Electric Dipole Moment of the *W* Boson and the Radiation Amplitude Zero

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(Received 22 May 1989)

The effect of an electric dipole moment (EDM) of the W boson is studied in the radiative decay $W^- \rightarrow \bar{u}d\gamma$. It is shown that the radiation amplitude zero which is present in this process provides a sensitive test of the possible compositeness of the W. The two possibilities, a large EDM ($\lambda \gtrsim 1$) and a significant magnetic moment ($\kappa \neq 1$), can, in principle, be distinguished.

PACS numbers: 14.80.Er, 12.15.Ji, 12.50.Fk, 13.38.+c

It is well known[1] that, aside from radiative corrections, an elementary W boson will have its magnetic moment

$$\mu = geh/2M_W c \tag{1}$$

given by $\kappa = 1$ or $g = \kappa + 1 = 2$. A composite W, however, will very likely have[2] $g \neq 2$. The electric dipole moment (EDM) of the W,

$$\lambda e/2M_W \, , \tag{2}$$

also acts as a test of compositeness of the W and could be a measure of CP violation in weak interactions. If the W is elementary, λ is expected to be extremely small. For instance in $SU(2) \times U(1)$, this quantity vanishes even at the one-loop order. Marciano and Querjeiro[3] have shown that the EDM of the W in an effective (nonrenormalizable) theory induces an EDM for the neutron through a loop effect. From the present limit on the EDM of the neutron they predict that

$$\lambda \leq 10^{-3} \, . \tag{3}$$

However, this result is model dependent. Other models may give larger values for λ. Here, however, we are proposing a model-independent way to measure λ experimentally. Since physics is an experimental science, λ should be measured, in spite of model predictions and theoretical prejudices. Therefore in what follows we will allow λ to be substantial. But, whether λ turns out to be large or small, it should be measured experimentally. In this paper we propose a method for doing this.

It has been shown that radiation amplitude zeros (RAZ)[4] can be used as a sensitive test of the g value of the W (and, hence, its possible compositeness). In this Letter we wish to point out that RAZ can also be used as a sensitive test of the dipole moment of the W.

A few years ago it was discovered[4] by Mikaelian, Samuel, and Sahdev that the angular distribution for $d\bar{u} \rightarrow W^- \gamma$ ($u\bar{d} \rightarrow W^+ \gamma$) vanishes at a certain angle provided the magnetic moment of the $W^\pm$ has the gauge-theory value $\kappa = 1$. They proposed using this peculiar behavior in $p\bar{p}$ and pp collisions, $p\bar{p}$ or $pp \rightarrow W^- \gamma X$, where a dip persists, as a means of measuring the magnetic moment of the W. Subsequently it was shown[5] that these RAZ are due to the complete destructive interference of the radiation patterns and occur whenever the process contains one real photon, only like-sign charges, and $g = 2$ for all particles with spin. These zeros are quite remarkable—the lowest-order amplitude vanishes for each spin state and the po-

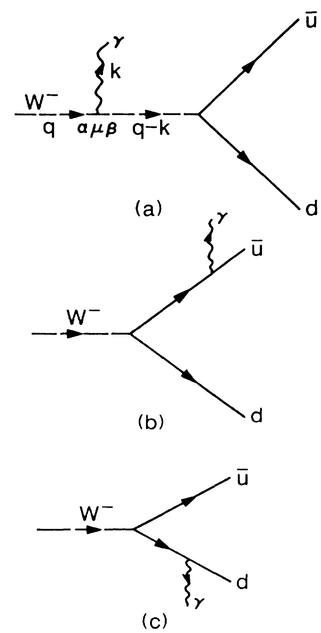

FIG. 1. Feynman diagrams contributing to the radiative decay $W^- \rightarrow d\bar{u}\gamma$.

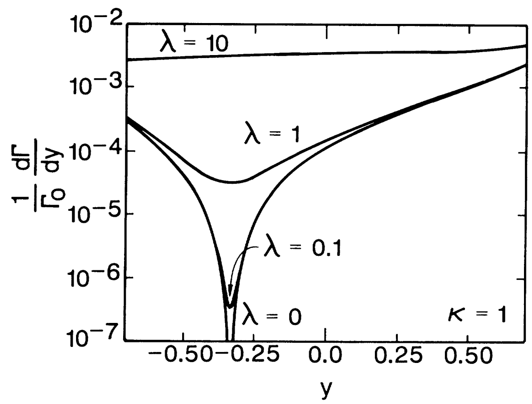

FIG. 2. $(1/\Gamma_0)d\Gamma/dy$ vs y for $\kappa=1$ and $0.2 \le x \le 1$ for various values of λ.

sition of the zero is independent of photon energy.

