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A NEW SCHEME FOR NONLEPTONIC DECAYS: PREDICTIONS OVER THE F^+ MESON

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ABSTRACT

A new dynamical scheme of hadronization for nonleptonic decays is proposed. As testable consequences, new predictions over the F^+ lifetime, over the branching ratio $BR(F^+ \to \ell \nu X)$ and over the decay $F^+ \to \pi^+ \pi^0$ (implying violation of the $\Delta I = 1$ rule) are given.

Key-words: Nonleptonic decays; F^+ meson; Hadronization; Strange and charmed mesons.

Contrary to the case of semileptonic decays, the nonleptonic decays of both strange and charmed pseudoscalar mesons exhibit a somewhat irregular behaviour.

For semileptonic decays of strange mesons, for instance, one has[1] $\Gamma(K^+\to\pi^0 l^+\nu) \approx \Gamma(K^0_L\to\pi^+ l\nu)$ (l=e,μ); similar results have recently been reported[2] for charmed mesons, $\Gamma(D^+\to Xe^+\nu) \approx \Gamma(D^0\to Xe^+\nu)$.

By contrast, in the non-leptonic decay of strange mesons, for instance,[1] $\Gamma(K^0_s\to\pi\pi) \approx 660\ \Gamma(K^+\to\pi^+\pi^0)$, while for charmed mesons one has the unexpected result[3] $\Gamma(D^0\to K^-\pi^+)/\Gamma(D^0\to\bar{K}^0\pi^0) \approx 2$ (predicted in the usual scheme[4] to be ≥ 18) and $\Gamma(D^+\to\bar{K}^0K^+)/\Gamma(D^+\to\bar{K}^0\pi^+) \approx 0.3$ (predicted[4] <0.1).

These different behaviors are presumably due to the fact that, contrary to leptons, quarks produced in weak interaction processes undergoe strong interactions i.e. the essentially unknown effects of confinement and hadronization induce this irregular behavior.

Various models and various review papers have appeared on this subject[4,5] to which the interested reader is referred.

In this letter we report some preliminary consequences of a model whose basis, mathematical aspects and physical consequences will be fully covered in forthcoming papers[6,7]. Here, we limit ourselves to the most striking consequences of our scheme concerning: i) The hadronic $\pi\pi$ decay of the charmed meson F^+ which is predicted to occur at an unexpectedly substantial rate

$$BR\,(F^+\to\pi^+\pi^0) \approx 0.043\,\left(1-\frac{\tau(F^+)}{\tau(D^+)}\right) \approx (3\text{-}4)\% \qquad (1)$$

(comparable to that of $D^0\to K^+\pi^-)^3$, ii) the semileptonic decays of F^+ which turn out to be such that

$$BR(F^+\to X\ell\nu)\ \leq 1/3\ \ BR(D^+\to X\ell\nu)$$

iii) the F^+ lifetime which is predicted to be

$$\tau(D^+) \geq 3\ \tau(F^+) \qquad (2)$$

or, more precisely, in the range

$$\tau(F^{+}) \approx (0.47 - 3)\,10^{-13}\ \mathrm{s}. \qquad (3)$$

which does not seem to contradict the present limits[1,8,9].

Predictions i) and ii) are, to the best of our knowledge, peculiar to our model. In particular, i) implies violation of the $\Delta I = 1$ rule as had already been noticed long ago[10]. We urge for an experimental check on them.

The starting point (quite generally accepted) is that the quark-antiquark pair produced in the weak decay of a meson behave as free particles over a distance x_0 (in the center of mass of the decaying meson) which we take to be representative of the distance beyond which hadronization takes place.

The next, crucial, point enforcing the confinement postulate is the assumption that a spread of momenta $\vec{p}_1$ and $\vec{p}_2$ of the quarks is possible within the distance x_0 due to the uncertainty principle. As a consequence, there will be a small but non-zero contribution of momenta distributions when the two quarks are produced in the same emisphere. This will enhance the so-called W-annihilation graphs (W.A. hereafter) which are otherwise suppressed by total angular momentum conservation. In other words, in a restricted confinement region beyond which hadronization occurs, a quark (an antiquark) may have helicity -1(+1, respectively) without which the WA contribution would be suppressed by total angular momentum conservation. We do not engage ourselves on the exact details by which hadronization takes place, but we limit ourselves to an intuitive empirical prescription on how, mathematically, the above mentioned spread of momenta of the quark-antiquark pair occurs over the distance x_0. Although very naive, this prescription (which we will briefly describe below referring the interested reader to subsequent work[6] for all the details), leads to the predictions which we have already mentioned and proves itself capable of a substantial agreement with existing data[7].

