

# SOLAR NEUTRINO EXPERIMENTS: AN OVERVIEW

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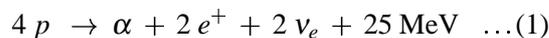
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This article describes the seven experiments Homestake, Kamiokande, SAGE, GALLEX, Super-Kamiokande, GNO and SNO which have so far provided data on the measurement of the solar neutrino fluxes. The detection mechanism, the salient features of the detectors and the results of each experiment are presented. How the solar neutrino problem has evolved and become more focused with each experiment is summarized. The goals for the future experiments are outlined.

**Key Words:** Standard Solar Model; Homestake; Gallium and Super-K Experiments; SNO and the Neutral Current Detection.

## 1 Introduction and History

The Sun is a copious source of electron neutrinos, produced in the thermonuclear reactions that generate solar energy. The underlying nuclear process is:



About 97-98% of the total energy released in the above process is in the form of heat and light. The rest 2-3% is carried away by the neutrinos. The photons get scattered and re-scattered by interaction with solar matter and an average photon takes about  $10^4$  years to come out. Neutrinos are weakly interacting and it takes about 8 minutes for them to reach Earth from the Sun. Thus neutrinos carry information about the Sun's interior. However this very fact that the neutrinos are weakly interacting makes it a difficult task to detect them and the typical requirements are large detector volume, high detection sensitivity and low background environments. Solar neutrinos were first detected in 1968 by the pioneering  $^{37}\text{Cl}$  experiment of Raymond Davis in the Homestake gold mine in Lead, South Dakota<sup>1</sup>. The main motivation was to test the hypothesis of the nuclear energy generation in stars. However when the results were reported the observed flux was found to be less than the theoretical prediction. This was the beginning of the solar neutrino problem. It was also the first experimental signature of the neutrino oscillation phenomena conjectured by Pontecorvo in 1957

and by Maki, Nakagawa and Sakata in 1962<sup>2</sup>. In fact before the results from the  $^{37}\text{Cl}$  experiment came Pontecorvo predicted that if solar neutrinos undergo a change of flavour then the observed fluxes can be less than the theoretical expectations. For almost two decades  $^{37}\text{Cl}$  was the only experiment measuring the solar neutrino flux. Next to join this pursuit was the Kamiokande neutrino-electron scattering experiment which not only confirmed the deficit problem, but also verified that the captured neutrinos are indeed of solar origin<sup>3</sup>. A further affirmation of the solar neutrino shortfall came from the radiochemical  $^{71}\text{Ga}$  experiments of the GALLEX<sup>4</sup> and the SAGE<sup>5</sup> collaborations. The triumph of the Ga-experiments lies in the detection of the primary  $pp$  neutrinos thereby checking the basic hypothesis of stellar energy generation. With all these experiments confirming the solar neutrino problem it was realised that the solar neutrinos can be used as an important tool to study neutrino properties and solar neutrino research entered a new era of high statistics precision experiments. Super-Kamiokande, the upgraded version of the Kamiokande experiment, started operation in 1996 and declared its first results in 1998<sup>6</sup>. It not only confirmed the solar neutrino deficit but it had enough statistics to divide the events into energy and zenith angle bins enabling one to study the incident neutrino spectrum shape and the presence of any difference in the observed rate at day and at night. The recent results on this have come from the Sudbury Neutrino

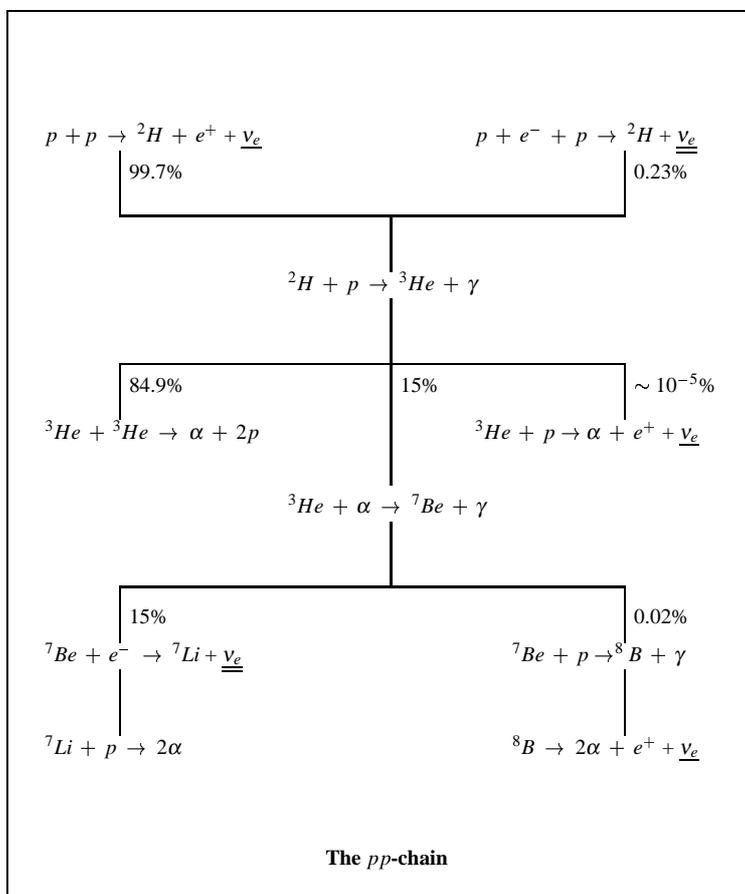


Fig. 1 The reactions of the  $pp$ -chain. The probability of a particular reaction is shown as a percentage. The neutrinos are shown underlined. Those with double underlines are mono energetic.

