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THE SOLAR NEUTRINO PUZZLE; UPDATE [1]

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Abstract

In this talk I will summarize the latest experimental results from the four solar neutrino experiments and discuss what this means for the flux of ^7Be and ^8B neutrinos. The implications for the solar models including the new versions with helium and heavy element diffusion will also be addressed. The exciting and important calibration results of the Gallex collaboration will be presented as well as the outlook for the next generation of solar neutrino experiments.

[1]Invited talk at the XV International Conference of Physics in Collision, Krakow, Poland, June 8 - 10, 1995.

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Current Experimental Situation

Over the last year new results from the four solar neutrino experiments have been reported. The results for Homestake[1], Kamiokande[2], Gallex[3] and SAGE[4] are

$$\begin{aligned} S^{ex}_{Home} &= 2.55 \pm 0.17 \pm 0.18 \quad SNU \\ S^{ex}_{Kam} &= 0.51 \pm 0.04 \pm 0.06 \quad \Phi^{^8B}_{BP} \\ S^{ex}_{Gallex} &= 79 \pm 10 \pm 6 \quad SNU \\ S^{ex}_{Sage} &= 69 \pm 11 \, ^{+5}_{-7} \quad SNU \end{aligned}$$

where the first uncertainty is statistical and second systematic. To form a combined result for gallium, the mean and statistical errors for SAGE and Gallex were combined in the standard way but a common systematic error of 6 SNU was used. Then the statistical and systematic errors are combined in quadrature for each experimental result giving

$$S^{ex}_{Cl} = 2.55 \pm 0.25 \quad SNU \tag{1}$$

$$S^{ex}_{H_2O} = 0.51 \pm 0.072 \quad \Phi^{^8B}_{BP} \tag{2}$$

$$S^{ex}_{Ga} = 74 \pm 9.5 \quad SNU. \tag{3}$$

To compare these experimental results with those from the standard solar models it is convenient to use one of the models as a reference model. I will use the 1992 solar model of Bahcall and Pinsonneault [5] as this reference solar model where the central values of the important solar neutrino fluxes are

$$\begin{aligned} \Phi^{pp}_{BP} &= 6.0 \times 10^{10} \; cm^{-2} sec^{-1} \\ \Phi^{^7Be}_{BP} &= 4.9 \times 10^{9} \; cm^{-2} sec^{-1} \\ \Phi^{^8B}_{BP} &= 5.7 \times 10^{6} \; cm^{-2} sec^{-1}. \end{aligned}$$

It is useful to normalize all solar neutrino fluxes to this model, by defining the renormalized neutrino fluxes as

$$\phi^i = \Phi^i / \Phi^i_{BP}. \tag{4}$$

In these normalized flux units the solar luminosity constraint is simply

$$1 = 0.913 \, \phi^{pp} + 0.071 \, \phi^{^7Be} + 4 \times 10^{-5} \, \phi^{^8B} \tag{5}$$

This will be used to determine ϕ^{pp} in terms of $\phi^{^7Be}$. Then the contribution of the ν_e^{pp}, $\nu_e^{^7Be}$ and $\nu_e^{^8B}$ to the chlorine, water and gallium solar neutrino experiments is

