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Latest results from SNO: enhanced flavour with a pinch of salt

Nick Jelley*†

Univ. Oxford

E-mail: N.Jelley@physics.ox.ac.uk

ABSTRACT: The Sudbury Neutrino Observatory (SNO) has precisely determined the total active ^{8}B solar neutrino flux without assumptions about the energy dependence of the ν_e survival probability. The addition of salt (NaCl) to the heavy water in the SNO detector enhanced the sensitivity to the neutral current interaction and allowed good statistical separation of events from charged and neutral current interactions. Results from this phase will be presented and their physics implications will be discussed.

1. Introduction

The Sudbury Neutrino Observatory (SNO) [1] is a 1000 tonne heavy water Cherenkov detector situated at a depth of 6800 ft in INCO's Creighton mine at Sudbury, Canada. Its main aim is to observe neutrinos from the Sun and investigate the origin of the observed deficit in their flux compared to the prediction of Standard Solar Models (the Solar Neutrino Problem). The detector uses ∼9500 photomultiplier tubes (PMTs) on a geodesic sphere of diameter 17.8 m to observe the Cherenkov light produced as a result of neutrino interactions occurring in the 1000 tonnes of D_2O. The D_2O is held in a 12 m diameter acrylic sphere, which is surrounded by a shield of 7000 tonnes of H_2O contained in a 34 m high barrel-shaped cavity of maximum diameter 22 m.

SNO can measure the flux of electron neutrinos from the Sun via the charged current (CC) reaction: $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$, and the total flux of all active neutrino flavours via the neutral current (NC) reaction $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$, ($x$ = e, μ, τ). Elastic scattering (ES) reactions $\nu_x + \mathrm{e}^- \rightarrow \nu_x + \mathrm{e}^-$, which are mainly sensitive to ν_e, also occur at a lower rate. A comparison of the CC and NC fluxes therefore allows a direct test of whether neutrino flavour change is occurring (independent of the actual solar neutrino flux).

*Speaker.

†On behalf of the SNO Collaboration

SNO first started taking data in the summer of 1999 with pure D_2O (Phase I). It reported its first results [2] with a kinetic energy threshold of 6.75 MeV on the flux of ν_e in the summer of 2001. With the threshold lowered to 5 MeV kinetic energy it announced its results on the total flux of all active neutrinos and on the day and night energy spectra in the summer of 2002 [3, 4]. The total flux was obtained by measuring the NC rate through observing the Cherenkov light following neutron captures on deuterons. A Standard-Model description with an undistorted ^{8}B spectrum and CC, ES and NC rates due only to ν_e interactions was rejected at greater than five sigma, and a comparison of the CC and NC flux provided strong evidence that neutrino flavour change is the cause of the Solar Neutrino Problem.

These results also placed constraints on the neutrino flavour mixing parameters and strongly favoured the LMA solution. This conclusion was confirmed, assuming CPT, by the KamLAND [5] reactor anti-neutrino oscillation experiment and the allowed region was confined to two adjacent areas in the LMA region, LMA I and LMA II, with LMA I preferred.

The next phase of SNO (Phase II) was with the addition of 2 tonnes of sodium chloride (salt) to the heavy water and this phase started in early summer 2001. The addition of salt to the heavy water improved the neutron capture efficiency as ^{35}Cl has a large capture cross section. Moreover, the amount of associated Cherenkov light is increased as the total energy of the γ rays released following neutron capture on ^{35}Cl is 8.6 MeV compared with 6.0 MeV on deuterium. The improvement in the capture efficiency in the Salt Phase compared to the pure D_2O phase is seen in Figure 1.

