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Baryon Masses in Diquark-Quark Model using Momentum Dependent Potential

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Abstract. The properties of baryons have been investigated assuming a baryon as diquak-quark system. A composite fermion (CF) model has been used to describe a diquark in an analogy with the usual electron behaving as composite fermion in two dimensional magnetic field**.** The masses of diquarks of different flavours are estimated in the context of the model with a momentum dependent potential. The masses of the baryons are estimated in diquak-quark configuration. Results are found to be in a good agreement with experimental findings as well as other theoretical estimates.

INTRODUCTION

Strongly correlated and deeply bound quark-quark pair is supposed to be the building blocks of baryons and exotics. It is suggested that within a hadron, two quarks having anti-symmetric in colors and spins are attracted to each other forming a low energy configuration as diquark. The prognosis of diquark came up at about the same time as the quark model itself. Gell-Mann [1] in his original paper has quoted the feasibility of diquark correlation. At the experimental level the regularities in the hadron spectra hints at the existence of diquark within the hadron. The concept of a diquark inside the baryon has enabled us to reduce 3-body (involving q-q-q) problem to a 2-body (involving q-qq) system. Baryons as diquark-quark system have been investigated by a number of authors. A quasi-particle model for a diquark has been suggested by Bhattacharya et al. [2] in an analogy with the quasi-particle model in the crystal lattice. They have investigated the magnetic moments of the exotics and non-exotic members of baryon anti-decuplet. Diquark has an important role in hadron spectroscopy and color super conductivity. Alexandrau et al. [3] have probed the existence of diquark correlations in lattice QCD considering methodically all the low energy diquark channels in a color-guage-invariant setup. They investigated the quark-quark correlation within the diquark and observed that the positive parity scalar diquark is the lightest one. Horsley et al. [4] have extended their work to the study of pattern of flavor symmetry breaking within QCD to QCD + QED and discussed the phenomenon for isospin splitting in the pseudoscalar meson and baryon octets. Huang et al. [5] have developed interpolating currents in the framework of HQET (Heavy Quark Effective Theory) and applied the QCD sum rule to estimate the masses of p-wave excited state J=1/2 spin doublet baryons. Joffe [6] has calculated the mass splitting in the baryon decuplet using the concept of polarization operator of quark current whereas Paulo et al [7] have investigated the energy momentum spectrum accompanied with guage invariant local baryon fields which are composites of three quark (anti-quark) fields. They have established Feynman-Kac formula and represented a spectrum of Fourier transformation for two point functions and concluded that the baryons and anti-baryons are tightly bound. They have also investigated the bound states of three (anti-) quarks where baryon and anti-baryon mass spectrum depends on $|\boldsymbol{s}|$ only. Kisslinger and Singha [8] have used a method of QCD sum rules to calculate the masses of charm, bottom and strange baryon. Doi et al. [9] have calculated the baryon forces by using the time dependent HALQCD model and investigated the central, tensor forces and phase shifts in $\boldsymbol{\Xi\Xi}(\boldsymbol{S_0^1})$ channel.

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THE MODEL

In the present work the baryon is considered to be a two body system consisting of quark-diquark where the diquark has been described in the framework of Composite Fermion (CF) model. It is well known that composite fermion is a quasi-particle and it is the state of an electron in strong magnetic field in two dimensions. Substantial amount of magnetic flux has been absorbed by electron in strong magnetic field transforming itself to a new particle called composite fermion. Rismita et al. [10] have suggested that diquark behaves like composite fermion in QCD vacuum and chromo-electromagnetic field and act as an independent entity like quasi-particle which interact weakly within the system. The effective mass of the diquark as composite fermion due to the presence of momentum dependent potential Vp between the quarks can be expressed as [11]

$$\frac{1}{m_D^*} = \frac{1}{(m_{q_i}+m_{q_j})} + \frac{1}{p_F}\left[\frac{dV(p)}{dp}\right]_{p=p_F} \tag{1}$$

