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Direct Probes of Neutrino Properties Using Solar-Neutrino Lines

Sandip Pakvasa and James Pantaleone[(a)]

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

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The spectrum of neutrinos from the Sun contains large fluxes of monoenergetic neutrinos which could be observed in the next generation of solar-neutrino detectors. Such observations directly probe neutrino parameters independent of uncertainties in the standard solar model. Small neutrino mass differences, $10^{-11} < m_2^2 - m_1^2 < 10^{-8}$ eV^2, would cause the measured flux of ^{7}Be-line neutrinos to oscillate with a period in the range of a week up to a year. A neutrino magnetic moment comparable to the present laboratory bound would produce large distortions in the spectrum of scattered electrons.

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Among the current solar-neutrino experiments, ^{37}Cl[1] and Kamiokande II[2] are primarily sensitive to neutrinos produced in the reaction $^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu$, while the SAGE[3] and GALLEX[4] ^{71}Ga experiments are primarily sensitive to neutrinos from $p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu$. Both reactions yield continuous β-decay spectra with endpoint energies of 14 and 0.42 MeV, respectively. However, in addition to these, and other neutrinos produced with a continuous spectrum, there are neutrinos produced in reactions with a two-body final state where the neutrino is almost monoenergetic.[5] The reaction $e + {}^7\mathrm{Be} \rightarrow {}^7\mathrm{Li} + \nu$ will produce neutrinos with an energy of 0.86 MeV and a spread in energies of about 1.3 keV, the temperature of the solar core. The flux of these ^{7}Be neutrinos is relatively large; in a typical neutrino-electron scattering experiment they would produce approximately 500 events/kton day. The flux is much larger than the integrated flux of the continuous-spectrum neutrinos, except for the lower-energy *pp* neutrinos. Thus the ^{7}Be-line neutrinos could be observed directly, in real time, by neutrino-electron scattering experiments in the next generation of solar-neutrino detectors with low backgrounds and low-energy thresholds.[6] Recent results on radio purity encourage us to believe that such an experiment is feasible in the near future.[7]

In addition to providing valuable information on the nuclear reactions occurring in the Sun, the narrow spectrum, large flux, and low energies of these line neutrinos make possible new methods of directly probing neutrino properties for which the continuous fluxes are unsuitable. As we discuss later, magnetic moments comparable to or below the present laboratory bounds would be easily observable with the line neutrinos. First, we shall discuss how neutrino oscillations could be observed as oscillations in time of the line-neutrino flux. Both of these techniques directly probe neutrino parameters in a manner independent of uncertainties from the absolute flux predictions of the standard solar model.

Neutrino oscillations occur when neutrinos have nonzero masses. The flavor eigenstates are typically not the mass eigenstates, so production of a neutrino results in production of a mixture of mass eigenstates. Interference between the mass eigenstates gives rise to oscillations in the neutrino flavor with distance. If the solar neutrinos oscillate, then the flavor content of the neutrino flux will oscillate with the radial distance from the Sun. However, the Earth-Sun distance R varies by 3.5% in six months. Thus the neutrino flux may oscillate in time, in addition to the 7% annual variation in the intensity from the $1/R^2$ modulation of the flux.

Assuming two neutrino flavors and plane waves,[8] the oscillations are proportional to $\cos(\phi)$. Here $\phi = 2\pi R/\lambda$, $\lambda = 4\pi E/\Delta$ is the neutrino-oscillation wavelength in vacuum, E is the neutrino energy, and $\Delta = m_2^2 - m_1^2$ is the difference in the squares of the neutrino masses. Distributions in R or E at production or detection can cause a spread[9] in phases about a central value, $\phi = \phi_0 + d\phi$, that have the effect of averaging out the oscillations. Distributions in R from the finite size of the detector are negligible, while the spread in production positions turns out not to be important because of matter effects as shown below. A realistic solar-neutrino experiment typically has a neutrino energy resolution $dE/E \sim 0.1-1.0$. For a continuous spectrum, this gives rise to a spread in the neutrino phase $d\phi \simeq (dE/E)\phi_0$. ϕ_0 is typically quite large; e.g., one oscillation in the 6 months between perihelion and aphelion implies $\phi_0 = 2\pi(1/0.035)$. Thus for a continuous neutrino spectrum, the spread in phases $d\phi$ is typically much larger than 2π and the oscillations are washed out.