Observatory in Canada which furnished direct evidence in favour of neutrino flavour transitions<sup>7</sup>. It also confirmed that the total flux of the solar neutrinos, coming from  ${}^8B$  decay, is in close agreement with the theoretical predictions from solar model calculations<sup>8,9</sup>. Finally on December 6, 2002 the solar neutrino problem came back a full circle with the reactor based experiment KamLAND in Japan providing terrestrial evidence in favour of the Large Mixing Angle (LMA) solution based on the Mikheyev-Smirnov-Wolfenstein effect<sup>10</sup> to this<sup>11</sup>.

In the next section we discuss the production mechanism of neutrinos in the Sun and the fluxes of these according to Standard Solar Model (SSM) calculations. In section 3 we describe the seven solar neutrino experiments which have so far measured the solar neutrino fluxes. In section 4 we discuss the solar neutrino problem and how it has evolved as more and more data became available. We also briefly comment

on the neutrino oscillation solution to the solar neutrino problem. Finally we discuss the future experiments.

## 2 Solar Neutrinos And The Standard Solar Model

The main reaction for production of solar neutrinos is given by eq. 1. The reaction is the effective process driven by a cycle of reactions (*e.g.* the  $pp$ -chain or the CNO cycle). The dominant set of reactions – the  $pp$ -chain – is depicted in Fig.1. These stellar thermonuclear fusion reactions, first understood by Bethe in 1939, form the basis for the present solar models. The algorithm of an SSM is to evolve a one  $M_{\odot}$  homogeneous cloud of hydrogen, helium and a small fraction of heavier elements from about 4.6 billion years ago to match the current luminosity and solar radius. These models are based on standard

thermodynamics and nuclear physics and assume that nothing happens to the neutrinos once they are produced in the solar interior. The input parameters are the initial heavy element abundance, radiative opacities, nuclear reaction rates, solar age, solar luminosity etc. The predictions are the temperature, density and composition profiles of the Sun and the solar neutrino fluxes. The most widely used solar model for neutrino flux calculations is the standard solar model (SSM) developed by Bahcall and his collaborators<sup>12-14</sup>. However there are a number of solar model calculations by different groups<sup>15</sup>. All these show a remarkable agreement (to within or better than 10%) between the predicted neutrino fluxes, if the same input parameters are employed. The solar model calculations are also in excellent agreement with helioseismological observations<sup>14</sup>.

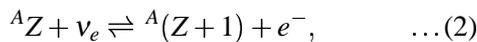
Fig.2 shows the solar neutrino spectrum from ref[16]. The SSM prediction of the pp(<sup>8</sup>B) solar neutrino fluxes are least (most) uncertain. These uncertainties are associated with the input parameters and considerable effort is directed towards reducing the margin of these uncertainties.

### 3 Solar Neutrino Experiments

The present solar neutrino detectors are of two types<sup>a</sup>

- (i) Radiochemical detectors
- (ii) Čerenkov detectors

In radiochemical experiments one employs a nuclear reaction of the form



where A denotes the mass number and Z denotes the proton number of the nuclei. The Q value of the reaction determines the threshold neutrino energy for the detector. The target is exposed to the Sun for a certain period of time after which the product is extracted using radiochemical techniques and counted by electron capture decays of the product nucleus. Thus it is not possible to determine the neutrino energy and direction. The experimentally challenging concept involved in this technique was the chemical separation of a small number of product nuclei from a large mass

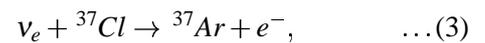
of target atom and the past and present radiochemical experiments have unequivocally demonstrated the validity of this procedure. The main systematic uncertainties involved in radiochemical experiments are due to extraction efficiency, counting efficiency and background.

In a Čerenkov detector on the other hand the charged leptons produced from neutrino interactions produce Čerenkov light while passing through the detector. This is recorded by photomultiplier tubes which produce an electrical pulse that is registered by the data acquisition electronics. Since the signal to noise ratio is very small at lower energies such a detector usually has higher threshold energies. But it has important advantages

- (i) it is a detector in real time;
- (ii) it gives directional information because the Čerenkov light allows a reconstruction of the incoming neutrino track;
- (iii) the recoil electron energy distribution gives information about the incident neutrino energy spectrum.

#### Radiochemical Detectors

**The Homestake Experiment:** The reaction involved in the detection is



which has a threshold of 0.814 MeV and is sensitive to the <sup>8</sup>B and <sup>7</sup>Be neutrinos. This method was first suggested by Pontecorvo in 1946 and independently by L. Alvarez in 1949. In 1959 it was realised that the measured <sup>3</sup>He(<sup>3</sup>He, 2p)<sup>4</sup>He cross-section is more than expected on the basis of theoretical calculations<sup>18</sup>. This signified that the pp chain does not terminate with the reaction <sup>3</sup>He(<sup>3</sup>He, 2p)<sup>4</sup>He but continues further resulting in the production of <sup>7</sup>Be and <sup>8</sup>B neutrinos as shown in Fig.1. Both of these have energies above 0.814 MeV, the threshold for reaction 3. This encouraged Raymond Davis to construct the first detector for solar neutrinos in the Homestake gold mine in South Dakota using <sup>37</sup>Cl in the form of perchloroethylene (C<sub>2</sub>Cl<sub>4</sub>). The plus points were the following

- (i) C<sub>2</sub>Cl<sub>4</sub>, a liquid at room temperature, was inexpensive and easily available;

<sup>a</sup> For a discussion on other type of detectors like cryogenic and bolometric detectors and geochemical solar neutrino experiments see ref.[17].

