Neutrino radiative-lifetime limits from the absence of solar γ rays

Georg G. Raffelt
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Föhringer Ring 6, D-8000 München 40, Federal Republic of Germany
(Received 29 October 1984)

Observational limits on the solar x- and γ-ray flux restrict the possible conversion of the solar neutrino flux into radiation. This yields a limit on the neutrino radiative lifetime of $\tau_{\nu_e}/m_{\nu_e} \gtrsim 7\times 10^9$ sec/eV. We discuss the dependence of this limit on the energy of the decay photon and on neutrino masses and mixing parameters. The original application of this method by Cowsik erroneously yields a more restrictive result due to a misrepresentation of observational data. The present work closely parallels a recent discussion by Vogel on the decay of reactor neutrinos, the solar limits, however, being almost ten orders of magnitude more restrictive. We stress that solar x-ray measurements are an important tool to set neutrino radiative-lifetime limits, although more restrictive limits from other astrophysical data exist.

In a recent *Physical Review* article,[1] Vogel has discussed in detail the limits on (anti)neutrino radiative lifetimes that can be obtained from the absence of single photon counts in a detector near a fission reactor which emits an antineutrino flux of known intensity and energy distribution. In this Brief Report we will follow the lines of Vogel's argument in detail while substituting the solar neutrino flux for the reactor antineutrino flux. The much more restrictive limit on the (anti)neutrino radiative lifetime thus obtained depends only on the low-energy part of the solar neutrino spectrum which is virtually independent of details of solar modeling.[2] An experiment to measure this part of the solar neutrino spectrum[3] will probably be performed within the next few years, and the anticipated confirmation of the calculated flux would place the solar neutrino radiative-lifetime limits on the same footing as a laboratory result.

The observational bounds on the solar x- and γ-ray flux have been previously used to set limits on interaction parameters of certain hypothetical particles which were believed to be produced in the sun.[4] In a "classic" paper[5] on various astrophysical bounds on neutrino radiative decays, Cowsik was the first to calculate a neutrino lifetime limit from the absence of solar x and γ rays above 20 keV. However, he erroneously quotes the solar γ-ray flux limit in units of an integrated flux ($\text{cm}^{-2}\text{sec}^{-1}$), while the original references[6,7] actually give differential fluxes in $\text{cm}^{-2}\text{sec}^{-1}\text{keV}^{-1}$. Therefore, Cowsik effectively ignores the energy bandwidth of about 300 keV of the photon signal expected from neutrino decay, and consequently his result is too restrictive by a factor of about 300.

There exist a large number of astrophysical bounds on neutrino radiative lifetimes,[5,8] which are, in general, more restrictive than laboratory and solar limits by many orders of magnitude. In several cases the calculated neutrino fluxes, which these limits are based upon, can be considered to be as reliably known as directly measured values. We believe, however, that some virtue remains in discussing what can be learned from directly observable neutrino fluxes on the question of radiative lifetimes of these particles.

We consider, then, decays of electron neutrinos of the sort

$$\nu_e \to \nu' + \gamma \ , \tag{1}$$

with (partial) proper lifetime τ_{ν_e}. For now we consider ν_e to be essentially a mass eigenstate for which the experimental limit $m_{\nu_e} < 46$ eV exists.[9] ν' is some neutral fermion, possibly some lighter neutrino. The energy of the decay photon in the neutrino rest frame is

$$\omega = r m_{\nu_e}/2, \quad 0 < r \leq 1 \ , \tag{2}$$

where m_{ν_e} is the mass of the electron neutrino. The dimensionless parameter r is the ratio between the actual photon energy ω and its possible maximum value, $m_{\nu_e}/2$, which is assumed when the particle ν' is massless. Limits on neutrino radiative lifetimes have generally been derived under the assumption that the mass of ν' can be neglected. Such a constraint, however, is not necessary and we prefer to derive the lifetime limit as a function of the parameter r.

Following Vogel,[1] we write the general form of the angular distribution of the decay photons in the ν_e rest frame as

$$\frac{dN}{d\cos\theta} = \tfrac{1}{2}(1 + a\cos\theta), \quad |a| \leq 1 \ . \tag{3}$$

θ is the angle between the directions of motion of ν_e and γ. It is assumed that the polarization vector of ν_e is (anti)parallel to its momentum. For Majorana neutrinos the decay would be isotropic, independent of their polarization, and thus $a=0$. For left-handed Dirac neutrinos and a massless ν', one has $a=1$ (see Refs. 10 and 11), which means that the photons are preferably emitted "backward."

