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LIGHT-FRONT APPROACH FOR STRONG AND WEAK DECAYS OF PENTAQUARKS

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Strong and weak decays of pentaquarks are studied in the framework of the light-front approach.

1. Introduction

The discovery of an exotic Θ^+ pentaquark by LEPS at SPring-8,[1] subsequently confirmed by many other groups, marked a new era for testing our understanding of the hadron spectroscopy and promoted a re-examination of the QCD implications for exotic hadrons. The mass of the Θ^+ is of order 1535 MeV and its width is less than 10 MeV from direct observations and can be as narrow as 1 MeV or even lower.[2] Many null results for the pentaquark search mostly from high energy experiments have also been reported. Therefore, if the Θ^+ pentaquark is real, it must be established beyond any doubt.

If the Θ^+ pentaquark exists, its minimum quark content is $uudd\bar{s}$. To understand those experimental measurements with positive results, we are facing three puzzles: (i) The doubly charged partner of Θ^+, namely, Θ^{++} with the quark content $uuud\bar{s}$, should be easily detected via the decay $\Theta^{++} \to K^+p$. The puzzle is why is it not seen so far while stringent limits have been set ? (ii) The naive constituent quark model in which quarks are uncorrelated implies a Θ^+ pentaquark mass of order 1900 MeV. Why is it so anomalously light ? (iii) The fall-apart strong decay $\Theta^+ \to KN$ is OZI super-allowed. Hence, if quarks in Θ^+ are uncorrelated, the width will be of order several hundred MeV. Why is the observed Θ^+ width so narrow ? These puzzles hint at a possible correlation among various quarks; two or three quarks could form a cluster. A popular correlated quark model has been advocated by Jaffe and Wilczek [3] in which the Θ^+ is a bound state of an $\bar{s}$ quark with two (ud) diquarks. The diquark is a highly correlated spin-zero object and is in a flavor anti-triplet and color anti-triplet state. Bose statistics of the scalar diquarks requires that the diquark pairs be in an orbital P wave state. The parity of Θ^+ is predicted to be positive owing to the diquark correlation.

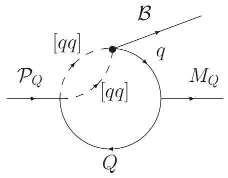

Fig. 1. Feynman diagram for a typical $\mathcal{P}_Q \to M_Q\mathcal{B}$ transition with $\mathcal{B}$ being an octet baryon, where the spin-zero diquarks ($[qq] = [ud], [us], [ds]$) are denoted by dashed lines and the corresponding operator $\mathcal{O}_{\rm eff}$.

2. Strong decays of pentaquarks

Consider the strong decay $\Theta^+ \to K^+n$. It can proceed through two processes: fall-apart decay with quark annihilation and the kaon emission process. The latter is expected to be severely suppressed (except in the infinite momentum frame where quark annihilation and annihilation are prohibited) as it involves the transition between Θ^+ and the 5-quark component of the nucleon. The fall-apart process is quite unique to the pentaquark and it cannot occur in the ordinary baryon decays. As mentioned before, if quarks are uncorrelated, the fall-apart mechanism will yield a width of several hundred MeV. Therefore, quark correlation is needed to suppress the OZI supper-allowed process. In the Jaffe-Wilczek model, this suppression can be understood as follows. First, one has to break the ud diquark pair so that one of the light quarks will combine with the $\bar{s}$ quark to form a kaon. Second, one has to overcome the P-wave potential barrier so that the rest three quarks form a s-wave nucleon. Hence, the Θ^+ decay width is narrow due to the breaking of diquarks and the transformation of the p-wave into s-wave configurations.

In a typical pentaquark decay to a meson and a baryon, the anti-quark is common to both pentaquark and the final state meson. To the leading order of the spectator approximation, the anti-quark can be considered as a spectator in the decay process depicted in Fig. 1. In this picture, there is a $\phi\phi \to \mathcal{B}q$ subprocess with $\phi\phi$ being a diquark pair and $\mathcal{B}$ a baryon. We use the effective Hamiltonian [4]

$$H_{\rm eff} = \frac{g_1}{M}\,\overline{\mathcal{B}}\gamma_5 q^c\phi\phi + \frac{g_2}{M^2}\,\overline{\mathcal{B}}i\gamma^\mu\gamma_5(q^c)\phi\partial_\mu\phi \tag{1}$$

to model the $\phi\phi \to \mathcal{B}q$ subprocess, where $M = \mathcal{O}(m_\phi, m_\mathcal{B})$ is a characteristic scale of the system. It turns out that only the g_2 term contributes to even-parity pentaquark decays. Although we do not know how to calculate g_2/M^2 from first-principles calculations, we can determine it from the Θ width, and use it to predict the decay widths of other light and heavy pentaquarks.

