Understanding penta quark with various quark models

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Abstract

The pentaquark state recently discovered has been studied with three quark models which either fit the nucleon spin structure or the NN scattering. A minimum Θ^+ mass of 1620 MeV is obtained both for the $\frac{1}{2}^{\pm}$ state. The mixing of various color structure configurations, which would reduce the mass of the penta-quark state, should be taking into account in the calculation of penta-quark mass.

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Eleven groups [1] claimed recently that they found a penta-quark state, now called Θ^+, with mass~1540 MeV, and width $\Gamma < 25$ MeV. This state is either identified from the decay product nK^+ or pK_s, but up to now no experiment has identified both. In addition, the NA49 collaboration claimed that they found the anti-decuplet partner Ξ^{--} of Θ^+ [2]. The HERA-H1 collaboration claimed that they found the charm penta-quark Θ_c [3].

These measurements might be contaminated by the normal meson production due to the kinematical reflection [4, 5]. The NA49 claim has been challenged by another CERN group based on Ξ spectroscopy data with higher statistics [6]. HERA-B p-nucleus reaction data has not found the Θ^+ [7]. BES J/Ψ decay data analysis has not found the Θ^+ either [8]. There are other groups that have not found the Θ^+ [9].

The results of the reanalysis of the K^+d and $K^0_L p$ scattering data are diverse [10, 11]. W.R. Gibbs reanalyzed the K^+d scattering data, taking into account the double scattering, and found a structure corresponding to a resonance with width of 0.9±0.2 MeV, which is either a 1.547±0.002 GeV $\frac{1}{2}^-$ or a 1.559±0.003 GeV $\frac{1}{2}^+$ state and $\frac{1}{2}^-$ is favored [12]. In addition, a very tiny bump had appeared in 1973 CERN $K^+p \to pK^0_s\pi^+$ inelastic scattering data [13].

Theoretical studies based on the chiral soliton quark model played an important role in triggering the Θ^+ searches [14]. In the chiral soliton quark model, the Θ^+ is a member of the anti-decuplet rotational excitation following the well established octet and decuplet baryons [15, 16]. The QCD background of this model has been debated between different groups [17, 18, 19, 20, 21, 22]

Various quark models have been proposed to understand the Θ^+, mainly aimed at understanding the parity, low mass and narrow width. In the naive quark model [23] the ground state should be an S-wave one and this means Θ^+ should be a negative parity state. The S-wave $uudd\bar{s}$ configuration will have S-wave KN components. However both the $I = 0, 1$ KN S-wave phase shifts are negative in the Θ^+ energy region [24] and this means that Θ^+ can not be an S-wave KN resonance, except the new analysis of Gibbs [12]. On the other hand, since the $I = 0$ KN P-wave P_{01} phase shifts are positive, there might be resonance in this channel and this is consistent with the $J^p = \frac{1}{2}^+$ predicted by the chiral soliton quark model. Bag model gave similar result [25, 26].

Various quark correlations have been proposed such as color Cooper pair and others [17, 27, 28] aimed to reconcile the difference between the quark model predictions and the

properties of Θ^+. It seems to be able to get an even parity penta-quark ground state with small width but hard to get as low as 1540 MeV mass [29]. For example, Yu. A. Simonov did a quantitative calculation based on the Jaffe-Wilczek configuration [17] by means of the effective Hamiltonian approach. The calculated Θ^+ mass is about 400 MeV higher than the observed 1540 MeV [30]. Different quark interaction mechanisms such as quark-gluon, Goldstone boson exchange and instanton interaction have all been tried to understand the Θ^+ [17, 31, 32]. It is fair to say up to now there is no *ab initio* dynamical calculation to obtain a Θ^+ mass as low as 1540 MeV with the constraint that these model parameters fit the normal hadron spectroscopy [33, 34].

