# Suppression of solar line neutrino oscillations

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Neutrino flavor oscillations can cause "seasonal" variations in the flux of $^7$Be and $p+e^-+p$ (*pep*) solar line neutrinos. This may be tested in a next-generation solar-neutrino experiment. An analytic expression for the suppression of *pep* neutrino oscillations from the line width is calculated. A comparison between the *pep* and $^7$Be lines indicates that $^7$Be neutrinos provide a far stronger probe of time variations.

Since the first proposals that neutrino flavors may oscillate, it has been realized that this could lead to time variations in the flux of neutrinos from the Sun.[1-7] In particular, the solar line neutrino fluxes offer what seems to be the best opportunity for directly probing large ranges of neutrino oscillation parameters by searching for induced "seasonal" variations. The line neutrino fluxes are almost monoenergetic (because of a two-body final state for the relevant solar nuclear reaction) and hence the vacuum oscillations remain coherent for many cycles. In addition, the line neutrino fluxes are predicted by the standard solar model[8] (SSM) to be much more intense than the heretofore observed $^8$B neutrino flux, and hence high-statistics experiments are feasible. This experimental possibility may be realized in the next generation of proposed solar-neutrino detectors.

In particular, the relatively small BOREXINO solar neutrino detector[9] may be able to observe the $^7$Be and $p+e^-+p$ (*pep*) neutrino lines at SSM counting rates of 50 counts/day and 2 counts/day, respectively. Despite the smaller counting rate, the *pep* neutrinos could still yield useful information on neutrino oscillations. The different energies of the $^7$Be (0.862 MeV) and *pep* (1.442 MeV) lines implies very different "seasonal" variations, which could be important for precise measurements of either oscillation parameters or of the core temperature.[4] Also, for small $m_2^2-m_1^2$, there are gaps in the parameter region of one line that can be filled in by study of the other line. The object of this Brief Report is to calculate the oscillation parameter range that can be probed by observing the *pep* neutrino line, and then compare it with that calculated previously[6] for the $^7$Be line.

For solar neutrinos, propagation through matter induces a resonance that can profoundly alter the flavor content[10,11] (for a recent review, see Ref. 12). Even at the small mass-squared differences where time variations are observable, matter effects can be important. For $m_2^2-m_1^2<10^{-5}$ eV$^2$, the electron-neutrino survival probability for line neutrinos takes the form[6,13,14]

$$P(\nu_e\rightarrow\nu_e)=(1-P_c)\sin^2\theta+P_c\cos^2\theta + 2\sin\theta\cos\theta\sqrt{P_c(1-P_c)}\cos(\phi+\beta)\ , \qquad (1)$$

where $\theta$ is the vacuum mixing angle and $P_c$ the level crossing probability at the neutrino resonance.[12] $\beta$ is a resonant phase shift[15] and

$$\phi=r(m_2^2-m_1^2)/2E \qquad (2)$$

is the vacuum-oscillation phase, where $E$ is the neutrino energy and $r$ is the distance from the neutrino resonance (N.B. not the solar core) to the detector.

The first two terms in Eq. (1) are just the classical probability, the same expression commonly used in the description of the Mikheyev-Smirnov-Wolfenstein (MSW) effect, and the last term is their interference. It is this interference term that describes neutrino oscillations and hence gives "seasonal" variations as the Earth-Sun distance changes annually. Equation (1) assumes that the neutrino energy is known precisely; however, for a realistic experiment Eq. (1) must be averaged over the spreads in observed $E$ and $r$. The interference term is observable only when the spread in $\phi$ values in the observed neutrino signal is small, $\phi<1$. The spread in $\phi$ comes entirely from the spread in neutrino energies $E$; spreads in $r$ are completely negligible when the changing Earth-Sun distance is accounted for. For line neutrinos, the spread in energies is very small ("independent" of detector energy resolution) compared to the central energy $E_0$, so that we can take $E=E_0+t$ and hence $\phi\approx\phi_0(1-t/E_0)$. Then the interference term averaged over the line width can be written as

$$\langle\cos(\phi+\beta)\rangle\approx\frac{\mathrm{Re}\left[\exp[i(\phi_0+\beta)]\int_{-\infty}^{\infty}dt\, d\Gamma/dE\, \exp(-i\phi_0 t/E_0)\right]}{\int_{-\infty}^{\infty}dt\, d\Gamma/dE}\ , \qquad (3)$$

where $d\Gamma/dE$ is the line spectrum. To calculate how the line spectrum suppresses oscillations we first must calculate the line width.

