Multi-quark states

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Abstract

The pentaquark state recently discovered has been discussed based on various quark model calculations. Odd parity for the state can not be ruled out theoretically because contributions related to non-trivial color structures have not been studied completely. Other multiquark states, especially dibaryons, have been discussed also. A strangeness -3 NΩ dibaryon has been shown to have a width as small as 12-22 keV and should be detectable in Ω high productivity reactions such as at RHIC, COMPAS and the planned JHF and FAIR projects.

I. MULTIQUARK STATE SEARCH

Multi-quark states are studied even before the advent of QCD. The development of QCD accelerated multi-quark studies because it is natural in QCD that there should be multi-quark states, including glueballs and quark-gluon hybrids. Prof. Yu. A. Simonov is one of the pioneers of multi-quark studies; he led an ITEP group that developed the quark compound bag model in the early 1980's to study hadron interactions and multiquark states[1].

For a long time, multi-quark states were only a theoretical speculation; experimental searches had not obtained definite evidence, even though there were various claims of the discovery of multi-quark states.

II. DISCOVERY OF THE PENTAQUARK

Eleven groups[2] claimed recently that they found a pentaquark state, now called Θ^+, with mass$\sim$1540 MeV, and width $\Gamma < 25$ MeV. Five measurements used a real or virtual photon-nucleus (p, d, or other nuclei) reaction and the resonance is inferred from the final state nK^+ or pK_s^0 invariant mass. A reanalysis of 1986 bubble chamber K-nucleus reaction data also found the Θ^+. Three most recent experiments used pp or p-nucleus reactions. One used old neutrino reaction data and one used deep inelastic ep scattering data. In addition, the NA49 collaboration claimed that they found the anti-decuplet partner Ξ^{--} of Θ^+[3]. The HERA-H1 collaboration claimed that they found the charm pentaquark Θ_c[4].

If we had not had bitter previous experience in the search for multiquark states, one would have accepted that the pentaquark state has been discovered. Taking into account the historical lessons that many low statistics multiquark signals eventually disappeared, the consensus is that high statistics data are necessary to confirm this state.

Moreover there are weaknesses among these measurements: Some "pentaquark signals" of the real or virtual photon reactions might be due to the kinematical reflection of the following normal meson production processes[5]

$$\begin{aligned} \gamma n \to f_2 n \to K^- K^+ n, \\ \gamma p \to a_2^+ n \to K\bar{K}n, \\ \gamma p \to f_2 p \to K\bar{K}p. \end{aligned} \tag{1}$$

Some measurements only measure the charged π^+, π^- decay products of K_s^0 to obtain the pK_s^0 invariant mass and there might be kinematical reflections in these events too[6]. Reanalysis of the vast K^+n and $K_L^0 p$ scattering data could not find the Θ^+ signal with a width $\geq$ few MeV[7], except the recent time delay and speed plot analysis where a signal appears around 1.57 GeV in the P_{01} (with the notation $L_{I(2J)}$) channel[8]. In addition, a very tiny bump had appeared in 1973 CERN $K^+p \rightarrow pK_s^0\pi^+$ inelastic scattering data[9].

The NA49 claim has been challenged by another CERN group based on Ξ spectroscopy data with higher statistics[10]. HERA-B p-nucleus reaction data has not found the Θ^+[11]. BES J/Ψ decay data analysis has not found the Θ^+ either[12]. There are other groups that have not claimed publicly that they have not found the Θ^+ signal.

III. WHAT IS THE PENTAQUARK

Theoretical studies based on the chiral soliton model played an important role in triggering the Θ^+ searches[13]. 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. It predicted an I=0 $J^p = \frac{1}{2}^+$ state with mass about 1540 MeV and width less than 15 MeV, quite close to the later experimental results. The QCD background of this model has been criticized by Jaffe and Wilczek[14] and the difficulties of the flavor SU(3) extension in the description of the meson-baryon scattering with strangeness was discussed by Karliner and Mattis[15].

Various quark models have been proposed to understand the Θ^+, mainly aimed at explaining the low mass and narrow width which is not a serious problem in the chiral soliton quark model but hard to understand in the usual quark model. First the ground state should be an S-wave one in the naive quark model[16, 17] 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 and this means that Θ^+ can not be an S-wave KN resonance. 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 of the spin-parity of Θ^+. If the Θ^+ is confirmed to be a positive parity state and there is no negative parity pentaquark state with lower energy then it will provide another example of an inverted energy level structure which has been a weak point of the naive quark model of the baryon spectrum: The first excited states of N and Δ have positive parity instead of negative parity as predicted by the naive quark model.

