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A Study of Pentaquark Θ State in Chiral Quark Model

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Abstract: The structure of the pentaquark state uudd-$\bar{s}$ is studied in the chiral quark model. Four configurations of $J^\pi=(1/2)^-$ and four of $J^\pi=(1/2)^+$ are considered. The results show that the isospin $T=0$ state is always the lowest one for both $J^\pi=(1/2)^-$ and $J^\pi=(1/2)^+$ cases in various models. But the theoretical value of the lowest one is still about 250 － 300 MeV higher than the experimental mass of Θ.

Key words: pentaquark state; quark model; chiral symmetry

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1 Introduction

Recently, LEPS Collaboration at SPring 8[1], DIANA Collaboration at ITEP[2], CLAS Collaboration at Jefferson Lab[3] and SAPHIR Collaboration at ELSA[4] report that they observed a new resonance Θ, with strangeness quantum number $S=+1$. The mass of this Θ particle is around $M_\Theta=1\,540$ MeV and the upper limit of the width is $\Gamma_\Theta< 25$ MeV. Since it has strangeness quantum number $S=+1$, it must be a 5-quark system. If it is really a pentaquark state, it will be the first multi-quark state people found. There are already many theoretical works to try to explain its properties with various quark models[5—7], but there is no concrete calculation from quark model available yet. Since the mass of Θ, M_Θ, is larger than the sum of nucleon mass and kaon mass, M_N+M_K, it is not easy to understand why its width is so narrow, unless it has very special quantum numbers. Therefore, a theoretically detailed analysis of the Θ particle's structure on quark level is very significant.

In this work, we calculate the energies of the pentaquark states in the chiral quark model. Four configurations of $J^\pi=\frac{1}{2}^-$ and four of $J^\pi=\frac{1}{2}^+$ are considered. Some qualitative information is obtained.

2 Theoretical Framework

For a 4q-$\bar{q}$ color singlet system, the 4q wave function includes three parts: orbital, flavor-spin $SU(3)\times SU(2)$ and color $SU(3)$ part. In Θ particle case, its strangeness is $+1$, 4q part only includes u and d quarks, and the anti-quark is $\bar{s}$. Four configurations for $J^\pi=\frac{1}{2}^-$ are considered, they are:

$$([4]_{orb}[31]^{\sigma f}_{ts=01}\bar{s},\ LST=0\,\frac{1}{2}\,0,\ J^\pi=\frac{1}{2}^-),$$

$$([4]_{orb}[31]^{\sigma f}_{ts=10}\bar{s},\ LST=0\,\frac{1}{2}\,1,\ J^\pi=\frac{1}{2}^-),$$

$$([4]_{orb}[31]^{\sigma f}_{ts=11}\bar{s},\ LST=0\,\frac{1}{2}\,1,\ J^\pi=\frac{1}{2}^-) \text{ and}$$

$$([4]_{orb}[31]^{\sigma f}_{ts=21}\bar{s},\ LST=0\,\frac{1}{2}\,2,\ J^\pi=\frac{1}{2}^-).$$

We also considered 4 configurations for $J^\pi=\frac{1}{2}^+$:

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$([31]_{orb}[4]^{\sigma f}_{ts=00}\bar{s}$, $LST=1\frac{1}{2}0$, $J^{\pi}=\frac{1}{2}^{+})$,

$([31]_{orb}[4]^{\sigma f}_{ts=11}\bar{s}$, $LST=1\frac{1}{2}1$, $J^{\pi}=\frac{1}{2}^{+})$,

$([31]_{orb}[4]^{\sigma f}_{ts=11}\bar{s}$, $LST=1\frac{3}{2}1$, $J^{\pi}=\frac{1}{2}^{+})$ and

$([31]_{orb}[4]^{\sigma f}_{ts=22}\bar{s}$, $LST=1\frac{3}{2}2$, $J^{\pi}=\frac{1}{2}^{+})$.

Their color part is $[211]^c$, i.e. $(\lambda\mu)_c=(10)$, combining (01) of $\bar{s}$, the total quantum number in color space is singlet. For $J^{\pi}=\frac{1}{2}^{-}$ states, color $[211]^c$ with spin-flavor $[31]^{\sigma f}$ constructs the total anti-symmetric structure of the 4q part; and for $J^{\pi}=\frac{1}{2}^{+}$ states, $[31]_{orb}$ replaces $[31]^{\sigma f}$ to make the anti-symmetrization.

