Ref.TH.2907-CERN

PARITY VIOLATION EFFECTS INDUCED BY A NEW GAUGE BOSON

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A B S T R A C T

We study the parity violation effects which could be induced by the new neutral gauge boson of supersymmetric theories. If it is light, this boson would not affect high energy scattering, but it could modify the parity violation effects expected in atomic physics. These may either be suppressed or enhanced compared to the predictions of the standard model.

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30 July 1980

Supersymmetry is a new invariance of field theory which associates bosons with fermions, and conversely ¹⁾. The corresponding algebra is closely related with the geometrical structure of space-time. Supersymmetric theories of particles involve, in addition to the standard neutral gauge boson Z' , a second one, Z'' ²⁾. The former is associated with the mixing between weak and electromagnetic interactions. The latter may be viewed, equivalently, as a particle mediating interactions of the weak type, or of the gravitational type. These interactions are essentially determined by the mass spectrum of the theory. However, the mass and gauge coupling constant of the new boson are not fixed : they may have the same order of magnitude as for the standard Z' , but they may also be much smaller ^{3),4)}.

Although this will not be directly useful in the present paper, we remind the reader of the origin of the connection with gravity. In a globally supersymmetric theory the new boson is, essentially, the bosonic partner of the massless spin- $\frac{1}{2}$ goldstino associated with the spontaneous breaking of the supersymmetry. If supersymmetry is realized locally the corresponding gauge particle, the spin- $\frac{3}{2}$ gravitino, acquires a mass (while the goldstino is eliminated). Under supersymmetry this particle is associated with both the massless spin-2 graviton and the new neutral spin-1 boson Z'' ⁵⁾.

The possible existence of a light gauge boson leads one to take into account propagator effects when discussing neutral current experiments. A light, weakly coupled, Z'' would modify lower q^2 but not higher q^2 phenomenology, giving no contribution to ordinary, high energy, neutral current processes ^{3),6)}. Therefore experiments searching for neutral current effects at low momentum transfer are of great interest, even if the neutral current structure at high momentum transfer were completely known.

We discuss elsewhere various aspects of the phenomenology of the new boson : effects in neutrino scatterings and e^+e^- annihilations, lifetime and decay modes, production in high energy hadronic collisions and kaon decays ^{4),7)}. A remarkable property of the new boson is that, if it is very light, it would be produced and interact like a pseudoscalar axion ^{7),8)} ; therefore the effective strength of its interaction should be relatively small, or its mass should be large enough (i.e., $\geq$ a few MeV/c^2) so that it would decay before its reinteraction could be detected. In this paper we want to concentrate on experiments which could detect a possible parity violating character of the new particle : in particular the SLAC electron-deuteron scattering experiment ⁹⁾, and the experiments searching for parity violation effects in atomic physics ^{6),10)}. The importance of the latter in the search for light gauge bosons has been stressed in Ref. 6).

In the simplest supersymmetric model the Z'' is coupled to a purely axial neutral current so that it does not induce any parity violating effect. But, in general, the new neutral current may also have a vector part ^{*)}, 2).

The interactions of the Z'' are, in fact, fixed by the mass spectrum of the theory. Let us denote generically by ψ any spin- $\frac{1}{2}$ lepton or quark, and by s and t its spin-0 partners. The couplings of Z'' , fixed by the values of the new hypercharge F'' , are proportional to the boson fermion mass² splittings ³⁾ :

$$\begin{cases} m^2(s) - m^2(\psi) \sim -F''(\psi_L) \\ m^2(t) - m^2(\psi) \sim +F''(\psi_R) \end{cases} \quad (1)$$

Since spin-0 leptons and quarks must be heavier than their spin- $\frac{1}{2}$ partners, we get, as a result of supersymmetry, the constraints :

$$\begin{cases} F''(\psi_L) < 0 \\ F''(\psi_R) > 0 \end{cases} \quad (2)$$

the over-all sign being purely a matter of convention. Therefore the new neutral current must have an axial part and the corresponding gauge invariance must be spontaneously broken.