Jaffe and Wilczek[14] proposed a $\{ud\}\{ud\}\bar{s}$ structure for the pentaquark state, where $\{ud\}$ means a di-quark in the color anti-triplet, spin 0, isospin 0 S-wave state. They assume a strong color-spin force to argue for such a di-quark structure, a color Cooper pair. The overall color singlet condition dictates that the four quarks must be in a color triplet state (in a color SU(3) [211] representation), which is antisymmetric with respect to the di-quark exchange in color space. The two quasi-boson di-quarks should be symmetric with respect to the overall di-quark exchange and this dictated the relative motion of the two di-quarks in a P-wave. In this way they get a positive parity Θ^+ state, the same as the chiral soliton quark model one. This model gives an antidecuplet spectrum different from the chiral soliton quark model ones and predicts a pentaquark octet based on phenomenological assumptions. Yu. A. Simonov did a quantitative calculation based on the Jaffe-Wilczek configuration by means of the effective Hamiltonian approach. This method obtained a quantitative fit of single baryon masses, but the calculated Θ^+ mass is about 400 MeV higher than the observed 1540 MeV[18]. F. Close pointed out that there should be a spin-orbit partner Θ^* with $J^P = \frac{3}{2}^+$ not too far from the Θ^+ mass[19].

An even more serious problem is the decay width. F. Buccella and P. Sorba suggested an approximate flavor symmetry selection rule to explain the narrow width of Θ^+ based on the Jaffe-Wilczek model[20]. However if the Jaffe-Wilczek correlated di-quark di-quark wave function is totally anti-symmetrized then there will still be an SU(6) totally symmetric component and no flavor symmetry selection rule to forbid the pentaquark to decay to a KN final state. Diakonov and Petrov even raised the criticism that the non-relativistic quark model might not make any sense for light flavor pentaquark states[21].

Fl. Stancu, D.O. Riska and L.Ya. Glozman gave another explanation of the special properties of the pentaquark state using their Goldstone boson exchange quark model[22]. The flavor-spin dependence of the Goldstone boson exchange qq interaction favors a totally symmetric flavor-spin wave function of the four light quarks. The overall color singlet dictates the four light quarks to be in a color triplet state, i.e., in a color SU(3) [211] representation which is the same as discussed in the Jaffe-Wilczek model. The Pauli principle further dictates the four light quarks to be in a [31] representation of SO(3), therefore they must be in a s^3p configuration. The kinetic energy increase might be compensated by a potential energy decrease. However the Goldstone boson exchange interaction itself might not be enough to form the Θ^+ and they have to introduce an additional $q - \bar{s}$ interaction due to η meson exchange which was argued not to exist in this model approach[23]. The narrow width of Θ^+ has not been discussed.

B.K. Jennings and K. Maltman did a comparative study of the three models of the Θ^+ mentioned above and related exotics[24]. They concluded that the three models appear to be different but might describe the same physics. They also pointed out that the narrow width of Θ^+ may be explained by the small overlap of the five quark model wave function and the KN one. But they avoid discussion of the mass of the pentaquark because that is dependent on estimates of the confinement and kinetic energy.

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[25]. 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,

$$B = aq^3 + bq^3q\bar{q} + \cdots . \tag{2}$$

The nucleon spin structure discovered in polarized lepton-nucleon deep inelastic scattering can be explained by allowing the nucleon ground state to have about 15% $q^3q\bar{q}$ component where the $q\bar{q}$ parts have pseudoscalar meson quantum numbers. In the Θ^+ mass calculation we assume it is a pure $uudd\bar{s}$ five quark state but with channel coupling. Our preliminary results are listed below:

	$pure KN$	$KN + K^*N$	$KN + K_8N_8$	$KN + K^*N + K_8N_8$
$I.S_{01}$ *negative parity*				
	2282	2157	1943	1766
$II.P_{01}$ *positive parity*				
	2357.1	2356.3	2357.0	2336.8

Here the calculated mass is in units of MeV and K_8N_8 means the K and N are both in color octets but coupled to an overall color singlet. These numerical results are under further check. However the following results will not change: The S-wave state will have a lower mass than that of the P-wave; the channel coupling plays a vital role in reducing the calculated S-wave Θ^+ mass; it is possible to obtain a mass close to the observed mass 1540 MeV of the Θ^+ if the overestimation of the K mass in this model is taken into account.

