CERN-TH.4090/85

ANOMALOUS PHOTON INTERACTIONS

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A B S T R A C T

It is pointed out that many models of the radiative decay of the Z^0 boson would necessitate a new two photon-two lepton effective interaction in an $SU(2) \times U(1)$ invariant theory. We study the effect of this interaction and show that its effect is negligible in QED processes at present energies. Possibilities of detecting it at future colliders are also discussed.

CERN-TH.4090/85

January 1985

The detection of the Z^0 boson at the CERN $\bar{p}p$ collider has produced three events where the charged leptonic final state is accompanied by a hard photon¹⁾. A number of models²⁾⁻⁴⁾ have been proposed to explain these anomalous events^{*}). Most of these assume a new phenomenological interaction based on some underlying structure for either the Z^0 or the leptons. An example is the model of Drell and Parke who assume that the dynamics gives rise to an effective Z^0 -boson-photon-lepton-lepton vertex in the low energy theory. They write as their effective interaction the Lagrangian for this vertex,

$$\mathcal{L}_{int} = \frac{1}{M_A^4} \left\{ C_L (\bar{l}_L \gamma^\mu l_L + \bar{\nu}_L \gamma^\mu \nu_L) + C_R \bar{l}_R \gamma^\mu l_R \right\} \times \epsilon_{\mu\nu\alpha\beta} (\partial^\nu B^{\alpha\beta}) B^\beta_\lambda, \quad (1)$$

where $B_\mu = \cos\theta_W A_\mu - \sin\theta_W Z_\mu$. $\mathcal{L}_{int}$ introduced in (1) is the operator of lowest dimensionality consistent with $SU(2) \times U(1)$, CP and chiral invariances.

It is clear that such an interaction would necessarily entail a new two photon-two lepton effective interaction [as would any other $SU(2) \times U(1)$ invariant model with an effective $Z\gamma\ell\ell$ interaction]. This raises the interesting question of whether the "new" physics (if any!) can be seen in photon interactions without the presence of a Z^0 and, also, whether such photon interactions necessitate additional constraints on models of radiative Z^0 decays. It is this point we wish to address in this note.

New physics from high energy photon interactions is also interesting from the point of view of planning for the SSC. Tannenbaum⁵⁾ has pointed out that a high intensity coherent photon beam is possible at the SSC with a beam energy of ~ 9 TeV. He estimates the luminosity for a liquid hydrogen target to be $\sim 6 \times 10^{31} \text{ cm}^{-2} \text{ sec}^{-1}$.

In studying the possible form for this new two photon-two lepton interaction, it is interesting to note that dimension-six operators are ruled out by electromagnetic gauge invariance (since the photon can enter the interaction only

*) References 2) and 3) are models for radiative Z^0 -decay. For a critique, see V. Barger et al., Phys.Rev. D30 (1984) 1513. The papers in Ref. 4) deal with the decay of a spinless particle which would look like radiative decays of the Z^0 . For a critique, see H. Baer et al., University of Madison preprint MAD/PH/215 (1984). Our analysis does not address the papers in Ref. 4). We note that like the other models, the Drell-Parke model is unable to account for the angular correlation of the photon.

the form $F^{\mu\nu}$). Dimension-seven interactions seem to give too large a contribution to the muon or electron magnetic moment⁶⁾. Even dimension interactions do not appear to have this problem since the lepton current must be either vector or axial vector and hence chirality-conserving. Thus, there are no self-mass or (g-2) corrections for the leptons in lowest order²⁾.

We are thus led to consider dimension-eight operators for our effective interaction. Assuming CP invariance and absence of derivatives in the lepton current, the unique form of this operator is that of Drell and Parke²⁾. We thus write

$$\mathcal{L}_{int}^{\gamma\gamma} = \frac{1}{M_\Lambda^4} \left\{ C'_L (\bar{l}_L \gamma^\mu l_L + \bar{\nu}_L \gamma^\mu \nu_L) + C'_R \bar{l}_R \gamma^\mu l_R \right\} \times \\ \times \epsilon_{\mu\nu\alpha\beta} (\partial^\nu F^{\alpha\lambda}) F^\beta{}_\lambda, \quad (2a)$$

with

$$(C'_L, C'_R) = \cos^2 \theta_W (C_L, C_R), \quad (2b)$$

where $C_L(C_R)$ appeared in (1).

We fix the magnitudes of our couplings by calculating the rate for $Z^0 \rightarrow l\bar{l}\gamma$ using (1) and requiring that $\Gamma_{l\bar{l}\gamma}/\Gamma_{l\bar{l}} = 0.1$. This gives

$$(C_L^2 + C_R^2) / M_\Lambda^8 \simeq 115 / m_Z^8, \quad (3)$$

where m_Z is the mass of the Z^0 .

