SLAC – PUB – 3308
March 1984
(T/E)

CONSTRAINTS ON RADIATIVE Z_0 DECAYS*

SIDNEY D. DRELL

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

STEPHEN J. PARKE

Fermi National Accelerator Laboratory
Batavia, Illinois 60510
and
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

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 $SU(2) \times U(1)$ 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 $0.6(M_Z/M_\Lambda)^4$ where M_Λ is the mass scale characterizing the "new physics." This ratio is less than the preliminary experimental indication of approximately 10% if M_Λ is greater than 150 GeV.

* Work supported in part by the Department of Energy, contract DE-AC03-76SF00515 and Fermilab is operated by the Universities Research Association Inc. under contract with the United States Department of Energy.

Observation of hard gammas accompanying the leptons in Z_0 decay has been reported.[1] Specifically two observed decays $Z_0 \rightarrow e^+e^-\gamma$ and one of $Z_0 \rightarrow \mu^+\mu^-\gamma$ 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, $W^{\pm} \rightarrow \ell^{\pm}\nu\gamma$.[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 $Z_0 \rightarrow \ell\bar{\ell}\gamma$? 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) $SU(2) \times U(1)$ gauge invariance. The lepton current is assumed to be an isosinglet due to the absence of $W^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ 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, inelastic scattering of polarized electrons from deuterium, neutrino-electron and neutrino-nucleon inelastic scattering. 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 150 GeV. This result indicates the interaction must be non-local on the scale of the Z_0 mass, and contradicts our original assumption.

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

$$\mathcal{L}_{eff} = \frac{1}{M_\Lambda^4}\left\{C_L(\bar{\ell}_L\gamma^\mu\ell_L + \bar{\nu}_L\gamma^\mu\nu_L) + C_R\,\bar{\ell}_R\gamma^\mu\ell_R\right\}\epsilon_{\mu\nu\sigma\tau}\,(\partial^\nu B^{\sigma\lambda})B^\tau{}_\lambda \qquad (1)$$

where $B^{\sigma\lambda}$ is the $U(1)$ hypercharge field strength,[6] $\epsilon_{\mu\nu\sigma\tau}$ is the Levi-Civita tensor, $M_\Lambda > M_Z$ is a mass defining the range, or mass scale, of Z_0 substructure and hence of "new physics". $C_{L,R}$ 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. Again we emphasize the purpose of this analysis is simply to establish limits on (1) and the rate of the decay $Z_0 \rightarrow \ell\bar{\ell}\gamma$ as derived from neutral current experiments. Results will differ for specific models relying on lighter particles with $M_\Lambda \lesssim M_Z$ leading to non-local contributions via intermediate closed loops.

Since (1) represents an effective lagrangian we analyze only its first order contributions. In second order it can give rise to four fermion contributions too but these would have to be combined with direct four-fermion terms arising from the underlying dynamics. We do not model, and therefore do not retain, such higher order effects. In lowest order (1) gives rise to no self-mass or g-2 corrections for the leptons because it is chirality conserving.

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.[7]

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 to leading order in $(M_Z/M_\Lambda)^2 \ll 1$:

$$\begin{aligned}\widetilde{\mathcal{L}}_{eff} = \frac{1}{M_\Lambda^2}\frac{3e^2}{16\pi^2}&\Big\{C_L(\bar{\ell}_L\gamma^\mu\ell_L + \bar{\nu}_L\gamma^\mu\nu_L) + C_R\bar{\ell}_R\gamma^\mu\ell_R\Big\}\\ &\cdot\Big\{\Big[(1-s^2)q^2 + \frac{1}{2}qa + \frac{a^2+b^2}{16(1-s^2)}\Big]\bar{\psi}\gamma_\mu\gamma_5\psi \\ &+ \Big[\frac{1}{2}qb + \frac{ab}{8(1-s^2)}\Big]\bar{\psi}\gamma_\mu\psi\Big\}\end{aligned} \tag{2}$$

