



## Magnetic Moments of The Baryon Anti-decuplet and Octet Pentaquark States

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### ABSTRACT

The magnetic moments of the baryon anti-decuplet and octet-pentaquark states have been estimated in the framework of diquark-diquark-antiquark configuration using the composite fermion (CF) model of diquark suggested by us. The masses of the diquark have been estimated in the CF approach and subsequently used to estimate the magnetic moments of baryon antidecuplet and octet penta quark states. Results are compared with existing predictions.

### Indexing terms/Keywords

Baryon anti-decuplet; octet-pentaquark; magnetic moments; composite fermion.

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## 1. INTRODUCTION

The baryons built of four quarks and an antiquark as the lowest Fock component, referred to as pentaquarks, are not forbidden by theory and have been discussed ever since the appearance of the quark model. The quark model has been very successful in the classification of baryons and mesons [1]. However, quantum chromodynamics (QCD) as the underlying theory of strong interaction allows a much richer baryon spectrum. In particular, there may exist hybrid baryons (qqqG) and multiquark baryons such as pentaquarks (qqqqq<sup>-</sup>), dibaryons (qqqqqq), etc. For over 30 years, physicists have searched for exotic particles known as pentaquarks that have a valence structure of four quarks and one antiquark. As symmetry properties have always played a significant role in describing the spectrum of hadrons they have had a central role in prediction of pentaquarks. The symmetry properties leads to the theoretical prediction that the antidecuplet and octet states can not be built from three quarks. Their quantum numbers require configuration with four quark and an antiquark. This motivates notion of pentaquarks. The antidecuplet also contain nucleon type state (N<sup>'</sup>) as well as  $\Sigma$  type states. These are sometimes referred to as crypto exotic pentaquarks. Once flavor symmetry breaking is switched on these states mix with the nucleon and  $\Sigma$  from the octet.

D. Diakonov et al [2] predicted a SU(3) flavor anti-decuplet of pentaquarks using a soliton model. The most striking prediction using this symmetry group is a narrow exotic state which has quark component uudds<sup>-</sup>. The discovery of  $\Theta^+$  by LEPs Collaboration [3] has motivated theorists to look more closely into the possible exotic states in quark models [4], chiral models [5,6], lattice QCD [7], nuclear-meson bound state models [8], constituent quark models [9,10], QCD sum rules [11-13] and in group theoretical approach [14]. The cross section for the  $\Theta^+$  production have been already described theoretically [15]. Jaffe and Wilczek [16] suggested that pentaquarks may belong to flavor octet  $8_f$  and antidecuplet  $10_f$  states. They have pointed out that a pentaquark may be described as a diquark-diquark-antiquark configuration. Shuryak and Zahed [17] suggested that the pentaquark mass may be lowered by replacing the pair of scalar diquarks with one scalar and one tensor diquark. The masses of octet pentaquarks were investigated by Majee and Raychaudhuri [18] in the context of QCD and they have suggested that the splitting between the mass of the octet state and that of the corresponding antidecuplet state is typically 500 to 600 MeV.

Pentaquarks are of special interest since the discovery of the  $\Theta^+$  particle by LEPs Collaboration [3]. They discovered a very narrow baryon state around 1540 MeV with strangeness  $S = +1$  which was confirmed by a series of experiments [19-22]. This state coincided with a pentaquark state with a mass of 1530 MeV/c<sup>2</sup> predicted in 1997 by D. Diakonov et al [2]. The Chiral Soliton model predicts a low lying antidecuplet state which is 210 MeV higher than experimental value measured by NA49 [23] collaboration. A resonance like structure with mass 1670 MeV and width 40 MeV has been observed in the Laboratory of Nuclear Science, Tohoku University [24]. This bump can be indication of a hidden strangeness pentaquark baryon  $N_5(1670)$  in the antidecuplet state. Barmin et al [25] have analyzed the DIANA data on the charge exchange reaction  $K^+Xe \rightarrow K^0pXe$  using increased statistics and modified selections. They have interpreted their observations as strong evidence for formation of a pentaquark baryon with positive strangeness,  $\Theta^+(uudds)$ , in the charge-exchange reaction  $K^+n \rightarrow K^0p$  on a bound neutron. Kuznetsov et al [26] have presented a study of quasi free compton scattering on the neutron in the energy range of 0.75-1.5 GeV. This result, being considered in conjunction with the recent evidence for a narrow structure at  $W \sim 1.68$  GeV in  $\eta$  photoproduction on the neutron, suggests the existence of a nucleon resonance with unusual properties. The mass is predicted as  $\sim 1.685$  GeV, whereas decay width is found to be  $\Gamma \leq 30$  MeV. The NA49 Collaboration provided an evidence for the existence in the decay mode  $\Xi^- \pi^+$  a narrow baryonic state with the mass of  $1.862 \pm 0.002$  GeV [27]. This state is considered as a candidate for the exotic pentaquark state  $\Xi_{3/2}^-$ . It may be noted that the result of NA49 Collaboration perhaps is inconsistent with data collected over the past decade [28]. However the existence of  $\Theta^+$  is yet to be confirmed but the prediction of  $\Theta^+$  gives a new impetus to the study of baryons as pentaquark states. Despite the null results, LEPs results as of 2009 continue to show the existence of a narrow state with a mass of 1524 MeV/c<sup>2</sup> with a statistical significance of  $5.1\sigma$  [29]. Experiments continue to study this discovery.