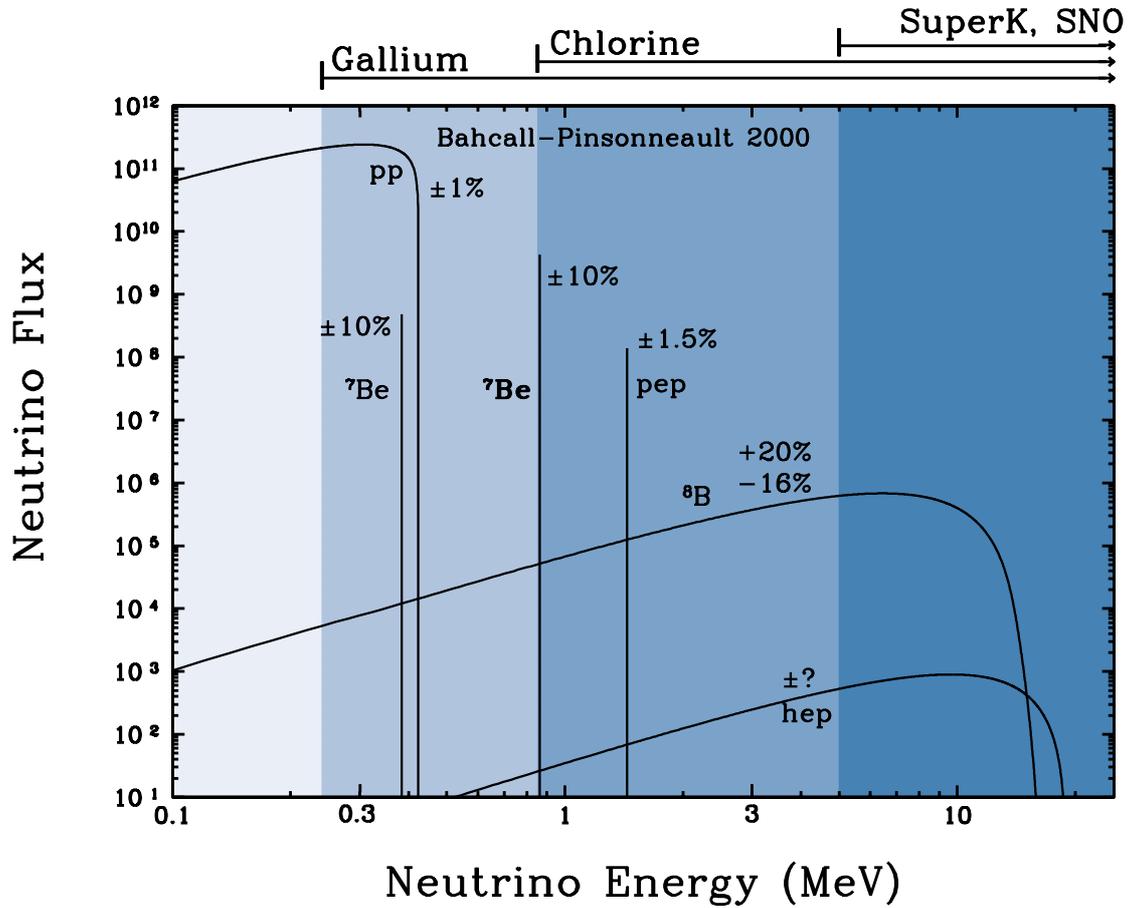


Fig. 2 Solar neutrino spectrum in the standard solar model as a function of neutrino energy. The continuous spectra are in units of  $\text{cm}^{-2}\text{MeV}^{-1}\text{s}^{-1}$ , while the mono-energetic lines are in  $\text{cm}^{-2}\text{s}^{-1}$ . Figure shows the  $\pm 1\sigma$  uncertainties in the model predictions of the various fluxes. Also shown are the energy ranges over which the solar neutrino experiments are sensitive<sup>16</sup>.

- (ii) the daughter nucleus  $^{37}\text{Ar}$  being an inert gas could be extracted easily;
- (iii) the transition of the  $^{37}\text{Cl}$  to the isobaric analogue state in  $^{37}\text{Ar}$  for energies greater than 5.8 MeV enhances the neutrino capture cross-section considerably making this process particularly suitable for studying the high energy  $^8\text{B}$  spectrum<sup>19</sup>.

The detector consists of a cylindrical tank 6.1 m in diameter and 14.6 m long. About 95% of the detector volume is filled with 615 tons of perchloroethylene. The underground location of 4200 m below the surface cuts down the production of  $^{37}\text{Ar}$  in the detector due to cosmic rays. The  $^{37}\text{Ar}$  produced is separated chemically from the  $\text{C}_2\text{Cl}_4$ , purified and counted in low background proportional counters. The counting depends upon observing the 2.82 KeV Auger electrons from the  $e^-$  capture decay of  $^{37}\text{Ar}$  (half life = 35 days).

The Homestake detector started operating from

1968 and has reported data taken in 108 runs over the period 1970-1994. The third column of Table I shows the predictions<sup>14</sup> for the neutrino capture rates in the Cl experiment for the different neutrino sources. Also shown for the Cl detector are the total predicted rate and the  $\pm 1\sigma$  uncertainties in the model calculations. The numbers quoted are in a convenient unit called SNU, defined as  $1 \text{ SNU} = 10^{-36} \text{ events/target atom/second}$ . The observed rate of solar neutrinos in the experiment is<sup>20</sup>  $2.56 \pm 0.16(\text{stat}) \pm 0.16(\text{syst}) \text{ SNU}$ . Compared to the prediction of Table I, this gives a ratio of observed to expected SSM rate of  $0.335 \pm 0.029$  implying a deficit in the solar neutrino flux. No significant time variation was reported by the data. The sources of systematic uncertainties are extraction efficiency, counting efficiency, neutrino production due to non-solar sources, event selection and variation in the half-life of the decaying background component resulting in a systematic uncertainty of  $\sim 7\%$  in a single run<sup>20</sup>. Since very