 

The reaction rate for $p+e+p \to D+\nu$ can be written as[16,17]

$$\Gamma \propto \int d^3\mathbf{p}_1 d^3\mathbf{e}\, d^3\mathbf{p}_2 d^3\mathbf{D}\, d^3\boldsymbol{\nu} f_1 f_2 f_e F(-1,v_{12}) F(2,v_e) \delta^4(\mathbf{P}_f - \mathbf{P}_i) . \quad (4)$$

Here the $f_a = \exp[-\mathbf{a}^2/(2M_a kT)]$ are the Boltzmann distribution functions with the temperature $kT \approx 1.3$ keV, and $\mathbf{a}$ and $M_a$ the relevant momentum and mass for particle $a$. $F(Z,v)$ is the Coulomb factor

$$F(Z,v) = \frac{2\pi\eta}{1-\exp(-2\pi\eta)} , \quad (5)$$

where $\eta = \alpha Z/v$ and $v$ is the velocity. $v_{12} = |\mathbf{p}_1 - \mathbf{p}_2|/M$ is the relative proton velocity and $v_e = |\mathbf{e}|/m$ is the electron velocity. Contributions to the matrix element in Eq. (4) that are constant, or only weakly momentum dependent, have been dropped since they cancel out in Eq. (3). Equation (4) is different from the corresponding expression for the $^7$Be width since for the *pep* reaction there is a three-body initial state.

Substituting Eq. (4) into Eq. (3) and performing some of the integrations, it turns out that the neutrino oscillations suppression factors separate, as they did for the simpler $^7$Be case. The average oscillation term can be rewritten as

$$\langle \cos(\phi+\beta) \rangle = \exp[-(\phi_0 \epsilon')^2/2] \mathrm{Re}\{\exp[i(\phi_0+\beta)] I_e I_{pp}\} , \quad (6)$$

where $\epsilon' = \sqrt{kT/2M_p}$. The first factor in Eq. (6) is also formally present for the $^7$Be line;[18] it is the suppression of oscillations from the line broadening due to the center-of-mass motion of the line, i.e., the "Doppler" broadening. The remaining two integrals are

$$I_e \propto \int_0^\infty d(\mathbf{e}^2) \exp[-(1+i\phi_0\epsilon)\mathbf{e}^2/(2mkT)] |\mathbf{e}| F(2,|\mathbf{e}|/m) , \quad (7)$$

$$I_{pp} \propto \int_0^\infty d(\mathbf{Q}^2) \exp[-(1+i\phi_0\epsilon)\mathbf{Q}^2/(4MkT)] |\mathbf{Q}| F(-1,|\mathbf{Q}|/M) , \quad (8)$$

where $\epsilon = (kT/E_0)$, $m$ and $M$ are the electron and proton masses, and $\mathbf{Q} = (\mathbf{p}_1 - \mathbf{p}_2)$. $I_e$ comes from the motion of the electron with respect to the center of mass and is also present for the $^7$Be line. $I_{pp}$ is from the relative motion of the initial-state protons and is not present for the $^7$Be line. The normalizations of the $I$'s are determined because when $\phi_0 \to 0$, the $I_a \to 1$.

With approximations, these two integrals can be evaluated analytically. For $I_e$, the exponential in the Coulomb factor can be neglected (at roughly the 27% level for the *pep* line, 8% for the $^7$Be line) to give

$$I_e = \frac{\exp[-i \arctan(\phi_0\epsilon)]}{\sqrt{1+(\phi_0\epsilon)^2}} , \quad (9)$$

which is the expression used in Refs. 4 and 6. For $I_{pp}$, there is a large Coulomb barrier so the exponential in the Coulomb factor dominates over the 1 in the denominator. The integration can then be performed by the method of steepest descents to yield

$$I_{pp} = [1+i(\phi_0\epsilon)]^{-5/6} \exp(-\delta\{[1+i(\phi_0\epsilon)]^{1/3}-1\}) , \quad (10)$$

where

$$\delta = 3[(\pi\alpha/2)^2 M/kT]^{1/3} \quad (11)$$

is about 14.

