Ref.TH.3030-CERN

SEARCH FOR LIGHT TECHNIMESONS

John Ellis, D.V. Nanopoulos

and

P. Sikivie

CERN--Geneva

ABSTRACT

The light neutral colour-singlet spin-zero bosons P^0 and P^3 expected in contemporary extended technicolour theories have some small induced flavour-changing couplings, even in monophagic theories where their couplings are mainly flavour-diagonal. Their non-observation in K^+ decay means that $m_{P^{0,3}} \geq 350$ MeV, leading one to expect direct quark-lepton transitions mediating $K_L^0 \rightarrow \mu e$ decay close to the present experimental upper limit. In the absence of some as yet unknown suppression mechanisms, either P^0 and P^3 should be observed in bottom decays with a branching ratio approaching 100% (which may already be experimentally excluded) and/or they should be observed in charm decays with branching ratios $\geq 1\%$ and/or the decay $K_L^0 \rightarrow \mu e$ should be detected within an order of magnitude of the present upper limit.

Ref.TH.3030-CERN

18 February 1981

One of the most interesting predictions of extended technicolour (ETC) theories¹⁾ is the existence of many spin zero bosons with masses $\lesssim 300 \text{ GeV}$ ²⁾. In the most explicit²⁾ existing ETC theories, the lightest of these are expected to be a pair of electrically and colour neutral bosons P^0 and P^3 which do not acquire masses from the strong, weak or electromagnetic interactions. Since other sources such as ETC interactions are not expected to push their masses above 100 GeV, it seems that in such theories the dominant couplings of the P^0 and P^3 to fermions must be flavour-diagonal in order to suppress flavour-changing neutral interactions. This can be achieved naturally in monophagic theories³⁾, i.e., theories in which all technicolour singlet fermions f of a given charge get their masses from the same technifermion condensate $\langle 0 | \bar{f}f | 0 \rangle \neq 0$. In such theories the P^0 and P^3 do not even acquire masses from ETC interactions⁴⁾ and it has been proposed⁵⁾ that their masses are generated by direct quark-lepton interactions of the Pati-Salam type. It has been estimated⁵⁾ from the upper limit⁶⁾ on $K_L^0 \rightarrow \mu e$ decay that the masses m_{PS} of the direct quark-lepton gauge bosons must be $\gtrsim 310 \text{ TeV}$. Since $m_{P^{0,3}} \sim m_{PS}^{-1}$, it then follows that $m_{P^{0,3}} \lesssim 3 \text{ GeV}$ or so.

Bosons as light as this will give problems⁷⁾ with flavour-changing neutral interactions unless their couplings are flavour-diagonal to a very good approximation as in monophagic theories. But even in these theories there are small flavour-changing couplings induced either by radiative corrections or else by four-fermion ETC-induced effective interactions⁸⁾ of the type

$$(\bar{f}_{L,R} \delta_m f_{L,R}) (\bar{F}_{L,R} \delta^* F_{L,R}) \quad (1)$$

The interactions (1) are distinct from those giving masses to the technicolour singlet fermions and cannot in general be flavour diagonalized simultaneously. They induce scalar and/or pseudoscalar couplings of $P^{0,3}$ which are generically of order $g^2 m_F^2 / m_W^2$ where g is the weak $SU(2)$ gauge coupling constant. In the models proposed so far, flavour-changing interactions of this magnitude must show up either for charge $2/3$ quarks and/or for charge $-1/3$ quarks. Although the present models are not completely realistic, such flavour-changing interactions may well exist in a wider class of theories embracing the real world.

In this paper we investigate the phenomenological consequences of these couplings. After a more careful estimate of their order of magnitude, we first show that they do not give problems for the $K_1 - K_2$ and $D_1 - D_2$ mass differences as long as $m_{P^{0,3}} \gtrsim O(500, 100) \text{ MeV}$ respectively. They then give no problems for the experimental upper limits on other flavour-changing neutral interactions either.