If all leptons and quarks get their masses through Yukawa couplings with a single pair of Higgs doublets, as in the model of Ref. 2), the gauge invariance of these couplings implies the extra relations

$$-F''(\psi_L) + F''(\psi_R) = 1 \quad (3)$$

The simplest solution, $F''(\psi_L) = -F''(\psi_R) = -\frac{1}{2}$, corresponds to a universal axial coupling of Z'' to leptons and quarks, and to a universal mass² splitting Δm^2 between their spin-0 partners and themselves.

*) We may also have more complicated mixings involving the photon and the two other neutral gauge bosons (leading to $\langle \text{photino} | \text{goldstino} \rangle \neq 0$), but we shall not consider such effects here.

Relations (3) imply the universality of the axial couplings of the Z'' , but not the one of its vector couplings, if they do exist. Using (2) and (3), we parametrize the values of the new hypercharge F'' as follows ^{*)} :

$$\begin{aligned} F''(\Psi_L) &= -\frac{1}{2} (1 - \cos \varphi) \\ F''(\Psi_R) &= \frac{1}{2} (1 + \cos \varphi) \end{aligned} \quad (4)$$

We may have different angles associated with the electron and its neutrino (φ_e), the u and d quarks (φ_d), and the members of the other families. These angles are related to the mass² splittings inside the multiplets of supersymmetry. In particular, we have ³⁾ :

$$\begin{aligned} m^2(s) - m^2(\psi) &= \frac{m^2(W_-) - m^2(w_-)}{4} (1 - \cos \varphi) \\ m^2(t) - m^2(\psi) &= \frac{m^2(W_-) - m^2(w_-)}{4} (1 + \cos \varphi) \end{aligned} \quad (5)$$

(w_- is the charged physical Higgs boson remaining after the spontaneous breaking of $SU(2) \times U'(1)$ by a pair of Higgs doublets : it belongs to the same multiplet of supersymmetry as the charged intermediate boson W_- .) Similar relations involve neutral gauge bosons, heavy fermions and Higgs bosons. The limiting situations $\cos \varphi = -1, 0$ or $+1$ correspond to a pure A-V, A or A+V new neutral current, respectively. However, $|\cos \varphi|$ cannot be too close to one, otherwise the theory would describe spin-0 particles which would be too light ^{**)}.

THE EFFECTIVE LAGRANGIAN DENSITY

Let us now compute the effects of a Z'' exchange. We use the expressions of the covariant derivative D_μ

$$i D_\mu = i \partial_\mu - \frac{g''}{2} F'' Z''_\mu - \dots \quad (6)$$

^{*)} If we considered ordinary gauge theories, dropping the requirement of supersymmetry, we would no longer have the constraints (2). The parametrization (4) and the subsequent neutral current analysis could still be used, with $\cos \varphi$ as an unconstrained real parameter.

^{**)} Equation (5), with $m(W_-) \approx 80 \text{ GeV}/c^2$, allows one to get limits on φ from limits on the masses of spin-0 particles. With $m(s), m(t) > 15 \text{ GeV}/c^2$ we get $|\cos \varphi| < 0.86$.

and of the Z'' mass :

$$m(Z'') = \frac{g'' v}{\sqrt{2}} = \frac{1}{r} \frac{g''}{g} m(W_-) \quad (7)$$

The model-dependent parameter r , equal to 1 in Ref. 2), would be smaller than 1 in the presence of an extra Higgs singlet making the Z'' heavier without modifying the W_- and Z' masses. The effective Lagrangian density associated with Z' and Z'' exchanges reads ⁴⁾ :

$$\mathcal{L}_{\text{eff}} = 2 G_F \sqrt{2} \left[(J_3^\mu - \sin^2 \theta J_{\text{em}}^\mu)^2 + \frac{r^2}{4} \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} (J''^\mu)^2 \right] \quad (8)$$

If the Z'' mass is small compared to the typical momentum transfer, the last term in (8) is negligible.

