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

Sachiko Takeuchi and Kiyotaka Shimizu[A]
Japan College of Social Work,
Kiyose, Tokyo 204-8555, Japan
[A]Department of Physics, Sophia University,
Chiyoda-ku, Tokyo 102-8554, Japan

Abstract

To describe $\Lambda(1405)$ as a resonance in the baryon-meson scattering by a quark model, we have investigated q^3-$q\overline{q}$ 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 $N\overline{K}$ threshold in the spin $\frac{1}{2}$, 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 $\Lambda(1405)$ nor the large mass difference between $\Lambda(1405, \frac{1}{2}^-)$ and $\Lambda(1520, \frac{3}{2}^-)$. 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 ($\sim$ 150 MeV) of the observed mass difference between the flavor-singlet and the flavor-octet spin-$\frac{1}{2}$ baryons, $\sim$ 200 MeV. Moreover, in order to give the large mass difference between $\Lambda(1405)$ and $\Lambda(1520)$, one has to assume a strong spin-orbit force between quarks, which is absent in other negative-parity baryons.

$\Lambda(1405)$ is a meson-baryon resonance found in the $\Sigma\pi$ scattering state. To investigate this baryon as a negative-parity baryon embedded in the $\Sigma\pi$ continuum is most appropriate. In ref [3], the idea that $\Lambda(1405)$ can be a $\mathrm{N\overline{K}}$ 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 $\Sigma\pi$-$\mathrm{N\overline{K}}$-$\Lambda\eta_{ud}$ coupled channel scattering calculation by the quark cluster model (QCM). Each baryon is treated as a $\mathrm{q}^3(0s)^3$ state, and the meson is assumed to be a $\mathrm{q\overline{q}}(0s)$ state. Moreover, we have introduced the conventional Λ^1, the flavor-singlet $\mathrm{q}^3(0s)^2 0p$ 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, ϕ_B and ϕ_M, and the relative wave function between these two clusters, $\chi(\boldsymbol{R}_{BM})$:

$$\Psi = \mathcal{A}_q[\ \phi_B\ \phi_M\ \chi(\boldsymbol{R}_{BM})\ ]. \tag{1}$$

A baryon consists of three quarks and a meson consists of quark and an antiquark; $\mathcal{A}_q$ 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:

$$\int [\ H_{RGM}(\boldsymbol{R},\boldsymbol{R}') - EN_{RGM}(\boldsymbol{R},\boldsymbol{R}')\ ]\ \chi(\boldsymbol{R}')d\boldsymbol{R}' = 0, \tag{2}$$

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]:

$$H_q = \sum_i (\frac{p_i^2}{2m_i} + V_0) - K_G + V_{\mathrm{Conf}} + V_{\mathrm{OGE}} + V_{\mathrm{Coll}} + V_{\mathrm{INS}}. \tag{3}$$

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:

$$\langle V_{3q-5q}\rangle \;=\; 6\ \langle B^*(q^3)_{123}|V_{3;4\overline{5}}\frac{1}{\sqrt{4}}(1-2P_{24}-P_{34})|B(q^3)_{123}M(q_4\overline{q}_5)\rangle \tag{4}$$

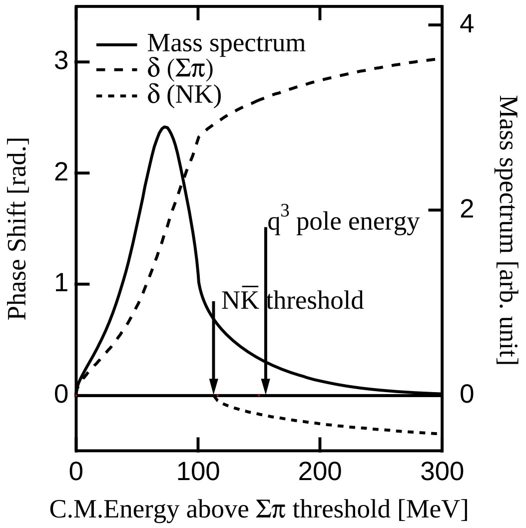

Figure 1: Mass spectrum and the phase shift (δ) of the $\Sigma\pi$ and $\mathrm{N}\overline{\mathrm{K}}$ coupled channel QCM.

with

$$V_{i;j\bar{k}} \;=\; \lambda_i \cdot \lambda_{\bar{k}j}\, \frac{\alpha_s}{4} \frac{\pi}{m_a^2} \left\{ \left(\frac{\boldsymbol{k}}{2m_a} - \frac{\boldsymbol{p}_i + \boldsymbol{p}'_i + i\boldsymbol{\sigma}_i \times \boldsymbol{k}}{2m_i} \right) \cdot \boldsymbol{\sigma}_{\bar{k}j} \right\} \delta^f_{\bar{k}j}, \qquad (5)$$

where m_a is the quark mass in the annihilating $\mathrm{q}_j\overline{\mathrm{q}}_{\bar{k}}$ pair, m_i is the mass of the i-th quark, and $\boldsymbol{k} = \boldsymbol{p}_j + \boldsymbol{p}_{\bar{k}}$.

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 $\mathrm{N}\overline{\mathrm{K}}$ 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 Λ^1, the $\mathrm{q}^3(0s)^2 0p$ state, is introduced into the system as a pole in the scattering. The energy of this Λ^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 $\mathrm{N}\overline{\mathrm{K}}$ 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 $\mathrm{N}\overline{\mathrm{K}}$ 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 $T=0$.

	flavor-type					color-spin-type			
	$\Sigma\pi$	$\mathrm{N}\overline{\mathrm{K}}$	$\Lambda\eta$	$\Xi\mathrm{K}$		$\Sigma\pi$	$\mathrm{N}\overline{\mathrm{K}}$	$\Lambda\eta$	$\Xi\mathrm{K}$
$\Sigma\pi$	-8	$\sqrt{6}$	0	$-\sqrt{6}$	$\Sigma\pi$	$-\dfrac{16}{3}$	$\dfrac{116\sqrt{7}}{21}$	$-\dfrac{16\sqrt{105}}{105}$	0
$\mathrm{N}\overline{\mathrm{K}}$		-6	$3\sqrt{2}$	0	$\mathrm{N}\overline{\mathrm{K}}$		0	$\dfrac{28\sqrt{15}}{15}$	0
$\Lambda\eta$			0	$-3\sqrt{2}$	$\Lambda\eta$			$\dfrac{112}{15}$	$-\dfrac{40\sqrt{70}}{21}$
$\Xi\mathrm{K}$				-6	$\Xi\mathrm{K}$				$-\dfrac{160}{21}$

which, as a simple model, agrees with the experimental value, $(-1.70\pm0.07)+i(0.68\pm0.04)$ 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 $\mathrm{N}\overline{\mathrm{K}}$ 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 $\mathrm{N}\overline{\mathrm{K}}$ channel. Thus, introducing the Λ^1 pole is necessary to reproduce the resonance. Actually, in the present case, the Λ^1 component of the wave function at the resonance is by about 2.8 larger than the $\mathrm{N}\overline{\mathrm{K}}$ component.

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

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