Status of the Borexino Solar Neutrino Experiment, 2006

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Abstract. The Borexino experiment is designed to measure the flux of ^{7}Be solar neutrinos. The experiment, having a 100-ton fiducial volume of organic liquid scintillator, should detect roughly 35 neutrinos per day in the energy range 250 - 1300 keV, a range lower than that of any previous real-time neutrino detector. Though the 862-keV ^{7}Be neutrinos make up roughly 10% of the total solar neutrino flux, they have not previously been directly observed. Their energy is at a delicate point for confirmation of the vacuum-to-matter oscillation transition. In these proceedings, I will present the status of the Borexino experiment as of August 2006, as we prepare for final filling of the detector.

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SOLAR NEUTRINOS

Neutrinos today make up one of the most active topics at the intersection of nuclear and particle physics. While landmark experiments (most recently including Super-Kamiokande [1], SNO [2] and KamLAND [3]) have nailed down basic aspects of neutrino oscillations, many questions remain unanswered. These include both problems of fundamental physics such as the ordering and absolute scale of the neutrino mass hierarchy, and uncertainties in astrophysical models of such phenomena as supernovae and even solar fusion. For instance, the relative rates at which various nuclear reactions in the Sun produce neutrinos are in many cases theoretically uncertain to 10% or greater [4]. Experiments have not yet been able to reduce these uncertainties, for the neutrinos with $E < 2$ MeV that make up ~99% of the solar ν flux have so far been observed only in radiochemical experiments, not on an individual event basis.

Canonical Neutrino Oscillations

Solar neutrinos are, to the best of our knowledge, always created in the ν_e flavor eigenstate. However, low-energy solar neutrinos "oscillate" as they travel through the vacuum between Sun and Earth: the principal mass eigenstate components ν_1, ν_2 interfere with each other. The oscillation wavelength is much smaller than the radius of the core of the Sun. Therefore, instead of seeing probability wave crests and troughs at Earth, we observe the ν_e state with a single probability that is given by the averaged value $P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta \approx 57\%$. ($\theta$ represents the solar mixing angle.)

The behavior of high-energy solar neutrinos is, on the other hand, governed mainly by the Mikheyev-Smirnov-Wolfenstein (MSW) effect [5,6]. Only electron neutrinos may interact with ordinary matter via charged current reactions. This fact alters the neutrino Hamiltonian in dense matter. The energy eigenstates ν_1^m, ν_2^m there are different from the mass eigenstates ν_1, ν_2 in vacuum, and also depend upon the local electron density n_e. For a neutrino of energy E in matter having $n_e >> \Delta m^2 c^4 / G_F E$ (or equivalently, for solar neutrinos of sufficiently high energy, $E > 2$ MeV), the ν_e flavor eigenstate is essentially equivalent to the higher-energy local energy eigenstate ν_2^m. As it travels out of the Sun, it evolves adiabatically into the vacuum mass eigenstate ν_2. These neutrinos thus do not oscillate between Sun and Earth; we will detect them as electron neutrinos with probability $P_{ee} = \sin^2\theta \approx 31\%$. A plot of P_{ee} as a function of E therefore should show a transitional region in the range 1-2 MeV, as the curve decreases continuously from the vacuum oscillation value to the MSW value.

According to the canonical MSW "large mixing angle" (LMA) model, the solar mixing angle is $\theta \approx 34^\circ$; the other solar oscillation parameter is $\Delta m^2 \approx 8 \times 10^{-5}$ eV^2 [7].

Observable Effects of Non-Standard Neutrino Interactions

If non-standard interactions (NSIs) occur between neutrinos and the fundamental particles of normal solar matter (e^-, u, d), they will introduce additional terms into the neutrino Hamiltonian in matter. The coefficients $\varepsilon_{\alpha\beta}$ of these terms ($\alpha, \beta \in \{e, \mu, \tau\}$) are *a priori* unknown, though some constraints exist. If they are allowed to vary, along with the neutrino oscillation parameters (Δm^2, θ), then several solutions satisfying the observed solar, atmospheric and reactor neutrino data may be found with non-zero $\varepsilon_{\alpha\beta}$, having values for the oscillation parameters that are non-trivially different from those of the LMA model. As detailed for instance in [8], these solutions would produce markedly different shapes for the P_{ee} curve in the transitional energy region (Fig. 1). Measuring the fluxes of the low-energy, monoenergetic ^{7}Be and *pep* solar neutrinos (with respective energies of 0.862 and 1.44 MeV) could experimentally distinguish between many NSI models and the canonical LMA model.

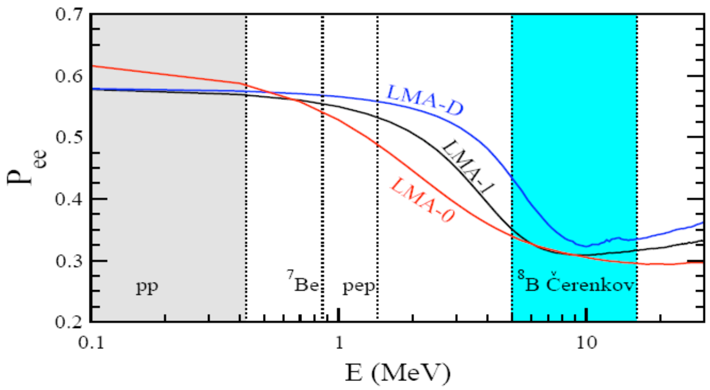

FIGURE 1. Comparison of the P_{ee} curve as a function of solar neutrino energy between the standard LMA model ("LMA-I") and models with non-standard neutrino interactions ("LMA-0" and "LMA-D"). The vertical lines labeled ^{7}Be and pep indicate the two monoenergetic neutrinos in the transition region. Figure taken from reference [8] and reproduced with permission from Elsevier.

