative intensities of each branch depend delicately on astrophysical models of the sun. Up to 1985, when only the Homestake Cl-Ar experiment[2] was in operation, the data indicated that the flux of ^{8}B neutrinos was within 25 to 50% of that expected from standard solar models. The fact that these models were able to predict to such precision the intensity of a 0.01% branch that varies as the 18th power of the central temperature of the sun must be regarded as a stunning achievement and a clear indication of the basic correctness of our understanding of how the sun and other stars function.

Nonetheless, the absence of perfect agreement raised speculation about possible exotic origins, such as neutrino oscillations. The model dependence of the ^{8}B flux calculation made such speculations interesting but not compelling. Now, however, steadily improving data from four independent experiments are available, as summarized in Table I. In the table, the Kamiokande result[3] has been increased 2% by radiative corrections according to the prescription of Bahcall, Kamionkowski, and Sirlin.[4] For subsequent calculations, a weighted average of 73.7 ± 7.7 SNU is adopted for the Ga experiments.

2 Calculation of Spectrum

Because the 3 types of experiment have different thresholds, a coarse neutrino spectroscopy of the sun has been made. The least model-dependent questions that can be asked are,

Table I. Experimental data on solar neutrino flux.

Experiment	Threshold (MeV)	Result	Unit	Reference
Cl-Ar	0.814	$2.55 \pm 0.17 \pm 0.18$	SNU	2
Kamiokande	7.0	$2.95\,^{+0.22}_{-0.21} \pm 0.36$	10^6 ν cm^{-2}s^{-1}	3
SAGE	0.233	$69 \pm 10\,^{+5}_{-7}$	SNU	5
Gallex	0.233	$77.1 \pm 8.5\,^{+4.4}_{-5.4}$	SNU	6
1 SNU = 10^{-36} captures per target atom per second.				

- *Is it possible to describe the neutrino spectrum with any combination of the known sources in hydrogen-burning?*
- *Is the total neutrino flux consistent with the solar luminosity?*

The spectral shape and endpoint of the neutrino data from Kamiokande show that ^{8}B neutrinos are emitted from the sun. The simplest description of the remainder of the spectrum is contributions from *pp* and ^{7}Be neutrinos. The *pep* reaction rate is taken to be a fixed branch, 0.23(2)%, of the *pp* rate.[7,8] We will consider below the question of how sensitive the conclusions are to these choices.

Defining the *pp*, ^{7}Be, and ^{8}B fluxes as Φ_1, Φ_7, and Φ_8, respectively, the experimental capture rates per 10^{36} target atoms per second (SNU) as $R_{\rm Cl}$ for Cl-Ar and $R_{\rm Ga}$ for Ga-Ge, and the experimental ^{8}B flux from Kamiokande as $R_{\rm Kam}$, the following equations result:

$$\begin{aligned} a_{C1}\Phi_1 + a_{C7}\Phi_7 + a_{C8}\Phi_8 &= R_{\rm Cl} \,, \\ a_{K8}\Phi_8 &= R_{\rm Kam} \,, \\ a_{G1}\Phi_1 + a_{G7}\Phi_7 + a_{G8}\Phi_8 &= R_{\rm Ga} \,. \end{aligned}$$

The coefficients are listed in Table II. Propagating the uncertainties in the cross sections and solving, one finds (in units of 10^{10} ν cm^{-2}s^{-1}):

$$\begin{aligned} \Phi_1 &= 7.8 \pm 1.5 \,, \\ \Phi_7 &= -0.40 \pm 0.24 \,, \\ \Phi_8 &= 0.00030 \pm 0.00004 \,. \end{aligned}$$

A negative flux is unphysical. The initial assumption that the data can be described as the sum of the three elementary neutrino spectra thus fails at the 95% confidence level, i.e., the statistical probability of obtaining such a result by chance is 5%.

A fourth neutrino-flux relationship is contained in the total solar luminosity, subject to the assumption of a quasi-static sun deriving its energy entirely from hydrogen burning. When neutrino losses are accounted for, the electromagnetic solar constant L in 10^{10} ν cm^{-2}s^{-1} is given by:

Table II. Cross-section coefficients.

