

# The Borexino Nylon Film and the Third Counting Test Facility

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# Abstract

The Borexino solar neutrino detector should begin operations in late 2006. This scintillation-based detector will observe low-energy neutrinos, in real time, down to about 250 keV. The experiment should further tighten constraints on the neutrino oscillation parameters, and confirm the Standard Solar Model of solar neutrino production. It may also observe geoneutrinos; supernova neutrinos, should the timing of the experiment be fortunate; and perhaps other processes beyond the scope of the Standard Model of particle physics.

At the heart of Borexino lie 300 tons of organic scintillator fluid, contained by a spherical vessel composed of transparent nylon film. Roughly 300 tons of passive buffer fluid lie between this inner vessel and a second outer nylon vessel. Both vessels are located inside a steel sphere that also supports over 2000 inward-pointing photomultiplier tubes. The two most vital components of Borexino are these nylon vessels and the scintillator itself. Numerous measurements made at Princeton of the physical and radiochemical properties of the vessel film are reported in this thesis.

A 4-ton prototype of Borexino, the CTF, has been used to study scintillator radiopurity for over ten years. However, certain peculiarities of its design make determining the spatial positions of radioactive decays within the detector difficult. The development of a new position reconstruction code that takes these problems into account is reported herein.

Several studies of radiopurity in the latest version of CTF were made using this new code. These include a proposal for individually tagging decays of radon and four daughter isotopes; an attempt to detect convection using the radon daughters; a hypothesis to explain peculiar behavior of the crucial isotope  $^{210}\text{Po}$ ; and an analysis of  $^{40}\text{K}$  contamination inside the detector based on models of the spatial distribution of external  $\gamma$  rays, leading to a somewhat concerning result. A final distillation test of the scintillator will take place

shortly, and will match as closely as possible the procedure used to purify scintillator for the full Borexino detector. Analyses run on CTF data collected after this test should prove vital in understanding the detector sensitivity of Borexino.

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# Introduction

This work discusses two important topics relating to the Borexino low-energy solar neutrino experiment. Before delving into the details, it gives a series of introductions to the prerequisite knowledge. Chapter 1 discusses the current state of neutrino physics. Chapter 2 describes the expected sensitivity of the Borexino detector to neutrinos originating from various sources, and Chapter 3 covers the physical design and components of the detector.

The first major topic is that of the thin nylon film making up the nested spherical scintillator containment vessels. Of the two vessels, the inner one contains 300 tons of organic scintillator fluid, the heart of the detector. The outer one encloses the inner one; between them is a region of buffer fluid. Beyond the outer vessel is another volume of buffer fluid, encased within a spherical steel structure that also supports over two thousand inward-pointing photomultiplier tubes. The design, construction, and installation of the vessels themselves are described briefly in a section of Chapter 3. Chapter 4 goes into detail about the material properties of the nylon film measured at Princeton University: its chemical properties, tensile strength, behavior when exposed to varying levels of humidity (both in air and immersed in scintillator), and innate level of radioactivity.

The scintillator fluid must, by its very nature, be the most radiopure component of the Borexino detector. A 4-ton prototype of Borexino has been operated for more than a decade, in three different incarnations, to study its radioactive contaminants. This Counting Test Facility (CTF) does not, unfortunately, have the sensitivity to prove once and for all that the Borexino scintillator is suitable, but only to point out potential areas of trouble with it. For reasons of practicality, the CTF incorporates some design elements that make data analysis difficult. Instead of an organic buffer fluid, for instance, water is used as a buffer in the CTF, leading to non-negligible refraction of light at the nylon vessel that separates the two liquids. The development of methods for accurately determining the positions of

events in the CTF and the analysis of data from the third CTF incarnation, operated from 2001 to date, therefore comprise the last five chapters of this work.

