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Superficial Non-Unitarity of the Quark-Mixing Matrix as a Possible Evidence for the Substructure of Quarks

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Abstract

Superficial non-unitarity of the quark-mixing matrix, which has been predicted to be momentum-transfer dependent due to the possible substructure of quarks, is discussed in composite models of quarks and leptons. A precise measurement of the momentum-transfer dependence of the branching ratios for inclusive hadronic decays of $\tau \rightarrow \nu_\tau +$ *hadrons* is proposed as one of the best experimental searches for a possible evidence for the substructure of quarks.

The standard model (or unified gauge theory) of electroweak interactions has been investigated theoretically and confirmed experimentally for the last more than three decades since its proposal in 1960's [1]. The natural extension to grand unification of strong and electroweak interactions has also been studied theoretically and tested experimentally for the last more than two decades since its proposal in 1970's [2]. Furthermore, a possible extension to supergrand unification of all elementary particle forces including gravity has been discussed for the last almost two decades.

As is well-known, the standard model has two clear defects: 1) the elementary Higgs scalar in the model suffers from a quadratically divergent self-mass, requiring "fine-tuning" and 2) the model needs so many arbitrary parameters including the two gauge coupling constants (g and g'), the Higgs mass squared (μ^2) and quartic coupling constant (λ), and the Higgs Yukawa coupling constants (Y's) or, equivalently, the quark and lepton masses (m_q's and m_ℓ's) and the quark and lepton mixing matrices (V and U). There are two ways to eliminate these defects: 1) modify the model into the minimal supersymmetric standard model by assuming that all the fundamental particles are associated with their superpartners [3] and 2) take the model as an "effective model" by assuming that all the "fundamental particles" are composed of "subquarks" (or "preons"), the more fundamental particles [4–6].

As it stands now, the standard model is not jeopadized by any experimental data except for those on the quark-mixing matrix [7], some of whose elements measured experimentally [8] and radiative-corrected theoretically [9], $|V_{ud}| = 0.9745 \pm 0.0007$, $|V_{us}| = 0.2205 \pm 0.0018$, $|V_{ub}| = 0.003 \pm 0.001$, seem to violate the unitarity of V (i.e., $VV^\dagger = V^\dagger V = 1$) at the 1σ level as [10]

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.0017 \pm 0.0015. \quad (1)$$

Obviously, there are three possibilities to save the unitarity of V: the apparent violation of unitarity is due to 1) the experimental errors, 2) the unknown fourth and higher generations of quarks and leptons [11], and 3) the unknown radiative corrections to the elements of V from unknown particles such as the superpartners of quarks and leptons [12] in the minimum supersymmetric standard model [13]. The purpose of this letter is to discuss the fourth possibility that the superficial non-unitarity of V is due to the possible substructure of quarks. We shall also propose a precise measurement of the momentum-transfer dependence of the branching ratios for inclusive hadronic decays of $\tau \rightarrow \nu +$ *hadrons* as one of the best experimental searches for a possible evidence for the substructure of quarks.

The weak charged current can be written in terms of hadrons (baryons and mesons) and leptons as a sum of so many phenomenological terms,

$$
\begin{aligned}
J_\mu \cong\ & \bar{\nu}_e\gamma_\mu(1-\gamma_5)e + \bar{\nu}_\mu\gamma_\mu(1-\gamma_5)\mu + \bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\tau \\
& + \frac{G^\beta}{G^\mu}\bar{p}\gamma_\mu(1-\frac{g_A^\beta}{g_V^\beta}\gamma_5)n + \frac{G^\Lambda}{G^\mu}\bar{p}\gamma_\mu(1-\frac{g_A^\Lambda}{g_V^\Lambda}\gamma_5)\Lambda + \cdots, \qquad (2)
\end{aligned}
$$

where G^β/G^μ, g_A^β/g_V^β, $\cdots$ are phenomenological parameters. It can also be written in terms of quarks, $U_i = (u_i, c_i, t_i)$ and $D_i = (d_i, s_i, b_i)$ $(i = 1,2,3)$, and leptons, $N = (\nu_e, \nu_\mu, \nu_\tau)$ and $L = (e, \mu, \tau)$, as the sum of at least twelve terms [7],

$$
\begin{aligned}
J_\mu &\cong \bar{N}\gamma_\mu(1-\gamma_5)L + \bar{U}_i\gamma_\mu(1-\gamma_5)VD_i \\
&= \bar{\nu}_e\gamma_\mu(1-\gamma_5)e + \bar{\nu}_\mu\gamma_\mu(1-\gamma_5)\mu + \bar{\nu}_\tau\gamma_\mu(1-\gamma_5)\tau \\
&\quad + V_{ud}\bar{u}_i\gamma\mu(1-\gamma_5)d_i + V_{us}\bar{u}_i\gamma_\mu(1-\gamma_5)s_i + \cdots, \quad i = 1,2,3, \qquad (3)
\end{aligned}
$$