We find that if the decays $K^+ \rightarrow \pi^+ P^{0,3}$ were kinematically accessible, their branching ratios would be so large^{*)} that necessarily

$$m_{P^{0,3}} \geq m_K - m_\pi \approx 350 \text{ MeV} \quad (2)$$

This limit already implies in the simplest ETC theories that the masses m_{PS} of the direct quark-lepton gauge bosons must be $\leq 2600 \text{ TeV}$, in which case the decay $K^0 \rightarrow \mu e$ should occur at a level within 10^{-3} or 10^{-4} of the present experimental limit^{**)} . A flavour-changing $b-s$ coupling induced by (1) would cause $B \rightarrow P^{0,3} + K + X$ to dominate bottom decays. A recent experimental upper limit¹⁰⁾ on $B \rightarrow \mu^+ \mu^- + X$ probably excludes this possibility, in which case (1) should induce a flavour-changing $c-u$ coupling yielding a branching ratio

$$B(D \rightarrow P^{0,3} + \text{pions}) \approx 1\% \quad (3)$$

Absence of such decays at the level (3) would mean that the decay could not be kinematically accessible, so that $m_{P^{0,3}} \geq 1700 \text{ MeV}$. This would reduce the inferred masses of the PS bosons so much that they would mediate $K_L^0 \rightarrow \mu e$ within one order of magnitude of the present upper limit⁶⁾. Thus a combination of K, D and B decays can provide searching tests of ETC theories.

We now turn to a more detailed discussion of the couplings to fermions of the P^0 and P^3 . We recall that in general monophagic theories³⁾ the ETC gauge bosons A couple to currents of the form

$$J_\mu^A = \sum_{f,n} \left(\bar{f}_{Ln} g_{Ln}^A(f) \gamma_\mu F_L(f) + \bar{f}_{Rn} g_{Rn}^A(f) \gamma_\mu F_R(f) \right) + (\text{herm. conj.}) \quad (4)$$

where f denotes a type of fermion ($u, \dots, d, \dots, e, \dots, \nu_e, \dots$), n is a generation index and $F(f)$ denotes the unique technifermion responsible for the masses of the ordinary fermions of type f . The exchanges of ETC gauge bosons yield an effective Lagrangian containing terms^{***)} such as

*) Even if the tree-level couplings are flavour-diagonal and the decay is induced by radiative corrections⁹⁾.

**) We note in passing that there are other ETC contributions^{3),5),7)} to $K_L^0 \rightarrow \mu e$ decay from the exchanges of leptoquark pseudoscalars and of horizontal ETC bosons, both of which are also expected to give decay rates close to the experimental upper limit.

***) Together with other terms which do not contribute to the effective couplings of the PGBs appearing when technicolour is complex.

$$-\sum_A \frac{g_A^2}{2M_A^2} J_A^\mu J_A^\mu \quad \Rightarrow \quad -\sum_{f,f'} \sum_{nm} \sum_A \frac{g_A^2}{M_A^2} \times$$

$$\times \left\{ (\bar{f}_{Ln} g_{Ln}^A(f) \gamma_\mu F_L) (\bar{f}'_{Ln} g_{Ln}^{A*}(f') \gamma^\mu f'_{Ln}) + (L \leftrightarrow R) \right. \\ \left. + (\bar{f}_{Ln} g_{Ln}^A(f) \gamma_\mu F_L) (\bar{f}'_{Rm} g_{Rm}^{A*}(f') \gamma^\mu f'_{Rm}) + (\text{herm. conj.}) \right. \\ \left. + \dots \right\} \quad (5)$$

In our previous paper³⁾ only the last term in Eq. (5) was considered: when Fierz transformed it yields

$$-2 \sum_{f,f'} (\bar{f}'_R F_L) \left(\sum_{nm} \bar{f}_{Ln} (\Gamma_{LR}^{ff'})_{nm} f'_{Rm} \right) + (\text{herm. conj.}) \quad (6)$$

where

$$(\Gamma_{LR}^{ff'})_{nm} \equiv \sum_A \frac{g_A^2}{M_A^2} g_{Ln}^A(f) g_{Rm}^{A*}(f') \quad (7)$$

The effective Lagrangian (6) yields the fermion mass matrices

$$m_f = \langle 0 | \bar{F} F | 0 \rangle \Gamma_{LR}^{ff} \quad (8)$$

where we estimate

$$\langle 0 | \bar{F} F | 0 \rangle \approx 0.024 \sqrt{\frac{3}{N_{TC}}} (\text{TeV})^3 \quad (9)$$