	Coefficient	Cross Section (10^{-46} cm^2)	Uncertainty (%, 1-σ)	Reference
Cl-Ar	a_{C1}	0.0374	10	7,9
	a_{C7}	2.38	1.2	9
	a_{C8}	10877	3	10
Kamiokande	a_{K8}	10000[a]	—	4
Gallium	a_{G1}	12.3	1	9,11
	a_{G7}	80.8	13	12
	a_{G8}	24300	$^{+33}_{-17}$	9

[a] Dimensionless. Kamiokande reports flux directly.

$$13.366(0.981\Phi_1 + 0.939\Phi_7 + 0.498\Phi_8) = L \ .$$

Experimentally, $L = 85.33$,[13] with an uncertainty of order 0.1%.

Comparing the electromagnetic luminosity with the neutrino luminosity derived from the three types of solar-neutrino experiment (Table III), one sees good agreement, setting aside for the moment the negative value of Φ_7. As expected, the total flux is dominated by the p-p flux. The solar neutrino problem is *not* manifest in the total flux, but the probability for this minimal standard-model (MSM) solution is also low.

Including the luminosity as a constraint reduces the uncertainties in the derived fluxes. The results in the constrained case are summarized in Table III next to those for the unconstrained case. The probability of this result being obtained from a physically-realizable set of fluxes (i.e., with the ^{7}Be flux being non-negative) is less than 1.2%.

Table III. Fitted values of the fluxes (10^{10} ν cm^{-2}s^{-1}).

Component	Value	Uncertainty	Value	Uncertainty	SSM[a]
	(luminosity unconstrained)		(luminosity constrained)		
pp	7.8	1.5	6.75	0.11	6.0
^{7}Be	−0.40	0.24	−0.26	0.11	0.49
^{8}B	0.00030	0.00004	0.00027	0.00003	0.00057
L	97	19	85.32	—	85.64
χ^2			0.49		
Probability	5%		1.2%		

[a] Ref. 7.

The assumptions made in reaching this conclusion do not include any features of solar models (one is shown, for reference, in Table III[7]). Therefore, either the shape of the ^{8}B spectrum is not as expected, containing more strength at low energies and less at high,[14] and/or the neutrino flavor content is not pure electron, which alters the relationship between the Kamiokande result and the radiochemical experiments (because Kamiokande detects, via the neutral-current interaction, neutrinos of all active flavors). These features are characteristic of neutrino-oscillation solutions, as has been discussed by many authors.[15–18] In contrast to the standard-physics solution, such solutions give an excellent account of all data. Once such solutions are admitted, the fluxes may in general be quite different.[19]

Setting the CNO neutrino flux to zero is not the source of this problem because CNO and ^{7}Be neutrinos play a qualitatively similar role in the three experiments, and forcing either one to be non-zero exacerbates the problem with the other.

The concept of a model-independent analysis of the solar-neutrino data has been dealt with extensively;[16,20–27] to this body of analysis we add (a) the probability that the existing data would be obtained from true values in the physical regime in the absence of new physics, (b) a test of consistency free of the luminosity constraint, (c) a test for inconsistency of the data with the total solar luminosity, and (d) an analysis of the dependence of the conclusions on the neutrino cross sections.

3 Neutrino Oscillation Solutions

With two-flavor mixing, there are two sets of neutrino-oscillation parameters Δm^2 and $\sin^2 2\theta$ that fit the data in the Mikheyev-Smirnov-Wolfenstein scenario of matter-enhanced oscillations. For the enhancement to occur, m_{ν_e} must be smaller than the admixed species. A third solution occurs for vacuum oscillations in which the wavelength of the oscillation for ^{8}B neutrinos is of order 1 A.U. These solutions are summarized in Fig.1 from Hata.[28]

Although we will not consider here explicit neutrino-oscillation solutions, we note that large-mixing-angle schemes (such as Foot[29]) that simply reduce the ν_e flux are equivalent to astrophysical solutions with the luminosity unconstrained and thus are disfavored at the same level of confidence.

4 Sensitivity to Inputs

While no astrophysical model inputs have been used in the analysis, the conclusions do depend on both neutrino cross sections and experimental uncertainties (statistical and systematic). These uncertainties have been propagated into the results given in Table III (using the largest values in the case of unsymmetrical errors).

