DO KAON DECAYS CONSTRAIN THE FIFTH FORCE?

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It is shown that all the gauge invariant models of the fifth force based on $SU(2)\times U(1)\times U'(1)$ group are consistent with the experimental data on charged kaon decays.

At present the standard $SU(3)\times SU(2)\times U(1)$ model is in good accord with all the existing data. However, a number of theoretical drawbacks of the model requires going beyond its framework, the low-energy gauge group often being larger than $SU(3)\times SU(2)\times U(1)$. The simplest and the most frequent case is the extension of the standard group by an additional $U(1)$ factor. For instance this possibility is realized in grand unified theories [1], supersymmetric [2] and superstring [3] theories. Recently, much interest has been given to the question of the possible existence of a new long-range interaction ("the fifth force") [4]. Can a new gauge X boson predicted by the $SU(3)\times SU(2)\times U(1)\times U'(1)$ model mediate the fifth force?

This question was discussed in refs. [5,6]. A number of constraints on the mass and coupling constant of a new $U(1)$ boson were obtained in ref. [7]. A rather strong constraint on the properties of light gauge bosons can be obtained from the analysis of the data on the decay $K^+\to\pi^+ + \text{nothing}$. Furthermore, a detailed investigation of this process is stimulated by the fact that at present BNL carries out a highly sensitive search for that process on the level of the branching ratio of order 10^{-10} [8]. Note that in the standard model the branching ratio for that process is of order 10^{-11} [9]. Consequently, the positive result of the experiment would signal the discovery of new light invisible particles, and it is interesting to know whether they can be new $U(1)$ bosons or not.

In ref. [5] in order to describe the geophysical gravitational anomalies, an X boson was introduced (called hyperphoton) interacting with a vector hypercharge current. Let us show that it is not possible to construct an $SU(3)\times SU(2)\times U(1)\times U'(1)$ model incorporating such an X boson. Let us confine for simplicity to the first and the second generations of quarks. In the weak basis one has

$$L_1=\begin{pmatrix}u\\d\end{pmatrix}_L,\ L_2=\begin{pmatrix}c\\s\end{pmatrix}_L,\quad u_R,\quad c_R,\quad d_R,\quad s_R. \tag{1}$$

Because there is mixing between different generations of quarks, the Yukawa interaction should include the following terms:

$$\mathscr{L}_H=f_1\bar{L}_1 H s_R+f_2\bar{L}_2 H s_R+f_3\bar{L}_1 H d_R+f_4\bar{L}_2 H d_R+\dots, \tag{2}$$

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where H is the Higgs doublet, which gives the mass to the down quarks (which Higgs boson gives mass to the up quarks is inessential here). From the U′(1) gauge invariance of (2) it follows that the U′(1) charges of L_1 and L_2, s_R and d_R (analogously for u_R and c_R) are equal to each other, correspondingly. Therefore they have equal U′(1) charges also in the physical basis. So, the interaction of the X boson with quarks is determined by three parameters: G_L is the U′(1) charge of the left-handed doublets, G_R^u and G_R^d are the U′(1) charges of up and down right-handed quarks. Consequently the lagrangian of the X-boson interaction with quarks in the general case has the form

$$\mathscr{L}_{\text{int}} = g'_X \Big(G_L \sum_{\text{up,down}} \bar{q}_L \gamma_\mu q_L + G_R^u \sum_{\text{up}} \bar{q}_R \gamma_\mu q_R + G_R^d \sum_{\text{down}} \bar{q}_R \gamma_\mu q_R \Big) \cdot X^\mu . \tag{3}$$

