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Can the s quark be treated as heavy in spectroscopy?

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In the heavy quark limit, the two mass eigenstates of the heavy-flavored mesons with $J^P = 1^+$ are labeled with the total angular momentum of the light system $j = 1/2$ and $3/2$. If the s quark were treated as heavy, both the d-to-s-wave ratio of the decay $K_1 \to K^*\pi$ and a recent analysis of the τ-decay mode $\tau \to \nu_\tau K_1$ would suggest that the lighter meson $K_1(1270)$ should be assigned to the $j = 3/2$ state, while the heavier $K_1(1400)$ be the $j = 1/2$ state. This level pattern would require the spin-orbit coupling for the strange mesons to be opposite in sign to that for the nonstrange mesons and for the charmonia.

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I. INTRODUCTION

The limit of the heavy b quark is certainly a good approximation to the real world. The heavy c quark may not be a bad approximation either. The s quark is not heavy, but not as light as the u and d quarks. In many cases the flavor SU(3) symmetry works well after nondegeneracy of the s quark mass is taken into account as symmetry breaking. However some features of s quark physics are understood if the s quark is regarded as heavy. A notable example is the Okubo-Zweig-Iizuka suppression of the decay $\phi \to \pi\pi\pi$, which is a direct consequence of the fact that the s quark mass, or twice the s quark mass, is heavier than the QCD scale. Are there other aspects of s quark physics that can be understood with the s quark being heavy? In this report, we address this question with a recent analysis of the τ decay [1].

In the flavor SU(3) symmetry where the s quark is treated as light, it is convenient to label the two $\bar{s}u$ states of $J^P = 1^+$ with ${}^3P_1$ and ${}^1P_1$. Symmetry breaking mixes the closely spaced ${}^3P_1$ and ${}^1P_1$ states into two mass eigenstates. On the other hand, if the s quark is treated as heavy and nearly static, the two mass eigenstates of $J^P = 1^+$ would be labeled with the total angular momentum $\mathbf{j}$ of the nonstrange light cloud, $j = 1/2$ and $3/2$ [2,3]. These levels would be degenerate with $J^P = 0^+$ and $J^P = 2^+$ states, respectively. In the heavy s-quark limit, the $j = 1/2$ state can decay into $K^*\pi$ in s wave, while the $j = 3/2$ state must go in d wave [2,3]. In the decay $\tau \to \nu_\tau K_1$, the weak current $\bar{s}\gamma^\mu\gamma_5 u$ can produce only the ${}^3P_1$ state in the flavor SU(3) limit and, as we see below, only the $j = 1/2$ state in the heavy s quark limit. The experimental data clearly favor the assignment of the heavier $J^P = 1^+$ state to $j = 1/2$ and the lighter one to $j = 3/2$. Such ordering of the $J^P = 1^+$ levels would require that the spin-orbit coupling for the strange mesons be opposite in sign to that for the nonstrange hadrons and the charmonia. It means that either treating the s quark as heavy is absurd, or that there is something interesting to explore in the QCD potential for the quark model.

II. d-TO-s-WAVE DECAY RATIO

Two resonances have been known as the strange mesons with $J^P = 1^+$. The lighter one at mass 1270 MeV decays preferentially into ρK, while the heavier one at 1400 MeV decays almost entirely into $K^*\pi$. If the s quark is treated as heavy, mass splitting of the p wave $\bar{s}u$ states is determined by the spin-orbit interaction $\mathcal{H}_{\rm int} = f(r)\boldsymbol{l}\cdot\mathbf{s}$, where $\mathbf{s}$ and $\boldsymbol{l}$ denote the spin and orbital angular momenta of the light nonstrange system. The meson states are labeled with the angular momentum $\mathbf{j} = \boldsymbol{l} + \mathbf{s}$. We expect, for $\langle f(r)\rangle > 0$,

$$|K_1(1270)\rangle = |j = 1/2\rangle \ , \qquad |K_1(1400)\rangle = |j = 3/2\rangle \ , \tag{1}$$

and, for $\langle f(r)\rangle < 0$,

$$|K_1(1270)\rangle = |j = 3/2\rangle \ , \qquad |K_1(1400)\rangle = |j = 1/2\rangle \ . \tag{2}$$

