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CONSTRAINTS ON THE WEAK ISOSPIN OF HEAVY QUARKS FROM NON-LEPTONIC TRANSITIONS*

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ABSTRACT

We examine non-leptonic transitions which could give straightforward information on the weak isospin of heavy quarks. The V,A structure of the (c,s) current is constrained by the K_L-K_S mass difference, which makes unlikely a right-handed piece of strength one. A sensitive test is provided by the comparison between pure parity conserving and pure parity violating decays in certain charge channels, as the F^+ decays $\phi\pi^+$ and $\eta\pi^+$, or the corresponding D^0 decays $K^{*-}\pi^+$ and $K^-\pi^+$. Both modes are expected to be important within the minimal GIM scheme. A significant $(c,s)_R$ piece would lead to a strong suppression of one of these modes and to an enhancement of the other one, according to the relative phase between the left and right parts of the current. The comparison of similar decay modes can give information on the V,A structure of the (t,b) current and even on the (c,d) and (c,b) currents at the Cabibbo-forbidden level.

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It is of great importance for any theoretical attempt to understand the weak interactions of hadrons to have an experimental determination of the weak isospin of the quarks.[1] For the u and d quarks, a careful study within $SU(2) \times U(1)$ of neutral current data in various processes leads to $I_3(u_L) = 1/2$, $I_3(d_L) = -1/2$, $I_3(u_R) = I_3(d_R) = 0$ to a good accuracy.[2] These results are stronger than the V - A structure of β-decay and imply the absence of any right-handed doublet involving the u and d quarks. For the strange quark, strange particle semileptonic decays tell us that the (u,s) current is left-handed. The determination of $I_3(s_L)$ and $I_3(s_R)$ from neutral current data is obviously very hard, since it would involve precise measurements of associate production of strange particles by neutral currents off the $s\bar{s}$ sea. In the case of the s quark, and a fortiori for heavier quarks, we are then left with the individual couplings to the other quarks.

Let us first concentrate on the important doublet (c,s). The Glashow-Iliopoulos-Maiani mechanism predicts a left handed current of strength $\cos\theta_c$. On the theoretical side (except for some attempts to understand non-leptonic transitions) the existence of a right-handed $(c,s)_R$ current is unexpected. However, experimentally, the absence of such a current is far from being established, as Harari has strongly pointed out.[1]

Several experimental tests have been proposed to determine the V,A structure of the (c,s) current. The most direct ones concern charm semileptonic decays. The inclusive lepton spectrum from D semileptonic decays is not particularly sensitive to this structure.[3] Although a large V−A piece seems compatible with the data, a large V+A current leading to a resulting dominant V is not excluded, as shown by Kane.[3] The best process would be the expected dominant semileptonic decay $D \to K^* \ell \nu$ to which the V and A parts contribute. A careful experimental study of this process would give much information on the (c,s) current.[4] The y distribution of dimuon events in $\bar{\nu}_\mu N$ scattering would test also the Lorentz structure of the (c,s) current. The present results are consistent with V−A but a large V+A admixture is not excluded.[5] Other tests have been proposed involving the measurement of the Λ polarization in semileptonic decay of charmed baryons, or the search for some rare decays of the charmed-strange meson F^+.[7] For instance, the leptonic mode $\mu^+\nu_\mu$ would be strongly suppressed if the resulting (c,s) current is purely vector. Notice however, that this does not rule out a combination of the type $(c,s)_L - (c,s)_R$ leading to a dominant axial current.

Since the determination of the V,A structure of the (c,s) current is rather involved, it is worth looking to other phenomena, as non-leptonic transitions, which could clearly distinguish between the various possibilities or at least help to confirm the

results to be obtained from the more direct semileptonic processes. Following similar arguments forbidding a $(c,d)_R$ current[8] we will first examine the K^0-$\bar{K}^0$ and D^0-$\bar{D}^0$ systems. We will later see that a clean test is provided by two body decay modes of the D^0 and F^+ mesons which are expected to be dominant according to the minimal GIM scheme. In what follows we assume a (c,s) current given by the left-handed piece of the GIM scheme plus a right-handed part of strength ε. Our aim is to find constrains on ε.