From (3) it is seen that the X boson interacts with the same coupling constant with s and d quarks, therefore it is impossible to construct an SU(3)×SU(2)×U(1)×U′(1) model in which the X boson would interact with the baryonic hypercharge $Y_B = B + S$ (as was suggested in ref. [5]). On the other hand, for the explanation of the geophysical data it is not necessary to assume that the X boson interacts with the baryonic hypercharge. Therefore, assume that the X boson interacts with the quark current of the general form (3) and ask the following question: can one obtain any constraints on its properties from the data on the decay $K^+ \to \pi^+ + \text{nothing}$. We will show that the answer is negative. First, let us note the following. In the case of a massless X boson, the decay $K^+ \to \pi^+ X$ is forbidden kinematically by angular momentum conservation. Indeed, in the kaon rest frame the momenta of the outgoing pion and the X boson are collinear (and opposite). Due to the zero mass of the X boson the projection of its spin on this axis is ±1, whereas the projection of the pion and the X-boson orbital momenta on this axis are zero. Since in the initial state we have zero angular momentum (K meson), we obtain the proof of the statement above. Therefore the decay rate $K^+ \to \pi^+ X$ should be proportional to the X-boson mass:

$$\Gamma \sim g'^2_X \, (m_X / m_K)^2 , \tag{4}$$

where g'_X is the X-boson coupling to quarks.

This result is supported by the direct calculations of the decay width which were carried out in the framework of an SU(2)×U(1)×U′(1) gauge model. The Higgs sector of this model contains the standard Higgs doublet H and the extra singlet scalar field ϕ, the vacuum expectation value of which determines the value of the X-boson mass. The interaction of the X boson with quarks is described by eq. (3) and in this case $G_L = \frac{1}{2}(G_X^u + G_R^d)$. The amplitude of the decay reads for $G_R^u \neq G_R^d$

$$M = \mathrm{i} g_X \frac{G_F}{\sqrt{2}} \sin\theta_c \cos\theta_c \Big(\tfrac{1}{2}(G_R^u + G_R^d)\, m_X^2 \cdot \tfrac{1}{2} f_+^+ \,(m_X^2)\, (p+k)_\mu \int_0^1 \mathrm{d}x \, x(1-x) \ln \frac{m_c^2 - m_X^2 (1-x) x}{m_u^2 - m_X^2 \, (1-x) x}$$

$$+ p_\mu \, (G_R^d - G_R^u) f^2 \, m_X^2 \frac{kp}{(pq)\,(kq)} \, (1 + \cos^2\theta_w) \Big) \varepsilon_\mu ,$$

and for

$G_R^u = G_R^d$

$$M = \mathrm{i} g_X \, G_R \frac{G_F}{\sqrt{2}} \sin\theta_c \cos\theta_c \, m_X^2 \Big[\tfrac{1}{2} f_+^+ \,(m_X^2)\, (p+k)_\mu \int_0^1 \mathrm{d}x \, x(1-x) \ln \frac{m_c^2 - m_X^2 x(1-x)}{m_u^2 - m_X^2 x(1-x)}$$

$$+ p_\mu \frac{1}{4\pi^2} \Big(\ln \frac{m_s^2}{m_u^2} - \tfrac{3}{2} \Big) \Big] \varepsilon_\mu ,$$

where $f_{+}^{\ddagger}(q_2)$ is the formfactor of the K–π transition, $f_\pi \approx f_K \approx f$, ε_μ is the polarization four-vector of the outgoing X boson.

Hence, in the framework of a gauge model, bosons with extremely small masses (carriers of a new long-range interaction) give negligible small contributions to the decay width of $K^+ \to \pi^+ +$ "nothing". Therefore one cannot obtain from existing experimental data any limits on the mass and the coupling constant of a new very light X boson.

It is worth noting that in a non-renormalizable theory the decay width of $K^+ \to \pi^+ X$ in the case of very small X-boson masses may behave in an essentially different way than that in a renormalizable theory. For instance, the case of an X boson interacting with the baryon hypercharge vector current was investigated in ref. [6]. It was shown that if the X boson is rather light the decay width is

$$\Gamma \sim g^2 \left(\frac{m_K}{m_X}\right)^2 .$$

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