In the chiral quark model the Hamiltonian of the system can be written as

$$H=\sum_i T_i - T_G + \sum_{i<j=1-4} V_{ij} + \sum_{i=1-4} V_{i5}, \quad (1)$$

where $\sum_i T_i - T_G$ is the kinetic energy of the system, V_{ij}, $i,j=1-4$ and V_{i5}, $i=1-4$ represent the interactions between quark-quark (q-q) and quark-anti-quark (q-$\bar{q}$), respectively.

$$V_{ij}=V_{ij}^{conf}+V_{ij}^{OGE}+V_{ij}^{ch}, \quad (2)$$

V_{ij}^{conf} is the confinement potential taken as the quadratic form, V_{ij}^{OGE} is the one gluon exchange (OGE) interaction and V_{ij}^{ch} represents the interactions from chiral field couplings. In the chiral $SU(3)$ quark model[8], V_{ij}^{ch} includes scalar meson exchange V_{ij}^{s}, pseudo-scalar meson exchange V_{ij}^{ps}, and in the extended chiral $SU(3)$ quark model, vector meson exchange V_{ij}^{v} potentials are also included,

$$V_{ij}^{ch}=\sum_{a=0}^{8}V_{s_a}(r_{ij})+\sum_{a=0}^{8}V_{ps_a}(r_{ij})+\sum_{a=0}^{8}V_{v_a}(r_{ij}). \quad (3)$$

Their expressions can be found in Refs. [8, 9]. The interaction between q and $\bar{q}$ includes two parts: direct interaction and annihilation part,

$$V_{i5}=V_{q\bar{q}}^{dir}+V_{q\bar{q}}^{ann},$$

$$V_{q\bar{q}}^{dir}=V_{q\bar{q}}^{conf}+V_{q\bar{q}}^{OGE}+V_{q\bar{q}}^{ch}, \quad (5)$$

with

$$V_{q\bar{q}}^{ch}(\boldsymbol{r})=\sum_i(-1)^{G_i}V_{qq}^{ch,i}(\boldsymbol{r}). \quad (6)$$

Here $(-1)^{G_i}$ describes the G parity of the ith meson. For the Θ particle case, $q\bar{q}$ can only annihilate into K and K* mesons, thus V_{i5}^{ann} can be expressed as:

$$V_{i5}^{ann}=V_{ann}^{K}+V_{ann}^{K^*}, \quad (7)$$

with

$$V_{ann}^{K}=\tilde{g}_{ch}^2\frac{1}{(\tilde{m}+\tilde{m}_s)^2-m_K^2}\cdot\left(\frac{1-\boldsymbol{\sigma}_q\cdot\boldsymbol{\sigma}_{\bar{q}}}{2}\right)_{spin}\left(\frac{2+3\lambda_q\cdot\lambda_{\bar{q}}^*}{6}\right)_{color}\cdot\left(\frac{19}{9}+\frac{1}{6}\lambda_q\cdot\lambda_{\bar{q}}^*\right)_{flavor}\delta(\boldsymbol{r}_q-\boldsymbol{r}_{\bar{q}}), \quad (8)$$

and

$$V_{ann}^{K^*}=\tilde{g}_{chv}^2\frac{1}{(\tilde{m}+\tilde{m}_s)^2-m_{K^*}^2}\cdot\left(\frac{3+\boldsymbol{\sigma}_q\cdot\boldsymbol{\sigma}_{\bar{q}}}{2}\right)_{spin}\left(\frac{2+3\lambda_q\cdot\lambda_{\bar{q}}^*}{6}\right)_{color}\cdot\left(\frac{19}{9}+\frac{1}{6}\lambda_q\cdot\lambda_{\bar{q}}^*\right)_{flavor}\delta(\boldsymbol{r}_q-\boldsymbol{r}_{\bar{q}}), \quad (9)$$

where $\tilde{g}_{ch}$ and $\tilde{g}_{chv}$ are the coupling constants of pseudo-scalar-scalar chiral field and vector chiral field in the annihilation case respectively. $\tilde{m}$ represents the effective quark mass. Actually, $\tilde{m}$ is quark momentum dependent, here we treat it as an effective mass.

Using these two models, we did an adiabatic approximation calculation to study the energies of the (uudd-$\bar{s}$) system.

3 Results and Discussions

We carry on the calculation by taking the parameters which can reasonably reproduce the experimental data of N-N and Y-N scattering[9, 10]. About the annihilation interaction between u(d)-$\bar{s}$, it is a complicated problem, in Eqs. (8) and (9), the quark effective masses $\tilde{m}$ and $\tilde{m}_s$, as well as the annihilation coupling constants $\tilde{g}_{ch}$ and $\tilde{g}_{chv}$ are subject to significant uncertainties. In our calculation, we treat $(\tilde{m}+\tilde{m}_s)$, $\tilde{g}_{ch}$ and $\tilde{g}_{chv}$ as parameters, and adjust them to fit the masses of K and K* mesons. All results of 4 configurations of $J^{\pi}=\frac{1}{2}^{-}$ and 4 of $J^{\pi}=\frac{1}{2}^{+}$ in the chiral $SU(3)$ quark model and the extended chiral $SU(3)$ quark model are listed in Table 1.