In the present work magnetic moment of baryon anti-decuplet and octet pentaquark states have been studied. The baryon magnetic moment is a fundamental observable as its mass, which encodes information of the underlying quark structure and dynamics. Although it may be difficult to determine its value experimentally, it is an essential ingredient in calculations of the photo and electroproduction cross sections of pentaquark baryons [30,31]. In the absence of experimental information, one has to rely on model calculations or a theoretical guideline to estimate them. Wang [32] investigated the magnetic moment of the  $\Theta^+$  particle in the light cone QCD sum rule considering a diquark-diquark-antiquark configuration. Liu et al. [33] estimated the magnetic moments of octet pentaquarks in addition to the antidecuplet in the context of different models. Inoue et al [34] studied the magnetic moments of exotic baryons  $\Theta^+$  and  $\Xi^-$  and their multiplet partners in the framework of a naive additive quark model considering them as pentaquark states in which four quarks and a single antiquark exist in their ground state orbit.

We have investigated the magnetic moment of octet pentaquark and antidecuplet states in the framework of Composite Fermion (CF) diquark model with a diquark-diquark-antiquark configuration. We suggest a Composite Fermion model for the diquark in analogy with the two dimensional electron gas in high magnetic field where electrons can be described as composite fermions [35]. We use this Composite Fermion concept of diquark to estimate the mass of diquark which is an important quantity for calculation of magnetic moment as it depends on the gyromagnetic ratio. Using these diquark mass values we investigate the magnetic moments of octet pentaquark and anti-decuplet states in the diquark-diquark-antiquark scheme. Results are compared with available data.



## 2.COMPOSITE FERMION (CF) MODEL OF DIQUARK

It has been observed that the strongly interacting particles sometimes behave like weakly coupled system and form a system of particles of new kind. The collective object behaves differently from the original coupled system but they possess well defined mass, spin, binding energy and other relevant properties. The quasi particle behaviour of electron in a crystal is an example of such system. The electron in the lattice changes behaviour and exists as an independent object. The nature of quasi particle is completely different and it is difficult to describe it in terms of the old particle comprising the system earlier.

Composite Fermion also represents such a state. It is the state of an electron in the strong magnetic field when the electron in two dimension absorbs a substantial amount of magnetic field transforming to a new particle called Composite Fermion. These electrons are quantized to form discrete kinetic energy levels (Landau level) and produce quantum Hall effect. It is known that spin degrees of freedom of CF is frozen at low temperature. The pairing of CF is due to the repulsive interaction and the mass of CF is generated dynamically from the interaction. It is a quantum particle collectively many body entity whose creation is due to the union of an electron and quantum mechanical phases (vortices). The fractional charges of CF are generated by quantization of screening.

We have suggested a similar type of model for diquark. It is well known that QCD vacuum possesses colour electromagnetic properties and paramagnetic behaviour. We assume that in the presence of QCD vacuum the two quarks form a Composite Fermion and behaves as an independent entity like quasiparticle which is weakly interacting within the system. The effective mass of the diquark as composite fermion can be computed in a gauge invariant way [36]. Using the energy theorem [37] with Landau's original picture of quasi particle in Fermi liquid, the effective mass of CF can be evaluated. In a Fermi liquid, the low lying excitations may be described as a stable quasiparticle and quasi-hole excitation. These low energy eigen states can be labelled as occupation configuration  $n_k$ . Such a state is smoothly connected to the corresponding state of the free Fermi system by adiabatically turning of interactions. The energy of such states can be evaluated by Hellman-Feynman theorem [38]. The energy difference between ground state and the excited state is related to the quasiparticle effective mass. Starting from the Hamiltonian of a composite fermion with a momentum cut off  $\Lambda$  the expression for the quasi particle mass in a gauge invariant system can be expressed as: [36] (with potential  $V=0$ ):