$$S^{th}_{Cl} = 6.2 \, \phi^{^8B} + 1.2 \, \phi^{^7Be} \quad SNU \tag{6}$$

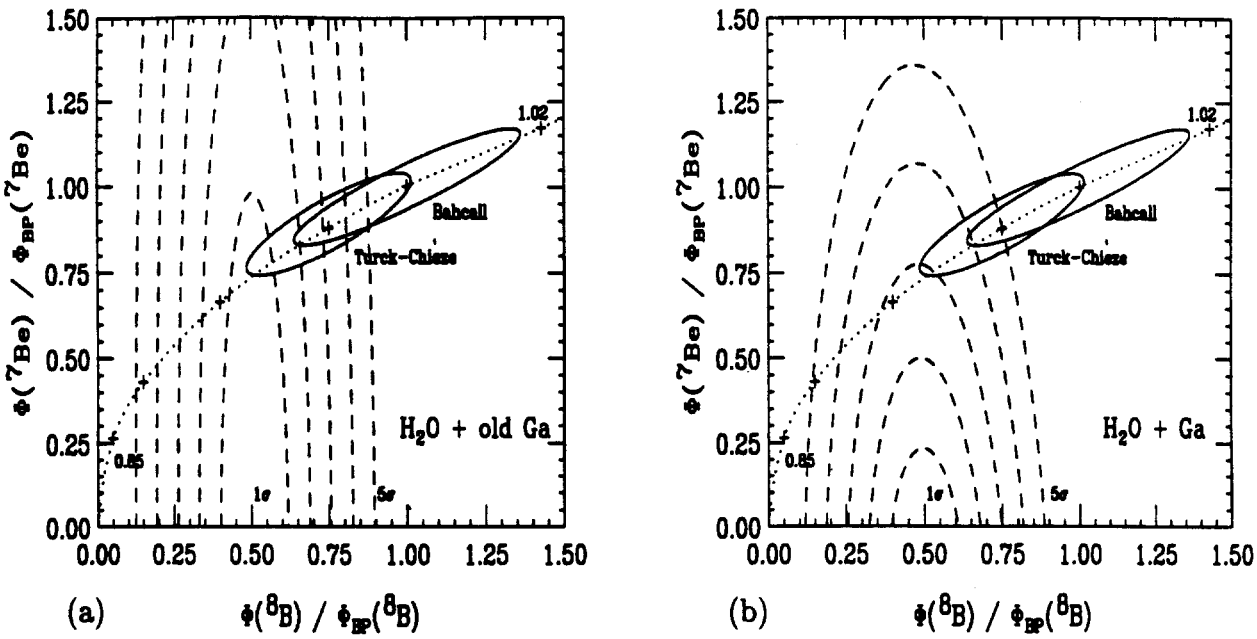

Figure 1: (a) The $\phi^{^7Be}$ verses $\phi^{^8B}$ plane using the results from Kamiokande and the old Gallex results. The dashed curves are the 1σ to 5σ contours for the χ^2 variable. The solid ellipses are the predictions of the solar models of Bahcall & Pinsonneault 1992 and Turck-Chièze & Lopes. The dotted line is the curve $\phi^{^7Be} = (\phi^{^8B})^{8/18}$ and the crosses on this line corresponding to solar core temperature of (0.85, 0.90, 0.95, 0.984, 1.00, 1.02) times the core temperature of the Bahcall & Pinsonneault's model. (b) Same as (a) but using the latest combined results from Gallex and SAGE as well as Kamiokande.

$$S^{th}_{H_2O} = \phi^{^8B} \quad \Phi^{^8B}_{BP} \tag{7}$$

$$S^{th}_{Ga} = 14\,\phi^{^8B} + 36\,\phi^{^7Be} + 71\,\phi^{pp} \quad SNU. \tag{8}$$

The coefficients in eq.(6)-(8) are determined using the assumptions that the state of the neutrinos is unaffected by the passage from the solar core to the terrestrial detectors, i.e. there is no change in the flavor, helicity or energy spectrum, and that the neutrino interaction cross sections used are corrected. The uncertainty on these cross sections is estimated to be a few per cent.

Using the luminosity constraint to eliminated the ν_e^{pp} flux, the contribution to the gallium experiments can be written as

$$S^{th}_{Ga} = 14\,\phi^{^8B} + 30\,\phi^{^7Be} + 78 \quad SNU. \tag{9}$$

The additional contributions from other specifies of neutrinos is less than 10% in the standard solar models [6].

