Fermi National Accelerator Laboratory

FERMILAB-Pub-89/204-A
September 1989

ON THE POSSIBLE TEST OF QUANTUM FLAVORDYNAMICS IN THE SEARCHES FOR RARE DECAYS OF HEAVY PARTICLES

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Submitted to the Soviet Journal of Nuclear Physics.

1. The planning electron-positron collider with the center of mass energy $\sim$ 10 GeV will open new possibilities in the studies of the physics of heavy particles (of leptons and of mesons, containing b quark). These possibilities are of special interest in the light of the recently developed models of quantum flavordynamics, including the broken symmetry of quark and lepton families. In particular, in the recently proposed model [1-3], based on the concept of spontaneously broken local chiral horizontal symmetry $SU(3)_H$ [3] with natural addition of global $U(1)_H$ symmetry (see also [4]), the breaking of the latter one results in the prediction of the Goldstone boson α, a familon [5,6] having both flavor diagonal and flavor nondiagonal couplings. In the most attractive version of this model – in the so-called model of the inverse hierarchy – α turns to couple most strongly with quarks and leptons of the third generation. The analysis [2] of cosmological and astrophysical consequences of the model opens the possibility for the scale η of $U(1)_H$ symmetry breaking, which determines the strength of α interaction with fermions, to be about 10^6 GeV. To the mentioned value of the scale η the predicted probability of $\tau \to \mu\alpha$ and $b \to s\alpha$ corresponds, being accessible to the experimental search. It is the aim of the present note to discuss the possibilities of such a search for two-particle familon decays in their dependence on the possible parameters of the model.

2. Quark and lepton masses are induced in the considered model [1,2] by their "see-saw" mixing with hypothetical superheavy fermions, getting their mass directly via their Yukawa couplings with Higgs scalars, arranging the family symmetry breaking. So the structure of superheavy fermion mass matrices $\hat{M}$ is determined with the accuracy of respective Yukawa coupling constants by the structure of vacuum expectation values (VEV) of these scalars $\xi^{(n)}$ ($n = 1, 2, 3$)

$$\hat{V}_H = \sum_n < \xi^{(n)} >= \begin{pmatrix} r_1 & p_1 & p_3 \\ \pm p_1 & r_2 & p_2 \\ \pm p_3 & \pm p_2 & r_3 \end{pmatrix} \quad (1)$$

(where "+" or "−" correspond to the choice of $SU(3)_H$ sextet and triplet scalars

$\xi^{(1,2)}$, respectively) and the mass hierarchy of heavy fermions masses M_1, M_2, M_3 (of the eigenvalues of the matrix $\hat{M}$) is in the direct dependence on the VEV hierarchy (1) $r_1 > p_1 \gtrsim r_2 \gtrsim p_2 > p_3 > r_3$, determining the hierarchy of horizontal symmetry breaking

$$SU(3)_H \otimes U(1)_H \xrightarrow{v_3} SU(2)_H \otimes U(1)'_H \xrightarrow{v_2} U(1)''_H \xrightarrow{v_1} I$$

$$v_3 > v_2 > v_1;\ v_3 = r_1;\ v_2 = \sqrt{p_1^2 + 4r_2^2};\ v_1 = \sqrt{p_2^2 + p_3^2 + 4r_3^2} \qquad (2)$$

The mass matrices $\hat{m}$ of ordinary quarks and leptons are in this case inversed relative to respective matrices $\hat{M}$: $\hat{m} \ \propto \ \hat{M}^{-1}$ and, consequently, their masses are inversely proportional to the masses of respective superheavy partners: $m_1 : m_2 : m_3 = M_1^{-1} : M_2^{-1} : M_3^{-1}$, i.e. they are in the inverse dependence on the hierarchy (2) of symmetry breaking. Assuming the Fritzsch [7] structure for the VEV matrix (1) $r_2 = r_3 = p_3 = 0$ and, correspondingly, for the mass matrices $\hat{M}$ of superheavy fermions [1,8] we obtain the inversed Fritzsch structure for mass matrices $\hat{m}$.

