The Palo Verde Neutrino Oscillation Experiment

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We report results of the measurement of the anti-neutrino flux and spectrum at a distance of about 800 m from the three reactors of the Palo Verde Nuclear Generating Station using a segmented gadolinium-loaded scintillation detector. We find that the anti-neutrino flux agrees with that predicted in the absence of oscillations $\bar{\nu}_e - \bar{\nu}_x$ oscillations with $\Delta m^2 > 1.12 \times 10^{-3}$ eV^2 for maximal mixing and $\sin^2 2\theta > 0.23$ for large Δm^2.

1 Introduction

The Palo Verde neutrino oscillation experiment [1] is located at the Palo Verde Nuclear Generating Station near Phoenix, Arizona. Two of the three reactors are 890 m from the detector while the third is at 750 m distance. The total thermal power of the reactors is 11.6 GW. Neutrino oscillation is searched for by looking for distortions or attrition in the spectrum of $\bar{\nu}_e$'s interacting via inverse β decay, $p+n \rightarrow e^+ + n$, at the detector. This experiment, along with the complementary Chooz experiment in France [2], were motivated by the original Kamiokande atmospheric anomaly result [3], and is sensitive to neutrino oscillation at large mixing angles down to mass differences Δm^2 of $\sim 10^{-3}$ eV^{-2}.

The detector is in a shallow underground site with a 32 m water equivalent overburden. The overburden eliminates the hadronic component of cosmic radiation and reduces the cosmic muon flux to 22 $m^{-2}s^{-1}$. All materials in the lab and detector were selected for low activity to reduce the ambient γ ray flux. The detector, shown in Figure 1, consists of an 11×6 array of acrylic cells filled with 11.3 tons of scintillator loaded 0.1% by weight with Gd. The signal, inverse β decay, $p+n \rightarrow e^+ + n$, produces a two part event correlated in time: the initial positron ionization and annihilation, and, $\sim$30 μs later, neutron capture on Gd releasing an 8 MeV γ cascade. Surrounding the central detector is a 1 m water buffer to attenuate γ's and neutrons emanating from the lab walls. Surrounding the passive buffer is a hermetic veto system to tag and time stamp cosmic muons passing through the detector.

Each cell is viewed by two 5 in. photomultipliers, one at each end. The relative time of arrival of signals is used to locate the longitudinal location of an energy deposit; the energy of the deposit is then determined by correcting the light seen at each end for attenuation due to propagation along the cell.

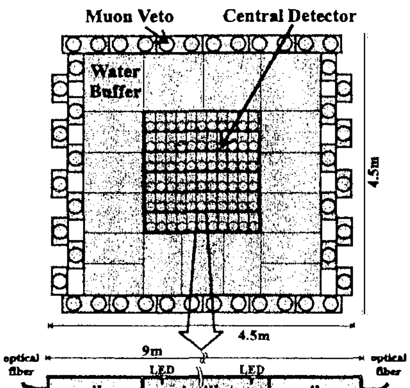

Fig. 1 Schematic view of the Palo Verde detector with one of the 66 target cells shown lengthwise at bottom.

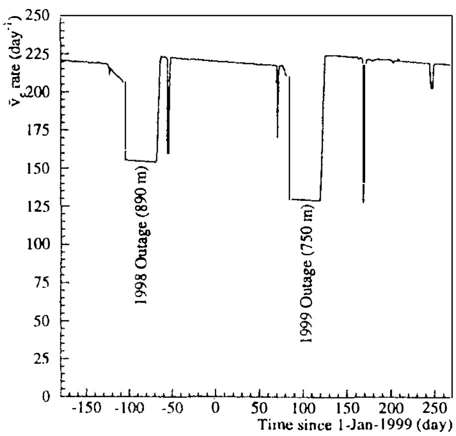

Fig. 2 The calculated $\bar{\nu}_e$ interaction rate in the detector target. The two long periods of reduced flux are reactor refuelings.

The segmentation allows background rejection at the trigger level by looking for patterns of energy deposits matching the inverse β decay signal. The prompt and delayed portion of the signal are both triggered by the same condition of coincident energy deposits: at least one cell above a high trigger threshold (the e^+ ionization or neutron capture cascade core) and at least two cells above a low threshold (e^+ annihilation γ's or neutron capture cascade tails) in a subset of the detector array.

The expected $\bar{\nu}_e$ interaction rate in the detector is calculated daily and used to compare to the rate seen in the data (see Figure 2). Previous generations of reactor $\bar{\nu}_e$ experiments have shown that the expected rate calculation is accurate to better than 3% [4]. We expect $\sim$220 interactions per day in the target with all three reactors at full power. Reactor refuelings provide periods of reduced $\bar{\nu}_e$ flux which may be used to subtract backgrounds.

