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ANOMALOUS Z DECAYS: EXCITED LEPTONS?

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We study the possibility that the recently observed $\ell^+\ell^-\gamma$ decays of the Z are due to the existence of an excited electron (muon) with approximately 75 GeV (60 GeV) mass. We point out that in a composite picture of leptons such states should fall in vectorlike SU(2) ⊗ U(1) multiplets, with weak isospin $I \leqslant 3/2$, and be coupled with a magnetic moment type transition to the light leptons. We study the relative rates of the $Z \to \ell^+\ell^-\gamma$ or $\nu\bar{\nu}\gamma$ and $W^+ \to \ell^+\nu\gamma$, $\ell^+\ell^-(f\bar{f})^+$, $\nu\bar{\nu}(f\bar{f})^+$ channels, as means of determining the weak isospin assignment of the excited leptons. All present information is seen to be compatible with the existence of the required excited leptons, including the absence of observed anomalies in the $e^+e^- \to \gamma\gamma$ cross sections and in the muon $(g-2)$. For spin 1/2, the distribution of the invariant mass for the direct lepton photon pair in $\ell^+\ell^-\gamma$ events is expected to be flat, leaving unexplained why, in the observed three events, this mass is found to be less than about 10 GeV.

The search for the intermediate vector boson Z has produced [1–3] on the side of ten $Z \to e^+e^-$ and one $Z \to \mu^+\mu^-$ events, three further events which have been interpreted [1,2] as $Z \to e^+e^-\gamma$ (2 events) and [3] $Z \to \mu^+\mu^-\gamma$ (1 event).

The probability that these events arise from internal bremsstrahlung has been evaluated to be very small [1–3]. One would expect only about 3 such events over 500 "normal" $Z \to \ell^+\ell^-$ events. Although the possibility of a statistical fluctuation cannot be excluded at present, it is interesting to explore the possibility that $\ell^+\ell^-\gamma$ events arise from an entirely new physical phenomenon.

The unique mechanism which could lead to a large rate of events of this kind is the existence of heavy leptons which decay into the presently known light leptons via photon emission, therefore behaving as excited electrons or muons. As an example, $e^+e^-\gamma$ events could arise from:

$$\begin{array}{l} Z \to E^{\pm}e^{\mp} \\ \qquad \hookrightarrow e^{\pm}\gamma\,. \end{array} \tag{1}$$

The branching ratio for the second step being essentially 1, one would have:

$$\Gamma(Z \to e^+e^-\gamma)/\Gamma(Z \to e^+e^-)$$
$$= 2\Gamma(Z \to E^-e^+)/\Gamma(Z \to e^+e^-)\,. \tag{2}$$

As we shall see in the subsequent analysis the latter ratio can easily be substantial.

The characteristics of the observed anomalous events[‡1] can fit the hypothesis of process (1) if the mass of the new leptons is either relatively small

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[‡1] The values of the high mass solutions for $e^+e^-\gamma$ events are: 89 ± 2.5 GeV for the UA1 event [3]; 74 GeV for the UA2 event (the mass value is here computed from the data of ref. [2]). For the $\mu^+\mu^-\gamma$ event, the mass is 59 GeV (private communication from the UA1 Collaboration).

($\lesssim$10 GeV) or very large ($\gtrsim$70 GeV). The first possibility is most likely excluded by the lack of observation of excited electrons at present e^+e^- facilities.

We will therefore adopt the second possibility which, as we shall see, is also compatible with recent unsuccessful searches of excited electron signal in the $e^+e^- \to \gamma\gamma$ cross section [4] and with the possible anomalies in the muon $(g-2)$.

In this paper we shall first explore the excited lepton hypothesis from a purely theoretical point of view, and then we shall analyse its phenomenological implications with respect to further decay modes of the Z and of the W.

The natural framework for the existence of such states is that where leptons (and most likely quarks) are composite states of more fundamental objects (preons) bound by yet unobserved strong forces.

The lightness of the observed leptons could be naturally related to the existence of a global, unbroken, chiral symmetry which would produce massless bound fermions in the absence of weak perturbations due to the SU(2) × U(1) gauge and Higgs interactions [5]. In this picture, the large mass of the new leptons arses from the underlying dynamics and not from the Higgs mechanism. Thus we expect the new leptons to be coupled to SU(2) × U(1) in a vector like fashion and, more generally, we expect their mass matrix to be essentially SU(2) × U(1) invariant and flavour diagonal, when Higgs breaking is neglected.

