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THE DISCOVERY AND PROPERTIES OF PENTAQUARKS

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The pentaquarks are exotic baryons formed of four quarks and an antiquarks. Their existence has been discussed in the literature over the last 30 years or more, first in connection with kaon nucleon scattering data. The subject has been revived by the end of 2002 when experimental evidence of a narrow baryon of strangeness $S = +1$, and mass $M \simeq 1530$ MeV has been found. This is interpreted as the lightest member of an SU(3)-flavor antidecuplet. Here we shall mainly review the predictions of pentaquark properties as e.g. mass, spin and parity, within constituent quark models. Both light and heavy pentaquarks will be presented.

Keywords: Pentaquarks; parity and spin; constituent quark models.

1. Historical Note and the Present Experimental Observation

The possible existence of exotic hadrons forming a baryon antidecuplet with spin 1/2 and positive parity has been mentioned in the literature even before the advent of QCD, in connection with the KN scattering data. [1] Later on, the existence of multiquark systems appeared as natural in QCD. Several constituent quark model calculations were performed, for example in Refs. 2, 3, 4. As a consequence, searches were made in the 1.74-2.16GeV/c^2 mass range (for a review see Ref. 5) and the lowest state was thought to have negative parity. At that time these exotic hadrons carried the name of Z* resonances. They were reviewed by the Particle Data Group (PDG) until 1986, when they were suppressed from the listings due to poor experimental evidence. However a new wave of theoretical interest appeared soon after, in the context of the chiral soliton or the Skyrme model. The first estimate of the lightest pentaquark mass, presently named Θ^+, was given by Praszalowicz [6], with a mass of the order 1.5 GeV . Ten years later Diakonov, Petrov and Polyakov [7], predicted not only a mass of a similar value but also a strong decay width not larger than 15 MeV, which means small on the hadronic scale. The pentaquark Θ^+ was identified as the lightest member of an SU(3)-flavor antidecuplet having positive parity and spin 1/2. The predictions of Ref. 7 have motivated and oriented new experimental searches of pentaquarks leading to the observation of a narrow resonance at about the predicted mass [8,9]. So far this observation has been confirmed by another nine

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*Plenary talk, MESON2004 Conference Proceedings, Crakow, June 4-8 2004 experimental groups [10], with various projectiles and targets. There are however a few experiments where Θ^+ has not been seen [11]. Although Θ^+ is now listed as a three-star resonance by PDG, one is perfectly aware that individual observations have limited statistics and further confirmation is desirable [12].

The interpretation of Θ^+ as a pentaquark $uudd\bar{s}$ was strengthened by the observation of another two narrow resonances at an invariant mass of about 1862 MeV, in the $\Xi^-\pi^+$ and $\Xi^-\pi^-$ channels of the $p+p$ scattering [13]. They were candidates for the $\Xi^0_{3/2}$ and $\Xi^{--}_{3/2}$ members of the antidecuplet, having a quark content $udss\bar{u}$ and $ddss\bar{u}$ respectively. However, no evidence for the $\Xi(1862)$ resonances has been found by other three experiments [14,15]. Thus the existence of $\Xi(1862)$ remains entirely controversial.

At the time when the observation of light pentaquarks became hopeless, theoretical predictions were oriented towards the heavy sector. Based on general arguments, the expectation was that that heavy pentaquarks would be more stable than the light ones, thus easier to be observed. Simultaneously, two independent studies [16] based on the one-gluon exchange hyperfine interaction predicted stable charmed strange pentaquarks of content $uuds\bar{c}$ or $udds\bar{c}$. The searches made for these pentaquarks at Fermilab remained however inconclusive [17]. These were negative parity pentaquarks. By this time, in the context of a constituent quark model based on a pseudo scalar meson exchange hyperfine interaction [18,19], heavy positive parity pentaquarks were proposed [20]. In the charm sector the content of the lowest pentaquark was $uudd\bar{c}$ with spin 1/2 or 3/2. Early this year the H1 Collaboration reported a narrow resonance at 3099 MeV which was interpreted as an anticharmed baryon with a minimal content $uudd\bar{c}$ of spin 1/2 or 3/2 [21]. However such a signal was not observed in a preliminary ZEUS analysis of $e-p$ collisions [22].

