Radiative neutrino decays and scattering experiments

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Existing measurements of the total $\bar{\nu}_e e^-$ cross section yield a very restrictive limit on the radiative decay of electron neutrinos, $\tau_{\nu_e} m_{\nu_e} > 3 \times 10^{13} \text{sec eV}$, which is even competitive with recent bounds from the nonobservation of $\gamma$ rays from SN 1987A. Our bound is not valid if the neutrino electric and magnetic transition moments are exactly equal, a cancellation which can occur only if neutrinos are of Dirac type. This is a new example for the important differences in the electromagnetic properties of Dirac versus Majorana neutrinos.

I. INTRODUCTION

Recently there have been renewed experimental efforts\textsuperscript{1,2} to constrain possible radiative decays $\nu_e \rightarrow \nu_x \gamma$ by searching for decay photons near nuclear power reactors. The original such limit\textsuperscript{3} had been derived to rule out radiative neutrino decays as a solution of the solar-neutrino problem. If $m_{\nu_e} > m_{\nu_x}$, these bounds are $\tau_{\nu_e} / m_{\nu_e} > 1 \text{sec/eV}$ (Ref. 4), 22 sec/eV (Ref. 1), and 300 sec/eV (Ref. 3), although this latter number should probably be discounted by an order of magnitude.\textsuperscript{4} Of course, if radiative neutrino decays were the explanation for the measured solar neutrino deficiency, the decay photons would be visible as a strong solar $\gamma$-ray flux, and observational bounds on this flux yield\textsuperscript{2} $\tau_{\nu_e} / m_{\nu_e} > 7 \times 10^9 \text{sec/eV}$. Finally, the recent nonobservation of a $\gamma$-ray burst in coincidence with the neutrino signal from the celebrated supernova 1987A yields $\tau_{\nu_e} / m_{\nu_e} > 0.8 \times 10^{15} \text{sec/eV}$ (Ref. 6), $1 \times 10^{15} \text{sec/eV}$ (Ref. 7), and $2 \times 10^{15} \text{sec/eV}$ (Ref. 8). In all of these results, $\tau_{\nu_e}$ refers to the radiative lifetime; i.e., the total lifetime is obtained by multiplication with the branching ratio for radiative decays.

Searching for photons from the radiative decay of particles, however, is not necessarily the most efficient experimental method to probe the relevant electromagnetic coupling vertex. This was first pointed out by Primakoff\textsuperscript{9} who proposed to measure the pion decay, $\pi^0 \rightarrow \gamma \gamma$, by measuring the cross section for the scattering process $\gamma N \rightarrow N \pi^0$ where $N$ symbolizes a heavy nucleus. In this "Primakoff effect" the role of one of the pion decay photons is played by the Coulomb field of the nucleus. Generalizing this method to the case of neutrino radiative decays, the scattering process $\nu_e e^- \rightarrow \nu_x e^-$, mediated by a virtual photon, contributes to the total cross section for $\nu_e e^- \rightarrow (\text{anything}) e^-$ which is measured by the recoil of the final-state electron. For light neutrinos or for nearly degenerate neutrino states this method is more efficient than the search for decay photons because the free decay rate depends on a $F_{EN}^2$ phase-space factor of the final-state photon.

While this observation is not new (it is certainly implied by the discussion of Bég, Marciano, and Ruderman\textsuperscript{10}), it has never been fully appreciated in the experimental literature. On the theoretical side, the consideration of neutrino scattering by anomalous electric and magnetic dipole moments leads to a new case for the important differences between the electromagnetic properties of Dirac versus Majorana neutrinos. Therefore we proceed to study what can be learned about neutrino radiative decays from scattering experiments.

II. ELECTRON NEUTRINOS

We begin our quantitative discussion with the case of Dirac electron neutrinos. The most general form for an effective Lagrangian describing their radiative decay is given by\textsuperscript{11}

$$\mathcal{L} = \bar{\nu}_e \sigma_{\mu \nu} (\mu + d \gamma^5) \nu_x F^{\mu \nu} / 2 + \text{H.c.},$$

where $F^{\mu \nu}$ is the electromagnetic field tensor and $\mu$ and $d$ are the magnetic and electric transition moments. The radiative decay width is found to be\textsuperscript{12}

$$\Gamma_{\nu_e} = \frac{|\mu|^2 + |d|^2}{8 \pi} m_{\nu_e} \left[ 1 - (m_{\nu_x} / m_{\nu_e})^2 \right]^3.$$  

Bounds on $\mu$ and $d$ from scattering experiments can thus be used to constrain $\Gamma_{\nu_e}$.

