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PHENOMENOLOGICAL COUPLING OF EXCITED LEPTON TO Z^0 AND Z^0 DECAY TO HARD $\gamma^{\star}$

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ABSTRACT

We explore the possibility of enhancing the decay $Z^0 \to e^+ e\gamma$ with a hard photon through the existence of an excited spin $\frac{1}{2}$ lepton coupling to Z^0 and γ while remaining consistent with constraints on these couplings from data on $e^+e^- \to \gamma\gamma$ and $g-2$. For an excited lepton mass less than the Z^0 mass, we find that the rate can be enhanced but does not peak for high photon energies. We set lower limits on the couplings for the case of the excited lepton heavier than Z^0, as a function of mass of the heavy lepton.

Recent data from the UA1 and UA2 collaborations[1] at CERN SPS has hinted at the possibility of some new physics in the interactions of the Z^0 's and W's beyond that of the standard model. These experiments find 3 of their 14 Z^0 events to include a hard photon. This is a far higher proportion of $\ell^+\ell^-\gamma$ events than can be accounted for within the standard model with radiative corrections.[2] On the other hand, the number of radiative W decays observed seems to be compatible with the standard model. Of course, before any firm conclusions can be drawn, more data must be obtained and studied. Pending this, we here address the possibility of enhancing the decay

$$Z^0 \rightarrow \ell^+\ell^-\gamma \tag{1}$$

through the existence of an excited lepton (e^* or μ^*) coupling to the Z^0 and photon. Other approaches to the possibility of enhancement of hard photon Z^0 decays have included the decay of Z^0 through some new scalar particle.[3] Also, the possibilities that the anomalous events are not Z^0 decays but rather the decays of some new scalar[4] or of a toponium[5] state have been studied.

We explore the compatibility of the desired enhancement with the constraints on ℓ^* couplings and masses provided by data on $e^+e^- \rightarrow \gamma\gamma$ [6] and contributions to $g-2$. Even if further data on Z^0 decays finally turn out to be consistent with the standard model, the results of the present calculation may still be of interest for other investigations.

In this paper, we assume the following phenomenological effective interactions of an excited lepton, ℓ^*, with the photon and lepton and Z^0 and lepton, respectively.

$$\mathcal{L}_{\ell^*\ell\gamma} = \frac{e}{2M}\bar{\psi}_{\ell^*}\sigma^{\mu\nu}(a - ib\gamma_5)\psi_\ell F_{\mu\nu} + \text{h.c.} \tag{2}$$

$$\mathcal{L}_{\ell^*\ell Z} = \frac{g}{2M\cos\theta_W}\bar{\psi}_{\ell^*}\sigma^{\mu\nu}(a_1 - ib_1\gamma_5)\psi_\ell F^{(Z)}_{\mu\nu} + \text{h.c.} \tag{3}$$

In the above, $F_{\mu\nu}$ is the electromagnetic field strength tensor while $F^{(Z)}_{\mu\nu}$ is that associated with the Z^0 .

$$F^{(Z)}_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu \ . \tag{4}$$

M is the mass of the excited lepton. The couplings a, b, a_1 and b_1 parametrize the strength of these anomalous interactions. Since the preliminary data seem to indicate hard photon events, we consider the derivative couplings of equations (2) and (3). Such interactions could be possible for models in which the leptons are composite and could perhaps contribute to an anomalous magnetic moment for Z^0, different from the gauge theory value.

For the interactions (2) and (3) above, it is straightforward to calculate the rate for the decay $Z^0 \to \ell^+\ell^-\gamma$ and the energy and angular distributions of the outgoing photon and leptons. The standard bremsstrahlung and excited lepton contributions to this decay are shown in Fig. 1. We define the following dimensionless quantities

$$\Delta = M^2/M_Z^2 \tag{5}$$

$$z = 2\omega/M_Z \tag{6}$$

$$\epsilon = E_{\min}/M_Z \tag{7}$$

In the above, ω is the photon energy. $E_{\min}$ is the minimum energy of any of the decay products, corresponding to experimental resolution. In our numerical calculations, we take $\epsilon = 0.002$; this corresponds to a resolution of about 1.5 GeV. We normalize all distributions to the decay rate of Z^0 into a lepton pair, Γ_0[2]

$$\Gamma_0 = \Gamma(Z^0 \to \ell^+\ell^-) = \frac{2G_F M_Z^3(a_\ell^2 + b_\ell^2)}{3\sqrt{2}\pi} \tag{8}$$