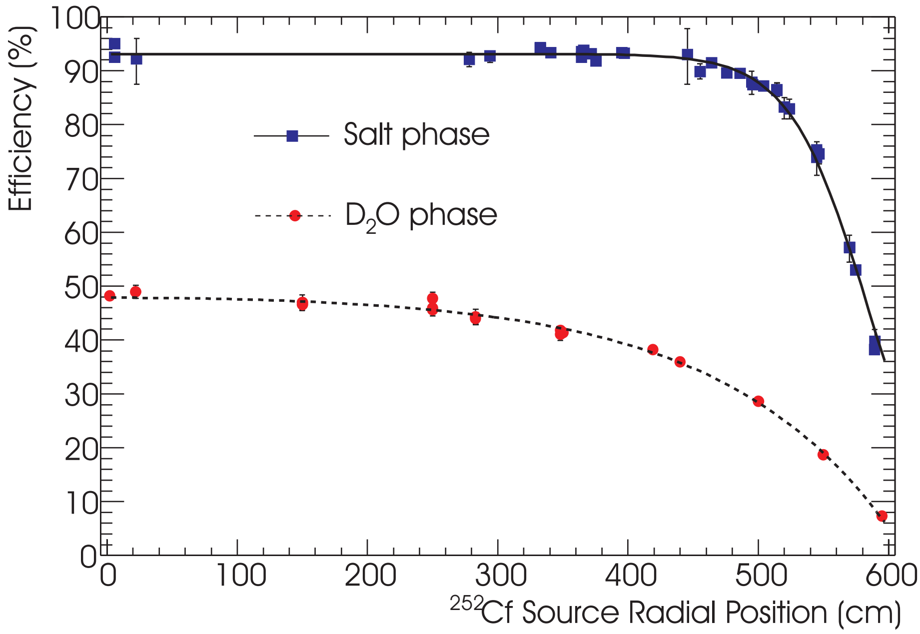

Figure 1: Neutron capture efficiency versus source radial position for the pure D_2O phase and salt phase deduced from a ^{252}Cf source with fits to an analytic function (salt) and to a neutron diffusion model (D_2O).

The detection efficiency for an effective kinetic energy threshold of 5.5 MeV and within the fiducial volume defined by $R_{\rm fit} < 550$ cm was 0.399 $\pm$0.010 (calibration) $\pm$0.009 (fiducial volume), a factor of approximately three increase from Phase I. The energy threshold and fiducial volume cut reduced Cherenkov event backgrounds from β-γ decays to less than 15 events.

The NC reaction produces neutrons and their capture on ^{35}Cl typically produces multiple γ rays ($\sim$ 2.5 per capture), while the CC and ES reactions produce single electrons. Each γ ray predominantly interacts through Compton scattering, producing an energetic electron. The Cherenkov light from neutron capture events relative to that from CC and ES events is therefore more isotropic as the light is typically from several electrons rather than one. This greater isotropy allows good statistical separation of the event types and allows a precise measurement of the NC flux to be made independent of assumptions about the CC and ES energy spectra which can be distorted by the effect of matter-enhanced oscillations.

The degree of isotropy of the Cherenkov light is reflected in the angular distribution of the photomultiplier-tubes that detected the light (the PMT hits). The angular distribution was expressed in terms of the average values, β_l, of the Legendre polynomial P_l of the cosine of the angle between PMT hits:

$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(cos\theta_{ij}),$$

with θ_{ij} the angle between the light paths to hits i and j from the reconstructed event position and N the number of hits.

The combination $\beta_1 + 4\beta_4 \equiv \beta_{14}$ was selected as a measure of event isotropy to optimise the separation of NC and CC events. Figure 2 shows a comparison of Monte Carlo simulations of β_{14} with data from a ^{252}Cf and a ^{16}N source, together with a Monte Carlo simulation for CC events. The ^{252}Cf and CC events have a lower kinetic energy threshold of 5.5 MeV, while the ^{16}N events have kinetic energies between $\sim$ 4 MeV and $\sim$ 6 MeV. The ^{16}N source emits 6.13 MeV γ rays, which undergo Compton scattering and produce electrons in this energy range. The CC electrons undergo relatively less multiple scattering per unit path length than the Compton scattered electrons from the ^{16}N source as they have higher energy. The 6.13 MeV γ rays also multiply Compton scatter and occasionally produce pairs. The average β_{14} for ^{16}N events is therefore lower (more isotropic) than for CC events.

