Λ(1405) AS A RESONANCE IN THE BARYON-MESON SCATTERING COUPLED TO THE q^3 STATE IN A QUARK MODEL

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Abstract

To describe Λ(1405) as a resonance in the baryon-meson scattering by a quark model, we have investigated q^3-q̄q̄ scattering systems with the flavor-singlet q^3 (0s)^2(0p) state, which is treated as a bound state embedded in the continuum. We found that the peak appears below the NK threshold in the spin 1/2, isospin 0 channel with an appropriate width. We also compare the mechanism to form such a resonance with that of the chiral-unitary-type model.

1 Introduction

Constituent quark models are known to reproduce most of the observed low-energy features of baryons. The picture that the baryon mass comes mainly from the masses of the three constituent quarks, which interact with each other by exchanging gluons and/or Goldstone bosons, seems appropriate [1, 2]. There, however, are some exceptions. For example, such quark models cannot give the observed light mass of Λ(1405) nor the large mass difference between Λ(1405, 1/2^-) and Λ(1520, 3/2^-). In the conventional constituent quark model, each of these baryons is treated as a system of three quarks in the flavor-singlet (0s)^2(0p) state. Then, the hyperfine interaction only gives a part (∼150 MeV) of the observed mass difference between the flavor-singlet and the flavor-octet spin-1/2 baryons, ∼200 MeV. Moreover, in order to give the large mass difference between Λ(1405) and Λ(1520), one has to assume a strong spin-orbit force between quarks, which is absent in other negative-parity baryons.
Λ(1405) is a meson-baryon resonance found in the Σπ scattering state. To investigate this baryon as a negative-parity baryon embedded in the Σπ continuum is most appropriate. In ref [3], the idea that Λ(1405) can be a N̅K bound state has been presented. A more systematic treatment may be found in the chiral unitary approach [4].

In the present work [5], we perform the Σπ-N̅K-Ληud coupled channel scattering calculation by the quark cluster model (QCM). Each baryon is treated as a 3\(s^0\) state, and the meson is assumed to be a q̅q(0s) state. Moreover, we have introduced the conventional Λ\(^1\), the flavor-singlet q̅q(0s)\(^2\)0p state, as a bound state embedded in the continuum (the Λ\(^1\) pole).

2 Model

In QCM, the wave function of a baryon-meson system is written as a product of the single baryon and meson wave functions, \(\phi_B\) and \(\phi_M\), and the relative wave function between these two clusters, \(\chi(R_{BM})\):

\[
\Psi = A_q[\phi_B \phi_M \chi(R_{BM})].
\]

(1)

A baryon consists of three quarks and a meson consists of quark and an antiquark; \(A_q\) in eq. (1) is an antisymmetrization operator among these four quarks. By integrating out the internal coordinates, we obtain the following RGM equation to determine the relative wave function:

\[
\int [H_{RGM}(R, R') - EN_{RGM}(R, R')] \chi(R')dR' = 0,
\]

where \(H [N]\) is the hamiltonian [norm] kernel.

The hamiltonian kernel can be obtained from the hamiltonian for quarks, \(H_q\), which consists of the kinetic term, the one-gluon-exchange term (OGE), the confinement term (Conf), the collective term (Coll), and the instanton-induced interaction term (INS) [5]:

\[
H_q = \sum_i \left( \frac{p_i^2}{2m_i} + V_0 \right) - K_G + V_{Conf} + V_{OGE} + V_{Coll} + V_{INS}.
\]

(3)

In the present work, we assume that the coupling between the scattering state and the Λ\(^1\) pole comes from OGE, which can be written as:

\[
\langle V_{3q-\bar{q}q} \rangle = 6 \langle B^*(q^3)_{123} | V_{345} \frac{1}{\sqrt{4}} (1 - 2P_{24} - P_{34}) | B(q^3)_{123} M(q_4\bar{q}_5) \rangle.
\]

(4)
3 Results

When the $\langle V_{3q-5q} \rangle$ term is switched off, there is no structure in the $\Sigma\pi$ phase shift below the $N\overline{K}$ threshold in the $T=0$ nor in the $T=1$ channels. It is because the kinetic energy of the system is large due to the light pion mass. It cancels the short-ranged attraction of OGE in the $\Sigma\pi$ channel.

A resonance, however, appears when the conventional $\Lambda^1$, the $q^3(0s)^20p$ state, is introduced into the system as a pole in the scattering. The energy of this $\Lambda^1$ pole is assumed to be 160 MeV above $\Sigma\pi$ threshold without the coupling. When the coupling is switched on, the pole energy is reduced by about 85 MeV, which corresponds to 1404 MeV; it becomes a resonance below the $N\overline{K}$ threshold (Fig. 1). The width of the peak in the mass spectrum is about 55 MeV, which also agrees reasonably with the observed one. The $N\overline{K}$ phase shift goes to negative: the scattering length is $-0.75 + i0.38$ fm,
Table 1: Matrix elements of the flavor-type operator, $-\langle \sum (F_i \cdot F_j) \rangle$, and the color-spin-type operator, $-\langle \sum (\lambda_i \cdot \lambda_j)(\sigma_i \cdot \sigma_j) \rangle$ for $T = 0$.

<table>
<thead>
<tr>
<th></th>
<th>$\Sigma \pi$</th>
<th>$N \bar{K}$</th>
<th>$\Lambda \eta$</th>
<th>$\Xi K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>flavor-type</td>
<td>$-8$</td>
<td>$\sqrt{6}$</td>
<td>$0$</td>
<td>$-\sqrt{6}$</td>
</tr>
<tr>
<td>color-spin-type</td>
<td>$\Sigma \pi$</td>
<td>$\frac{16}{3}$</td>
<td>$\frac{116\sqrt{7}}{21}$</td>
<td>$-\frac{16\sqrt{105}}{105}$</td>
</tr>
<tr>
<td></td>
<td>$N \bar{K}$</td>
<td>$0$</td>
<td>$\frac{28\sqrt{15}}{15}$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\Lambda \eta$</td>
<td>$0$</td>
<td>$-3\sqrt{2}$</td>
<td>$\Lambda \eta$</td>
<td>$\frac{112}{15}$</td>
</tr>
<tr>
<td>$\Xi K$</td>
<td>$-6$</td>
<td>$\Xi K$</td>
<td>$-\frac{160}{21}$</td>
<td></td>
</tr>
</tbody>
</table>

which, as a simple model, agrees with the experimental value, $(-1.70 \pm 0.07) + i(0.68 \pm 0.04)$ fm [6], reasonably well.

In the baryon-meson picture where the flavor-flavor type interaction, $-F \cdot F$, is employed, the peak appears because of the attraction in the $N \bar{K}$ channel [7]. (See Table 1.) In the present scheme of the color-spin interaction, where the hyperfine interaction is proportional to $-(\lambda \cdot \lambda)(\sigma \cdot \sigma)$, there is no such an attraction in the $N \bar{K}$ channel. Thus, introducing the $\Lambda^1$ pole is necessary to reproduce the resonance. Actually, in the present case, the $\Lambda^1$ component of the wave function at the resonance is by about 2.8 larger than the $N \bar{K}$ component.

In summary, our results show that (1) there is a strong attraction in the $\Sigma \pi$ channel but not in the $N \bar{K}$ channel, (2) no peak is found in the $\Sigma \pi$-$N \bar{K}$-$\Lambda \eta_{ud}$ coupled channel QCM calculation if we employs the realistic reduced mass for the kinetic energy, and (3) a reasonable peak appears if the $\Lambda^1$ pole is included above the $N \bar{K}$ threshold.

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References