Although it is a common perception that the solar neutrino problem stands or falls on the validity of the Cl-Ar experiment, the Kamiokande datum is four times more critical in the unconstrained fit than Cl-Ar and is still a factor of 2 more critical in the constrained fit. By 'critical' is meant the number of standard deviations change in an experimental result to produce a given change in ϕ_7, i.e., the value of $(\partial\phi_7/\partial R)\sigma_R$. The Ga datum is almost irrelevant in the determination of the ^{7}Be flux when the luminosity is a free parameter, but dominates it when the luminosity is fixed. This sensitivity draws attention to the importance of the neutrino cross

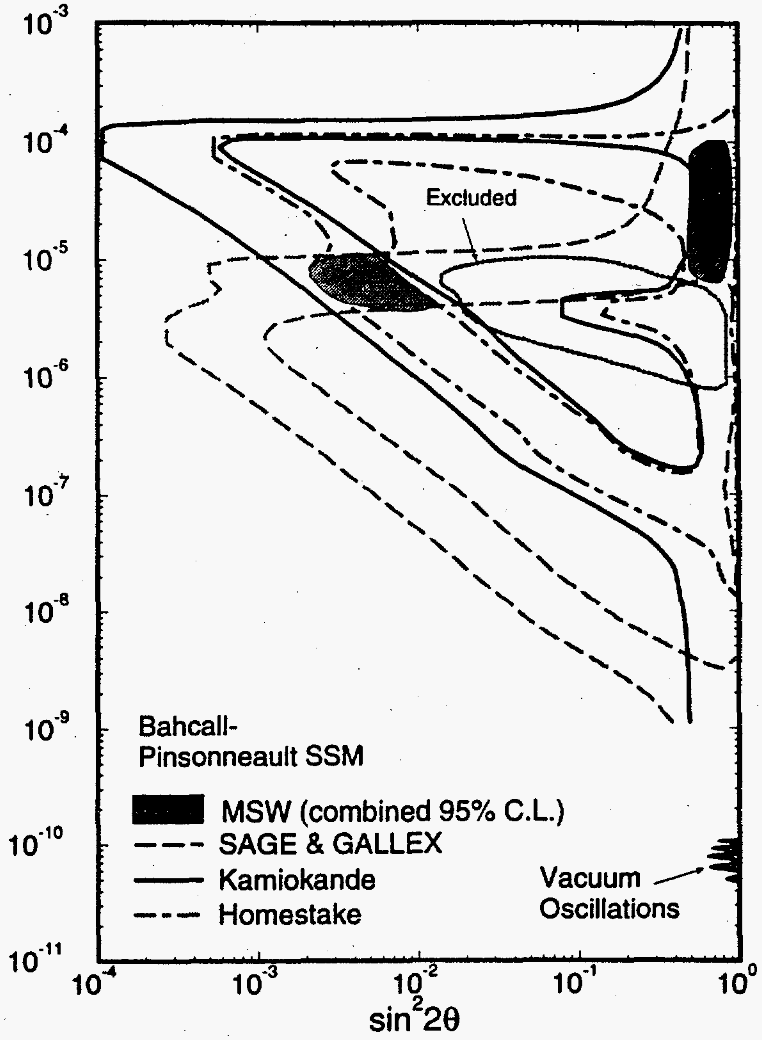

Fig. 1. Constraints on the possible values of the mixing angle θ and the difference of squares of neutrino eigenmasses Δm^2 from solar-neutrino data, as calculated by Hata. The contour marked 'Excluded' is excluded by virtue of the absence of a day-night variation in the Kamiokande data.

sections, a_{G7} and a_{G8}, which are determined in part by (p,n) reactions to excited states, with uncertainties that are difficult to assess. Hata and Haxton[12] have pointed out that the Gallex and SAGE ^{51}Cr source calibration experiments[30] are, in fact, experimental confirmation that a_{G7} is close to the expected value unless a novel effect has caused the extraction efficiency to be low, and a_{G7} is correspondingly larger than expected. In the latter case, the calibration data make the response of the Gallex detector to ^{7}Be neutrinos virtually independent of the efficiency, while the response to *pp* and ^{8}B neutrinos scales almost linearly with the efficiency. From the calculated negative correlation between Φ_7 and a_{G1}, the efficiency of Gallex and SAGE would both have to be reduced to 75% of the measured values to bring the derived ^{7}Be flux up to zero.

Our inclusion of the *pep* neutrinos contributes -0.11 to Φ_7 in the unconstrained fit and only -0.03 when the luminosity is constrained. While in principle model-dependent, the 0.23% *pep* fraction is one of the most reliably determined model parameters, depending chiefly on the electron density and only weakly on temperature and on nuclear wave functions.[31]

Table IV. Values of Φ_7 (10^{10} ν $cm^{-2}s^{-1}$) obtained from experimental results taken in pairs and the luminosity constraint.

