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Exploration of the open-charm pentaquark states

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We perform a systematic study on the interactions of the $\Sigma_c^{(*)}D^{(*)}$ systems within the framework of chiral effective field theory. We introduce the contact term, one-pion-exchange and two-pion-exchange contributions to describe the short-, long-, and intermediate-range interactions. The low energy constants of the $\Sigma_c^{(*)}D^{(*)}$ systems are estimated from the $N\bar{N}$ scattering data by introducing a quark level Lagrangian. With three solutions of LECs, all the $\Sigma_c^{(*)}D^{(*)}$ systems with isospin $I = 1/2$ can form bound states, in which different inputs of LECs may lead to distinguishable mass spectra. In addition, we also investigate the interactions of the charmed-bottom $\Sigma_c^{(*)}\bar{B}^{(*)}$, $\Sigma_b^{(*)}D^{(*)}$, and $\Sigma_b^{(*)}\bar{B}^{(*)}$ systems.
Among the obtained bound states, the bindings become deeper when the reduced masses of the corresponding systems are heavier.

Summary

Inspired by the recently observed P_c and P_{cs} pentaquarks, we perform a systematic study on the interactions of the $\Sigma_c^{(*)}D^{(*)}$ systems to explore the possible P_{cc} states. We include the contact term, one-pion-exchange, and two-pion-exchange interactions within the framework of chiral effective field theory.

Due to G-parity transformation law, the expressions of the one-pion-exchange and two-pion-exchange effective potentials of the $\Sigma_c^{(*)}D^{(*)}$ systems are opposite and identical to those of the $\Sigma_c^{(*)}\bar{D}^{(*)}$ systems, respectively.

In principle, the LECs of the $\Sigma_c^{(*)}D^{(*)}$ systems should be fixed from the experimental data or lattice QCD simulations, which are not available at present. Alternatively, we introduce a quark level contact Lagrangian to bridge the LECs determined from the $N\bar{N}$ scattering data to the unknown $\Sigma_c^{(*)}D^{(*)}$ systems.
With the LECs fitted from the $N\bar{N}$ scattering data, we obtain four sets of (c_s, c_t) parameters describing the contributions of the contact terms. We present three cases to study the binding energies of the $\Sigma_c^{(*)}D^{(*)}$ systems.

The mass spectrum of the $[\Sigma_c^{(*)}D^{(*)}]_J^{I=1/2}$ molecules depend on the values of the LECs. In Case 1, a relatively small central potential and a large spin-spin interaction are introduced. The obtained P_{cc} mass spectrum is very similar to that of the $\Sigma_c^{(*)}\bar{D}^{(*)}$ systems. However, the mass spectra obtained in Cases 2 and 3 are different from that of the Case 1.

In this work, to estimate the binding energies of the P_{cc} pentaquarks, we only consider the S-wave interactions between $\Sigma_c^{(*)}$ and $D^{(*)}$. The $S - D$ wave mixing is not included in this work. On the one hand, the LECs introduced from the short-range contact tensor term can not be estimated at present, we only consider the leading order contact terms for cutting down the unknown parameters. Thus, the $S - D$ tensor force from the leading order one-pion-exchange (two-pion-exchange) is neglected for consistency.

From the effective potentials of the $[\Sigma_c^{(*)}D^{(*)}]_J^{I=1/2}$ systems, we find that the attractive force between the $\Sigma_c^{(*)}$

and $D^{(*)}$ arises mainly from the short-range interactions. Although this short-range-interaction-dominant mechanism is consistent with our understanding of the P_c, Z_c (Z_b), and $X(3872)$ states, these phenomenologically determined LECs still need further support from experimental data or lattice QCD simulations.

We determine the couplings g, g_2, and g_4 by calculating the partial decay widths of the D^*, Σ_c, and $\Sigma_c^{(*)}$ systems, the other axial couplings g_1, g_3, and g_5 can be correspondingly obtained in the framework of the quark model. Thus, the width effects of the $\Sigma_c^{(*)}$ and $D^{(*)}$ are partly encoded in these parameters. However, it is difficult to introduce widths into the Schr\"odinger equation when we solve the binding energies of the $\Sigma_c^{(*)}D^{(*)}$ systems. The present method can only provide rough positions to the considered P_{cc} pentaquark.

We briefly discuss the strong decay behaviors of the P_{cc} pentaquarks. The (cqq)-$(c\bar{q})$ and (ccq)-$(q\bar{q})$ are the two types of decay modes. Correspondingly, the $\Lambda_c D$, $\Lambda_c D\pi$, and $\Xi_{cc}\pi$ are expected to be important channels to search for these $[\Sigma_c^{(*)}D^{(*)}]_J^{I=1/2}$ molecules.

We also study the interactions of the $\Sigma_c^{(*)}\bar{B}^{(*)}$, $\Sigma_b^{(*)}D^{(*)}$, and $\Sigma_b^{(*)}\bar{B}^{(*)}$ to search for possible P_{cb}, P_{bc}, and P_{bb} pentaquarks. The corresponding systems with $I=1/2$ can also form molecular states. In addition, among the studied systems, the binding becomes deeper when the reduced masses of the systems are heavier.

Because the uncertainties from the quark model assumptions cannot be quantified, thus the $\Sigma_c^{(*)}D^{(*)}$ systems still need further study. If lattice QCD calculations are performed to extract physical observable quantities in the future, we can fit the lattice results to extrapolate to the physical pion mass to obtain the LECs for the $\Sigma_c^{(*)}D^{(*)}$ systems. The width effects and the $S-D$ wave mixing effects can also be studied by solving the corresponding Lippmann-Schwinger equations.

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