$$\hat{M} = \begin{pmatrix} M_{11} & M_{12} & 0 \\ \pm M_{12} & 0 & M_{23} \\ 0 & \pm M_{23} & 0 \end{pmatrix} \Rightarrow \hat{m} = \begin{pmatrix} m_{13}^2/m_{33} & 0 & m_{13} \\ 0 & 0 & m_{23} \\ m_{13} & \pm m_{23} & m_{33} \end{pmatrix} \qquad (3)$$

In this case one can estimate with the accuracy to Yukawa constants the hierarchy (2) of symmetry breaking.

$$\eta : \eta_1 : \eta_2 \sim \begin{cases} 1 : (m_\tau/m_e)^{1/2} : (m_\tau/m_e)^{1/2}(m_\tau/m_\mu)^{1/2} = 1 : 60 : 240 \\ 1 : (m_b/m_d)^{1/2} : (m_b/m_d)^{1/2}(m_b/m_s)^{1/2} = 1 : 30 : 150 \\ 1 : (m_t/m_u)^{1/2} : (m_t/m_u)^{1/2}(m_t/m_c)^{1/2} = 1 : 100 : 650 (m_t = 60\mathrm{GeV}) \end{cases} \qquad (4)$$

where $\eta \equiv v_1$; $\eta_1 \equiv v_2$; $\eta_2 \equiv v_3$.

The pointed inverse dependence of ordinary fermion masses on the hierarchy of the symmetry breaking takes place in the model [1,2] both for up-type and down-type quarks, and for neutrinos and charged leptons.

The diagonalization of mass matrices $\hat{m}$ is performed with the use of unitary transformations. For example, one has for up-type and down-type quarks:

$$\hat{m}_u \to V_u^{+} \hat{m}_u V_u' = \hat{m}_u^{diag} = diag(m_u, m_c, m_t)$$

$$\hat{m}_d \to V_d^{+} \hat{m}_d V_d' = \hat{m}_d^{diag} = diag(m_d, m_s, m_b) \qquad (5)$$

For symmetric matrices $\hat{m}$ one has $V' = V^*$. If nondiagonal elements of $\hat{m}$ are antisymmetrical, $V' = diag(1, -1, 1) \cdot V^*$. Note, that the symmetry or antisymmetry of nondiagonal elements of matrices $\hat{m}$ is determined, respectively, by the choice of sextet or triplet $SU(3)_H$ representation of scalar fields, acquiring VEVs η_1, and η.

The breaking of global $U(1)_H$ ($U(1)_H''$) symmetry results in the appearance of Nambu-Goldstone boson α, the familon with both flavor diagonal and flavor nondiagonal couplings, having, c.f., for down-type quarks the form:

$$\mathcal{L} = i\alpha g_{ij} \bar{d}_i (i \; sin \; \phi_{ij} + \gamma_\phi \; cos \; \phi_{ij}) d_j + h.c.$$

$$(i, j = d, s, b; \; i \neq j) \qquad (6)$$

where

$$g_{bs} = \frac{m_b}{\eta} S_{bs}, \; g_{bd} = \frac{m_b}{\eta} \; S_{bd}, \; g_{sd} = \frac{m_s}{\eta} S_{ds} \left(\frac{\eta}{\eta_1}\right)^2 . \qquad (7)$$

