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A Study on Baryon Masses with Diquark as Composite Fermion

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ABSTRACT

Diquarks are described in the framework of composite fermion (CF) model of quasi particle. The masses of the light [Λ^0, Σ^-, Ξ^-, Ω], heavy [Λ^+_c, Λ^0_b, Σ^+_c, Σ^0_b, Ξ^0_c, Ξ^0_b, Ω^0_c, Ω^-_b], doubly heavy [Ξ^{++}_{cc}, Ξ^+_{cc}, Ξ^0_{cb}, Ξ^+_{cb}, Ξ^0_{bb}, Ξ^-_{bb}, Ω^+_{cc}, Ω^0_{cb}, Ω^-_{bb}] and triply heavy [Ω_{ccc}, Ω_{ccb}, Ω_{cbb}, Ω_{bbb}] baryons have been studied for $J^P = (1/2)^+$ and $(3/2)^+$ states, considering the diquark-quark configuration for the baryons. The results are found to be in good agreement with available experimental data and other theoretical works.

Indexing terms/Keywords

Fermi momentum; composite fermion model; baryon mass.

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1.INTRODUCTION

Since the early days of quark model the possibility that quarks might cluster pairwise in baryons, leading to a simple two-body structure, has been suggested by many authors [1−6]. The diquark concept during the last few years has become increasingly popular as a means of understanding many aspects of baryonic properties and reactions, particularly for heavy baryons. The role of diquark in baryon spectroscopy has been discussed by a number of authors [1−3]. Shuryak et al [2] have studied the roles of instantons in quantum chromodynamics. According to them instantons are relevant for the structure of the QCD vacuum as well as for the structure of hadrons. They have asserted that the QCD instanton produces

deeply bound diquark which may be building block in formation of multiquark state. They have estimated masses, decay width of pentaquark state with $(ud)^2$s^bar state. Cakir et al [4] have investigated the resonant production of first generation scalar and vector diquarks in LHC collider and observed that LHC collider predicts larger values of cross sections. They have emphasized that the diquarks with different mass range could be investigated in LHC with suitable values of cross section. Stability of such a correlated two quark system which has been described as an independent object and supposed to be an important component of the hadron structure, should be studied with much attention. In order to predict the observed masses of the pentaquark states Jaffe and Wilczek (JW) [5] have proposed a diquark model where the structure of the θ^+ is considered in terms of two diquarks and a strange anti-quark system. A similar model was also proposed by Karliner and Lipkin (KL) [6] with two diquarks and an anti-quark having two different wave functions described by different colour and spin couplings of the three constituents. Recently Karliner and Rosner [7] have estimated masses, production and decays of doubly heavy baryons like Ξ_{cc}, Ξ_{bb} and Ξ_{bc} for J = 1/2 and J = 3/2 states. They have discussed the detection of Ξ_{cc}, Ξ_{bb} and Ξ_{bc} in details. Shuryak and Schafer et al [8] have developed the possibility of forming quark-quark and quark - anti-quark system by Instanton Induced Interaction (III). The formation of bound state of quark-quark or quark - anti-quark systems due to III has also been studied by Betman et al [9]. They have predicted that such bound state is formed inside the hadron as a bubble of the size of the instanton radius. Bhattacharya et al [10] have described the

diquark as a low-lying excited state which behaves like a quasi-particle in the crystal lattice. Oka [11] has made a detailed study on the diquark correlation in the context of different models. There is considerable controversy about the properties and effects of diquarks. In the context of lattice QCD the diquark masses have been estimated by [12, 13]. Wetzorke et al [14] have used the landau gauge for diquarks and have investigated the spectrum of the diquarks.

In the present work a model for diquark describing it as a composite fermion [15] has been suggested. We have suggested that the diquark can be described in a gauge invariant way in the system of gauge interaction like two dimensional electron gas in high magnetic field where electrons can be described as composite fermions (CF) [16]. This in turn may form Fermi liquid like state near the fermi surface. We have estimated the effective mass of the diquark in the framework of CF model. The effective mass of CF has been studied by a number of authors. Girlich et al [17] have studied CF mass with general two particle potential $r^{-\alpha}$ for polarized electron in lowest hadron level whereas Onoda et al [18] have observed that the CF effective mass shows a non-monotonic behaviour. Stern et al [19] have studied the effective mass of CF of quantum hall effect using fermi liquid theory. Raghavchari [15] have suggested a model for CF effective mass in a gauge invariant way which is like fermi quasi particle in fermi liquid but with a finite momentum cut-off parameter. In the present work we have used similar formulation for diquark as suggested in [15] and have computed the

masses of diquarks. We have subsequently investigated the masses of both light and heavy baryons. We compare our results with the available experimental data and other theoretical works.