Such zeros occur in a variety of processes, including the radiative W-boson decays $W^- \to d\bar{u}\gamma$ and $W^- \to e\bar{\nu}\gamma$ which we write as $W \to q_i \bar{q}_j \gamma$. Grose and Mikaelian[6] have shown that these processes do have a RAZ if $\kappa = 1$. Subsequently it was shown by Samuel and Tupper[7] that, using the variables

$$x = \frac{2E_\gamma}{M_W}, \quad y = \frac{E_q - E_{\bar{q}}}{E_\gamma}, \tag{4}$$

the zero condition takes the simple form $(Q = Q_i + Q_j)$

$$y = \bar{Q} = \frac{Q_i - Q_j}{Q_i + Q_j}, \tag{5}$$

independent of x. It was shown that if $\kappa \ne 1$ the zero is spoiled. Here we will show that the zero is also spoiled if $\lambda \ne 0$.

The relevant diagrams are shown in Fig. 1. The coupling of the photon to the W, Fig. 1(a), due to $\lambda \ne 0$ is given by

$$A_{\alpha\beta\mu} = ie\lambda \epsilon_{\alpha\beta\mu\nu} k^\nu, \tag{6}$$

where k is the external photon momentum. In terms of these variables, the differential decay rate is given by

$$\frac{1}{\Gamma_0}\frac{d^2\Gamma}{dx\,dy}(W \to q\bar{q}\gamma) = \left[\frac{\alpha}{2\pi}\right]\left\{(y-\bar{Q})^2 \frac{1-x+x^2(1+y^2)/4}{x(1-y^2)} + \frac{1-\kappa}{4}(y-\bar{Q})xy + \left[\frac{1-\kappa}{4}\right]^2 x\left[1-x+\frac{(1-y^2)(1+x)}{2}\right] + \frac{\lambda^2}{64}[2(1-x)+(1-y^2)(1+x)]\right\}. \tag{7}$$

This reduces to our previous result when $\lambda = 0$. The interference terms between λ and the previous amplitude vanish since the EDM amplitude is CP violating and the rest of the amplitude is CP conserving. Γ_0 is given by

$$\Gamma_0 = \frac{\alpha M_W}{4\sin^2\theta_W}. \tag{8}$$

In Figs. 2–4 we plot

$$\frac{1}{\Gamma_0}\int_{0.2}^{1} dx \frac{d^2\Gamma}{dx\,dy} = \frac{1}{\Gamma_0}\frac{d\Gamma}{dy} \tag{9}$$

vs y. It can be seen (Fig. 2) that for $\kappa = 1$ low values of λ, $\lambda < 10^{-3}$, have no effect, as the strong dip characteristic of the standard model persists at $(Q_i = -\frac{1}{3}$, $Q_j = -\frac{2}{3})$

$$y = \bar{Q} = -\tfrac{1}{3}. \tag{10}$$

However, as soon as one gets to higher values of λ compatible with a composite W the dip is spoiled. Hence, this provides a rather sensitive measure of λ.

We have also studied the combined effect of both an

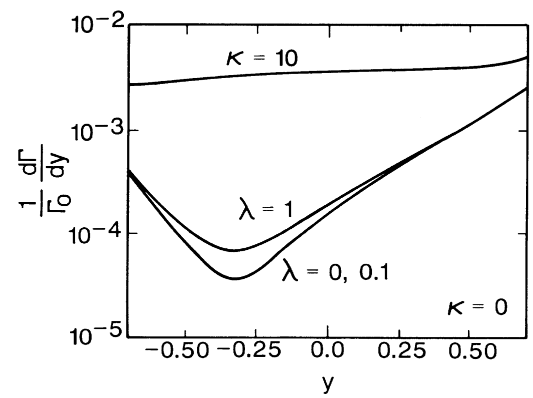

FIG. 3. $(1/\Gamma_0)d\Gamma/dy$ vs y for $\kappa=0$ and $0.2 \le x \le 1$ for various values of λ.