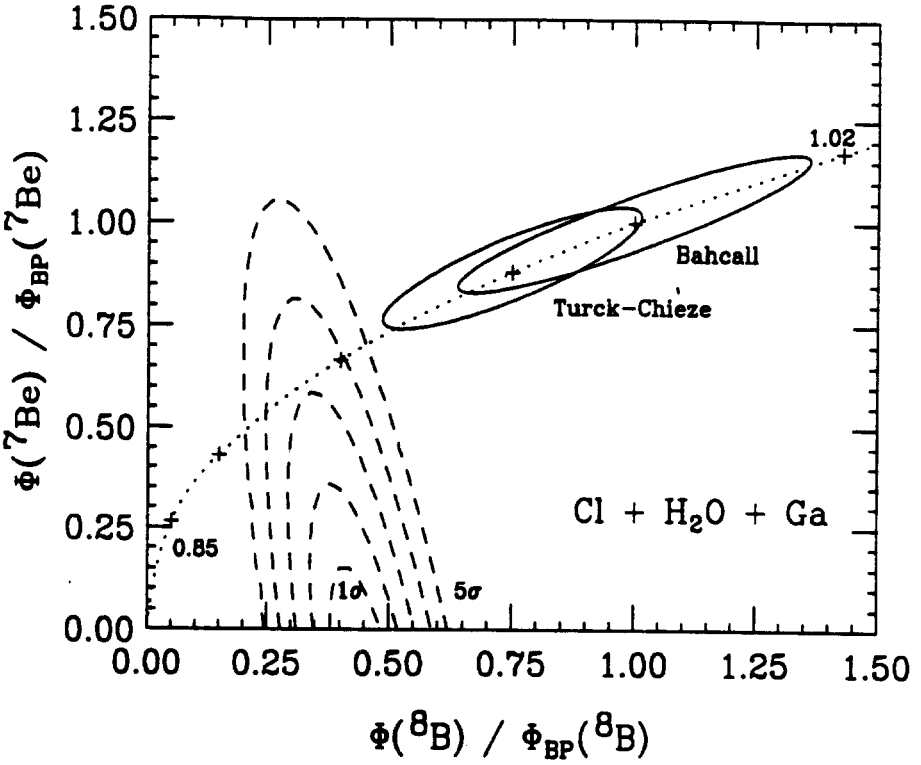

Figure 2: Similar to Fig. 1 but using the latest experimental results from all four solar neutrino experiments.

The experimental results, (1), (2) and (3), are now used to fit the two parameters, $\phi^{^7Be}$ and $\phi^{^8B}$, of the model, eq.(6), (7) and (9). The χ^2 variable was calculated for the four cases; all three results together and the three ways of choosing two out of three. Since the minimum value of χ^2 occurs at negative values of $\phi^{^7Be}$ for all four cases, the constraint

$$\phi^{^7Be} \geq 0 \tag{10}$$

was imposed [7]. Fig. 1 shows the difference in the exclusion using only the Kamiokande and new Gallium (Gallex and SAGE combined) as compared to the previous result from Gallex (83 $\pm$ 21 *SNU*). The total theoretical range for the solar models of Bahcall and Pinsonneault (1992) [5] and Turck-Chièze & Lopes [8] are also shown in this figure by the labelled ellipses. Fig. 2 shows the exclusion using all of the latest solar neutrino experimental results. This argument was first presented by the authors of ref. [9] and updated by the authors of ref. [10].

Bahcall [11] has argued that by using the Kamiokande measurement to determine $\phi^{^8B}$ then the Chlorine experiment puts an upper limit on the $\phi^{^7Be}$ at the 95% C.L. equal to 0.41,

that is,

$$\Phi^{^7Be} \;<\; 2.0 \times 10^9 \; cm^{-2} sec^{-1}. \tag{11}$$

Similarly, he has used the Gallium plus Kamiokande plus Luminosity constraint to show that $\phi^{^7Be} < 0.53$ at 95% C.L. that is,

$$\Phi^{^7Be} \;<\; 2.6 \times 10^9 \; cm^{-2} sec^{-1}. \tag{12}$$

These results suggest that $\phi^{^7Be} < \phi^{^8B}$. Remember however that both the ^7Be and ^8B neutrinos are produced from the same parent in the sun, that is, ^7Be via electron and proton interactions respectively. Also the ^8B neutrinos are more sensitive to changes in the solar core temperature, T_c, than the ^7Be neutrinos, T_c^{18} verses T_c^8 respectively. Therefore it is very difficult to arrange $\phi^{^7Be} < \phi^{^8B} < 1$ in standard solar models.