Here a_ℓ and b_ℓ are the standard model vector and axial vector couplings of the Z^0 to leptons

$$a_\ell = \frac{1}{4} - \sin^2\theta_W \tag{9a}$$

$$b_\ell = -\frac{1}{4}\ . \tag{9b}$$

We consider first the case of the excited lepton with mass less than M_Z; that is, $\Delta < 1$. For this case, the rate for $Z^0 \to \ell^+\ell^-\gamma$ via a real intermediate ℓ^* subsequently decaying radiatively is given by

$$\Gamma(Z^0 \to \ell^*\ell \to \ell^+\ell^-\gamma) = \frac{g^2 a_1^2 M_Z}{24\cos^2\theta_W \pi\Delta}(1-\Delta)^2(1+2\Delta)A \tag{10}$$

where

$$A = \frac{\Gamma_{e^*\to e\gamma}}{\Gamma_{e^*\to \mathrm{all}}} = \left(\frac{e^2a^2}{8\pi}M\right)\Big/\Gamma_{e^*\to \mathrm{all}} \tag{11}$$

is the ratio of the partial width of $e^* \to e\gamma$ relative to its total width. If the only decay channel available for ℓ^* is $\ell\gamma$, then $A = 1$, and (3) becomes independent of the value of a. For simplicity, we have neglected the axial couplings. The branching ratio for $Z^0 \to \ell^+\ell^-\gamma$ to $Z^0 \to \ell^+\ell^-$ is

$$B = \frac{\Gamma(Z^0 \to \ell^+\ell^-\gamma)}{\Gamma(Z^0 \to \ell^+\ell^-)} = \frac{a_1^2(1-\Delta)^2(1+2\Delta)}{\Delta\, 2(a_\ell^2 + b_\ell^2)}A\ . \tag{12}$$

The value of B is determined, for a given ℓ^* mass by the $Z^0\ell^*\ell$ coupling, a_1. To know what a_1 can be used in (12), we have to determine the constraints on the couplings a and a_1. These come from essentially two considerations. The coupling a for a heavy lepton of mass M is constrained by the absence of e^* effects in $e^+e^- \to \gamma\gamma$.[6] The curve in Fig. 2b of Ref. 6 gives the maximum value of a as a function of M. The constraint on the product of aa_1 comes from an analysis of $Z^0\ell^*\ell$ contributions to electron $g-2$ in a manner similar to what was carried out by Renard for $\gamma\ell^*\ell$ contribution to electron $g-2$.[7] Following a calculation similar to Renard,[7] we also find the dominant contributions come from $\ell\ell^*$ mixing effects and that

$$\frac{4(G_F M_Z^2)}{\pi^2}\, aa_1 \frac{m}{M} \lesssim 2 \times 10^{-10} \;, \qquad (13)$$

Here m is lepton mass. This leads to the constraint

$$\frac{aa_1}{M} \leq \left(\frac{\pi^2}{1000\ TeV}\right) \qquad\qquad (\Delta < 1)\;. \qquad (14)$$

We have not included the corrections to $g-2$ proportional to a_1^2. These could provide further constraint on a_1. We proceed as follows. Taking the UA1, UA2 data at face value implies a branching ratio B of about (3/14). Using $A = 1$ in (12), and $B = 3/14$, we can calculate a_1 as a function of M. We find

$M(GeV)$	20	40	60	80
a_1	0.052	0.11	0.20	0.61

The constraint (14), then leads to values of a:

M	20	40	60	80
$a_{\max}$	3.83×10^{-3}	3.64×10^{-3}	2.92×10^{-3}	1.29×10^{-3}

These values for a lie considerably below the constraint curve given in Fig. 2b of Ref. 6. Thus if one attempts to explain the large branching ratio B in terms of excited ℓ^* intermediate states, one does not run into any difficulties with constraints provided by data on electron $g-2$, $e^+e^- \to \gamma\gamma$, etc. In this respect we agree with the conclusions of Ref. 8. The choice of mass M for ℓ^* then comes essentially from considerations of energy and angular distributions obtained by the decay products. In this sense we agree with the considerations put forward by Cabibbo *et al.*[9] For instance, the distribution in photon energy is flat for this excited lepton explanation of the enhanced Z^0 radiative decay rate. This is not consistent with the hard photon events observed.