**Table I**

The predictions for the solar neutrinos fluxes and neutrino capture rates in the Cl and Ga detectors from<sup>14</sup>. The expected <sup>8</sup>B flux is  $5.05 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ .

source	Flux ( $10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ )	Cl (SNU)	Ga (SNU)
<i>pp</i>	$5.95(1.00^{+0.01}_{-0.01})$	0.0	69.7
<i>pep</i>	$1.40 \times 10^{-2}(1.00^{+0.015}_{-0.015})$	0.22	2.8
<i>hep</i>	$9.3 \times 10^{-7}$	0.04	0.1
<sup>7</sup> <i>Be</i>	$4.77 \times 10^{-1}(1.00^{+0.10}_{-0.10})$	1.15	34.2
<sup>8</sup> <i>B</i>	$5.05 \times 10^{-4}(1.00^{+0.20}_{-0.16})$	5.76	12.1
<sup>13</sup> <i>N</i>	$5.48 \times 10^{-2}(1.00^{+0.21}_{-0.17})$	0.09	3.4
<sup>15</sup> <i>O</i>	$4.80 \times 10^{-2}(1.00^{+0.25}_{-0.19})$	0.33	5.5
<sup>17</sup> <i>F</i>	$5.63 \times 10^{-4}(1.00^{+0.25}_{-0.25})$	0.0	0.1
Total		$7.6^{+1.3}_{-1.1}$	$128^{+9}_{-7}$

few <sup>37</sup>Ar atoms are produced in each run the statistical uncertainty is 30-50%. However the cumulative statistical uncertainty for the total 108 runs is comparable to the systematic uncertainty. The main uncertainty in the theoretical prediction is due to the uncertainties associated with the <sup>8</sup>B flux calculation.

**The <sup>71</sup>Ga Experiments:** There are three experiments SAGE, GALLEX and GNO which employ the following reaction (suggested first by Kouzmine in 1965):



This reaction has a low threshold of 0.233 MeV and the detectors are sensitive to the basic *pp* neutrinos. Since the *pp*-chain is mainly responsible for the heat and light generation in the Sun, detection of these neutrinos constitutes an important step towards confirming the accepted ideas of solar energy synthesis. Also the predicted flux is relatively free of the astrophysical uncertainties. The SSM prediction for this according to ref. [14] is  $128^{+9}_{-7}$  SNU. In Table I we present the contribution of each of the sources as well as the total rate according to ref.[14].

#### Soviet American Gallium Experiment( SAGE)

The SAGE experiment in the deep underground Baksan Neutrino Observatory has been measuring the solar neutrino capture rate since 1990 and it is still continuing to take data. It uses 50 tons of metallic Ga in liquid form as the target. This is contained in seven chemical reactors. The advantage of the metallic target is its low sensitivity to radioactivity compared to

any other form. The <sup>71</sup>Ge produced is separated by stirring vigorously with a mixture of hydrogen peroxide and dilute hydrochloric acid. The Ge is extracted as GeCl<sub>4</sub> which is subsequently converted to GeH<sub>4</sub> by sodium borohydride. The counting is done in a proportional counter by observing the Auger electrons and X-rays emitted in the <sup>71</sup>Ge electron capture decay producing an L peak at 1.2 KeV and K peak at 10.4 KeV. Data of 92 runs during the period from January 1990 to December 2001 gives a solar neutrino capture rate of<sup>21</sup>  $70.8^{+5.3}_{-5.2}$  (stat)  $^{+5}_{-7}$  (syst) SNU. SAGE has performed a calibration test with a  $\sim 0.5$  MCi <sup>51</sup>Cr source. This gave results consistent with expectations demonstrating that there are no unknown experimental errors that can count for the observed deficit.

#### GALLEX

The GALLEX experiment is located in the Gran Sasso underground laboratory in Italy. The detector consists of 30 tons of Ga in the form of GaCl<sub>3</sub> – HCl solution. Ge is produced in the form of volatile GeCl<sub>4</sub>. After an exposure of about three weeks the GeCl<sub>4</sub> formed is extracted by bubbling nitrogen through the solution and then passing through two gas scrubbers where the GeCl<sub>4</sub> is absorbed in water. This is finally converted to the counting gas GeH<sub>4</sub> (germane). The counting is done as in SAGE. The chemical form of Ga used in GALLEX is advantageous for the extraction of the product.

GALLEX has taken data during the period May 1991 to January 1997 and the combined result of a total of 65 runs is  $77.5 \pm^{+7.6}_{-7.8}$  SNU, where the statistical and systematic errors are combined in quadrature<sup>22</sup>. GALLEX has performed an overall calibration of their detector using the two neutrino lines at 746 KeV (90%) and 426 KeV (10%) of a <sup>51</sup>Cr source. Following the same extraction and counting procedures as in the solar neutrino runs, the ratio of measured <sup>71</sup>Ge to the expected value obtained is  $R = 1.04 \pm 0.12$ , viz. in good agreement with the expectations.

#### Gallium Neutrino Observatory (GNO)

GNO is the upgraded version of GALLEX. The target and extraction procedure used in this experiment is the same as GALLEX but the counting system was modified resulting in an improvement in the signal to background ratio. This is taking data since 1998. From a total of 35 solar runs GNO reports an observed

rate of  $67.7 \pm 7.2(\text{stat}) \pm 3.2(\text{syst}) \text{ SNU}^{23}$ . GNO is still continuing to take data. The future goals are

- (i) to reduce the systematic error at 3% level;
- (ii) to use a more sophisticated analysis based on neural networks to re-analyze the data;
- (iii) to improve the knowledge of the  $\nu_e$  capture cross section of  $^{71}\text{Ga}$  to better than 5% using a  $> 2.5 \text{ MCi}$  Cr source.