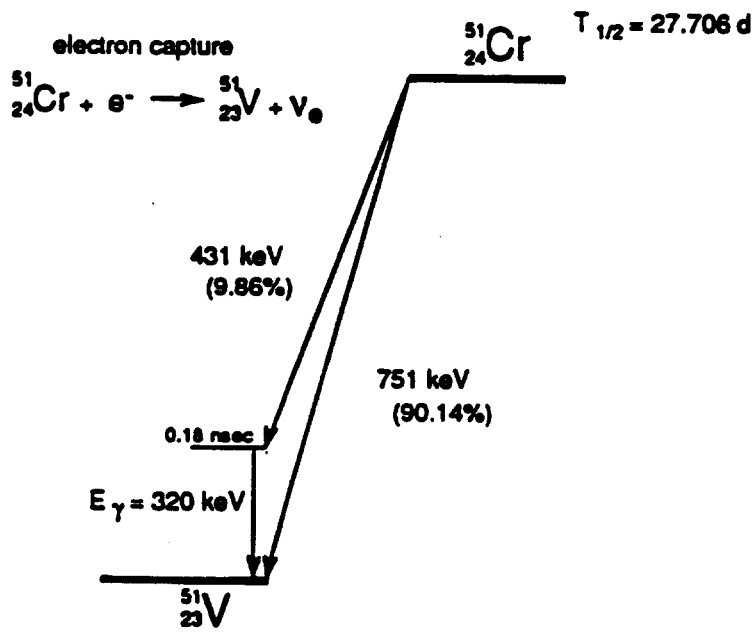

Figure 3: Characteristics of the decay of ^{51}Cr. The "751 keV" line combines the 746 and 751 keV lines and "431 keV" line combines the 426 and 431 keV lines.

Calibration of the Gallium Experiment

From June to October 1994 the Gallex detector [12] was exposed to a 61.9 $\pm$ 1.2 PBq neutrino source which emits neutrinos in electron capture in ^{51}Cr, see Fig. 3. This source

was made by bombarding enriched chromium in a nuclear reactor. The initial source activity produced a flux of neutrinos at the detector which was approximately 15 times the solar neutrino flux. This collaboration used three different methods to measure the initial source strength; neutron flux capture calculation, calorimetry and by measuring the 320 keV gamma ray emitted from small samples. The average of these measurements was used to compare with the strength obtained from observing the neutrino capture in the Gallex detector of $64.1 \pm 6.6 \pm 3.3\ PBq$, see Fig. 4.

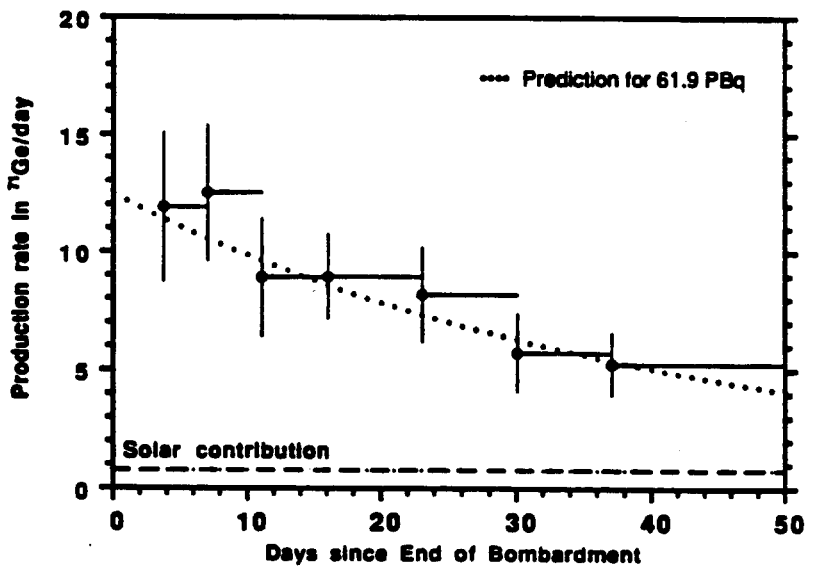

Figure 4: Number of ^{71}Ge atoms produced per day during the course of the source experiment (first 7 runs only). The points for each run are plotted at the beginning of each exposure, with the horizontal lines showing the duration of the exposures. The predicted curve (dotted line), which decreases with the known half-life of ^{51}Cr, is based on the relationship between the directly measured source strength and the 0.189 ^{71}Ge production rate per day. The curve also includes the constant 0.78/day production rate due to solar neutrinos and side reactions (dashed line).