2. Present Approaches

It would be difficult to make a review of 250 manuscripts or more, posted on the LANL archives since July 1st 2003 (part of them already published). On the theoretical side one could merely make an inexhaustible list of the subjects under study. Some of these are:

- Determination of spin and parity of Θ^+ (polarization experiments)
- Consistency between the calculated and/or observed limit on the width of Θ^+ and the KN partial wave analysis
- Calculation of the photo-production cross sections on proton and neutron, useful in determining the yet unknown production mechanism of Θ^+
- The chiral soliton model revisited, limits on masses & widths of the antidecuplet members
- The Skyrme model revisited (bound state or rigid rotator)
- Group theoretical classification of $q \times q \times q \times q \times \bar{q}$ states and mass formulae
- The pentaquark Θ^+ and its antidecuplet partners in constituent quark models

- The octet-antidecuplet or higher representation mixing
- Interpretation of Θ^+ as a heptaquarks or as $K\pi N$ molecule
- The description of pentaquarks in the instanton model
- Pentaquark results from QCD sum rules
- Pentaquarks in lattice calculations
- Magnetic moments of pentaquarks
- Θ^+ in relativistic heavy ion collisions

The chiral soliton model describes Θ^+ as a collective excitation of the mean chiral field in the spin and isospin space. That is considered as the main reason for the low mass and the very small width of Θ^+. In the chiral soliton model, Θ^+ and its partners form an antidecuplet with $J^P = 1/2^+$, all being narrow resonances [7]. The predictions of the chiral soliton model for the masses and widths of the antidecuplet have recently been re-analyzed [23]. The mass ranges are estimated to be 1430 MeV $< M(\Theta^+) <$ 1660 MeV and 1790 MeV $< M(\Xi^{--}) <$ 1970 MeV and the width of Θ^+ remains small.

The chiral soliton model is more fundamental, it naturally incorporates relativistic effects, but it is more difficult to apply to hadron spectroscopy. Contrary, the constituent quark model is essentially phenomenological, but it is more intuitive and more appropriate to describe spectra and decay of baryons and mesons. The two models are rather complementary. Then the question is whether or not constituent quark models can accommodate the pentaquark antidecuplet predicted by the chiral soliton model.

In a naive estimate, the nucleon mass is approximately the sum of masses of the constituent quarks. Taking $m_u = m_u =$ 315 MeV one gets 945 MeV for the nucleon. In a similar way the constituent quark model gives $M(\Theta^+) = 4\ m_u + m_s \simeq$ 1700 MeV for a mass difference $m_s - m_u \simeq$ 150 MeV. This value of $M(\Theta^+)$ is larger than the original chiral soliton model prediction and the present average of the experimental value.

However in a proper calculation the total mass results from the above free mass term plus contributions from the kinetic energy, the confinement potential and the (short range) hyperfine interaction. Then the main issues in any quark model are:

- The spin and parity of Θ^+
- The absolute mass of Θ^+
- The splitting between the isomultiplets of the antidecuplet
- The strong decay width
- The role of the SU(3)-flavor mixing representations.

In the following we shall address these questions. There are two widely used constituent quark models: the one-gluon exchange model where the hyperfine interaction has a color-spin (CS) structure and the pseudoscalar meson (or Goldstone boson) exchange, where the hyperfine interaction has a flavor-spin (FS) structure. Below these models will be often called the CS and FS models.

The FS model gives a good description of the baryon spectra, reproducing the correct order of positive and negative parity levels in low energy spectra of both non-strange and strange baryons, in contrast to the CS model. But this model does not provide a description of the meson spectra as the CS model does. The FS model gets some support from the large N_c QCD limit, where the exact symmetry is the flavor-spin symmetry.