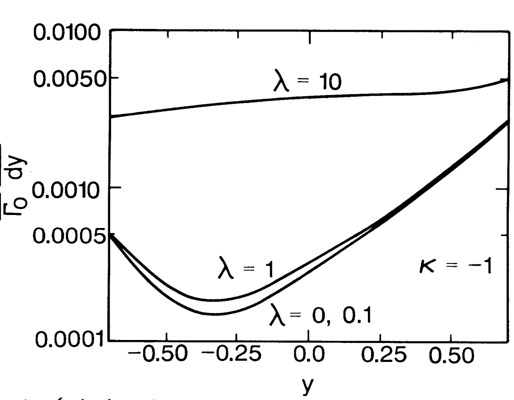

FIG. 4. $(1/\Gamma_0)d\Gamma/dy$ vs y for $\kappa=-1$ and $0.2 \le x \le 1$ for various values of λ.

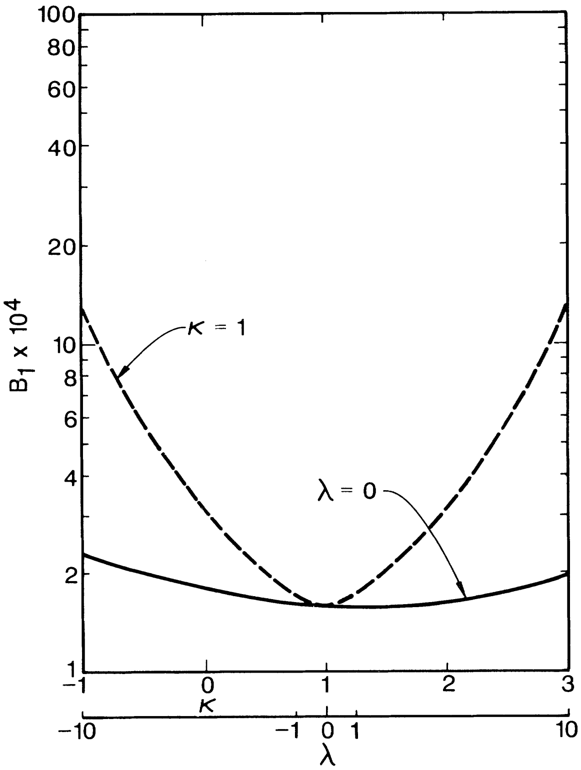

FIG. 5. Branching ratio B_1 vs κ for $\lambda=0$ and B_1 vs λ for $\kappa=1$.

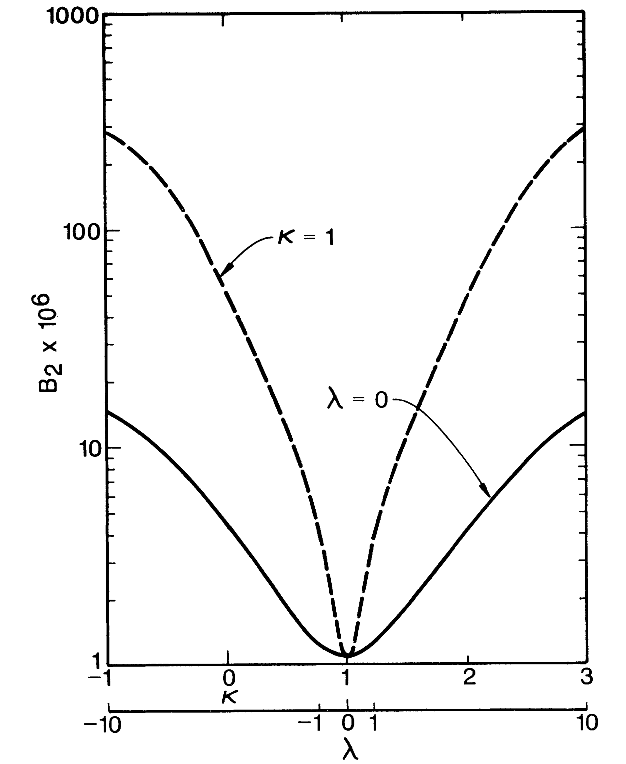

FIG. 6. Branching ratio B_2 vs κ for $\lambda=0$ and B_2 vs λ for $\kappa=1$.

anomalous magnetic and electric dipole moment for the W, by taking the two typical values $\kappa=0$ and $\kappa=-1$ while varying λ (Figs. 3 and 4). We conclude that unless λ is extremely large (or order 1 to 10) the modification to the standard-model distribution is more sensitive to an anomalous nongauge value for the magnetic moment of the W than to a nonvanishing EDM. This is easily explained by the fact that the rate is quadratic in λ but linear in $\Delta\kappa=\kappa-1$.