The ratio of the source activity as measured by Gallex to that obtained from the other methods was

$$1.04 \pm 0.12. \tag{13}$$

This result validates the radiochemical methods of the Gallex experiment and since 90% of

the neutrinos from the ^{51}Cr source have an energy close to the energy of the ^{7}Be neutrinos the Gallex experiment is fully efficient at detecting neutrinos of this energy. This is a very important milestone for solar neutrino experiments.

In the autumn of 1995 the ^{50}Cr will be re-irradiated and the calibration will be repeated. SAGE is also performing a calibration test and counting of samples from this test will continue throughout the summer of 1995.

Improved Solar Models

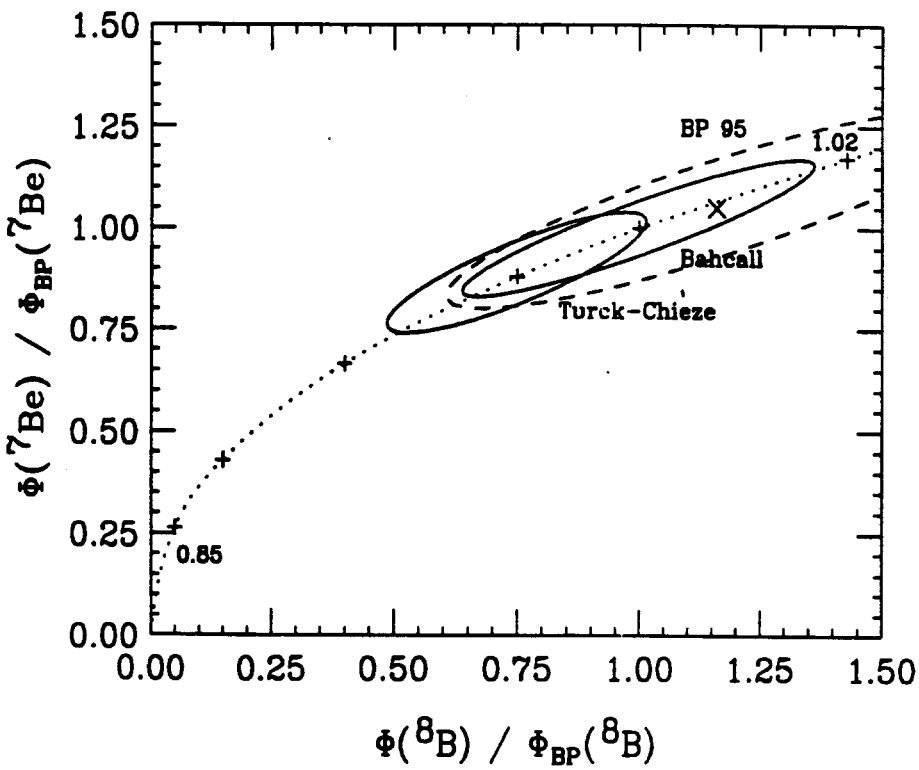

Figure 5: Comparison between the Bahcall & Pinsonneault '95 solar model (dashed ellipse) and solar models of Turck-Chièze & Lopes and Bahcall & Pinsonneault '92 (solid ellipses). The cross in the center of the dashed ellipse is the central value for the BP95 model.

The inclusion of helium and heavy element diffusion has improved the consistency of the solar models by Proffit [13], Kovetz and Shaviv [14] and Bahcall and Pinsonneault [15] with helioseismology. The important parameters are the surface abundance of helium,

$$Y_S = 0.242 \pm 0.003 \tag{14}$$

and the depth of the convective zone,

$$R_{CZ} = 0.713 \pm 0.003\, R_{\odot}. \tag{15}$$

Bahcall and Pinsonneault '95 ('92) models give the surface abundance of helium at 0.247 (0.273) and the fractional depth of the convective zone as 0.712 (0.707) respectively. Clearly the inclusion of diffusion improves the consistency in these parameters.