3. The Parity and Spin of the Pentaquark Θ^+ in Constituent Quark Models

A pentaquark state, described as a $q^4\bar{q}$ system can be obtained from the direct product of a baryon (q^3) and a meson ($q\bar{q}$) state. In the flavor space this involves the direct product

$$8_F \times 8_F = 27_F + 10_F + \overline{10}_F + 2(8)_F + 1_F \tag{1}$$

which shows that the antidecuplet $\overline{10}_F$ is one of the possible multiplets.

An important issue is the parity and spin of a pentaquark antidecuplet. The parity is given by $P = (-)^{\ell+1}$ where ℓ is the angular momentum of the system and - 1 the parity of the antiquark. Thus to obtain a positive parity the whole system must contain at least one (or an odd number) of units of angular excitation.

Few years ago, based on group theory arguments, it has been shown that the lowest state of heavy pentaquarks has positive parity [20] in the FS model. The proof can be straightforwardly extended to light pentaquarks. In a similar way one can show that the CS model also leads to positive parity for the lowest state when the q^4 subsystem has isospin $I = 0$ [24], compatible with the content $uudd\bar{s}$ of Θ^+ . In both models the hyperfine attraction is large enough to overcome the excess of kinetic energy brought by the excitation of a quark to the p-shell and that is why the positive parity appears below the negative parity state which does not contain any orbital excitation.

4. Dynamical Calculations for the Mass Spectrum in the Flavor-Spin Model

To our knowledge, there are practically no dynamical calculations for the pentaquark antidecuplet in a Hamiltonian model containing a CS hyperfine interaction. The literature is restricted to some attempts based either on a schematic [25,26] CS interaction

$$V_{CS} = -\sum_{i<j}^{5} C_{ij}^{CS} \lambda_i^c \cdot \lambda_j^c \vec{\sigma}_i \cdot \vec{\sigma}_j , \tag{2}$$

where all spatial variables have been integrated out and the parameters C_{ij}^{CS} are fitted to ordinary baryons, or on simple models where the existence of correlated diquark pairs in the orbital space is postulated, but not dynamically demonstrated

[27]. In the latter case there is no antisymmetrization between quarks belonging to different diquarks. In a related problem, as for example the nucleon-nucleon interaction, the antisymmetrization between quarks belonging to different nucleons has been proved crucial in describing the potential at short distances, see e. g. [28,29]. There is no reason to neglect the antisymmetrization in q^4 subsystems.

Below we present dynamical calculations in the FS model. For the q^4 subsystem we use the following Hamiltonian [19]

$$H = \sum_i m_i + \sum_i \frac{\vec{p}_i^{\,2}}{2m_i} - \frac{\vec{P}^2}{2M} + \sum_{i<j} V_{conf}(r_{ij}) + \sum_{i<j} V_\chi(r_{ij}) \ , \tag{3}$$

$$V_{conf}(r_{ij}) = -\frac{3}{8}\lambda_i^c \cdot \lambda_j^c \, C \, r_{ij} \ , \tag{4}$$

$$\begin{aligned} V_\chi(r_{ij}) = \Bigg\{ & \sum_{F=1}^{3} V_\pi(r_{ij}) \lambda_i^F \lambda_j^F \\ & + \sum_{F=4}^{7} V_K(r_{ij}) \lambda_i^F \lambda_j^F + V_\eta(r_{ij}) \lambda_i^8 \lambda_j^8 + V_{\eta'}(r_{ij}) \lambda_i^0 \lambda_j^0 \Bigg\} \vec{\sigma}_i \cdot \vec{\sigma}_j \ . \end{aligned}$$

The analytic form of $V_\gamma(r)$ ($\gamma = \pi, K, \eta$ or η') is

$$V_\gamma(r) = \frac{g_\gamma^2}{4\pi} \frac{1}{12 m_i m_j} \{ \theta(r - r_0) \mu_\gamma^2 \frac{e^{-\mu_\gamma r}}{r} - \frac{4}{\sqrt{\pi}} \alpha^3 \exp(-\alpha^2 (r - r_0)^2) \} \ , \tag{5}$$

with the parameters:

$$\begin{gathered} \tfrac{g_{\pi q}^2}{4\pi} = \tfrac{g_{\eta q}^2}{4\pi} = \tfrac{g_{Kq}^2}{4\pi} = 0.67, \ \tfrac{g_{\eta' q}^2}{4\pi} = 1.206, \\ r_0 = 0.43 \ \text{fm}, \ \alpha = 2.91 \ \text{fm}^{-1}, C = 0.474 \, fm^{-2}, \ m_{u,d} = 340 \ \text{MeV}, \ m_s = 440 \ \text{MeV} \\ \mu_\pi = 139 \ \text{MeV}, \ \mu_\eta = 547 \ \text{MeV}. \ \mu_{\eta'} = 958 \, \text{MeV}, \ \mu_K = 495 \ \text{MeV}. \end{gathered} \tag{6}$$

which lead to a good description of low-energy non-strange and strange baryon spectra. Fixing the nucleon mass at $m_N = 939$ MeV, this parametrization gives for example $m_\Delta = 1232$ MeV and the Roper resonance $N(1440)$ at 1493 MeV. The lowest negative parity states $N(1535)$ and $N(1520)$ appear at 1539 MeV, i. e. above the Roper resonance, in agreement with the experiment.

Note that in this model the SU$(3)_F$ symmetry is broken due to the the mass difference between the s and the u or d quarks and due to the differences in the pseudoscalar meson masses.

For the light pentaquark antidecuplet of which Θ^+ is a member, the above Hamiltonian must be supplemented by a term containing a $q\bar{q}$ interaction. In Ref. 30 this interaction was chosen to be spin dependent, but flavor independent. Its schematic form was

$$V_{q\bar{q}} \ = \ V_0 \sum_i^4 \vec{\sigma}_i \cdot \vec{\sigma}_{\bar{s}}. \tag{7}$$

Here V_0 is a phenomenological constant, which should correspond to the ground state matrix element of the spin-spin part of the η-meson exchange interaction. The role of the interaction (7) is to lower the energy of the whole system towards stability. In Ref. 31 it was assumed that an interaction of type (7) lowers all members of the antidecuplet by the same amount which was fixed such as to reproduce the mass of Θ^+.

Table 1. The pentaquark antidecuplet mass spectrum (MeV) in the FS model.

Penta	$\mathbf{Y,\ I,\ I_3}$	**Present results** Ref. 31	**Carlson et al.** Ref. 32
$\mathbf{\Theta^+}$	$\mathbf{2,0,0}$	**1540**	**1540**
$\mathbf{N_{\overline{10}}}$	$\mathbf{1,1/2,1/2}$	**1684**	**1665**
$\mathbf{\Sigma_{\overline{10}}}$	$\mathbf{0,1,1}$	**1829**	**1786**
$\mathbf{\Xi^{--}}$	$\mathbf{-1,3/2,-3/2}$	**1962**	**1906**

5. The Wave Function

It is useful to first look at the q^4 subsystem. For isospin $I = 0$ (the *uudd* system) and spin $S = 0$ the lowest totally antisymmetric state reads

$$\left|\psi^+(q^4)\right\rangle = \left|[31]_O[211]_C\left[1^4\right]_{OC}\ ;[22]_F[22]_S[4]_{FS}\right\rangle \tag{8}$$

which represents the inner product of the orbital (O), color (C), flavor (F) and spin (S) wave functions of the q^4 subsystem, all written in terms of partitions $[f]$ associated to various degree of freedom. The $[4]_{FS}$ part is totally symmetric which allows the maximum possible attraction in the FS model. It is combined with the totally antisymmetric $[1^4]_{OC}$ part, so the total is an antisymmetric wave function. The antiquark is then coupled to $|\psi^+\rangle$. The symmetry $[31]_O$ requires an s^3p structure i. e. a quark must be excited to the p-shell. Thus the state (8) has positive parity. One can write such an excited state by using the internal coordinates

$$\vec{x} = \vec{r}_1 - \vec{r}_2\ , \quad \vec{y} = (\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)/\sqrt{3},$$
$$\vec{z} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3 - 3\vec{r}_4)/\sqrt{6}\ , \quad \vec{t} = (\vec{r}_1 + \vec{r}_2 + \vec{r}_3 + \vec{r}_4 - 4\vec{r}_5)/\sqrt{10}\ .$$

