Nucleon Disappearance via “Invisible” Modes in SNO

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Introduction

Certain models where "Invisible Modes" such as $n \rightarrow \nu\nu\nu$ are dominant have been predicted*.

The signature of the "Invisible" Modes fall in the sensitivity range of SNO making a study viable.

SNO published an upper limit to this mode in 2004 on the possible disappearance of either neutron or proton from a ^{16}O nucleus,

S. N. Ahmed *et al.* (SNO Collaboration), Phys. Rev. Lett. **92**, 102004 (2004).

This presentation is on that analysis.

*Mohapatra and Perez-Lorenzana, Phys. Rev. D67, 075015 (2003)

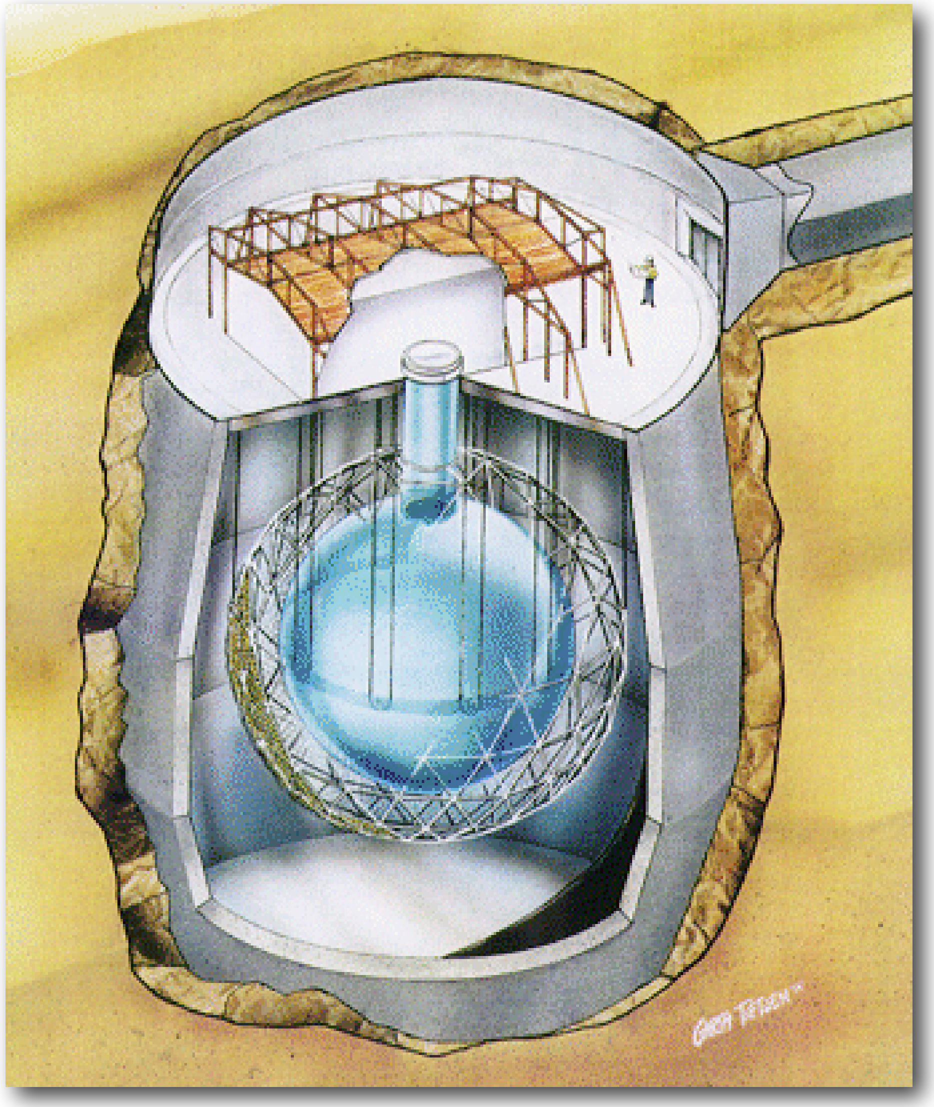
SNO Detector

The SNO detector is a heavy water Cherenkov detector.