2.COMPOSITE FERMION (CF) MODEL OF DIQUARK

It has been observed that the strongly interacting particles sometimes behaves 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 posses 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 [15]. Using the energy theorem [20] with landau 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 $n_{k\text{^}bar}$. 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 [21]. 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 Λ

the expression for the quasi particle mass in a gauge invariant system can be expressed as: [15] (with potential V=0):

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

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

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

Where m_D^* is the mass of the diquark, m_{q1} , m_{q2} are the constituent masses of the quark flavours. We have computed the masses of the diquarks of different flavor using the above expression (2). Fermi momentum has been estimated using work of Bhattacharya et al [22, 23], where a relation between the fermi momentum and the radius of the corresponding meson has been derived. We have assumed that the fermi momentum (p_f) of meson of same flavour as the p_f of diquark. The radii of diquarks are given input from existing literature [3, 24 − 27]. With m_u = m_d = 0.360GeV, m_s = 0.54GeV, m_c = 1.71 GeV, m_b = 5.05 GeV from [6], Λ=0.573 GeV for light sector [28] and 0.6533 GeV for heavy sectors [29], the diquark masses have been estimated using the expression (2) and 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[3]	0.8[26]	0.5820	0.713	0.4898	0.5957
[us]	1.212[24]	1.006[3]	0.4706	0.5669	0.4287	0.5913
[uc]	1.1 [25]	0.861[3]	0.5185	0.6624	0.9158	1.4052
[sc]	1.08[25]	0.785[3]	0.5281	0.7266	1.0363	1.6958
[ub]	0.88[25]	0.805[3]	0.6481	0.7085	3.568	4.0775
[sb]	0.82[25]	0.723[3]	0.6956	0.7889	4.0244	4.5258
[cc]	0.576[3]	0.56[27]	0.9902	1.0185	3.124	3.1531
[bc]	0.483[3]	0.482[3]	1.1809	1.1834	6.4575	6.4599
[bb]	0.35[3]	0.343[3]	1.6297	1.6629	9.9712	9.9811

The mass formula of the baryon can be expressed as:

$$M_B = m_q + m_D + E_{BE} + E_S \quad \text{------(3)}$$

where m_q is the heavy or light quark mass, m_D is diquark mass. E_{BE} is the binding energy. Considering a harmonic oscillator type of potential between quark and diquark like $V(r)= ar^2$ we have estimated EBE with a=0.02 GeV^3 for triply heavy sector [30] and a=0.06 GeV^3 for light and heavy sectors [31] using Statistical Model wave function [22, 23].

The spin term E_S runs as,

$$E_S = 8/9\,(\alpha_s / m_q m_D)\, S_q \cdot S_D\, |\psi(0)|^2 \quad \text{------(4)}$$

where α_s is the strong interaction constant, S_q is the spin of the quark and S_D is spin of diquark and both are vector quantities.The masses of the baryons have been estimated using expression (3). The relevant baryon radii values are taken from [32 − 38] and α_s =0.59 has been given input from [39]. The masses of light baryons and heavy baryons are displayed in Table-2 and Table-3 respectively whereas the masses of the doubly heavy baryons and triply heavy baryons have been displayed in Table-4, 5 and 6 respectively

Table 2. Mass spectrum ($J^p = 1/2^+$ and $3/2^+$) of light baryons

Baryon	Baryon mass (GeV) for $J^p = 1/2^+$ our-work	expt.[40,41]	Baryon mass (GeV) for $J^p = 3/2^+$ our-work	expt.[40,41]
Λ^0	1.1188	1.1156	1.3086	_
Σ^-	1.3295	1.1974	1.449	1.387
Ξ^-	1.1237	1.3217	1.3948	1.535
Ω^-	1.551	_	1.5200	1.672

