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The Sudbury Neutrino Observatory

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Abstract

This review paper provides a summary of the published results of the Sudbury Neutrino Observatory (SNO) experiment that was carried out by an international scientific collaboration with data collected during the period from 1999 to 2006. By using heavy water as a detection medium, the SNO experiment demonstrated clearly that solar electron neutrinos from ^{8}B decay in the solar core change into other active neutrino flavors in transit to Earth. The reaction on deuterium that has equal sensitivity to all active neutrino flavors also provides a very accurate measure of the initial solar flux for comparison with solar models. This review summarizes the results from three phases of solar neutrino detection as well as other physics results obtained from analyses of the SNO data.

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1. Introduction

The Sudbury Neutrino Observatory (SNO) was initiated in 1984 primarily to provide a definitive answer to the Solar Neutrino Problem [1]. Ever since the pioneering calculations of solar neutrino fluxes by John Bahcall and the pioneering measurements by Ray Davis in the 1960s, it was known that there was a discrepancy between the observed fluxes and the calculations. The persistence of the problem motivated Herb Chen to contact Canadian scientist Cliff Hargrove, a former colleague, to explore whether there was a possibility that enough heavy water could be made available on loan to perform a sensitive measurement and determine whether the neutrinos change their type in transit from the core of the Sun. The unique properties of deuterium could make it possible to observe both the electron neutrinos produced in the core of the Sun and the sum of all neutrino types [2]. With the immediate involvement of George Ewan, who had been exploring underground sites for future experiments, a collaboration of 16 Canadian and US scientists was formed in 1984, led by Chen and Ewan as Co-Spokesmen [3]. UK scientists joined in 1985, led by David Sinclair as UK Spokesman.

An initial design was developed, to be sited 2 km underground in Inco's Creighton mine near Sudbury, Ontario, Canada and preliminary approval was obtained from Atomic Energy of Canada Limited (AECL) for the loan of 1000 tonnes of heavy water. Unfortunately Herb Chen passed away tragically from leukemia in 1987. The collaboration continued with Art McDonald and Gene Beier as US Spokesmen and grew with the addition of other institutions in the US and Canada for a total of 13 institutions. In 1989, funding was provided jointly by Canadian, US and UK agencies and McDonald became Director of the project and the scientific collaboration.

2. Science of solar neutrinos and detection by SNO

Fig. 1 shows the fluxes of neutrinos from the pp chain reactions that comprise the principal power source in the Sun [4]. Overall the series of reactions can be summarized as: $4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.73$ MeV. Also shown are the thresholds for neutrino detection for the chorine, gallium and H_2O-based experiments that took place before the SNO results were first reported in 2001. These experiments were either exclusively (chlorine, gallium) or predominantly (H_2O) sensitive to the electron-type neutrinos produced in the Sun. They all showed deficits of factors of two to three compared to the fluxes illustrated in Fig. 1. It was not possible, however, for these experiments to show conclusively that this was due to neutrino flavor change rather than defects in the solar flux calculations. With heavy water (D_2O) containing deuterium, the SNO experiment was able to measure two separate reactions on deuteron (d):

1. $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + e^-$, a charged current (CC) reaction that was sensitive only to electron-flavor neutrinos, and
2. $\nu_x + \mathrm{d} \rightarrow \mathrm{n} + \mathrm{p} + \nu_x$, a neutral current (NC) reaction that was equally sensitive to all neutrino types.

A significant deficit in the ^{8}B ν flux measured by the CC reaction over that measured by the NC reaction would directly demonstrate that the Sun's electron neutrinos were changing to one of the other two types, without reference to solar models. At the same time, the NC reaction provided a measurement of the total flux of ^{8}B solar neutrinos independent of neutrino flavor change. The CC reaction was detected by observing the cone of Cherenkov light produced by the fast moving electron. The NC reaction was detected in three different ways in the three