However, for the line neutrinos, $dE/E \simeq 10^{-3}$ from the production spectrum, almost independent of detector resolution. Thus oscillations are smeared out only when ϕ_0 is larger than 10^4, which is equivalent to about one oscillation per week. Using the energy of the line neutrinos, and the fact that the mean $R \simeq 1.5 \times 10^{11}$ m, gives an upper limit on the neutrino mass difference squared for which neutrino oscillations can be directly observed of $\Delta < 10^{-8}$ eV^2. To obtain a more precise limit on the neutrino-oscillation parameters, the oscillations must be averaged over the neutrino line spectrum, $\langle \cos(\phi) \rangle$.

The spread in energies of the ^{7}Be neutrino line comes primarily from two different sources; the thermal spreads in the electron's and the ^{7}Be nucleus's energies. The matrix element is a constant and the Fermi function contributes a factor of 1/(velocity) which cancels with a velocity factor in the electron phase space. Thus it turns out that all of the dependence on neutrino energy comes from the initial-state Boltzmann distribution factors. For an infinitely heavy nucleus, the thermal spread in electron energies relative to the nucleus gives a neutrino spectrum of

$$\frac{dF}{dE} \propto \begin{cases} \exp\left[-\frac{(E-E_0)}{E_0 \epsilon} \right], & E \geq E_0, \\ 0, \quad E < E_0, \end{cases} \qquad \epsilon = kT/E_0, \tag{1}$$

where E is the neutrino energy, k is Boltzmann's constant, and T is the temperature of the solar core. For a nucleus of mass M and a fixed electron energy, the spread in nuclear velocities gives rise to a "Doppler broadening" of the neutrino line:

$$\frac{dF}{dE} \propto \exp\left[-\frac{1}{2} \left(\frac{E-E_0'}{E_0' \epsilon'} \right)^2 \right], \qquad \epsilon' = \sqrt{kT/M}. \tag{2}$$

E_0 and E_0' are constants, approximately 0.86 MeV. For continuum capture of electrons on ^{7}Be (80% of the flux[10]) the true line width is a convolution of Eqs. (1) and (2), while for bound-state capture (20% of the flux), only Eq. (2) is relevant.

There is a small contribution to the line width from scattering of the electron, ^{7}Be, or ^{7}Li nucleus off of other particles in the medium. The primary effect of this scattering is to give the initial particles a thermal spectrum, which was assumed in Eqs. (1) and (2). However, emission and absorption of thermal photons can distort the spectrum from that calculated in Eqs. (1) and (2). Similar thermal-spectral distortions were calculated in Ref. 11 for the process $e^+ + n \rightarrow p + \bar{\nu}$. Following Ref. 11, we estimate the additional broadening of the ^{7}Be line width to be down from Eqs. (1) and (2) by a factor of order $\alpha(kT/m_e) \simeq 10^{-5}$, and hence negligible.

Averaging neutrino oscillations over the line width leads to damping of the oscillations when the average phase ϕ_0 becomes large. The damping factors from the partial line widths of Eqs. (1) (Ref. 12) and (2) are $1/[1+(\phi_0\epsilon)^2]^{1/2}$ and $\exp[-(\phi_0\epsilon')/2]$, respectively. For the continuum capture process, where the line width is a convolution of Eqs. (1) and (2), it turns out that the resultant modulation factor is just the product of these two modulation factors, to order $\sqrt{m/M}$. With increasing ϕ_0, the first modulation factor starts to drop off before the second because $\epsilon > \epsilon'$; however, the second eventually overtakes the first. Thus both modulation factors are of equal importance for continuum capture.

Since the ^{7}Be neutrinos are produced in the core of the Sun, matter effects on their propagation must be taken into account[13,14] (for a review, see Ref. 15). This is because the background electrons induce a larger mass for electron neutrinos than for other flavors. A resonance occurs when the induced mass difference A is comparable to the vacuum mass splitting, $A = \Delta\cos(2\theta)$. θ is the vacuum mixing angle and $A = 2\sqrt{2}G_F N_e E$, where G_F is the Fermi constant and N_e is the number density of electrons.