The first neutral current is the same as in the standard model :

$$\begin{aligned} J_3^\mu - \sin^2 \theta J_{\text{em}}^\mu &= \frac{1}{2} \bar{\nu}_e \gamma^\mu \frac{1 - i\gamma_5}{2} \nu_e \\ &+ \left(-\frac{1}{4} + \sin^2 \theta\right) \bar{e} \gamma^\mu e + \left(\frac{1}{4} - \frac{2}{3} \sin^2 \theta\right) \bar{u} \gamma^\mu u + \left(-\frac{1}{4} + \frac{1}{3} \sin^2 \theta\right) \bar{d} \gamma^\mu d \\ &+ \frac{1}{4} \bar{e} i \gamma^\mu \gamma_5 e - \frac{1}{4} \bar{u} i \gamma^\mu \gamma_5 u + \frac{1}{4} \bar{d} i \gamma^\mu \gamma_5 d + \dots \end{aligned} \quad (9)$$

while the second one reads :

$$\begin{aligned} J''^\mu &= \sum_{\Psi = \nu_e, e, u, d, \dots} \left(F''(\Psi_L) \bar{\Psi}_L \gamma^\mu \Psi_L + F''(\Psi_R) \bar{\Psi}_R \gamma^\mu \Psi_R \right) \\ &= -\frac{1}{2} (1 - \cos \varphi_e) \bar{\nu}_e \gamma^\mu \frac{1 - i\gamma_5}{2} \nu_e \\ &+ \frac{1}{2} \cos \varphi_e \bar{e} \gamma^\mu e + \frac{1}{2} \cos \varphi_d (\bar{u} \gamma^\mu u + \bar{d} \gamma^\mu d) \\ &+ \frac{1}{2} (\bar{e} i \gamma^\mu \gamma_5 e + \bar{u} i \gamma^\mu \gamma_5 u + \bar{d} i \gamma^\mu \gamma_5 d) + \dots \end{aligned} \quad (10)$$

THE PARITY VIOLATING ELECTRON-QUARK INTERACTION

The parity violating part in the electron-quark interaction can be parametrized as follows

$$\mathcal{L}_{\text{eff}}^{\text{PV}} = \frac{G_F}{\sqrt{2}} \left\{ \bar{e} i \gamma_\mu \gamma_5 e \left[C_{AV}^u \bar{u} \gamma^\mu u + C_{AV}^d \bar{d} \gamma^\mu d \right] + \bar{e} \gamma_\mu e \left[C_{VA}^u \bar{u} i \gamma^\mu \gamma_5 u + C_{VA}^d \bar{d} i \gamma^\mu \gamma_5 d \right] \right\} \quad (11)$$

with

$$\left\{ \begin{array}{l} C_{AV}^u = \frac{1}{2} - \frac{4}{3} \sin^2 \theta + \frac{r^2}{2} \cos \varphi_d \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \\ C_{AV}^d = -\frac{1}{2} + \frac{2}{3} \sin^2 \theta + \frac{r^2}{2} \cos \varphi_d \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \end{array} \right. \quad (12)$$

$$\left\{ \begin{array}{l} C_{VA}^u = \frac{1}{2} - 2 \sin^2 \theta + \frac{r^2}{2} \cos \varphi_e \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \\ C_{VA}^d = -\frac{1}{2} + 2 \sin^2 \theta + \frac{r^2}{2} \cos \varphi_e \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \end{array} \right. \quad (13)$$

For $r^2 \cos \varphi = 0$, or $q^2 \gg m_{Z''}^2$, we recover the same formulas as in the standard model.

The SLAC electron-deuteron scattering experiment ⁹⁾, which measures a parity violating interference between electromagnetic and other (weak or gravitational) neutral current amplitudes, is sensitive, up to small corrections, to the parameters

$$\left\{ \begin{array}{l} C_1 = \frac{2}{3} C_{AV}^u - \frac{1}{3} C_{AV}^d = \frac{1}{2} - \frac{10}{9} \sin^2 \theta + \frac{r^2}{6} \cos \varphi_d \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \\ C_2 = \frac{2}{3} C_{VA}^u - \frac{1}{3} C_{VA}^d = \frac{1}{2} - 2 \sin^2 \theta + \frac{r^2}{6} \cos \varphi_e \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \end{array} \right. \quad (14)$$

Experiments looking for parity violation effects in heavy atoms are sensitive to a nearly orthogonal combination of C_{AV}^u and C_{AV}^d , the effects associated with the coefficients C_{VA}^u and C_{VA}^d being suppressed ^{6),10)}. It reads ^{*)} :

$$\begin{aligned} Q_w &= 2 Z (2 C_{AV}^u + C_{AV}^d) + 2 N (2 C_{AV}^d + C_{AV}^u) \\ &= Z (1 - 4 \sin^2 \theta + 3 \kappa^2 \cos \varphi_d) + N (-1 + 3 \kappa^2 \cos \varphi_d) \end{aligned} \quad (15)$$

Whether the same set of coefficients $\{C_{AV(VA)}^{u(d)}\}$ can be used to describe both SLAC-type experiments and atomic physics experiments depends on the value of the Z'' mass compared to typical values of the momentum transfer.