$$1/m^* = 1/m (1 + \Lambda^4/2p_f^4) \text{ -----(1)}$$

where  $m^*$  is the effective mass of quasiparticle,  $m$  is the constituent particle mass.  $p_f$  is the Fermi momentum and  $\Lambda$  is a cut off parameter. Applying the CF picture for diquark, the effective mass of diquark has been expressed as :

$$1/m_D^* = [1/(m_{q1}+m_{q2})] (1 + \Lambda^4/2p_f^4) \text{ -----(2)}$$

Where  $m_D^*$  is the mass of the diquark,  $m_{q1}$ ,  $m_{q2}$  are the constituent masses of the quark flavours constituting the diquark. Fermi momentum  $p_f$  has been estimated using work of Bhattacharya et al [39,40]. The radii of diquarks are given input from existing literature [41- 43]. With  $m_u = m_d = 0.360\text{GeV}$  and  $m_s = 0.54\text{GeV}$  from [44],  $\Lambda=0.573\text{ GeV}$  for light sector [45] the diquark masses have been estimated for  $J_p = 1/2^+$  and  $3/2^+$  using the expression (2) and are furnished in Table-1.

**Table 1. Diquark Radius, Fermi momentum ( $p_f$ ) and Diquark Mass**

Diquark content [qq]	Diquark radius (fm)		Fermi mom. Computed (Gev)		Diquark mass computed (GeV)	
	Scalar	Vector	Scalar	Vector	Scalar	Vector
[ud]	0.98 <sup>[39]</sup>	0.8 <sup>[41]</sup>	0.5820	0.713	0.4898	0.5957
[us]	1.212 <sup>[40]</sup>	1.006 <sup>[39]</sup>	0.4706	0.5669	0.4287	0.5913

## 3.MAGNETIC MOMENT OF MULTI-QUARK STATES

The magnetic moment of a compound system is the sum of the magnetic moments of its constituents ( $\mu_i$ ) with the spin ( $s_i$ ) and orbital ( $l_i$ ) contributions such as:

$$\mu = \sum_i \mu_i = \sum_i (g_i s_i + l_i) \mu_i \text{ -----(3)}$$

where  $\mu_i$  (the magneton of the  $i$ th constituent),  $s_i$  and  $l_i$  are vector quantities and  $g_i$  is the  $g$  factor, where

$$\mu_i = e_i / 2m_i \text{ -----(4)}$$

In a five quark configuration, pentaquark has been considered to consist of two scalar diquarks and one spin-1/2 anti-quark. In such case the magnetic moment of it can be written as:

$$\mu = (g_1 0 + l_1) \mu_1 + (g_2 0 + l_2) \mu_2 + (g_3 1/2 + l_3) \mu_3 = l_1 \mu_1 + l_2 \mu_2 + g_3 1/2 \mu_3 \text{ -----(5)}$$



Considering scalar diquark with spin 0 as in Jaffe and Wilczek’s work[16], the magnetic moment for a three-body system (two scalar diquarks and one anti-quark) with relative angular momentum  $l=1$  state, can be written as [46]

$$\mu = l_1 \mu_1 + l_2 \mu_2 + g_3 \frac{1}{2} \mu_3 \text{ -----(6)}$$

As scalar diquarks are considered to be spin-0 particles, the magnetic moments arises due to the relative momentum of the diquarks and the spin of the anti-quark. Considering the wave function for diquarks of Liu et al [33], we have estimated the magnetic moments of anti-decuplet and octet pentaquark states by using the expressions of magnetic moments of these pentaquark states from [16].

Now considering the pentaquark as a bound state of one scalar, one vector diquark and one spin-1/2 anti-quark as in Shuryak and Zahed’s work [17], the magnetic moment of penta quark can be expressed as:

$$\mu = (g_1 0 + 0) \mu_1 + (g_2 1 + 0) \mu_2 + (g_3 \frac{1}{2} + 0) \mu_3 = g_2 1 \mu_2 + g_3 \frac{1}{2} \mu_3 \text{ -----(7)}$$

The magnetic moment of a pentaquark comes from the spin of the anti-quark and the spin of the vector diquark (the total spin of the two quarks inside the vector diquark is one). Considering the work of Liu et al [33] the magnetic moments of anti-decuplet and octet pentaquark states have been estimated by using the expressions of magnetic moments of corresponding pentaquark states from [17].