These considerations identify the possible couplings of the excited leptons to the corresponding massless ones to be of the anomalous magnetic moment type, both for the photon and for W and Z. The explicit form depends upon the spin and SU(2) × U(1) quantum numbers of the excited leptons: in the present paper we restrict ourselves to the spin = 1/2 hypothesis, and consider all possible assignments for the weak I-spin, namely 0, 1/2, 1, 3/2. Higher I-spin values would forbid the transition $E \to e + Z$ or $E \to e + \gamma$, to leading order.

A potential problem when vector like, spin 1/2 leptons are put together with the usual lefthanded doublet–righthanded singlet leptons, is that of flavour changing neutral currents [6], which may arise after diagonalization of the full mass matrix.

We note however that if the Higgs coupling induces in the mass matrix non diagonal terms of order m connecting a light with a heavy lepton, a mixing of order m/M is produced between light and heavy leptons, and mixing of order $(m/M)^2$ is produced between light leptons of different flavours, M being the mass scale of the heavy leptons. The latter mixing gives rise to flavour changing neutral current processes which are suppressed in rate by a factor of order $(m/M)^4$ with respect to normal weak interactions. This suppression is sufficient to comply with the present experimental limits, provided that m is not greater than, say, the τ-mass.

The flavour changing neutral current problem is of course not present for spin higher than 1/2 or for weak isospin greater than 1, where a doublet of Higgs fields is unable to couple old with new leptons.

We now proceed to discuss the phenomenological implications of a heavy excited lepton in W and Z decays, considering first the weak I-spin 1/2 assignment and restricting to the electron case. Let us denote by ℓ_L the conventional doublet:

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \tag{3}$$

and by L the excited doublet:

$$L = \begin{pmatrix} E_0 \\ E \end{pmatrix}. \tag{4}$$

The relevant interactions can be written in terms of two independent coupling constants, f and f' (expected to be of order unity) according to:

$$\mathcal{L} = (gf/M)(\bar{L}\sigma_{\mu\nu}q^\nu \tfrac{1}{2}\boldsymbol{\tau}\ell_L + \text{h.c.})W^\mu$$
$$+ (g'f'/M)(-\tfrac{1}{2}\bar{L}\sigma_{\mu\nu}q^\nu\ell_L + \text{h.c.})B^\mu, \tag{5}$$

g and g' are the usual SU(2) and U(1) coupling constants, M the heavy lepton mass and we have inserted for convenience the usual hypercharge factor of −1/2 in the U(1) current.

Eqs. (1) and (5) lead to the result:

$$r = \Gamma(Z \to e^+e^-\gamma)/\Gamma(Z \to e^+e^-)$$
$$= (fc^2 - f's^2)^2(2 + M_Z^2/M^2)(1 - M^2/M_Z^2)^2$$
$$\times (1 - 4s^2 + 8s^4)^{-1}, \tag{6}$$

where $s^2 = 1 - c^2 = \sin^2\theta_W \simeq 0.22$. Using for definiteness:

$$M_Z = 92\,\text{GeV}, \quad M_W = 81\,\text{GeV}, \quad M = 75\,\text{GeV}, \tag{7}$$

we obtain:

$$r \simeq 0.78(fc^2 - f's^2)^2 \, . \tag{8}$$

As expected, the excited lepton hypothesis can easily account for a large value of r. For example $r = 0.2$ would correspond to:

$$|fc^2 - f's^2| = 0.5 \, . \tag{9}$$

Eq. (5) can also be used to compute the rate for the related processes:

$$\mathrm{Z} \to \bar{\mathrm{E}}_0 \nu \quad \text{or} \quad \bar{\nu}\mathrm{E}_0 \to \nu\bar{\nu}\gamma \, , \tag{10}$$

$$\mathrm{W}^+ \to \bar{\mathrm{E}}\nu \quad \text{or} \quad \mathrm{e}^+\mathrm{E}_0 \to \mathrm{e}^+\nu\gamma \, . \tag{11}$$

