ANOMALOUS RADIATIVE Z^0 DECAY

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We examine some possible mechanisms which can explain the anomalous radiative Z^0 decays that were observed recently. They are (I) an anomalous $Z^0\gamma\gamma$ interaction, and (II) the virtual effect of monopole–fermion bound states or of fermion monopoles. In the latter two cases, a mass scale in the TeV region is required for the explanation of the experimental data.

The discovery of the intermediate vector bosons [1], $W^\pm$ and Z^0, at the expected masses seems to give strong support for the standard SU(2) × U(1) electroweak theory [2]. On the other hand, an unexpectedly large number of radiative Z^0 decays, $Z^0 \to \ell^+\ell^-\gamma$, with hard photon energy (3 events among 12 $\ell^+\ell^-$ events) may call for an unusual mechanism, or even for a modification of the standard model, if confirmed by further experiments. The unsuccessful search for the radiative decay of the $W^\pm$ boson has given an upper bound on the branching ratio [3]: $\Gamma(W^\pm \to \ell^\pm\nu\gamma)/\Gamma(W^\pm \to \ell^\pm\nu) < 0.1$.

Some efforts have already been made to explain the observed anomalous radiative Z^0 decay in terms of nonstandard composite vector bosons [4] or bound states of vector bosons [5]. While the former approach deviates significantly from the standard SU(2) × U(1) model, the latter has to assume a strong coupling among the vector bosons and an accidental mass degeneracy of the Z^0 boson with a bound state of two vector bosons. In this article, we examine possibilities for explaining the observed radiative Z^0 decay based on (I) an anomalous $Z^0\gamma\gamma$ interaction, and (II) bound states of a monopole and a charged fermion, or a fermionic monopole.

(I) Anomalous $Z^0\gamma\gamma$ interaction. Assume the existence of a $Z^0\gamma\gamma$ interaction written in momentum space $[(k_1 + k_2, \epsilon_\mu(Z^0)) \to (k_1, \epsilon_\sigma^{(1)}) + (k_2, \epsilon_\rho^{(2)})]$,

$$\begin{aligned} R_{\rho\sigma\mu}&(k_1,k_2) \\ &= A_1(k_1,k_2)[(k_1\cdot k_2)k_1^\tau\epsilon_{\tau\sigma\rho\mu} + k_1^\rho k_1^\tau k_2^\xi\epsilon_{\tau\xi\sigma\mu}] \\ &+ A_2(k_1,k_2)[(k_1\cdot k_2)k_2^\tau\epsilon_{\tau\sigma\rho\mu} + k_2^\sigma k_1^\tau k_2^\xi\epsilon_{\tau\xi\sigma\mu}] \\ &+ A_3(k_1,k_2)(k_2^2 k_1^\tau\epsilon_{\tau\sigma\rho\mu} + k_2^\rho k_1^\tau k_2^\xi\epsilon_{\tau\xi\sigma\mu}) \\ &+ A_4(k_1,k_2)(k_1^2 k_2^\tau\epsilon_{\tau\sigma\rho\mu} + k_1^\sigma k_1^\tau k_2^\xi\epsilon_{\tau\xi\rho\mu}) , \end{aligned} \tag{1}$$

where gauge invariance is satisfied, and Bose statistics for two photons requires

$$A_2(k_1,k_2) = -A_1(k_2,k_1) ,$$

and

$$A_4(k_1,k_2) = -A_3(k_2,k_1) . \tag{2}$$

Eq. (1), which corresponds to the diagram in fig. 1a, can arise from a triangular diagram with a fermion loop (a so-called anomalous diagram [6]), and, for constant A_i's, it corresponds to the local lagrangian

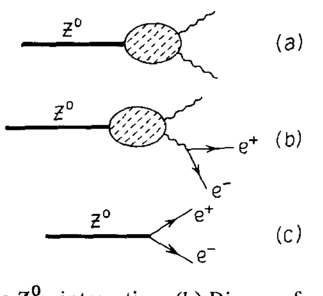

Fig. 1. (a) The $Z^0_{\gamma\gamma}$ interaction. (b) Diagram for $Z^0 \to e^+e^-\gamma$. (c) Diagram for $Z^0 \to e^+e^-$.

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$$\mathcal{L} = Z_\mu(A_1\partial_\rho\tilde{F}_{\mu\lambda}F_{\lambda\rho} + A_3\tilde{F}_{\mu\lambda}\partial_\rho F_{\lambda\rho}) \,. \tag{3}$$

Our assumption is that the magnitude of the amplitudes, A_1 and A_3, is of the order of unity, so that the decay rates $\Gamma(Z^0 \to e^+e^-\gamma)$ and $\Gamma(Z^0 \to e^+e^-)$, is given by the diagrams, figs. 1b and 1c, are comparable. The characteristics of such anomalously large $Z^0\gamma\gamma$ interactions are:

(i) The decay rate of the physical process $Z^0 \to 2$ physical photons is zero because of the Yang theorem [7] (a vector meson cannot decay into two physical photons). This conclusion can be confirmed by computing the decay rate $\Gamma(Z^0 \to 2\gamma)$ based on the matrix element, eq. (1).