Other non-standard neutrino behaviors, such as mass-varying neutrinos [9], have also been proposed, many of which could also be detected through their effect on the vacuum to matter P_{ee} transition.

THE BOREXINO EXPERIMENT

The Borexino experiment [10] is a neutrino observatory designed to detect the ^{7}Be solar neutrinos and, if conditions are good, *pep* neutrinos predicted by the Standard Solar Model [4]. In particular, it will attempt to verify that they oscillate in the expected manner, check the SSM prediction for the relationship between neutrino flux and solar luminosity, and explore the vacuum-matter transition. Borexino also has the secondary goals of detecting antineutrinos produced by radioactive isotopes in the Earth [11,12]; observing accelerator neutrinos from CERN; and, in the event of fortunate timing, measuring the spectrum of neutrinos from a galactic supernova [13].

Unlike many previous solar neutrino experiments, Borexino's detection mechanism is primarily based not on Cherenkov light, but on scintillation light produced when neutrinos scatter electrons from molecules of a liquid benzene derivative, pseudocumene, with an added fluor, PPO [14]. The 380-nm light is detected by an array of > 2200 photomultiplier tubes. The active portion of the detector consists of 300 tons of ultra-pure scintillator. To improve the S/N ratio, only data from a central fiducial volume (nominally 100 tons) will be used.

The scintillator is surrounded by concentric layers of graded shielding (Fig. 2): volumes of inactive buffer fluid; nylon containment vessels that retard inward migration of radon gas; and an outer water tank that blocks external neutrons and γ rays, while also permitting the detection and veto of muons produced by cosmic rays. To reduce the muon rate to a manageable value, the detector is located under 3500 meters water equivalent of rock, in the Laboratori Nazionali del Gran Sasso (LNGS) underground facilities of central Italy. As radiopurity is extremely important for the detector, a prototype 4-ton Counting Test Facility, or CTF [15,16], has been operated for years to study how to purify the scintillator. Recent CTF results indicate that attaining the required scintillator radiopurities in Borexino is entirely feasible.

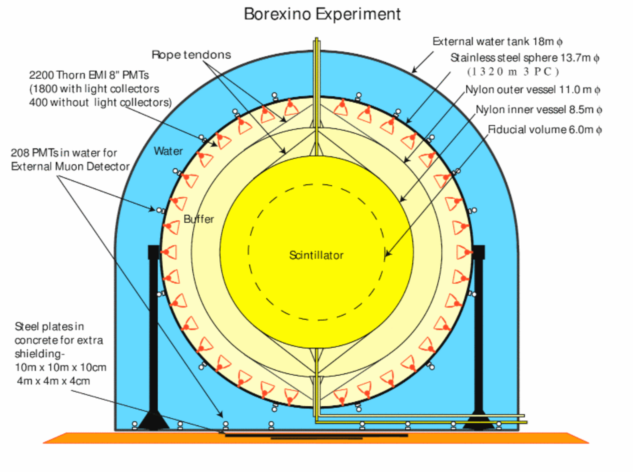

FIGURE 2. The design of the Borexino neutrino detector.

BOREXINO RECENT HISTORY AND STATUS

On August 16, 2002, about 50 liters of pseudocumene were by mistake released into a drain in the underground lab, which (unbeknownst to the experiment) had an outlet into a surface stream. The ramifications were unpleasant [17]. Fluid operations (both water and pseudocumene) were forbidden for > 2 years, and it became clear that the drainage systems of the laboratory would have to be completely reworked.

The controlling agency of the lab, the Istituto Nazionale di Fisica Nucleare (INFN), embarked on a massive reconstruction of these systems. This was a complicated and delicate procedure, as natural springs near the laboratory also supply drinking water for nearby cities. One of the underground highway tunnels that pass by the lab was reconstructed for the installation of new pipes, closing access to traffic for six months. In addition to this $50M project, barriers against possible large-scale liquid spills were installed, and sealant was added on the floors of the LNGS experimental halls.

Installation of Borexino nevertheless continued in parallel. In 2004, a watershed year, the nylon containment vessels were installed and inflated to a spherical shape. Following work included modifications and commissionings of purification plants, further CTF tests of the plants, and purging of the detector with special low-Ar/Kr N_2 gas. Permission to use water on a large scale was granted at the end of July, 2006.

The next month, water filling of the detector began. When it is complete, Borexino will be usable as a water Cherenkov detector for the ν beam produced at CERN. Once the outer water tank has also been completely filled, water in the detector may be replaced by scintillator, the final step in making the experiment fully operational. The first low-*E* solar ν signals, for which scintillator is needed, are expected in 2007.

ACKNOWLEDGMENTS

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