We turn now to the case of the decay[1] proceeding through an excited lepton with mass greater than M_Z; we find the rate relative to Γ_0 to be the following:

$$\frac{\Gamma(Z^0 \to \ell^+\ell^-\gamma)}{\Gamma_0} \equiv R = \frac{\alpha}{16\pi(a_\ell^2+b_\ell^2)}\Bigg\{16(a_\ell^2+b_\ell^2)\left[\ell n^2\left(\frac{\epsilon}{1-\epsilon}\right)-\frac{\pi^2}{6}\right.$$
$$\left.+\,2\,\mathrm{Li}_2\frac{\epsilon}{1-\epsilon}\Big)+\frac{1}{4}(5+3\epsilon)(1-3\epsilon)+\frac{3}{2}(1-2\epsilon)\ell n\left(\frac{\epsilon}{1-2\epsilon}\right)\right]$$
$$+\,\mathrm{Re}\Big[a_\ell^*(bb_1+aa_1)\Big]\left(\frac{8}{\Delta}\right)\left[\Delta(1-\Delta)^2\ell n\Big(1-\frac{1}{\Delta}\Big)+\frac{1}{3}-\frac{3}{2}\Delta+\Delta^2\right]$$
$$-\Big[(b^*b_1^*-a^*a_1^*)(bb_1-aa_1)+(b^*a_1^*+b_1^*a^*)(b_1a-a_1b)\Big]$$
$$\times\left[\frac{1}{2\Delta^2}\left\{-\frac{1}{4}+\frac{27}{12}\Delta+6\Delta^2-9\Delta^3-\frac{3\Delta}{2}(1-\Delta)(1-6\Delta^2+\Delta)\,\ell n\left(1-\frac{1}{\Delta}\right)\right\}\right.$$
$$-\,\Delta(1-4\Delta)\Big\{-\mathrm{Li}_2\Big(\frac{1}{2}\Big)+\mathrm{Li}_2\Big(\frac{\Delta}{2\Delta-1}\Big)+\frac{1}{2}\ell n^2\Big(2-\frac{1}{\Delta}\Big)-\frac{1}{2}\ell n^2(2)\Big\}$$
$$\left.\left.-\,\frac{1}{12\Delta}-\frac{1}{2}+3\Delta-3\Delta(1-\Delta)\,\ell n\Big(1-\frac{1}{\Delta}\Big)\right]\right\} \tag{15}$$

Here $\Delta > 1$. We have neglected the light lepton mass. The coefficient of each term reflects its origin. That is, the first term is the standard bremsstrahlung contribution[2]; the second arises from the interference of the bremsstrahlung contribution with the decay through an excited lepton. The third term is the excited lepton contribution. Of course, in the limit $\Delta \to \infty$, Eq. (15) reduces to the bremsstrahlung rate. The dilogarithm (Spence function) is defined as follows

$$\mathrm{Li}_2(x) = -\int_0^x dt\, \frac{\ell n(1-t)}{t} \ . \tag{16}$$

For our numerical study of the enhancement of the radiative Z^0 decay rate, we neglect the axial couplings b and b_1 relative to the vector couplings, a, a_1. Then taking a and a_1 real by C and CP invariance, the relative rate (15) becomes a quadratic equation in (aa_1). In Fig. 2 we display the solution to this equation as a function of Δ for two values of the relative rate $R = \frac{1}{16}$ and $\frac{3}{14}$. The dashed lines are for $\epsilon = 0.03$. The solid line is for $\epsilon = 0.002$ and $R = \frac{3}{14}$. The two curves for $R = \frac{3}{14}$ illustrate the logarithmic dependence of the bremsstrahlung rate on ϵ. The curves correspond to lower limits on the coupling aa_1 needed to achieve the desired enhancement of the radiative decay. For example, to obtain a relative rate of 3/14 with a 120 GeV/c^2 excited lepton, the dimensionless coupling aa_1 must be greater than about 70.