### *Čerenkov Detectors*

**The Kamiokande Experiment:** The Kamiokande (Kamioka Nucleon Decay Experiment) experiment<sup>24</sup> was started in 1983 to look for proton decay. In 1985 it was renovated for the solar neutrino research to test the anomaly observed by the  $^{37}\text{Cl}$  experiment by direct detection techniques. The Kamiokande detector, located in a deep mine at Kamioka, Japan, uses 4500 tons of pure water of which the inner 2140 tons was employed as the fiducial volume for solar neutrino observations. Both the outer and the inner walls of the cylindrical detector are lined with Photomultiplier tubes (PMT). These detect the Čerenkov light emitted by electrons which are scattered in the forward direction by solar neutrinos

$$\nu_e + e \rightarrow \nu_e + e. \quad \dots(5)$$

Unlike eq. (3), neutrinos and antineutrinos of all flavours can contribute to the above. The  $\nu_\mu$  and  $\nu_\tau$  react *via* the neutral current which is suppressed by a factor of 1/6 compared to the  $\nu_e$  interaction which can be mediated by both charged and neutral currents. The recoil electron energy threshold in Kamiokande is 7.5 MeV. Thus it can sample only the  $^8\text{B}$  neutrinos. Using the timing information and the ring pattern of the hit PMTs the vertex position and the direction of the recoil electrons are reconstructed. These can be used to provide information on the incoming neutrino direction. Kamiokande found an excess of events peaking in the direction of the Sun and thus verified for the first time that the captured neutrinos originate from the Sun. The observed rate<sup>24</sup> is  $2.82 \pm 0.19(\text{stat}) \pm 0.33(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$  while the theoretical prediction according to<sup>14</sup> is  $5.05 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ . The recoil spectrum measured by Kamiokande is consistent with the solar  $^8\text{B}$  neutrino spectrum, with an overall reduction in flux.

**SuperKamiokande:** Super-Kamiokande is an upgraded version of Kamiokande with the detector volume increased to 50 ktons of which the fiducial volume is

22.5 kilotons. It is viewed by approximately 13,000 PMTs. It has collected data for the period between May 31, 1996 to 15 July 2001 (1496 days). In July 2001 data taking was stopped for detector upgrade. In November 2001 there was an accident in the SK detector which destroyed 6777 inner and 1110 outer photomultiplier tubes respectively. Partial reconstruction of the detector has been achieved till date. During the 1496 effective days SK has observed  $22400 \pm 800$  solar neutrino events. The total observed rate in SK is<sup>25</sup>  $2.35 \pm 0.02 (\text{stat}) \pm 0.08 (\text{syst}) \times 10^6/\text{cm}^2/\text{sec}$  which is almost half the prediction of the SSM ref.[14]. The threshold energy for recoil electrons in SK was 6.5 MeV to start with and then it was brought down to 5.0 MeV.

SK has sufficient statistics to divide both the day time and night time observed events into recoil electron energy bins. Such a precision measurement would require an accurate calibration of the energy scale which is performed using an electron linear accelerator. Fig. 3 plots data/SSM as a function of the recoil electron energy. The plot does not reveal any significant spectral distortion. The correlated systematic uncertainties shown by gray lines are due to the calculation of the  $^8\text{B}$  neutrino spectrum, the absolute energy calibration and the energy resolution. Fig.3 also shows the the day/night asymmetry as a function of energy. This asymmetry is seen to be consistent with zero at all energies.

In order to study the spectral distortion and the day-night variation of the solar neutrino flux in greater details, the SK collaboration have divided their data into eight energy bins and seven solar zenith angle bins<sup>25</sup>. The data shows no significant distortion of the  $^8\text{B}$  spectrum with solar zenith angle variation. This binning helps to study the energy dependence of the suppression rate as well as the predicted day night asymmetry together in the most efficient manner. Apart from the zenith angle dependence SK has also reported the seasonal variation of the solar flux. The data is consistent with the expected annual variation due to orbital eccentricity of the Earth.

**The Sudbury Neutrino Observatory (SNO):** SNO is an imaging Čerenkov heavy water detector containing 1 kton of pure  $\text{D}_2\text{O}$ . It is located at a depth of 2092m (6010m water equivalent) in Creighton mine near Sudbury, Ontario, Canada. The heavy water is contained in an acrylic vessel 12m in diameter and thickness 5.5 cm. A geodesic support structure mounted