The results are furnished in Table 2, 3 and 4 along with the results of other predictions. Note that magnetic moments are very sensitive to the diquark mass.

**Table 2. Magnetic moments of anti-decuplet pentaquark states in two scalar diquark and one anti-quark configuration. Set I[4]:  $m_{ud}=720$  MeV,  $m_{us}=m_{ds}=900$  MeV; Set II[16]:  $m_{ud}=420$  MeV,  $m_{us}=m_{ds}=600$  MeV.**

State (Y,I,I <sub>3</sub> )	Our- work	Other work[33]	
		Set I	Set II
(2,0,0)	0.123	0.08	0.29
(1,1/2,1/2)	0.118	0.037	0.22
(1,1/2,-1/2)	-0.003	0.12	0.22
(0,1,1)	0.030	-0.009	0.14
(0,1,0)	-0.003	0.06	0.12
(1,0,-1)	-0.115	0.13	0.09
(-1,3/2,3/2)	0.104	-0.06	0.06
(-1,3/2,1/2)	0	0	0
(-1,3/2,-1/2)	-0.104	0.06	-0.06
(-1,3/2,-3/2)	-0.209	0.12	-0.12



**Table 3. Magnetic moments of octet pentaquark states in two scalar diquark and one anti-quark configuration. Set I[4]:  $m_{ud}=720$  MeV,  $m_{us}=m_{ds}=900$  MeV; Set II[16]:  $m_{ud}=420$  MeV,  $m_{us}=m_{ds}=600$  MeV; Set III[48]:  $m_{ud}=506$  MeV,  $m_{us}=m_{ds}=700$  MeV.**

State (Y,I,I <sub>3</sub> )	Our- work	Other work[33] Set I	Other work[33] Set II	Other work[48] Set III
(1,1/2,1/2)	0.095	0.018	0.21	0.139
(1,1/2,-1/2)	0.265	0.50	0.65	0.594
(0,1,1)	0.134	0.007	0.14	0.094
(0,1,0)	-0.117	-0.13	-0.13	-0.121
(1,0,-1)	-0.368	-0.27	-0.41	-0.337
(-1,1/2,1/2)	0.283	0.41	0.46	0.439
(-1,1/2,-1/2)	-0.388	-0.35	-0.52	-0.447
(0,0,0)	0.113	0.25	0.37	0.332

**Table 4: Magnetic moments of anti-decuplet pentaquark and octet pentaquark states in one scalar, one vector diquark and one anti-quark configuration.**

State (Y,I,I <sub>3</sub> )	Our- work	Other work[33]	State (Y,I,I <sub>3</sub> )	Our- work	Other work[33]
(2,0,0)	0.25	0.23	-	-	-
(1,1/2,1/2)	0.150	0.26	(1,1/2,1/2)	0.114	0.20
(1,1/2,-1/2)	0.058	0.09	(1,1/2,-1/2)	0.299	0.55
(0,1,1)	0.173	0.30	(0,1,1)	0.325	0.35
(0,1,0)	0.080	0.13	(0,1,0)	-0.021	-0.07
(1,0,-1)	-0.012	-0.04	(0,1,-1)	-0.252	-0.50
(-1,3/2,3/2)	0.144	0.33	-	-	-
(-1,3/2,1/2)	0.102	0.16	(-1,1/2,1/2)	0.483	0.68
(-1,3/2,-1/2)	0.01	-0.01	(-1,1/2,-1/2)	-0.267	-0.53
(-1,3/2,-3/2)	-0.082	-0.17	-	-	-
-	-	-	(0,0,0)	0.028	0.33



## 4. DISCUSSIONS

In the present work we have estimated the magnetic moments of baryon anti-decuplet and octet pentaquark states in the context of composite fermion model of diquark. Many experimental efforts are now focussing on octet and decuplet pentaquark, so at this point theoretical estimates are of immense importance. Thomas [47] mentioned that at present the theoretical calculations hold the precision lead and there is need for new ideas so that the experimental determinations may also reach such a level. However, pentaquark magnetic moments may be extracted from the comparison of theoretical and further experiments in the near future which may help to reveal the exact dynamics underlying the formation of pentaquarks. It may be pointed out magnetic moments are quite sensitive to the diquark mass parameters. Some uncertainty may come from the radii of the diquarks which are not exactly known and have a substantial contribution in determining the the fermi momentum.

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