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CONSTRAINTS ON RADIATIVE Z_0 DECAYS*

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ABSTRACT

We study an effective local interaction as a possible source of hard photons in the decay $Z_0 \to \ell \bar{\ell} \gamma$. We restrict the form of this interaction by the requirements that it be gauge invariant, CP invariant and chirality conserving. Including constraints derived from the agreement of the standard model in other neutral current experiments, we find the ratio of radiative to non-radiative leptonic decay widths is given by $17(M_Z/M_\Lambda)^4$ where M_Λ is the mass scale characterizing the "new physics." This ratio is less than the preliminary indication of approximately 10% if M_Λ is greater than 350 GeV.

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Observation of hards gammas accompanying the leptons in Z_0 decay has been reported.[1] Specifically two observed decays $Z_0 \to e^+e^-\gamma$ and one of $Z_0 \to \mu^+\mu^-\gamma$ suggest a ratio of radiative to non-radiative decay widths that is an order of magnitude larger than anticipated from normal radiative corrections to the lepton current.[2] The observed γ is harder than anticipated on the basis of QED radiative corrections to the decay of a point-like elementary Z_0 vector boson. At the same time, no comparable γ emission has been detected in charged heavy boson decay, $W^\pm \to \ell^\pm\nu\gamma$.[3]

These observations are preliminary and further data and analysis will be required before any conclusion can be made with confidence about the significance of these events.[4] Nevertheless they raise an interesting question that we address here: What limits do already established properties of the neutral current interaction put on possible corrections to the standard model[5] leading to processes $Z_0 \to \ell\bar{\ell}\gamma$? Are the observed radiative decays consistent with these limits?

We approach this question by positing the existence of a local interaction between the lepton current and the Z_0 and γ field strengths and their derivatives, which is a phenomenological representation of possible underlying structure (compositeness) of the Z_0 and leptons on the mass scale greater than M_Z. Certain invariance properties are preserved in writing the interaction:

(1) U(1) gauge invariance for the γ and Z_0 fields. SU(2)× U(1) is sacrificed due to the absence of $W^\pm \to \ell^\pm\nu\gamma$ events.

(2) CP invariance

(3) Chiral invariance in order to preserve present notions of the "lightness" of lepton masses.

We then find that within this set of assumptions the added interaction is severely limited by the established agreement of the standard model with observations of the interference between the neutral weak and the electromagnetic interaction in Bhabha scattering, atomic physics transitions and inelastic scattering of polarized electrons from deuterium. The constraints from these experiments imply that if this interaction is to explain the observed rate of radiative Z_0 decays to leptons then the mass scale characterizing the "new physics" cannot be larger than 350 GeV.

In addition to the conditions used above we will assume the interaction to be an iso-singlet since no hard gammas are observed in $W^{\pm}$ decay. This assumption extends the analysis to neutrino-electron and neutrino-nucleon inelastic scattering results which establish a limit on the added interaction that is the same order of magnitude as the limits from the electron processes, but complementary.[6]

The effective interaction we study is given by a dimension 8 operator of the form

$$L_{eff} = \frac{1}{M_\Lambda^4}\Big\{C_L(\bar{\ell}_L\gamma^\mu\ell_L + \bar{\nu}_L\gamma^\mu\nu_L) + C_R\,\bar{\ell}_R\gamma^\mu\ell_R\Big\}\epsilon_{\mu\nu\sigma\tau}(\partial^\nu F^{\sigma\lambda})G^\tau{}_\lambda \quad (1)$$

where $F^{\sigma\lambda}$ and $G^{\tau\lambda}$ are respectively the γ and Z_0 field strengths, $\epsilon_{\mu\nu\sigma\tau}$ is the Levi-Civita tensor, $M_\Lambda > M_Z$ is a mass defining the range, or mass scale, of Z_0 substructure and $C_{L,R}$ are dimensionless coupling constants. The Levi-Civita tensor is required in the interaction so that the total interaction term in the Langrangian is CP even.