QCD sum rule and lattice QCD both have been used to calculate the penta-quark, the results are diverse. One Lattice QCD group reported they have not observed either $I = 0$ or $I = 1$, $J^p = \frac{1}{2}^{\pm}$ bound penta-quark state [35]. Two groups observed odd and one observed even parity state [36]. The pitfalls of these lattice QCD calculations have been discussed in [37]. The Θ^+ is a resonance state and so its mass should be a complex number. It might be difficult to detect such a complex number in an Euclidean Monte Carlo calculation. QCD sum rule calculations are diverse too. Zhu and Sugiyama *et al.* favor negative parity ones while others favor positive parity [38]. Kondo *et al.* suggested to remove the reducible part from the correlation function and after do that they got positive parity penta-quark.

Our group has done three quark model calculations. The first one is an application of the Fock space expansion model which we developed to explain the nucleon spin structure [39]. The naive quark model assumes that the baryon has a pure valence q^3 configuration. This is certainly an approximation. One expects there should be higher Fock components,

$$B = aq^3 + bq^3 q\bar{q} + \cdots. \tag{1}$$

The nucleon spin structure discovered in polarized lepton-nucleon deep inelastic scattering shows that there are intrinsic non-perturbative sea quark components in nucleon and indeed the nucleon spin structure can be explained by a dynamical model of nucleon where the ground state has about 15% $q^3 q\bar{q}$ component. This means that even the nucleon ground state might be a mixing of tri- and penta-quark components. In the Θ^+ mass calculation we assume it is a pure $uudd\bar{s}$ five quark state but with channel coupling. Our results are listed below:

Here the calculated mass is in units of MeV and $K_8 N_8$ means the K and N are both

TABLE I: Quark shell model calculations

	pure KN	$KN + K^*N$	$KN + K_8N_8$	$KN + K^*N + K_8N_8$
S_{01} Parity= $-$	2282	2157	1943	1766
P_{01} Parity= $+$	2357.1	2356.3	2357.0	2336.8

in color octets but coupled to an overall color singlet. The S-wave state has strong channel mixing: the amplitudes of KN, K^*N, K_8N_8, $K_8^*N_8$ are -0.54, -0.29, -0.54, -0.29 respectively. On the other hand the channel mixing is weak for the P-wave state: The amplitudes of KN, $K^*N\frac{1}{2}$, $K^*N\frac{3}{2}$, K_8N_8, $K_8^*N_8\frac{1}{2}$, $K_8^*N_8\frac{3}{2}$ are 0.968, -0.1, ~ 0, -0.07, 0.224, ~ 0 respectively. Here the $\frac{1}{2}$ and $\frac{3}{2}$ are the channel spin. The S-wave state definitely has a lower mass than that of the P-wave; the channel coupling plays a vital role in reducing the calculated S-wave Θ^+ mass. In obtaining these results we use the model parameters which fit the nucleon mass with five quark components mixed to q^3 configuration. Neglecting the five quark component, this model will give $M(N) = 1.2$ GeV, $M(K) = 0.8$ GeV. Therefore it is possible to reduce the penta-quark mass further by taking into account hepta-quark component and other channels coupling. We like to point out that our calculation is in fact a quark shell model calculation. The large scale shell model calculation of nuclear structure shows that it is possible to obtain approximate correct energy and wave function of a nuclear state if the Hilbert space is large enough. This should be true for quark shell model as well.

Lattice QCD and non-perturbative QCD both show that confinement might be due to gluon flux tube (or gluon string) formation in a quark system. The ground state energy of the gluon field in a $q\bar{q}$ meson and q^3 baryon can be approximated by a potential [40]

$$
\begin{aligned}
V_{q\bar{q}} &= -\frac{A_{q\bar{q}}}{r} + \sigma_{q\bar{q}}r + C_{q\bar{q}} \\
V_{3q} &= -A_{3q} \sum_{i<j} \frac{1}{|\vec{r}_i - \vec{r}_j|} + \sigma_{3q}L_{min} + C_{3q}, \\
\mathcal{L}_{min} &= \sum_i L_i.
\end{aligned}
\tag{2}
$$

L_i is the distance between the quark i and the Y-shaped gluon junction. $\vec{r}_i$ is the position of quark i. The first term in Eq.(2) is the color Coulomb interaction and the second term is similar to a linear confinement potential.