We also display, in Figs. 3 and 4, some kinematic distributions for the decay (1). These are all normalized to a relative rate Γ/Γ_0 of 3/14, with $\epsilon = 0.002$. The differential distribution with expect to $z = 2\omega/M_Z$ is given for $\Delta = 1.125$, 1.5, 1.97 in Figs. 3a,b,c, respectively. The limits on z are $2\epsilon \leq z \leq 1 - \epsilon$. The distributions peak at large z; that is, the decay into hard photons is enhanced, as desired. (The peaking at low z is the standard bremsstrahlung behaviour.)

The differential rate in $\cos\theta$, where θ is the angle between the photon and electron momenta is given for the same values of Δ in Fig. 2a,b,c, also normalized to $\Gamma/\Gamma_0 = 3/14$ and with $\epsilon = 0.002$. The distribution peaks sharply at large backward angles. From kinematic and spin considerations, one expects the photon and the less energetic lepton to be separated by a small angle. That is, for decay through an e^{*-}, the photon should be nearer to the positron; $\cos\theta$ peaks towards -1. For decay through an e^{*+}, the photon should follow the electron; however, this region of phase space is suppressed for ϵ corresponding to a realistic value of experimental resolution, so peaking at $\cos\theta \to +1$ is not so pronounced. (The lower limit on $\cos\theta$ is $-1+2\epsilon^2$ while the upper limit is $1-8\epsilon$.) For an extremely small value of ϵ, the peaking at $\cos\theta = +1$ is more pronounced; however, this is not to be expected experimentally.

To conclude, we find that an excited lepton explanation of the Z^0 radiative decay events is not inconsistent with other constraints if the lepton mass is less than the Z^0 mass. However, our phenomenological interaction does not explain the tendency to hard photon events observed experimentally. For the case of the excited lepton mass larger than the Z^0 mass, there is an enhancement for our interactions (2) and (3) of hard photon events as well as a tendency for the photon to make a large angle with the electron. We place a lower limit on aa_1, the product of the photon and Z^0 couplings to the excited lepton, as a function of heavy lepton mass. We emphasize that further experimental information is necessary to make firm conclusions.

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FIGURE CAPTIONS

1. The Feynman Diagrams for radiative Z^0 decay.

2. Lower limit on the coupling aa_1 for given values of R and resolution, as a function of excited lepton mass. The curves are labelled with the corresponding values of R and ϵ.

3. Differential rate with respect to z, a dimensionless quantity corresponding to photon energy, relative to the decay rate of Z^0 into leptons for (a) $\Delta = 1.125$, (b) $\Delta = 1.5$, (c) $\Delta = 1.97$.

4. Differential rate with respect to $\cos\theta$, where θ is the angle between the photon and electron momenta. (a), (b), and (c) correspond to the same values of Δ as in Fig. 3.