Chapter 5 begins by discussing a theoretical likelihood-based approach to determining the expected spatial resolution of a scintillation-based detector. The ability of a detector to perform position reconstruction (determine the spatial position of an event) is important in separating events due to external radioactivity (on the surface of the detector, for instance) from those that actually represent the desired signal. Better spatial resolution implies a better separation efficiency. The results derived are general, and applicable to any large unsegmented scintillator-based detector. They may potentially be useful, therefore, in the design of new detectors intended to look for dark matter or to observe neutrinoless double  $\beta$  decay. The chapter concludes by presenting the expected radial distributions for “internal” events (those uniformly distributed throughout the scintillator) and “surface” events (those on the outer surface of the scintillator volume).

Chapter 6 describes the CTF itself. Topics covered include the physical design of the detector; the data acquisition system; the format of the data files (which is not, to my knowledge, documented anywhere else); and the history of the CTF and its previous results.

Chapters 5 and 6 provide the necessary background for Chapter 7, which discusses the many difficulties faced by any attempt to perform position reconstruction in the CTF. Some methods to overcome them are proposed, and these methods are compared using data from two sets of source calibration runs (data acquisition on a pointlike radioactive source moved to different known positions inside the CTF). A preferred algorithm to deal with the effects of refraction at the scintillator-water interface uses a numerical series expansion of a time-of-flight function for a light ray traveling from points inside the scintillator to points at the photomultiplier tube cathodes. The timing statistics of multiple photoelectrons detected at a single photomultiplier are also carefully considered. The performance of the preferred algorithm, developed by the author at Princeton, is compared to that of other position reconstruction codes that have been used with CTF data.

Finally, Chapters 8 and 9 present results for the radioactive contamination of the CTF scintillator and vessel, respectively, that were obtained using the reconstruction code described in Chapter 7. Particular attention is paid to the heavy-element decay chains  $^{238}\text{U}$  and  $^{232}\text{Th}$ . A likelihood-based method of tagging five isotopes in the  $^{238}\text{U}$  decay chain ( $^{222}\text{Rn}$ ,  $^{218}\text{Po}$ ,  $^{214}\text{Pb}$ ,  $^{214}\text{Bi}$ ,  $^{214}\text{Po}$ ) is proposed, and through Monte Carlo simulations and data analysis, found to be quite promising for use in Borexino. The distribution and behavior of the isotope  $^{210}\text{Po}$  (an indicator of the more problematic  $^{210}\text{Bi}$ ) are found to be consistent with the presence of small particulate matter in the scintillator. In addition, the distribution of  $\gamma$  rays produced by the electron-capture decay of  $^{40}\text{K}$  is simulated with three different models; two of the models yield a result suggesting significant  $^{40}\text{K}$  contamination of the scintillator. A final distillation test of the scintillator, to take place within the next few months, will match as closely as possible the purification procedure used in the full Borexino detector. Analyses of CTF data collected after this test, performed in a similar way to those discussed in this work, should prove vital in determining the effectiveness of the distillation.

This work, despite its length, could not possibly discuss all aspects of the Borexino experiment and the CTF in an even-handed manner. For in-depth coverage of related topics of interest, the reader is referred to the literature on the Borexino experiment.

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# Introducing the Neutrino

The neutrino is perhaps the most negligible piece of matter that can be imagined. It is immune to effects of the electromagnetic and strong nuclear forces. Its mass, originally thought to be zero, is less than one-millionth that of the electron. The only one of the four fundamental forces that can affect it significantly is the weak nuclear force, the least powerful of the short-range interactions. When its existence was first postulated by Pauli in 1931, it was thought of as a sort of ghost particle whose offense against Occam's razor was deemed only slightly more palatable than the violation of matter conservation that would otherwise occur in some radioactive decays.

From this inauspicious beginning, the neutrino became one of the most-studied particles of the last quarter of the twentieth century. At the beginning of the twenty-first, the interest of the scientific community shows no sign of waning. Paradoxically, much of this interest results from the same reluctance to interact with other matter that made the neutrino so difficult to discover in the first place. Neutrinos produced at the center of the Earth, the Sun, or even in supernovae can tell us a lot about conditions in those otherwise inaccessible places—once we solve the problems of detecting them, that is!

The neutrino is even more fascinating because it is one of the first particles directly observed to contradict the predictions of the highly successful Standard Model of particle physics. It is not supposed to have a mass, but it does. It is supposed to exist as three separate