For D^0-$\bar{D}^0$ or K^0-$\bar{K}^0$ systems one should consider in addition to the minimal theory (Fig. 1a) the diagram 1b. We get, for K_L-K_S (the interference vanishes),

$$m_{K_L} - m_{K_S} = K\, m_c^2 \sin^2\theta_c \left[\cos^2\theta_c + 2\varepsilon^2 \left(\log \frac{M_W}{m_c} - 1\right)\right] \qquad (1)$$

where

$$K = \frac{G}{\sqrt{2}}\, f_K^{\,2}\, m_K\, \frac{\alpha}{4\pi}\, \frac{1}{M_W^2 \sin^2\theta_W} .$$

The experimental value $m_{K_L} - m_{K_S} = 0.5 \times 10^{10}\ \mathrm{sec}^{-1}$ is in nice agreement with a realistic value of the charmed quark mass m_c = 1.5 GeV, as predicted by Gaillard and Lee.[9] In a somewhat unrealistic situation as m_c = 1 GeV and M_W = 37.4 GeV we could have a right-handed current of strength $\varepsilon \simeq 0.5$. If M_W = 75 GeV, m_c = 1.5 GeV and $\varepsilon = 1$ or $\varepsilon = 0.5$ we would get a mass difference too large by respectively a factor ~ 7 or ~ 2.5. We conclude that this simple estimation excludes a $(c,s)_R$ current of large strength.

It is well known that the GIM scheme gives a very small $D^o - \bar{D}^o$ mixing.[10] The mixing is negligible even if there is a large right-handed current. We should now substitute in (1) m_c by m_s. The relevant quantity which enters in the ratio of equal to opposite charge kaons, measuring the amount of $D^o - \bar{D}^o$ mixing is $\delta m/\Gamma$, where Γ is the average of total widths of the two CP eigenstates. A reasonable order of magnitude for Γ could be given by the simple free quark model estimate (incoherent sum of quark color diagrams)

$$\Gamma_D \cong \frac{G^2}{192\,\pi^3}\, m_c^5 \;\; F(x_c) \cdot 5 \cdot (1 + \varepsilon^2) \qquad (2)$$

where $F(x_c) = 1 - 8x_c^2 + 8x_c^6 - x_c^8 - 24x_c^2 \log x_c$, $x_c = m_s/m_c$, and $5 = 3$ (from hadrons) + 2 (from semileptonic e or μ). For $m_c = 1.6$ GeV and $x_c = 1/3$ we get $\Gamma = 2.5\,(1 + \varepsilon^2) \times 10^{12}\ \mathrm{sec}^{-1}$. Due to the small D lifetime we get a very small mixing effect, even if we take the strength of the right handed current $\varepsilon = 1$, since we obtain $\delta m/\Gamma \sim 10^{-3}$. The observed absence of $D^o - \bar{D}^o$ mixing (within large errors)[11], although rules out a flavor changing neutral (c,u) current at order G, cannot constrain a RH (c,s) piece.

The GIM current $\cos\theta_c (c,s)_L$, combined with a right-handed current $\varepsilon(c,s)_R$, would lead to a dominant vector or axial-vector current according to the sign of ε. A particularly simple and sensitive text is then provided by the comparison of pure parity conserving and pure parity violating non-leptonic decays. Although non-leptonic decays are poorly understood relative to semileptonic

processes, in some particular charge channels only the vector or axial vector (c,s) current contributes appreciably. This would lead to clean selection rules if the right-handed current is comparable in strength to the left-handed current. As an example let us first consider the F^+ decays $\phi\pi^+$ (parity conserving, P-wave) and $\eta\pi^+$ (parity violating, S-wave). These modes are particularly interesting since they are expected to be dominant within the GIM scheme.[12] What is specific to these modes is that they involve two charged pseudoscalar mesons. In all the diagrams one can draw a W boson is coupled directly to a charged pseudoscalar meson through the axial current. There is no freedom then for the other coupling: it must be V for $\eta\pi^+$ and A for $\phi\pi^+$. This is illustrated by the diagrams of Fig. 2.[†] We only draw diagrams for which the strong interactions are Zweig-ruled allowed. The arguments which follow are however also valid for diagrams forbidden by the Zweig rule. Note that the pole diagrams of Fig. 2b are topologically equivalent to those of Fig. 2a and are just another way of computing these contributions through vector (for $\eta\pi^+$) an axial-vector (for $\phi\pi^+$) dominance. Moreover, due to the fact that the η contains non-strange quarks, we have for $F^+ \to \eta\pi^+$ the specific graph 2c. This contribution is forbidden by vector current conservation, since the initial state is a pseudoscalar which couples