In general, there are other electromagnetic form factors besides the dipole moments, but because of gauge invariance, only the dipole moments contribute to radiative decays.\textsuperscript{11} The other form factors contribute, however, to the scattering process $\bar{\nu}_e e^- \rightarrow \bar{\nu}_x e^-$. However, the dipole interaction Eq. (1) only couples neutrinos of opposite chirality, while all other terms, including the conventional weak interactions, couple states of equal chirality. Thus for relativistic neutrinos there is no interference between the electromagnetic dipole (EMD) contributions and the other contributions to the total scattering cross section.

The measured cross section for $\bar{\nu}_e e^-$ scattering has been previously used\textsuperscript{13,14} to constrain the diagonal magnetic dipole moment for $\nu_e$. On the basis of a cross-section measurement using reactor antineutrinos,\textsuperscript{15} Kyuldjiev\textsuperscript{14} finds an upper bound of $1.52 \times 10^{-10} \mu_B$. 

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where $\mu_B = e/2m_e$ is the Bohr magneton. His analysis, however, includes the standard weak-interaction contribution. This contribution possibly interferes with anomalous electromagnetic contributions other than the EMD term. Therefore it appears that a more reliable bound is found by attributing the complete cross section to the EMD scattering. Then the bound is weakened to $2.35 \times 10^{-10} \mu_B$, at 90% C.L. and we shall use this latter result for our analysis.

The $\nu_e$ emerging from a nuclear reactor are left-handed ultrarelativistic particles, whence the $\gamma_S$ matrix in Eq. (1) is equivalent to $\gamma_L$ and the coupling constant for the EMD scattering process $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$ is effectively $\langle \mu - d \rangle$. Thus Kyuldjiev's bound translates into $|\mu - d| < 2.35 \times 10^{-10} \mu_B$. With Eq. (2) this yields

$$\tau_{\nu_e} m_{\nu_e}^3 > 3.4 \times 10^{18} \text{sec eV}^3 \frac{|\mu - d|^2}{|\mu|^2 + |d|^2} \times [1 - (m_{\nu_e}/m_{\nu_e})^2]^{-3}.$$ 

This result is much more restrictive than all bounds which are based on the nonobservation of decay photons from observed neutrino fluxes. Only in the upper range of allowed masses, $m_{\nu_e} < 18 \text{eV}$, the limit based on SN 1987A is slightly more restrictive. Our result becomes more restrictive as $\nu_e$ and $\nu_x$ become degenerate, while the other bounds are degraded because the photon spectrum becomes too soft. Note that one of the recent experimental studies was specifically dedicated to the case of nearly degenerate neutrinos in that the authors searched for decay photons in the visible spectrum near a power reactor.

The present limits are invalidated, however, if the electric and magnetic transition moments are equal in phase and magnitude. If $CP$ is conserved, $\mu$ and $d$ are both real and there is no relative phase between them. In the standard model of purely left-handed weak interactions with massive neutrinos and neutrino mixing, the transition moments can be calculated and one finds $d/\mu = (m_{\nu_e} - m_{\nu_x})/(m_{\nu_e} + m_{\nu_x})$. Thus for $m_{\nu_x} \rightarrow 0$ one has $|\mu - d| \rightarrow 0$ and the scattering rate is suppressed. However, the absolute magnitude of the dipole moments is so small in this case that the present limits are of no practical meaning. In order to have dipole moments in the $10^{-10} \mu_B$ regime or larger one needs to invoke "exotic particle physics" beyond the standard model where typically $\mu = d$ would not occur. Thus, while the possibility $\mu = d$ cannot be excluded with absolute confidence, one would need extremely fine-tuned neutrino properties in order to avoid our limits.