In the solar core, $A \simeq 10^{-4}$ eV^2, which is much larger than the $\Delta < 10^{-8}$ eV^2 upper limit for observing time variations. Thus neutrinos for which time variations are observable are always produced in a parameter region far above the resonance, where the electron neutrino is predominantly the upper mass eigenstate (to order Δ/A). Since neutrino oscillations cannot arise with only one mass eigenstate, no neutrino oscillations take place in the solar core. It is still possible to get neutrino oscillations in vacuum if the one mass eigenstate produced in the core converts to more than one mass eigenstate as it leaves the Sun. When the neutrinos go through the resonance layer (which will lie near the surface of the Sun), there will be a crossing from one mass eigenstate to another if the transition is nonadiabatic. We denote the probability for this crossing as P_c, so the probability for not crossing is $1-P_c$. The vacuum probability for detecting the upper (lower) mass eigenstate as an electron-neutrino flavor eigenstate is $\sin^2\theta$ ($\cos^2\theta$).

Then the survival probability for an electron neutrino produced in the core, and averaged over the line width for continuum capture, can be written as

$$\langle P(\nu_e \rightarrow \nu_e)\rangle = \sin^2\theta(1-P_c)+\cos^2\theta P_c + [1+(\phi_0\epsilon)^2]^{-1/2}\exp[-(\phi_0\epsilon')/2]\sin\theta\cos\theta\sqrt{P_c(1-P_c)}\,2\cos(\phi_0+\beta)\,. \quad (3)$$

The first two terms in Eq. (3) are just the classical probability, the same expression commonly used for describing the Mikheyev-Smirnov-Wolfenstein (MSW) effect[16] (Fig. 1). The last term in Eq. (3) is the cross term between the first two terms and describes the neutrino oscillations. This term also contains the two oscillation damping factors which come from averaging over the continuum line width; for bound-state capture the first damping factor is not present. ϕ_0 is the average vacuum neutrino phase, as measured from the resonance layer. $\beta \equiv \beta_m - \arctan(\epsilon\phi_0)$, where β_m is a known, additional phase, acquired as the neutrino goes through the resonance layer.[17] P_c generally depends on the neutrino energy; however, it is essentially a constant in the average over the line width. Equation (3) agrees with the exact solution for an exponential density distribution, in the limit that the production density becomes large. We shall use the form of P_c which comes from this exact solution, and which is commonly used in descriptions of the MSW effect.[18] When the transition is adiabatic, $P_c \rightarrow 0$, and only one mass eigenstate emerges from the Sun; hence there are no neutrino oscillations. In the extreme nonadiabatic limit, $P_c \rightarrow \cos^2\theta$, and Eq. (3) just reduces to the expression for oscillations in vacuum.[19]

Figure 2 shows the values of the mass difference and mixing angle for which the signal in a solar-neutrino–electron scattering experiment would oscillate by 5% of the standard-solar-model value. The region inside the contour corresponds to larger time variations. The reduction of the variations from neutral-current scattering of the non-electron-neutrino flavor was included.[20] The 15% variation of the core temperature over the ^{7}Be production region was not included. Above $\Delta = 3\times10^{-10}$ eV^2 the full range of the cosine could be seen. Below this, the vacuum oscillation wavelength is longer than dR and the variation of the cosine will be less than maximal. However, large variations are still potentially observable if the average phase is such that the variations in the Earth's orbit occur near an inflection point of the cosine, and not near an extremum value where the first derivative vanishes. This is the reason for the large fluctuations of the contour at the bottom of Fig. 2.

In addition to searching for time variations in the line-neutrino flux, the spectrum of the scattered electrons in $\nu+e \rightarrow \nu'+e'$ provides a good place to search for new types of neutrino interactions. For example, a magnetic moment of $1.7\times10^{-10}e/2m$ would produce an event rate, in the observable energy range above the pp neutrinos, equal to that from weak scattering. Such a nonzero neutrino magnetic moment would be discernible from errors in the total flux prediction by the distortion of the spectrum as shown in Fig. 3. The electron energy spectrum from weak scattering is flat while magnetic moment scattering is singular at low electron energies. Thus values of the magnetic moment comparable to or somewhat lower than the present laboratory limit[21] of $4\times10^{-10}e/2m$ could easily be probed. If the flux of electron neutrinos from the Sun is suppressed due to the precession of the neutrino magnetic moment, as has been postulated to solve the solar-neutrino problem,[22] the sensitivity to observing the magnetic moment scattering is enhanced. This is because the weak scattering "back-