Because m_f and Γ_{LR}^{ff} are proportional to one another, the effective interaction (6) gives flavour-diagonal couplings of $P^0, 3$

$$g_{P^{0,3}}(f \gamma_\mu f) \sim \frac{m_f}{F_P} \quad (10)$$

where F_P is the technipseudoscalar decay constant

$$\langle 0 | \bar{F} \gamma_\mu \gamma_5 F | P_F(q) \rangle = i q_\mu \frac{F_P}{\sqrt{2}} \quad (11)$$

determined to be

$$F_P = \frac{2m_W}{g} = \sqrt{\frac{1}{2}} G_F^{-1/2} \approx 250 \text{ GeV} \quad (12)$$

There is a numerical coefficient of order $(\sqrt{3})^{\pm 1}$ in (10) which depends on the specific³⁾ monophagic model chosen. The (as we shall see) approximate flavour diagonalization of the P^0 and P^3 couplings to ordinary fermions is essential if the flavour-changing neutral interactions they mediate are to be kept below the experimentally acceptable limits^{3), 7)}.

In the above analysis of Eq. (5) we ignored⁸⁾ the first term on the right-hand side, which gives new small $O(g^2 m_f^2 / m_W^2)$ contributions of the PGBs. It can be Fierz transformed into

$$\sum_{f, f'} (\bar{F}'_L \delta_\mu F_L) \sum_{n, m} (\bar{f}_{Ln} (\Gamma_{LL}^{ff'})_{nm} \delta^\mu f'_{Lm}) + (L \leftrightarrow R) \quad (13)$$

where

$$(\Gamma_{LL}^{ff'})_{nm} \equiv \sum_A \frac{1}{\mu_A^2} g_{Ln}^A(f) g_{Lm}^{A*}(f') \quad (14)$$

and similarly for $(\Gamma_{RR}^{ff'})_{nm}$. Using the PCAC expression (11) we find induced scalar and pseudoscalar couplings

$$P_{F'F} \left(\frac{F_P}{\sqrt{2}} \right) q^\mu \left[\bar{f} \delta_\mu \left(\Gamma_{RR}^{ff'} \frac{1+\gamma_5}{2} - \Gamma_{LL}^{ff'} \frac{1-\gamma_5}{2} \right) f' \right] \frac{1}{2} \quad (15)$$

which can be rewritten as

$$\frac{1}{4} \left(\frac{F_P}{\sqrt{2}} \right) P_{F'F} \bar{f} \left\{ m_f \left[\Gamma_{RR}^{ff'} (1+\gamma_5) - \Gamma_{LL}^{ff'} (1-\gamma_5) \right] \right. \\ \left. - \left[\Gamma_{RR}^{ff'} (1-\gamma_5) - \Gamma_{LL}^{ff'} (1+\gamma_5) \right] m_{f'} \right\} f' \quad (16)$$

These induced couplings (16) were not discussed in our previous treatment³⁾ of monophagic theories. Diagonalization of the mass matrix Γ_{LR}^{ff} (7) does not in general entail the diagonalization of Γ_{LL}^{ff} and Γ_{RR}^{ff} . In fact, because of SU(2) weak invariance, the Γ_{LL}^{ff} are identical for the charge 2/3 and charge -1/3 quarks. Then they would be simultaneously diagonalizable only if either they and/or the generalized Cabibbo matrix U_{KM} were trivial. Thus there must be flavour-changing couplings of P^0 and P^3 either for charge 2/3 quarks and/or for charge -1/3 quarks of the type (16), and the rest of this paper is devoted to an analysis of their phenomenological consequences.

The precise values of these couplings are not determined by monophagy alone, but one may use a specific model to motivate "reasonable" guesses as to their orders of magnitude. We have a toy model¹¹⁾ in which $SU(N)_{ETC}$ is broken down to $O(N-2)_{TC}$, providing two generations of charge 2/3 and charge -1/3 quarks with different mass matrices and non-trivial Cabibbo angles. In this model we find induced scalar couplings of the P^0 and P^3 which are diagonal

$$\frac{F_P}{\sqrt{2}} \frac{m_u^2, m_c^2}{\langle 0 | F F | 0 \rangle} \quad (17a)$$

for the charge $2/3$ quarks, but have a non-diagonal $\bar{s}\gamma_5 d$ component:

$$\frac{F_P}{\sqrt{2}} \frac{m_s m_c \sin \theta_c \cos \theta_c}{\langle 0 | \bar{F} F | 0 \rangle} \approx \frac{G_F}{\sqrt{2}} m_s m_c \sin \theta_c \cos \theta_c \quad (17b)$$

where we approximated $\langle 0 | \bar{F} F | 0 \rangle \approx F_P^3$ and used Eq. (12). We therefore estimate that in general there are off-diagonal neutral couplings either for charge $+2/3$ and/or for charge $-1/3$ quarks of the order of magnitude

$$O\left(\frac{m_{2/3} m_{-1/3} \sin \theta_c}{F_P^2}\right) \approx \frac{G_F}{\sqrt{2}} m_{2/3} m_{-1/3} \sin \theta_c \quad (18)$$

where we put in the masses of appropriate $SU(2)_L$ "partner" quarks (e.g., u and d , c and s , t and b) and $\sin \theta_c$ is an estimate of a generalized Cabibbo angle. Even if tree couplings of the general form (18) are absent for either charge $+2/3$ or charge $-1/3$ quarks, radiative corrections⁹⁾ analogous to those in a model with monophagic fundamental Higgs doublets will generate off-diagonal $(1-\gamma_5)$ couplings of order

$$\frac{(\sqrt{2} G_F)^{3/2}}{8\pi^2} \left(m_{-1/3}^2 m_{2/3}^2 \text{ or } m_{2/3}^2 m_{-1/3}^2\right) \sin \theta_c \ln \left(\frac{m_w^2}{m_f^2}\right) \quad (19)$$

These couplings are considerably smaller than the induced tree-level couplings (18), but may be of phenomenological relevance if (18) is absent either for $+2/3$ or for $-1/3$ charge quarks. A summary of the implications of the off-diagonal couplings (18) and (19) is set out in the Table which we now discuss in detail.

To be compatible with the known $K_1 - K_2$ mass difference, if the estimate (18) applies to the neutral off-diagonal $(\bar{s}d)$ coupling then we need

$$\frac{1}{m_{P^0}^2} \left(\frac{G_F}{\sqrt{2}}\right)^2 m_s^2 m_c^2 \sin^2 \theta_c \lesssim \frac{1}{2} \times 10^{-12} \text{ GeV}^{-2} \quad (20)$$

and hence, taking $m_s \approx 150 \text{ MeV}$, $m_c \approx 1.5 \text{ GeV}$

$$m_{P^0,3} \gtrsim O(500) \text{ MeV} \quad (21)$$

A similar analysis of the $D_1 - D_2$ system yields a less severe constraint $m_{P^0,3} \gtrsim O(100) \text{ MeV}$ if the estimate (18) applies to the off-diagonal $(\bar{c}u)$ coupling. These constraints on the P^0 and P^3 masses are set out in the first rows of the Table. No interesting constraints emerge if the dominant flavour-changing $(\bar{s}d)$ or $(\bar{c}u)$ couplings are of type (19), and experimental limits on other flavour-changing processes do not improve these limits on the P^0 and P^3 masses.

Another limit on their masses comes from $K^\pm$ decay. If the estimate (18) is relevant to the $(\bar{s}d)$ transition we find that if the decay $K^+ \rightarrow \pi^+ P^{0,3}$ is kinematically accessible

$$\frac{\Gamma(K^+ \rightarrow \pi^+ P^{0,3})}{\Gamma(K^+ \rightarrow \pi^+ \pi^0)} \gtrsim O(1) \quad (22)$$

in which case we would conclude that $m_{P^{0,3}} \gtrsim 350$ MeV. However, it may be that the estimate (18) only applies to the charge $+2/3$ quarks, or that the coupling of form (18) happens to be purely pseudoscalar. In either case, the radiative correction coupling⁹⁾ (19) would give

$$\frac{\Gamma(K^+ \rightarrow \pi^+ P^{0,3})}{\Gamma(K^+ \rightarrow \pi^+ \pi^0)} = O(10^{-5}) \quad (23)$$

and we again reach the conclusion (2). This seems to be the best limit one can reliably extract from considering the interactions of kaons and is displayed in the third row of the Table.