It consists of 1 kiloton of pure heavy water (D2O) that is contained in a 12m diameter spherical acrylic vessel (AV). This vessel is submerged in pure light water. 9,456 Photo-Multiplier Tubes (PMTs) are mounted on a spherical support of 17.8m diameter.

The experiment was divided into three phases:

The first phase was the pure D2O phase. In the second phase, two tons of salt were added. In the third phase, ^{3}He proportional counters (the Neutral Current Detection [NCD] array) were added.



At the time of publication, only data from phases one and two were available for analysis of the "invisible" mode $n \rightarrow \nu\nu\nu$.

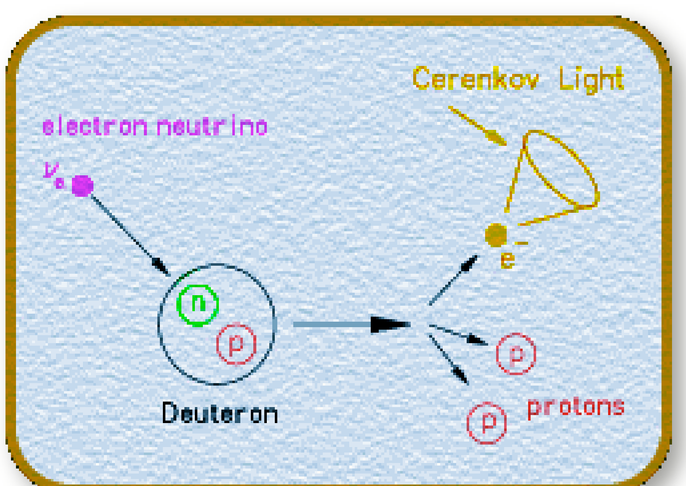
SNO Channels

SNO's primary goal is to measure the electron neutrino and total neutrino flux from the sun:

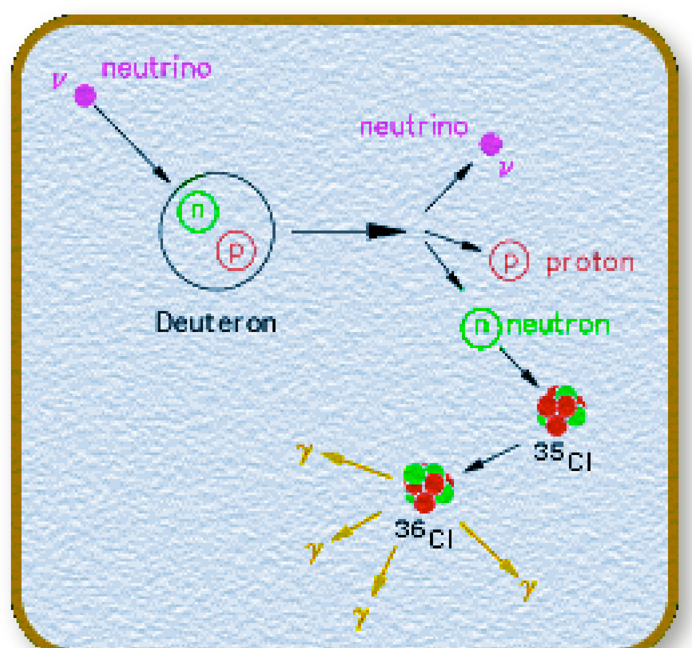
$\nu_e + D \rightarrow p + p + e^-$ Charge Current (CC)
$\nu_x + D \rightarrow n + p + \nu_x$ Neutral Current (NC)
$\nu_x + e^- \rightarrow \nu_x + e^-$ Elastic Scattering (ES) where ($x = e, \mu, \tau$).

In the case of CC and ES a Cherenkov cone from the electron can be directly observed while for the NC case the neutron has to be captured first.