where 1,2,3 and 4 denote the quarks and 5 the antiquark. There are 3 independent basis vectors of symmetry [31] or alternatively three distinct Young tableaux. These basis vectors can be expressed in terms of independent shell model type states $|n\ell m\rangle$ as [20]

$$\psi_1 = \begin{array}{l}\boxed{1}\boxed{2}\boxed{3}\\ \boxed{4}\end{array} = \langle \vec{x}\,|000\rangle\,\langle \vec{y}\,|000\rangle\,\langle \vec{z}\,|010\rangle\ \ , \tag{9}$$

$$\psi_2 = \begin{array}{l}\boxed{1}\boxed{2}\boxed{4}\\ \boxed{3}\end{array} = \langle \vec{x}\,|000\rangle\,\langle \vec{y}\,|010\rangle\,\langle \vec{z}\,|000\rangle\ \ , \tag{10}$$

$$\psi_3 = \begin{array}{l}\boxed{1}\boxed{3}\boxed{4}\\ \boxed{2}\end{array} = \langle \vec{x}\,|010\rangle\,\langle \vec{y}\,|000\rangle\,\langle \vec{z}\,|000\rangle\ \ , \tag{11}$$

This means that the angular excitation $\ell = 1$ can be carried by any of the relative coordinates $\vec{x}$, $\vec{y}$ or $\vec{z}$, with equal probability, as implied by the state (8). This is entirely different from other pictures promulgated in the literature. The pentaquark orbital wave function is obtained by multiplying each ψ_i by $\left\langle \vec{t}\,|000\right\rangle$ which describes an S-wave state of $\overline{q}$ relative to the q^4 subsystem. Then each orbital wave function becomes a product of four independent individual wave function, one for each relative coordinate.

6. The Light Pentaquark Antidecuplet

In practice we make a Gaussian Ansatz for each of the individual wave functions and perform variational calculations. For simplicity we restrict to two variational parameters in the 5-body wave function, one which we assume to be identical for all three internal coordinates of q^4 and a different one for the relative coordinate of q^4 to $\bar{q}$. The antidecuplet mass spectrum obtained from such variational calculations is exhibited in Table 1. Details of the calculations can be found in Ref. 31. Table 1 compares our results with those of 32. In the latter, the FS interaction V_χ of (5) is reduced to a form similar to (2)

$$V_{FS} = -\sum_{i<j}^{4} C_{ij}^{FS} \lambda_i^F \cdot \lambda_j^F \vec{\sigma}_i \cdot \vec{\sigma}_j\ . \tag{12}$$

Here C_{ij}^{FS} are radial two-body matrix elements specific to the FS model, fitted to reproduce the ground state masses of ordinary baryons. Note that the sum runs over the quarks only. In contrast to the present results, in Ref. 32 there is no kinetic term, no η'-meson exchange and no SU(3) breaking in the η-meson exchange due to quark masses. Moreover, the radial two-body matrix elements do not contain orbital excitation due to the angular momentum $\ell = 1$, although the parity is assumed to be positive. In both calculations the mass of Θ^+ is fixed to 1540 MeV. One can see that the present calculations lead to larger splittings between the isomultiplets than those of Ref. 32. Then, in terms of the hypercharge Y, they can be parametrized by the linear mass formula $M \simeq 1829 - 145\,Y$ while those of Ref. 32 by $M \simeq 1786 - 122\,Y$.

As mentioned above, the Hamiltonian (3) breaks the SU(3)$_F$ symmetry. Thus mixing of representations appears naturally. In particular one expects and important mixing between the $\overline{10}_F$ and 8_F representations (both present in the right hand side of Eq. (1)). This implies that octet and antidecuplet states with identical Y, I and I_3 should mix. These are N and Σ states. The mixing leads to physical states, which are either "mainly antidecuplet" or "mainly octet". This mixing was discussed in Ref. 31 where it was found that, besides the free mass term, a substantial additional contribution to the coupling between $\overline{10}_F$ and 8_F comes from the combined effect of the kinetic energy term and the hyperfine interaction. However the resulting mixing angle was 35.34^0 for N and - 35.48^0 for Σ, thus close to the ideal mixing angle 35.26^0 for N and -35.26^0 for Σ. (We recall that the ideal mixing is due to the free mass term only.) Then, for example, the "mainly octet" pentaquark is at 1451 MeV and the "mainly antidecuplet" at 1801 MeV (for details see Ref. 31).