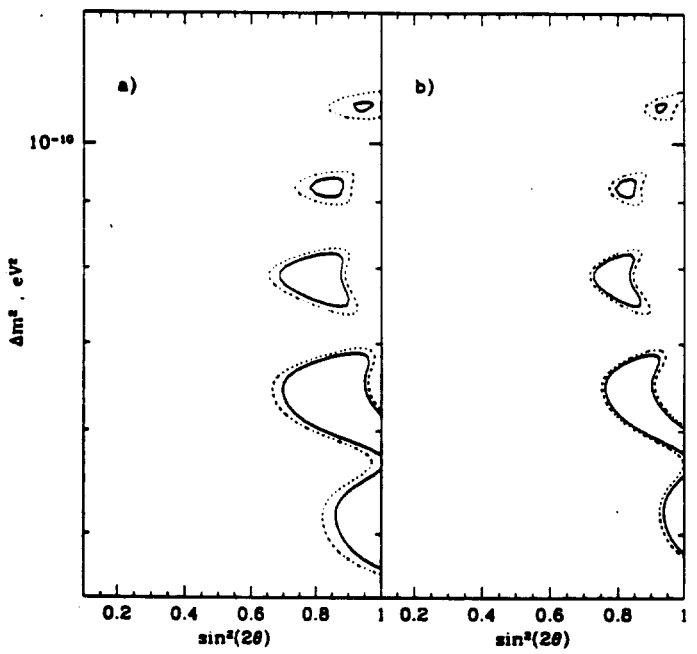

Figure 6: Allowed parameter space for the "Just-so" oscillation solution to the solar neutrino puzzle by Krastev and Petcov. (a) includes and (b) does not include the theoretical uncertainties in the analysis.

However the flux of both ^7Be and ^8B neutrinos increases compared to their '92 model

$$\Phi_{^7Be} = 5.1\,(1 \pm 0.06) \times 10^9\ cm^{-2}s^{-1} \tag{16}$$

$$\Phi_{^8B} = 6.62\,(1 \pm 0.16) \times 10^6\ cm^{-2}s^{-1} \tag{17}$$

This increase in fluxes leads to an increase in the expected Chlorine and Gallium counting rates to 9.3 ± 1.3 SNU and 137 ± 8 SNU as well as an increase in the flux for the Kamiokande experiment. The effect of these increased fluxes on our comparison of theory verses experiment for the solar neutrino flux is shown in Fig. 5. Clearly these new models do not help resolve the discrepancy between the solar models and the solar neutrino experiments.

Neutrino Oscillation Solutions

The latest iso-SNU contour plots by Krastev and Petcov [16] for the "Just So" solution is given in Fig. 6 and for the MSW solution by Hata and Langacker [17] in Fig. 7.

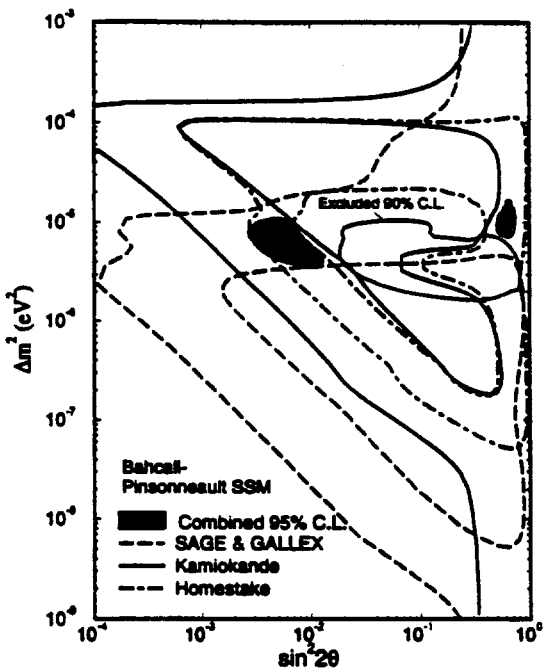

Figure 7: The updated result of the combined MSW analysis assuming the Bahcall-Pinsonneault '92 model, see Hata and Langacker.

Next Generation Experiments

SuperKamiokande is 10 times larger than Kamiokande III with a fiducial volume of 22 ktons and 11,000 20" PMTs. This detector will observe about 10^4 solar neutrino events per year in the neutrino-electron elastic scattering mode,

$$\nu_x + e \rightarrow \nu_x + e \tag{18}$$

and hopes to observe distortions in the solar neutrino energy spectrum after about two years of running, see fig. 8. This mode is primarily sensitive to electron-neutrinos.