† Note that this is not true for $F^+ \to K^+\bar{K}^o$, $K^+\bar{K}^{*o}$ or for the corresponding D^+ decays: $D^+ \to \bar{K}^o\pi^+$ and $D^+ \to \bar{K}^{*o}\pi^+$. In this case there is another graph (Fig. 2d) which spoils the simple selection rules which hold for $F^+ \to \phi\pi^+$, $\eta\pi^+$ or $D^o \to K^{*-}\pi^+$, $K^-\pi^+$.

to the non-strange $u\bar{d}$ quarks. Let us now compute the diagrams 2a. We will neglect QCD factors in the effective Lagrangian. We think that this is a safe simplification because we are interested in the ratio of these rates. Inserting the vacuum as intermediate state we have the matrix elements (setting $\cos\theta_c = 1$)

$$\frac{G}{\sqrt{2}}\,(1 \pm \varepsilon)\left\langle \pi^+ \middle| \bar{u}\,\gamma_\mu\gamma_5 d \middle| 0 \right\rangle \left\langle \begin{matrix}\eta\\ \phi\end{matrix} \middle| \bar{s} \begin{Bmatrix}\gamma_\mu \\ \gamma_\mu\gamma_5\end{Bmatrix} c \middle| F^+ \right\rangle \qquad (3)$$

These are respectively pure Fermi and pure Gamow-Teller transitions. Computing the matrix elements $\langle F^+|\ldots|\eta,\phi\rangle$ in the non-relativistic limit we get the rates[††]

$$\Gamma(F^+ \to \eta\pi^+) = \frac{1}{6\pi} f_\pi^2 G^2 k_\pi \frac{E_\eta}{M_F} \omega_\pi^{\,2} (1+\varepsilon)^2 \qquad (4)$$

$$\Gamma(F^+ \to \phi\pi^+) = \frac{1}{4\pi} f_\pi^2 G^2 k_\pi^3 \frac{E_\phi}{M_F} (1-\varepsilon)^2 \qquad (5)$$

The factors $(1 \pm \varepsilon)^2$ express the fact that one of these modes is forbidden if the resulting (c,s) current is respectively pure A or pure V. In general, any decay of the type $F^+ \to (s\bar{s})\pi^+$, where $(s\bar{s})$ is any J^P meson (as η, η', ϕ or f) is pure parity violating (for $J^P = 0^-, 1^+, \ldots$) or pure parity conserving (for $J^P = 0^+, 1^-, \ldots$) and the above selection rules would follow if $\varepsilon = -1$ or $+1$.

Other decays useful for our analysis could be $F^+ \to \eta\rho^+$ (P-wave, parity conserving) and $F^+ \to \eta A_1^{\,+}$ (P-wave, parity violating). Only the diagrams 2a and 2b contribute,

[††] The rate for the mode $\eta'\pi^+$ is obtained multiplying (4) by 1/2.

with ρ^+ and $A_1^{\,+}$ playing now the role of π^+. These modes are expected to be important since ρ^+ and $A_1^{\,+}$ have the same quantum numbers as the vector and axial-vector current, which can connect them to the vacuum. But now ρ^+ is coupled to the vector current, and since $F^+ \to \eta\rho^+$ is parity conserving, only the V-piece $1+\varepsilon$ of the (c,s) current contributes. Similarly, for $F^+ \to \eta A_1^{\,+}$, only the A part $1-\varepsilon$ will contribute. This generalizes to any decay of the form $F^+ \to (s\bar{s})\rho^+$ or $F^+ \to (s\bar{s})\,A_1^+$, where $(s\bar{s})$ is any meson.