We now turn to the modifications to QED that arise due to the presence of $\mathcal{L}_{int}^{\gamma\gamma}$ given by (2). Consider first the case when both the photons in (2) are real. The matrix element of the photon part of (2) is then given by

$$\langle 0 | \epsilon^{\mu\nu\rho\sigma} (\partial_\nu F_{\rho\lambda}) F^\lambda{}_\sigma | \gamma(k_1) \gamma(k_2) \rangle \\ \equiv \epsilon_\alpha(k_1) \epsilon_\beta(k_2) \Gamma^{\mu\alpha\beta}(k_1, k_2), \quad (4)$$

where

$$\begin{aligned} \Gamma^{\mu\alpha\beta}(k_1, k_2) = & \epsilon^{\mu\alpha\beta\eta_1} (k_1 - k_2)_{\eta_1} k_1 \cdot k_2 \\ & + \epsilon^{\mu\alpha}{}_{\eta_1\eta_2} k_1^{\eta_1} k_2^{\eta_2} k_1^\beta - \epsilon^{\mu\beta}{}_{\eta_1\eta_2} k_1^{\eta_1} k_2^{\eta_2} k_2^\alpha. \end{aligned} \quad (5)$$

Equation (5) is the only form which will satisfy both gauge invariance and Bose symmetry, i.e.,

$$k_1^\alpha \Gamma_{\mu\alpha\beta}(k_1, k_2) = k_2^\beta \Gamma_{\mu\alpha\beta}(k_1, k_2) = 0$$

and

$$\Gamma_{\mu\alpha\beta}(k_1, k_2) = \Gamma_{\mu\beta\alpha}(k_2, k_1).$$

It is possible to rewrite (5) in the form

$$\begin{aligned} \epsilon_\alpha(k_1) \epsilon_\beta(k_2) \Gamma^{\mu\alpha\beta}(k_1, k_2) = \\ - (k_1 + k_2)^\mu \epsilon^{\alpha\beta}{}_{\eta_1\eta_2} k_1^{\eta_1} k_2^{\eta_2} \epsilon_\alpha(k_1) \epsilon_\beta(k_2), \end{aligned} \quad (6)$$

where we have assumed the photons are on their mass-shell.

As an explicit example involving real photons, we consider pair annihilation $\lambda + \bar{\lambda} \rightarrow \gamma + \gamma$. From Eq. (6), the photon part of the matrix element is proportional to the sum of the photon momenta which is equal to the sum of the lepton momenta, $p_1 + p_2$. The matrix element is thus proportional to $(p_1 + p_2)_\mu$ times $\bar{v}(p_1) \gamma^\mu (a + b \gamma_5) u(p_2)$ with $a = \frac{1}{2}(C'_L + C'_R)$ and $b = \frac{1}{2}(C'_R - C'_L)$. The vector part of the matrix element is thus zero whereas the axial vector part is proportional to the lepton mass. The cross-section is given by

$$\sigma = \frac{(C'_R - C'_L)^2}{8\pi} \frac{m^2 E^4}{M_A^8}, \quad (7)$$

where E is the energy of each of the colliding leptons in the centre-of-mass frame, and m is the mass of the lepton. The cross-section is thus small for $E \gg m$ and, in fact, zero if $C'_L = C'_R$. To estimate this cross-section, we take $C'_R = 0$. Then

$$\sigma = 10^{-31} \frac{m^2 E^4}{m_Z^6} \text{ cm}^2. \quad (8)$$

This can be compared to the answer from QED,

$$\sigma = \frac{\pi \alpha^2}{m E} \left(\ln \frac{2E}{m} - 1 \right). \quad (9)$$

If ℓ is the electron, (9) is larger than (8) till $E \gtrsim 300 m_Z$ (at which scale our assumption of the effective interaction has long since broken down).

Equation (6) implies a small rate even for processes where one of the leptons is off-mass-shell. For example, consider the diagrams for $\ell\bar{\ell} \rightarrow \gamma\gamma\gamma$ shown in Fig. 1. It is easy to show that these two graphs sum to zero if we use (6) and ignore the mass of the leptons. This is also the reason why we have not considered neutrino-induced interactions^{*)}. The implications of the interaction in Eq. (2) for the neutrino counting experiment has been considered elsewhere⁷⁾.

Thus, as a consequence of Eq. (6) we are led to consider processes where at least one of the photons is off mass shell. We choose a process which is potentially of interest for a photon beam facility at SSC, $\gamma + t \rightarrow t + \ell + \bar{\ell}$. It is a target fermion of mass m and ℓ is the produced fermion of mass M . There are two possible graphs involving the new interaction (2). These are shown in Fig. 2. In the limit of large photon energy, the total cross-section in the rest frame of the target is,

$$\sigma = \frac{7}{960} \frac{\alpha}{\pi^2} \frac{(C'_R - C'_L)^2}{M_\Lambda^8} m^3 \omega^3, \quad (10)$$

where ω is the energy of the incident photon. Naively, one may have expected an ω^6 behaviour for this cross-section. The power would have been reduced due to the chiral nature of the interaction but clearly there are, according to Eq. (10), even more cancellations than would be required based on chiral invariance alone. The terms involving M are lower order in ω . Also, it is amusing to see that (10) vanishes when the lepton current in Eq. (2) is purely vector. Numerically, for $C'_R = 0$,