$I_e$ and $I_{pp}$ have two parts: (1) the phases, which give subtle distortions to the sinusoidal oscillation, and (2) the magnitudes, which vanish at large $\phi_0$ and suppress the oscillations. The dominant oscillation suppression factor for *pep* line neutrinos is in Eq. (10). For the *pep* line, $I_e$ and the "Doppler" suppression factors are roughly comparable to each other, while $I_{pp}$ drops off roughly two to three times faster.

Comparing the $^7$Be and *pep* neutrino oscillation suppression factors, it turns out that the *pep* oscillations are suppressed roughly twice as fast. This is mostly because $I_{pp}$ is not present for the $^7$Be line. Smaller differences come from the "Doppler" suppression factor, which is more severe for the *pep* line because of the smaller total mass; and from $I_e$, which is less severe for the *pep* line because of its higher energy. This is demonstrated in Fig. 1, which shows the oscillation parameter range probed by "seasonal" variation measurements of the *pep* and $^7$Be lines. Figure 1 includes matter effects, Eq. (1), and uses Eq. (6) and Eqs. (9)–(11) to describe the suppression of oscillations. The higher energy of the *pep* line acts

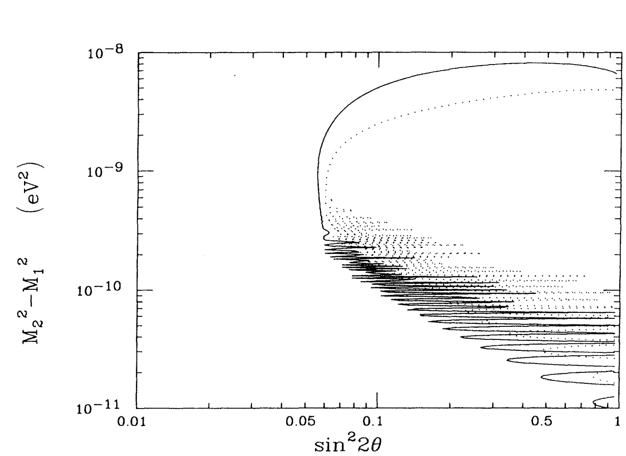


FIG. 1. Contour plot for $(F_{max} - F_{min}) = 5\%$ time variation in the *pep* (dotted) and $^7$Be (solid) line neutrino counting rate as measured in a neutrino-electron scattering experiment.

to shift the probed region up from that for the $^7$Be line, as can be seen from the bottom of the graph. However at large $m_2^2 - m_1^2$ the suppression factors (and matter effects) determine the contours, and here the much larger suppression factors for the *pep* line force the upper *pep* contour to lie well inside the upper $^7$Be contour.

When comparing the $^7$Be and *pep* oscillation parameter regions, there are other influences that must be considered in addition to the line width suppression factors discussed above. The smaller *pep* flux means that it is much more sensitive to backgrounds. In particular, neutrino fluxes from the CNO cycle are predicted by the SSM (with extremely large uncertainties) to give a scattered electron flux in BOREXINO comparable to that from the *pep* line. This may reduce the observability of "seasonal" variation using the *pep* line neutrinos.

In summary, the spectrum of the *pep* neutrino line has been averaged over to calculate the corresponding neutrino oscillation suppression factors. The *pep* suppression factors are formally identical to those for the $^7$Be line, with the addition of a new factor due to the relative motion of the protons in the initial state. The *pep* neutrino oscillations are suppressed twice as fast as the $^7$Be line neutrinos. This, plus the SSM prediction of a smaller intensity for the *pep* neutrinos, and also the possibility of a background in BOREXINO from the CNO solar neutrinos, all imply that "seasonal" variations will be easier to observe in the $^7$Be line than in the *pep* solar-neutrino line.

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