No lower dimensional operator can be written consistent with our stated assumptions. The only other possible dimension 8 operator differs from (1) by moving the derivative from the photon field onto the Z_0 field and leads to the same conclusion.[7]

This phenomenological interaction allows us to predict the rate for $Z_0 \to \ell \bar{\ell} \gamma$ and the interaction of a lepton with charged quarks and leptons via the process of Fig. 1. The interaction of the Z_0 and γ with the quarks and leptons is given by the standard model. Treating (1) as an effective interaction we do not allow either the Z_0 or γ to be absorbed by the same lepton line that emitted it.[8]

The loop integral in Fig. 1 depends quadratically on the cutoff which we take as $M_\Lambda > M_Z$. This leads to the effective local four-fermion interaction (G_F is the Fermi constant)

$$\tilde{L}_{eff} = \frac{1}{M_\Lambda^2} \frac{e}{32\pi^2} \frac{M_Z G_F^{1/2}}{2^{3/4}} \left\{ C_L(\bar{\ell}_L \gamma^\mu \ell_L + \bar{\nu}_L \gamma^\mu \nu_L) + C_R \bar{\ell}_R \gamma^\mu \ell_R \right\} \cdot (qa\, \bar{\psi} \gamma_\mu \gamma_5 \psi + qb\, \bar{\psi} \gamma_\mu \psi) \tag{2}$$

where qe is the electric charge of the "target", ψ, and a and b are respectively the vector and axial couplings of the target to the Z_0. Values appropriate to the different experiments are listed in Table 1. For the atomic physics experiment one takes a coherent sum over the quark constituents of the nucleon as well as over the nucleons themselves. For the inelastic scattering experiments the sum over nucleons is incoherent.

Such an effective Langrangian is constrained by the measurements that support the standard model.[9] The tightest constraints come from neutrino scattering giving a limit to C_L,

$$|C_L| \leq 0.29 f$$

where $f \equiv (32\pi/e)\, 2^{1/4}\, (M_\Lambda/M_Z)^2$, and from the atomic parity violation experiments giving a limit on $C_R - C_L$,

$$|C_R - C_L| \leq 0.22 f \quad .$$

We combine these to give an overall limit of

$$(C_R^2 + C_L^2)^{1/2} \leq (0.59) f \quad . \tag{3}$$

Table 2 summarizes the restrictions derived from each of the individual interference experiments.

Constraints can also be obtained for an interaction similar to (1) but with the leptons replaced by quarks. The atomic parity violation experiments and the polarized electron experiment performed at SLAC will both give limits.[10] These limits will be less restrictive because to have the electrons coupled axially in the effective four-fermion interaction they must couple vectorially to the Z_0 which introduces a small factor $(1 - 4\sin^2\theta_W) \approx 0.08$.

The interaction (1) also allows the Z_0 to decay into $\ell\bar{\ell}\gamma$ [11] with a rate compared to $\ell\bar{\ell}$ pairs of

$$\begin{aligned} \Gamma_{\ell\bar{\ell}\gamma}/\Gamma_{\ell\bar{\ell}} &= \frac{\sqrt{2}\,(G_F M_Z^2)^{-1}}{4608\,\pi^2}\,(C_R^2 + C_L^2)\left(\frac{M_Z}{M_\Lambda}\right)^8 \\ &\approx 3.2 \times 10^{-4}\,(C_R^2 + C_L^2)\left(\frac{M_Z}{M_\Lambda}\right)^8 \quad . \end{aligned} \tag{4}$$

Using the constraint (3) we obtain the limit

$$\Gamma_{\ell\bar{\ell}\gamma}/\Gamma_{\ell\bar{\ell}} \leq 17\left(\frac{M_Z}{M_\Lambda}\right)^4 \quad . \tag{5}$$

If we require this ratio to be 10% as suggested by the data, then M_Λ is less than 350 GeV! The bounds in Eichten et al.[9] were quoted in terms of a larger scale $M_\Lambda \approx 1$ TeV assuming that a strong force binds the constituents of the leptons. However only the single parameter C/M_Λ^2 has been determined by the interference measurements. Thus, the independent limit of (5) with

$M_\Lambda \approx 350$ GeV corresponds to an assumption of intermediate coupling; $g^2/4\pi \approx 1/10$ according to the conventions of Ref. 9.