As of the time of this conference many of the PMTs had been checked and pre-assembled. The start of installation was expected in June 1995 and completion in March 1996 with physics scheduled for April 1996.

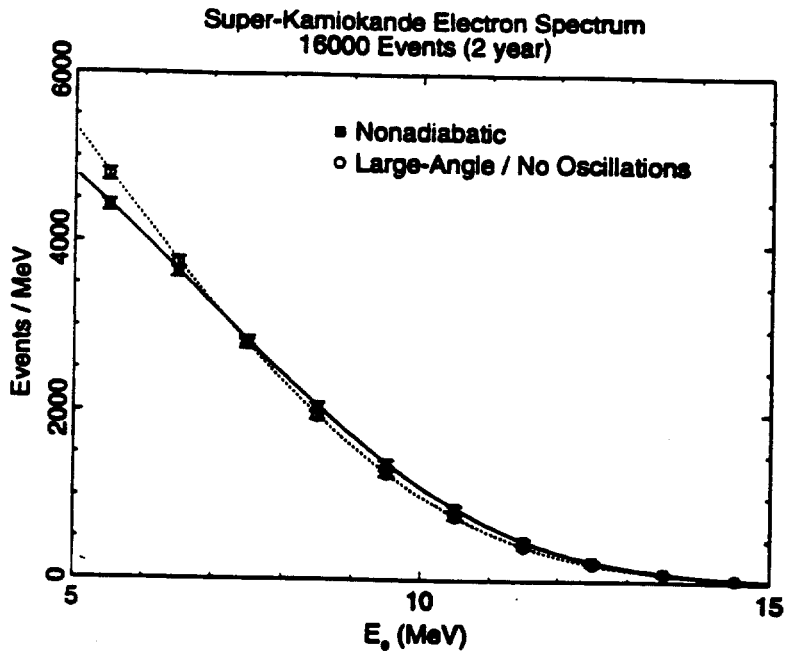

Figure 8: The Super-Kamiokande electron spectrum expected for the adiabatic and large-angle solutions, from Hata and Langacker.

Sudbury Neutrino Observatory consists of 1000 tons of heavy water surrounded by a light water shield. This detector will be able to observe solar neutrinos in three modes,

$$\nu_x + e \rightarrow \nu_x + e \tag{19}$$

$$\nu_e + d \rightarrow e + p + p \tag{20}$$

$$\nu_x + d \rightarrow \nu_x + p + n \tag{21}$$

where x represents e, μ or τ. The expected rates for these reactions is 10^3, 10^4 and 3×10^3 events per year. The second of these modes will be able to measure the solar electron neutrino spectrum, see Fig. 9, whereas the last reaction will measure the total solar neutrino flux regardless of the neutrinos flavor. At the time of this conference construction of this detector was proceeding according to schedule with completion set for spring/summer 1996.

Borexino detector consists of 100 tons of liquid scintillator with a very low threshold 0.25 MeV. Again this detector is sensitive to