Here S_{ij} $(i, j = d, s, b)$ are the angles of the down-type quark rotation matrix $\hat{V}_d$ and the phases ϕ_{ij} arise owing to complexity of mass matrix elements and depend on the details of its structure. In the case of Fritzsch structure of the matrix $\hat{M}$ (and, respectively, of inversed Fritzsch structure of the matrix $\hat{m}$) $\phi_{ds} = \phi_{sb} = \frac{\pi}{2}$, $\phi_{db} = 0$ and the constants g_{ij} are expressed in the terms of quark masses as follows

$$g_{bs} = \frac{m_b}{\eta}\sqrt{\frac{m_s}{m_b}} \; , \; g_{bd} = \frac{m_b}{\eta}\sqrt{\frac{m_d}{m_b}}\left(\frac{m_d}{m_s}\right), \; g_{ds} = \frac{m_s}{\eta}\sqrt{\frac{m_d}{m_s}}\left(\frac{m_d}{m_b}\right) \qquad (8)$$

Note, that in the general case $\phi_{ij} \neq 0$ the Lagrangian (5) leads to CP violating effects in the familon decays.

Familon interaction with up-type quarks and with charged leptons has the form similar to (6)-(8).

3. The possibilities of experimental search for $\mu \to e\alpha$ decay were discussed in Ref. [9]. According to [9] the differential probability of this decay is

$$\frac{d\Gamma}{d\cos\theta}(\mu \to e\alpha) = \frac{1}{2}\Gamma_o\left[1 - \vec{\xi}_\mu\vec{\xi}_e + 2(\vec{\xi}_\mu\vec{n})(\vec{\xi}_e\vec{n})\right] \tag{9}$$

where the total probability of decay is given by

$$\Gamma_o = \frac{1}{16\pi}g_{\mu e}^2 m_\mu \ . \tag{10}$$

Here $\vec{n}$ is the direction of the outgoing electron and $\vec{\xi}_e$ and $\vec{\xi}_\mu$ are μ and e polarization vectors, respectively.

To discriminate this decay from the background of the leptonic decay $\mu \to e\overline{\nu}_e\nu_\mu$ both high energy resolution in the electron spectrum measurement is to be achieved, determining according to [9] the signal/background ratio:

$$B = \Gamma(\mu \to e\alpha)/\int_{E_{max}-\Delta E}^{E_{max}}\frac{d\Gamma}{dE}dE = \frac{6\pi^2 g_{\mu e}^2}{G_F^2 m_\mu^4}\frac{1}{\Delta\varepsilon}\ , \Delta\varepsilon = \frac{\Delta E}{E_{max}}\ , \tag{11}$$

and the dependence (9) on μ and e polarization is to be taken into account.

The data [10] on the searches for $\mu \to e\alpha$ decay $Br(\mu \to e\alpha) < 2 \cdot 10^{-6}$ lead to the restriction $g_{\mu e} < 1.8 \cdot 10^{-11}$, giving, c.f., for inversed Fritzsch structure of charged lepton mass matrix the constraint $\eta > 5 \cdot 10^5$ GeV. Differential and total probabilities of $\tau \to \mu\alpha$ and $\tau \to e\alpha$ decays the form similar to (11) and (12) with the substitution of respective masses and constants. The predicted branching ratios of these decays are:

$$Br(\tau \to \mu\alpha) = 3 \cdot 10^{-3}(10^6\text{GeV}/\eta)^2(g_{\tau\mu}/g_{\tau\mu}^F)^2$$

$$Br(\tau \to e\alpha) = 7 \cdot 10^{-5}(10^6\text{GeV}/\eta)^2(g_{\tau e}/g_{\tau e}^F)^2\ , \tag{12}$$

where numerical estimations are given for Fritzsch parametrization (9) with $g_{ij} = g_{ij}^F$. The modern experimental restrictions are $Br(\tau \to \mu(e)\alpha) < 2.7 \cdot 10^{-2}$ [11].

In the further discussion of familon decays of mesons we'll restrict ourselves by consideration of two-body decays only, which are preferable from the viewpoint of their pure kinematical signature (for meson at rest familon from its decay is not observed and one detects only monochromatic meson in the final state). To describe these decays the information on respective hadronic form factors is to be involved. The standard approach to obtain such an information is based on the ideas of chiral theory and on the estimations, using QCD sum rules. We'll base our further discussions of this approach. However, there is another approach [12] in the estimation of hadronic form factors, leading, as we'll show, to significantly different predictions of the probability of respective transitions.

