MESON CLOUD EFFECTS ON BARYON MOMENTS

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Considering a baryon to be surrounded by meson cloud, we calculate the magnetic moments. We observe that in the presence of quark structure of the baryon, moments agree well with experiment.

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1. Introduction

In the recent years, understanding of the strong interactions and the hadrons have advanced much. But due to the lack of exact dynamics in the soft region, static and low energy phenomena of the hadrons are not fully explained. Magnetic moments of baryons belong to these. Though the naive quark model yields a first order good fit [1, 2] the recently observed precise hyperon moments, specially low $\mu(\Sigma^+)$ and large $\mu(\Xi^-)$ show significant discrepancies. Moreover, the SU(6) symmetric quark model appears an over-simplification of physics of the hadrons [3], as gluon exchange occurring among the quarks inside the hadrons may not keep baryon wave functions SU(6) symmetric in the low energy sector [4]. The more plausible models like the bag models [5] besides suffering from violations similar to those of naive model, yield low proton moment. Various approaches have been considered to improve the agreement between the theory and the experiment [6–10] but with partial success. Magnetic moments have also been obtained in a cloudy bag model [7] which seems to revive the role of the meson dynamics in the study of the hadrons. Significance of the meson dynamics [11] have already been observed ni the study of nucleon-nucleon interaction [12].

In the present paper, we study the mesonic effects on the baryon moments in a meson cloud model of baryon, where baryon core is surrounded by the cloud of the mesons. This picture can be arrived at in the light of the knowledge of Quantum Chromodynamics (QCD). For instance, the QCD perturbative mass expansion [11] around the chiral limit for a baryon involves nonanalytic terms which correspond to the meson cloud energies in the meson cloud model. This also explains the flavour asymmetries in the hadron mass spectrum [11]. We differ from pion-cloud bag model as we include contributions due to strange as well as non trange mesons. The significance of kaon cloud contributions to magnetic moments has also been discussed by Żenczykowski [8]. Firstly, we calculate the baryon moments considering core baryon to be pointlike. Later, we study the effects of quark structure of baryons also. Better agreement for hyperon moments follows in the latter case. The neutron moment seems to require u quark mass to be less than d quark mass. In Section 2, we calculate mesonic effects to the baryon moments. Effects due to the quark structure are considered in Section 3. Summary and conclusions are given in the last Section.

2. *Meson cloud effects on moments*

The idea of the pion cloud around the nucleon had been the first attempt to explain the large anomalous parts of the nucleon moments [12]. Later, it also described well the Δ-resonances, moments and π-N scattering, etc. Recently, the understanding of the strong interactions has grown in the development of the Quantum Chromodynamics. So it becomes significant to view the status of the meson cloud model in the light of QCD. In the chiral limit, the baryon multiplets are mass degenerate and the pseudoscalar mesons are massless. If the masses of the light quarks are turned on, these multiplets split. In the chiral perturbation theory [13] the baryon masses can be obtained as a perturbative quark mass expansion in the QCD via the following perturbative part of the QCD Hamiltonian [11]:

$$H_{\text{I}} = \int d^3x(m_{\text{u}}\bar{u}u + m_{\text{d}}\bar{d}d + m_{\text{s}}\bar{s}s). \tag{2.1}$$

Expanding around the chiral limit [14] the baryon mass involves:

$$M^2 = A + m_{\text{u}}B^{\text{u}} + m_{\text{d}}B^{\text{d}} + m_{\text{s}}B^{\text{s}} + \ldots, \tag{2.2}$$

where A and B's are respective coefficients in the expansion. But the expansion being around the chiral limit, the massless states generate infrared singularities. Following the methodology used in Quantum Electrodynamics, these divergencies can be removed by considering soft meson (0^-) emission with derivative coupling. Here the probability amplitude for generating more than one meson is smaller by powers of k/f_{P}. Finally, the nonanalytic terms $\propto m_{\text{P}}^3$ appear in the baryon mass expansion [15]:

$$M^2 = A' + m_{\text{u}}B'^{\text{u}} + m_{\text{d}}B'^{\text{d}} + m_{\text{s}}B'^{\text{s}} + C_1 m_\pi^3 + C_2 m_{\text{K}}^3 + \ldots, \tag{2.3}$$

where the coefficients C_1 and C_2 involve the axial charge, the meson decay constants, etc.