Most of constituent quark models use a quadratic or linear potential to model the quark

confinement,

$$V_{conf}(\vec{r}_{ij}) = -a\vec{\lambda}_i \cdot \vec{\lambda}_j \vec{r}_{ij}^{\,n},$$

$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j, \qquad n = 1, 2. \tag{3}$$

Here λ_i^a $(a = 1 \cdots 8)$ is the color SU(3) group generator. For a single hadron, $q\bar{q}$ mesons or q^3 baryons, such a modelling can be achieved by adjusting the strength constant a of the confinement potential. The color factor $\vec{\lambda}_i \cdot \vec{\lambda}_j$ gives rise to a strength ratio $1/2$ for baryon and meson which is almost the ratio for the minimum length of the flux tube to the circumference of the triangle formed by three valence quarks of a baryon.

How to extend the confinement potential to multiquark systems is an open question. There is a lattice QCD calculation of the penta-quark potential recently [41]. The ground state energy of the gluon field in a penta-quark with color structure $qq(\bar{3})\bar{s}(\bar{3})qq(\bar{3})$ can be expressed as

$$V_{5q} = \frac{\alpha_s}{4} \sum_{i<j} \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{|\vec{r}_i - \vec{r}_j|} + \sigma_{5q} L_{min} + C_{5q}. \tag{4}$$

Here $qq(\bar{3})$ means a color anti-triplet qq pair. L_{min} is the minimum length of the color flux to connect the five quarks.

From general SU(3) color group considerations, there might be other color structures for a penta-quark: $q^3(1)q\bar{s}(1); q^3(8)q\bar{s}(8)$; $qq(\bar{3})qq(\bar{3})\bar{s}(\bar{3})$, etc. The first one is a color singlet meson-baryon channel; the second is the hidden color meson-baryon channel; the third is the color structure used in the Jaffe-Wilczek model. One guesses the energy of these color configurations can be expressed in a similar manner as those given in Eq.(2) and (4). Can the two body confinement interaction Eq.(3) describe the confinement interaction properly for these color structures? It is a question needed to be studied further [42]. A penta-quark state should be a mixing of these color structures. Our first model calculation mentioned above shows that channel coupling reduces the calculated ground state penta-quark mass. It should be true in general that these different color channel mixing will reduce the ground state energy.

To do a model calculation for a multi-quark system with the above multi-body interaction and multi-channel coupling is numerically quite involved. We have developed a model, called the quark delocalization, color screening model (QDCSM): 1. We re-parameterize the

confinement potential Eq.(3) to take into account the effect of channels coupling in multi-quark systems induced by various color structures, which are not possible for a $q\bar{q}$ meson and q^3 baryon; 2. To take into account the orbital excitations but keep the numerical calculation simple we still use quark cluster bases but a delocalized quark orbital wave function is used to allow the multi-quark system to choose its own favorable configuration, i.e., to allow the multi-quark system to vary from the asymptotic hadronic cluster state to a genuine multi-quark state and all intermediate configurations [43]. This model explains the existing BB interaction data (bound state deuteron and NN, $N\Lambda$, $N\Sigma$ scattering) well with all model parameters fixed by hadron spectroscopy except for only one additional parameter, the color screening constant μ which is determined by the deuteron properties. More important, *it is the unique model, so far, which explains a long-standing fact: The nuclear force and the molecular force are similar except for the obvious difference of length and energy scales; the nucleus is approximately an A nucleon system rather than a 3A quark system* [44].
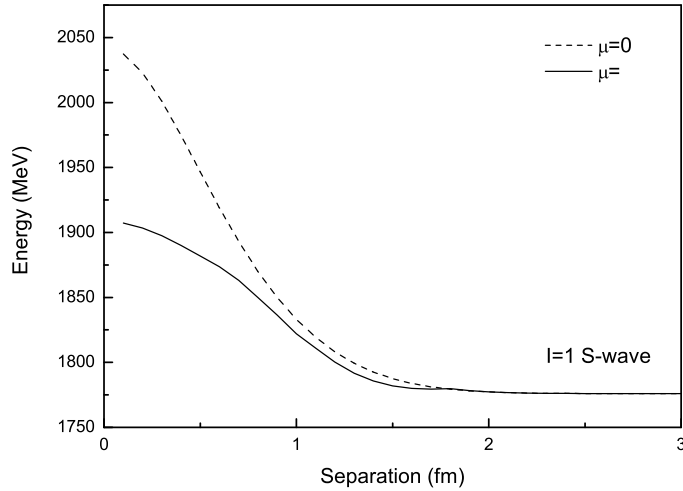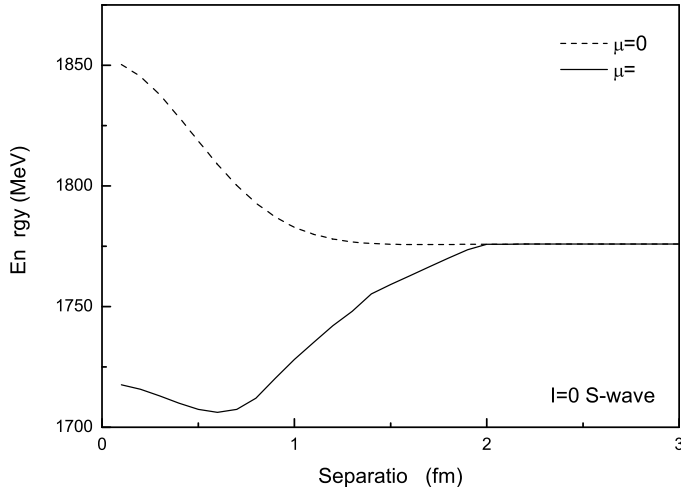