To implement the above ideas, we will, specifically, assume that in the rest frame of the decaying meson, each of the quark-antiquark member of the pair produced by the weak interaction responsible for the decay of the parent meson is described by a wave function of the form

$$\Psi(x) = \omega(p)\, \exp - ip.x\, \exp. -x^2/2x_0^2 \tag{4}$$

i.e. the quarks behave as essentially free particles within the confinement region of dimension x_0.

To have the standard form of the Dirac equation

$$(\not{p}-m)\omega(p)\, \exp(-ipx) = 0$$

we see that $\Psi(x)$ must obey

$$\left(i\gamma^\mu\partial_\mu + i\,\frac{\vec{\gamma}.\vec{x}}{x_0^2} - m\right)\Psi(x) = 0 \tag{5}$$

where the non-hermitian "potential" $i\vec{\gamma}.\vec{x}/x_0^2$ (which disappears as $x_0\to\infty$ is a direct consequence of our wave function being a free wave damped by a gaussian.

That the "potential" be non-hermitean is, physically, quite natural. Quantum mechanically, the presence of a non-hermitean part in the Hamiltonian is, in fact, related to the probability being in general not conserved as a function of time

$$\frac{d}{dt}<\Psi/\Psi> = \frac{1}{i}\left\langle H-H^{+}\right\rangle \tag{6}$$

Physically, this is exactly what we expect to happen if, outside the domain x_0, the quarks hadronize and, therefore, do not appear as asymptotic states.

An immediate consequence of (5) is the birth of new terms violating both the axial as well as the vector current conservations (which, again, disappear for large values of x_0)

$$\partial_\mu \bar{\psi}' \gamma_5 \gamma_\mu \psi = -2\, \bar{\psi}' \frac{\vec{\gamma}\cdot\vec{x}}{x_0^2} \gamma_5 \psi + i(m+m')\bar{\psi}'\gamma_5 \psi \qquad (7)$$

$$\partial_\mu \bar{\psi}' \gamma_\mu \psi = -2\, \bar{\psi}' \frac{\vec{\gamma}\cdot\vec{x}}{x_0^2} \psi + i(m'-m)\bar{\psi}'\psi \qquad (8)$$

It is rather straightforward to verify[6] that the current violating terms (7,8) implied by our model are generated by the so-called spin or dipole density current[11] which gives a non-zero contribution here whereas its effect would vanish for truly free particles.

A subtle point which we will not discuss here (see Ref. 6) is the non-manifest covariance of our model (eq. 5) which in the present case we can ignore as we will always work in the rest frame of the decaying meson.

We now use the wave function (4) to evaluate the implicit $F^+\to u\bar{d}$ W.A. decay width in the F^+ rest frame. Taking $m_u=m_d=0$, we get the W.A. contribution

$$\Gamma^{W.A.}(F^+\to u\bar{d}) = \frac{G^2}{2} f_F^2\, a_1^2 \frac{M^3}{\pi^{3/2}} \cos^4\theta \,\cdot$$

$$\cdot\left[\frac{\sqrt{\pi}}{2M^2x_0^2}\, \mathrm{erf}\left(\frac{x_0 M}{\sqrt{2}}\right) - \left(\frac{1}{\sqrt{2}Mx_0} + \frac{1}{6}\sqrt{2}\,x_0 M\right) \exp\left(-\frac{x_0^2 M^2}{2}\right)\right] \qquad (9)$$

where f_F is the F decay constant, M is the mass of the F meson.

In (9), a_1 is given by

$$a_1 = (2c_+ + c_-)/3 \qquad (10)$$

where c_+ and c_- are the coefficients which appear in the effective Hamiltonian[4]. The above term a_1 corresponds in the usual vernacular[4] to the transitions with the $q\bar{q}$ in a color singlet. We neglect here the octet contribution which is very small in the present case. Taking $x_0=1$ GeV^{-1} and $a_1=1.21$ (corresponding to $c_+=0.66$, $c_-=2.3$) and letting f_F vary between 200 to 600[4,5,12] MEV we obtain

$$\Gamma^{W.A.}(F^+\to u\bar{d}) = (2.2-20)\ 10^{12}\ sec^{-1} \qquad (11)$$

Taking the D^+ decay width as corresponding to the so-called W.R.(W-Radiation) contribution ($\tau(D^+) = 9.2\ 10^{-13}$ sec)[1], i.e.

$$\Gamma^{W.R.}(F^+) = \Gamma(D^+) = 1.09\ 10^{12}\ sec^{-1} \qquad (12)$$

we see that the value estimated in our model for the W.A. contributions to the F^+ decay width is at least of the order of twice its W.R. contribution. We therefore get

$$\tau(D^+) \geq 3\tau(F^+) \qquad (2)$$

which is in quite good agreement with the experimental observations[1] ($\tau(F^+) = 2.8\ ^{+1.6}_{-0.7}\ 10^{-13}$ sec, $\tau(D^+) = 9.2\ ^{+1.3}_{-1.0} 10^{-13}$ sec).

