Prospects for a day-night ^{37}Cl solar-neutrino oscillation experiment

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If neutrino oscillations in the solar interior are responsible for the suppressed ^{8}B solar-neutrino flux measured by the Homestake ^{37}Cl detector, then for certain values of neutrino mass difference and mixing angle, distinct day-night differences in the counting rate are expected due to propagation effects in the Earth. We describe the plans to measure day-night variations with the ^{37}Cl detector, and present the results of calculations of ^{37}Cl detector sensitivity and expected results.

I. INTRODUCTION

The ^{37}Cl solar-neutrino detector in the Homestake Gold Mine,[1,2] has been operating since 1970. The result of 88 extractions is a measured $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ rate of 0.39±0.05 ^{37}Ar atoms/day above a terrestrial background of 0.08±0.03 atoms/day, or 2.1±0.3 SNU (1 solar-neutrino unit$=10^{-36}$ neutrino interactions/target atom/day) above a terrestrial background of 0.4 SNU. This measured value is a factor of 3–4 lower than the values of 5.8–8.2 SNU predicted by standard solar-model calculations.[3,4] It has been suggested that neutrino oscillations in the solar interior[5,6] may be responsible for the discrepancy between theory and experiment: if electron neutrinos are produced with the predicted intensities in the Sun's dense core region, then, for certain values of neutrino mass difference and mixing angles, the ν_e will oscillate into ν_μ or ν_τ as they travel outward through the solar interior. For neutrino eigenstates with mass differences $5\times 10^{-8} \leq \delta m^2 \leq 10^{-4}$ eV^2 and vacuum mixing angles $0.02 \leq \sin 2\theta \leq 0.9$, the required factor of 3–4 suppression in the flux results naturally. The oscillation occurs in a region of the Sun where the electron density satisfies the condition

$$n_e(\mathrm{cm}^{-3}) = \frac{\delta m^2 \cos 2\theta}{2\sqrt{2} G_F E} = 6.0\times 10^{23} Y_e \rho(\mathrm{g\,cm}^{-3}) \ . \quad (1)$$

Here E is the neutrino energy, $G_F = 1.166\,36\times 10^{-5}$ GeV^{-2} is the Fermi constant, Y_e is the number of electrons per nucleon, and ρ is the mass density.

For appropriate values of δm^2 and $\sin 2\theta$ the oscillation can occur in the Earth (where $\rho \sim 3-13$ g cm^{-3}) as well as in the Sun.[7] In this case the detector is not sensitive to the ν_μ/ν_τ beam reaching the Earth by day, but is sensitive to the ν_e which can be regenerated as the ν_μ/ν_τ travel upward through several thousand km of rock at night. The ν_e-induced ^{37}Ar rate can therefore be expected to vary as a function of the neutrino pathlength through the Earth; i.e., we expect day-night and summer-winter counting rate differences. In the following, we present the results of an analysis of time variations in the ^{37}Cl detector, and discuss the prospects for modifying the experiment to look for day-night counting rate differences.

II. NEUTRINO OSCILLATIONS AND DAY-NIGHT EFFECTS IN ^{37}Cl

Nonstandard solar models, neutrino decay, magnetic moment effects, and oscillations have all been suggested as possible explanations for the observed ^{37}Cl counting rate. Parke and Walker[8] have discussed the implications of various combinations of ^{37}Cl and ^{71}Ga results in terms of neutrino oscillations. In particular, they calculate the counting rates to be expected as a function of mass difference and mixing angle for oscillations in the Sun. Here we consider terrestrial effects, and find that for the case of large mixing angles, sizable day-night counting rate differences due to ν oscillations in the Earth may be detectable in the ^{37}Cl experiment.

For simplicity we assume oscillations between two neutrino flavors only:[9] ν_e and ν_l ($l = \mu, \tau$). The ν_e and ν_l eigenstates are related by

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta \quad \text{and} \quad \nu_l = \nu_2 \cos\theta - \nu_1 \sin\theta \ .$$

If the mass difference is $\delta m^2 = m_1{}^2 - m_2{}^2$, the time development is given by

$$i\frac{d}{dt}\begin{bmatrix}\nu_e(t)\\ \nu_l(t)\end{bmatrix} = \begin{bmatrix}\frac{\delta m^2}{2E}\cos 2\theta + \sqrt{2} G_F n_e & -\frac{\delta m^2}{4E}\sin 2\theta \\ -\frac{\delta m^2}{4E}\sin 2\theta & 0\end{bmatrix} \times \begin{bmatrix}\nu_e(t)\\ \nu_l(t)\end{bmatrix} \ . \quad (2)$$

Here the $\sqrt{2} G_F n_e$ term comes from charged-current interactions of ν_e with the ambient electrons; both ν_e and ν_l undergo neutral-current interactions. When Eq. (1) is satisfied, the diagonal term disappears; even if the off-diagonal mixing terms are small, they are then the only terms remaining, so that flavor mixing must then occur.

