A Preliminary Look at the Physics Reach of a Solar Neutrino TPC: Time-Independent Two Neutrino Oscillations

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The results of work presented in greater detail in Snowmass[1] is presented. A solar neutrino TPC can determine the neutrino mass and mixing parameters to a precision varying from 3 to 100%, depending on the exact parameter region. The reduction factor of the allowed parameter space is estimated to be of order 20.

1. Introduction.

If it is true that one of the neutrino mass scales is at or below $10^{-5}\mathrm{eV}^2$, it is unlikely that precision measurements of those regions can be done with terrestrial experiments.

Further, completion of the solar neutrino program may require the evaluation of the solar neutrino energy spectrum, both in the ν_e component and in the sum of the other two components, ν_x.

This paper will discuss the physics reach of a solar neutrino TPC containing many tons of ^{4}He under high pressure. The rationale for developing such a device is that it can cover the rest of the solar neutrino program while measuring the mass and mixing parameters anywhere between a few percent to 100%, depending on the exact mass-mixing region. In the first year of data taking, this device would unambiguously observe (pp) neutrinos and distinguish between the LMA and SMA solution.

A TPC is radically different from all other solar neutrino experiments in that it measures the direction of the target particle (the electron). It also has a much finer granularity than other detectors, easily distinguishing between electron and non-electron events, and events of multiplicity one and events of multiplicity two or higher.

Directionality provides three things.

First, in our approach, the scattering of a solar neutrino off of a target electron ($\nu e \to \nu e$) results in a completely reconstructed electron track (Fig.1). From the simultaneous reconstruction of the electron recoil energy (T_e) and its angle with respect to the solar axis ($\theta_\odot$), the neutrino energy for each event is given by

$$E_\nu = \frac{mT_e}{p\cos\theta_\odot - T_e}\ . \tag{1}$$

At 100 keV electron energy, and 10 Atm, the electron flies for about 9 centimeters, allowing tracking.

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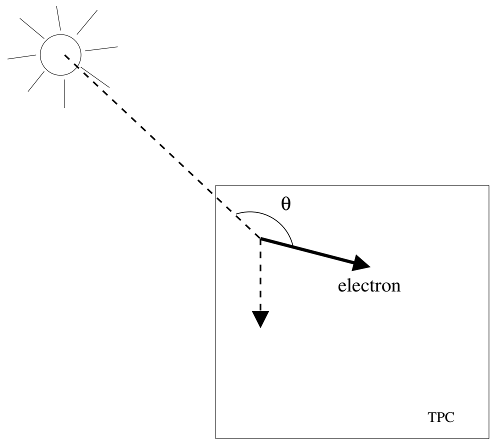

Figure 1: The solar neutrino detection scheme. The recoiling electron energy and direction are measured, and the neutrino energy is reconstructed according to Eq. 1. Only a small fraction of the solid angle around the solar axis is considered at any given time.

Second, directionality allows a direct reduction of backgrounds by a factor of four to ten. Only events pointing in a cone directly opposite the solar angle are considered, with a $\cos\theta_{\odot}$ cut ranging from 0.5 to 0.8. Directionality allows us to measure, up to statistical fluctuations, all the backgrounds that affect the experiment. The method compares the event rates pointing towards the Sun (which measure the backgrounds) against the rate of those recoiling away from the Sun (which include both signal and background). By "all the backgrounds" we mean both internal (^{14}C, ^{85}Kr, Rn) and external backgrounds (^{238}U, ^{232}Th, ^{40}K, and cosmogenic activity in the surrounding materials).

One consequence of a direct measure of the background is that the errors will be statistically dominated. Under any realistic circumstances, the number of background events far exceeds the number of signal events, and 1% detector calibration is possible using well-tagged, kinematically constrained background events[1], in practice making all sorts of systematic errors negligible.