The multiple scattering of electrons is handled within SNOMAN by EGS4 [6] and the good agreement between Monte Carlo and data seen in Figure 2 required a small correction to be made to EGS4 to allow for the neglect of the Mott terms in the electron scattering cross-section and other approximations in the treatment of multiple scattering [7]. Electrons are spin 1/2 and those of interest in SNO are relativistic over most of their range. The relativistic single scattering cross section is due to Mott [8]; the Rutherford formula is multiplied by a factor $M(\theta, \beta, Z)$ given by:

$$M(\theta, \beta, Z) = 1 - \beta^2 sin^2\frac{\theta}{2} + \pi\beta\frac{Ze^2}{\hbar c} sin\frac{\theta}{2}(1 - sin\frac{\theta}{2}),$$

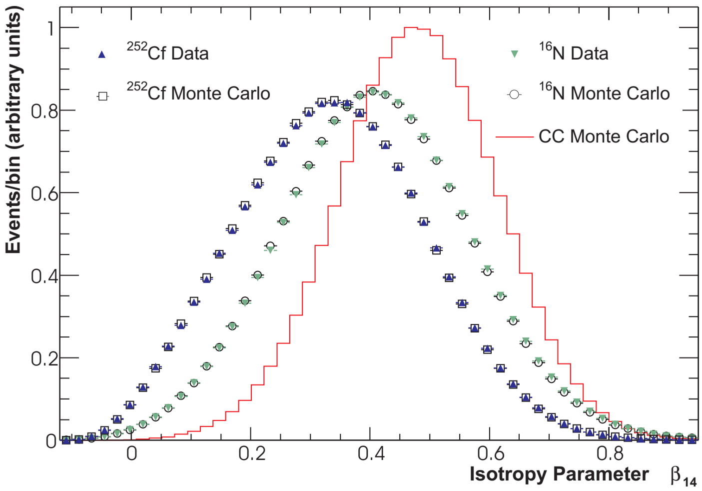

Figure 2: Event isotropy from data and Monte Carlo calculations of a ^{252}Cf source, a ^{16}N source, and CC events.

where θ is the single scattering angle and Z the charge of the scattering nucleus. This factor is one for θ equal to zero and $1 - \beta^2$ for θ equal to π. The angular distribution with the Mott terms present is therefore a little tighter than with pure Rutherford scattering.

The systematic uncertainty on β_{14} distributions generated by Monte Carlo for signal events was evaluated by comparing ^{16}N calibration data to Monte Carlo calculations for events throughout the fiducial volume and running period. The uncertainty on the mean value of β_{14} is 0.87%. The Monte Carlo calculations have also been verified with neutron events from ^{252}Cf, 19.8 MeV γ ray events from a ^{3}H(p,γ)^{4}He source, high-energy electron events (dominated by CC and ES interactions) from the pure D_2O phase, neutron events following muons, and with low-energy calibration sources.

Essential to an accurate determination of the NC, CC and ES fluxes is a precise determination of any backgrounds. As photodisintegration of deuterons mimics the disintegration of deuterons by neutrinos, the accurate measurement of the radioactivity from thorium and uranium decay chains in the heavy water in SNO is essential for finding the total solar neutrino flux. The number of neutrons predicted by the Standard Solar Model that are produced by the neutral current interaction of solar neutrinos with deuterons is about 15 per day per 1000 tonne of heavy water. In the thorium decay chain ^{208}Tl is produced with a branching ratio of 36% and in its decay a 2.614 MeV γ ray is emitted with a 99.8% probability. The chance that this γ ray photodisintegrates a deuteron is 2.07×10^{-3}, giving a probability that a neutron is generated of 7.45×10^{-4} per Th decay. An upper limit on ^{232}Th of 3.8×10^{-15}g/g corresponds to a photodisintegration background of one neutron per day per 1000 tonnes of heavy water. This level is less than 10% of the predicted NC rate. In the uranium decay chain ^{214}Bi is produced, and in its decay the probability that a γ ray with an energy greater than 2.2 MeV is emitted is only $\sim$2%. The probability that a neutron is generated is 3.12×10^{-5} per U decay and this sets a corresponding upper limit on ^{238}U of 3.0×10^{-14}g/g.

