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STATUS OF SOLAR NEUTRINO EXPERIMENTS

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A summary of the status of four solar neutrino experiments is presented. The Homestake ^{37}Cl data are presented and the possible time dependence of the data is addressed. Data from 1040 days of operation of the Kamiokande II detector are presented next. The status of the ^{71}Ga experiment in the Baksan Neutrino Observatory, which has operated for a short time, is discussed. The summary concludes with a discussion of the status of the Sudbury Neutrino Observatory, which has been under construction since the beginning of 1990.

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1. INTRODUCTION

Two decades after the initial experimental attempts to measure neutrinos produced by nuclear fusion reactions in the core of the sun using a ^{37}Cl detector, the field of experimental solar neutrino physics has become lively, with a variety of complementary detectors taking data, commencing data taking, or under construction. The "solar neutrino puzzle," which is the deficit of neutrino interactions observed in the ^{37}Cl detector¹ relative to the number expected from calculations,² has stimulated these experiments. The plausibility that the fundamental properties of neutrinos are responsible for the deficit has increased with the observation that matter induced neutrino flavor transformation³ of ν_e to ν_μ or ν_τ , the Mikheyev-Smirnov-Wolfenstein, or MSW effect, could account for this deficit. The possible time correlation with the solar cycle of the ^{37}Cl data has led

to suggestions⁴ of neutrino magnetic moments which are larger than predicted by the electroweak theory of neutrino interactions, but which are not excluded by experiment. The solar model which leads to the neutrino flux prediction can also be challenged. Modification of the solar model as a resolution of the puzzle may be less exciting than neutrino physics to many attendees of this conference, but is a scientifically compelling motivation for complementary experiments.

The conference presentations summarized below are not a complete summary of work in the field of solar neutrino experiments. The time dependence of the Homestake ^{37}Cl experiment is discussed in the first presentation. The results from the Kamiokande II detector follow. The ^{71}Ga experiments are represented by a status report on the experiment in the Baksan Neutrino Observatory, and the discussion is concluded with a status report on the Sudbury Neutrino Observatory. The interested reader may refer to reference 2 for background information and descriptions of other experiments.

2. TIME DEPENDENCE OF THE SOLAR NEUTRINO FLUX OBSERVED AT HOMESTAKE

The ^{37}Cl solar neutrino experiment has been operating continuously in the Homestake Gold Mine in Lead, South Dakota, U.S.A., for more than twenty years except for a period in 1985 and 1986 when the circulation pumps were not operating. The detector contains 615 tonnes of C_2Cl_4 , in which the natural abundance of ^{37}Cl is 24%. Solar neutrinos are detected through the inverse beta decay of ^{37}Cl to ^{37}Ar , which decays to ^{37}Cl by electron capture with a half life of 35 days. Every thirty to sixty days the Argon atoms are purged from the detector. They are collected in a proportional counter which is sensitive to the electron capture of the ^{37}Ar through the observation of 2.82 keV in Auger electron energy.

The data consist of proportional counter signals which are characterized by the amplitude of the signal, which is proportional to the total energy deposited in the counter, and the rise time of the pulse. The localized energy deposition of the Auger electrons produces a much faster rise time than extended ionization from beta rays and cosmic rays, while electronic noise has a faster rise time than the signal. A two dimensional plot of rise time versus amplitude then isolates the signal region such that the background in the signal region due to processes in the proportional counter is small compared to the signal rate. The principal background in the measurement is due to the interaction of high energy muons in the C_2Cl_4 , and corresponds to an ^{37}Ar production rate of 0.08 ± 0.03 atoms per day relative to an average signal rate of about 0.5 atoms per day. The extraction efficiency of the Argon is measured for each extraction by adding a known volume of ^{36}Ar or ^{38}Ar to the detector.

The ^{37}Ar production rate for each extraction during the period 1970.3 to 1989.4 is displayed in Figure 1. The left ordinate of the figure is ^{37}Ar atoms produced per day and the right ordinate is

Figure 1: The response of the Homestake ^{37}Cl detector since 1970.