For the strong decay $\mathcal{P} \to M\mathcal{B}$, we have calculated the matrix element $A(\mathcal{P} \to M\mathcal{B}) = (g_2/M^2)\bar{u}\langle M|i\gamma^\mu\gamma_5 q^c\phi\partial_\mu\phi|\mathcal{P}\rangle$. The matrix elements can be expressed in terms of form factors. We first computed the form factors in the spacelike region and then extrapolated them to the timelike region. Taking 1 MeV as a benchmark for the Θ width, it is found that $g_2/M^2 \approx 10.2\,\mathrm{GeV}^{-2}$. We have estimated the strong decays $\Xi^{--}_{3/2} \to \Xi^-\pi^-, \Sigma^-K^-$, $\Theta^0_c \to pD^-$, $\Sigma_{5c} \to pD^-_s, pD^{*-}_{s0}$ and $\Xi^0_{5c} \to \Sigma^+D^-_s, pD^{*-}_{s0}$

by normalizing to the Θ^+ width. We found that $\Xi^{--}_{3/2} \to \Xi^-\pi^-, \Sigma^-K^-$, $\Sigma_{5c} \to pD_s^-, pD_{s0}^{*-}$ and $\Theta_c^0 \to pD^-$decay rates are of the order of a few MeV, while $\Xi^0_{5c} \to \Sigma^+D_s^-, \Sigma^+D_{s0}^{*-}$ decay rates are of order tens of MeV.[4] If we take $m_{\Xi^{--}_{3/2}} = 1862 \pm 2$ MeV as observed by NA49,[5] we will have $\Gamma(\Xi^{--}_{3/2} \to \Xi^-\pi^-)/\Gamma(\Theta^+ \to pK^0) \simeq 2.2$ which is consistent with the observed width of $\Gamma(\Xi^{--}_{3/2}) \leq 18$ MeV.[5]

3. Weak decays of heavy pentaquarks

If the light Θ^+ is real, it is expected the existence of the stable heavy pentaquark Θ_Q by replacing $\bar{s}$ by $\bar{Q}$. Whether the heavy pentaquark lies above or below the strong decay threshold is rather controversial. A narrow resonance in D^*p mass distribution with mass $3099 \pm 3 \pm 5$ MeV and width 12 ± 3 has been reported by H1,[6] but it has not been confirmed by many other groups. If the heavy pentaquarks lie below the strong decay threshold, they can be searched for only through weak or electromagentic decays.

We apply the relativistic light-front approach to calculate the pentaquark to pentaquark transition form factors.[7] In the heavy quark limit, heavy-to-heavy pentaquark transition form factors can be expressed in terms of three Isgur-Wise functions: two of them are found to be normalized to unity at zero recoil, while the third one is equal to 1/2 at the maximum momentum transfer, in accordance with the prediction of the large-N_c approach [8] or the quark model.[9] Therefore, the light-front model calculations are consistent with the requirement of heavy quark symmetry.

We have calculated form factors and Isgur-Wise functions in [7]. Decay rates of the weak decays $\Theta_b^+ \to \Theta_c^0\pi^+(\rho^+)$, $\Theta_c^0 \to \Theta^+\pi^-(\rho^-)$, $\Sigma'^+_{5b} \to \Sigma'^0_{5c}\pi^+(\rho^+)$ and $\Sigma'^0_{5c} \to N_8^+\pi^-(\rho^-)$ with Θ_Q, Σ'_{5Q} and N_8 being the heavy anti-sextet, heavy triplet and light octet pentaquarks, respectively, are obtained. For weakly decaying Θ_b^+ and Θ_c^0, the branching ratios of $\Theta_b^+ \to \Theta_c^0\pi^+$, $\Theta_c^0 \to \Theta^+\pi^-$ are estimated to be at the level of 10^{-3} and a few percents, respectively.

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