For Majorana neutrinos, in general classes of gauge theories $\mu$ and $d$ are, respectively, real and imaginary so that $|\mu - d|^2 = |\mu|^2 + |d|^2$ and the above cancellation never occurs. If $CP$ conservation holds, either $\mu = 0$ or $d = 0$ and, again, no cancellation occurs. Therefore, only in the case of $CP$ conservation with Dirac neutrinos can the electric and magnetic dipole terms cancel each other in scattering experiments. This is, we believe, a new case for the important differences between the electromagnetic properties of Dirac and Majorana neutrinos.

### III. MUON NEUTRINOS

For $\nu_\mu$, the latest upper bound on the diagonal magnetic moment from $\nu_\mu e^- \rightarrow \nu_\mu e^-$ scattering experiments is $9.5 \times 10^{-10} \mu_B$ at 90% C.L., where, however, the standard-model contribution to the cross section has been included in the analysis. One finds $\tau_{\nu_\mu} m_{\nu_\mu}^3 > 2 \times 10^{17}$ sec eV$^3$ with an analogously dependence on the relative phase and magnitude of the transition moments and on the mass difference with the daughter neutrino as in Eq. (3). The direct searches for decay photons in the laboratory yield $\tau_{\nu_\mu}/m_{\nu_\mu} > 0.11$ sec/eV. Since $\nu_\mu$ may be as heavy as 250 keV, the search for decay photons is a much more sensitive method in the upper range of allowed $\nu_\mu$ masses. Also, very restrictive constraints on $\tau_{\nu_\mu}/m_{\nu_\mu}$ can be derived from SN 1987A.

We now specifically consider the possible transition movements between $\nu_\mu$ and $\nu_x$ and we write the effective interaction Lagrangian as in Eq. (1) with $\nu_\mu$ replaced by $\nu_x$ and with $\mu$ and $d$ not referring to the $\nu_x - \nu_\mu$ transition moments. Then the $\bar{\nu}_e e^-$ scattering data yield $|\mu - d| < 2.35 \times 10^{-10} \mu_B$ while the $\nu_\mu e^-$ scattering data yield $|\mu + d| < 9.5 \times 10^{-10} \mu_B$. The relative sign change between $\mu$ and $d$ occurs because both experiments are conducted with initially left-handed neutrinos. Therefore one has very restrictive constraints on these transition moments independently of their relative phase and magnitude.

### IV. BOUNDS FROM HORIZONTAL BRANCH STARS

Stronger bounds on the electromagnetic transition moments can be derived from the observed lifetimes of helium-burning stars. The electromagnetic couplings would allow for the plasmon decay process $\gamma_{pl} \rightarrow \nu_x \bar{\nu}_x$ and $\gamma_{pl} \rightarrow \nu_x \nu_x$ to occur in the interior of stars. This would lead to an "exotic energy-loss mechanism" and accelerate the evolutionary time scale of horizontal branch stars beyond observed limits unless the limit $|\mu|^2 + |d|^2)^{1/2} \leq 1 \times 10^{-11} \mu_B$. For Dirac neutrinos, the number of final states is twice that for Majorana neutrinos since then $\nu_\mu \bar{\nu}_e$ and $\nu_\mu \nu_x$ are distinct states. Thus for Dirac neutrinos this bound is $0.7 \times 10^{-11} \mu_B$. The less restrictive case yields

$$\tau_{\nu_\mu} m_{\nu_\mu}^3 > 2 \times 10^{21} \text{sec eV}^3 [1 - (m_{\nu_e}/m_{\nu_\mu})^2]^{-3}.$$ 

This limit is more restrictive than all the above mentioned results, and there is no "loophole" from possible cancellation or degeneracy effects. It is based, of course, upon an "experimentally" less direct method.

### V. SUMMARY

In summary we find that the most powerful constraints on the $\nu_e$ radiative decay which are based on observed neutrino fluxes arise from $\bar{\nu}_e e^-$ scattering experiments, and from the absence of a $\gamma$-ray burst associated with SN 1987A. The former bound is invalidated if an unlikely cancellation between the electric and magnetic transition moments for Dirac neutrinos occurs, the latter bound...
does not apply to nearly degenerate neutrinos. A less direct limit which is based on the observed lifetimes of horizontal branch stars is more restrictive and is not afflicted with any "loopholes" arising from special values of neutrino parameters.

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