Fig.1. The effective potentials for I=1 S-wave.

Fig.2. The effective potentials for I=0 S-wave.

The penta-quark mass has been calculated with this model (QDCSM) in a single color singlet KN channel approximation. As explained before, the effect of the coupling of other color structures and orbital excitations is assumed to have been included in the modelling of QDCSM. In the $I = 1$ S-wave KN channel, a pure repulsive effective interaction is obtained as shown in Fig.1 (corresponding to curve with $\mu = 1$). This is consistent with the KN scattering data and helps to rule out the $I = 1$ possibility for the Θ^+. For comparison the naive quark model result is also shown in Fig.1 (corresponding to curve with $\mu = 0$), which shows a stronger repulsion. In the $I = 0$ S-wave KN channel, an effective attraction is obtained and shown in Fig.2 ($\mu = 1$ curve). This is inconsistent with the VPI KN scattering phase shifts [24] but might be consistent with Gibbs new results [12]. A Θ^+ mass of 1706 MeV is obtained from the minimum of Fig.2 $\mu = 1$ curve. Part of the overestimate of the Θ^+ mass is due to the overestimate of K mass, which is 650 MeV in this approach. This can be eliminated as follows: One first gets an effective interaction potential from Fig.2 $\mu = 1$ curve by subtracting its asymptotic value, then add a zero point oscillating energy $\frac{3\hbar^2}{4\mu_{KN}R_0^2}$ (μ_{KN} is the reduced mass of K and N, $R_0 = 0.6fm$ is the minimum point of the effective potential) and the rest mass of N and K. In this way one obtains $M(\Theta^+) = 1615MeV$. It is still about 75 MeV higher than the observed value 1540 MeV. More precise dynamical calculation might reduce the Θ^+ mass further. Fig.2 $\mu = 0$ curve shows the naive quark model result for comparison. It is almost a pure repulsive interaction and will not accommodate a Θ^+ resonance. The K^+n effective potential is shown in Fig.3, which is a very weak repulsive