(ii) The Yang theorem also implies that the residue of the pole of the photon propagator in fig. 1b for the decay process $Z^0 \to \ell^+\ell^-\gamma$ should vanish. [This statement again can be proven by calculating the radiative decay rate $\Gamma(Z^0 \to \ell^+\ell^-\gamma)$ based on the general amplitude, eq. (1).] In other words, there is no $1/q^2$ factor in the radiative decay rate which enhances events with a small lepton pair invariant mass. The invariant mass distribution, then, is dictated by the phase space factor and should be peaked around the middle of the possible kinematic range. This is consistent with the observed lepton pair invariant masses in radiative Z^0 decay [3]; $60.9^{+8.4}_{-6.8}$, 42.7 ± 2.4, and 49.8 GeV.

(iii) For radiative $W^\pm$ decay, there is no counterpart of diagram (b) in fig. 1. Hence, no anomaly in radiative $W^\pm$ decay is predicted. This is consistent with recent observations [3]. It should be pointed out also that there is no enhancement in the $Z^0 \to \nu\bar{\nu}\gamma$ decay mode in this model.

(iv) Since the introduction of anomalous $Z^0\gamma\gamma$ interactions leads to a change in the self energy of the Z^0, we have to examine [8] whether it is consistent with the observed ρ-parameter, where $\rho = m_W^2/m_Z^2\cos^2\theta_W$, m_W, m_Z, and θ_W being the masses of $W^\pm$

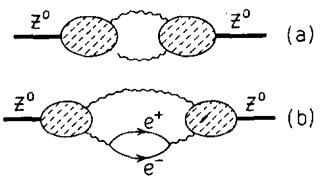

Fig. 2. (a) Self energy of Z^0 by the $Z^0\gamma\gamma$ interaction, diagram of fig. 1a. (b) Self energy of Z^0 by diagram in fig. 1b.

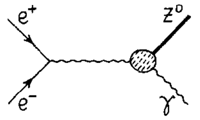

Fig. 3. The $Z^0\gamma$ production by e^+e^- collision.

and Z^0, and the weak interaction angle respectively. First of all, the contribution of fig. 2a to the Z^0 self energy vanishes since the dispersive part, which is nothing but the decay rate $\Gamma(Z^0 \to \gamma\gamma)$, does not exist, as described above. The largest contribution to the correction for the Z^0 mass is, therefore, due to fig. 2b, which is of the order of αm_Z, where $\alpha = e^2/\hbar c$ is the fine structure constant. This can be tested by a precision measurement of the ρ-parameter or the Z^0 and $W^\pm$-masses in the future. At present the model is consistent with experimental data ($\rho \cong 1$ within a few %).

(v) The anomalous $Z^0\gamma\gamma$ interaction yields a significant Z^0 production in e^+e^- collisions at higher energies, by the one-photon exchange process $e^+e^- \to \gamma \to Z^0\gamma$, as shown in fig. 3. This gives an extra handle for studying the properties of the Z^0 boson.

(vi) How do we get anomalously large $Z^0\gamma\gamma$ interactions? This is a problem yet to be solved in the future, but the models based on a virtual magnetic monopole, which will be discussed below, indicate that such a possibility does exist.

In order to have more specific models for anomalous radiative Z^0 decay, we consider the effect of a virtual magnetic monopole of relatively low mass. We note first that the existence of magnetic monopoles is required for GUT models or any other gauge theories which are spontaneously broken from a simple gauge group into a group that contains a U(1) subgroup [9]. A characteristic of monopoles is that they couple strongly to a photon due to the Dirac condition [9,10].

$$g_m e = 2\pi n \,, \quad n = 1, 2, \ldots \,, \tag{4}$$

where g_m and e are the magnetic charge of the monopole and the electric charge of the electron and the proton, respectively. As a result, the interaction between a magnetic monopole and a charged particle is the strongest existing in nature, over a wide range of mass scales. It is, therefore, very likely to have strong bound systems of monopoles and charged particles which couple to a photon strongly [11]. It is also possible to have a fermionic monopole as a classical solution. In fact, there exists a large literature on the subject [11–14]. There are also charged counterparts of monopoles, called dyons [15].

The couplings of the Z^0 and $W^\pm$ boson to these monopole families are similar to that of the photon at the large GUT mass scale, where all couplings are regular i.e. of the order of e (not of the $1/e$ type). This can be seen by looking into the behavior of the monopole solution [9] at the origin. At low mass scales (or at large distances), on the other hand, a disparity between the photon and massive vector bosons develops due to SU(2) × U(1) symmetry breaking and only the photon–monopole interactions have the coupling $2\pi n/e$, eq. (4).