Where m_{q_i} and m_{q_j} are the constituent quark masses, m_D^* is the effective diquark mass and p_F is fermi momentum. The interaction in between the quarks forming a diquark is assumed to be momentum dependent potential and we have used V_p as [12] which runs as:

$$V_p = \frac{C(\rho/\rho_0)}{1+(\frac{p}{\Lambda})^2_{p=p_F}} \tag{2}$$

Here Λ is the momentum scale and C is a constant ρ and ρ_0 are density of the medium and normal nuclear density respectively. We can estimate the effective masses of diquarks using the expression (2) and (1). Λ is taken to be =100 MeV [13]

To estimate the Fermi momentum we use the Van-Royen-Weissoff formula in the limit of low energy which relates the decay constant for meson and the ground state wavefunction at the origin $\psi_B(0)$ as,

$$f_B^2 = \frac{12}{m_B}|\psi_B(0)|^2 \tag{3}$$

The wave function for meson is used from the statistical model [14] which runs as:

$$|\psi(r)|^2 = \frac{315}{64\pi r_B^{9\backslash 2}}(r_{\boldsymbol{B}} - r)^{3\backslash 2}\Theta(r_{\boldsymbol{B}} - r) \tag{4}$$

where $r_{\boldsymbol{B}}$ is the radius parameter of the corresponding meson and $\Theta(r_{\boldsymbol{B}} - r)$ is step function.
At the origin $r = 0$, equation (4) can be recast as:

$$|\psi(r)|^2 = \frac{315}{64\pi r_B^3} \tag{5}$$

According to the assumption of the statistical model [14], the number density of quark (n_q or antiquarks $n_{\bar{q}}$) also represents the probability density of a meson i.e., $n_{\bar{q}} = |\psi_B(r)|^2$. The average densityof quarks $n_{\bar{q}}$ (for antiquarks) is expressed as [14]:

$$n_{\bar{q}} = \frac{1}{2}|\psi(0)|^2 = \frac{315}{128\pi r_B^3} \tag{6}$$

The average Fermi momentum [15] for the corresponding average number density of quarks or antiquarks is given by

$$p_f^3/3\pi^2 = n_{\bar{q}} \tag{7}$$

or,

$$p_f^3 = \frac{1}{2}|\psi(0)|^2 3\pi^2 \tag{8}$$

From equations (6) and (7) we arrive at,

$$p_f r_B \ = \ 2.85 \tag{9}$$

Considering the analogy between the meson and the diquark of same flavor, the fermi momentum p_f have been calculated for various diquarks using the relation (9) with the input of radii of different diquark. We have used r_{ud}= 5.38 GeV^{-1}, r_{us}= 4.77 GeV^{-1}, r_{bs}= 3.4 GeV^{-1} ,r_{cs}=4.3 GeV^{-1}[16], $r_{dc=uc}$=1.02 GeV^{-1}, $r_{bd=bu}$=1.61GeV^{-1}. r_{dc} and r_{bd} have been calculated from the charge radius [17,18] whereas r_{ss}=5 GeV^{-1} [19] and r_{cc}=3.5 GeV^{-1} , r_{bb}= 1.05 GeV^{-1} [20]. Constituent quark masses are taken as $m_u = m_d$ = 0.35 GeV, m_s = 0.54 GeV, m_c = 1. 24 GeV and m_b = 4.2 GeV [16]. With Λ =100 MeV and C = 500MeV, diquark masses are estimated using equation (1) and (2) with the input of estimated p_f from (9). Results are displayed in Table 1.

The mass of a baryon can be expressed as [21]:

$$M_B = m_q + m_D + E_{BE} + E_S \tag{10}$$

where m_q is the mass of a quark and m_D is the effective mass of the corresponding diquark. $E_{BE}$is the binding energy for the baryon and is given by:

$$E_{BE} = < \psi|V_l|\psi > \tag{11}$$

The potential between the quark and the diquark is assumed to be of linear type and can be expressed as

$$V_l = ar_B \tag{12}$$

where a is interaction parameter and given input as a = 0.11GeV^2 [22], r_B is the radius of the corresponding baryon. The radius parameter for different baryons has given input from literature [23-28]. The spin interaction E_S is given by [29]

$$E_S = \frac{8}{9}\frac{\alpha_s}{m_q m_D}\overrightarrow{S_q}\overrightarrow{S_D}|\psi(0)|^2 \tag{13}$$