	Kamiokande	Ga
Cl	–0.39(22)	–0.20(14)
Kamiokande		–0.22(13)

An interesting question is whether the present situation may simply reflect an experimental result outside of its estimated uncertainty. Table IV shows the values of ϕ_7 derived in luminosity constrained fits of the three types of experiment in pairs. It may be seen that the anomaly emerges in all combinations of pairs of experiment.

5 Future Experiments

Experiments that specifically test the neutrino-oscillation hypothesis are under construction. Both SuperKamiokande and the Sudbury Neutrino Observatory (SNO)[32] are water-Čerenkov detectors, the former at the Kamioka mine in Japan, and the latter at the INCO nickel mine in Sudbury, Ontario. SNO uses 1000 tonnes of 99.92% isotopically enriched heavy water as a target and 7000 tonnes of light water as a shield. With heavy water three reactions of neutrinos with deuterium can be observed.

$$d+\nu_e \rightarrow p+p+e^- - 1.44\text{ MeV} \qquad \text{(CC)}$$

$$d+\nu_x \rightarrow p+n+\nu_x - 2.22\text{ MeV} \qquad \text{(NC)}$$

$$e^- + \nu_x \rightarrow e^- + \nu_x \qquad \text{(ES)}$$

The first of these reactions proceeds by the charged-current (CC) interaction of electron neutrinos. The second is the neutral-current (NC) disintegration of deuterium and can be initiated with equal probability by any of the active neutrinos (ν_e, ν_μ, or ν_τ). The third is the elastic scattering of neutrinos (ES), and is also the process to be observed in SuperKamiokande. While all flavors can scatter, the cross section for electron neutrinos is about 6 times that for other flavors as a result of the additional charged-current channel.

These experiments therefore have the capability of revealing the presence of neutrino oscillations largely independent of solar properties. In SNO, if the NC rate exceeds the CC rate (suitably normalized for cross sections), then neutrinos must be oscillating. Both SNO and SuperKamiokande can provide the neutrino energy spectrum (SNO via the CC reaction, SuperKamiokande via the elastic-scattering y-distribution). If that differs from the known ^8B spectrum, neutrino oscillations are indicated. Measuring the spectrum to sufficient accuracy will be very challenging in both experiments.

Charged-current events are detected in SNO by an array of 9,500 photomultipliers surrounding the acrylic sphere that holds the D_2O. The detection of a free neutron is the signal that a NC event has occurred. Heavy water is an excellent moderator, and two techniques for detecting the neutron are being implemented. One is to dissolve in the heavy water several tonnes of $MgCl_2$. When a neutron captures on ^{35}Cl, it emits an 8.6-MeV γ, which showers. The resulting Čerenkov radiation can be detected by the PMT array in the same way CC events are detected. The second method is to detect the neutron in ^3He proportional counters made with ultrapure materials and distributed throughout the heavy water. In the latter approach, the NC and CC events become completely distinct and no longer represent "backgrounds" to each other. SNO, a Canada-U.S.-U.K. collaboration, will be complete May 1997.

SuperKamiokande, with a total mass of 50,000 tonnes of light water, and a fiducial mass of about 22,000 tonnes, makes use of 11,000 50-cm phototubes to detect Čerenkov light. SuperKamiokande, a Japan-U.S. collaboration, will be complete April 1, 1996.

Both SNO and SuperKamiokande have detection thresholds of about 5 MeV electrons (2.2-MeV neutrinos for the NC reaction in SNO). In order to explore the solar neutrino spectrum, particularly the ^7Be flux, at low energies, the Borexino scintillation detector is being developed by a U.S.-Italian collaboration at the Gran Sasso Laboratory in Italy. Successful demonstration of low backgrounds in a 4-tonne prototype has opened the way to construction of the full 240-tonne detector.

6 Conclusions

At an interesting level of confidence (almost 99%), there exists a solar neutrino problem independent of solar models, except for the assumptions of neutrino production by light elements and a steady-state sun. Moreover, even abandoning the steady-state sun assumption does not deliver a satisfactory solution at the 95% confidence level. The extent of the problem is even more severe than those confidence levels might suggest because the true value of the ^7Be flux cannot be exactly zero (especially in view of the observation of ^8B neutrinos, which can only result from reactions on ^7Be), nor can the flux of CNO neutrinos be exactly zero. However, those effects cannot be quantified without appeal to astrophysical models. At the present level of significance, the data strongly suggest new neutrino physics, and, at the same level, they demonstrate that the solution to the solar neutrino problem is not to be found in the realm of astrophysics. Definitive resolution of this question can be expected once SNO and SuperKamiokande are in operation.

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