As one can see from (11), the W.A. contribution to the width depends strongly on the poorly known parameter f_F. This means that $\tau(F^+)$ can vary within the range

$$\tau(F^+) = (0.47 - 3.0)\times 10^{-13}\ sec. \qquad (3)$$

as f_F varies between 600 to 200 MeV respectively. One can turn things around and use the experimental value for $\tau(F^+)$ to estimate f_F to be $f_F \approx 200$ MeV.

It is interesting to notice that the lower value we find for $\tau(F^+)$ falls below the acceptance region of a recent experimental search[13] of F^+. One could speculate that this may be the origin of the negative result reported in that investigation. On the other hand, our upper value in (3) is very close to the values reported recently[8,9].

Given that in our model the W.A. contribution occurs only in the non leptonic decay, this means that only W.R. contributes to the semileptonic decay implying that

$$\Gamma(D^+\to X\ell\nu) = \Gamma(D^0\to X\ell\nu) = \Gamma(F^+\to X\ell\nu) \qquad (13)$$

As a consequence of (11) and (13)

$$1\% \leq BR(F^+\to \ell\nu X) \leq 1/3\ BR(D^+\to \ell\nu X) \leq 6\% \qquad (14)$$

As far as we know, our model is the only one to produce these predictions since the usual results is that the semileptonic B.R. of F^+ should be equal to that of D^+ and larger than the D^0 one (while, in our case, the W.A. does not contribute to the $\ell\nu$ channel).

Going back to our model, we see that it violates the sum rule $\Delta I=1$ which predicts $A(F^+\to\pi^+\pi^0)=0$. In fact, using equation (8) we get

$$A(F^+\to\pi^+\pi^0) = if_F[(m_u-m_d)\ \langle\pi^+\pi^0|u\bar{d}|0\rangle -$$

$$-2\langle\pi^+\pi^0|u\vec{\gamma}.\vec{x}\bar{d}|0\rangle/x_0^2] \qquad (15)$$

where the first (and usual) term is practically zero, while the second vanishes only in the limit $x_0\to\infty$. That violation of $\Delta I=1$ would imply $F^+\to\pi^+\pi^0$ was pointed out long ago[10] whereas the possibility that isospin symmetry be broken, has been advocated to explain the large NNπ parity violating coupling[14]. Also, the data[3] do not seem to support at all the $\Delta I=1$ rule leading to $A(D^0\to K^-\pi^+)+\sqrt{2}\ A(D^0\to\bar{K}^0\pi^0)= A(D^+\to\bar{K}^0\pi^+)$.

Considering the evaluation of $\Gamma(F^+\to\pi^+\pi^0)$, we recall that, according to the usual scheme[15], the W.A. contribution to $M\to M_1+M_2$ is given by

$$\langle M_1M_2|H|M\rangle = \langle M_1M_2|V^\mu|0\rangle\langle 0|A_\mu|M\rangle \qquad (16)$$

with

$$\langle M_1M_2|V^\mu|0\rangle = f_+(q^2)(P_1{}^\mu-P_2{}^\mu) + f_-(q^2)\ (P_1{}^\mu+P_2{}^\mu)$$

$$\langle 0|A_\mu|M\rangle = if_MP_\mu \qquad (17)$$

where $P_\mu=P_{1\mu}+P_{2\mu}$, and where $f_\pm(q^2)$ are the usual form factors. Thus, carrying out the calculation for $M\to q_1\ \bar{q}_2\to M_1 + M_2$ one would get (aside from the proper combinations of Cabibbo's angle)

$$|A|^2 = G^2 [f_+^2(q^2)\,(m_{M1}^2 - m_{M2}^2) + f_-^2(q^2)\, m_M^2]^2\, f_M^2/2 \tag{18}$$

Thus, in the usual scheme, $\Gamma(F^+ \to \pi^+\pi^0)$ is pratically zero because of the smallness of $(m_{\pi^+} - m_{\pi^0})$ and of $f_-(q^2)$.