2 Calibration

The detector must be calibrated carefully since the measurement requires knowledge of the absolute $\bar{\nu}_e$ interaction detection efficiency. We use a system of LED and fiber flashers to monitor weekly the timing characteristics, linearity, and gain of the photomultipliers. The energy response of the detector, a function of position due to light attenuation in the scintillator, is determined by measuring the Compton scattering spectrum from various γ sources at several longitudinal positions along each cell. Since the Gd scintillator degrades with time this source scan is repeated every three months.

Since the trigger efficiency is a function of thresholds (Voltage) while only energy (charge) is measured, the $\bar{\nu}_e$ detection efficiency is estimated using a Monte Carlo which includes a detailed simulation of the detector response including the photomultiplier pulse shape. In addition to calibrations required for event reconstruction, various measurements were made to confirm the Monte Carlo simulation accurately models detector response. A ^{22}Na source was used to measure the trigger low and high trigger thresholds in terms of energy at the center of each cell and compared with the prediction of Monte Carlo simulation, as shown in Figure 3. Similarly we checked position and energy resolutions and found good agreement.

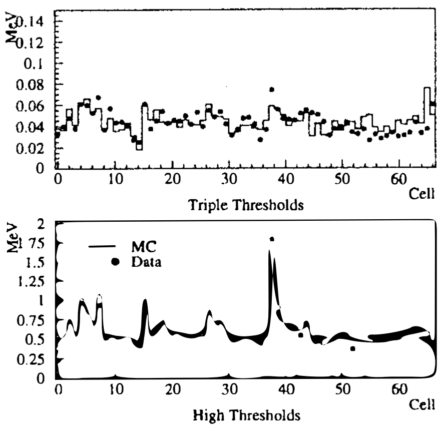

Fig. 3 Trigger thresholds in MeV at the center of each of the 66 cells as measured and predicted by Monte Carlo.

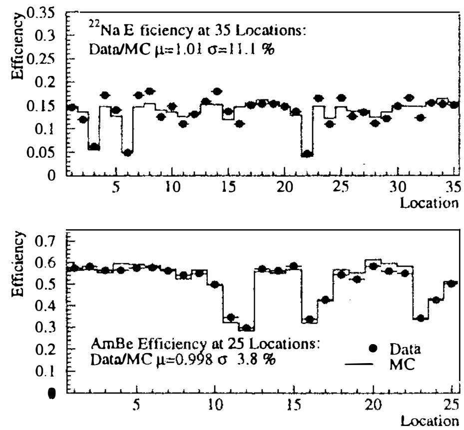

Fig. 4 Comparison of data and Monte Carlo detection efficiency for Am-Be and ^{22}Na source runs at various locations. Locations at the edge of the detector tend to have lower efficiencies.

We used a ^{22}Na and Am-Be source to measure positron and neutron absolute detection efficiency, respectively, at various locations in the target fiducial volume. On average, the data and Monte Carlo agreed well in overall detection efficiency as shown in Figure 4. These calibrations together represent a test of the Monte Carlo's fidelity to the entire $\bar{\nu}_e$ signal, and were used in estimating the systematic uncertainty in our efficiency estimate.

3 Analysis

The data presented here has 67 days in 1998, 31 days of which a reactor at 890 m was off for refueling. After improvements made to the trigger and detector in early 1999, an additional 134 days of data have been analyzed including 23 days of data with the 750 m distant reactor off. Due to changed detector efficiency and live time we treat the two years' full flux data set separately in the analysis.

The $\bar{\nu}_e$ events were selected by the following criteria:

- The prompt and delayed portion of the events should have at least one hit above 1 MeV and two hits above 50 keV, to verify the trigger.
- The prompt portion is required to resemble a positron, i.e. the annihilation γ's each less than 600 keV.
- The prompt and delayed portion must be correlated in time and space, i.e. within three columns, two rows, one meter longitudinally and 150 μs.
- Either of the two portions must have more than 3.5 MeV reconstructed energy to reject γ backgrounds.
- The time since the previous muon in the veto must be greater than 150 μs to reject cosmic ray backgrounds.

After $\bar{\nu}_e$ selection substantial background remains. Backgrounds come in two types, those able to mimic the time correlation signature (correlated) and those due to random coincidences of two triggers (uncorrelated). The latter can be measured due to the different time structure of the time between prompt and delayed trigger, as shown in Figure 5. This background, due mostly to γ's is small at 9% of the data set.

