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Finding the Radiation Amplitude Zero in $W\gamma$ Production- Is it Unique to the Standard Model?

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Abstract

In the light of recent experimental observation of the Radiation Amplitude Zero (RAZ) in $W\gamma$ production by CDF at Fermilab, we consider its consequences. Is the RAZ unique to the Standard Model (S.M.)? Although it is not for $\bar{\nu}_e e^- \to W^-\gamma$, in the case of $d\bar{u} \to W^-\gamma$, which is the case of experimental interest, observation of the RAZ implies that the S.M. must be correct.

It is now 18 years since Radiation Amplitude Zeros were discovered by Mikaelian, Samuel and Sahdev, (1). These zeros which were found in the process

$$\begin{aligned} d\bar{u} &\to W^-\gamma \\ \bar{\nu}e &\to W^-\gamma \\ u\bar{d} &\to W^+\gamma \\ \nu e^+ &\to W^+\gamma \end{aligned} \tag{1}$$

were proposed as a means of measuring the magnetic moment of the W boson, even though the W was discovered only 4 years later.

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These zeros are quite remarkable- the lowest-order amplitude vanishes for each spin state and the position of the zero is independent of the photon energy. (For massless quarks, it depends only on the quark charges) The RAZ provides a test of the magnetic moments of both the W and the quarks; further, the position of the zero enables a direct measure of the fractional quark charges by real photons. It was later pointed out that the zero also occurs in radiative W decay (2), where, in this case, the energy distribution vanishes along a certain line in the Dalitz plot. For related earlier work, see references (3) and (4).

Subsequently, (5-7) it was shown that these amplitude zeros can arise more generally, originating as the destructive interference of radiation patterns in gauge-theory tree amplitudes for massless gauge-boson emission. This is therefore a property of gauge theories; anomalous electromagnetic moments, for example, would spoil the perfect cancellations and such anomalies are forbidden in gauge couplings. For a specific analysis of the effect of W anomalous moments in the $u\bar{d} \to W^+\gamma$ reaction see ref (8). Of course, anomalous moments come up in higher-order corrections, and indeed RAZ do not appear beyond the tree approximation in any theory. For a careful assessment of QCD corrections see ref (9). For a generalization to more photons and gluons, see ref (10)

Can we observe these zeros experimentally? A necessary condition is that all of the charges in both the initial and final states must be of the same sign or neutral. The best bet for observing RAZ experimentally is in the originally suggested sub-processes

$$\begin{aligned} d\bar{u} &\to W^-\gamma \\ u\bar{d} &\to W^+\gamma \end{aligned} \tag{2}$$

which can be seen in the processes

$$p\bar{p} \to W^{\pm}\gamma X \tag{3}$$

A recent rapidity study by Baur *et al* (11) has given us a new and effective tool in the radiation zero analysis. They have shown that laboratory rapidity correlation involving the photon and the charged decay lepton display a pronounced dip corresponding to the RAZ.

Since it now seems certain that CDF at Fermilab will soon observe RAZ experimentally for the first time, a troubling thought occurs. *Is there an ambiguity? Could RAZ occur if* $\kappa + \lambda = 1$ *even if we do not have a S.M. W boson,* $\kappa = 1$, $\lambda = 0$*?* We will show that although such an ambiguity does exist for

$$\bar{\nu}_e e^- \to W^-\gamma \tag{4}$$

it does not occur for the experimentally relevant process

$$d\bar{u} \rightarrow W^{-}\gamma \tag{5}$$

In the following we will consider only the 2 processes

$$\bar{\nu_e} e^{-} \rightarrow W^{-}\gamma$$

and

$$d\bar{u} \rightarrow W^{-}\gamma \tag{6}$$

The corresponding results for $\nu_e e^{+} \rightarrow W^{+}\gamma$ and $u\bar{d} \rightarrow W^{+}\gamma$ can easily be obtained from them.

We begin with the angular distribution

$$\frac{d\sigma}{dA}(q_i\bar{q_j} \rightarrow W^{-}\gamma) = F(s, t, u, Q_i, \kappa, \lambda) \tag{7}$$

where

$$\begin{aligned} s + t + u &= M_W^2 \\ t &= -\frac{1}{2}(s - M_W^2)(1 - \cos\theta) \\ u &= -\frac{1}{2}(s - M_W^2)(1 + \cos\theta) \end{aligned} \tag{8}$$

and θ is the angle between the W^{-} and the quark/electron in the center-of-mass frame. Q_i is the charge of the quark/electron, and κ and λ are the parameters which determine the W magnetic moment

$$\mu_W = \frac{e}{2M_W}(1 + \kappa + \lambda) \tag{9}$$

and its electric quadrupole moment

$$Q_W = -\frac{e}{M_W^2}(\kappa - \lambda) \tag{10}$$

For the S.M., $\kappa = 1$ and $\lambda = 0$ and so

$$\mu_W = \frac{e}{M_W} \tag{11}$$

$$Q_W = -\frac{e}{M_W^2} \tag{12}$$

F is determined by crossing from

$$\frac{d\sigma}{dA}(\gamma q_i \rightarrow q_j W^{-}) \tag{13}$$

which is given in ref(12).

First we observe that for the S.M. ($\kappa = 1$ and $\lambda = 0$), the RAZ does indeed occur at

$$\cos\theta = -(1 + 2Q_i) \tag{14}$$

We now set $\lambda = 1 - \kappa$, leaving κ as a free parameter. We first consider $\bar{\nu}_e e^- \to W^- \gamma$ where $Q_i = -1$ and $\cos\theta = 1$. Here the RAZ is in the forward direction. By considering various values of s and $\cos\theta = 1$ we find that

$$F(s, t(\cos\theta = 1), u(\cos\theta = 1), -1, \kappa, 1 - \kappa) \equiv 0 \tag{15}$$

for any value of κ! Thus in this case we have an ambiguity. Observing the RAZ in this case does not imply the S.M.! This is indeed disturbing.

We now turn to the experimentally important process

$$d\bar{u} \to W^- \gamma \tag{16}$$

Here the RAZ occurs at $\cos\theta = -\frac{1}{3}$ as $Q_i = -\frac{1}{3}$. We set $\cos\theta = -\frac{1}{3}$ and $\lambda = 1 - \kappa$. This time we find that

$$F(s, t(\cos\theta = -1/3), u(\cos\theta = -1/3), -1/3, \kappa, 1 - \kappa) \propto (1 - \kappa)^2 \tag{17}$$

Thus in this case $F \neq 0$ unless $\kappa = 1$ and, hence $\lambda = 0$. Thus nature is kind to us as the observation of a RAZ in this process requires the S.M. values $\kappa = 1$ and $\lambda = 0$ and, hence, means that the S.M. has survived another test beautifully!

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