Table 3. Mass spectrum ($J^p = 1/2^+$ and $3/2^+$) of heavy baryons

Baryon	Baryon mass (GeV) for $J^p = 1/2^+$ our-work	expt.[40,41]	Baryon mass (GeV) for $J^p = 3/2^+$ our-work	expt.[40,41]
Λ^+_c	2.9377	2.2864(+-)0.00014	3.04477	_
Λ^0_b	5.5891	5.6202(+-)0.0016	5.7168	_
Σ^+_c	2.4577	2.4529(+-)0.0004	2.5690	2.518
Σ^0_b	5.5751	5.808	5.7169	5.829
Ξ^0_c	2.1687	2.4708+0.00034 -0.0008	2.4464	2.646
Ξ^0_b	5.5069	5.7924(+-)0.003	5.7201	_
Ω^0_c	2.6724	2.6952(+-)0.0017	2.6312	2.768
Ω^-_b	5.9631	6.165(+-)0.023	5.9176	_

Table 4. Mass spectrum ($J^P = 1/2^+$ and $3/2^+$) of doubly heavy Ξ baryon

Baryon	Baryon mass (GeV) our-work for $J^P = 1/2^+$	expt.[40,41]	others	Baryon mass (GeV) our-work for $J^P = 3/2^+$	expt.	others
Ξ^{++}_{cc}	3.9496	_	3.579[] 3.730[] 3.480[] 3.627(+-)0.012[]	3.9807	_	3.708[] 3.800[] 3.610[] 3.690(+-)0.012[]
Ξ^{+}_{cc}	3.5308	3.5189(+-)0.0009	3.584[42] 3.755[43] 3.480[44] 3.627(+-)0.012[7]	3.6222	_	3.713[42] 3.828[43] 3.610[44] 3.690(+-)0.012[7]
Ξ^{0}_{cb}	6.9065	_	6.95[49] 7.01[50] 6.914(+-)0.139[7]	6.9205	_	7.02[49] 7.10[50] 6.933(+-)0.012[7]
Ξ^{+}_{cb}	7.2534	_	6.965(+-)0.09[48]	7.2569	_	7.06(+-)0.09[48]
Ξ^{0}_{bb}	10.6764	_	10.339[42] 10.114[43] 10.093[45] 10.162(+-)0.012[7]	10.6873	_	10.468[42] 10.165[43] 10.330[46] 10.184(+-)0.012[7]
Ξ^{-}_{bb}	10.5389	_	10.23[47,48] 10.344[42] 10.30[50]	10.551	_	10.28[47,48] 10.473[42] 10.34[50]

Table 5: Mass spectrum ($Jp=1/2^+$ and $3/2^+$) of the doubly heavy Ω baryon

Baryon	Baryon mass (GeV) our-work for $J^P = 1/2^+$	others	Baryon mass (GeV) our-work for $J^P = 3/2^+$	others
Ω^{+}_{cc}	3.6843	3.74(+-)0.07[47,48] 3.76[49] 3.718[42]	3.8590	3.82(+-)0.08[47,48] 3.89[49] 3.847[42]
Ω^{0}_{cb}	7.0225	7.045(+-)0.09[47,48] 7.05[49] 7.05[50]	7.0769	7.12(+-)0.09[47,48] 7.11[49] 7.13[50]
Ω^{-}_{bb}	10.6455	10.37(+-)0.1[47,48] 10.32[49] 10.34[50]	10.6581	10.40(+-)0.1[47,48] 10.36[49] 10.38[50]

Table 6: Mass spectrum (Jp=1/2$^+$ and 3/2$^+$) of the triply heavy Ω baryon

Baryon	Baryon mass (GeV) our-work for $J^p = 1/2^+$	others	Baryon mass (GeV) our-work for $J^p = 3/2^+$	others
Ω_{ccc}	4.8508	_ _ _	4.8916	4.803[42] 4.925[52] 4.9(0.25)[53]
Ω_{ccb}	8.355	8.229[42] 8.018[51] _	8.3575	8.358[42] 8.025[51] 8.200[52]
Ω_{bbc}	11.695	11.280[51] _	11.6974	11.287[51] 11.48[52] 11.738[42]
Ω_{bbb}	15.0329	_ _ _	15.0449	15.118[42] 14.760[52] 14.7(0.3)[53]