4. Only scalar familon α interaction contributes $K \to \pi\alpha$ decay, induced by $s \to d\alpha$ transition. For pseudoscalar α coupling the matrix element $< K|\bar{s}\gamma_5 d|\pi >$ vanishes owing to P-parity selection rules. For scalar α coupling one has

$$< K|\bar{s}d|\pi >= (m_s - m_d)^{-1} < K|\partial_\mu \bar{s}\gamma_\mu d|\pi >=$$

$$= (m_s - m_d)^{-1}(p_K - p_\pi)_\mu (f_+(p_K + p_\pi)_\mu + f_-(p_K - p_\pi)_\mu) \simeq f_+ \frac{m_K^2}{m_s}, \quad (13)$$

where p_K and p_π are momenta of K and π mesons, respectively, $f_+(0) = 1$, $m_s = (175 \pm 50)\mathrm{MeV}$, $m_d = (9 \pm 3)\mathrm{MeV}$, and in the final expression $(p_K - p_\pi)^2 = m_\alpha^2 \simeq 0$ is taken into account. One obtains from Eqs. (8) and (13), that the branching ratio of $K \to \pi\alpha$ decay is

$$Br(K \to \pi\alpha) = \frac{g_{sd}^2}{16\pi}\frac{m_K^3}{m_s^2}\Gamma_{tot}^{-1}(K) = 2.65 \cdot 10^{-6} sin^2\phi_{ds} \left(\frac{g_{ds}}{g_{ds}^F}\right)^2 \left(\frac{10^6\mathrm{GeV}}{\eta}\right)^2 \quad (14)$$

Comparison with the experimental restriction $Br(K \to \pi\alpha) < 3.8 \cdot 10^{-8}$ [13] results in the lower limit

$$sin\ \phi_{sd}\ \eta \left(\frac{\eta_1}{\eta}\right)^2 > 3 \cdot 10^9\mathrm{GeV} \quad (15)$$

This limit is the most strong: $\eta > 7 \cdot 10^6$GeV for inversed Fritzsch structure of the matrix $\hat{m}$, when $\phi_{sd} = \frac{\pi}{2}$. For relatively large (22) - element of matrix $\hat{m}$ ϕ_{sd} may be equal to 0, and the lower limit (15) is removed.

5. $c \to u\alpha$ transitions induce the decays $D \to \pi\alpha$ (via the scalar interaction) and $D \to \rho\alpha$ (via the pseudoscalar interaction). The probabilities of these decays are:

$$\Gamma(D \to \pi\alpha) = \frac{sin^2\phi_{uc}}{16\pi} g_{uc}^2 \frac{m_D^3}{m_c^2} f_+^2$$

$$\Gamma(D \to \rho\alpha) = \frac{cos^2\phi_{uc}}{8\pi} g_{uc}^2 m_D F_+^2 \tag{16}$$

Putting into these expressions the values for f_+ and F_+ $f_+ \sim f_+ \sim 0.6 \div 0.7$ [14] one obtains for the branching ratios of these decays the following estimations:

$$Br(D \to \pi\alpha) = 1.3 \cdot 10^{-8} sin^2\phi_{uc} \left(\frac{g_{uc}}{g_{uc}^F}\right)^2 \left(\frac{10^6\text{GeV}}{\eta}\right)^2$$

$$Br(D \to \rho\alpha) = 10^{-8} cos^2\phi_{uc} \left(\frac{g_{uc}}{g_{uc}^F}\right)^2 \left(\frac{10^6\text{GeV}}{\eta}\right)^2 \tag{17}$$

Taking into account possible variation of g_{uc}, the experimental search for these decays with the branching ratio $10^{-5} \div 10^{-7}$ is of interest.

