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Calculation of mass of $Y(4140)$ by introducing mixed molecule state in quark model

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Abstract

Using the general form of the Bethe–Salpeter wave functions for the bound states consisting of two vector fields given in our previous work, we investigate the molecular state composed of $D_s^{*+}D_s^{*-}$. However, for the SU(3) symmetry the component $D_s^{*+}D_s^{*-}$ is coupled with the other components $D^{*0}\bar{D}^{*0}$ and $D^{*+}D^{*-}$. Then we interpret the internal structure of the observed $Y(4140)$ state as a mixed state of pure molecule states $D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$ and $D_s^{*+}D_s^{*-}$ with quantum numbers $J^P = 0^+$. In this paper, the operator product expansion is used to introduce the nonperturbative contribution from the vacuum condensates into the interaction between two heavy mesons. The calculated mass of $Y(4140)$ is consistent with the experimental value, and we conclude that it is a more reasonable scenario to explain the structure of $Y(4140)$ as a mixture of pure molecule states.

1. Introduction

The narrow state $Y(4140)$ was discovered by CDF Collaboration [1] and its structure does not fit the conventional $c\bar{c}$ charmonium interpretation. Then possible interpretations beyond quark–

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antiquark state have been proposed, such as hadronic molecule state [2] and tetraquark state [3]. Following the CDF result, it is suggested in Ref. [2] that the $Y(4140)$ is a molecular state of $D_s^{*+}D_s^{*-}$. However, there are some defects in Ref. [2]: the numerical result sensitively depends on the adjustable parameter, the heavy vector mesons D_s^{*+} and D_s^{*-} are considered as pointlike objects, and the definite spin-parity quantum numbers J^P of the $Y(4140)$ can not be deduced in theory. More importantly, the previous work [2] dealt with this two-body system $D_s^{*+}D_s^{*-}$ in the formalism of quantum mechanics and the potential between two heavy mesons was constructed in perturbation theory. Therefore the nonperturbative effects in quantum chromodynamics (QCD), for example, the condensates of vacuum can not be considered in their work.

In quantum field theory, the most general form of the Bethe–Salpeter (BS) wave functions for the bound states composed of two vector fields of arbitrary spin and definite parity has been given [4]. In this work, we apply the general formalism to investigate the molecular state of $D_s^{*+}D_s^{*-}$ and consider that the effective interaction between these two heavy mesons is derived from one light vector meson exchange. In Ref. [4], we have deduced that in our approach one light pseudoscalar meson exchange has no contribution to the potential between two heavy vector mesons. Because of the SU(3) symmetry of the light vector mesons, one strange meson (K^*) exchange should be considered. From one strange meson exchange, it is necessary to consider the mixing of three pure molecule states $D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$ and $D_s^{*+}D_s^{*-}$, which is not considered in Refs. [2,4]. Therefore, we assume that the $Y(4140)$ state is a combination of three pure molecule states $D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$ and $D_s^{*+}D_s^{*-}$.

To construct the interaction kernels between two heavy vector mesons $D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$ and $D_s^{*+}D_s^{*-}$, we still consider that the heavy vector meson is a bound state composed of a light quark and c-quark and investigate the interaction of the light meson with the light quark in the heavy meson, which will be emphatically reconsidered in this work. As is well known, the nonperturbative contribution plays an important role in the case of QCD at low energy. It is necessary to note that the more nonperturbative effects should be taken into account when we investigate the light meson interaction with quark in the heavy meson. In this work, we introduce the operator product expansion and obtain the heavy meson BS wave function including the contribution from the condensates of vacuum. From the improved heavy meson BS wave function, we can obtain the heavy meson form factors which contain the contribution from the nonperturbative effects of QCD. Through these further form factors we can obtain the heavy meson interaction with light meson and the potentials between two heavy vector mesons without an extra parameter. Obviously, this approach is closer to QCD than in our previous works [4–7]. Then numerically solving the relativistic Schrödinger-like equation with these potentials, we obtain the wave functions of the pure molecule states $D^{*0}\bar{D}^{*0}$, $D^{*+}D^{*-}$ and $D_s^{*+}D_s^{*-}$, respectively. Finally, using the coupled-channel approach, we can obtain the masses and the wave functions of the mixed states and then the definite quantum numbers of the $Y(4140)$ system can be deduced.

This paper is organized in the following way. In Sec. 2 we show the general form of BS wave functions for the bound states consisting of two vector fields. After constructing the interaction kernel between two heavy vector mesons, we introduce the mixed state of three pure molecule states. Sec. 3 shows the procedure of the instantaneous approximation. Sec. 4 shows how to obtain the heavy meson BS wave function and form factor which contain the contribution from the vacuum condensates. Then the interaction potentials between two heavy vector mesons and the masses of the pure molecule states are calculated. Sec. 5 gives the numerical result and our conclusion is presented in Section 6.