Test for the Existence of the Neutral Vector Boson of Weak Interactions

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An experiment is proposed to detect the possible existence of a neutral vector boson (W_0) weakly coupled to leptons. It is shown that this boson would exhibit itself as a resonance in high-energy e^+-e^- scattering into two-lepton final states. This resonance makes the boson contribution comparable to and distinguishable from the electromagnetic contribution to the e^+-e^- scattering process. Observation of the resonance would permit a direct measurement of the lepton-W_0 coupling constant and provide also a test of the hypothesis of universality of the weak interactions. The experiment should become possible shortly when high-energy colliding beams of electrons and positrons are available.

1. INTRODUCTION

A SUBJECT of great interest at the present time is the question of the existence of vector bosons (W bosons) which mediate the weak interactions. Experiments with high-energy neutrinos are now in progress with the aim of detecting charged W bosons, but there has been no practical experiment suggested to establish the presence of neutral W bosons.

It is known that strangeness changing decays which could occur via a W_0 intermediate boson, such as $K\to\pi+\mu_++\mu_-$ or $K\to\pi+e_++e_-$, are not observed. On the other hand, there is no experimental evidence against the existence of a W_0 weakly coupled only to lepton currents and strangeness conserving currents[1]; and there are also group theoretical arguments in favor of the existence of W_0 bosons.

It is the purpose of this paper to propose an experiment which should exhibit the effect of a neutral vector boson in interaction with leptons, if such a boson exists.

The experiment proposed is high-energy electron-positron elastic scattering. This process can occur through exchange of a weakly coupled W_0, and through exchange of a photon as in ordinary Bhabha scattering.[2] One might think that the small magnitude of the weak coupling constant would make the effect of the W_0 boson unobservable when in competition with electromagnetic interactions. However, there is a sharp resonance in the weak scattering which does not exist in the Bhabha process. This narrow resonance has the effect of making the scattering via the W_0, and the Bhabha scattering, of the same order of magnitude in the neighborhood of the resonance.

We present in the next section the results of our calculation. In the final section we discuss the implications of these results.

2. CALCULATIONS AND RESULTS

In lowest order in the weak-coupling constant g the only contributions to electron-positron scattering due to a weakly coupled neutral vector boson W_0 come from the Feynman diagrams shown in Fig. 1. The coupling between the vector boson and the lepton fields is assumed to be of the standard V-A form, and the boson propagator is taken to be the usual $(\delta_{\mu\nu}-q_\mu q_\nu/\mu^2)\times(q^2-\mu^2)^{-1}$ expression. Using the well-known Feynman rules, the differential cross section corresponding to the combined effect of the diagrams in Fig. 1 is calculated to be

$$d\sigma/d\Omega=[1/(8\pi)^2s]X, \tag{1}$$

where X is

$$X=\frac{g^4}{(q^2-\mu^2)^2}\left[(s+q^2-2m^2)^2-\tfrac{3}{2}q^2(s+q^2-2m^2)+\tfrac{3}{4}q^4-2m^2q^2\left(\frac{m}{\mu}\right)^2+q^4\left(\frac{m}{\mu}\right)^4\right]$$
$$+\frac{g^4}{(s-\mu^2)^2}\left[(s+q^2-2m^2)^2-\tfrac{3}{2}s(s+q^2-2m^2)+\tfrac{3}{4}s^2-2m^2s\left(\frac{m}{\mu}\right)^2+s^2\left(\frac{m}{\mu}\right)^4\right]$$
$$+\frac{g^4}{(q^2-\mu^2)(s-\mu^2)}\left[2(s+q^2-2m^2)^2+q^2s\left(\frac{m}{\mu}\right)^4-4m^2(q^2+s)\left(\frac{m}{\mu}\right)^2\right].$$

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[1] See, for example, L. B. Okun, in *Proceedings of the 1962 International Conference on High-Energy Physics at CERN*, edited by J. Prentke (CERN, Geneva, 1962), p. 845; J. Bell, CERN Report 63-37, 1963 (unpublished).

[2] We shall restrict the term "Bhabha scattering" to the electron-positron elastic scattering caused by the electromagnetic interaction.

The expression for the cross section is in the center-of-mass system. $s=(K+K_+)^2$ is the square of the total energy in this system; $q^2=(K'-K)^2$ is the square of the four-momentum transfer, sometimes called t in the literature; and m and μ are, respectively, the masses of the electron and of W_0.

In expression (1) the first term represents the contribution of Fig. 1(a), the second term that of Fig. 1(b), and the last term the contribution of the interference between the two figures. Comparing this expression with the corresponding one for the lowest order Bhabha scattering[3] (involving the exchange of a single photon) one can see that the only term which is not negligibly small in (1) is the resonant term coming from Fig. 1(b).