The rates are given by

$$\Gamma(F^+ \to \eta\rho^+) = \frac{1}{6\pi}\, G^2 \frac{g_\rho^{\,2}}{m_\rho^{\,2}}\, k_\rho^{\,3} \frac{E_\eta}{M_F} (1+\varepsilon)^2 \qquad (6)$$

$$\Gamma(F^+ \to \eta A_1^{\,+}) = \frac{1}{6\pi}\, G^2 \frac{g_{A_1}^2}{m_{A_1}^2}\, k_{A_1}^{\,3} \frac{E_\eta}{M_F} (1-\varepsilon)^2 \qquad (7)$$

where $g_{A_1} \simeq g_\rho$, g_ρ is defined by $\langle \rho^+ | V_\mu^{d\bar{u}} | 0 \rangle = g_\rho \varepsilon_\mu^{(\rho)}$, so that $g_\rho = \frac{\sqrt{2}\, m_\rho^{\,2}}{f_\rho}$ with $f_\rho^2/4\pi \simeq 2$.

Taking $\varepsilon = 0$, we get, from the estimation (1) for the total width, a branching ratio for $\eta\pi^+$ of about 3%, and the ratios:

$$\Gamma(\eta\pi^+) : \Gamma(\phi\pi^+) : \Gamma(\eta\rho^+) : \Gamma(\eta A_1^{\,+}) \cong$$
$$\cong (1+\varepsilon)^2 : 0.9(1-\varepsilon)^2 : 1.3(1+\varepsilon)^2 : 0.3(1-\varepsilon)^2 \qquad (8)$$

If the strength of the $(c,s)_R$ current is significantly different from zero we will have a clear pattern of suppression or enhancement of $\eta\pi^+$ and $\eta\rho^+$ relative to $\phi\pi^+$ and ηA_1^+ according to the relative phase between the left and right parts. The absence of a sizeable right-handed piece will imply comparable rates for $\eta\pi^+$, $\phi\pi^+$, and $\eta\rho^+$.

It is important to note that the ratios (8) cannot distinguish between pure V - A and pure V + A, since the rates depend on the absolute value of the vector or axial-vector couplings. However, the inclusive lepton spectrum in D decays is inconsistent with pure V + A, and a large V - A piece seems to be present. With this rough information from the lepton spectrum, non-leptonic transitions can help to rule out a V + A piece.

Another example of the same situation is given by the D^o decays

$$D^o \to K^-\pi^+,\quad K^{*-}\pi^+,\quad K^-\rho^+,\quad K^-A_1^+.$$

We have here the same kind of selection rules as before but for another reason: only the diagrams 2a and 2b are possible if we safely neglect the Cabibbo-forbidden diagrams (W^- coupled directly to K^-). The rates are given by the same expressions as before with (4), (6) and (7) multiplied by a factor 3/2 . We get the ratios:

$$\Gamma(K^-\pi^+) : \Gamma(K^{*-}\pi^+) : \Gamma(K^-\rho^+) : \Gamma(K^-A_1^+) \cong \cong (1+\varepsilon)^2 : 0.6(1-\varepsilon)^2 : (1+\varepsilon)^2 : 0.1(1-\varepsilon)^2 \tag{9}$$

and $BR(K^-\pi^+) \simeq 3.6\%$ for the GIM current.

Let us now discuss the experimental situation. Concerning the F^+ decays, the results are very preliminary and somewhat contradictory.[13] $\eta\pi^+$ has been observed at DESY, but it has not been observed at SLAC. A peak in the invariant mass of $(K^+K^-\pi^+ + K^+K^-\pi^+\pi^+\pi^- + K^+\bar{K}^o)$ at 2.040 GeV has been observed at SLAC in an early experiment, but not confirmed by a more recent one. Although the situation is still unclear, it will certainly be settled very soon.