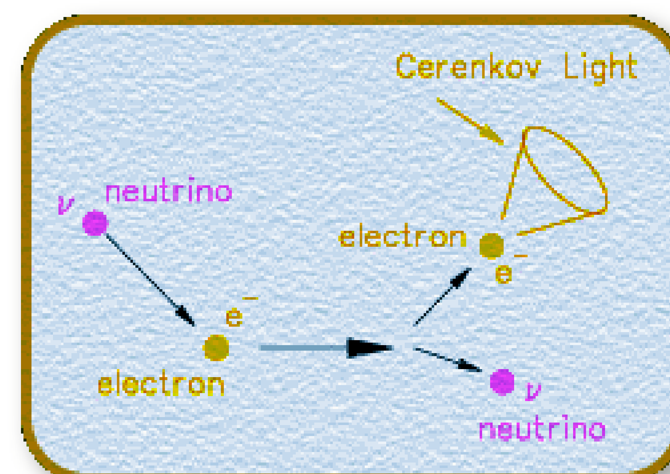
For the NC the neutron has to be captured by a nucleus: D, ^{35}Cl (phase II). The subsequent gamma(s) will give Cherenkov radiation through Compton-scattered electron(s).



CC



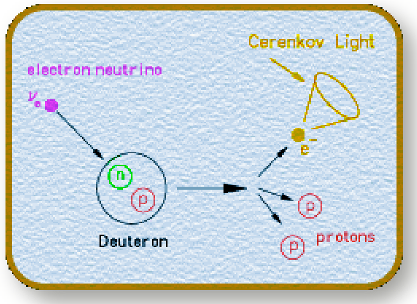
NC



ES

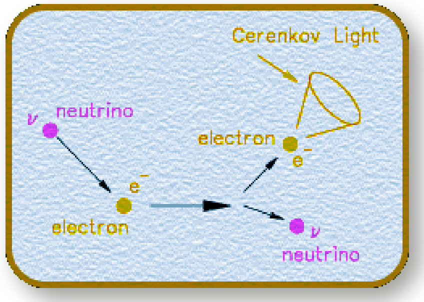
SNO Channels

For CC and ES:



CC

The resulting Cherenkov electron will have energy spectra that depend on the energy of the incoming solar neutrino.

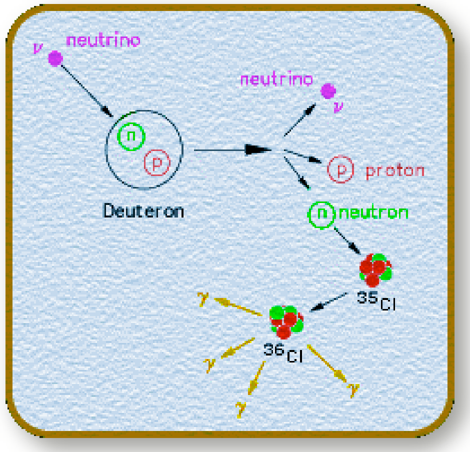


ES

For NC:

Phase 1: Emission of a single 6.25 MeV gamma ray from neutron the capture on deuterium. The neutron detection efficiency for this phase 1 is 0.144 +/- 0.005.

Phase 2: Emission of 8.6 MeV of energy in gamma rays from neutron capture on ^{35}Cl (more isotropic). The neutron detection efficiency for phase 2 is 0.399 +/- 0.010.



NC

Invisible Mode Signature

The disappearance of a neutron or a proton in an ^{16}O nuclei will create an unstable nucleus.

In the case of a nucleon disappearance in ^{16}O, the subsequent de-excitation of $^{15}O^*$ or $^{15}N^*$ can lead to a single gamma ray production.

More specifically, $^{15}O^*$ has a branching ratio of 44% for producing a 6.18 MeV gamma and a 2% for a 7.03 MeV gamma.

While, $^{15}N^*$ has a branching ratio of 41% for producing a 6.32 MeV gamma and a 4% for a 7.0 MeV gamma.

Invisible Mode Signature

Since the NC signal is a 6.25 MeV gamma and the signature for the invisible mode decay is 6.18 MeV and 6.32 MeV gammas, it becomes clear that in the search for nucleon disappearance, the background is the NC interaction.

Energy resolution of the detector is not good enough to resolve the difference.

In both phases, the gamma efficiencies in nucleon decay are similar while the efficiency of detection of neutrons produced by the ^{8}B in the sun is very different because of the introduction of ^{35}Cl.

This difference makes this analysis of the "invisible" decay mode possible.