Solar Neutrino Units, or SNU ($1 \text{ SNU} = 10^{-36}$ events per target atom per second). The conversion of units is $1 \text{ }^{37}\text{Ar}$ atom per day = 5.35 SNU. Table 1 summarizes the results of the measurements since 1970, and also tabulates the results for the period when both the Homestake and Kamiokande II detectors were operational. The errors quoted in the table are all one standard deviation errors.

The expected counting rate in the ^{37}Cl detector is predicted from "standard" models of stellar evolution which utilize input data on nuclear reaction rates and calculations of solar opacity. Two recent calculations² predict 7.9 ± 2.6 SNU (3σ error) and 5.8 ± 1.3 SNU (1σ error). The two calculations differ primarily in the choice of the solar opacity and in the cross section for the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction. It is evident that the long term result is substantially below the expectation from the calculations.

Table 1. Summary of ^{37}Ar Production Rates
(Atoms/day in 615 tonnes of C_2Cl_4)

Period of Observation	1970.3 - 1989.4	1986.8 - 1989.4
Average ^{37}Ar production rate	0.518 ± 0.036	0.87 ± 0.13
Cosmic ray background	0.08 ± 0.03	0.08 ± 0.03
^{37}Ar above known backgrounds	0.438 ± 0.047	0.79 ± 0.13
^{37}Ar production rate (SNU)	2.33 ± 0.25	4.2 ± 0.7

The data accumulated over the past two decades are consistent with a time independent flux, but a closer look at Figure 1 indicates that the residuals with respect to the average response appear to vary systematically in time. The runs during 1979-1980 and the runs during 1988-89 are systematically lower than the average, while the periods preceding these low runs are systematically higher than the long term average. The time dependence appears to be anti-correlated with the solar sunspot cycle, and correlated with the solar diameter, both of which are measures of solar activity.

Solar neutrinos are created in the fusion reactions in the core of the sun, while solar activity is associated with the outer convective and surface regions of the sun. A time dependence in the solar neutrino flux is therefore suggestive of a particle physics interpretation, of which the magnetic interaction of neutrinos with solar magnetic fields⁴ is the most popular. Because the number of counts per run in the ^{37}Cl experiment is small, verification of a time dependence at the level suggested by this experiment will await the construction of a detector with a counting rate one or two orders of magnitude larger than the existing detector.

3. RESULTS FROM 1040 DAYS OF REAL TIME, DIRECTIONAL SOLAR NEUTRINO DATA

The Kamiokande II collaboration, which has detected solar neutrinos through the observation of recoil electrons from neutrino-electron elastic scattering, has accumulated a real time data sample consisting of 450 days of data with an electron total energy threshold of 9.3 MeV, and 590 days with an energy threshold of 7.5 MeV⁵. The reduced threshold for the more recent data was made possible through improvements in the response of the water Čerenkov detector, and through the reduction of radioactivity induced backgrounds. These data demonstrate unequivocally that ^8B is produced by nuclear fusion in the sun, and allow studies of the absolute flux of ^8B neutrinos from the sun, the energy spectrum of the neutrinos as inferred from the recoil electron energy spectrum, and the time dependence over a three year period when solar activity as manifested by sunspot counts changed by almost one order of magnitude.

Neutrino-electron elastic scattering produces recoil electrons which have a direction in the laboratory which is highly correlated with the direction of the incident neutrino. The angular distribution of electrons with respect to the direction from the sun is shown in Figure 2 for electrons having recoil energy above 9.3 MeV. The distribution of electron directions is comprised of an isotropic background and a peak in the forward direction. The histogram is the solar model prediction for the shape and intensity of the signal distribution after including the effects of detector resolution. The forward peak is clear evidence that the sun is indeed the source of the signal. A complete analysis of the angle and energy distributions of the 450 and the 590 day data

Figure 2: The angular distribution of candidate recoil electrons from neutrino-electron elastic scattering with respect to the direction from the sun. The horizontal line represents a fit to the isotropic background while the histogram represents the expected response using the standard solar model of reference 2. The data show a clear peak in the forward direction, as expected, but the intensity is substantially below the expectation.