6. Consider decays, induced by $b \to d\alpha$ and $b \to s\alpha$ transitions. For scalar coupling of α these are $B \to \pi\alpha$ and $B \to K\alpha$ decays, for pseudoscalar one these are $B \to \rho\alpha$ and $B \to K^*d$, respectively. The estimation, similar to (18) gives for branching ratios of these decays

$$Br(B \to K\alpha) = \Gamma_B^{-1} \frac{sin^2\phi_{bs}}{16\pi} g_{bs}^2 \frac{m_B^3}{m_b^2} f_{BK+}^2 = 2 \cdot 10^{-2} sin^2\phi_{bs} \left(\frac{10^6\text{GeV}}{\eta}\right)^2$$

$$Br(B \to \pi\alpha) = \Gamma_B^{-1} \frac{sin^2\phi_{bd}}{16\pi} g_{bd}^2 \frac{m_B^3}{m_b^2} f_{B\pi+}^2 = 6 \cdot 10^{-4} sin^2\phi_{bd} \left(\frac{10^6\text{GeV}}{\eta}\right)^2$$

$$Br(B \to \rho\alpha) = \Gamma_B^{-1} \frac{cos^2\phi_{bd}}{8\pi} g_{bd}^2 m_B F_{B\rho+}^2 = 1.22 \cdot 10^{-3} cos^2\phi_{bd} \left(\frac{10^6\text{GeV}}{\eta}\right)^2 \tag{18}$$

$$Br(B \to K^*\alpha) = \Gamma_B^{-1} \frac{cos^2\phi_{bs}}{8\pi} g_{bs}^2 m_B F_{BK^*+}^2 = 4 \cdot 10^{-2} cos^2\phi_{bs} \left(\frac{10^6\mathrm{GeV}}{\eta}\right)^2 \quad ,$$

where $\Gamma_B = 10^{12}$ 1/s is the total width of B meson and for numerical estimation of f_+ and F_+ the following values there taken in accordance with [14]: $f_{BK+} \sim F_{BK^*+} \sim 0.4 \div 0.5$ and $f_{B\pi+} \sim F_{B\rho+} \sim 0.3 \div 0.4$. Experimental data [15] provides the upper limit $Br(B \to K\alpha) < 0.35$.

7. Note, that there is another approach [12] in the estimation of formfactors of the transitions, considered in pp. 4-6. This approach is based on the generalization of PCAC for the case of broken global flavor symmetry. It leads to the prediction, that the constants f_P of two-body leptonic decays of pseudoscalar mesons P are proportional to the sum of masses m_1 and m_2 of constituent quarks, forming the meson, so that [12]

$$f_P = f_\pi \frac{m_1 + m_2}{m_u + m_d} \tag{19}$$

and to the sum rule, generalizing the Callan-Treiman relation and putting one-to-one correspondence between these constants and formfactors f_+ and f_- of three-body semileptonic decays $P_1 \to P_2 + \ell + \hat{\nu}$ [12], giving

$$f_+^{12} = \frac{f_{P_1}^2 + f_{P_2}^2}{2f_{P_1}f_{P_2}} = 1 + \frac{(f_{P_1} - f_{P_2})^2}{2f_{P_1}f_{P_2}} \; ; f_-^{12} = \frac{f_{P_1}^2 - f_{P_2}^2}{2f_{P_1}f_{P_2}} \tag{20}$$

Putting into Eq. (19) the values of constituent quark masses $m_u = m_d = 350$ MeV, $m_s = 500$ MeV, $m_c = 1400$ MeV, $m_b = 5$ GeV, one obtains for formfactors f_+ and $F_+ = f_+$ (the latter is fulfilled automatically in the approach [12]) the following estimations:

$$f_+^{K\pi} = \frac{f_K^2 + f_\pi^2}{2f_K f_\pi} = 1 + \frac{(f_K - f_\pi)^2}{2f_K f_\pi} = 1.03$$