Turning now to D^o decays, here we have already some data. The branching ratios which are of interest for us are

$D^o \to$	$K^-\pi^+$	2.2 ± 0.6 %	(ref. 14)
	$\bar{K}^o\pi^+\pi^-$	3.5 ± 1.1 %	(ref. 14)
	$K^-\pi^+\pi^o$	12 ± 6 %	(ref. 15)
	$K^-\pi^+\pi^+\pi^-$	3.2 ± 1.1 %	(ref. 14)

For the mode $K^-\pi^+$ we get in our simple model a branching ratio $0.03 \times (1+\varepsilon)^2/(1+\varepsilon^2)$. This means that a large negative ε seems excluded. For positive ε we get a branching ratio which is rather insensitive to ε. What would be important to detect the presence or absence of a right-handed piece ($\varepsilon > 0$) would be the separation of the quasi-two body modes $K^{*-}\pi^+, K^-\rho^+$ from the multibody decays $\bar{K}^o\pi^+\pi^-$ and $K^-\pi^+\pi^o$. A more difficult separation would also be necessary for the mode $K^-A_1^+$. As for the three body decays, it is important to note that there is not yet a careful Dalitz plot analysis. Only for the decay $\bar{K}^o\pi^+\pi^-$ the present data does not seem to indicate strong $K^{*-}\pi^+$ and $\bar{K}^o\rho^o$ signals,[14] although the experimentalists consider this indication as very preliminary and subject to further study. Let us assume however that $\bar{K}^o\pi^+\pi^-$ is dominated by the ground state quasi-two body modes: $K^{*-}\pi^+$, $\bar{K}^o\rho^o$. We could go further with our model and compute the ratio of these rates. The diagram contributing to $\bar{K}^o\rho^o$ is of the form 2d. Assume the minimal GIM scheme, $\varepsilon = 0$. Performing a Fierz transformation and taking into account the color factors we get a ratio in amplitude (neglecting SU(3)-breaking effects which are similar for both modes), $A(\bar{K}^o\rho^o)/A(K^{*-}\pi^+) = 1/3\sqrt{2}$. $K^{*-}\pi^+$ is then predicted to be the dominant ground state mode. Note that K^{*-} decays into $\bar{K}^o\pi^-$ 2/3 of the time. We see then from this very simple model that the experimental BR for $\bar{K}^o\pi^+\pi^-$ appears to be rather large. Even if, as indicated by the data, the $K^{*-}\pi^+$ signal is not strong, there is no clear contradiction with our prediction $K^{*-}\pi^+ \sim K^-\pi^+$ for $\varepsilon = 0$, since we must multiply by 3/2 the fraction of $K^{*-}\pi^+$ in the $\bar{K}^o\pi^+\pi^-$ events to compare with $K^-\pi^+$.† We think that at present the comparison of $K^-\pi^+$ and $\bar{K}^o\pi^+\pi^-$ is not in clear disagreement with the minimal GIM scheme. Moreover, other two body decays involving 2^+ states, $K^{**-}\pi^+$ and $\bar{K}^o f$ can contribute to the rate $\bar{K}^o\pi^+\pi^-$. These decays will populate different regions of the Dalitz plot, diluting the effect of $K^{*-}\pi^+$. We think that it is important to have a Dailtz plot analysis with higher statistics to decide.

† The non-observance of $\bar{K}^o\rho^o$ would be due to another phenomenon: the color factor 1/3 of diagrams 2d.

As for the $K^-\pi^+\pi^o$ we have now three possible decays $K^{*-}\pi^+$, $K^-\rho^+$, $\bar{K}^{*o}\pi^o$. $\bar{K}^{*o}\pi^o$ will be small relative to the others due to the color factor. We get, for $\frac{1}{3}\Gamma(K^{*-}\pi^+) + \Gamma(K^-\rho^+)$, 4.3 % within the minimal GIM scheme. This is almost compatible, only one s.d. away. Let us consider however the possibility of $\varepsilon > 0$. Note that the result is not very sensitive to ε : if $\varepsilon = 1$ we gain about less than a factor of 2. The crucial point to confirm or exclude a RH current would be the comparison between $K^-\pi^+$, $K^{*-}\pi^+$ $K^-\rho^+$.