$$\nu_x + e \rightarrow \nu_x + e \tag{22}$$

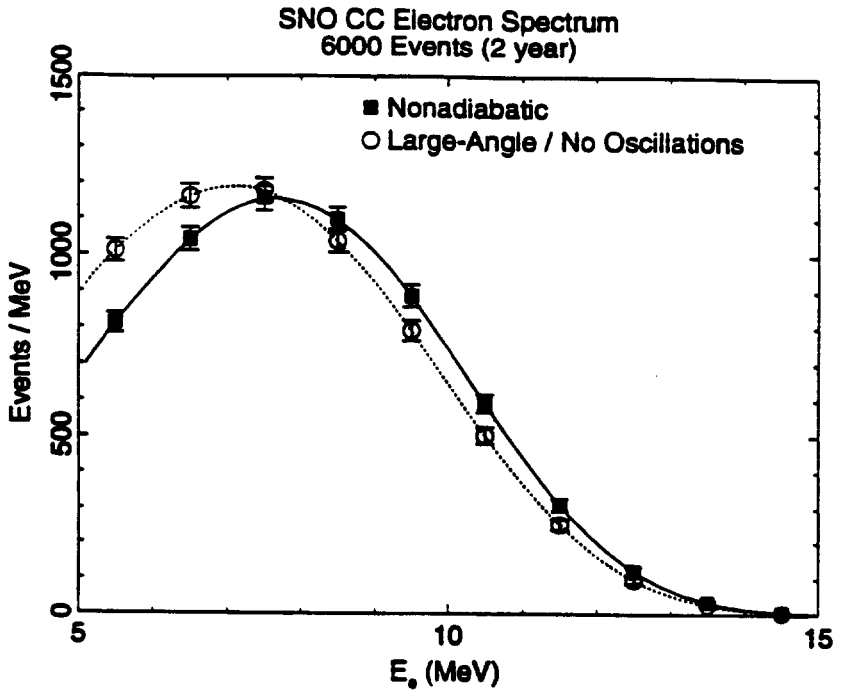

Figure 9: The SNO charged current spectrum expected for the adiabatic and large-angle solutions, from Hata and Langacker.

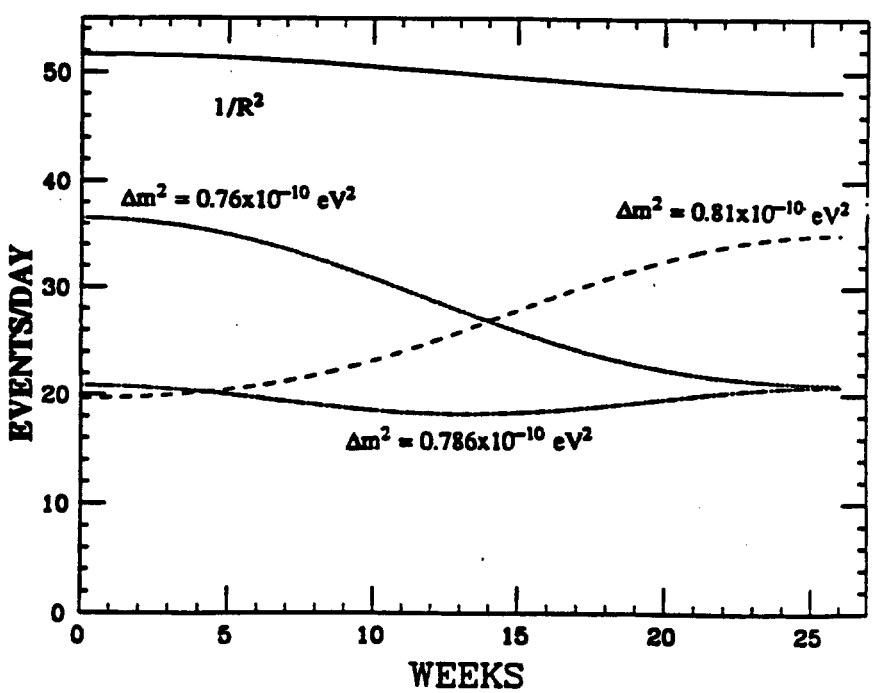

Figure 10: Seasonal variation of the ^7Be signal via "just-so" vacuum oscillations. Shown for comparison is also the $1/R^2$ effect arising from the earth's motion only, from Borexino proposal.

but with such a low threshold this detector will be sensitive to ^7Be neutrinos. If the standard solar model fluxes is correct this detector can expect 20,000 events per year. For the MSW solution to the solar puzzle the rate will be much less. Because of the large event rate this detector will be able to see the $1/R^2$ variation in the solar neutrino flux. Also this detector is very sensitive to neutrino oscillations in the "Just-so" scenario, see Fig. 10. As of May 1995 this collaboration had demonstrated that they can achieve the purity levels required to set a 0.4 MeV threshold in a 6 ton prototype.

Conclusions

The calibration of the Gallex detector is a very important milestone for the field of solar neutrinos giving us confidence in all of the radio-chemical solar neutrino experiments. With the turning on of SuperKamiokande and the Sudbury Neutrino Observatory next year and Borexino a few years later this is an exciting time for the field of solar neutrinos. We will learn whether or not the solar neutrino puzzle is new, exciting neutrino physics or some problem with our understanding of the solar interior. These experiments must resolve this issue as soon as possible.

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