The physics of the appearance of the nonanalytic terms in the QCD mass expansion can be discussed in terms of meson cloud model, the so called static model [16]. In the chiral limit, the baryon is surrounded by cloud of meson P that extends to infinity. As the quark masses are turned on, the meson cloud shrinks and follows Yukawa potential, $\exp(-2\pi m_{\text{P}} r)$. In this model the nonanalytic terms appearing in the QCD, correspond to the meson cloud energies obtained from meson and source interaction. These can also contribute to flavour asymmetries in the baryon octet as the different baryon gets different shares of meson cloud energies, e.g., nucleon cloud consists mainly of pions, where cloud surrounding the Ξ contains kaons predominantly [11].

The physical baryon in this model would involve meson (P) dressed states also, as:

$$|B\rangle_{\text{physical}} = |B\rangle_{\text{bare}} + \sum_{P} |B'P\rangle, \tag{2.4}$$

where summation is over all the possible pseudoscalar mesons for $m_B \geqslant m_{B'}$ and appropriate C. G. coefficients are to be added in (2.4). The magnetic moment of a baryon gets following contributions in this model:

(*i*) Intrinsic Dirac moment of the bare baryon ($\mu_{\text{Dirac}} = e_B/2m_B$).

(*ii*) Anomalous moment which is attributed to strong interaction interference with electromagnetic one via Yukawa interaction g^2(B'BP). This anomalous part gets contributions from orbital angular momentum of charged mesons ($\mu_{\text{meson}} = e_P/2m_P$).

(*iii*) Anomalous contribution due to baryon core (B′) while being surrounded by mesons. Due to the baryon being heavier than the meson, such recoil effects are expected to be small in magnitude. Therefore, we neglect these for the sake of simplicity.
Total magnetic moment of baryon then becomes:

$$\mu_{\text{total}} = \mu_{\text{Dirac}} + A \sum_{P} \frac{1}{2I_P+1}\, g^2_{B'BP} \mu_{\text{Meson}}, \tag{2.5}$$

where $\mu_{\text{Dirac}} = e_B/2m_B$ is the intrinsic moment and $\mu_{\text{Meson}} = e_P/2m_P$ is pseudoscalar meson contributions due to orbital momentum. The $(2I_P+1)$ is the isospin factor. Parameter A controls the space part of the strong dynamics and can only be evaluated in an exact quantum theory of the strong interaction and $g^2_{B'BP}$ is Yukawa interaction coupling. We use SU(3) symmetry to determine these couplings. Expressions for various moments are given in Appendix. Fixing the parameter A from proton moment we obtain other moments as shown in column (*ii*) of the table. Though the values for hyperon moments obtained do not agree with experiment, we notice that the effects are in the right direction, as mesonic effects have lowered $\mu(\Sigma^+)$, $\mu(\Xi^0)$ and raised $\mu(\Xi^-)$ moment. One may attribute the discrepancies to SU(3) breaking in the strong couplings and in tne parameter A. But we feel that tne discrepancies are due to tne fact tnat tne quark structure of tne baryons has been ignored so far. We consider this in the next Section.

3. *Effects of quark structure on moments*

In the last Section, we have considered a baryon to be elementary, but it is an established fact that the baryons posses quark structure, which can also contribute to the anomalous moments. Conventionally, this part is calculated in the nonrelativistic model [1] or in the bag models [5]. Historically, the result $\mu(p)/\mu(n) = -3/2$ has been a cornerstone of the nonrelativistic models and so seems to demand any other contributions to be negligible. From the theoretical point of view, this looks like an over-simplification of physics inside the hadrons as deep inelastic scattering and Drell-Yan processes reveal complex structure for hadrons. Moreover, the u quark mass expectations ($m_u < m_d$) would also alter the results. In the light of these facts, we replace the intrinsic Dirac moment μ_{Dirac} in (2.5) with the quark model moments. The total magnetic moment of the baryon then will be given by [18]

$$\mu_{\text{total}} = p(\mu_{\text{quark model}}) + 1 - p)\mu_{\text{meson cloud}}, \tag{3.1}$$

where p is the probability of finding the baryon in bare baryon state and $(1-p)$ is the probability of finding it in the disassociated baryon and meson cloud state [18]. We fix the parameters A and p with proton and Λ moments. It is interesting to remark that required value of $p = 0.68$ scales down intrinsic proton moment to 1.9 n.m., i.e., same as given by the bag model [5] calculations. The calculated moments for the baryons are displayed in column *(iii)* of the Table. All the hyperon moments have improved considerably and are in well agreement with the observed values. Only the neutron moment is found to be large (−2.09). One may attribute this discrepancy to the difference in quark masses, since m_u is expected to be lower than m_d. In fact, with $m_u/m_d = 0.85$, neutron moment can be obtained to be −1.913 without affecting other moments significantly.

