Estimate of the branching ratio for Z→νν[over ¯]γγ

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An estimate of the branching ratio for $Z \to \nu\bar{\nu}\gamma\gamma$

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The effective interaction for two neutrino, two photon coupling is used to find an approximate width for the decay of the Z boson into the $\nu\bar{\nu}\gamma\gamma$ final state.

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An experimental upper bound exists for the branching ratio of $Z \to \nu\bar{\nu}\gamma\gamma$. In the early 1990s, both the L3 and OPEL groups looked for the decay at LEP. The net result was the limit [1] $BR(Z \to \nu\bar{\nu}\gamma\gamma) \leq 3.1 \times 10^{-6}$. Larios et al. [2] used this result together with a model where the neutrinos have a magnetic moment to put limits on the magnetic moment of ν_τ and, with a model of scalar couplings between the neutrinos and the photons, to put limits on the scalar couplings. (Of course, if the neutrinos are Majorana they do not have magnetic moments.)

Relevant to this decay, there is an effective two neutrino-two photon coupling [3–5] given by

$$\mathcal{L}_{\rm eff}^{\rm SM} = \frac{1}{32\pi}\frac{ig^2\alpha}{M_W^4} A \left[\bar{\psi}\gamma^\nu(1-\gamma^5)(\partial^\mu\psi) - (\partial^\mu\bar{\psi})\gamma^\nu(1-\gamma^5)\psi\right] F_{\mu\lambda}F_\nu^\lambda\,, \tag{1}$$

where g is the electroweak gauge coupling, α is the fine structure constant, ψ is the neutrino field, and $F_{\mu\nu}$ is the electromagnetic field tensor. For center of mass energies less than m_e the parameter A is given explicitly by [3, 4, 6]

$$A = \left[\frac{4}{3}\ln\left(\frac{M_W^2}{m_e^2}\right) + 1\right]. \tag{2}$$

This expression can be obtained by expanding the loop integrals for the $\gamma\gamma \to \nu\bar{\nu}$ scattering amplitudes in powers of the center of mass energy divided the internal masses [3] or by calculating the scattering of neutrinos by a homogeneous magnetic field [6] and keeping the term quadratic in the magnetic field tensors.

For the energies of interest here, A is obtained by using Eq. (1) to calculate $\gamma\gamma \to \nu\bar{\nu}$ and fitting to the numerical result shown in Fig. 4 of reference [5]. This figure shows that the exact cross section for $\gamma\gamma \to \nu\bar{\nu}$ scattering in the range $m_e \leq \sqrt{s} \leq 100\,\text{GeV}$ behaves like $(\sqrt{s})^6$, just as predicted by Eq. (1). The fit gives gives

$$A = 13.66\,, \tag{3}$$

independent of neutrino flavor.

We can get an approximate expression for the amplitude for the Z decay into two neutrinos and two photons by coupling the neutrino field, or the anti-neutrino field, of (1) to the standard model $Z\nu\bar{\nu}$ interaction. This is obviously gauge invariant for the photons. Furthermore, if both neutrinos in the coupling (1) are contracted, we obtain an amplitudes for $Z \to \gamma\gamma$ that must vanish if $\mathcal{L}_{\rm eff}^{SM}$ is a reasonable expression to use in Z decay. This is not self evident, but can be seen from the resulting expression

$$T(Z \to \gamma\gamma) \sim \epsilon_\alpha(P) X_{\mu\nu} \int \frac{d^4s}{(2\pi)^4}\frac{(2s+P)^\mu}{s^2(s+P)^2}{\rm Tr}\left[\gamma^\alpha \not{s}\gamma^\nu(\not{s}+\not{P})(1+\gamma^5)\right]\,, \tag{4}$$

where $\epsilon_\alpha(P)$ is the polarization vector of the Z with momentum P and

$$X_{\mu\nu} \equiv \langle\, k_1, \epsilon_1, k_2, \epsilon_2 | F_{\mu\lambda}(0)F_\nu^\lambda(0)|0\rangle\,, \tag{5}$$

is the matrix element of the photons. The integral can only depend on some combination of $P^\alpha P^\mu P^\nu$, $P^\alpha g^{\mu\nu}$, $P^\mu g^{\alpha\nu}$, and $P^\nu g^{\alpha\mu}$. The first two vanish since $\epsilon(P)\cdot P = 0$. The final two are also zero for the same reason once we use $P^\mu X_{\mu\nu} \sim P_\nu$ or $P^\nu X_{\mu\nu} \sim P_\mu$ and $P = k_1 + k_2$.