One can extend similar considerations to D and B decays. Using the estimate (18) for the $(\bar{c}u)$ transition we find

$$\Gamma(c \rightarrow u P^{0,3}) \approx \frac{G_F^2 m_c^3 m_s^2 \sin^2 \theta_c}{16\pi} \quad (24)$$

so that if we estimate

$$\Gamma(c \rightarrow \text{all}) \approx 5 \frac{G_F^2 m_c^5}{192\pi^3} \quad (25)$$

and take $m_s \sim 150$ MeV, $m_c \sim 1.5$ GeV we get

$$\frac{\Gamma(D \rightarrow P^{0,3} + \text{pions})}{\Gamma(D \rightarrow \text{all})} \approx 16 \quad (26)$$

The branching ratio for $D \rightarrow P^{0,3} + \text{pions}$ would therefore be large if $m_{P^{0,3}} \lesssim m_D - m_\pi \approx 1700$ MeV, particularly in the case of $D^\pm$ decays since the $D^\pm$ lifetime seems to be several times longer than those of the D^0 and $\bar{D}^0$. The P^0 and P^3 are expected to decay predominantly as pseudoscalars, with strong isospins mainly 0 and 1 respectively. Therefore, depending on their masses, decay modes such as 4π , $\eta\pi\pi$, $K\bar{K}\pi$ and 3π , $K\bar{K}\pi$ might dominate their respective hadronic decay modes. One also expects the decays $P^{0,3} \rightarrow \mu^+ \mu^-$ to be present with branching ratios (calculating using $\alpha_s \approx 0.4$ for the $P^0 \rightarrow gg$ decay):

$$\frac{\Gamma(P^{0,3} \rightarrow \mu^+ \mu^-)}{\Gamma(P^{0,3} \rightarrow \text{hadrons})} \approx \begin{cases} \frac{\Gamma(P^0 \rightarrow \mu^+ \mu^-)}{\Gamma(P^0 \rightarrow s\bar{s}, u\bar{u}, d\bar{d} + gg)} \approx \frac{(3 \text{ or } \frac{1}{3}) m_\mu^2}{(1 \text{ or } 9)(m_s^2 + m_u^2 + m_d^2) + 0.1 m_{P^0}^2} \\ \frac{\Gamma(P^3 \rightarrow \mu^+ \mu^-)}{\Gamma(P^3 \rightarrow s\bar{s}, u\bar{u}, d\bar{d})} \approx \frac{(3 \text{ or } \frac{1}{3}) m_\mu^2}{(1 \text{ or } 9)(m_s^2 + m_u^2 + m_d^2)} \end{cases} \quad (27)$$

in the two monophagic models of Ref. 3). If D decays yield no unexpected bumps in any of these channels at the expected level, one would conclude either that $m_{P^{0,3}} \geq 1700$ MeV or that the estimate (18) applies not to charge $+2/3$ quarks but to charge $-1/3$ quarks. In this latter case a $(\bar{c}u)$ coupling of the type (19) gives a branching ratio for $D \rightarrow P^{0,3} + \text{pions}$ less than 10^{-10} , as shown in the third row of the Table. In fact, it seems to us likely that the estimate (18) and hence the branching ratio (26) should apply to the $(\bar{c}u)$ coupling. The reason is that (18) does not seem to apply to the $(\bar{b}s)$ coupling, suggesting that Eq. (18) must apply to the charge $+2/3$ quarks. Using (18) for the $(\bar{b}s)$ transition we would deduce

$$\frac{\Gamma(b \rightarrow s P^{0,3})}{\Gamma(b \rightarrow c f \bar{f})} \approx \frac{12\pi^2}{(5 \text{ to } 10)} \left(\frac{m_t^2}{m_b^2} \right) > 100 \quad (28)$$

The branching ratios (27) therefore lead us to expect

$$\frac{\Gamma(B \rightarrow \mu^+ \mu^- X)}{\Gamma(B \rightarrow \text{all})} \approx (2 \text{ to } 50) \% \quad (29)$$

A recent CESR experiment¹⁰⁾ has established an upper bound $BR(B \rightarrow \mu^+ \mu^- X) \leq 1.7\%$ which excludes our first (colourless ETC) monophagic model if $m_{P^{0,3}} \leq 4$ GeV as expected and creates concern for the second (coloured ETC) model. Improvements in the experimental upper limit on the branching ratio (29) are of course welcome, but we infer provisionally that the coupling (18) is absent for charge $-1/3$ quarks and therefore should show up for charge $2/3$ quarks with the implication (26) if $m_{P^{0,3}} \lesssim 1700$ MeV.