where qe is the electric charge of the "target", ψ, $s^2 \equiv \sin^2\theta_W \approx 0.22$ 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.[8] The tightest constraints come from neutrino scattering giving a limit to $C_L - 0.15C_R$,

$$|C_L - 0.15C_R| < 0.19f$$

where $f \equiv (8\pi^2/3e^2)\, 2^{1/2}\, (M_\Lambda^2 G_F)$, ($G_F$ is the Fermi constant) and from the atomic parity violation experiments giving a limit on $C_R - C_L$,

$$|C_R - C_L| \leq 0.32f \quad .$$

We combine these to give an overall limit of

$$(C_R^2 + C_L^2)^{1/2} \leq (0.66)f \quad . \tag{3}$$

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.[9] 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 $(1 - 4\sin^2\theta_W) \approx 0.12$.

The interaction (1) also allows the Z_0 to decay into $\ell\bar{\ell}\gamma$ [10] with a rate compared to $\ell\bar{\ell}$ pairs of

$$\begin{aligned} \Gamma_{\ell\bar{\ell}\gamma}/\Gamma_{\ell\bar{\ell}} &= \frac{\sqrt{2}s^2(1-s^2)(M_Z^2 G_F)^{-1}}{320\,\pi^2}\,(C_R^2 + C_L^2)\left(\frac{M_Z}{M_\Lambda}\right)^8 \\ &\approx 8.7\times 10^{-4}\,(C_R^2 + C_L^2)\left(\frac{M_Z}{M_\Lambda}\right)^8 \quad . \end{aligned} \tag{4}$$

Using the constraint (3) we obtain the limit

$$\Gamma_{\ell\bar{\ell}\gamma}/\Gamma_{\ell\bar{\ell}} \leq 0.62\left(\frac{M_Z}{M_\Lambda}\right)^4 \quad . \tag{5}$$

If we require this ratio to be no less than 10% as suggested by the data, then M_Λ is less than 150 GeV![11] The bounds in Eichten et al.[8] 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 $M_\Lambda \approx 150$ GeV corresponds to an assumption of intermediate coupling, $g^2/4\pi \approx 1/50$, according to the conventions of Ref. 8.

Three further comments are in order

1. The limit on $M_\Lambda < 150$ GeV is so low that it strongly suggests that the experimental results, if verified, are incompatible with a local interaction of form (1) as required by only theoretical assumptions. Form factors resulting from a non-local interaction will suppress the amplitudes in the calculation of Fig. (1) leading to the effective interaction (2). Such non-locality could be an expression of contributions from new particles of mass $\approx M_Z$ as noted by a number of authors. Our results show that one <u>needs</u> such a low scale of new physics if $SU(2) \times U(1)$ gauge, CP, and chiral invariance are to be maintained.

2. The absence of decays $Z_0 \to \nu\bar{\nu}\gamma$ indicates $|C_L| < \frac{1}{3}|C_R|$ corresponding to three types of neutrinos and less than one observed decay. This additional restriction leads to a still smaller value for $M_\Lambda < 130$ GeV.

3. There still remains a problem in the angular correlation reported in Ref. 1.

The local interaction (1) does not explain the tight correlation of the photon with one of the electrons suggested by the data.

If these hard γ's prove to be inconsistent with ordinary bremsstrahlung it is apparent that their interpretation will be very interesting. We thank Michael Peskin and Gary Feinberg for very valuable discussions; Duane Dicus for pointing out a numerical error in our earlier draft; and a referee for helpful remarks.