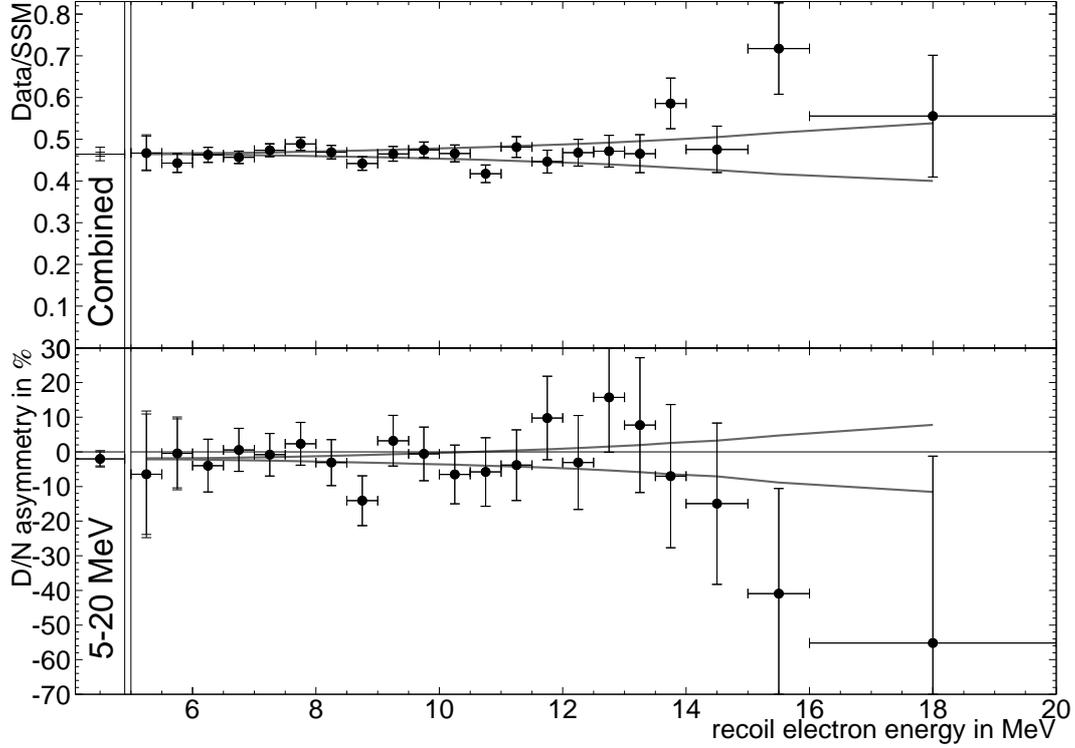


Fig. 3 Super K recoil energy spectra along with the  $\pm 1\sigma$  error bars for 1496 day data. Also shown is the variation of the day/night asymmetry with energy<sup>25</sup>.

with an array of 9456 photomultiplier tubes surrounds the acrylic vessel. The detector is immersed in 7 kton of ultra-pure  $H_2O$  within a barrel shaped cavity.

The deuterium in the heavy water enables the detection of all three types of neutrinos. There are three main detection processes

$$\nu_e + d \rightarrow p + p + e^- \quad (CC) \quad \dots(6)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES) \quad \dots(7)$$

$$\nu_x + d \rightarrow n + p + \nu_x \quad (NC) \quad \dots(8)$$

The ES reaction is the same as used by SK. Its great advantage is the strong directional correlation with the Sun. For the CC reaction the energy of the recoil electron is strongly correlated with the incident neutrino energy and thus can provide information on the  $^8B$  energy spectrum. It also has an angular correlation with the Sun which goes as  $1 - 0.34 \cos \theta_\odot$ . It has a much larger cross section than the ES reaction and can produce more statistics. Both the ES and the CC reaction are detected by the Čerenkov light produced by the recoil electron. The threshold kinetic energy of the recoil electron is 5 MeV for SNO ES and CC. For the NC reaction the threshold neutrino energy is 2.2 MeV, the binding energy of the deuteron.

The produced neutron is thermalised and can be captured by another nucleus. This nucleus emits a gamma ray which Compton scatters electrons which are observed through Čerenkov radiation. The detection efficiency depends on the neutron capture efficiency. Neutrons can be captured directly on deuteron to give tritium and a 6.25 MeV gamma which carries the tritium binding energy. But this process is not very efficient with a capture efficiency of 29.9%. The neutron capture efficiency can be increased to about 83% by adding salt (NaCl) in heavy water. The Chlorine has a high capture cross-section for the neutrons. This process results in a gamma ray cascade with a peak around 8 MeV. Since in both the processes the neutron is eventually observed through the Čerenkov light generated by the electron the NC signal is entangled with the CC and ES signal. To observe exclusively the neutrons the SNO collaboration will employ  $^3He$  proportional counters (neutral current detectors) which will be installed in the heavy water.  $^3He$  has a large capture cross section for the thermalised neutrons producing an energetic proton-triton pair which ionise the gas in the counter resulting in an electrical pulse. Although this method requires complex hardware the advantage is that it gives an independent measurement

for NC events.

The unique feature of SNO is the NC reaction which is equally sensitive to all neutrino flavours. Thus this can provide a direct model independent measurement of the  ${}^8\text{B}$  flux. The comparison of the CC and NC rate can provide the “moking gun” evidence in favour of a  $\nu_\mu/\nu_\tau$  component in the Sun. This evidence can also be obtained to some extent by comparing the CC and ES rates but the latter has a limited sensitivity to NC events.

SNO has declared the data taken between the period Nov 2 1999 to May 28 2001 consisting of 306.4 live days in April 2002<sup>8</sup>. The neutral current data corresponds to those due to neutron capture on deuteron. Fig.4 shows the number of events vs the kinetic energy of the recoil electrons  $T_{eff}$ , the reconstructed direction of the events w.r.t the Sun  $\cos\theta_\odot$  and the volume weighted radial variable  $(R/R_{AV})^3$ . Since all the three processes are observed through the Čerenkov light produced by electrons the SNO collaboration gives the total number of the CC+ES+NC events. To determine the individual rates one needs a further assumption of standard spectral shape above  $T_{eff} = 5$  MeV. The flux of  ${}^8\text{B}$  neutrinos measured in each reaction in SNO assuming no energy distortion is

$$\phi_{CC} = 1.76 \pm 0.06(stat)_{-0.11}^{+0.09}(sys) \times 10^6 \text{cm}^{-2} \text{rms}^{-1} \dots(9)$$

$$\phi_{ES} = 2.39 \pm 0.24(stat)_{-0.12}^{+0.12}(sys) \times 10^6 \text{cm}^{-2} \text{s}^{-1} \dots(10)$$

$$\phi_{NC} = 5.09 \pm 0.44(stat)_{-0.43}^{+0.46}(sys) \times 10^6 \text{cm}^{-2} \text{s}^{-1} \dots(11)$$

SNO has also measured the spectra and rates at day and night. For the charged current events, assuming a constant spectral shape SNO finds a day-night flux difference of  $14\% \pm 6.3\%_{-1.4}^{+1.5\%}$  of the average rate<sup>9</sup>. The dominant sources of the systematic uncertainties in SNO are due to the energy calibration and resolution.