We find:

$$\begin{aligned} r_\nu^0 &= \Gamma(\mathrm{Z} \to \nu\bar{\nu}\gamma)/\Gamma(\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-) \\ &= r\,[(fc^2 + f's^2)/(fc^2 - f's^2)]^2 \, , \end{aligned} \tag{12}$$

$$\begin{aligned} r^+ &= \Gamma(\mathrm{W}^+ \to \mathrm{e}^+\nu\gamma)/\Gamma(\mathrm{W}^+ \to \mathrm{e}^+\nu) \\ &= \rho(r/c^4)\,[fc^2/(fc^2 - f's^2)]^2 \, , \end{aligned} \tag{13}$$

with r given by eq. (6), ρ being a factor which takes into account the ratio of phase spaces and the ratio of $\Gamma(\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-)$ to $\Gamma(\mathrm{W} \to \mathrm{e}^+\nu)$:

$$\begin{aligned} \rho = {} & [(M_\mathrm{W}^2 + 2M^2)/(M_\mathrm{Z}^2 + 2M^2)] \\ & \times [(M_\mathrm{W}^2 - M^2)/(M_\mathrm{Z}^2 - M^2)]^2 \\ & \times (M_\mathrm{Z}/M_\mathrm{W})^4 (1 - 4s^2 + 8s^4)^{-1} \simeq 0.08 \, . \end{aligned} \tag{14}$$

This numerical value corresponds to the masses given in eq. (7). According to our earlier discussion, the excited leptons E and E_0 have been assumed to be mass degenerate.

Unlike the other I-spin assignments we discuss below, the $I = 1/2$ case does not lead to a unique ratio between the $\mathrm{e}^+\mathrm{e}^-\gamma$ rate and the other available channels. Eqs. (6), (12) and (13) give however the interesting bounds on r^+:

$$\frac{\rho}{4c^4}\left(\sqrt{r} - \sqrt{r_\nu^0}\right)^2 \leqslant r^+ \leqslant \frac{\rho}{4c^4}\left(\sqrt{r} + \sqrt{r_\nu^0}\right)^2 \, . \tag{15}$$

Assuming $r_c^0 < r$ (no single γ event, corresponding to process (10) has thus far been announced by the experimental groups who have observed the $\mathrm{e}^+\mathrm{e}^-\gamma$ events) one obtains:

$$r^+ < (\rho/c^4) r \simeq 0.026 \, , \tag{16}$$

which is considerably more stringent than the limit on the rate for process (11) given in ref. [3].

A further limitation on the couplings f and f' arises from the non observation of anomalies in the process $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$. An excited electron exchange in the t-channel would give an anomalous contribution to the QED cross section, whose size depends upon the combination:

$$\Lambda^2 = 2\sqrt{2}M^2/|f + f'] \, . \tag{17}$$

The present data imply [4] $\Lambda \leqslant 60$ GeV, i.e.

$$|f + f'| \leqslant 4.2 \, . \tag{18}$$

This bound can be transformed into a bound for r_ν^0:

$$\begin{aligned} r_\nu^0 \leqslant {} & [\sqrt{r}(c^2 - s^2) + (\sqrt{r}/|fc^2 - f's^2|) \\ & \times 2c^2s^2|f + f'|]^2 \simeq 2.3 \, . \end{aligned} \tag{19}$$

The bound in eq. (19) is not very informative, but it shows the compatibility of the present discussion with the $\mathrm{e}^+\mathrm{e}^- \to \gamma\gamma$ data.

A more stringent limitation is obtained in the case of the excited muon, by comparison with the allowed deviations from pure QED prediction for $(g - 2)$. The purely electromagnetic contribution arising from the exchange of an excited muon coupled to the photon as in eq. (5) has been computed in ref. [7]. In our notation:

$$\delta(g - 2) = (9\alpha/16\pi)(f + f')^2(m_\mu/M)^2 \, . \tag{20}$$

The m_μ^2 dependence arises from the need of chiral symmetry breaking in the muon sector, which follows from the V–A coupling in eq. (5). The corresponding effect for the electron is completely negligible. From eq. (20) we find, in the muon case:

$$|f + f'| < 1.4 \, , \tag{21}$$

for $M = 60$ GeV and: $\delta(g - 2)_\mathrm{exp} = 0.85 \times 10^{-8}$, according to ref. [8]. Assuming a similar rate for $\mu^+\mu^-\gamma$ as for $\mathrm{e}^+\mathrm{e}^-\gamma$, we obtain from (21) the bound:

$$\Gamma(\mathrm{Z} \to \nu_\mu\bar{\nu}_\mu\gamma)/\Gamma(\mathrm{Z} \to \mu^+\mu^-) < 0.45 \, . \tag{22}$$

The bounds (21) and (22) are only qualitative due to the lack of a complete calculation of the $(g - 2)$ induced by the excited lepton in the full electroweak theory.