Finally, we considered the case where only either $\Delta\kappa$ or λ were nonvanishing, i.e., either an SU(2) gauge value for the magnetic moment but with an anomalous EDM or vice versa, to see whether it is possible to distinguish between these two situations.

In Figs. 5–7 we compare our results for $\kappa=1$, $\lambda\neq0$ and $\lambda=0$, $\kappa\neq1$. In each case the branching ratios $B(W^-\to d\bar{u}\gamma)$ are plotted. Figure 5 corresponds to B_1 ($x>0.2$ and $-0.7<y<0.7$). Figure 6 shows the case B_2 ($x>0.2$ and $-0.5\leq y<-0.17$) and Fig. 7 corresponds to B_3 ($x>0.2$ and $-0.35<y<-0.317$). It can be seen from these figures that the two cases $\lambda=0$, $\kappa\neq1$ and $\kappa=1$, $\lambda\neq0$ are different and can, in principle, be distinguished in such an experiment. Such an experiment would be, however, very difficult and would require more than the 10^4 W^+W^- pairs expected at the CERN e^+e^- collider LEP II. However, the Tevatron at Fermi-

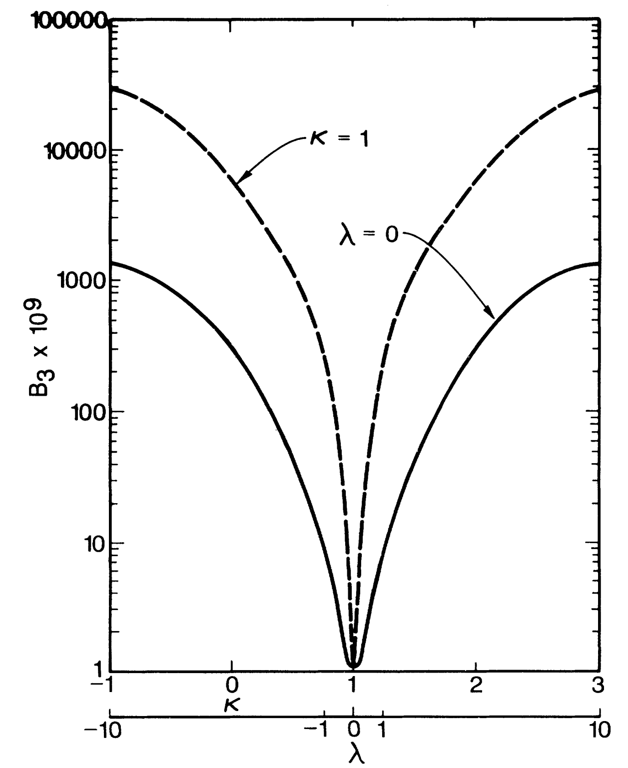

FIG. 7. Branching ratio B_3 vs κ for $\lambda=0$ and B_3 vs λ for $\kappa=1$.

lab has already obtained 5000 W bosons and expects a great many more.[8]

This experiment is already under way by the Collider Detector at Fermilab (CDF) Collaboration[9] at the Tevatron (Fermilab). Some radiative W decays have been observed. This should allow limits to be placed on κ. When the next run takes place in about a year or so they will have as many as 100000 W events. One can see from Figs. 5–7 that this will be a sufficient number to do this experiment and obtain a definite value for λ and κ. This will test the standard model (SM) to see if $\lambda = 0$ and $\kappa = 1$ (as required by the SM).

Two of us (C.H. and M.A.S.) would like to thank W. J. Marciano for helpful discussions. Two of us (J.W. and M.A.S.) would also like to thank Leon Lederman for inspiring discussions. One of us (M.A.S.) would like to thank Mark Timko and Darryl Dibitonto for helpful discussions. This work was supported by the U.S. Department of Energy under Grant No. DE-FG05-85ER40215.

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