7. The decay width of Θ^+

So far there are only schematic studies of the strong decay width of Θ^+. On one hand one tries to attribute the narrowness of the pentaquark resonance to the smallness of the overlap between a compact $q^4\bar{q}$ state and the kinematically allowed final state [33,34]. The size of this overlap results from the algebraic structure of the wave function (8). On the other hand the smallness of the width is thought to be due to the spatial structure [35] of Θ^+, but there is no dynamical proof of this structure.

8. The Charmed Antisextet

The study of the charmed pentaquarks is entirely similar to that of the light antidecuplet. The essential difference is that the quark-antiquark interaction can be neglected, due to the heavy mass of the antiquark.

Table 2. Masses (MeV) of the positive parity antisextet charmed pentaquarks in various models.

Penta	**I**	**Content**	**FS model** Ref. 20	**$\mathbf{D-D-\bar{c}}$ model** Ref. 37	**$\mathbf{D-T}$model** Ref. 38	**Lattice** Ref. 39
$\mathbf{\Theta_c^0}$	**0**	**u u d d $\bar{\mathbf{c}}$**	**2902**	**2710**	$\mathbf{2985 \pm 50}$	**2977**
$\mathbf{N_c^0}$	**1/2**	**u u d s $\bar{\mathbf{c}}$**	**3161**			**3180**
$\mathbf{\Xi_c^0}$	**1**	**u u s s $\bar{\mathbf{c}}$**	**3403**			**3650**

The lowest charmed pentaquarks form an antisextet which is a sub-multiplet with charm quantum number $C = -1$ of the $\overline{60}$ representation of $SU(4)_F$ [36]. The light antidecuplet and octet belong to the same representation, but have $C = 0$. The three members of the antisextet having zero charge are presented in Table 2 together with their quark content. The absolute masses of the antisextet members (an exact SU(2) symmetry is assumed), as calculated in the FS model and extracted from Table II of Ref. 20, are compared with results recently obtained from lattice calculations, Ref. 39, where the lowest charmed pentaquarks turn out to have positive parity as well. One can see that the FS model and the lattice results lead to rather similar predictions. For completeness we also indicated the only available mass from the diquark-diquark-$\bar{c}$ (D-D-$\bar{c}$) model of Ref. 37 and that obtained in Ref. 38 in the diquark-triquark (D-T) model. The mass of Θ_c^0 in the (D-D-$\bar{c}$) model is far below the other results. As mentioned in the introduction, the observation of Θ_c^0 is controversial at present. It is the task of future, perhaps dedicated experiments, to clarify this situation.

9. Conclusions

In regard to the light pentaquarks the conclusion is that the constituent quark models can accommodate the pentaquark Θ^+ and its antidecuplet partners, the lowest antidecuplet states having positive parity and spin 1/2. However the absolute mass of Θ^+ cannot be determined. The situation is similar to the ordinary baryons where the nucleon ground state is always fitted to the experimental value. The mass splitting between the antidecuplet isomultiplets has been calculated in the FS model. The mixing between the antidecuplet and octet pentaquarks was calculated dynamically in the FS model as well and has been found close to the ideal mixing. More elaborate five particle calculations than those based on the variational method used here are desirable. The calculation of the decay width should be performed dynamically.

Manifestly, the existence and properties of the pentaquarks is a fast moving field. It is expected to change at least the usual practice of baryon spectroscopy. Of particular importance is to understand the role of the chiral symmetry implemented in the chiral soliton model where the mass of Θ^+ is so low and its width is so narrow. It will be exciting if the pentaquarks will firmly be confirmed experimentally.

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