Where $\overrightarrow{S_q}$ and $\overrightarrow{S_D}$ are the spins of the quark and diquark respectively. The wave function (4) is used to calculate the binding energyE_{BE}. The baryon masses have been estimated using the expression (10). The estimated baryon masses such as $\Lambda^0[ud]s$, $\Sigma^-[dd]s$, $\Lambda^0[ud]s$, $\Lambda_c^+[ud]c$, $\Lambda_b^+[ud]b$, $\Xi^-[us]s$, $\Xi_{cc}^+[dc]c$, $\Omega_c^0[ss]c$, $\Xi_{cc}^{++}[uc]c$ etc.are displayed in Table 2 along with the experimental values [30] and other theoretical works [31].

CONCLUSION AND DISCUSSION

In the present work diquark masses are estimated considering diquark as a composite fermion in the presence of the chromo-electromagnetic field in QCD vacuum. The baryon masses are estimated with the input of the diquark masses in the framework of quark-diquark configuration of a baryon. The results obtained are found to be in good agreement with experimental as well as other theoretical estimates. It is interesting to observe that large number of baryon masses estimated with CF model are reproduced well and lie close to the experimental estimates. It may be mentioned that the baryon masses of $\Omega^-[ss]s$, $\Lambda_c^+[ud]c$, $\Xi_c^0[ds]c$ and $\Omega_c^0[ss]c$ are very close to the experimental results. For the masses of $\Lambda_b^+[ud]b$ and $\Omega_b^-[ss]b$ masses estimated are smaller than experimental values. The experimental masses of heavier baryons are yet to be determined. They are compared with other theoretical works. It may be mentioned that the uncertainty in the radius parameter of diquarks and baryons may induce some uncertainty in the results obtained. Extensive studies are going on to reveal the exact nature of diquark correlation. The current work describes diquark as composite fermion. The results obtained are very encouraging and may throw light on our attempt towards the understanding of the fundamental constituent of matter.

Table I: Diquark masses.

Diquark content [qq]	[ud]	[us]	[ss]	[uc]	[sc]	[ub]	[sb]	[cc]	[bc]	[bb]
Diquark Mass computed in GeV	0.646	0.835	0.985	1.589	1.636	4.53	4.335	2.351	5.293	8.387

Table II: Masses of Baryons.

Baryon	**Baryon masses in GeV Our work**	**Experimental Findings in GeV**	**Baryon masses in GeV Other work**
$\Lambda^0[ud]s$	1.305	1.115[30]	1.26[31]
$\Sigma^-[dd]s$	1.405	1.197[30]	1.26[31]
$\Xi^-[ds]s$	1.573	1.322[30]	1.44[31]
$\Omega^-[ss]s$	1.699	1.627[30]	-
$\Lambda_c^+[ud]c$	2.229	2.286[30]	2.27[31]
$\Lambda_b^+[ud]b$	4.935	5.620[30]	4.92[31]
$\Sigma_c^+[ud]c$	2.0881	2.453[30]	2.27[31]
$\Sigma_b^+[uu]b$	4.954	5.811[30]	4.92[31]
$\Xi_c^0[ds]c$	2.219	2.471[30]	2.45[31]
$\Xi_b^0[us]b$	5.102	5.791[30]	5.1[31]
$\Omega_c^0[ss]c$	2.375	2.695[30]	2.63[31]
$\Omega_b^0[ss]b$	5.306	6.046[30]	5.28[31]
$\Xi_{cc}^{++}[uc]c$	3.102	-	3:46[31]
$\Xi_{cc}^+[dc]c$	2.916	-	3:46[31]
$\Xi_{bb}^0[ub]b$	8.965	-	8:76[31]
$\Xi_{bb}^-[db]b$	8.911	-	8:76[31]
$\Xi_{cb}^+[uc]b$	6.054	-	6:11[31]
$\Xi_{cb}^0[dc]b$	5.909	-	6:11[31]
$\Omega_{cc}^+[sc]c$	2.957	-	3:64[31]
$\Omega_{cb}^+[sc]b$	5.9	-	6:29[31]
$\Omega_{bb}^-[bb]s$	8.682	-	8:94[31]
$\Omega_{ccc}[cc]c$	3.681	-	4.65[31]
$\Omega_{bbb}[bb]b$	12.662	-	12.6[31]
$\Omega_{ccb}[cc]b$	6.851	-	7.3[31]
$\Omega_{bbc}[cb]b$	9.794	-	9.95[31]