Several different techniques were employed to determine the amount of thorium and uranium in the heavy and light water. In the chemical assays radium ions were extracted by passing the water through either MnO_x or HTiO ion exchange media [9, 10]. For MnO_x radon daughters in the U and Th chains were subsequently released and counted by alpha spectroscopy, while for HTiO the radium was concentrated and the number of decay daughter β-α coincidences determined. Measurements of the background from ^{222}Rn, which breaks the secular equilibrium in the U decay chain, were made by periodically extracting and cryogenically concentrating ^{222}Rn, which was subsequently counted in ZnS(Ag) scintillation cells [11]. These *ex-situ* assays showed that the limits on the Th and U were met.

Independent measurements of the U and Th decay chain nuclei were made by analysing Cherenkov light produced in the radioactive decays. Statistical separation of the Tl and Bi events was obtained using the difference in isotropy of the events. In the low energy monitoring window (4.5 - 5.0 MeV effective kinetic energy and within 450 cm of the centre of the detector for activity in the D_2O), the events are dominated by those from the β decay of ^{214}Bi to the ground state of ^{214}Po and from the β decay of ^{208}Tl to excited states of ^{208}Pb, which subsequently emit a 2.614 MeV γ ray plus one or more γ rays. The ^{208}Tl decays are therefore generally more isotropic as they give rise to several electrons that emit Cherenkov light, rather than primarily one. Results from this *in-situ* method were consistent with those from the *ex-situ* techniques. The number of background neutron events from deuteron photodisintegration was $73.1^{+24.0}_{-23.5}$ out of a total of 3055 events.

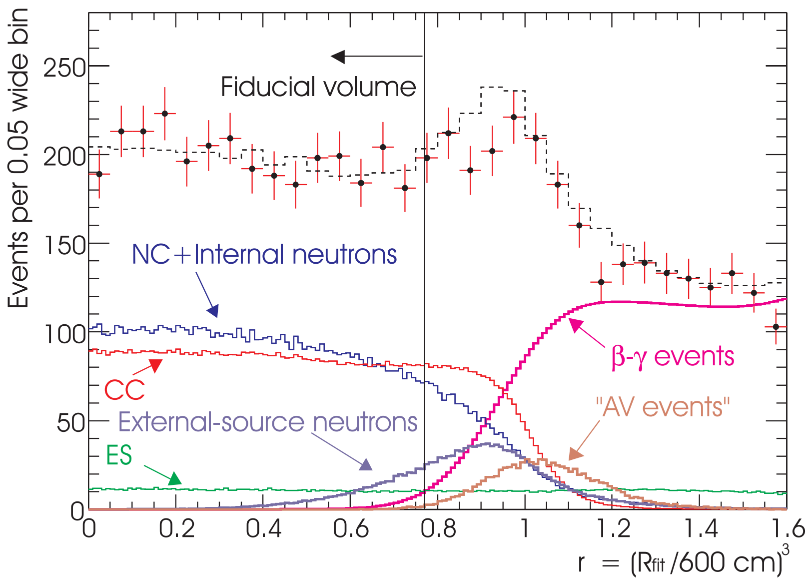

Figure 3: Volume-weighted radius (ρ) distribution (acrylic vessel=1). Shown are the distributions for CC, ES, NC+internal and external-source neutrons, scaled from the fit, and separately determined external background distributions.