If we believe the present preliminary impression that there is not a large $K^{*-}\pi^+$ signal, we should face the possibility of a RH piece which could suppress $K^{*-}\pi^+$ relative to $K^-\rho^+$ and $K^-\pi^+$. However, if we need this RH current of about strength one, leading to a pure vector (c,s) current (which, incidently, is not incompatible with the inclusive lepton spectrum), then we will be in trouble to explain the $K_L - K_S$ mass difference.

Let us now see that the comparison between similar decays can help to study the V,A structure of other currents. Although neutral current data assign to a good approximation the d quark to a left-handed doublet, it is worth looking for similar arguments which could help to exclude a $(c,d)_R$ current at the Cabibbo-forbidden level. For K_L-K_S we get the same expression (1) with the substitution $\sin^2\theta_c \leftrightarrow \cos^2\theta_c$. In the unlikely case $m_c = 1$ GeV and $M_W = 37.4$ GeV, a RH piece of strength $\varepsilon = 0.5 \sin\theta_c$ could be allowed. If $\varepsilon = \sin\theta_c$ and $m_c = 1.5$ GeV, $M_W = 75$ GeV, we obtain a $K_L - K_S$ mass difference too large by a factor ~ 7. This excludes a $(c,d)_R$ piece of strength $\sin\theta_c$. The same argument as before follows also for the Cabibbo-forbidden transitions $D^o \to \pi^+\pi^-$, $\pi^+\rho^-$, $\pi^-\rho^+$, $\pi^-A_1^+$, for which the only surviving mechanism in the exact SU(3) limit is 2a (we can also have a contribution from the "penguin" diagram[16] which is also Cabibbo-suppressed but first order in the mass difference $m_s - m_d$). Similar rates for these processes (up to differences in phase space) will exclude a $(c,d)_R$ piece at the Cabibbo-forbidden level.

Comparison of similar decays can also be useful for currents involving heavier quarks. The Cabibbo matrix for the presumed three left-handed quark doublets $(u,d)_L$, $(c,s)_L$, $(t,b)_L$[17] predicts dominant decays $b \to c + \bar{u}d$ $(\ell\,\bar{\nu}_\ell)$ (Cabibbo-suppressed) and $t \to b + u\bar{d}$ $(c\bar{s}, \bar{\ell}\nu_\ell)$ (Cabibbo-allowed). For the B decays, future rough results on the inclusive lepton spectrum (comparable to present data for charm) will indicate if there is an important V - A current, as expected theoretically. Limits on the B's lifetime will indicate if the decays are Cabibbo-forbidden, and the observation of multi-leptons if $b \to c$ is dominant. Then, comparison of the rates $B^o(b\bar{d}) \to D^+\pi^-$, $D^{*+}\pi^-$, $D^+\rho^-$, $D^+A_1^-$ will be useful to exclude a $(c,b)_R$ current, even at the Cabibbo-forbidden level.

The same argument applies to the $T^o(t\bar{u})$ decays: $T^o \to B^-\pi^+$, $B^{*-}\pi^+$, $B^-\rho^+$, $B^-A_1^+$ and to the (t,b) current.

In conclusion, we have seen that certain non-leptonic transitions can give straightforward information on the V,A structure of currents involving heavy quarks. In particular, the $K_L - K_S$ mass difference seems to rule out an important $(c,s)_R$ current. As for the D^o decay modes, the observation ~~of~~ $K^-\pi^+$ excludes - like the inclusive lepton spectrum - a resultant pure axial (c,s) current. A clear way to discard or establish a RH current would be the experimental separation of the modes $K^-\rho^+$ and $K^{*-}\pi^+$ and the observation of the decays of the F meson, $F^+ \to \phi\pi^+, \eta\pi^+, \eta\rho^+$.

When this paper was essentially finished, we noticed a recent preprint (Y. Abe, K. Fujii, S. Osanai and K. Satô, Hokkaido University) pointing out the interest of two body decays in connection with a right-handed (c,s) current. These authors infer from the data that there is a strong $D^o \to K^-\rho^+$ signal. To our knowledge there is not a Dalitz plot analysis allowing this conclusion.