A SHORT DISCUSSION OF THE EXPERIMENTS

Let us now discuss briefly how present experiments can constrain these parameters. We first mention that a Z'' exchange gives a very small contribution to the muon anomaly. Using the results of Ref. 11), we find, for $m_{Z''} \gg m_\mu$:

$$a_\mu^{(Z'')} \simeq - \kappa^2 \frac{G_F m_\mu^2}{8 \pi^2 \sqrt{2}} \left(\frac{5}{3} - \frac{1}{3} \cos^2 \varphi_\mu \right) \quad (16)$$

and, for $m_{Z''} \ll m_\mu$:

$$a_\mu^{(Z')} \simeq - \kappa^2 \frac{G_F m_\mu^2}{8 \pi^2 \sqrt{2}} \quad (17)$$

(The last expression is identical to the one which would be obtained from the exchange of a massless pseudoscalar axionlike particle.) Such a contribution, at most of the order of $2 \cdot 10^{-9}$ in magnitude, does not spoil the agreement between theory and experiment for the muon anomaly, established at the level of $2 \cdot 10^{-8}$ ¹²⁾.

^{*)} In writing formula (15) we assume that $m_{Z''}$ is not too small, so that the range of the Z'' exchange potential is short compared to the extensions of the electron wave-functions and of the nucleus. Then the relativistic enhancement factors associated with the Z' and Z'' exchange potentials are the same. Otherwise the parity violation effects of Z'' would be reduced compared to those of Z' , especially for heavy atoms.

The existence of the Z'' can affect the SLAC experiment only if :

i) the parameter r is not too small ; ii) the Z'' coupling is not purely axial, i.e., $\cos \varphi \neq 0$; iii) it is relatively heavy, i.e., $m_{Z''} \geq \text{typical } q \sim 1 \text{ GeV}/c^2$. Assuming the Z'' mass to be large enough, we compare formula (14) with the experimental results of Ref. 9) (See Fig. 1). It is no longer possible, as in the standard model, to determine $\sin^2 \theta$ from this single experiment. Instead we get a constraint between $\sin^2 \theta$, $r^2 \cos \varphi_d$ and $r^2 \cos \varphi_e^*$). Even if we demand $\sin^2 \theta \approx 0.23$ this constraint allows for relatively large values of $r^2 \cos \varphi$, as shown in Fig. 2. If we only demand $0.20 < \sin^2 \theta < 0.26$, the allowed region for $r^2 \cos \varphi$ is represented in Fig. 3. In particular $|\cos \varphi_d| \approx 1$ is excluded if $r = 1$ [see also footnote **) on p. 3].

There are also constraints coming from e^+e^- annihilation and $\nu_\mu^{(-)}$ scattering experiments. If Z'' is relatively light one can search for it as a narrow resonance in e^+e^- annihilation ⁷⁾. If it is heavy we may get useful information on the new neutral current from PETRA experiments. [In particular if $\sin^2 \theta = \frac{1}{4}$ and $\cos \varphi = 0$, both Z' and Z'' are axially coupled to the electron and the muon. The Z'' contributions to $e^+e^- \rightarrow e^+e^-$, or $\mu^+\mu^-$, scattering amplitudes are equal to r^2 times the standard Z' contributions, in the local limit ; i.e., using a standard notation, we have $h_{AA} = \frac{1}{4}(1+r^2)$, $h_{AA} = h_{VA} = 0$.]