We integrate Eq. (2) numerically, assuming the ν_e are produced at the center of the Sun with an intensity and spectrum given by the standard solar-model calculations of Bahcall *et al.*[3,10] We include all the contributions from the *p-p*, *pep*, ^{7}Be, ^{8}B, and CNO reactions. In the absence of oscillations, the detected ^{37}Ar production rate should be 5.8 SNU; of this, 4.3 SNU are expected to come from ^{8}B. We take the values of the electron density as a function of location inside the Sun from Ref. 10, and compute the ν_e and ν_l fluxes at the Earth taking into account both matter oscillations inside the Sun and vacuum oscillations in interplanetary space. Our results agree well with other similar calculations.[8,11] The solid line in Fig. 1 shows the values of δm^2 and $\sin 2\theta$ which result in a rate of 2.1 SNU measured by the chlorine detector. The horizontal branch ($\delta m^2 \sim 10^{-4}$ eV^2, discussed by Mikheyev and Smirnov[5] and Bethe[6]) corresponds to the case in which high-energy neutrinos are depleted. Along the diagonal branch ($\delta m^2 \sin^2 2\theta \sim 3 \times 10^{-8}$ eV^2, described by Mikheyev and Smirnov[5] and Rosen and Gelb[6]), low-energy neutrinos are depleted. In both these cases, the ν_e-ν_l oscillation occurs at densities well above terrestrial densities.

The vertical branch corresponds to the case of vacuum mixing as modified by passage through the matter of the Sun. Over this branch, the suppression is roughly the same at all neutrino energies. It is in this case of large mixing angles, however, that the mass density ρ can be small enough so that Eq. (1) can be satisfied in the Earth. The dashed line in Fig. 1 shows the Earth's effect. We use a phenomenological model of the Earth's interior density profile taken from Cook.[12] The electron/nucleon ratio is taken to be $Y_e = 0.5$ uniformly throughout the Earth. For each value of δm^2 and $\sin 2\theta$ we then calculate the ν_e flux and resulting ^{37}Ar rate as a function of the Sun's zenith angle (i.e., the pathlength through the Earth). We sum over an entire year, weighting the results by the exposure factor at each zenith angle at the Homestake location (Lead, SD, USA), and plot those values of δm^2 and $\sin 2\theta$ which yield a value of 2.1 SNU as the dashed line in Fig. 1.

The Earth's effect can be sizable for $10^{-6} \le \delta m^2 \le 10^{-5}$ eV^2. For the case $\delta m^2 = 5 \times 10^{-6}$ eV^2, $\sin 2\theta = 0.84$, we plot the ^{37}Ar rate versus zenith angle in Fig. 2. The number of minutes per year spent at each zenith angle is shown by the shaded region. If the Sun were directly overhead, the ^{37}Ar rate would be only 1.3 SNU. [In fact, at the Homestake latitude (44° N) the Sun never gets closer than 22° to the vertical.] The ^{37}Ar rate stays low until the Sun reaches the horizon. At a zenith angle of approximately 90°, the rate abruptly increases to above 3 SNU. At this point, it fluctuates up and down through the night. Over a full year, the average production rate is computed by folding the smooth curve of SNU versus zenith angle together with the exposure factor. The result in this case is an average ^{37}Ar rate of 1.9 SNU.

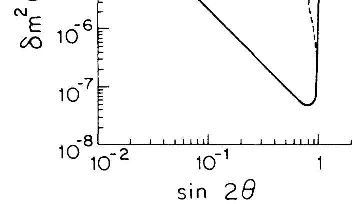

FIG. 1. Region of δm^2 vs $\sin 2\theta$ allowed by results of the ^{37}Cl experiment. Solid line assumes only solar effects; dashed line incorporates effects of neutrino oscillations in the Earth.

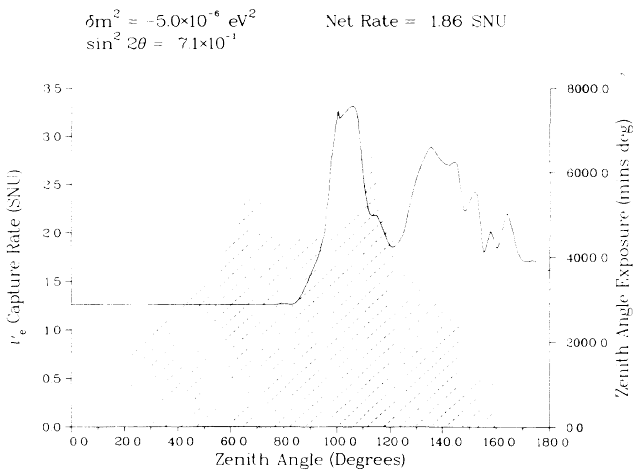

FIG. 2. ^{37}Ar rate vs the Sun's zenith angle. Shaded region gives yearly exposure at each zenith angle.