Neutron backgrounds from atmospheric neutrino interactions and ^{238}U fission were estimated with the aid of the code NUANCE [12] and from event multiplicities (23.0 ± 7.2 events). Neutron activation of ^{23}Na produces ^{24}Na, which has a 15 hr half-life and emits a 2.75 MeV γ ray on decay that can photodisintegrate the deuteron. Residual activation after calibrations and ^{24}Na production in the water circulation system and in the heavy water in the "neck" of the vessel were determined and found to be relatively small (8.4 ± 2.3 events). The total internal neutron background was estimated to be $111.3^{+25.3}_{-24.9}$ events.

Neutrons and γ rays produced at the acrylic vessel and in the light water can propagate into the fiducial volume and the latter can photodisintegrate deuterium. The enhanced neutron capture efficiency of salt makes these external-source neutrons readily apparent, and an additional distribution function was included in the analysis to measure this component. A class of background events identified and removed from the analysis in Phase I ("AV events") reconstruct near the acrylic vessel and were characterised by a nearly isotropic light distribution. Analyses limit this background to less than 5.4 events for the present data (see Figure 3).

In order to minimise the possibility of introducing biases, a blind analysis procedure was used which excluded an unknown fraction ($< 30\%$) of the final data set, included an unknown admixture of muon-following neutrons, and applied an unknown scaling parameter to the NC cross-section. After fixing all parameters and analysis procedures, the blindness constraints were removed and an extended maximum likelihood analysis was performed. This was based on the distributions of isotropy, cosine of the event direction to the Sun, and radius within the detector. The spectral distributions of the ES and CC events were not constrained. The isotropy, $\cos\theta_{\odot}$, and effective kinetic energy distributions for the selected events are shown in Figure 4, with statistical uncertainties only.

The data were taken for a period totaling 254.2 live days and the data set was reduced to 3055 events after data reduction similar to that decribed in [3] and analysis selection requirements. The fitted number of events give equivalent ^{8}B fluxes (in units of 10^6 cm^{-2}s^{-1}):

$$\phi_{CC} = 1.59^{+0.08}_{-0.07}(\text{stat})\ ^{+0.06}_{-0.08}(\text{syst})$$
$$\phi_{ES} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10(\text{syst})$$
$$\phi_{NC} = 5.21 \pm 0.27(\text{stat}) \pm 0.38(\text{syst}).$$

The ratio of the ^{8}B flux measured with the CC and NC reactions is

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.306 \pm 0.026(\text{stat}) \pm 0.024(\text{syst}),$$

which disfavours no flavour transformation at greater than the equivalent of seven σ. These results are consistent with the previous SNO measurements and the NC flux is in excellent agreement with the predicted solar ^{8}B flux [13].

In the global analysis of all solar neutrino data, the LMA region is selected, as shown in Figure 5(a). A global analysis including the KamLAND reactor anti-neutrino results [5] shrinks the allowed region further, with a best fit point of $\Delta m^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2 and $\theta = 32.5^{+2.4}_{-2.3}$ degrees, where the errors reflect the one σ constraints on the two- dimensional region (Figure 5(b)). With the SNO salt phase measurement the allowed LMA region is constrained to the lower island (LMA I) at $> 99\%$ CL. The best fit values with marginalized