Third, the electron recoil spectrum depends on the neutrino flavor. The number of measured events in $\{E_\nu,\ T_e\}$ bins is related to the νe scatter cross-sections by

$$\frac{d^2N}{dE_\nu dT_e} = P_e\frac{d\sigma_{\nu_e e}}{dT_e} + (1-P_e)\frac{d\sigma_{\nu_\mu}}{dT_e} \quad (2)$$

$$(3)$$

$$= F_1 - s(1-P_e)F_2 \quad (4)$$

where

$$F_1(E_\nu, T_e) = (1/2+s)^2 + s^2(1-T_e/E_\nu)^2 - s(1/2+s)\left(1-\frac{mT_e}{E_\nu^2}\right) \quad (5)$$

$$F_2(E_\nu, T_e) = 2 - \frac{mT_e}{E_\nu^2} \quad (6)$$

and $s = \sin^2\theta_W$. Given enough statistics, the ν_e and ν_x fluxes can be extracted independently.

2. Simulation results.

Fig. 2 shows the measured neutrino energy spectrum for an exposure of 70 Ton-yrs, with realistic cuts, a background rate of order a few hundred events per day, and an electron angular resolution of 15 degrees at 100 keV kinetic energy. For more details, see[1]. Table 1 shows the expected mass and mixing precisions to be obtained under such conditions. These values were obtained by globally fitting the spectrum, assuming the SSM predictions.

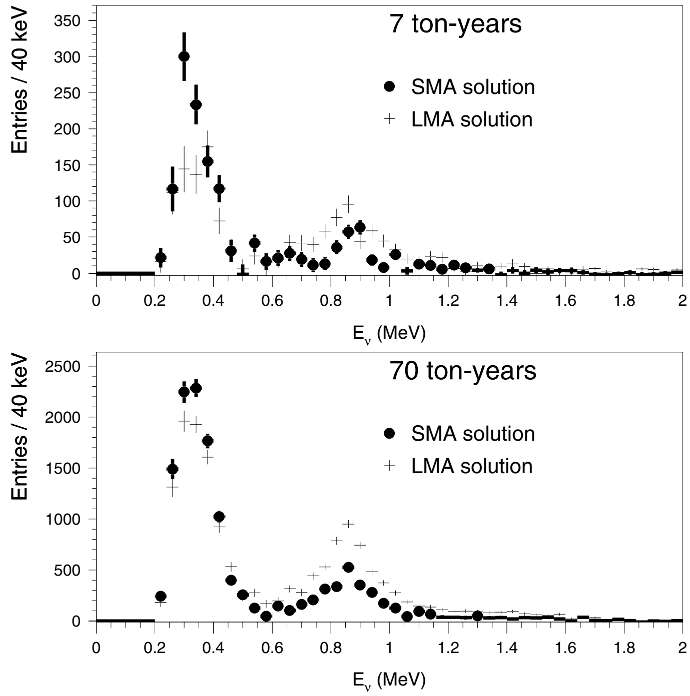

Figure 2: MC prediction of experimental neutrino energy spectrum for LMA (dots) and SMA (crosses) solutions. The top (bottom) plot corresponds to 7 (70) Ton-years.

By comparing the 95% allowed region with the current one[2], the expected parameter space reduction factor is 20 in the so-called LMA region. The so-called SMA region is not favored by the current data, so a similar factor could not be obtained. The numbers are indicative because, in practice, the LMA and SMA regions imply two neutrino oscillations, which is not the case in Nature. It is very possible that the great amount of information recovered by the TPC, and its purely statistical error, can help disentangle a three neutrino solution.

In conclusion, a solar neutrino TPC could measure to good precision (about 1%) the solar neutrino energy spectrum, and substantially shrink the allowed parameter space region.

Table I Physics reach of the TPC for an exposure of 70 ton-years. All errors in percent of the central value.

Parameter	Value(%)
$\delta(\Delta m^2)$, LMA	~ 30
$\delta(\Delta m^2)$, SMA	3 to 10
$\delta(\sin^2 2\theta)$, LMA	~ 7
$\delta(\sin^2 2\theta)$, SMA	5 to 100
Reduction factor, LMA	~ 20
Reduction factor, SMA	NA

References

[1] G. Bonvicini *et al*, hep-ph/0109199.
[2] J. Bahcall, M. C. Gonzalez-Garcia and C. Pena-Garay, hep-ph/0106258.