During the time of flight from sun to Earth, $t_\odot = 499$ sec, a fraction $(m_{\nu_e}/E)(t_\odot/\tau_{\nu_e})$ of solar neutrinos of energy E decay. From the calculated solar neutino flux $j_\nu(E)$ at the Earth [see Ref. 2 and Fig. 1, curve (a)] and using (3) one can then derive the expected photon flux from neutrino decay

$$j_\gamma(\omega) = \frac{1}{r}\frac{m_{\nu_e}}{\tau_{\nu_e}} t_\odot \int_{\omega/r}^{\infty} \left[1 - a + 2a\frac{\omega/r}{E}\right] \frac{j_\nu(E)}{E^2}\, dE \ . \tag{4}$$

[There is an apparent misprint concerning the sign of a in the corresponding Eq. (6) of Ref. 1.] In Fig. 1, curve (b), we display this function for $r=1$, $\tau_{\nu_e}/m_{\nu_e} = 1$ sec/eV, and $a = 0, \pm 1$.

The structure of this function is such that the spectrum for other values of r can be obtained—in a doubly loga-

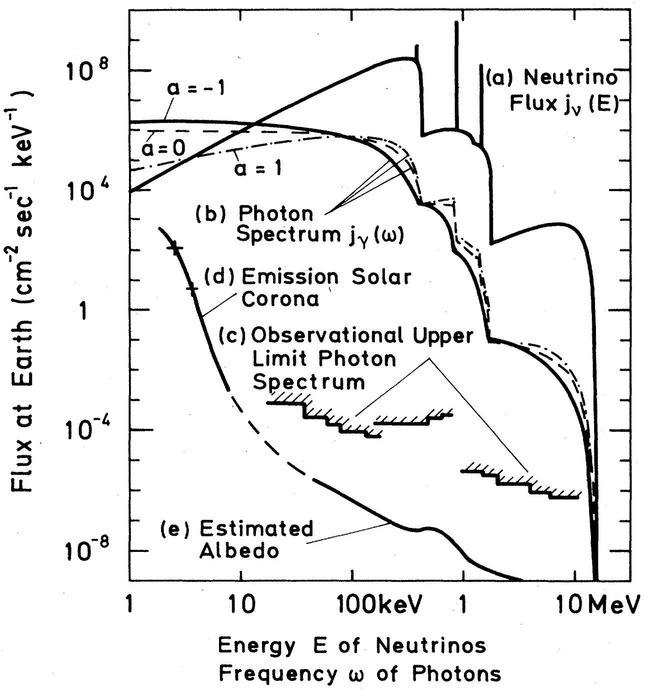

FIG. 1. (a) Predicted solar neutrino flux $j_\nu(E)$ according to Ref. 2. The leftmost "bump" stems from the *pp* reaction, $p+p \rightarrow d+e^+ +\nu_e$, and contributes 6.1×10^{10} $cm^{-2}sec^{-1}$ to the total flux of 6.6×10^{10} $cm^{-2}sec^{-1}$ at the Earth. The three "spikes" correspond to electron-capture reactions. Their width is dominanted by the thermal motion of the sources in the solar interior. For convenience we have normalized them such as if they had rectangular shape and a width of exactly 1 keV. (b) Spectrum of photons $j_\gamma(\omega)$ from the decay of the solar neutrino spectrum (a) through the process $\nu_e \rightarrow \nu' + \gamma$. ν' is assumed to be massless, corresponding to $r=1$, and $\tau_{\nu_e}/m_{\nu_e}=1$ sec/eV is used. (c) Upper limit on the x and γ radiation of the quiet sun according to Refs. 6 and 7. (d) Emission of the hot solar corona ($T=4.5\times10^6$ K) according to Ref. 7. The data points "+" are taken from Ref. 12. (e) Estimated solar albedo according to Ref. 7.

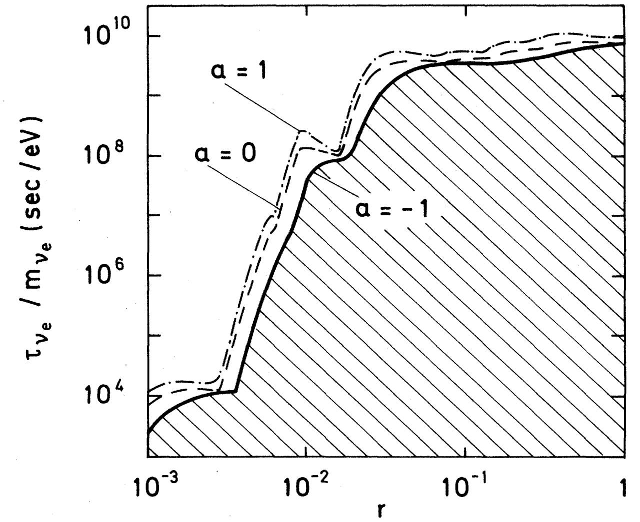

FIG. 2. Possible values for the electron neutrino's lifetime-over-mass ratio τ_{ν_e}/m_{ν_e} and for the energy fraction $r=\omega/(m_{\nu_e}/2)$ which is carried away by the photon in the reaction $\nu_e \rightarrow \nu' + \gamma$ are restricted to the white area in this plot. Curve $a=-1$ yields the most conservative limits.