The above considerations can immediately be extended to the other possible I-spin assignments. In all cases, given the I-spin, the U(1) hypercharge of the excited lepton is uniquely determined by requiring that process (1) is indeed allowed. The resulting electric charge structure of the multiplets is as follows:

$$
\begin{array}{llll}
I=0 & \mathrm{E}^- \leftrightarrow \mathrm{e}_\mathrm{R} & \text{singlet}\,, & \\
I=1 & \begin{bmatrix} \mathrm{E}^0 \\ \mathrm{E}^- \\ \mathrm{E}^{--} \end{bmatrix} \leftrightarrow \mathrm{e}_\mathrm{R} & \text{triplet}\,, & (23) \\
I=3/2 & \begin{bmatrix} \mathrm{E}^+ \\ \mathrm{E}^0 \\ \mathrm{E}^- \\ \mathrm{E}^{--} \end{bmatrix} \leftrightarrow \ell_\mathrm{L} & \text{triplet}\,. &
\end{array}
$$

We have indicated the light lepton multiplet to which the heavy lepton is coupled and the SU(2) behaviour of the corresponding transition. For $I \geqslant 1$ doubly charged leptons appear, which undergo β-decay according to the scheme:

$$\mathrm{E}^{--} \to \mathrm{e}^- \mathrm{f}_\mathrm{d} \bar{\mathrm{f}}_\mathrm{u}\,, \tag{24}$$

where e.g. f_d denotes any down-like light fermion (e, μ, ..., d, s...). β-decay is also implied for E^+ ($I = 3/2$) and for E^0 ($I = 1$):

$$\mathrm{E}^+ \to \nu \mathrm{f}_\mathrm{u} \bar{\mathrm{f}}_\mathrm{d}\,, \tag{25}$$

$$\mathrm{E}^0(I=1) \to \mathrm{e}^- \mathrm{f}_\mathrm{u} \bar{\mathrm{f}}_\mathrm{d}\,, \tag{26}$$

while the neutral lepton E^0 ($I = 3/2$) is allowed to decay into $\nu + \gamma$, similarly to the $I = 1/2$ case. The necessity of exotic excited leptons for $I \geqslant 1$ leads to the appearance of the further decay channels:

$$\mathrm{W}^+ \to \mathrm{e}^+\mathrm{e}^- \mathrm{f}_\mathrm{u} \bar{\mathrm{f}}_\mathrm{d}\,, \tag{27}$$

$$\mathrm{W}^+ \to \nu\bar{\nu} \mathrm{f}_\mathrm{u} \bar{\mathrm{f}}_\mathrm{d}\,. \tag{28}$$

In any case, only one coupling is allowed by the SU(2) X U(1) symmetry. The rates for the various processes can be given in terms of the $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-\gamma$ rate and the ratio ρ defined in eq. (14). Results are reported in table 1. The quantity $B_{\mathrm{f}\bar{\mathrm{f}}}$ is the branching ratio of each particular $\mathrm{f}\bar{\mathrm{f}}$ channel in the β-decays eqs. (24)–(26). $B_{\mathrm{f}\bar{\mathrm{f}}}$ is given by standard counting of the degrees of freedom. For example the final state $\mathrm{e}^+\mathrm{e}^-\mu^+\nu_\mu$ in W^+ decay has:

$$B_{\nu\mu^+} = \tfrac{1}{12}\,,$$

for three generations of massless fermions.

The single γ channel, corresponding to process (10), seems to be most promising for a first discrimination of the different possibilities. A non vanishing r_ν^0 would exclude the possibility of internal bremsstrahlung and $I = 0, 1$, at the same time. A value $r_\nu^0 \neq r$ would indicate $I = 1/2$ uniquely. W^+ modes are more spectacular, although suppressed by the common factor $\rho \simeq 0.1$.

Table 1
Relative rates of Z and W into $\ell\bar{\ell}\gamma$ and $\ell\bar{\ell}\,\mathrm{f}\bar{\mathrm{f}}$ channels. $c^2 = \cos^2\theta_\mathrm{W} = 1 - s^2$; f, f' and $\rho \simeq 0.1$ are defined in text, eqs. (5) and (14). $B_{\mathrm{f}\bar{\mathrm{f}}}$ is the branching ratio for the virtual W in the β-decay eqs. (24)–(26) to produce a charged $\mathrm{f}\bar{\mathrm{f}}$ pair. $B_{\mathrm{f}\bar{\mathrm{f}}} = \frac{1}{12}$ ($\frac{1}{4}$) for a $\nu\mathrm{e}^+$ ($\frac{1}{4}$) ($\mathrm{u}\bar{\mathrm{d}}$) pair and for three massless generations.