3. Conclusions :

In the present work we have suggested a composite fermion model for diquark and estimated the masses of light andheavy baryons. The mass of Λ^0 (1.1188 GeV) for J^p = 1/2+estimated in current work is in very good agreement with experimental findings (1.1156 GeV) [40, 41] whereas for Σ^+_c, Λ^0_b reasonably good agreement have been obtained. Fordoubly heavy baryons, the mass of (3.5308 GeV) for J^p = 1/2+ agrees very well with the experimental value Ξ^+_{cc}(3.5189±0.0009 GeV) [40, 41]. The masses of Ξ^0_{bb}, Ξ^-_{bb} , Ξ^+_{cb} and Ω^+_{cc} , Ω^0_{cb} , Ω^-_{bb} are compared with theoretical works [42, 43, 45−50] as their experimental values are not yet available. The masses of the triply heavy sector have been furnished in Table-4 with existing theoretical works [42, 51 − 53]. Results show good agreement. However, the small discrepancies in results with that of experimental value may be attributed to the uncertainty in the radius of diquarks and the particle.

It may be mentioned that the radius of the diquarks have been used from the work of different authors. The radius is almost comparable to the size of nucleon in some cases and may put some constraints in using the gauge invariant way. However diquark as gauge invariant manner have been investigated by number of authors. Alexandrou et al [54] have

investigated diquark in hadron using a gauge invariant set up which combines a diquark with a static quark with spacial co-relation of two light quarks inside the diquark. They have shown that scalar diquark form with size ~ 0.9 fm whereas the vector diquark put a lower bound 4.1(7)fm on its size. The gauge invariant description of massive high spin particle have also been studied by Zinoviev et al [55] and others [56, 57].

The exact nature of diquark is not yet known. Diquark has been described in the framework of different model and subsequently used to study the spectroscopic, decay and electromagnetic properties of baryons and exotics. In the present work we have used the radii of diquarks estimated by different authors in different variants of diquark model. The masses of diquark of same flavour estimated in different models varies within the range 50 ~ 100 MeV. Ebert has estimated the heavy diquark masses in the context of relativistic quark model and obtained the $[bc]_D$ mass ~ 6.519 GeV and 6.526 GeV for scalar and vector diquark whereas we have obtained the values as 6.4515 Gev and 6.455 GeV with the input of the radius of [bc] diquarks from [3] in the composite fermion model. The agreement is quiet good. In the current work the radius of [cc] has been given input from the work of Ebert et al [27] and we have obtained the mass of vector [cc] as 3.15 Gev in CF model whereas they have obtained the value as 3.22 GeV. The [ud] mass has been predicted by Jaffe et al [5] as 420 MeV whereas we have estimated the mass of [ud] as 489 MeV with the input of scalar radius from the work of Castro et al [3]. KL model [6] predicted the mass of scalar [ud] as 720 MeV and vector [ud] as 900 MeV. Their prediction is closer to the estimated value of Castro et al [3] 770 MeV and 910 MeV respectively. Apart from this a number of models of baryons have been described by number of authors [7, 58 − 61] which reproduces the observed baryon properties very well. Salem et al [58] have investigated baryon system in a model where constituent quarks are bound by a suitable hyper central potential and have obtained a good description of ground state of light and strange baryons. Saleli et al [60] have investigated strange and non-strange baryon upto 3GeV spectra in a non-relativistic model with enharmonic potential. Using the variational approach Ghalenovi et al [61] have studied the strange, charm and beauty baryon masses with coulomb and linear confining terms whereas spin-isospin dependent potential has been regarded as a perturbation.

A completely satisfactory microscopic explanation of diquark co-relation is not yet available. The composite fermion model for diquark suggested in present work is found to be very successful in describing the masses of the baryons over a wide ranges starting from light, heavy, doubly heavy and triply heavy baryons. It is interesting to observe that the diquark in presence of chromo electromagnetic QCD vacuum may behave like composite fermion representing collective property of the system like electrons in strong magnetic field. It would be pertinent to point out that diquark quantum number is hypothesized by Gell-Mann himself as elementary constituent [62]. Description of diquark as composite fermion which represents a quasi- particle representing the collective properties is closely related to this proposition. It is widely accepted that diquark is building block of baryons. The diquark as CF may throw some light on the understanding of structure and dynamics of the baryons and may not be far from reality.

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