The mass of GUT monopoles is expected to be of the order of 10^{16} GeV and the effect of virtual monopoles is negligibly small by the decoupling theorem, despite their large coupling to photons. However, there is a circumstance where this may not be the case. A zero energy bound state of a monopole and a charged fermion (with anomalous magnetic moment) is physically realized as a massless particle, which, in turn acquires a mass by the Higgs mechanism of the electroweak SU(2) × (1) symmetry breaking. The possible mass range of such an object is 100 GeV – 10 TeV. An alternative possibility is that the symmetry breaking of a GUT into the final $SU_c(3) \times U(1)$ group contains two mass scales, the grand unified mass scale and the electroweak mass scale. Therefore, there could be two types of monopoles with corresponding mass scales, in principle. With these preparations, we discuss the second model.

(II) Charged-fermion–monopole bound states. The vector bosons couple to fermions in the ordinary manner of electroweak theory, while the photon couples to the magnetic monopole with strength $2\pi n/e$. Some of the diagrams which contribute to radiative Z^0 decay are given in fig. 4. The matrix element of diagram (a) is of order

$$\sum g(2\pi n/e)^2 e(m_Z/M)^2 , \qquad (5)$$

to be compared with that of $Z^0 \to \ell^+\ell^-, g$, where the summation in eq. (5) runs over all possible charged-fermion–monopole bound states, and M is the mass of the monopole bound state. The contribution of fig. 4b is obtained from eq. (5) by replacing one of the factors $2\pi n/e$ by g, and therefore much smaller than

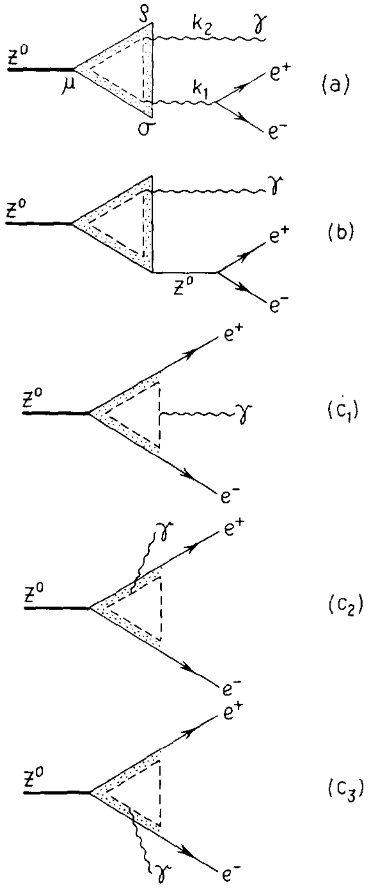

Fig. 4. (a) Diagram for $Z^0 \to \gamma\gamma \to e^+e^-\gamma$ with the loop of a monopole–charged-fermion bound state. (b) Diagram for $Z^0 \to Z^0\gamma \to e^+e^-\gamma$ with the loop of a monopole–charged-fermion bound state. (c) Diagram for $Z^0 \to e^+e^-\gamma$ with the loop of a monopole–charged-fermion bound state and a monopole (broken line).

that of fig. 4a (i.e. $\sim O(\alpha)$). With the assumption of a monopole mass $\gg M$, the contribution of fig. 4c becomes also negligible.

From eq. (5), it follows that for the value of $M \sim 1$ TeV, (or $(M_Z/M)^2 \sim O(\alpha)$) the amplitude of fig. 1a can be of the order of g. In other words, model (II) reduces to model (I). All arguments given in (I), then can be applied to model (II). There are some differences in the two models, however.

(i) Radiative decay of the $W^\pm$ boson can occur by the diagram of fig. 5. However, this gives a small contribution as in the case in fig. 3b.

(ii) In this model, three photon decay of the Z^0

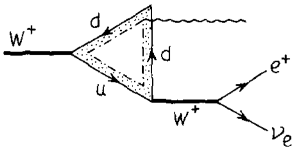

Fig. 5. Diagram for $W^+ \to e^+\nu_e\gamma$.

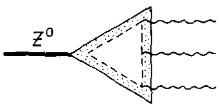

Fig. 6. Diagram for $Z^0 \to 3\gamma$ with the loop of a monopole–charged-fermion bound state.

boson ($Z^0 \to 3\gamma$), can occur by fig. 6, which amplitude is expressed as

$$\sum g(2\pi n/e)^3(m_Z/M)^4 \ . \tag{6}$$

This can be of the order

$$(2\pi n/e)(m_Z/M)^2 \sim e \ , \tag{7}$$

and can be comparable to the decay mode $Z^0 \to e^+e^-\gamma$.

Finally, the following model leads to essentially the same prediction as that of (II)

(II′) The virtual effect of a fermionic monopole with low mass scale. In this case, the relevant diagrams for radiative Z^0 decay are given by figs. 4a and 4b and all arguments are the same as in model (II).

Finally, it should be pointed out that any modification of the electroweak SU(2) × U(1) theory in the TeV region will call for a change in the estimate of the grand unified mass scale, m_X, and inevitably lead to a modification of the prediction of the lifetime of nucleons.

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