For the heavy s quark, $K_2^*(1430)$ of $J^P = 2^+$ and $K_0^*(\sim 1430)$ of $J^P = 0^+$ would be the $j = 3/2$ and $1/2$ states, respectively. Unfortunately the K_0^* width is so wide (~ 300 MeV) and mass measurement is so poor that we cannot determine the sign of $\langle f(r)\rangle$ from the K_2^*-K_0^* mass difference. The sign of $\langle f(r)\rangle$ has not been known either for the charmed mesons or for the bottom mesons. However, we know the d-to-s-wave ratio of the decay $K_1 \to K^*\pi$ [4]:

$$\Gamma(K_1 \to (K^*\pi)_{d\ \rm wave})/\Gamma(K_1 \to (K^*\pi)_{s\ \rm wave}) = \begin{cases} 1.0 \pm 0.7 & \text{for } K_1(1270), \\ 0.04 \pm 0.01 & \text{for } K_1(1400)\ . \end{cases} \tag{3}$$

Since $K^*(890)$ is a $j = 1/2$ state, only the $j = 1/2$ resonance is allowed to decay into $K^*\pi$ in s wave by angular momentum conservation for the light system. The high accuracy of the value 0.04 ± 0.01 for $K_1(1400)$ in Eq. (3) strongly suggests that the $K_1(1400)$ meson ought to be assigned to the $j = 1/2$ state.

III. THE DECAY $\tau \to \nu_\tau K_1$

The flavor SU(3) symmetry is opposite to the heavy quark picture, but sometimes complementary to it. In the symmetry limit where the s quark is degenerate with the u, d quarks, one state belongs to the $^1P_1$ octet of negative charge conjugation, while the other is a member of the $^3P_1$ octet of positive charge conjugation. They are the octet partners of the $b_1(1235)$ and $a_1(1260)$ mesons, respectively. Because of their near degeneracy, the two $\bar{s}u$ states strongly mix with each other through even a small SU(3) symmetry breaking to form the mass eigenstates

$$\begin{aligned} |K_1(1270)\rangle &= |^1P_1\rangle\cos\theta_K + |^3P_1\rangle\sin\theta_K \,, \\ |K_1(1400)\rangle &= |^3P_1\rangle\cos\theta_K - |^1P_1\rangle\sin\theta_K \,. \end{aligned} \tag{4}$$

The mixing angle θ_K is constrained by the masses and the strong decay branching ratios of the resonances to $\theta_K = (32^{+6}_{-2})^\circ$ or $(57^{+2}_{-3})^\circ$ [5]. A recent analysis of the τ decay by the TPC/Two-Gamma Collaboration [1] has shown that the $K_1(1400)$ final state dominates over the $K_1(1270)$ final state by roughly 2 to 1 within errors:

$$\begin{aligned} B(\tau \to \nu_\tau K_1(1270)) &= 0.41^{+0.41}_{-0.35} \times 10^{-2} \,, \\ B(\tau \to \nu_\tau K_1(1400)) &= 0.76^{+0.40}_{-0.33} \times 10^{-2} \,. \end{aligned} \tag{5}$$

These numbers favor $\theta_K = (32^{+6}_{-2})^\circ$ over $\theta_K = (57^{+2}_{-3})^\circ$ since for $\theta = 32^\circ$ the $K_1(1400)$ contains more of $^3P_1$ than the $K_1(1270)$ does. A mixing of $\theta \approx 30^\circ$ can be quite easily realized with a small symmetry breaking [5].

In the case of the heavy s quark, we need to compute the production ratio of the $j = 1/2$ and $3/2$ states through the weak current $\bar{s}\gamma^\mu\gamma_5 u$. This computation is a little different from recombining $^3P_1$ into the sum of $j = 1/2$ and $3/2$ through the 6-j symbols. The weak current $\bar{s}\gamma^\mu\gamma_5 u$ would produce the $^3P_1$ state alone if $m_s = m_{u,d}$. When $m_s \gg m_{u,d}$, the weak current actually produces the $^3P_1$ and $^1P_1$ states in the ratio of $\sqrt{2}$ to 1 in amplitude. Our problem is to rewrite this particular linear combination of $^3P_1$ and $^1P_1$ into the $j = 1/2$ and $3/2$ states. The actual computation is elementary. In the rest frame of the produced K_1 meson, the space component of the weak current contributes to production of the p wave resonances:

$$\bar{s}\gamma\gamma_5 u \to -[2m_u(E_\mathbf{p} + m_u)]^{-1/2}\chi_s^\dagger \boldsymbol{\sigma}(\boldsymbol{\sigma}\cdot\mathbf{p})\chi_u, \tag{6}$$

while the time component is only for $^1S_0$. Here we have treated the light nonstrange system as if it were a single constituent u quark. This is sufficient for our purpose since what is relevant to us is only the O(3) property of the light cloud in the rest frame of the heavy s quark. When the right-hand side of Eq. (6) is decomposed into the $^{2S+1}L_J$ states of $\bar{s}u$, we find, up to an overall normalization,

$$\chi_s^\dagger \boldsymbol{\sigma}(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})\chi_u = \sqrt{2/3}|^3P_1\rangle + \sqrt{1/3}|^1P_1\rangle \,, \tag{7}$$

where $\hat{\mathbf{p}} = \mathbf{p}/|\mathbf{p}|$. Recombination of $|^3P_1\rangle$ and $|^1P_1\rangle$ into $|j = 3/2\rangle$ and $|j = 1/2\rangle$ is given by

$$\begin{aligned} |j = 3/2\rangle &= \sqrt{1/3}|^3P_1\rangle - \sqrt{2/3}|^1P_1\rangle \,, \\ |j = 1/2\rangle &= \sqrt{2/3}|^3P_1\rangle + \sqrt{1/3}|^1P_1\rangle \end{aligned} \tag{8}$$

in our sign convention. In terms of the eigenstates of $\mathbf{j}$ the right-hand side of Eq. (7) is purely of $j = 1/2$:

$$\chi_s^\dagger \boldsymbol{\sigma}(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})\chi_u = |j = 1/2\rangle \,. \tag{9}$$

The reason for Eq. (9) is transparent. Operation $(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})$ on χ_u means that the spin angular momentum 1/2 of χ_u and the orbital angular momentum 1 represented by $\hat{p}$ are combined into $j = 1/2$. Then $\chi_s^\dagger$ is contracted to $(\boldsymbol{\sigma}\cdot\hat{\mathbf{p}})\chi_u$ with another $\boldsymbol{\sigma}$ to make $J = 1$ for $\mathbf{J} = \mathbf{j} + \mathbf{s}_s$. *Therefore the strangeness-changing axial-vector current produces only the nonstrange cloud of $j = 1/2$ in the limit of the heavy s quark.* The $K_1(1400)$ dominance in the recent data analysis shown in Eq. (5) strongly favors the assignment of the $K_1(1400)$ to the $j = 1/2$ state in agreement with the d-to-s-wave ratio.

IV. DISCUSSION

Both the d-to-s-wave ratio and the decay $\tau \to \nu_\tau K_1$ clearly favor the assignment that the lighter $K_1(1270)$ meson be the $j = 3/2$ state and the heavier $K_1(1400)$ meson be the $j = 1/2$ state. To realize this level ordering, the sign of the spin-orbit coupling must be opposite to that for the nonstrange mesons $[m(f_2) > m(a_0)]$ and for the charmonia $[m(\chi_{c2}) > m(\chi_{c0})]$. The predictions of the heavy s quark that we have derived above are subject to corrections due to the finiteness of m_s. Since m_s is too close to $\Lambda_{\rm QCD}$, the $1/m_s$ expansion is questionable at best. Therefore an immediate and natural reaction is that the idea of the heavy s quark is absurd. Nevertheless, we are asking here whether the two pieces of experimental information discussed above are fortuitous. We can take either of two standpoints here. For some reason the heavy s quark picture works in strange meson spectroscopy and the sign of the spin-orbit splitting is opposite to what we naively expect. This will raise a challenging question for quark model practitioners. If one insists that the heavy s quark does not work, the agreement of the d-to-s-wave ratio and of the τ decay with the $j = 1/2$ assignment of the $K_1(1400)$ meson is a mere accident. Let us keep the idea of the heavy s quark in mind as a possibility until more evidence comes up for or against it. A comparison with improved D and B meson spectroscopy in the future will be most interesting and will eventually clarify the issue.

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