I	$\frac{\Gamma(\mathrm{Z}\to\mathrm{e}^+\mathrm{e}^-\gamma)}{\Gamma(\mathrm{Z}\to\mathrm{e}^+\mathrm{e}^-)}$	$\frac{\Gamma(\mathrm{Z}\to\nu_\mathrm{e}\bar{\nu}_\mathrm{e}\gamma)}{\Gamma(\mathrm{Z}\to\mathrm{e}^+\mathrm{e}^-)}$	$\frac{\Gamma(\mathrm{W}^+\to\mathrm{e}^+\nu_\mathrm{e}\gamma)}{\Gamma(\mathrm{W}^+\to\mathrm{e}^+\nu)}$	$\frac{\Gamma(\mathrm{W}^+\to\mathrm{e}^+\mathrm{e}^-(\mathrm{f}\bar{\mathrm{f}})^+)}{\Gamma(\mathrm{W}^+\to\mathrm{e}^+\nu)}$	$\frac{\Gamma(\mathrm{W}^+\to\nu_\mathrm{e}\bar{\nu}_\mathrm{c}(\mathrm{f}\bar{\mathrm{f}})^+)}{\Gamma(\mathrm{W}^+\to\mathrm{e}^+\nu)}$
0	r	0	0	0	0
1/2	r	$r\left(\frac{fc^2+f's^2}{fc^2-f's^2}\right)^2$	$\rho r\left(\frac{f}{fc^2-f's^2}\right)^2$	0	0
1	r	0	0	$\frac{\rho r}{c^2} B_{\mathrm{f}\bar{\mathrm{f}}}$	0
3/2	r	r	$\frac{\rho}{2c^2} r$	$\frac{3}{4}\frac{\rho r}{c^2} B_{\mathrm{f}\bar{\mathrm{f}}}$	$\frac{3}{4}\frac{\rho r}{c^2} B_{\mathrm{f}\bar{\mathrm{f}}}$

Finally, we consider the kinematic features of the $e^+e^-\gamma$ events. Of course, the invariant mass of one of the two lepton-pairs must fall at a definite value, M, in all events. There is only one undetermined kinematical quantity, namely the mass of the other lepton–γ pair, which we call μ.

The normalized distribution of μ^2 is the same for all spin 1/2 cases considered here and it is computed to be:

$$\mathrm{d}P/\mathrm{d}\mu^2 = [2M_Z^4/(M_Z^2 - M^2)^2(M_Z^2 + 2M^2)]$$
$$\times\,[(1 - M^2/M_Z^2) + (2M^2/M_Z^2 - 1)\,\mu^2/M_Z^2]\,, \quad (29)$$
$$0 \leqslant \mu^2 \leqslant M_Z^2 - M^2\,,$$

for M given in eq. (7).

The distribution in μ^2 is essentially flat [‡2]. The anomalous events so far observed are characterized by a rather small value of μ^2 [$\mu^2 < (10\ \mathrm{GeV})^2$]. In view of the limited statistics available at present, it is premature to attach much significance to this feature. It is possible that a higher spin value for the excited lepton provides a sharper distribution.

Summing up, we have seen that the excited lepton hypothesis can explain in a natural way the anomalous $e^+e^-\gamma$ events, being compatible with the present lack of observation of related signals in W decay and in the $e^+e^- \to \gamma\gamma$ cross section. The hypothesis does not explain the small value of μ^2 found in both events: we must assume here a statistical fluctuation. Similar considerations apply to the $\mu^+\mu^-\gamma$ event.

We have restricted to spin 1/2 excited leptons, however the results in table 1 are general; a higher spin may attenuate the small μ^2 problem.

An excited lepton could easily be accomodated within the present theoretical framework if indeed electrons and muons (and quarks) are composite objects. The mass value indicated by the data is however considerably smaller than current theoretical estimates of a compositeness mass scale. There may be a possible conflict with the order of magnitude lower bound on the electron compositeness radius found in ref. [9] to be about $(750\ \mathrm{GeV})^{-1}$. In view of the lack of understanding of preon dynamics, this need not be a serious argument against our interpretation.

A real answer to this issue will arise only from further experimental data.

[‡2] The distribution in eq. (29) is computed for unpolarized Z and with no kinematical cuts. The bulk of Z produced in $p\bar{p}$ collisions has in fact $J_Z = \pm 1$ along the beam axis. This feature, together with the cuts applied on the electron and photon $p_\perp$ could, in principle, modify the distribution of the observed events. By a numerical analysis we have verified that cuts similar to those imposed by the UA1 collaboration do not alter significantly the distribution given in (29). We thank Dr. S. Petrarca for help in this calculation, and Professor G. Salvini for useful information.

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