The results of the individual runs since 1970 are plotted in Fig. 3(a). The error bars are the 1σ limits derived from a maximum-likelihood analysis, as described by Rowley *et al.*[2] and Cleveland.[13] Each run is plotted at the mean time of exposure for the run, based on weighting by the 35-day ^{37}Ar decay half-life.[2] Although the individual values fluctuate from the background level up to the level predicted by standard solar-model calculations, the average over 88 runs is 2.1 ± 0.3 SNU. The thick line in Fig. 3(a) is a five-point running average of the data, which shows a distinct dip near the time of the 1980 solar maximum.[1]

In the case of argon atoms produced at a rate $P(t)$ over the time interval $t = 0$ to $t = T$, and then extracted and counted with efficiency ϵ for a time long compared to the ^{37}Ar $1/e$ decay time τ', the number of ^{37}Ar atoms detected is

$$D = \epsilon e^{-T/\tau'} \int_0^T P(t) e^{t/\tau'} dt \ . \tag{3}$$

For the measured points in Fig. 3(a), the (assumed constant) production rate is then taken to be

$$P = \frac{D}{\epsilon \tau' (1 - e^{-T/\tau'})} \ . \tag{4}$$

In the present case of a nonconstant $P(t)$, in order to compare to the measured data, we reconstruct an equivalent rate by again using Eqs. (3) and (4): in this case, the thinner curve in Fig. 3(a) shows the expected result

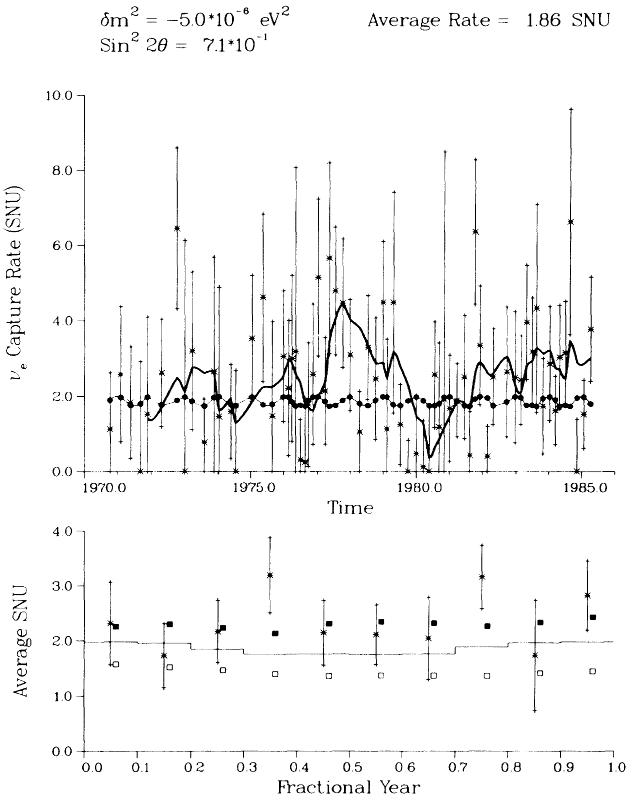

FIG. 3. (a) Measured ^{37}Ar rate since 1970. Thick line is five-point running average. Thin line is result of calculation. (b) $\times$, measured points folded modulo 1 yr. Smooth curve is the calculation from Fig. 2. □, calculated daytime rate. ■, calculated nighttime rate.

$$P=\frac{1}{e^{T/\tau'}-1}\int_0^T P(t)e^{t/\tau'}\frac{dt}{\tau'} \tag{5}$$

based on our calculations for the particular case $\delta m^2=5\times10^{-6}$ eV^2, $\sin 2\theta=0.84$. We use the actual starting and stopping times for the individual runs, and see a noticeable summer-winter effect. Since the Sun spends more time below the horizon during the winter than during the summer, the peak winter-time production rate is approximately 0.2 SNU higher than the lowest summer-time rate. Although Cribier *et al.*[7] point out that the data exclude large summer-winter differences for $\sin 2\theta \leq 0.5$, at the somewhat larger mixing angle of Fig. 3 the expected summer-winter difference is far too small to be visible above the observed fluctuations in the ^{37}Ar counting rate.