Obviously, ETC theories would derive considerable circumstantial support from any discovery of a light neutral pseudoscalar particle, although alternative origins are possible⁹⁾ for such objects. If none are found in D decay at the level (26), it would suggest in the theoretical framework discussed here that $m_{P^{0,3}} \geq 1700$ MeV. We recall that these masses are related to those of leptoquark gauge bosons PS:

$$\left. \begin{aligned} m_{P^0} &\approx \left(\frac{310 \text{ TeV}}{m_{PS}} \right) \times 1.7 \text{ GeV} \\ m_{P^3} &\approx \left(\frac{310 \text{ TeV}}{m_{PS}} \right) \times 1.5 \text{ GeV} \end{aligned} \right\} (\times 2^{0\pm 1}) \quad (30)$$

where we have used the estimate (9) with a guessed factor of $2^{\pm 1}$ error. We therefore have

$$R_{\mu e} \equiv \frac{\Gamma(K_L^0 \rightarrow \mu e)}{\Gamma(K^+ \rightarrow \mu^+ \nu)} \approx 6 \times 10^{-10} \left(\frac{m_{P^3}}{1.5 \text{ GeV}} \right)^4 (\times 16^{0\pm 1}) \quad (31)$$

and the lower bound (2) already implies $m_{PS} \geq 1300 \text{ TeV} (\times 2^{\pm 1})$ and hence

$$R_{\mu e} \geq 2 \times 10^{-12} (\times 16^{0\pm 1}) \quad (32)$$

A lower limit of 1700 MeV on $m_{P^{0,3}}$ would imply that $R_{\mu e}$ should be within one order of magnitude of the present experimental upper limit⁶⁾.

Non-observation of $B \rightarrow P^{0,3} + X$, $D \rightarrow P^{0,3} + X$, and $R_{\mu e}$ at the levels estimated in this paper would pose difficulties for the class of ETC theories discussed here. How general is this class? We have argued that ETC theories must be monophagic if they are to avoid more serious problems with flavour-changing neutral interactions^{3),7)}. Then ETC interactions do not contribute⁴⁾ to $m_{P^{0,3}}$ and the only known contributions are those⁵⁾ of the PS bosons of Eq. (30). We have then argued⁸⁾ that even in monophagic theories the P^0 and P^3 should have some flavour-changing interactions of the magnitude (18). Radical surgery would be needed to avoid the conclusion that either $P^{0,3}$ should show up in B decays with a probability $\approx 100\%$ (which may already be excluded¹⁰⁾) and/or they should appear in D decays with branching ratios $\approx 1\%$ and/or the decay $K_L^0 \rightarrow \mu e$ should occur within an order of magnitude of the present experimental upper limit.

ACKNOWLEDGEMENTS

We thank S. Dimopoulos, M.K. Gaillard, G. Giradi and M. Wise for useful and important discussions. We also thank other members of the ECFA/LEP exotic particles working group¹²⁾ for their interest and encouragement.

TABLE

Process	Implications if induced non-diagonal couplings of type (18) are only present for	
	charge $-1/3$ quarks	charge $2/3$ quarks
$K_1 - K_2$ mass difference	$m_{P^{0,3}} \geq O(500) \text{ MeV}$	—
$D_1 - D_2$ mass difference	—	$m_{P^{0,3}} \geq O(100) \text{ MeV}$
$K^\pm \rightarrow \pi^\pm P^{0,3}$ decay	$m_{P^{0,3}} \geq 350 \text{ MeV}$	$m_{P^{0,3}} \geq 350 \text{ MeV}$
$D \rightarrow P^{0,3} X$ decay	B ratio $\leq 10^{-10}$	B ratio $\sim 1\%$
$B \rightarrow P^{0,3} X$ decay	B ratio $\sim 100\%$	B ratio $\sim 0.1\%$

There must be induced non-diagonal couplings either for charge $-1/3$ and/or for charge $2/3$ quarks.

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