interaction resulted from a cancellation of the $I = 1, 0$ channel ones. This result shows it is hard to get reliable K^+n scattering amplitude from K^+d scattering data because it is a small component in comparison to the big K^+p amplitude. Gibbs analysis shows the additional complications [12]. To get reliable $I = 0$ scattering phase shifts from K^+n is even harder because one has to get two big ones (corresponding to $I = 1, 0$ separately), which have opposite sign and so cancel each other, from a small one corresponding to $(I = 1) + (I = 0)$. For the P-wave channels, we only obtain spin averaged effective KN interactions because the spin-orbit coupling has not been included yet. In the $I = 0$ channel, there is a strong attraction (shown in Fig.4), as wanted in other quark models with correlations. However in our model the P-wave attraction is not strong enough to overcome the kinetic energy increase to reduce it to be a ground state. This is consistent with the lattice and QCD sum rule results [36, 38]. In the $I = 1$ channel, only a very weak attraction is obtained. This rules out the $I = 1$ Θ^+ again.
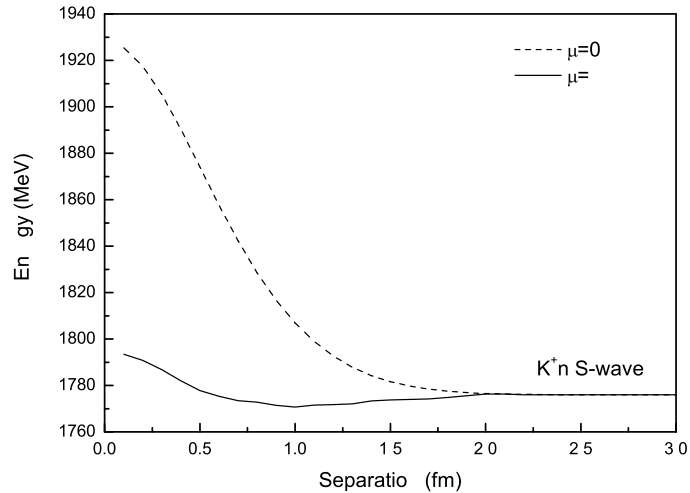
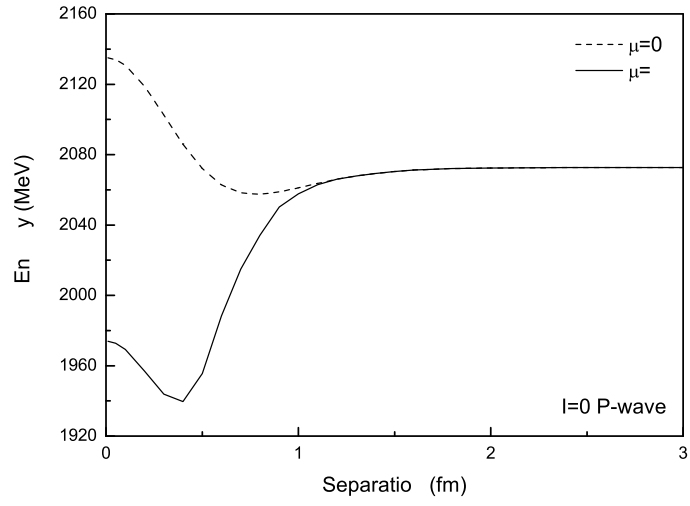

Fig.3. The effective potentials for K^+n S-wave.

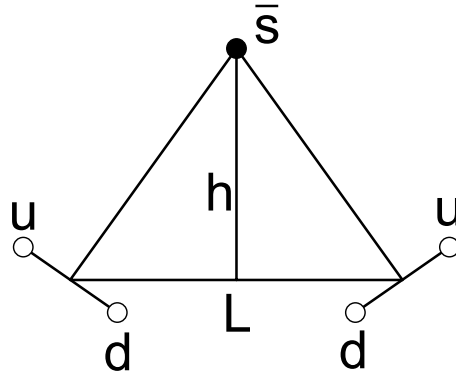Fig.4. The effective potentials for I=0 *P*-wave.
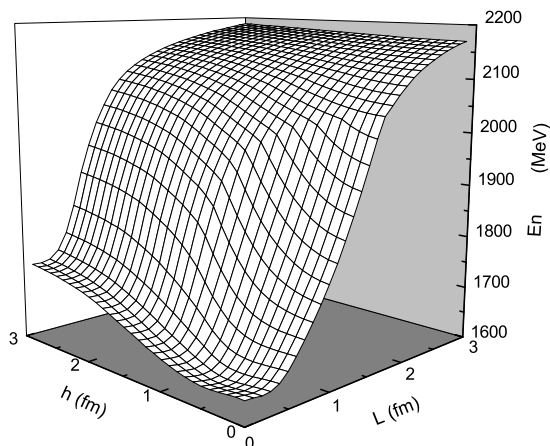

Fig.5. The Jaffe-Wilczek configuration.