REFERENCES

1. UA1 Collab., G. Arnison et. al., Phys. Lett. 126B, 398 (1983). UA2 Collab., P. Bagnaia et. al., Phys. Lett. 129B, 130 (1983).
2. F. Berends et. al., Nucl. Phys. B202, 63 (1982). G. Passarino, Phys. Lett. 130B, 115 (1983). G. Pancheri and Y. Srivastava, Phys. Lett. 137B, 117 (1984). M. Caffo, R. Gatto and E. Remiddi, Phys. Lett. 139B, 439 (1984).
3. UA1 Collab., G. Arnison et. al., Phys. Lett. 135B, 250 (1984).
4. R. D. Peccei, Phys. Lett. 136B, 121 (1984). N. Cabibbo, L. Maiani and Y. Srivastava, Phys. Lett. 139B, 359 (1984). M. J. Duncan and M. Veltman, Phys. Lett. 139B, 310 (1984). L. Bergstrom, Phys. Lett. 139B, 102 (1984). F. M. Renard, Phys. Lett. 139B, 449 (1984). M. Leurer, H. Harari and R. Barbieri, Phys. Lett. 141B, 455 (1984).
5. S. Weinberg, Phys. Rev. Lett. 10, 1264 (1967). A. Salam, Proceedings of the 8^{th} Nobel Symposium, ed. by N. Svartholm, Almquist and Wiksells, Stockholm, 1968. S. L. Glashow, Nucl. Phys. 22, 579 (1961).
6. In terms of Z_μ and A_μ, the Z_0 and γ gauge fields respectively, B_μ is given by the linear combination $B_\mu = \cos\theta_W\, A_\mu - \sin\theta_W\, Z_\mu$, where θ_W is the Weinberg angle.
7. 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. Nor do we allow the two fermion or two boson lines to join together.
8. E. Eichten, K. D. Lane, M. E. Peskin, Phys. Rev. Lett. 50, 811 (1983). Tasso Collab., M. Althoff, et. al., Z. Phys. C22, 13 (1984). E. D. Commins and P. H. Bucksbaum "Weak interactions of leptons and quarks" Table

12.1, page 423, Cambridge University Press (1983) and references contain within. C. Bouchiat and C. A. Piketty, Phys. Lett. 128B, 73 (1983), and P. S. Drell and E. D. Commins, LBL preprint 17692.

9. 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. The observation of such events in $p\bar{p}$ collisions implies that this particle couples to quarks and/or gluons.

10. Using the above constraints the cross section for $e^+e^- \rightarrow Z_0 + \gamma$ is only femtobarns at SLC/LEP energies.

11. The limit on M_Λ is still smaller, by $2^{1/4}$, if we choose 20% for the experimental ratio, corresponding to 3 events with hard gammas out of a total of 15.

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

TABLE 2

Summary of Constraints by experiment.

Experiment	Constraint
$\nu - e$ scattering	$\lvert C_L - 0.15 C_R \rvert < 0.19 f$
$\nu - q$ scattering	$\lvert C_L \rvert < 0.43 f$
Parity Violation in Atoms	$\lvert C_R - C_L \rvert < 0.32 f$
Polarized Electron Scattering	$\lvert C_R - C_L \rvert < 0.67 f$ $\lvert C_R + C_L \rvert < 1.40 f$
Bhabha	$\lvert C_R - C_L \rvert < 1.7 f$
Combined	$(C_R^2 + C_L^2)^{1/2} < 0.66 f$

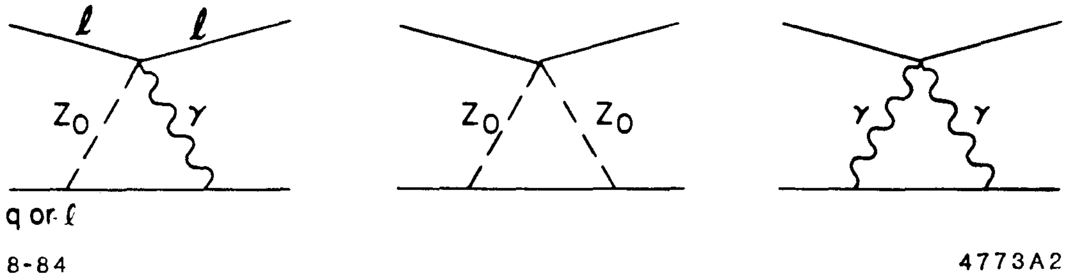

Figure 1

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