rithmic representation such as Fig. 1—by simply shifting it "to the left" by the amount $|\log_{10} r|$ and "upward" by the same amount, the shape itself remaining unchanged. For $r=10^{-1}$, as an example, it is shifted to the left and upward by one decade each.

The photon flux $j_\gamma(\omega)$ expected from neutrino decay must lie below the observational bounds or measurements of the solar x and γ radiation. In Fig. 1, curve (c) we show the upper-limit photon spectrum of the quiet sun from balloon-flight measurements[6,7] in the range 20 keV $\lesssim \omega \lesssim 10$ MeV. For energies below approximately 10 keV the emission is dominated by an intense bremsstrahlung spectrum [Fig. 1, curve (d)] of the hot solar corona ($T \approx 4.5\times10^6$ K), which is observationally established from rocket-flight measurements.[12]

The above requirement excludes the shaded area of $(r, \tau_{\nu_e}/m_{\nu_e})$ values in Fig. 2. Since $a=-1$ is the worst case in the sense that the photon spectrum is squeezed furthest toward low frequencies, the corresponding curve in Fig. 2 yields the most conservative limit on τ_{ν_e}/m_{ν_e}. Then we obtain for $r=1$ the limit

$$\tau_{\nu_e}/m_{\nu_e} > 7\times10^9 \text{ sec/eV} , \qquad (5)$$

which compares with the reactor limit 1 sec/eV of Ref. 1 and with a similar reactor limit,[13] which is the basis for the relevant listing of 3×10^2 sec/eV in the Particle Data Group compilation.[9] According to a criticism by Vogel,[1] this latter number should be reduced by an order of magnitude. For $0.03 \leq r \leq 1$ our limit remains above the 10^9 sec/eV level, while it drops quite fast for lower r values. In the range above 0.03 we consider the limit firm, because it depends only on the low-energy part of the solar neutrino spectrum.

The observational upper-limit photon flux is several orders of magnitude above the expected solar albedo [Fig. 1, curve (e)], leaving much room for an observational improvement of our limits. The actual solar albedo could be much lower than this estimate, because the cosmic-ray flux hitting the surface of the sun could be substantially reduced from the galactic average due to shielding effects by the solar magnetic field.[7] In principle our limits could be further improved by a factor of about 25 if one could achieve an angular resolution of a few minutes of arc, because neutrino-decay photons would appear to come from the center of the solar disc. This should be so because the low mass limit for electron neutrinos guarantees an ultrarelativistic γ factor, which suppresses strong angular deviations between ν_e and γ in the observer's frame. Furthermore one could, in principle, use the polarization characteristics of neutrino-decay photons[11] to distinguish them from direct solar x or γ radiation.

In contrast with our above assumption the electron neutrino could be a mixture of mass eigenstates ν_j with masses $m_1 \leq m_2 \leq \cdots \leq m_n$,

$$\nu_e = \sum_{j=1}^{n} U_{ej}\nu_j . \qquad (6)$$

A decay of ν_e would then really correspond to a decay of its heavy-neutrino admixtures into radiation and lighter-neutrino species, and the standard model of weak interactions provides detailed predictions on the relevant decay widths.[11]

The simplest case of this sort is where only U_{e1} and U_{e2} are of significance in (6), and where m_2 is so small that the solar production of the ν_2 component is not inhibited by threshold effects ($m_2 \lesssim 100$ keV). Then the solar ν_2 spectrum is obtained by multiplying $j_\nu(E)$ by $|U_{e2}|^2$, and the spectrum of decay photons is obtained by substituting τ_2/m_2 for τ_{ν_e}/m_{ν_e}. Furthermore, r is related to the neutrino masses such that our previous limits can be translated to the present case through the substitutions

$$\frac{\tau_{\nu_e}}{m_{\nu_e}} \to |U_{e2}|^{-2}\frac{\tau_2}{m_2}, \quad r = 1 - \left(\frac{m_1}{m_2}\right)^2 . \tag{7}$$

If we assume that more than one heavy component of ν_e is important, but assume that the mass ratios are such that $r \gtrsim 0.03$ for all relevant decays and that the masses are lighter than about 100 keV, we obtain the limit

$$\left(\sum_{j=2}^{n} |U_{ej}|^2 \frac{m_j}{\tau_j}\right)^{-1} \gtrsim 10^9 \text{ sec/eV} . \tag{8}$$

More complicated situations are thinkable, of course, where the photon spectrum must be individually calculated for each choice of masses, decay widths, and mixing parameters. In this Brief Report, however, we have restricted our discussion to the most important limiting cases.