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FIGURE CAPTIONS

Fig. 1: Diagrams contributing to the $D^o - \bar{D}^o$ or $K^o - \bar{K}^o$ (with $s \longleftrightarrow c, u \longleftrightarrow d$) mixing parameter.

Fig. 2: Types of diagrams contributing to F and D decays.

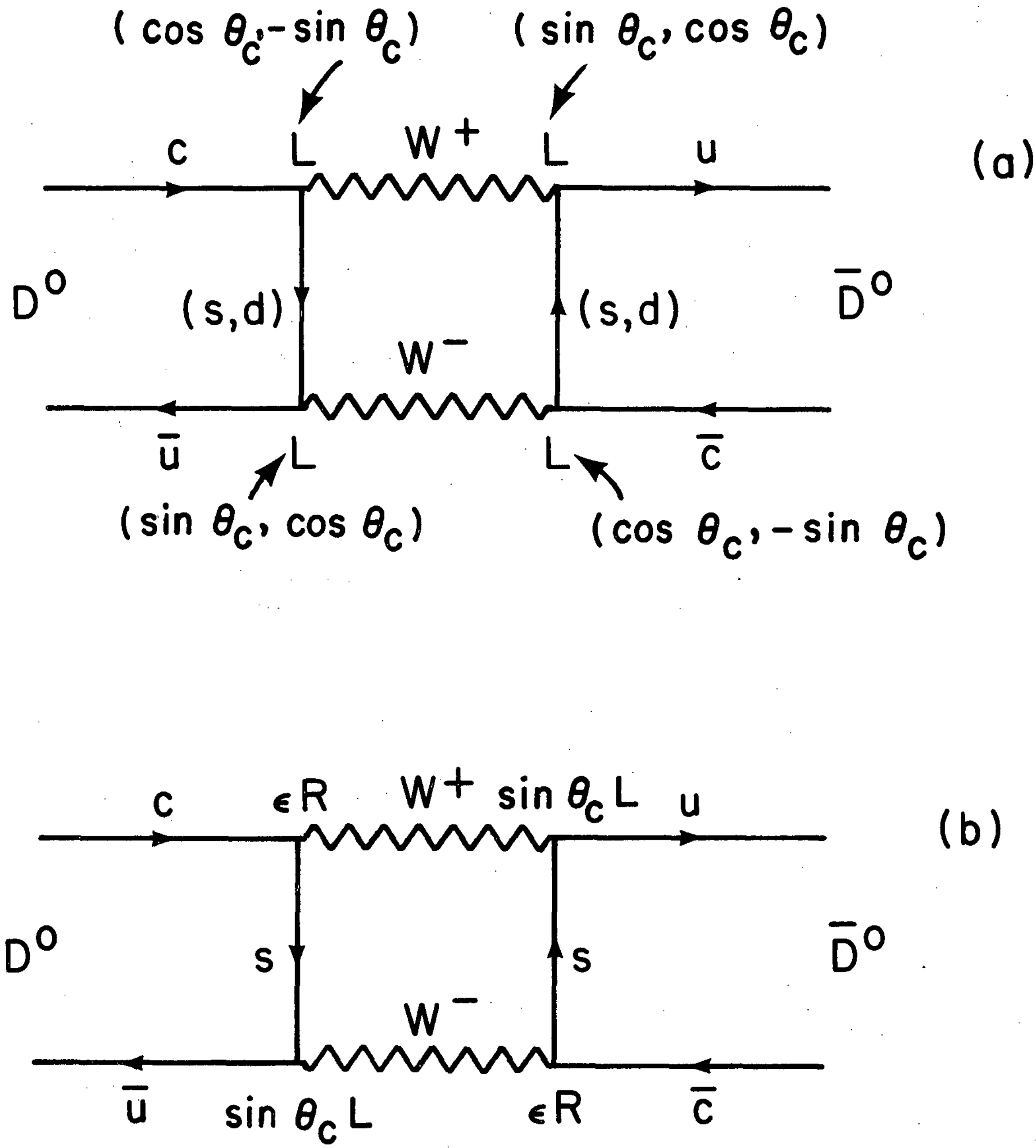

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Fig. 1

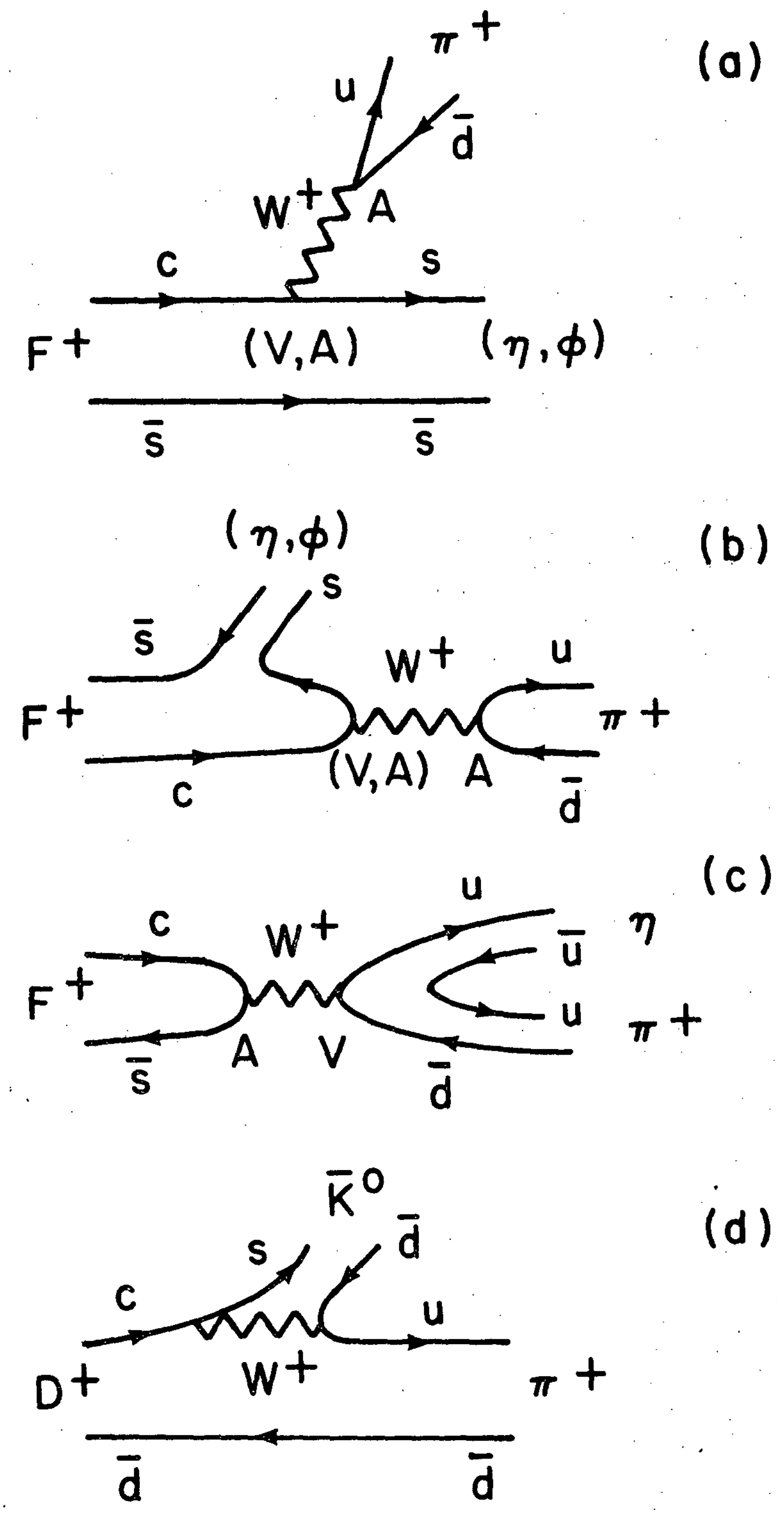

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Fig. 2

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