Extraction of Limit

The signal for an invisible mode can be calculated by the excess of NC-like signal over the true solar neutrino NC rate. This excess is equal to the rate of nucleon gamma production up to a misidentification factor $f_{\gamma n}$:

$$R_\gamma \epsilon_\gamma f_{\gamma n} = R_n - \epsilon_n \mathcal{R}_{NC}$$

R_γ	rate of nuclear gamma-ray due to nucleon decay
R_n	extracted rate nominally attributed to NC interactions
$\mathcal{R}_{NC}$	actual production rate due to solar neutrino NC interactions
$\epsilon_\gamma,\ \epsilon_n$	detection efficiencies for both process

The same equation holds in the salt phase:

$$R_\gamma \epsilon'_\gamma f'_{\gamma n} = R'_n - \epsilon'_n \mathcal{R}_{NC}$$

Note that between phase, the production rate from solar neutrino will not change between phases. Since the rate of solar induced NC rate on deuterium remains the same in both phases, the rate of induced nucleon gamma can be found:

$$R_\gamma = \frac{R_n - \frac{\epsilon_n}{\epsilon'_n} R'_n}{\epsilon_\gamma f_{\gamma n} - \epsilon'_\gamma f'_{\gamma n} \frac{\epsilon_n}{\epsilon'_n}} \equiv \frac{\Delta R_n}{\epsilon_\gamma f_{\gamma n} - \epsilon'_\gamma f'_{\gamma n} \frac{\epsilon_n}{\epsilon'_n}}$$

$f_{\gamma n}$ (fraction of detected nuclear gamma rays that are mistaken for Neutrons)

Extraction of Limit

To allow a comparison between both phases, the flux of CC data was constrained in both phases to follow the shape of the ^{8}B spectrum. Values for R_n and R_n' were then extracted.

$$\begin{aligned} \Delta R_n &= R_n - \frac{\epsilon_n}{\epsilon_n'} R_n' \\ &= (686.8 \pm 83.9) - (656.0 \pm 49.3) \\ &= 30.8 \pm 97.3 \end{aligned}$$

This value can be turned into an upper limit. Upper limit for relative neutron efficiency at 90% CL:

$$\boxed{\Delta R_n < 180.6 \text{ per year}}$$

Extraction of Limit

Gammas with energies of the invisible mode decay signature were generated by simulation. Solar neutrino extraction code was applied to these generated events.

The misidentification probability is extracted by the resulting excess NC events in both the 6.18 (6.32) and 7 MeV simulated gammas (weighted by their respective branching ratios).

It was found that for phase 1, the extracted value of the misidentification factor was $f_{\gamma n} = 0.99^{+0.01}_{-0.02}$. Since there is no way to distinguish between a nuclear gamma and a neutron, this is expected.

It was found that for phase 2, the extracted value of the misidentification factor was $f'_{\gamma n} = 0.75^{+0.01}_{-0.01}$.

Furthermore, the efficiencies for detecting nuclear gammas were also extracted from those spectrum.

	neutron	proton
ϵ_γ	$= 0.51 \pm 0.01$	(0.59 ± 0.01)
ϵ'_γ	$= 0.361 \pm 0.005$	(0.425 ± 0.006)

Results

The upper limit on the rate of nuclear gamma is extracted at a 90% CL for both the neutron and proton disappearance.

$$R_\gamma^{\text{lim}} < 443 \text{ (neutron)} \qquad R_\gamma^{\text{lim}} < 385 \text{ (proton)}$$

The values for a nucleon decay through invisible mode can now be estimated:

$$\tau_{\text{inv}} > \frac{N_{np}}{R_\gamma^{lim}} \varepsilon_\gamma$$

where N_{np} is the number of neutrons or proton in the D2O fiducial volume, ε_γ is the efficiency of producing 6-7 MeV gamma (~45%).

The final limit obtained at 90% CL are:

$$\textit{for proton modes:} \quad \tau_{\text{inv}} > 2.1 \times 10^{29} \text{ years.}$$
$$\textit{for neutron modes:} \quad \tau_{\text{inv}} > 1.9 \times 10^{29} \text{ years.}$$

Conclusion

An analysis of phase I and II was presented. At the time of publication the limit was 400 time more stringent than the previous limit.

Since the publication, KamLAND has published a limit that is a factor of 3 better than the one published by SNO.*

The addition of the third phase of SNO will not offer improvement on the current limits.

*PRL 96, 101802 (2006)