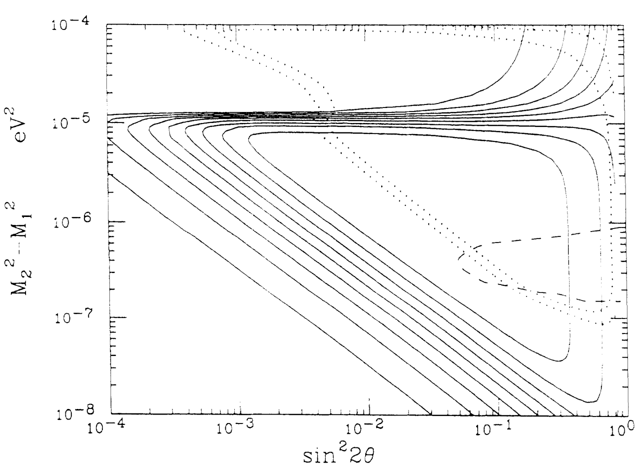

FIG. 1. Contour plot of the fraction (0.1–0.9) of the electron-neutrino survival probability, using the classical expression, for ^{7}Be-line neutrinos (solid lines). The dashed lines show the region where day-night variations of the ^{7}Be neutrinos are relevant. Also shown are ^{37}Cl contours for a flux of 2.3 ± 0.25 solar-neutrino units (dotted lines).

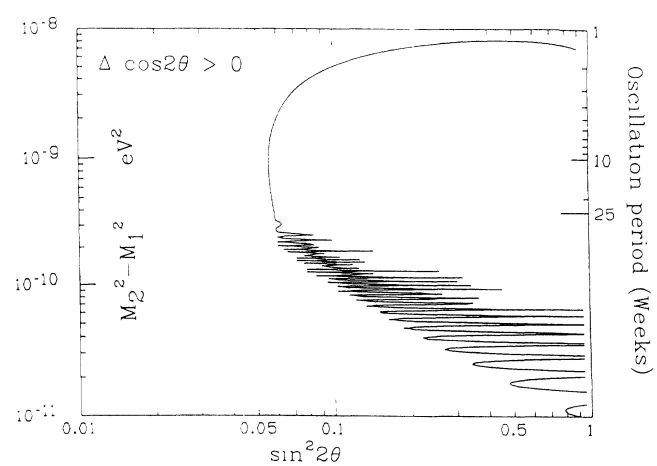

FIG. 2. Contour plot for a 5% (of the standard-solar-model value) time variation in (max−min) of the ^{7}Be neutrino flux as measured in a neutrino-electron scattering experiment.

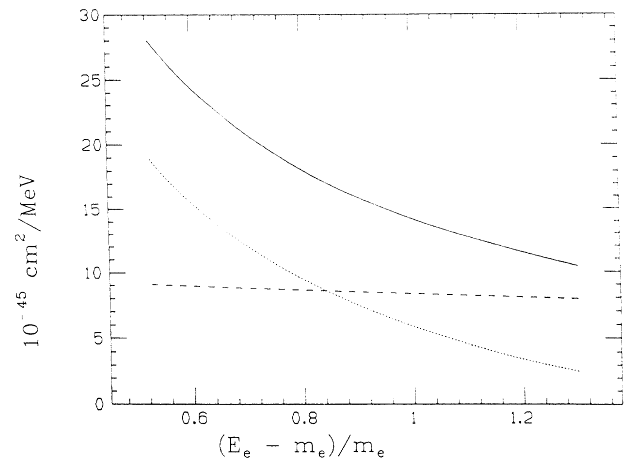

FIG. 3. The observable electron spectrum from scattering of ^{7}Be-line neutrinos, as a function of electron kinetic energy: weak scattering (dashed line), magnetic-moment scattering with $\mu = 1.7\times10^{-10} e/2m$ (dotted line), and the total (solid line).

ground," which comes predominantly from the electron-neutrino flavor, is suppressed while the magnetic moment "signal" is unchanged.

In conclusion, observations of the ^{7}Be neutrino line can be used to constrain the properties of neutrinos, independent of solar-model details.

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Note added.— We would like to emphasize that δm^2 in the range 10^{-10}–5×10^{-11} eV^2 has been shown to be a perfectly viable solution to the Homestake, as well as Kamiokande, experiments within the standard-model fluxes. This is seen clearly in two recent analyses.[23] In a recent paper,[24] it is shown that the possible anticorrelation of the Homestake data with the sunspot activity and the near constancy of the Kamiokande data can both be explained if the ν_e magnetic moment is at least as large as $4\times10^{-10}\mu_B$. With the use of the ^{7}Be neutrino line these parameter ranges can be probed unambiguously.

[a]Present address: Physics Department, University of California, Riverside, CA 92521.

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