Using our wave function (4), we get instead of eq. (17)

$$|A(F^+ \to \pi^+\pi^0)|^2 = \frac{G^2}{2} a_1^2 f_F^2 \left\{ \frac{a}{\phi}\left[f_+^2(m_F^2)\, m_F^2 \left(2m_{\pi^+}^2 + 2m_{\pi^0}^2 - m_F^2 \right)\right] + \right.$$
$$+ \frac{b}{\phi}\left[f_+^2(m_F^2)\, \left(m_{\pi^+}^2 - m_{\pi^0}^2 \right)\right] + \frac{a+b}{\phi} \cdot$$
$$\left. \cdot \left[f_-^2(m_F^2)\, m_F^4 + 2 f_+(m_F^2) f_-(m_F^2)\, m_F^2 \left(m_{\pi^+}^2 - m_{\pi^0}^2 \right)\right]\right\} \tag{19}$$

where a_1 was defined in eq. (8), whereas

$$a = \frac{1}{12\pi^{3/2}}\left[-\frac{3\sqrt{\pi}}{2m_F^2 x_0^2}\, \mathrm{erf}\left(\frac{x_0 m_F}{\sqrt{2}}\right) + \left(\frac{3}{\sqrt{2}\, m_F x_0} + \frac{x_0 m_F}{\sqrt{2}}\right) \exp\left(-\frac{x_0^2 m_F^2}{2}\right)\right] \tag{20}$$

$$b = \frac{1}{12\pi^{3/2}}\left[\left(\frac{3}{2} + \frac{3}{2m_F^2 x_0^2}\right) \mathrm{erf}\left(\frac{x_0 m_F}{\sqrt{2}}\right) + \left(\frac{-3}{\sqrt{2}\, m_F x_0} - \sqrt{2}\, x_0 m_F\right) \exp\left(-\frac{x_0^2 m_F^2}{2}\right)\right] \tag{21}$$

and ϕ is the phase space integral

$$\phi = \frac{1}{8\pi} \tag{22}$$

Notice that in the limit $x_0 \to \infty$

$$\lim_{x_0 \to \infty} a/\phi = 0 \quad , \quad \lim_{x_0 \to \infty} b/\phi = 1 \tag{23}$$

and the free solution (18) is recovered.

Neglecting now all terms proportional to $(m_{\pi^+} - m_{\pi^0})$ and to $f_-(q^2)$ and using $x_0 = 1\ \mathrm{GeV}^{-1}$ we get from eqs. (19-22)

$$|A(F^+\to\pi^+\pi^0)|^2 = 0.86\ a_1{}^2 G^2 f_F f_+(m_F)\ \cos^4\theta \qquad (24)$$

Since $\Gamma(F^+\to\pi^+\pi^0) = |(A(F^+\to\pi^+\pi^0)|^2\ \Phi(m_\pi/m_F,\ m_\pi m_F)/16_\pi\ m_F$, where

$$\Phi^2(x,y) = [1-(x+y)^2)\ (1-(x-y)^2]$$

we obtain

$$\Gamma(F^+\to\pi^+\pi^0) = 0.86\ 10^{-2}\ a_1\ G^2\ f_F f_+(m_F{}^2)\ \cos^4\theta \qquad (25)$$

to be compared with (9)

$$\Gamma^{W.A.}(F^+\to ud) = 2.0\ 10^{-1}\ a_1{}^2\ G^2\ f_F{}^2\ \cos^4\theta \qquad (7)$$

Taking $f_+(m^2{}_F) = 1$[16] we get estimates independent of f_F and a_1:

$$\frac{\Gamma\ (F^+\to\pi^+\pi^0)}{\Gamma^{W.A.}(F^+\to u\bar{d})}\quad 0.043 \qquad (26)$$

Using our previous conclusion $\Gamma^{W.A.}(F^+) \geq \Gamma^{W.R.}(F^+)$ we come to the anticipated prediction (1)

$$B.R.(F^+\to\pi^+\pi^0) \geq (3\text{-}4)\% \qquad (27)$$

Of course, the above result could be somewhat modified should $f_+(m_F{}^2)$ turn out to be noticeably different from 1.

Although we have already shown a result, eq. (2), where the agreement with the data corroborates our model, and although the latter accomodates a large bulk of experimental data, as we will show elsewhere[7], we think it would be of great interest to have direct experimental verification of our approach in the form of its two main predictions (1) and (14).

It is interesting to note that eq. 7, adds a new term in the violation of PCAC. Thys may support one of the conclusions reached in ref. 17.

It is quite understood that our model leads also to other decays of the form $F^+\to MM$ (such as $\rho^+\pi^0$, $\rho^+\eta$, $K^+\bar{K}^{0*}$ ect) which do not violate $\Delta I=1$ and which can also proceed via W.R. and of which the $K^+\bar{K}^{0*}$ has recently been seen at a fairly conspicuous rate[9]. These decays can also be studied in our model and we plan to do so at a later time.

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