where $V_{UD}(= V_{ud}, V_{us}, \cdots)$ are the nine parameters called CKM quark-mixing matrix elements. Note that no lepton-mixing (i.e., $U = 1$) and the only three generations of quarks and leptons are assumed for simplicity unless otherwise stated in this letter. Furthermore, in the minimal composite model of quarks and leptons [4-6] it can be most simply written in terms of an iso-doublet of spinor subquarks with charges $\pm 1/2$, w_1 and w_2 (called "wakems" standing for weak and electromagnetic), as a single term

without any free parameters,

$$J_\mu = \bar{w}_1\gamma_\mu(1-\gamma_5)w_2. \qquad (4)$$

In other words, the CKM matrix elements can be taken as the expectation values of this subquark current as [14]

$$
\begin{aligned}
\bar{U}_i\gamma_\mu(1-\gamma_5)VD_i &\cong \langle U_i \mid \bar{w}_1\gamma_\mu(1-\gamma_5) \mid D_i\rangle, \ \text{i.e.}, \\
V_{ud}\bar{u}_i\gamma_\mu(1-\gamma_5)d_i &\cong \langle u_i \mid \bar{w}_1\gamma_\mu(1-\gamma_5)w_2 \mid d_i\rangle, \\
V_{us}\bar{u}_i\gamma_\mu(1-\gamma_5)s_i &\cong \langle u_i \mid \bar{w}_1\gamma_\mu(1-\gamma_5)w_2 \mid s_i\rangle, \cdots. \qquad (5)
\end{aligned}
$$

This is the best example for the principle of "triplicity of hadrons, quarks, and subquarks" [15], which asserts that a certain physical quantity can be taken equally well as a composite operator of hadrons, of quarks, or of subquarks.

By using the algebra of subquark currents [16], the (approximate) unitarity of V (i.e., $VV^\dagger \cong V^\dagger V \cong 1$) has been demonstrated [17]. Furthermore, given the experimental value of V_{us}, all the other matrix elements can be successfully explained or predicted by using the five relations derived in the minimal composite model of quarks [18]. In fact, given a set of the relations of

$$
\begin{aligned}
& V_{us} \cong -V_{cd}^*,\ V_{cb} \cong -V_{ts}^*,\ \mid V_{cb} \mid \cong (m_s/m_b) \mid V_{us} \mid, \\
& \mid V_{ub} \mid \cong (m_s/m_c) \mid V_{us}V_{cb} \mid,\ \mid V_{td} \mid \cong \mid V_{us}V_{cb} \mid, \qquad (6)
\end{aligned}
$$

we have obtained the solution of [6]

$$
\begin{pmatrix}
\mid V_{ud} \mid & \mid V_{us} \mid & \mid V_{ub} \mid \\
\mid V_{cd} \mid & \mid V_{cs} \mid & \mid V_{cb} \mid \\
\mid V_{td} \mid & \mid V_{ts} \mid & \mid V_{tb} \mid
\end{pmatrix}
$$

$$
= \begin{pmatrix} \underset{(0.9745\pm0.0007)}{0.975} & \underset{(\text{input})}{0.2205 \pm 0.0018} & \underset{(0.003\pm0.001)}{0.0017} \\ \underset{(0.218\sim0.224)}{0.2205 \pm 0.0018} & \underset{(0.9738\sim0.9752)}{0.975} & \underset{(0.032\sim0.048)}{0.021} \\ \underset{(0.004\sim0.015)}{0.0046} & \underset{(0.030\sim0.048)}{0.021} & \underset{(0.9988\sim0.9995)}{0.9996} \end{pmatrix} \quad (7)
$$

where the values indicated in the parentheses denote the experimental [8,9], to which our predicted values should be compared. Note that the theoretical values for V_{ud}, V_{cs}, and V_{tb} and the experimental ones for V_{cs}, V_{td}, V_{ts}, and V_{tb} are all estimates from the assumed unitarity of V, which is subject to doubt in this letter.