Table 1　Energies of pentaquark states in different chiral quark model　MeV

Configuration	Chiral $SU(3)$ Quark Model $b_u=0.50$ fm	Ex. Chiral $SU(3)$ Quark Model $b_u=0.45$ fm
$J^{\pi}=\frac{1}{2}^{-}$		
$[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{01}\bar{s}$	1 801	1 843
$[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{10}\bar{s}$	2 049	2 089
$[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{11}\bar{s}$	2 117	2 115
$[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{21}\bar{s}$	2 323	2 314
$J^{\pi}=\frac{1}{2}^{+}$		
$[31]_{orb}[4]^{\sigma}_{fs}\mathcal{L}_{00}\bar{s}$	2 271	2 270
$[31]_{orb}[4]^{\sigma}_{fs}\mathcal{L}_{11}\bar{s}$ $(S=\frac{1}{2})$	2 308	2 296
$[31]_{orb}[4]^{\sigma}_{fs}\mathcal{L}_{11}\bar{s}$ $(S=\frac{3}{2})$	2 362	2 367
$[31]_{orb}[4]^{\sigma}_{fs}\mathcal{L}_{22}\bar{s}$	2 426	2 412

From Table 1, one can see that: (1) The isoscalar state ($T=0$) is always the lowest state both in $J^{\pi}=\frac{1}{2}^{-}$ and in $J^{\pi}=\frac{1}{2}^{+}$ cases, and ($[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{01}\bar{s}$, $LST=0\ \frac{1}{2}\ 0, J^{\pi}=\frac{1}{2}^{-}$) is always the lowest one in different models; (2) The results of the chiral $SU(3)$ quark model and the extended chiral $SU(3)$ quark model are quite similar, although the short range interactions of these two models are different; (3) The energy of the lowest state, ($[4]_{orb}[31]^{\sigma}_{fs}\mathcal{L}_{01}\bar{s}$, $LST=0\ \frac{1}{2}\ 0, J^{\pi}=\frac{1}{2}^{-}$), is about 250—300 MeV higher than the experimental value of the Θ mass.

In our results, the states of $J^{\pi}=\frac{1}{2}^{-}$ are always lower than those of $J^{\pi}=\frac{1}{2}^{+}$, even in the extended chiral $SU(3)$ quark model, in which the OGE interaction is almost totally replaced by vector meson exchanges. According to Stancu and Riska's argument[6], the state of $T=0$, $J^{\pi}=\frac{1}{2}^{+}$ can be lower than the state of $T=0$, $J^{\pi}=\frac{1}{2}^{-}$, because the spin-flavor dependent interactions from Goldstone-Boson exchange potential offer more attractions to the state of $T=0$, $J^{\pi}=\frac{1}{2}^{+}$. In our calculation, it is true that π and ρ meson exchanges do contribute very strong attractions to the state of $T=0$, $J^{\pi}=\frac{1}{2}^{+}$, but when the interactions between u(d) and $\bar{s}$ are included, especially the annihilation terms are considered, the state of $T=0$, $J^{\pi}=\frac{1}{2}^{-}$ gets more attractions. This is because that among 4 pairs u(d)-$\bar{s}$ interactions, the state of $T=0$, $J^{\pi}=\frac{1}{2}^{-}$ has 1 pair u-$\bar{s}$ of $(0s)^2$ with spin $s=0$ and color singlet $(00)_c$(i. e. K meson's quantum numbers) and $\frac{1}{3}$ pair of $(0s)^2 s=1\ (00)_c$, the other part is color octet, but the state of $T=0$, $J^{\pi}=\frac{1}{2}^{+}$ only has $\frac{1}{12}$ pair of $(0s)^2 s=0\,(00)_c$, $\frac{1}{4}$ pair of $(0s0p)s=0\,(00)_c$, $\frac{1}{4}$ pair of $(0s)^2 s=1\,(00)_c$, $\frac{3}{4}$ pair of $(0s0p)s=1(00)_c$ and the other part is color octet. If we take the annihilation interaction to fit the masses of K and K*, the state of $T=0$, $J^{\pi}=\frac{1}{2}^{-}$ must be the lowest.

4　Conclusions

The structures of pentaquark states are studied by an adiabatic approximation calculation in the chiral quark model. Our results show that the state $T=0$, $J^{\pi}=\frac{1}{2}^{-}$ is the lowest one, and its energy is about 250—300 MeV higher than the Θ's mass. It seems that it is impossible to reproduce the observed low mass and narrow width of Θ by quark models with reasonable model parameters in the adiabatic approximation, and a dynamical calculation may be necessary for the further study.

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五夸克态 Θ 的手征夸克模型研究

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摘 要: 在手征夸克模型的框架下, 研究了五夸克态 uudd$\bar{s}$ 的结构. 分别考虑了 $J^{\pi}=(1/2)^{-}$ 和 $J^{\pi}=(1/2)^{+}$ 的各四个组态. 结果表明对于不同的模型, 不论 $J^{\pi}=(1/2)^{-}$ 和 $J^{\pi}=(1/2)^{+}$, $T=0$ 的态的能量总是最低的. 但是最低态的能量的理论计算值仍比 Θ 质量的实验值高 250—300 MeV.

关 键 词: 禁闭夸克态; 夸克模型; 手征对称性