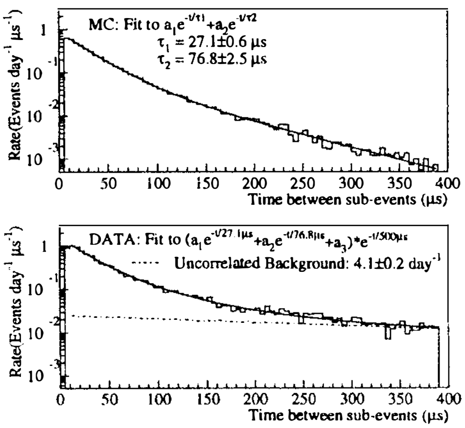

Fig. 5 The time elapsed between prompt and delayed portions of neutrino candidate events for Monte Carlo simulation and data. The tail at longer times in the data is uncorrelated background.

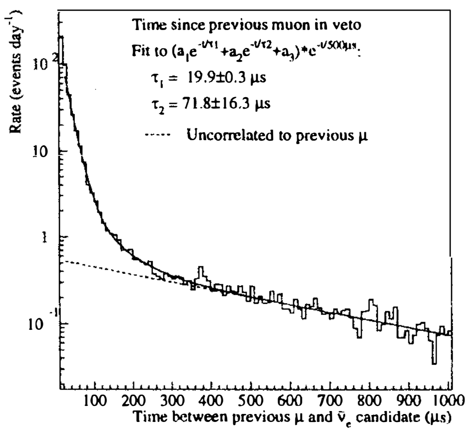

Fig. 6 The time between the previous muon traversing the veto and the neutrino candidate events.

Correlated backgrounds come mainly from cosmically induced fast neutrons from μ capture or from spallation in the detector or lab walls. This background tends to be correlated with cosmic μ's, as illustrated in Figure 6, but cannot be fully rejected due to μ's passing through the lab without hitting the veto. These neutrons can either cause proton recoils while thermalizing in the target resembling a positron and then capture, or create secondary neutrons both of which are captured in the target. The spectrum and yield of these fast neutrons is poorly understood and as such cannot be subtracted directly. We subtract the remaining background using two different methods.

3.1 Analysis with on-off *method*

The simplest method of subtracting background is to subtract the full power candidate rate from the reduced flux rate. Assuming the backgrounds to remain constant, one is left with only $\bar{\nu}_e$ signal after the subtraction. By tracking the rate of candidates following shortly after a tagged veto hit, we can track the correlated background rates and find them to be constant over each year's data set. This method suffers two statistical disadvantages, however, in that in the subtraction one treats the signal contribution of the two reactors which remain at full power as background, and the statistical power is limited to that of the reduced flux period, generally only one month long. After subtraction and efficiency correction we see 95±19 (77±14) $\bar{\nu}_e$/d in 1998 (1999), compared to the expected interaction rate of 63 (88) from the 1998 (1999) refueling reactor. We see no significant deviation from expected rates. The subtraction also yields an observed positron energy spectrum, which agrees well with expected as shown in Figure 7. From these results we use the Feldman and Cousins prescription [5] to attain an excluded region in the plane of mixing and mass difference parameters, as shown in Figure 7. We estimate the systematic uncertainty of this method to be 10%, due mainly to the selection cuts.

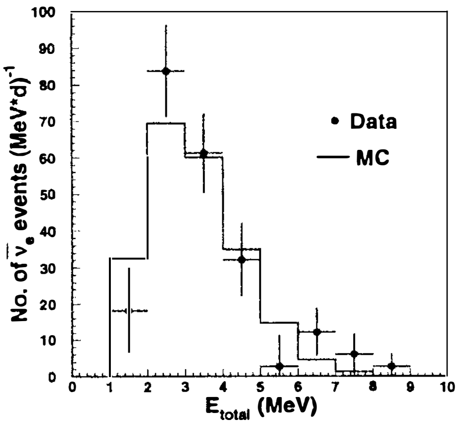

Fig. 7 The observed positron energy spectrum after the *on-off* background subtraction.

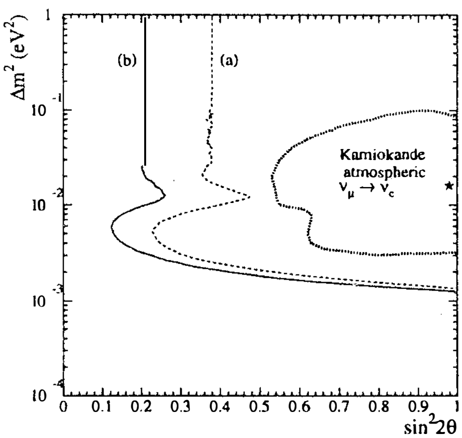

Fig. 8 The excluded region of the $\sin^2 2\theta$, Δm^2 parameter space from (a) the *on-off* analysis and (b) the *swap* analysis.