Quite possibly, confinement is due to gluon flux tube (or gluon string) formation in the QCD vacuum. Yu. A. Simonov proposed a field correlator method to study the non-Abeliean non-perturbative properties of QCD and found a Y-shaped gluon flux tube (or string), but not a Δ-shaped one, in a baryon. The ground state energy can be approximated by a potential[26]

$$V_{3q} = -A_{3q}\sum_{i<j}\frac{1}{|\vec{r}_i-\vec{r}_j|} + \sigma_{3q}L_{min} + C_{3q},$$
$$L_{min} = \sum_i L_i. \qquad (3)$$

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.(3) 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,

$$V_{conf}(\vec{r}_{ij}) = -a\vec{\lambda}_i\cdot\vec{\lambda}_j\vec{r}_{ij}^{\,n},$$
$$\vec{r}_{ij} = \vec{r}_i - \vec{r}_j, \qquad n = 1, 2. \qquad (4)$$

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 are a few lattice QCD calculations of pentaquarks which obtained an S-wave ground state[27]. However they have not given the color flux tube or string structure as the Simonov group did for mesons, baryons and glueballs. But from general SU(3) color group considerations, there might be the following color structures: $q^3(1)q\bar{s}(1)$; $q^3(8)q\bar{s}(8)$; $qq(\bar{3})qq(\bar{3})\bar{s}(\bar{3})$, etc. Here the number in parentheses is the color SU(3) representation labelled by its dimensions. 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.

New color structures will give rise to additional interactions which have not been taken into account in the quark model calculations of the pentaquark so far. And our first model calculation mentioned above shows that hidden color channel coupling reduces the calculated pentaquark mass.

We have developed a model, called the quark delocalization, color screening model (QDCSM), to take into account the additional interaction in multiquark systems induced by various color structures, which are not possible for a $q\bar{q}$ meson and q^3 baryon, by a re-parametrization of color confinement[28]. This model explains the existing BB interaction data (bound state deuteron and NN, NΛ, NΣ scatterings) well with all model parameters fixed in hadron spectroscopy except for only one additional parameter, the color screening constant μ. More importantly, *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*[29].

A preliminary calculation of the pentaquark mass has been done with this model (QDCSM) in the color singlet KN configuration. In the I=1 S-wave KN channel, a pure repulsive effective interaction is obtained. This helps to rule out the I=1 possibility for the Θ^+. In the I=0 S-wave KN channel, a Θ^+ mass of 1615 MeV is obtained in an adiabatic approximation. More precise dynamical calculation might reduce the calculated mass further. 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, as wanted in other quark models. However in our model the P-wave attraction is not strong enough to overcome the kinetic energy increase to reduce it to a ground state. This is consistent with the lattice and QCD sum rule results[27, 30]. In the I=1 channel, only a very weak attraction is obtained. This rules out the I=1 Θ^+ again.

In a third model, we use the $\{ud\}\{ud\}\bar{s}$ configuration. The color structure is the same as the Jaffe-Wilczek one but the four non-strange quarks are totally anti-symmetrized. 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. The height and the length 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 around 1.3-1.4 GeV corresponding to a color screening parameter $\mu = 1.0 -$

$0.8 fm^{-2}$. This gives rise to an effective attraction with a minimum at around 50-150 MeV, qualitatively similar to our second model result but with the possibility of further reducing the calculated Θ^+ mass to be closer to the observed value.

As mentioned before these numerical results have to be checked further and the QDCSM is only a model of QCD. Based on these results we cannot definitively claim that the ground state of the Θ^+ is $IJ^P = 0\frac{1}{2}^-$. However, this possibility has not been ruled out because color confinement contributions of various nontrivial color structures for a pentaquark system have not been studied thoroughly. This can be checked by devising pentaquark interpolating field operators with these nontrivial color structures in lattice QCD calculations.

Suppose the Θ^+ is finally verified to be a 1540 MeV narrow width ($\sim$ 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 mirror to light the way for the study of hadron structure.