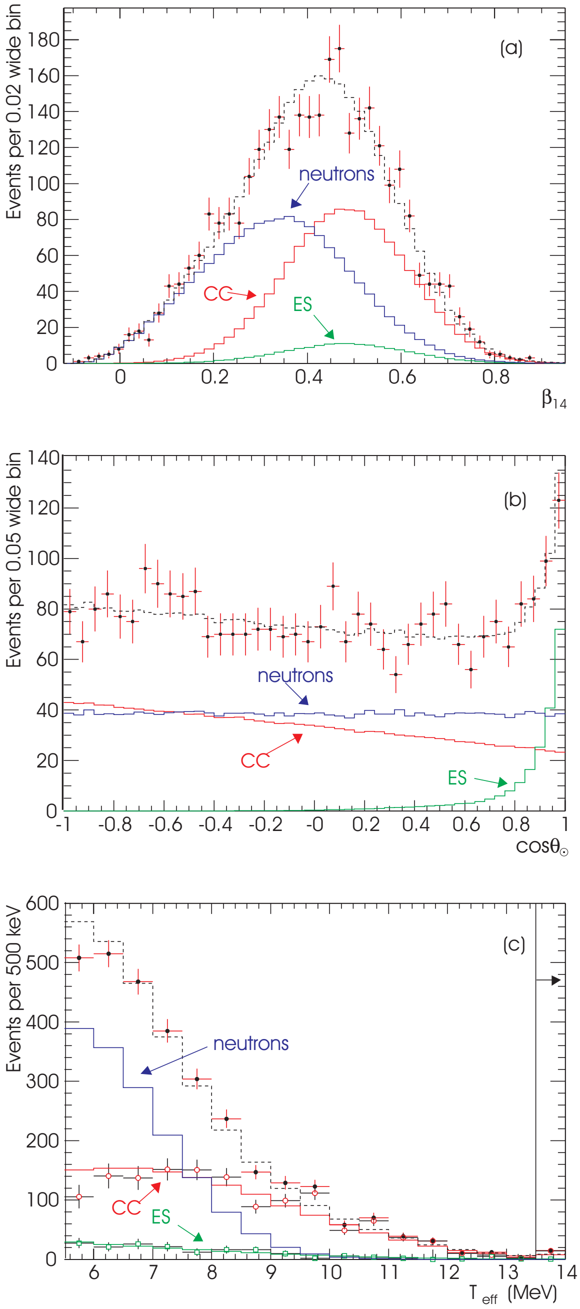

Figure 4: Distributions of (a) β_{14}, (b) $\cos\theta_{\odot}$, and (c) effective kinetic energy for the selected events. The CC and ES spectra are extracted from the data using β_{14} and $\cos\theta_{\odot}$ distributions in each energy bin. Differential systematics are not shown.

uncertainties are $\Delta \mathrm{m}^2 = 7.1^{+1.0}_{-0.3} \times 10^{-5}$ eV^2 and $\theta = 32.5^{+1.7}_{-1.6}$ degrees. This result disfavours maximal mixing at over five σ.

SNO has now removed the salt from the heavy water and is currently installing ^{3}He proportional counters in the heavy water. These counters will allow event-by-event separa-

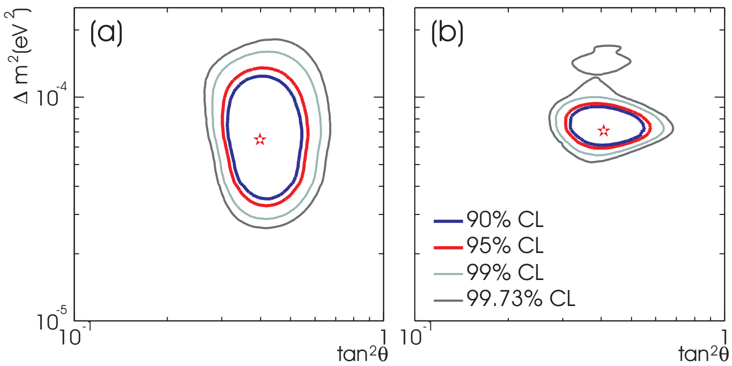

Figure 5: Global neutrino oscillation contours. (a) Solar global: D_2O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is $\Delta m^2 = 6.5 \times 10^{-5}$, $\tan^2\theta = 0.40$. (b) Solar global + KamLAND. The best-fit point is $\Delta m^2 = 7.1 \times 10^{-5}, \tan^2\theta = 0.41$.

tion of CC and ES from NC events as the neutrons will be detected through the reaction: $n + {}^3He \rightarrow p + t$. The systematic errors on the NC flux determination are quite different from those in Phase I and Phase II, where neutrons were detected through their associated Cherenkov light, and the results are expected to provide further valuable information on the neutrino mixing parameters and on the total active solar neutrino flux.

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