$\nu_\mu^{(-)}$ scattering experiments can be described in terms of six parameters u_L, d_L, ϵ_L and u_R, d_R, ϵ_R which have the same values as in the standard model, plus the extra contributions

$$\pm \frac{r^2}{8} (1 - \cos \varphi_\mu) (1 \mp \cos \varphi_{d,e}) \frac{m_{Z''}^2}{m_{Z''}^2 + q^2} \quad (18)$$

This formula extends formula (15) of Ref. 4) to situations in which the new neutral current is not purely axial ; the upper (lower) signs correspond to the left-handed (right-handed) fermion fields, respectively. These contributions can be sufficiently small if r is larger than one, or if the new neutral current is not purely axial, or if the Z'' is light. Roughly speaking, if the Z'' mass is larger than the typical momentum transfer in $\nu_\mu^{(-)}$ nucleon scattering experiments, we find, using the neutral current analysis of Ref. 13), the constraints :

*) Asymmetry measurements in electron-proton scattering ⁹⁾ give a similar constraint on these parameters (the experimental uncertainties are larger, but the Z'' contributions to the parameters C_1 and C_2 are twice as large for the proton as for the deuteron).

$$\begin{aligned} r^2 (1 - \cos \varphi_\mu) (1 - \cos \varphi_d) &\lesssim \frac{1}{2} \\ r^2 (1 - \cos \varphi_\mu) (1 + \cos \varphi_d) &\lesssim 1 \end{aligned} \quad (19)$$

From $(\bar{\nu}_\mu)$ electron scattering experiments we get constraints on r , φ_μ and φ_e if $m_{Z''} \gtrsim$ a few hundreds of MeV/c^2 . Their precise expression will depend on the careful analysis of experiments which are presently underway.

The effects of the Z'' could be searched for in reactor neutrino experiments (if $m_{Z''} \gtrsim 1 \text{ MeV}/c^2$) and atomic physics experiments. The latter could be sensitive to a very light Z'' . But the existence of a Z'' lighter than a few MeV/c^2 is also constrained by beam dump experiments looking for the reinteraction of neutral long-lived particles ^{7),14)}: the effective strength of the interaction, measured by the parameter r , would have to be small, and effects in atomic physics would be very hard to detect (see also the footnote on p. 6).

Let us now return to the experiments searching for parity violation effects in heavy atoms such as cesium, thallium or bismuth. They are sensitive to the "weak charge" Q_W , which has the same value as in the standard model, Q_{WS} , plus an extra term :

$$Q_W = Q_{WS} + 3 r^2 \cos \varphi_d A \quad (20)$$

For $\sin^2 \theta \approx \frac{1}{4}$ we get the simplified formula

$$Q_W \simeq -N + 3 r^2 \cos \varphi_d A \quad (21)$$

The results of the experiments ¹⁵⁾ may therefore be quite different from what is expected in the standard model : the parity violation effects could be suppressed if $r^2 \cos \varphi_d \approx (N/3A)$, but they could also be several times as large as expected.

CONCLUSION

It would be extremely useful if electron-nucleon scattering experiments and atomic physics experiments on hydrogen and heavy atoms could lead to independent determinations, at different values of the momentum transfer, of the four coefficients C_{AV}^u , C_{AV}^d , C_{VA}^u and C_{VA}^d describing the parity violating electron-quark interactions. Atomic physics experiments are particularly interesting since they can be sensitive to a new neutral current not affecting high energy phenomena. The fact that this neutral current is related to gravity can be one more motivation to search for it. But, independently of any theoretical prejudice, the low energy structure of neutral currents is certainly a domain worth being studied.

ACKNOWLEDGEMENTS

I wish to thank C. Bouchiat for helpful discussions.

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FIGURE CAPTIONS

Figure 1 Constraints on the parameters C_1 and C_2 from asymmetry measurements in the SLAC electron-deuteron scattering experiments. The central line corresponds to the prediction of the standard model ; the two parallel lines upper left and lower right correspond to the limiting situations $r^2 \cos \phi_d = -r^2 \cos \phi_e = -1(+1)$, respectively (assuming the Z'' mass to be somewhat larger than $\sim 1 \text{ GeV}/c^2$). The dotted square corresponds to $\sin^2 \theta = 0.23$.

Figure 2 Constraints on $r^2 \cos \phi_d$ and $r^2 \cos \phi_e$ from the SLAC experiment, assuming $\sin^2 \theta = 0.23$ and $m_{Z''}$ larger than $\sim 1 \text{ GeV}/c^2$. The two contours correspond to the 1 σ and 90% confidence levels.

Figure 3 Constraints on $r^2 \cos \phi_d$ and $r^2 \cos \phi_e$, as before but with $0.20 < \sin^2 \theta < 0.26$.

Fig. I

Fig.2

Fig. 3