However there still remains a problem in the angular correlation reported in Ref. 1. The probability for γ emission derived from Eq. (1) is proportional to $(k \cdot \pi)^2\ (k \cdot p_1)\ (k \cdot p_2)$ where π, k, p_1, p_2 are the four vectors of the Z_0, γ and the two leptons respectively. This gives a factor of $(1 - \cos\theta)$ which enhances the probability for the photon and one of the leptons emerging back to back in the Z_0 rest frame, θ being the angle between that lepton and the photon. This however does not explain the tight correlation suggested by the data.

If these hard γ's prove to be inconsistent with ordinary bremsstrahlung their interpretation will be very puzzling as well as interesting. We thank Michael Peskin and Gary Feinberg for very valuable discussions.

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6. No limits have been reported on $Z_0 \to \nu \bar{\nu} \gamma$; if these do not occur then C_L should be set equal to zero.
7. This is because the Z_0 and γ carry the same momenta to leading order in $M_\Lambda > M_Z$ in the interference processes being studied. A derivative on the product $(F^{\sigma\lambda} G^{\tau}{}_{\lambda})$ is equivalent (L_{eff} differs only by a total derivative) to a coupling to the derivative of the lepton current. Such an interaction is also possible in principle but ruled out by assumption. In particular, it leads to a velocity dependent interaction instead of the effective four-fermion coupling (2) which forms the basis of our comparisons. Equation (1) could result from the coupling of the Z_0 field to an ordinary spin $\frac{1}{2}$ lepton and to a massive higher spin fermion which decays subsequently to a lepton by radiating a photon.

8. Nor do we allow the two fermion or two boson lines to join together. We also do not go beyond a lowest order treatment of Eq. (1) since it is a very singular effective interaction.

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10. These experiments will give similar constraints if the hard gamma-lepton pair events come from the decay of a particle other than the Z_0. Since, the observation of such events in $p\bar{p}$ collisions implies that this particle couples to quarks and/or gluons.

11. The cross section for $e^+e^- \to Z_0 + \gamma$ is $\frac{C_R^2+C_L^2}{3072}\frac{(S-M_{Z_0}^2)^5}{S^2 M_A^8}$. At SLC/LEP energies and using the constraints above this is femtobarns.

TABLE 1

Couplings for the effective four-fermian interaction.

ψ	q	a	b
ν	0	1	-1
e, μ	-1	$-(1-4s^2)$	1
u	$\frac{2}{3}$	$(1-\frac{8}{3}s^2)$	-1
d	$-\frac{1}{3}$	$-(1-\frac{4}{3}s^2)$	1
p	1	$(1-4s^2)$	-1
n	0	-1	1

$$s^2 \equiv \sin^2\theta_W \approx 0.23$$

TABLE 2

Summary of Constraints by experiment.

Experiment	Constraint
$\nu - e$ scattering	$\|C_L\| < 0.29f$
$\nu - q$ scattering	$\|C_L\| < 0.40f$
Parity Violation in Atoms	$\|C_R - C_L\| < 0.22f$
Polarized Electron Scattering	$\|C_R - C_L\| < 0.81f$ $\|C_R + C_L\| < 2.0f$
Bhabha	$\|C_R - C_L\| < 0.88f$
Combined	$(C_R^2 + C_L^2)^{1/2} < 0.59f$

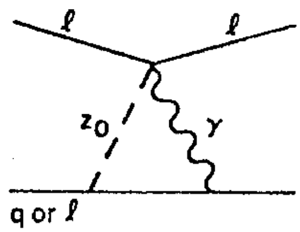

Fig. 1

FIGURE CAPTIONS

1. Graph for lepton scattering from quarks or leptons via the process in Eq. (1).