Institute of Physics Publishing
doi:10.1088/1742-6596/49/1/041

Journal of Physics: Conference Series **49** (2006) 176–177
Structure of Exotic Nuclei and Nuclear Forces

Few-Body Problems with Strangeness

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Abstract. We solve a five-body problem of pentaquark ($q^4\bar{q}$) state of $\Lambda(1405)$. The hamiltonian, which reproduces reasonably well the energies of ground state baryons (N, Λ, Σ, Ξ and Δ) and mesons (π, K, ρ, K^*), includes kinetic energy of semi-relativistic form, linear confinement potential, and a color-magnetic interaction with Gaussian form factor. Flavor symmetry breaking ($m_s > m_{u,d}$) is taken into account. The energy calculated for the pentaquark state of $\Lambda(1405)$ is lower than the energy for the three-quark state. The present result suggests that the $\Lambda(1405)$ is a pentaquark-dominated state if the color-magnetic potential plays a leading role of the quark-quark and quark-antiquark interactions.

1. Introduction

Recent experimental report [1] on a new observation of strange tribaryon $S^0(3115)$ has had a significant impact on nuclear physics. The existence of deeply bound $\bar{K}$-nuclear systems has been predicted by Akaishi, *et al.*[2, 3], based on an assumption of $\Lambda(1405)$ being a bound state of $\bar{K}+N$. However, the $S^0(3115)$ is different from that was originally predicted at the earlier time since the isospin ($I=1$) of $S^0(3115)$ does not match the isospin ($I=0$) predicted by the theory. Moreover, the mass of $S^0(3115)$ is about 100 MeV lighter than the value by the first-days theoretical prediction. The goal of our study is to understand the structure of the $S^0(3115)$, and one of the keys to get rid of the discrepancy between the experiment and the theory would be firstly to focus on the structure of the $\Lambda(1405)$. Therefore, the purpose of this work is to study the exotic structure of $\Lambda(1405)$, especially focusing on the pentaquark ($q^4\bar{q}$) state of the system.

Table 1. Parameters of the present model.

$m_{u,d}$	m_s	V_0	C	α	Λ
0.34 GeV	0.5508 GeV	0.4534 GeV	0.08265 (GeV)^2	1.08	0.204 fm

Table 2. Energies of baryons and mesons, given in units of MeV. The energies of the three-body model and the five-body model for $\Lambda(1405)$ are also given.

	Baryons					Mesons				$\Lambda(1405)$	
	N	Δ	Λ	Σ	Ξ	π	K	ρ	K^*	(q^3)	$(q^4\bar{q})$
Calc.	949	1266	1116	1208	1336	141	543	771	907	1405	1292
Expt.	939	1232	1116	1193	1318	137	496	776	892	1406 ± 4	

2. Interactions and Method

The hamiltonian is given by

$$H = \sum_{i=1}^{A} \sqrt{m_i^2 + \boldsymbol{p}_i^2} + \sum_{i<j} V_{ij}^{(\mathrm{conf})} + \sum_{i<j} V_{ij}^{(\mathrm{CM})}, \qquad \left(\text{with} \sum_{i=1}^{A} \boldsymbol{p}_i = 0\right), \tag{1}$$

where m_i and $\boldsymbol{p}_i$ are the mass and the momentum operator of the i-th quark (or antiquark). The two-body interaction consists of a confinement potential and a color-magnetic potential:

$$\begin{aligned} V_{ij}^{(\mathrm{conf})} &= \left(-\tfrac{3}{8}\right)\left(\lambda_i^C \cdot \lambda_j^C\right)(-V_0 + C r_{ij}), \quad \text{and} \\ V_{ij}^{(\mathrm{CM})} &= -\alpha \frac{2\pi}{3 m_i m_j}\left(\frac{\lambda_i^C}{2} \cdot \frac{\lambda_j^C}{2}\right)(\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \times \frac{1}{\left(2\sqrt{\pi}\Lambda\right)^3} \exp\left\{-\frac{r_{ij}^2}{4\Lambda^2}\right\}, \end{aligned} \tag{2}$$

where $r_{ij} = |\boldsymbol{r}_i - \boldsymbol{r}_j|$ is the interparticle coordinate. The present color-magnetic potential has a Gaussian form factor with the size parameter Λ. All of the parameters of the present hamiltonian are given in Table 1.

The energy of the system is calculated by the stochastic variational method. The reader is referred to Refs.[4, 5] for details and recent applications.

3. Results

Table 2 lists the energies of three-body calculations (ground state baryons) and of two-body calculations (mesons) as well as the energies of three-body model and of the five-body model for the $\Lambda(1405)$. All of the calculated energies of the ground state baryons and the mesons reasonably well reproduce the experimental values. The energy calculated for the $(q^4\bar{q})$ state of the $\Lambda(1405)$ is lower than that for the (q^3) state. Therefore, the present result suggests that the $\Lambda(1405)$ is a pentaquark-dominated state if the color-magnetic potential plays a leading role of the $q - q$ and $q - \bar{q}$ interactions. In the present model, the $(q^4\bar{q})$ state is a bound state since the energy obtained for the $(q^4\bar{q})$ state is lower than both the $\pi + \Sigma$ and the $\bar{K} + N$ thresholds, which are calculated to be 1348 MeV and 1492 MeV, respectively. More realistic model, e.g., taking account of effective meson-exchange force or coupling potential between (q^3) and $(q^4\bar{q})$, will be described in future publication.

Acknowledgments

This study was supported by Grants-in-Aid for Young Scientists (B) (No. 17740174 and No. 15740161) from the Japan Society for the Promotion of Science (JSPS). Part of the calculations were made by using RIKEN Super Combined Cluster (RSCC).

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