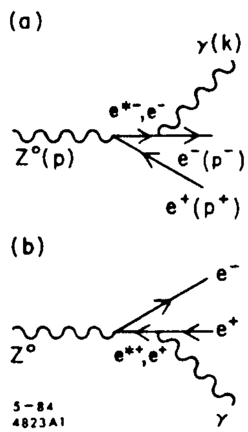

(a)
γ(k)
e*⁻, e⁻
Z°(p)
e⁻(p⁻)
e⁺(p⁺)
(b)
e⁻
e⁺
Z°
e*⁺, e⁺
γ
5-84
4823A1

Fig. 1

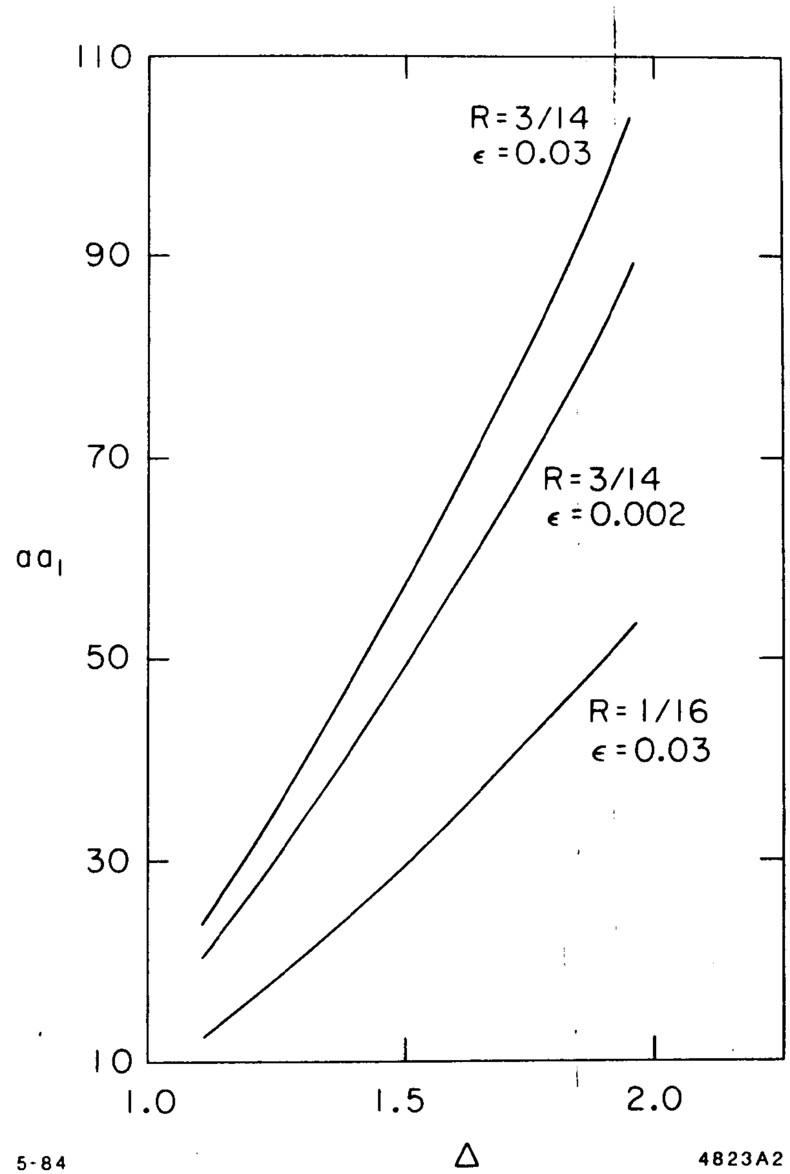
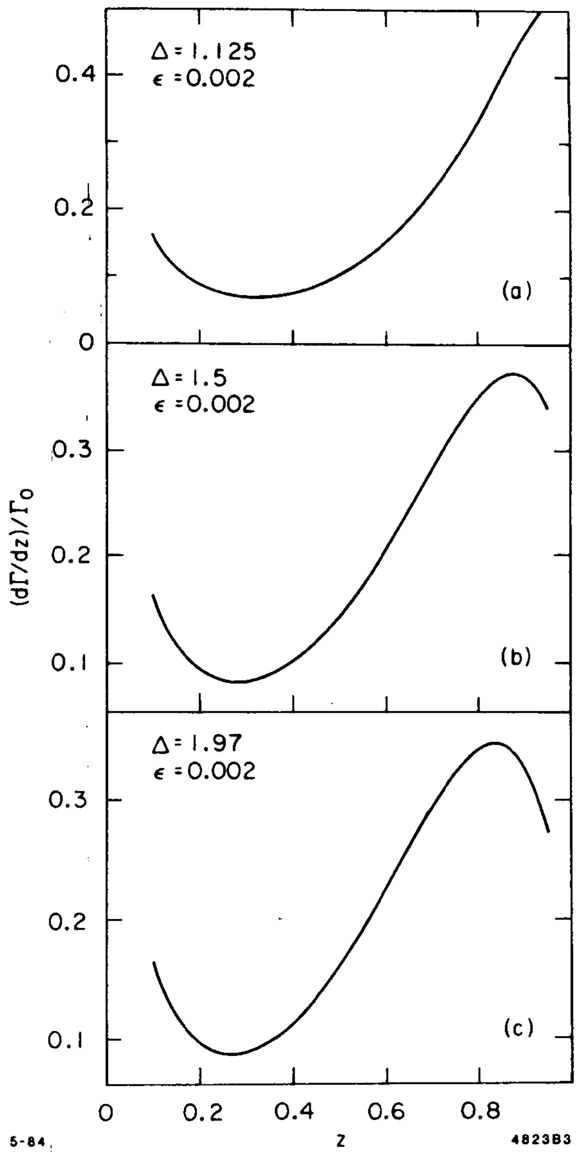
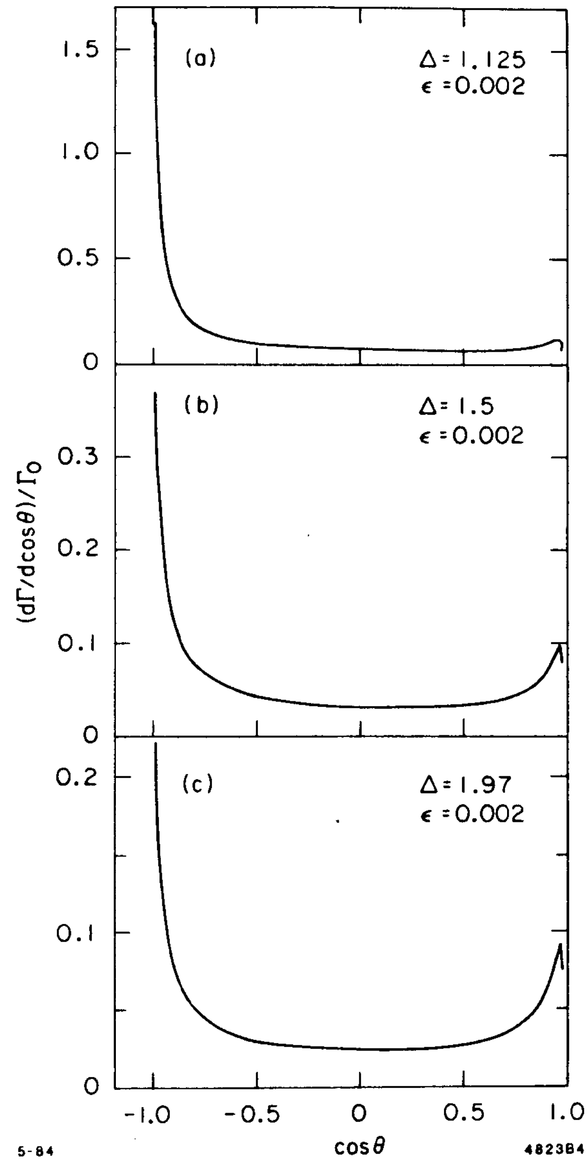

110
90
70
50
30
10
1.0
1.5
2.0
aa₁
Δ
R = 3/14
ε = 0.03
R = 3/14
ε = 0.002
R = 1/16
ε = 0.03
5-84
4823A2

Fig. 2



Δ = 1.125
ε = 0.002
(a)
Δ = 1.5
ε = 0.002
(b)
Δ = 1.97
ε = 0.002
(c)
(dΓ/dz)/Γ0
0.4
0.2
0
0.3
0.2
0.1
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
z
5-84
4823B3

Fig. 3



(a)
Δ = 1.125
ε = 0.002
(b)
Δ = 1.5
ε = 0.002
(c)
Δ = 1.97
ε = 0.002
(dΓ/dcosθ)/Γ0
1.5
1.0
0.5
0
0.3
0.2
0.1
0
0.2
0.1
0
-1.0
-0.5
0
0.5
1.0
cosθ
5-84
4823B4

Fig. 4