3.2 Analysis with swap *method*

A second method of subtracting background takes advantage of the asymmetry between the prompt and delayed portions of the neutrino signal [6]. The data selections and trigger treat the two portions of the event identically with the exception of the cut designed to isolate the annihilation γ's of the prompt portion of the signal. The number of candidates remaining after the normal selections can be written as:

$$N = B_{\rm unc} + B_{\rm nn} + B_{\rm pn} + S_{\bar{\nu}_e} \tag{1}$$

where $B_{\rm unc}$, $B_{\rm nn}$, and $B_{\rm pn}$ are the uncorrelated, two neutron capture, and proton recoil backgrounds respectively, and $S_{\bar{\nu}_e}$ is the signal. We can then apply the positron selection to the delayed portion of the event instead of the prompt to get a second candidate set:

$$N' = B_{\rm unc} + B_{\rm nn} + \epsilon_1 B_{\rm pn} + \epsilon_2 S_{\bar{\nu}_e}. \tag{2}$$

Note that the prompt and delayed portions of the first two backgrounds are symmetric, and have equal efficiency for both selections. The relative efficiency for proton recoil and $\bar{\nu}_e$ events are parameterized

Period	1998 ON	1998 OFF 890 m reactor off	1999 ON	1999 OFF 750 m reactor off
time (days)	35.97	31.35	110.95	23.40
$\bar{\nu}_e$ overall efficiency (%)	7.46	7.72	11.2	11.1
$(1-\epsilon_1)B_{pn}$ (day^{-1}) μ spallation	0.88	0.91	1.35	1.33
$(1-\epsilon_1)B_{pn}$ (day^{-1}) μ capture	0.58	0.58	0.86	0.86
N (day^{-1})	38.2 ± 1.0	32.2 ± 1.0	52.9 ± 0.7	43.9 ± 1.4
N' (day^{-1})	24.6 ± 0.8	21.2 ± 0.8	32.3 ± 0.5	31.7 ± 1.2
N_ν (day^{-1})	16.5 ± 1.4	13.5 ± 1.4	25.1 ± 0.9	15.0 ± 1.9
Background $B_{unc} + B_{nn} + B_{pn}$ (day^{-1})	21.7 ± 1.0	18.7 ± 1.0	27.8 ± 0.6	28.8 ± 1.3
R_{obs} (day^{-1})	221 ± 19	174 ± 17	225 ± 8	137 ± 17
R_{calc} (day^{-1})	218	155	218	130

Table 1: Results for the *swap* analysis, including the various background estimates. Uncertainties are statistical only.

by ϵ_1 and ϵ_2 respectively. Subtracting the two sets then gives

$$N - N' = (1-\epsilon_1)B_{pn} + (1-\epsilon_2)S_{\bar{\nu}_e}. \tag{3}$$

where we estimate ϵ_2 to be 0.159 using Monte Carlo. The subtraction then preserves the majority of the signal and leaves only ϵ_1 and B_{pn} to be addressed. The fast neutrons which contribute to B_{pn} come from μ capture and μ spallation.

The spectrum and yield of the former is poorly known. To measure B_{pn}, however, we note events in the data set with prompt energies above 10 MeV contain only proton recoil events. We can then use Monte Carlo to find the ratio of events above this energy to those in the $\bar{\nu}_e$ energy range. We attain this ratio for various possible fast neutron spectra, and find that it is relatively decoupled from the form of the originating fast neutron spectrum. To estimate $\epsilon_1^{\text{spall.}}$, we similarly simulate various spectra to find $\epsilon_1^{\text{spall.}} = 1.14 \pm 0.07$ after averaging over spectra; the spallation neutron proton recoil background is very symmetric and almost entirely eliminated in the subtraction.

The spectrum and yield fast neutrons from μ capture is reasonably well known and we can calculate $\epsilon_1^{\text{capture}} = 0.77 \pm 0.32$ and $(1-\epsilon_1)B_{pn}$ from μ capture to be 0.58 (0.86) events/day in 1998 (1999), from both capture in the lab walls and muons missed by the veto and captured in the detector shielding.

After correcting the subtraction, $N - N'$ for proton recoil contributions, we find the number of $\bar{\nu}_e$ events seen for each period as summarized in Table 1. Again we see no significant deviation from the expected interaction rate and can find an excluded region in the oscillation parameter plane, Figure 8. Note that the statistical power of this subtraction is substantially better than the *on-off* method. We estimate the systematic uncertainty of this analysis to be 8%. Systematic effects encountered previously due to time varying effects cancel in this analysis, but have an additional component due to uncertainties in calculating B_{pn}.

In conclusion, the Palo Verde neutrino oscillation experiment sees no evidence of oscillation in the $\bar{\nu}_e \to \bar{\nu}_x$ channel. Together with results from Super Kamiokande [7] and Chooz [2], the atmospheric neutrino anomaly is very unlikely to be caused by $\nu_\mu \to \nu_e$ oscillations. We plan to take at least two more refueling outages in data, roughly doubling the data set presented here.

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