TABLE

Baryon moments in the presence of meson cloud

Particle	With point like baryon (n.m.)	With quark structure of baryon (n.m.)	Experiment [18] (n.m.)
p	2.79*	2.79*	2.793
n	−1.79	−2.09	−1.913
Λ	−0.42	−0.61*	−0.613±0.004
Σ^+	1.79	2.37	2.33±0.13
Σ^-	−1.82	−1.19	−1.41±0.25
Ξ°	−0.69	−1.25	−1.250±0.014
Ξ^-	−1.58	−0.68	−0.75±0.07[2]

* input.

4. *Summary and conclusions*

In this paper, we have studied the effects due to pion and kaon meson clouds on the baryon moments. The meson cloud picture, established in nucleon-nucleon interaction, can also be arrived at within the developments of QCD as this model provides a simple description of the nonanalytic terms arising in the QCD mass expansions for the baryons. We have evaluated all the moments in this model treating the baryon firstly as an elementary particle. In this case, equal anomalous moments for proton and neutron follows. But the hyperon moments are found to be low for Λ, Σ^+ and Ξ° baryons and large for Σ^- and Ξ^- baryons. However, it may be noticed that produced effects due to meson cloud are in the required direction. We have attributed this discrepancy to the neglect of the quark structure of the baryons. Introducing that, we obtain a better agreement for the moments. We may remark here that in pion-cloud bag model considerations [7] also, a nice agreement for hyperon moments have been obtained. But for non-strange sector it yields $\mu(p) = 2.65$ n.m.

and $\mu(p)/\mu(n) = -1.32$. Żenczykowski [8] has evaluated kaon cloud contributions to the magnetic moments in the framework of the cloudy bag model. We differ from his approach, as he has studied the effects of the kaon cloud only and we have considered the contributions due to the strange as well as nonstrange mesons. Secondly the kaon cloud effects alone can not explain the experimentally observed ratio $\mu(\Xi^-)/\mu(\Lambda)$, which is found to be consistent with the theoretical value obtained in the present calculations. The discrepancy in the results of the two approaches may be attributed to the neglect of the pion cloud effects which tend to increase the magnitude of $\mu(\Xi^-)$ over $\mu(\Lambda)$.

We wish to conclude that meson cloud dynamics, which has been confirmed in low energy nucleon-nucleon interaction, seems to play an important role in the study of the baryon magnetic moments.

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APPENDIX

Contributions to magnetic moments of the baryons

. Particle	Intrinsic Dirac (n.m.)	Meson cloud (n.m.)	Naive quark model (x e/18 m_u) $x = \frac{m_u}{m_d}$, $y = \frac{m_u}{m_s}$
p	1	$\frac{4}{9} A g^2_{\pi NN} \frac{N}{\pi}$	$x+8$
n	0	$-\frac{4}{9} A g^2_{NN\pi} \frac{N}{\pi}$	$-4x-2$
Λ	0	$-\frac{1}{3} A g^2_{N\Lambda K} \frac{N}{K}$	$-3y$
Σ^+	N/Σ	$\frac{2}{9} A(g^2_{\Sigma\Sigma\pi}+g^2_{\Lambda\Sigma\pi}) \frac{N}{\pi}$	$y+8$
Σ^-	−N/Σ	$-\frac{2}{9} A(g^2_{\Sigma\Sigma\pi}+g^2_{\Lambda\Sigma\pi}) \frac{N}{\pi}$	$-4x+y$
		$-A/3 g^2_{N\Sigma K} \frac{N}{K}$	
Ξ^0	0	$-A/3 g^2_{\Sigma\Xi K} \frac{N}{K} + \frac{2}{9} A g^2_{\Xi\Xi\pi} \frac{N}{\pi}$	$-4y-2$
Ξ^-	−N/Ξ	$-A/3(g^2_{\Sigma\Xi K}+g^2_{\Lambda\Xi K}) \frac{N}{K}$	$x-4y$
		$-\frac{2}{9} A g^2_{\Xi\Xi\pi} \frac{N}{\pi}$	

where N, Σ, Ξ, π and K denote their masses respectively.

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