Now we come to the main point: as already predicted in 1977 [14], an immediate consequence of our picture of the CKM matrix in the minimal composite model of quarks is that the matrix elements must depend on the momentum transfer ($q = p - p'$) between quarks (whose momenta are p and p') as the form factors of hadrons, i.e.,

$$
V_{UD}(q^2)\bar{U}_i(p')\gamma_\mu(1-\gamma_5)D_i(p) \cong \langle U_i(p') \mid \bar{w}_1\gamma_\mu(1-\gamma_5)w_2 \mid D_i(p)\rangle. \quad (8)
$$

Note that we have introduced and shall assume hereafter, unless otherwise stated, the only one form factor (similar to F_1 for the electromagnetic form factors of baryons) by ignoring not only the difference between the vector and axial-vector form factors but also all the other form factors such as the one similar to F_2 for the electromagnetic form factors of baryons since both the difference and the latter form factors may be much smaller than the former for some good reasons [19] and their effects may well be neglected in discussions in this letter.

The algebra of subquark currents [16] includes the familiar commutation relation of isospin currents,

$$
\delta(x_0 - y_0)[J_0^+(x), J_0^-(y)] = 2\delta^4(x-y)J_0^3(x), \quad (9)
$$

for

$$
J_\mu^\pm(x) = \bar{w}(x)\gamma_\mu\tfrac{1}{2}\tau^\pm w(x),\ J_\mu^3(x) = \bar{w}(x)\gamma_\mu\tfrac{1}{2}\tau_3 w(x), \quad (10)
$$

where $w = (w_1, w_2)$, $\tau^\pm = \tau_1 \pm i\tau_2$, and $\tau_i (i = 1,2,3)$ are the Pauli isospin matrices. This relation sandwiched between $\langle U_i(p') \mid$ and $\mid U_i(p')\rangle$ ($\langle D_i(p) \mid$ and $\mid D_i(p)\rangle$) leads to the unitarity of $V(q^2)$ for an arbitrary momentum-transfer squared, i.e. [20],

$$
V(q^2)V^\dagger(q^2)(= V^\dagger(q^2)V(q^2)) = 1 \quad (11)
$$

if the single-quark intermediate states $\mid D_i(p)\rangle$ ($\mid U_i(p)\rangle$) form a complete set for states with the quantum numbers of $D_i(U_i)$, i.e.,

$$
\sum_{D,p} \mid D_i(p)\rangle\langle D_i(p) \mid = 1 \ (\sum_{U,p'} \mid U_i(p')\rangle\langle U(p') \mid = 1). \quad (12)
$$

Here, however, it can be clearly seen that not only the single-particle states of the unknown fourth and higher generations of quarks previously discussed as the possibility 2) but also all the other states except for the single-particle states of the first, second, and third generations of quarks may play roles of intermediate states giving non-vanishing contributions, break the completeness condition (12), and, therefore, violate the unitarity relation (11). In composite models of quarks, the latter include excited states of quarks and continuum ("scattering") states of constituent subquarks. In this case, we can expect that the sign (or direction) of such deviation from the unitarity of V is always negative, i.e., $\sum_D \mid V_{UD}(q^2) \mid^2 < 1$ and $\sum_U \mid V_{UD}(q^2) \mid^2 < 1$ since the possible contributions of such intermediate states are positive. We shall go back to this possibility later.

Even if the unitarity relation (11) holds, it indicates, e.g.,

$$
\mid V_{ud}(0) \mid^2 + \mid V_{us}(0) \mid^2 + \mid V_{ub}(0) \mid^2 = 1 \quad (13)
$$

but does not $| V_{ud}(q_1^2) |^2 + | V_{us}(q_2^2) |^2 + | V_{ub}(q_3^2) |^2 = 1$ for $q_1^2 \neq q_2^2$, $q_2^2 \neq q_3^2$, or $q_3^2 \neq q_1^2$. In this case, however, we can obtain many useful relations, e.g.,

$$Re[V_{ud}(0)^* V'_{ud}(0) + V_{us}(0)^* V'_{us}(0) + V_{ub}(0)^* V'_{ub}(0)] = 0, \quad (14)$$

by expanding $V(q^2)$ into a power-series of q^2 as $V(q^2) = V(0) + q^2 V'(0) + \cdots$. Suppose that the apparent violation of the unitarity of V indicated in Eq. (1) is only superficial and due to the momentum-transfer dependence of V, i.e.,

$$\begin{aligned} &| V_{ud}(< q_1^2 >) |^2 + | V_{us}(< q_2^2 >) |^2 + | V_{ub}(< q_3^2 >) |^2 - 1 \\ \cong\ & 2\{(< q_1^2 > - < q_3^2 >) Re[V_{ud}(0)^* V'_{ud}(0)] \\ & + (< q_2^2 > - < q_3^2 >) Re[V_{us}(0)^* V'_{us}(0)]\} \neq 0, \end{aligned} \quad (15)$$