In order to estimate the order of magnitude of its contribution to the cross section near the resonance we have attributed a width Γ to the resonance, modifying appropriately the propagator. This has been done by adding an imaginary term $i\Gamma$ to the denominator of the propagator. An estimate of Γ was made by calculating the rate of decay of W_0 into lepton pairs. Assuming a value of 1.5 GeV for the mass of W_0 and $g^2/4\pi\approx 1.6\times 10^{-6}$ we found

$$\Gamma\approx g^2\mu/(8\pi)\approx 1.2\times 10^{-3}\text{ MeV}.$$

This resonance is very sharp. Experimentally, the beams of electrons at these high energies have a width Δ of about 2 MeV. What one measures therefore is a cross section averaged over the energy width of the beam. We have calculated this average using a Gaussian weight function of width Δ centered at the energy μ. Since the Bhabha cross section has a minimum in the backward direction, we have chosen this angle as the one at which to estimate the ratio of the differential cross section we calculated to the Bhabha one. Taking the extreme relativistic limit of these cross sections we find the result

$$\left\langle\left(\frac{d\sigma}{d\Omega}\right)_{W_0}\right\rangle_{\text{av}}=\frac{1}{(8\pi)^2 s}\bar{X}$$

$$\bar{X}=g^4\frac{3}{4}\left\langle\frac{s^2}{(s-\mu^2)^2}\right\rangle_{\text{av}}=g^4\frac{3}{4}\frac{\pi^{1/2}}{4}\frac{\mu^2}{\Delta\Gamma},\quad (2)$$

where the angular brackets mean "averaged over the energy width of the beam." Since, in the extreme relativistic limit,

$$(d\sigma/d\Omega)_B=e^4/(4\pi)^2\mu^2,$$

one finds[4]

$$\left\langle\left(\frac{d\sigma}{d\Omega}\right)_{W_0}\right\rangle_{\text{av}}\Big/\left(\frac{d\sigma}{d\Omega}\right)_B\approx 2.\quad (3)$$

[3] See, for example, J. M. Jauch and F. Rohrlich, *The Theory of Photons and Electrons* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1955).

[4] Strictly speaking, the numerator in Eq. (3) should contain also the interference terms between weak and electromagnetic coupling. However, for simplicity we have omitted this contribution since it does not change the order of magnitude of the ratio in (3). Its effects would be to increase somewhat the ratio.

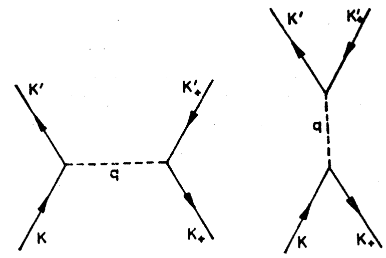

FIG. 1. Lowest order Feynman diagrams for electron-positron scattering via a weakly coupled neutral vector boson.

3. DISCUSSION OF THE RESULTS

Our estimate (3) shows the striking result that if a weakly coupled W_0 vector boson exists, it can give an observable contribution to a process which can take place also via an electromagnetic coupling. The two contributions are comparable because, as shown by our calculation, the presence of the resonance compensates for the smallness of the weak coupling constant. We have not introduced form factors in our calculations but we believe our estimate would not be essentially changed since the form factors would affect both the Bhabha and the weak process in a similar way, and because the resonant behavior is unaffected.

The experiment to be done in order to reveal the W_0 will become possible shortly when high-energy colliding beams of electrons and positrons will be available. The experiment should be done at a fixed angle, and the energy is to be varied in search for the resonance.[5] If the charged W boson will by then have been discovered, one should look for the resonance in the neighborhood of the charged W rest-mass energy. A tentative estimate of the expected counting rates in such a colliding beam experiment can be made using Frascati's data for the storage ring now under test.[6] This gives a result of the order of a count every ten hours.

However, improvements in storage-ring techniques should increase this estimate significantly. For example, an increase in particle density in the storage ring by a factor of 10 would raise the counting rate by a factor of a 100.

If the resonance is observed, one can not only conclude the existence of the W_0, but also deduce directly the magnitude of the $e-W_0$ coupling constant.

A similar resonant effect should also be observable in the process $e_+ + e_- \rightarrow \mu_+ + \mu_-$. At these energies the resonant cross sections for the W_0 mediated processes are essentially unaffected by the mass difference between muon and electron. By subtracting the electro-

[5] Our results have been presented for the specific case of backscattering. However, as long as one keeps to large angles, the results do not depend critically on the angle. In fact, there might be some experimental advantage in doing the experiment at other angles. For instance, at 90° the bremsstrahlung background is much reduced, and also one can accept counts from both negative and positive charges.