*) The cross-section due to this interaction for the process $\gamma\gamma \rightarrow \nu\bar{\nu}$ which may have been significant for the evolution in the early Universe is zero.

$$\sigma = 1.6 \times 10^{-35} \left(\frac{m^3 \omega^3}{m_z^6} \right) \text{ cm}^2. \quad (11)$$

Clearly, this is tiny compared to the cross-section from ordinary QED which, for $\omega \gg m$, M is,

$$\sigma = \frac{28}{9} \frac{\alpha^3}{M^2} \ln \frac{2\omega}{M}. \quad (12)$$

Thus for producing a muon pair from a 1 GeV target, (12) exceeds (11) until $\omega \gtrsim 3350 m_z$ whereas for e^+e^- pairs, ω needs to be even greater. Thus directly detecting a new photon interaction of the form (2) seems way beyond the scope of a 9 TeV photon beam proposed for the SSC⁵⁾.

Finally, motivated by the fact that CELLO has recently reported⁸⁾ an excess of events in $e^+e^- \rightarrow \mu^+\mu^-$ for $\sqrt{s} > 33$ GeV, and for $\mu\gamma$ masses greater than 30 GeV, we have computed the contribution of the new interaction in (2) to the cross-section. We find,

$$\sigma = \frac{\alpha}{30\pi^2} (C'_L - C'_R)^2 \frac{E^6}{M_A^8}, \quad (13)$$

in the centre-of-mass frame with E being the beam energy. Most of these photons are hard and, in general, not collinear with either the beam or the produced muons. As in (10), this vanishes if the current is purely vector. Numerically, this cross-section is biggest if $C'_L = -C'_R$. In that case, using (3), we have,

$$\sigma_{\max} = 1.5 \times 10^{-34} \left(\frac{E}{m_z} \right)^6 \text{ cm}^2.$$

For $E = m_z/4$, $\sigma_{\max} = 0.036$ pb which is too small to account for the CELLO data. For $E \approx 30$ GeV (TRISTAN energy), $\sigma_{\max}$ arises to 0.2 pb.

At this point, it is worth noticing that unlike the process $e^+e^- \rightarrow \gamma\gamma$ which had a very small cross-section, the process $e^+e^- \rightarrow \gamma(k_1)Z(k_2)$ due to the point $e^+e^-Z\gamma$ vertex is not suppressed because of the massive nature of the Z . In fact, the analogue of (6) becomes

$$\epsilon_\alpha(k_1) \epsilon_\beta(k_2) \Gamma^{\mu\alpha\beta}(k_1, k_2) = -(k_1+k_2)^\mu \epsilon^{\alpha\beta\eta_1\eta_2} k_{1\eta_1} k_{2\eta_2}^\times \\ \times \epsilon_\alpha(k_1) \epsilon_\beta(k_2) - m_Z^2 \epsilon^{\mu\alpha\beta\eta_1} k_{1\eta_1} \epsilon_\alpha(k_1) \epsilon_\beta(k_2). \quad (14)$$

The first term, as before, leads to a negligible contribution when contracted into the lepton current but the presence of the second term leads to the cross-section,

$$\sigma(e^+e^- \rightarrow Z\gamma) = \frac{\sin^2 2\theta_W}{768\pi} \frac{C_L^2 + C_R^2}{M_A^8} m_Z^2 s^2 \left(1 - \frac{m_Z^2}{s}\right)^3 \left(1 + \frac{m_Z^2}{s}\right). \quad (15)$$

Here, $\sqrt{s}$ is the centre-of-mass energy of the colliding beams. Using Eq. (3), we find $\sigma(s=2m_Z^2) \approx 1.2$ nb which is large compared to the standard model cross-section^{*)}. Such a growth in the cross-section would be clearly visible at LEP. Moreover, for a given beam energy, the photons are monoenergetic ($E_\gamma = (s-m_Z^2)/2\sqrt{s}$) and the decay products of the Z would reconstruct the Z mass^{**)}.

In summary, we have noted that the new interactions proposed to explain the anomalous radiative decays of the Z^0 boson would, assuming $SU(2) \times U(1)$ invariance, necessitate new two-photon-two-lepton interactions. We have studied the possibility of detecting these "anomalous" photon interactions in purely electrodynamic processes. We find that these new interactions give very tiny contributions to ordinary QED processes, at least when one (or both) of the photons are real. The ideal place for detecting (or ruling out) such an interaction seems to be via the detection of very hard photons produced in the process $e^+e^- \rightarrow \mu^+\mu^-\gamma$ at high energies.

*) Admittedly, $s = 2m_Z^2$ is too close to scale $M_A \sim 150$ GeV [see Ref. 2)] for this estimate to be really reliable. Our only point is that the cross-section is large and grows very rapidly.

**) Amusingly, if quarks participated with the same couplings as leptons in Eq. (1), the process $\bar{p}p \rightarrow Z\gamma + X$ would have a cross-section of 0.46 nb at the CERN collider. This would be correspondingly reduced if they coupled according to their weak isospin. Non-observation of this process, of course, rules out such couplings. We thank Dr. H. Baer for the numerical computation of this number.

- Figure 1 -

- Figure 2 -