#### 4 Summary of the experimental results and their implications

In Table II we present the ratio of the observed to the expected total rates in the Ga, Cl, SK and SNO experiments. The observed  $\nu_e$  fluxes in all the experiments are less than the expectations from SSM and

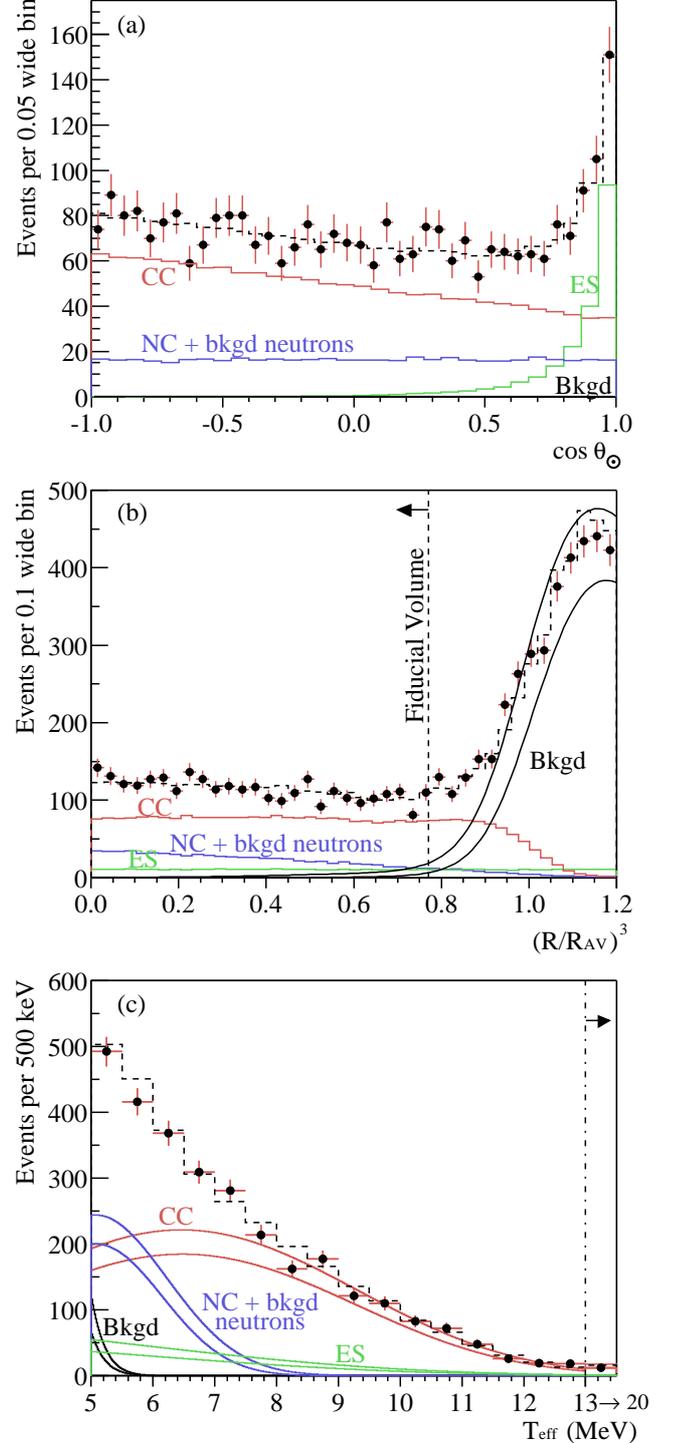


Fig. 4 Number of events observed at SNO vs. (a)  $\cos\theta_\odot$ , (b)  $(R/R_{AV})^3$ , (c) kinetic energy. Also shown are the Monte Carlo predictions for the CC, ES and NC+background events. The dashed line represents the summed components. The uncertainties are  $\pm 1\sigma$ . The figure is taken from from ref.[8].

**Table II**

The ratio of the observed solar neutrino rates to the corresponding SSM predictions<sup>14</sup>. The Ga rate corresponds to the combined SAGE and GALLEX+GNO data. Also shown is the composition of the observed fluxes. The SNO rates are obtained assuming no spectral distortion

experiment	$\frac{obsvd}{BPB00}$	composition
Cl	$0.335 \pm 0.029$	${}^8B$ (75%), ${}^7Be$ (15%)
Ga	$0.584 \pm 0.039$	$pp$ (55%), ${}^7Be$ (25%), ${}^8B$ (10%)
SK	$0.459 \pm 0.017$	${}^8B$ (100%)
SNO(CC)	$0.347 \pm 0.027$	${}^8B$ (100%)
SNO(ES)	$0.473 \pm 0.074$	${}^8B$ (100%)
SNO(NC)	$1.008 \pm 0.122$	${}^8B$ (100%)

this constitutes the essence of the solar neutrino problem. However as more and more data accumulated it became more focused. If we combine the  ${}^8B$  flux observed in SK with the Cl experimental rate, it shows a strong suppression of the  ${}^7Be$  neutrinos. The  $pp$  flux constrained by solar luminosity along with the  ${}^8B$  flux observed in SK leaves no room for the  ${}^7Be$  neutrinos in Ga. This vanishing of the  ${}^7Be$  neutrinos renders a purely astrophysical solution to the solar neutrino problem impossible and neutrino flavour conversion was conjectured as a plausible solution. This was beautifully confirmed by the SNO data.