IV. TETRAQUARKS, HYBRIDS AND GLUEBALLS

By the end of 1970, Jaffe had already suggested that the scalar mesons with masses less than 1 GeV ($\sigma(600)$, $f_0(980)$, $a_0(980)$, $\kappa(900)$) might be $qq\bar{q}\bar{q}$ states[31]. The "discovery" of a pentaquark enhances this possibility. In addition there are a few new candidates for tetraquarks: the BABAR experiment observed a resonance of M=2317 MeV, $\Gamma < 10$ MeV in the $D_s^+\pi^0$ invariant mass analysis[32]. CLEO confirmed this resonance and observed a new D_{sJ}^+(2463 MeV) state[33]. These might be $q\bar{q}c\bar{s}$ tetraquark states. Belle observed a resonance of 3872 Mev in the $J/\Psi\pi^+\pi^-$ channel[34] in B meson decay. CDF-II confirmed this resonance in $p\bar{p}$ collisions[35]. This might be a $D^0\bar{D^{*0}}$ molecular state.

There have been glueball and hybrid candidates. In general these states will be mixed and also mixed with tetraquark states. The "discovery" of a pentaquark state will make the identification of glueballs and hybrids even harder[36].

V. DIBARYONS

Immediately after the development of MIT bag model, Jaffe predicted the deeply bound dibaryon H, an I=S=0 uuddss flavor singlet state[37]. Long term extensive searches for the H have been null. Yu.A. Simonov proposed the quark compound bag model and various dibaryon resonances were predicted[38]. E.L. Lomon extended the R-matrix formalism to dibaryon studies[39]. This model explains the NN scattering data well because it has the aid of the boundary condition model of the NN interaction[40]. It predicted a 2.7 GeV NN resonance and an experimental signal had been claimed.

A direct extension of the naive quark model[16, 17] to baryon-baryon (BB) interactions only gives rise to the short range repulsion of the NN interaction but not the intermediate range attraction nor the well established long range one π exchange tail in the meson exchange model. This means that important physics has been missed in the application of the naive quark model to the BB interaction. One possibility arises from spontaneously broken chiral symmetry and the related Goldstone boson exchange[41]. I.T. Obukhovsky and A.M. Kusainov applied such a hybrid model, with both gluon and Goldstone boson exchange, to the NN interaction[42]. Z.Y. Zhang et al. extended this hybrid model from SU(2) to SU(3) and used it to predict dibaryon resonances[43]. Such a direct extension with a universal σ-u,d,s quark coupling will overestimate the σ meson contribution in high strangeness channels and makes their predicted mass of the di-Ω too low[44].

V.B. Kopeliovich et al. studied the dibaryon with the Skyrmion model and predicted dibaryons up to high strangness -6. But after taking into account the Casimir energy, these dibaryons become unbound[45].

We have studied the dibaryon candidates in the u, d, s three flavor world systematically with both non-relativistic and relativistic versions of the QDCSM in an adiabatic approximation[46]. This model has been mentioned before. The main new ingredients are: *Baryon distortion or internal excitation in the course of interaction is included by allowing the quark mutual delocalization between two interacting baryons and a variational* *method is developed to let the interacting baryon choose its own favorable configuration; a new parametrization of color confinement is assumed to take into account the contribution of nontrivial color structures which are not possible in a $q\bar{q}$ meson and q^3 baryon.* Only a few states remain after filtration with a more precise dynamic calculation: A nonstrange $IJ^p = 03^+$ d^* (M=2165-2186 MeV, Γ=5.76-7.92 MeV)[47] and a strangeness -3 $IJ^P = \frac{1}{2}2^+$ NΩ (M=2549 MeV, Γ=12-22 KeV). The H and di-Ω are near threshold states and might be unbound when the model uncertainty is taken into account[48]. There are few broad NΔ and ΔΔ resonances with widths of 150 MeV-250 MeV in the energy range 2.1-2.2 GeV which might make the identification of the d^* even harder and all of them might be the origin of the observed broad resonance of the pp and np total cross section in that energy region. The strangeness -3 NΩ state is a very narrow dibaryon resonance and might be detected in high Ω productivity reactions such as at RHIC, COMPAS and the planned JHF in Japan and FAIR in German.

VI. 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 not be kept inside. One expects they will be discovered sooner or later. 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.

Nonpertubative and lattice QCD have revealed the color flux tube (or string) structure of the $q\bar{q}$ and q^3 states. The multi-quark system will have more color structures. How do these color structures interplay within a multiquark state? Nuclear structure seems to be understood in terms of colorless nucleons within a nucleus. We emphasized that other color structures should be studied and the multi-quark systems provide a good field to do that. 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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