Fig.6. The energies for Jaffe-Wilczek configuration ($\mu = 1$).

In a third model, the Jaffe-Wilczek configuration $\{ud\}\{ud\}\bar{s}$ is used but the four non-strange quarks are totally antisymmetrized. The space part is fixed to be an equilateral triangle with the two diquarks sitting at the bottom corners and the $\bar{s}$ at top (see Fig.5). The height h and the length L of the bottom side of the triangle are taken as variational parameters in addition to the quark delocalization. A three body variational calculation with the QDCSM has been done. The minimum of this variational calculation is 1621 MeV corresponding to a triangle of $h = 0.6fm, L = 0.6fm$ (see Fig.6). The Θ^+ mass is similar to our second model one. Fig.7 shows the result obtained with the naive quark model Hamiltonian, the minimum is 1799 MeV corresponding to a vanishing triangle.
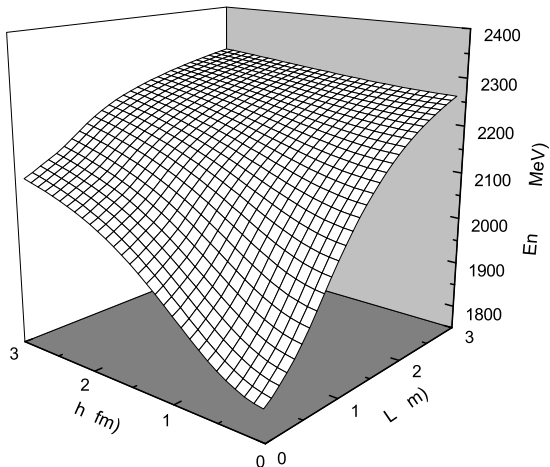
Fig.7. The energies for Jaffe-Wilczek configuration ($\mu = 0$).

Based on these three model results the $IJ^P = 0\frac{1}{2}^{\pm}$ are both possible to be the ground state of the Θ^+. A multi channel coupling quark model calculation with various nontrivial color structures are needed to check if the observed Θ^+ mass can be obtained in quark model approach and which parity is the ground state.

Suppose the Θ^+ is finally verified to be a 1540 MeV narrow width (~ 1 MeV) $IJ^P = 0\frac{1}{2}^+$ state. Then an interesting scenario similar to that of nuclear structure at the 1940's turned to the 1950's will recur. The low lying, even parity rotational excitation of nuclei is hard to explain by the naive Mayer-Jenson nuclear shell model; Bohr and Mottelson had to introduce the rotational excitation of a deformed liquid drop model. Later, nucleon Cooper pairs were introduced because of the strong short range pairing correlation. In 1970's-1980's, an S-D Cooper pair interaction boson model was developed and the collective rotation was re-derived from this model which is based on Mayer-Jenson's nuclear shell model but with nucleon pair correlation. In the description of the pentaquark, one has introduced the chiral soliton rotational excitation, quark color Cooper pairs and much more. The historical lessons of nuclear structure study might be a good pharos to light the way for the study of hadron structure.

Summary: Multi-quark states have been studied for about 30 years. The Θ^+, if further confirmed, will be the first example. Once the multi-quark "Pandora's box" is opened, the other multi-quark states: tetra-quark, hexa-quark (or dibaryon), etc., can no longer be kept inside. One expects they will be discovered sooner or later and there are claims that some tetra-quark states have been observed [45, 46, 47, 48]. A new landscape of hadron physics will appear and it will not only show new forms of hadronic matter but will also exhibit new features of low energy QCD.

Nonperturbative and lattice QCD have revealed the color flux tube (or string) structure of the $q\bar{q}$, q^3 and even $q^4\bar{q}$ states. The multi-quark system will have more color structures. How do these color structures interplay within a multi-quark state? Nuclear structure seems to be understood in terms of colorless nucleons within a nucleus. Multi-quark states might be not so. We emphasized that the effect of non-trivial color structures of multi-quark system should be studied. The low mass and narrow width of the Θ^+ might be related to such new structures instead of to residual interactions.

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