where $< q_i^2 >$ $(i = 1, 2, 3)$ are the average momentum-transfers squared relevant to the processes in which V_{uD} $(D = d, s, b)$ are measured experimentally. Since $< q_1^2 > \sim (m_n - m_p)^2$, $< q_2^2 > \sim m_K^2$, and $< q_3^2 > \sim m_B^2$, $< q_1^2 > \ll < q_2^2 > \ll < q_3^2 >$. Then, Eqs. (1) and (15) indicate $2Re[V_{ud}(0)^* V'_{ud}(0) + V_{us}(0)^* V'_{us}(0)] \cong (0.0017 \pm 0.0015) / < q_3^2 >$. For small q^2, $V_{UD}(q^2)$ can be approximated by

$$V_{UD}(q^2) \cong V_{UD}(0) \left(1 \pm \frac{q^2}{\Lambda_{UD\pm}^2}\right), \quad (16)$$

where $\Lambda_{UD\pm}$ are constant parameters representing the size inverses of U and D quarks. Therefore, $\pm | V_{ud}(0) |^2 / \Lambda_{ud\pm}^2 \pm | V_{us}(0) |^2 / \Lambda_{us\pm}^2 \cong (0.0017 \pm 0.0015) / 2 < q_3^2 >$. It suggests that the non-unitarity of V indicated in Eq. (1) may be superficial and due to the possible substructure of quarks if the size inverse of quarks is smaller than $10^2 < q_3^2 >^{1/2}$ (~ 0.5 TeV). It is interesting to see that this upper bound on the size inverse of quarks is of the same order of magnitude as the lower bound previously

obtained by us [21] from the recent HERA ep scattering data. In this case, the signs of the derivatives (or slopes) of $V'_{UD}(0)$ are either positive or negative so that the relation (14) may be satisfied. However, some model calculations [20] strongly indicate that all $| V_{UD}(q^2) |$ for the same generation of U and D (such as $| V_{ud}(q^2) |$, $| V_{cs}(q^2) |$, and $| V_{tb}(q^2) |$) decrease as $| q^2 |$ increases while some for the different generation of U and D (such as $| V_{us}(q^2) |, \cdots$) increase. This seems very natural since the quark-mixing matrix elements are essentially the magnitudes of overlapping between the two wave functions of U and D quarks which are composite states of subquarks.

In order to find whether the apparent non-unitarity of V in Eq. (1) is really due to the substructure of quarks, not only more precise measurements of the matrix elements of V and more accurate calculations of the radiactive corrections to V but also a direct observation of the momentum-transfer dependence of the matrix elements is highly desirable. Theoretically, one of the best ways to observe it seems to measure the ratio of the differential cross section for strangeness (charm, "bottomness", or "topness") changing neutrino (electron) processes, $\overset{(-)}{\nu} + \binom{p}{n} \to \ell^{\pm} +$ $hadrons$ $(e + p \to \nu_e +$ $hadrons$), to that for conserving ones since, e.g.,

$$\frac{d\sigma(\bar{\nu} + p \to \ell^+ + \ hadrons \ \text{ with } \Sigma S = -1)/dq^2}{d\sigma(\bar{\nu} + p \to \ell^+ + \ hadrons \ \text{ with } \Sigma S = 0)/dq^2} \cong \frac{| V_{us}(q^2) |^2}{| V_{ud}(q^2) |^2}. \quad (17)$$

Experimentally, however, it seems difficult to distinguish the strangeness changing processes from the conserving ones by detecting and identifying all produced hadrons in a final state. Also, since radiative corrections to the differential cross sections for these processes are strongly momentum-transfer dependent, to extract the small momentum-transfer dependence of V from the experimental data seems very difficult (though not impossible).

The best way to observe the momentum-transfer dependence of V seems to measure the differential branching widths for inclusive hadronic decays of $\tau \to \nu_\tau + \textit{hadrons}$ as a function of q^2, the momentum-transfer squared of leptons or the invariant mass squared of hadrons. The point is the following: although calculation of the branching widths for exclusive hadronic decays such as $\tau \to \nu_\tau + \pi^-$, $\nu_\tau + K^-$, and $\nu_\tau + \pi^- + \pi^0$ depends not only on the CKM matrix elements but also on other dynamical parameters such as the decay constants (f_π, f_K, etc.), the coupling constants (g_ρ, g_{K^*}, etc.) and the form factors of hadrons [22], that for inclusive ones depends only on the matrix elements and the spectral functions for the product of weak charged currents [23]. In fact, the differential branching ratio for the inclusive hadronic decay of $\tau^- \to \nu_\tau + \textit{hadrons}$ which are produced by hadronization of a D quark and a $\bar{U}$ antiquark can be expressed in terms of the matrix element and spectral functions as