In Fig. 3(b), we plot the data folded modulo 1 year. The smooth curve shows the calculated result, with a wintertime enhancement and a summertime dip. The measured data, however, appear to peak during spring and autumn. Again, the levels of the variations in the measured data are far higher than the calculated oscillation effects. In order to enhance the effect to the level where it might be observed above the measured fluctuations in the experimental data, it appears necessary to look not at long-term variations but at the day-night differences themselves. Extractions lasting for about 20 h are currently performed roughly once every two months. It seems feasible, however, to reduce the extraction time to 3–4 h and carry out these extractions twice a day: once near sunset for the daytime exposure, and again near sunrise for the nighttime exposure. It should be emphasized that a sizable day-night difference occurs only in a small region of the mass-difference–mixing-angle plot; however, if the effect exists, it may be an exceptionally clean signal independent of solar models.

Currently, the argon extraction is initiated by circulating the 615 tons of perchlorethylene (C_2Cl_4) through a set of spray nozzles which thoroughly mix the liquid with helium. The He-Ar mixture is carried through a condenser and molecular sieve to remove perchlorethylene vapor, and the argon atoms are adsorbed on a charcoal trap at liquid-nitrogen temperature. At the end of the extraction, the circulation is stopped, the charcoal trap is heated, and the argon is collected, purified, and placed in a proportional counter. The counter is then housed inside a shield, and the decays of the ^{37}Ar atoms are counted over several half-lives ($\tau=35$ days). The argon extraction efficiency is monitored quantitatively by introducing a small quantity of nonradioactive ^{36}Ar or ^{38}Ar at the beginning of each run, and then measuring the total amount of argon extracted. The ^{37}Ar extraction efficiency is typically 92%.

The day-night experiment is performed similarly. At the end of the day, the previous several hours worth of argon are extracted and left in the daytime charcoal trap at liquid-nitrogen temperature. At the end of the night, the previous several hours worth of nighttime argon are extracted and left in the nighttime trap. In order to accumulate enough argon to count, it will be necessary to add to the respective day and night samples for a total run of typically 30–60 days. At the end of the full 30–60-day run, the separate day and night traps can then be warmed up, and the two argon samples can be loaded into separate proportional counters. The counting procedures will be identical to the current procedures. In addition to separate day and night extraction lines, a third line will be provided as well to allow for either solar flares or unanticipated problems.

In Fig. 3(b) we show an example of expected day and night counting rates. Daytime is taken as those hours when the Sun is no more than 100° from the zenith; the remainder of the 24 h is assigned to the nighttime. We assume 95% extraction efficiency and 50% counting efficiency, and assume a constant background level of 0.4 SNU. We take the total runs to be 30 days in length, and include leakage effects of nighttime argon atoms into the day samples and vice versa. For the case of Fig. 3 ($\delta m^2=5\times10^{-6}$ eV^2, $\sin 2\theta=0.84$) we find an average of 1.6 detected daytime ^{37}Ar in a 30-day run and 2.4 detected nighttime ^{37}Ar. The day-night difference after 2 yr is then $2.6-1.4=1.2\pm0.5$ SNU. In Table I we give the results calculated for two years of 30-day day-night accumulations assuming a range of values of mass difference and mixing angle. In every case, the capture rate which would be measured in the present ^{37}Cl detector, with extractions every month (average SNU), is

TABLE I. Calculated number of ^{37}Ar after two years of day-night extractions.

δm^2 (eV^2)	$\sin 2\theta$	Avg SNU in present detector	Two years day-night accumulation Night atoms	Day atoms	Night-day (SNU)
1.0×10^{-4}	0.39	1.95	45	55	0.03 ± 0.5
6.0×10^{-5}	0.93	2.05	56	49	0.71 ± 0.5
4.0×10^{-5}	0.84	1.99	56	57	0.0 ± 0.5
4.0×10^{-5}	0.93	2.18	55	58	0.31 ± 0.5
2.0×10^{-5}	0.93	2.31	54	65	0.05 ± 0.5
1.0×10^{-5}	0.93	2.13	57	53	0.63 ± 0.5
5.0×10^{-6}	0.84	1.86	57	39	1.2 ± 0.5
3.0×10^{-6}	0.78	1.95	66	35	1.9 ± 0.5
3.0×10^{-6}	0.84	2.17	70	42	1.8 ± 0.5
2.0×10^{-6}	0.84	2.16	70	41	1.8 ± 0.5
1.0×10^{-6}	0.84	1.85	56	39	1.2 ± 0.5
1.0×10^{-7}	0.48	2.19	54	59	0.25 ± 0.5
1.0×10^{-7}	0.93	2.09	55	53	0.52 ± 0.5
6.0×10^{-8}	0.93	2.14	53	57	0.33 ± 0.5

within 1σ of 2.1 SNU. For $10^{-6}\leq\delta m^2\leq5\times10^{-6}$ eV^2, the night-day differences are in the range $(2-4)\sigma$ after two years of running.

The day-night measurement seems feasible over a small range of neutrino mass difference and mixing angle, and it appears that observation (or nonobservation) of day-night differences in ^{37}Cl, coupled with lower-energy ^{71}Ga results, may give new and clear information about both neutrino properties and the Sun.

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