Figure 3: The time dependence of the signal observed in the Kamiokande-II detector. The first two data points have an electron total energy threshold of 9.3 MeV, and the last three data points have a threshold of 7.5 MeV.

sets yields for the intensity

$$\text{Data/SSM} = 0.46 \pm 0.05(\text{stat}) \pm 0.06(\text{syst})$$

where "SSM" refers to the standard solar model of Bahcall and Ulrich. The intensity shows a clear deficit relative to the prediction, confirming the existence of a deficit of neutrinos as observed in the ^{37}Cl experiment. It is also interesting to note that the statistical error has reached the level of the systematic error. In Figure 3 the data are divided into five subsamples of approximately 200 days each. The data show no statistically significant time dependence over a three year interval during which the sunspot number, a measure of solar activity, changed from approximately 25 to 180.

Analysis of these data with respect to the MSW effect has two components⁶. The average flux, relative to a calculated prediction, results in an allowed triangular region in $(\Delta m^2, \sin^2 2\theta)$ space, where the analysis assumes two flavor mixing. This triangle of acceptable parameters can stretch slightly if a different solar model prediction is employed. Independent of the absolute flux predicted by a solar model, the horizontal or "adiabatic" side of the triangle corresponds to a suppression of high energy ν_e . Since the Kamiokande detector measures the recoil electrons from neutrinos in this region, the *shape* of the electron energy distribution can be used to exclude much of the upper side of the triangle. This is shown in Figure 4, in which the allowed regions of the mass and mixing space are shown at the 68% (hatched area), 90% (solid line), and 95% (dashed line) confidence level. Consistency between the average response of the ^{37}Cl detector and the Kamiokande detector is only possible in the diagonal and vertical regions of the triangle.

4. THE SOVIET-AMERICAN GALLIUM EXPERIMENT

The only feasible detection of the abundant pp neutrinos, which have an energy spectrum endpoint of 0.424 MeV, is through the inverse beta decay of ^{71}Ga . A Soviet-American collaboration has been operating 30 tons of an eventual 60 ton ^{71}Ga detector in the Baksan Neutrino Observatory in the Soviet Caucasus since the beginning of January, 1990. The experiment uses a radiochemical technique to extract the ^{71}Ge from liquid metallic gallium.⁷

Preliminary results from four one month exposures of the 30 tons of gallium are shown in Figure 5. In this figure the counts accumulated at each day from the start of counting for each extraction are added together. In the absence of background, the response curve should show counts accumulating as an exponential decrease in the counting rate characterized by the 11.4 day half life of ^{71}Ge . Background counts are randomly distributed, and accumulate as a straight line with slope determined by the background counting rate. These two extremes, the rate predicted by the solar model with no background, and all background, are indicated by the two smooth curves in the figure. The total counting rate observed should be the sum of the signal plus background. The

Figure 4: The region of $(\Delta m^2, \sin^2 2\theta)$ allowed by the Kamiokande data alone, using the solar model of reference 2 for the expected value. A large region of the horizontal, or adiabatic region is excluded by the agreement of the shape of the background subtracted signal relative to the expected shape.

Figure 5: The response of the Baksan ^{71}Ga detector. The plot shows the accumulated counts as a function of counting time in the proportional counters for four runs. A constant background in the counters produces a linearly rising total number of counts as a function of time, as represented by the dot-dashed line in the figure. If there were no background, the response would be an inverse exponential with the 11.4 day half life of ^{71}Ge , as represented by the dashed line in the figure.

data are indicated by the cumulative distribution histogram, which shows no evidence of a signal above the background.