$$\frac{d\Gamma(\tau^- \to \nu_\tau + \textit{hadrons}\text{ from } D\bar{U})}{\Gamma(\tau^- \to \nu_\tau + e + \bar{\nu}_e)dq^2} = \frac{12\pi^2 S_{EW} |V_{UD}(q^2)|^2}{m_\tau^2}(1 - \frac{q^2}{m_\tau^2})^2[(1 + \frac{2q^2}{m_\tau^2})\rho^{(1)}_{UD}(q^2) + \rho^{(2)}_{UD}(q^2)], \quad (18)$$

where $S_{EW}(\cong 1.0194)$ is the radiative correction factor calculated in the standard model of electroweak interactions [24] and $\rho^{(i)}_{UD}(q^2)(i = 1, 2)$ are the spectral functions of the weak charged currents of $J^{UD}_\mu[\equiv \bar{U}_i\gamma_\mu(1 - \gamma_5)D_i]$ defined by

$$(q_\mu q_\nu - q^2 g_{\mu\nu})\rho^{(1)}_{UD}(q^2) + q_\mu q_\nu \rho^{(2)}_{UD}(q^2) \equiv \sum_n (2\pi)^3\delta^4(q - p_n)\langle 0 \mid J^{UD}_\mu(0) \mid n\rangle\langle n \mid J^{UD}_\nu(0)^\dagger \mid 0\rangle. \quad (19)$$

Furthermore, for large q^2 (much larger than m_ρ^2, $m_{K^*}^2$, etc.), the spectral functions can be approximated to a very good accuracy by the quark-loop calculation with radiative-gluon corrections as

$$\rho^{(1)}_{UD}(q^2) = \frac{1}{2\pi^2}[1 + \frac{\alpha_s(q^2)}{\pi} + O(\alpha_s^2, \frac{m^2_{U,D}}{q^2})]$$

and

$$\rho^{(2)}_{UD}(q^2) = O\left(\frac{m^2_{U,D}}{2\pi^2 q^2}\right), \quad (20)$$

where $\alpha_s(q^2)$ is the running gluon coupling constant known experimentally [8]. Therefore, it seems promising to observe the momentum-transfer dependence of $V_{UD}(q^2)$ by measuring the differential branching ratio for the inclusive hadronic decay of $\tau^- \to + \textit{hadrons}$ from $D\bar{U}$ as a function of q^2, the invariant mass squared of hadrons.

Before conclusion, let us go back to the possibility that the unitarity relation (11) is violated due to the possible existence of excited states of quarks and/or continuum states of constitutent subquarks. If this is the case, the commutation relation of subquark currents (9) leads to the following sum rule for "inelastic structure functions of a quark" [16] for the inelastic neutrino (antineutrino) scattering of $\overset{(-)}{\nu} + q \to \textit{hadrons}$:

$$\int \frac{d(p \cdot q)}{m_q}[\bar{W}^q_2(p \cdot q, q^2) - W^q_2(p \cdot q, q^2)] = 4I^q_3 = \begin{cases} 2 \text{ for } q = U \\ -2 \text{ for } q = D \end{cases} \quad (21)$$

where I^q_3 is the third component of the isospin of q quark and $\overset{(-)}{W^q_2}(p \cdot q, q^2)$ is defined by

$$-(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2})\overset{(-)}{W^q_1}(p \cdot q, q^2) + \frac{1}{m_q^2}(p_\mu - \frac{p \cdot q}{q^2}q_\mu)(p_\nu - \frac{p \cdot q}{q^2}q_\nu)\overset{(-)}{W^q_2}(p \cdot q, q^2) + \overset{(-)}{X^q_{[\mu,\nu]}}(p, q) \equiv \sum_n (2\pi)^3\delta^4(p + q - p_n)\frac{E_q}{m_q}\langle q_i(p) \mid J^\pm_\mu(0) \mid n\rangle\langle n \mid J^\mp_\nu(0) \mid q_i(p)\rangle. \quad (22)$$

Therefore, it is interesting to see that this "generalized Adler sum rule" [25] can be taken as a generalization of the generalized unitarity relation of the CKM quark-mixing matrix (11).

In conclusion, we hope that the future experiments in "τ factories" will tell us whether the apparent non-unitarity of the quark-mixing matrix is due to the substructure of quarks by observing the momentum-transfer dependence of the matrix elements.

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