$$F_+^{D\rho} = f_+^{D\pi} = \frac{f_D^2 + f_\pi^2}{2f_D f_\pi} = 1 + \frac{(f_D - f_\pi)^2}{2f_D f_\pi} = 1.4$$

$$F_+^{BK^*} = f_+^{BK} = \frac{f_B^2 + f_K^2}{2f_B f_K} = 1 + \frac{(f_B - f_K)^2}{2f_B f_K} = 3 \tag{21}$$

$$F_+^{B\rho} = f_+^{B\pi} = \frac{f_B^2 + f_\pi^2}{2f_B f_\pi} = 1 + \frac{(f_B - f_\pi)^2}{2f_B f_\pi} = 3.8$$

Moreover, the approach [12], changing the view on the quark equations of motion, leads to the change in Eqs. (13), (14) the current quark mass by the corresponding constituent quark mass, decreasing, respectively, the total probability of $K \to \pi\alpha$ decay (14) and weakening the restriction (15). On the other hand, the enhancement of formfactors (20) increases significantly the predicted branching ratios of familon decays of D mesons and, especially, of B mesons.

It should be noted, that the value of formfactor $f_+^{DK} = 1.2$, predicted in the approach [12], contradicts the estimations of this value $f_+^{DK} \leq 0.8$, obtained in [14] on the base of the data [16]. Detailed check of these data in the measurements of the widths of semileptonic decay $D^+ \to K^\circ \ell^+ \nu_\ell$ and of leptonic decay $D^+ \to \mu^+ \nu_\mu$ makes it possible to test the validity of approach [12].

8. So, the above discussion shows, that even the most conservative estimations of widths of two body familon decays of B mesons and τ leptons gives the opportunity of effective search for such decays at the scale $\eta \sim 10^6 \div 10^7$ GeV. In the combination with further searches for $\mu \to e\alpha$, $K \to \pi\alpha$ and $D \to \pi(\rho)\alpha$ decays, whose probability is predicted at the level accessible to the sensitivity of the modern experiment, the search for familon B and τ decays turns to be an important source of direct information on the structure of matrices $\hat{V}_u$, $\hat{V}_d$, $\hat{V}_\ell$ of quark and lepton mixings (both on the rotation angles s_{ij} and on phases ϕ_{ij}) and, consequently, on the structure of their mass matrices. In the contrast to Kabayashi-Maskava matrix of quark mixing in the charged weak current $\hat{V}_{KM} = \hat{V}_u^+ \hat{V}_d$, detailization of which provides the information on the combination of $\hat{V}_u$ and $\hat{V}_d$ matrices parameters only, without fixing each of them separately, the discovery and study of meson familon decays will give direct

information on each of these matrices. In its turn it makes possible to determine the mixing in the currents violating the conservation of baryon number, what will give more reliable predictions for the lifetime and partial widths of proton decay.

On the other hand, familon decay searches may be viewed as experimental test of physical foundations of the cosmology of massive unstable neutrino, originating from the quantum flavordynamics with low scale of horizontal symmetry breaking [2]. Provided that this scale is $\eta \sim 10^6 \div 10^7$ GeV, nontrivial cosmological scenario of successive $\nu_\tau \to \nu_\mu \alpha$ and $\nu_\mu \to \nu_e \alpha$ decays of ν_τ and ν_μ, dominating in the Universe at $10^9 \div 10^{12}$s and $t \sim 10^{12} \div 10^{16}$s, respectively. This scenario, providing the physical grounds for description of the large scale structure of the Universe, gives an interesting example of the combination of attractive features of cold dark matter and unstable dark matter scenarios, predicting the presence of the two characteristic scales $R_s \sim$ 100 kpc and $R_S \sim 30$ Mpc. In the framework of the approach [2] realization of this scenario in the cosmological evolution is unambiguously related with the prediction of B and τ familon decays at the level of estimations, given in the present paper.

This work was completed at Fermi National Accelerator Laboratory under the auspices of NASA grant NAGW-1340.

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