Since the CC reaction is sensitive only to  $\nu_e$  and the ES reaction is sensitive to both  $\nu_e$  and  $\nu_\mu/\nu_\tau$  a higher ES flux would signify the presence of  $\nu_\mu/\nu_\tau$ . The combination of SNO CC and SK ES data provides a  $3.3\sigma$  signal for  $\nu_e$  transition to an active flavour (or against  $\nu_e$  transition to solely a sterile state). The combination of the SNO NC and CC data gives

$$\phi_{\mu\tau} = (3.41_{-0.64}^{+0.66}) \times 10^6 \text{cm}^{-2}\text{s}^{-1} \quad \dots (12)$$

This establishes neutrino flavour conversion to a state containing an active neutrino component at  $5.3\sigma$  level. Incorporating the SK measurement as an extra constraint confirms this at  $5.5\sigma$  level.

There can be various mechanisms of neutrino flavour conversion among which the most popular is neutrino oscillations which requires neutrinos to have mass and mixing. If one takes all the data from the seven experiments into account namely the data on total rates from Cl and Ga, the SK zenith-angle spectral data and the SNO spectral data and performs a global  $\chi^2$  -analysis, two regions in the mass squared differ-

ence ( $\Delta m^2$ ) and mixing angle (expressed as  $\tan^2 \theta$ ) parameter space remain allowed. The favoured solution from the solar data is the Large Mixing Angle (LMA) region<sup>26</sup> which covers a range  $3 \times 10^{-5} \text{eV}^2 \leq \Delta m^2 \leq 3 \times 10^{-4} \text{eV}^2$  and  $0.25 \leq \tan^2 \theta \leq 0.87$  at 99.73% C.L. ( $3\sigma$ ). Confirmation in favour of this solution came recently from the KamLAND experiment in Japan which used reactor  $\bar{\nu}_e$ s to look for neutrino oscillation<sup>11</sup>. The first KamLAND results have already demonstrated remarkable capability to constrain the LMA region from its data on the spectrum of  $\bar{\nu}_e$ . At 99% C.L. the LMA region gets bifurcated into two zones – a low  $\Delta m^2$  region (low-LMA) around the global best-fit point with  $\Delta m^2 = 7.17 \times 10^{-5} \text{eV}^2$  and  $\tan^2 \theta_{12} = 0.44$  and a high  $\Delta m^2$  region (high-LMA) around  $\Delta m^2 = 1.49 \times 10^{-4} \text{eV}^2$  and  $\tan^2 \theta_{12} = 0.43$  having less (by  $\approx 2\sigma$ ) statistical significance<sup>27</sup>.

## 5 Future Prospects

With KamLAND confirming the LMA solution and the SK and SNO experiments measuring the solar  ${}^8B$  flux the two major goals of solar neutrino research are (i) precise determination of the neutrino mass and mixing parameters and (ii) to observe the low energy end of the solar neutrino spectrum consisting of the  $pp$ , CNO and the  ${}^7Be$  line.

The Borexino liquid scintillator detector located in the Gran-Sasso underground laboratory in Italy will measure the  ${}^7Be$  flux via neutrino electron scattering reaction<sup>29</sup>. The main problem in the measurement of the low energy fluxes is the background reduction. A 4 ton prototype called counting test facility (CTF) has demonstrated extremely low radioactive level ( $10^{-16} \text{g/g}$  of U/Th) in Borexino. With KamLAND confirming LMA solution to the solar neutrino problem Borexino should observe a rate of  $\sim 0.64$  of the predicted rate and no day-night asymmetry.

Till now the  $pp$  neutrinos have been observed in the Ga experiments using radiochemical techniques. Among these SAGE and GNO will continue taking data and accumulate statistics. There is continued exploration of a 100 ton Ga experiment for reducing the statistical error. Ga experiments with increased statistics and reduced systematics can determine the  $pp$  flux more accurately. A radiochemical Li detector is proposed to measure the CNO fluxes<sup>30</sup>. But the crying need in the field of low energy solar neutrinos is real time detectors. The daunting task at

these low energies is to reduce the radioactive backgrounds and various techniques are being discussed. XMASS is a liquid xenon scintillator detector planned to be installed in Kamiokande site. It will use the neutrino electron elastic scattering reaction to measure the pp flux<sup>31</sup>. Other real time experiments which will use  $\nu - e$  scattering for measuring the pp and CNO fluxes are HELLAZ, HERON, CLEAN, MUNU and GENIUS projects. HELLAZ is studying the possibility of measuring electron tracks generated in pressurised He while HERON<sup>32,33</sup> is planning for bolometric detection using super-fluid He. MUNU<sup>34</sup> will use projection chamber filled with CF<sub>4</sub>. GENIUS is a proposed double beta decay experiment having simultaneously the capability of real time detection of low energy neutrinos by suitably reducing the background<sup>35</sup>. Charged current reactions for measuring low energy neutrino fluxes are studied in LENS, MOON and SIREN proposals<sup>31</sup>. The measurement of low energy fluxes is technically quite challenging and it is still at a nascent stage with feasibility studies of the various

proposed projects underway.

## 6 Conclusions

Solar neutrino experiments have played a key part in determining the fundamental properties of neutrinos. They also provide sensitive tests of solar models. Apart from establishing the presence of  $\nu_\mu/\nu_\tau$  component in the solar  $\nu_e$  flux with a significance of  $5.3\sigma$  the data released by the SNO collaboration demonstrated that the total <sup>8</sup>B flux measured in the SNO NC reaction is in close agreement with the Standard Solar Model predictions. The first and the second generation of experiments have contributed a great deal in advancement of our knowledge in the fields of particle physics, astrophysics and experimental techniques. Research and development studies are in progress for new experiments to measure the low energy solar neutrino fluxes for realising the goal of performing solar neutrino spectroscopy over the whole energy range. Solar neutrinos will continue to enrich our knowledge with the existing and future experiments.

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