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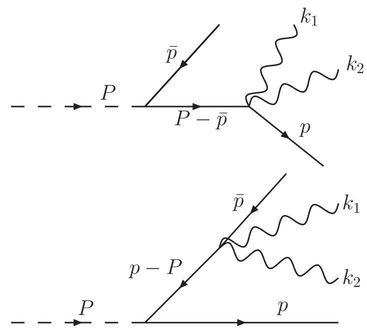

FIG. 1: The diagrams for $Z \to \nu\bar{\nu}\gamma\gamma$ using the $\nu\bar{\nu}\gamma\gamma$ effective Lagrangian are shown.

Coupling (1) to the $Z\nu\bar{\nu}$ vertex, as shown in Fig. (1), gives an amplitude for $Z \to \nu\bar{\nu}\gamma\gamma$ that has no free parameters. It is given by

$$\mathcal{M} = \frac{g^3 \alpha A}{64\pi \cos\theta_W M_W^4} \bar{u}(p) \left[\not{\epsilon} \frac{(\not{p} - \not{P})}{(p-P)^2} (\bar{p} - p + P)^\mu \gamma^\nu + (\bar{p} - p - P)^\mu \gamma^\nu \frac{(\not{P} - \not{\bar{p}})}{(P-\bar{p})^2} \not{\epsilon} \right] (1-\gamma^5) v(\bar{p}) X_{\mu\nu} \,. \tag{6}$$

After squaring and integrating over the four-body phase space, the resulting width for each neutrino is [7]

$$\Gamma(Z \to \nu\bar{\nu}\gamma\gamma) \;=\; \frac{\alpha^5 \, A^2}{\sin^6\theta_W \cos^2\theta_W} \frac{M_Z^9}{M_W^8} \frac{1}{90\,\pi^4} \frac{1}{2^{18}} \left(\frac{28}{15}\pi^2 - \frac{3146341}{173250} \right) , \tag{7}$$

$$= \; 1.55 \times 10^{-14}\,\text{GeV} \,, \tag{8}$$

or a branching ratio of 6.2×10^{-15}.

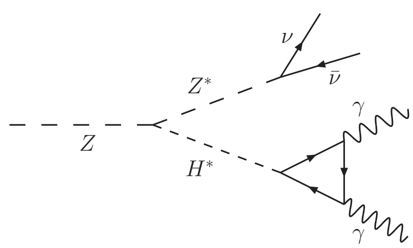

FIG. 2: The diagram for $Z \to \nu\bar{\nu}\gamma\gamma$ using the $Z \to Z^* H^*$ vertex is shown.

We can also get an estimate of this partial width by calculating $Z \to Z^* H^*$, $Z^* \to \nu\bar{\nu}$, $H^* \to \gamma\gamma$ where Z^* and H^* are off-shell Z and Higgs bosons. Using the expression for Higgs to two photon decay from [8] or [9] with the Higgs mass replaced by the scalar product of the photon momenta, $2k_1 \cdot k_2$, we get

$$\Gamma(Z \to \nu\bar{\nu}\gamma\gamma) \;=\; 1.7 \times 10^{-17}\,\text{GeV} \,. \tag{9}$$

This is much smaller than the estimate above because the Z^* and H^* propagators are far off shell and the triangle loop has no enhancement factor like A that comes from using Eq. (1), which is the effective interaction that replaces the $\gamma\gamma \to \nu\bar{\nu}$ box diagrams.

Of course, (7) or (8) is only a rough estimate. In addition to the diagrams we have calculated, there are numerous other loop diagrams where the Z decays into $e\bar{e}$ or W^+W^- and the charged particles convert into neutrinos by the exchange of W or an electron. Because the final states are neutral, the photons in the final state must radiated from one of the charged particles in the loop. One example of such a process is shown in Fig. (3). But all these contributions come from pentagon diagrams that are not expected to give a total branching ratios larger than (8). What Eq. (8) shows is that, within the Standard Model, the branching ratio for this process is extremely small and will be difficult to observe at the predicted level. Any detection of this decay at a substantially larger branching ratio is likely to be a sign of physics beyond the Standard Model.

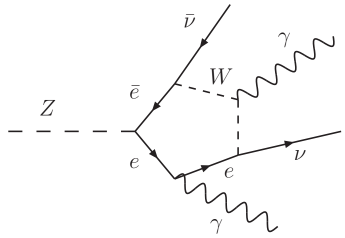

FIG. 3: One of the remaining diagrams contributing to $Z \to \nu\bar{\nu}\gamma\gamma$ is illustrated.

Acknowledgments

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