The standard solar model predicts a counting rate of 132 SNU for the ^{71}Ge experiment. Four one month exposures should have produced a total of 14 signal counts in the first 30 days of counting, while the best fit to the data is zero signal with the 68% and 95% confidence levels being 72 and 138 SNU, respectively, provided the ratio of the ^{71}Ge extraction efficiency to the natural Ge extraction efficiency is 1.00. A smaller ratio corresponds to weaker statements about the statistical sensitivity of the experiment. Although this ratio must be verified experimentally, preliminary experimental and theoretical work indicates there is no reason it should differ from 1.00. Future plans call for continuing studies of the extraction efficiency, calibration using a ^{51}Cr neutrino source, and implementation of the full 60 tons of gallium available to the experiment.

5. STATUS OF THE SUDBURY NEUTRINO OBSERVATORY

The Sudbury Neutrino Observatory (SNO) is the newest solar neutrino project to begin construction. It exploits the Canadian D_2O reserve and the availability of a deep mine owned by INCO, Ltd., near Sudbury, Ontario. One thousand tonnes of D_2O are used as a target for the reactions

$$\nu_e + e^- \rightarrow \nu_e + e^-, \quad \nu_e + d \rightarrow p + p + e^-, \quad \nu_x + d \rightarrow \nu_x + p + n$$

The neutrino electron elastic scattering is the reaction measured in the H_2O Kamiokande detector. The inverse beta decay reaction occurs only for the flavor ν_e , and, because the electron carries the energy of the neutrino, less the threshold energy, measures the spectrum of the ν_e . The third reaction, neutrino disintegration of the deuteron, occurs for all flavors of neutrino. Comparison of the rates of these last two reactions is a direct test of neutrino flavor transformation.

The detector is located at a depth of 2070 m, rendering cosmic ray induced backgrounds insignificant. The detector is shielded from the cavity walls by pure H_2O , as indicated in Figure 6. It is viewed by 20 cm photomultiplier tubes with good time resolution, and light concentrators which increase the light collected by the individual PMTs by a factor of 1.7. The detector materials are selected for low radioactivity to minimize background events. The acrylic vessel which contains the D_2O , the surrounding H_2O , and the D_2O itself must be very pure in order to minimize deuteron photo-disintegration by the 2.4 and 2.6 MeV gamma rays from the decay of ^{214}Bi and ^{208}Tl . Neutrons produced by this reaction are backgrounds for the flavor independent neutrino disintegration of the deuteron. Present studies show that these backgrounds are controllable.

The counting rate in the SNO detector is large compared to the current generation of detectors.

Figure 6: Line drawing of the Sudbury Neutrino Observatory detector. The cavity is at a depth of 2070 meters. It is 22 meters at the waist and 33 meters high. The target is 1000 tonnes of D_2O contained in an acrylic vessel. It is shielded by 7300 tonnes of pure H_2O , and is viewed by approximately 9000 photomultiplier tubes.

The reactions $\nu_e + d \rightarrow p + p + e^-$ and $\nu_\mu + d \rightarrow \nu_\mu + p + n$ should each give rise to about ten observed events each day. This high counting rate will be very sensitive to the time dependence observed in the ^{37}Cl experiment. If neutrinos change their flavor between their origin in the sun and their detection on earth, the SNO experiment will demonstrate flavor transformation conclusively. It is expected that data taking will begin in early 1995.

6. DISCUSSION AND CONCLUSIONS

The long standing solar neutrino problem first observed in the ^{37}Cl detector has been confirmed by the Kamiokande experiment. The possible time dependence of the signal from the ^{37}Cl detector is not confirmed by the Kamiokande detector. Preliminary results from the Soviet-American gallium experiment are very exciting. Should more data from this experiment and from the GALLEX ^{71}Ga experiment in the Gran Sasso Laboratory measure a flux substantially lower than that predicted by the standard solar model, the first confirmed indication of neutrino flavor transformation, and hence, non-zero neutrino mass will have been made. The SNO experiment is sensitive to the flavor transformed neutrinos, and will be the highest rate experiment of those presently operating or under construction. The 1990's should be an exciting time for neutrino physics.

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