[6] C. Bernardini *et al.*, Frascati Annual Conference, Report LNF 63/47, June 1963, p. 133 (unpublished); C. Bernardini G. F. Corazza, G. Ghigo, and B. Touschek, Nuovo Cimento **18**, 1293 (1960).

magnetic contribution at the resonance[7] one may compare directly the $e-W_0$ and $\mu-W_0$ coupling constants. This would provide, therefore, a clear test of the universality of the weak interactions.

We have also considered the possibility that a similar resonant effect could be produced by a boson coupled to the electron-positron field electromagnetically (similar to the ρ or ω coupling to photons). However, our estimate shows that because of its much larger width ($\Gamma \gtrsim 10$ MeV) its effect is negligible compared to the Bhabha cross section.

Note added in proof. Dr. R. Gatto has kindly informed us (private communication, 10 June 1964) that the processes $e_+ + e_- \rightarrow W_0 \rightarrow e_+ + e_-$ and $e_+ + e_- \rightarrow W_0 \rightarrow \mu_+ + \mu_-$ have already been suggested [N. Cabibbo and R. Gatto, Phys. Rev. **124**, 1577 (1961), Sec. 7]. The brief calculations done earlier are essentially in agreement with the results given above. Dr. Gatto has also conveyed to us the information that recent work at Frascati indicates their Adone storage ring should be capable of a resolution of 0.5 MeV at 2-BeV total energy. The consequence of such an improved resolution would be to multiply the result given in Eq. (3) above by a factor of 4.

[7] Unlike the W_0 mediated processes, the electromagnetic contributions are different for the muon and electron final states.

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Dynamics of the $d_{3/2}$ Unitary Multiplets

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A dynamical model of pseudoscalar meson-baryon scattering in the $J^P = 3/2^-$ state is proposed to support the conjecture of Glashow and Rosenfeld that the $N^{**}(1512)$ resonance is a member of a unitary-symmetry octet. The dynamical mechanism analyzed here is based on the Cook-Lee model of the higher pion-nucleon resonances. It is shown that the coupling to inelastic vector meson-baryon states in a generalized two-channel formalism yields an octet of $d_{3/2}$ resonances and a unitary singlet as well. The baryon, pseudoscalar-meson, and vector-meson octets are each assumed degenerate, so that the Cook-Lee model is immediately adaptable to an analysis of resonant unitary multiplets as a function of f, the Yukawa mixing parameter. It is found that, for $f = 0.326$, the attraction is slightly greater for the octet than for the singlet. The 2×2 octet amplitude is diagonalized by a rotation through an angle $\theta^* = 45°$; the Yukawa mixing parameter is $f^* = 0.428$. The $N^{**}N\pi$ coupling constant is computed to be $g^{*2}/(4\pi) = 0.150\ m_\pi^{-2}$, which may be compared with the observed N^{**} width.

I. INTRODUCTION

The conjecture has been made by Glashow and Rosenfeld[1] that the $N^{**}(1512)$ resonance is a member of a unitary-symmetry octet with spin-parity $3/2^-$. According to them, its partners in the octet should be the $Y_0^*(1520)$, the $Y_1^*(1660)$, and a Ξ^* (undiscovered). These assignments were based chiefly on an analysis of partial widths for two-body decay modes. Martin[2] has also analyzed widths, and his approach, a different one, reveals discrepancies in the octet assignment. He argues in particular that the Y_0^* is more likely a unitary singlet than a member of an octet. It is the purpose of this paper to present a dynamical mechanism which yields both singlet and octet systems of $d_{3/2}$ resonances.

In Sec. II the model is presented which leads to the results cited above. In Sec. III the analysis of resonant unitary multiplets is given.

II. DYNAMICAL MODEL

The prototype of the mechanism adopted here is the Cook-Lee model[3] of the higher πN resonances. For the $d_{3/2}$ state their model exploits the circumstance that an s-wave ρN system may be coupled by unitarity to the d-wave πN system. Virtual ρ production feeds the elastic channel and provides enough attraction to produce the N^{**} below the inelastic threshold. The dominant force driving the left-hand cuts in their two-channel model is assumed to arise from one-pion-exchange coupling the πN and ρN channels. That it is allowable to neglect a specific exchange force, so

[1] S. L. Glashow and A. H. Rosenfeld, Phys. Rev. Letters **10**, 192 (1963).

[2] A. W. Martin, Nuovo Cimento (to be published).

[3] L. F. Cook and B. W. Lee, Phys. Rev. **127**, 283 (1962); **127**, 297 (1962).