The author thanks Leo Stodolsky for discussions of this work and for helpful comments on the manuscript.

[1]P. Vogel, Phys. Rev. D **30**, 1505 (1984).
[2]J. N. Bahcall, Rev. Mod. Phys. **50**, 881 (1978); J. N. Bahcall, W. F. Huebner, S. H. Lubow, P. D. Parker, and R. K. Ulrich, *ibid.* **54**, 767 (1982).
[3]W. Hampel, Nature **308**, 312 (1984).
[4]See, e.g., K. Sato and H. Sato, Prog. Theor. Phys. **54**, 1564 (1975); G. Raffelt and L. Stodolsky, Phys. Lett. **119B**, 323 (1982).
[5]R. Cowsik, Phys. Rev. Lett. **39**, 784 (1977).
[6]K. J. Frost, E. D. Rothe, and L. E. Peterson, J. Geophys. Res. **71**, 4079 (1966).
[7]L. E. Peterson, D. A. Schwarz, R. M. Pelling, and D. McKenzie, J. Geophys. Res. **71**, 5778 (1966).
[8]R. Cowsik, Phys. Rev. D **19**, 2219 (1979); D. A. Dicus, E. W. Kolb, and V. L. Teplitz, Phys. Rev. Lett. **39**, 168 (1977); **39**, 973(E) (1977); Astrophys. J. **221**, 327 (1978); D. A. Dicus, E. W. Kolb, V. L. Teplitz, and R. V. Wagoner, Phys. Rev. D **17**, 1529 (1978); S. W. Falk and D. N. Schramm, Phys. Lett. **79B**, 511 (1978); T. Goldmann and G. J. Stephenson, Jr., Phys. Rev. D **16**, 2256 (1977); **19**, 2215 (1979); J. E. Gunn, B. W. Lee, I. Lerche, D. N. Schramm, and G. Steigman, Astrophys. J. **223**, 1015 (1978); R. C. Henry and P. D. Feldman, Phys. Rev. Lett. **47**, 618 (1981); J. B. Holberg and H. B. Barber, Astrophys. J. (to be published); B. H. J. McKellar and S. Pakvasa, Phys. Lett. **122B**, 33 (1983); R. Kimble, S. Bowyer, and P. Jakobsen, Phys. Rev. Lett. **46**, 80 (1981); L. M. Krauss, Phys. Lett. **128B**, 37 (1983); D. Lindley, Mon. Not. R. Astron. Soc. **188**, 15P (1979); Report No. Fermilab-Pub-84/115-A, 1984 (unpublished); A. L. Melott and D. W. Sciama, Phys. Rev. Lett. **46**, 1369 (1981); S. Miyama and K. Sato, Prog. Theor. Phys. **60**, 1703 (1978); Y. Rephaeli and A. S. Szalay, Phys. Lett. **106B**, 73 (1981); A. De Rújula and S. L. Glashow, Phys. Rev. Lett. **45**, 942 (1980); K. Sato and M. Kobayashi, Prog. Theor. Phys. **58**, 1775 (1977); H. L. Shipman and R. Cowsik, Astrophys. J. **247**, L111 (1981); J. Silk and A. Stebbins, *ibid.* **269**, 1 (1983); F. W. Stecker, Phys. Rev. Lett. **45**, 1460 (1980); M. S. Turner, in *Neutrino 81,* proceedings of the International Conference on Neutrino Physics and Astrophysics, Maui, Hawaii, 1981, edited by R. J. Cenie, E. Ma, and A. Roberts (University of Hawaii, Honolulu, 1981), Vol. I, p. 95.
[9]Particle Data Group, Rev. Mod. Phys. **56**, S1 (1984).
[10]L. F. Li and F. Wilczek, Phys. Rev. D **25**, 143 (1982).
[11]R. E. Shrock, Nucl. Phys. **B206**, 359 (1982).
[12]G. Chodil, R. C. Jopson, H. Mark, F. D. Seward, and C. D. Swift, Phys. Rev. Lett. **15**, 605 (1965).
[13]F. Reines, H. W. Sobel, and H. S. Gurr, Phys. Rev. Lett. **32**, 180 (1974).