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REFERENCES

1. A. Gell Mann.; Phys. Lett. **8**, 214 (1964).
2. A. Bhattacharya, A. Sagari A, B. Chakrabarti and S. Mani, AIP Conference Proceedings, **1149**, 593 (2009).
3. C. Alexandrau, P. de Forcrand and B. Lucini, Phys. Rev. Lett., **97**, 222002(1-4) (2006).
4. R. Horseley et al., Jour. of Phys. G: Nucl. and Part. Phys., **43**, 1 (2016).
5. C.S. Huang, A. Zhang and S. Zhu, arXiv:hep-ph/0007330v2 (2000).
6. B. L. Joffe, Nucl. Phys. B, **188**, 317 (1981).

7. A. Paulo, F. da Veiga, M.O. Carroll and Schor Ricardo, Commu. Math. Phys., **245**, 383 (2004).
8. L. S. Kisslinger and B. Singha, Int. Jour. Mod. Phys., **33(23)**, 1850139 (2018).
9. T. Doi et al., Proce. 12th Inter. Confer. on HYP (2015).
10. R. Ghosh and A. Bhattacharya.,Int. J. Theor. phys., **56**, 2335 (2017).
11. R. K. Pathria., 'Statistical Mechanics'(Second Edition)(Butterworth Hienemann, New Delhi, (2001).
12. C.Gale, G. Bertsch and S. DasGupta; Phys. Rev. C, **35(5)**, 1666 (1987).
13. K. Igi and S.Ono, Phys. Rev. D, **33(11)**, 3349 (1986).
14. S. N. Banerjee et al., Phys. Scr., **34**, 314 (1986); **37**, 201 (1988).
15. L. D. Landau and E. M. Lifshitz,: Statistical Physics, Part I, p-166. Pergamon.
16. B. Chakrabarti, A. Bhattacharya and S. Mani, Phys. Scr. **79**, 025103 (2009).
17. K. K. Pathak., N.S. Bordoloi and D.K. Choudhury, Phys. Sc. Int. J, **7(4)**, 281 (2015).
18. C. WenHwang, Eur. phys. J. C, **23**, 585 (2002).
19. S. N. Banerjee et al, Int.J. Mod. Phys. A, **4**, 943 (1989).
20. S. N. Banerjee et al,Int.J. Mod. Phys. A, **4**, 5575 (1989).
21. R. Ghosh, A. Bhattacharya and B. Chakrabarti, Jour. Mod. Phys., **6**, 2070 (2015).
22. H. J. Schnitzer, Phys. Rev. Lett., **35**, 1540(1975).
23. B. Chakrabarti, A. Bhattacharya and S.N. Banerjee, Phys. Scr. **61**, 49 (2000).
24. M. E.de Souza, Papers in Phys. **3(030003)**, 1, (2011).
25. M. E.de Souza,arXiv:hep-ph/0207301v1 (2002).
26. A. J. Buchmann and R. F. Lebed, Phys. Rev. D. **67**, 016002 (2003).
27. C. Albertus, J. E. Amaro, E. Hernandez and J. Nieves, AIP Conference proceedings, **717(1)**, 566 (2004).
28. C. Albertus, E. Hernandez, J. Nieves and J. M.Verde-Velasco, Eur. Phys. J. A. **32(2),** 183 (2007).
29. A. Bhattacharya and S. N. Banerjee, Prog. Theor. Phys. **77(1)**, 16 (1987).
30. C. Patrignani et al., [PDG], Chin. Phys. C, **40(10)**, 1 (2016).
31. R. Ghosh, A. Bhattacharya and B. Chakrabarti, Jour. Adv. Phys. **10(3)**, 2816 (2015).