Transition magnetic moments of $J^P = \frac{3}{2}^+$ decuplet to $J^P = \frac{1}{2}^+$ octet baryons

Harleen Dahiya

Department of Physics
Dr. B.R. Ambedkar National Institute of Technology
Jalandhar

QNP2018 Tsukuba, JAPAN
November 13-17, 2018

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Internal Structure

- Quantum Chromodynamics (QCD) provides a fundamental description of hadronic and nuclear structure and dynamics.
- Internal Structure: The knowledge of internal structure of nucleon in terms of elementary quark and gluon degrees of freedom in QCD provide a basis for understanding more complex, strongly interacting matter.
- Knowledge has been rather limited because of confinement and it is still a big challenge to perform the calculations from the first principles of QCD.

Fundamental quantities

Electromagnetic Dirac and Pauli form factors: further related to the static low-energy observables

- **Structure:** Magnetic moments
  Dirac theory (1.0 μ_N) and experiment (2.5 μ_N).
  Proton is not an elementary Dirac particle but has an inner structure.
- **Size:** Spatial extension.
  Proton charge distribution given by charge radius r_p.
- **Shape:** Nonspherical charge distribution.
  Quadrupole moment of the transition $N \to \Delta$.
- Relation between the properties??

Quantum chromodynamics (QCD): present theory of strong interactions

- At high energies, (α_s is small), QCD can be used perturbatively.
- At low energies, (α_s becomes large), one has to use other methods such as effective Lagrangian models to describe physics.
- Wide range of applications ranging from the dynamics and structure of hadrons and nuclei to the properties and phases of hadronic matter at the earliest stages of the universe.
- New experimental tools are continually being developed to probe the non-perturbative structure of the theory, for example the hard diffractive reactions, semi-inclusive reactions, deeply virtual Compton scattering etc..
- Many fundamental questions have not been resolved. The most challenging nonperturbative problem in QCD is to determine the structure and spectrum of hadrons in terms of their quark and gluon degrees of freedom.

Proton Spin Problem: The driving question

- 1988 European Muon Collaboration (Valence quarks carry 30% of proton spin).
- Naive Quark Model contradicts this results (Based on Pure valence description: proton = 2u + d).
  "Proton spin crisis"
- Confirmed by the measurements of polarized structure functions of proton in the deep inelastic scattering (DIS) experiments by SMC, E142-3 and HERMES experiments.
- Provides evidence that the valence quarks of proton carry only a small fraction of its spin suggesting that they should be surrounded by an indistinct sea of quark-antiquark pairs.

Flavor Structure

- 1991 NMC result: Asymmetric nucleon sea ($\bar{d} > \bar{u}$).
  Recently confirmed by E866 and HERMES.
- Measured quark sea asymmetry established that the study of the structure of the nucleon is intrinsically a nonperturbative phenomena.
- Sum Rules
  - Bjorken Sum Rule: $\Delta_3 = \Delta u - \Delta d$
  - Ellis-Jaffe Sum Rule: $\Delta_8 = \Delta u + \Delta d - 2\Delta s$
    (Reduces to $\Delta_8 = \Delta\Sigma$ when $\Delta s = 0$)
  - Strange quark fraction: $f_s \simeq 0.10$
  - Gottfried Sum Rule: $I_G = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)]dx = 0.254 \pm 0.026$

Quark Sea

- Recently, a wide variety of accurately measured data have been accumulated for
  static properties of hadrons: masses, electromagnetic moments, charge radii etc.
  low energy dynamical properties: scattering lengths and decay rates etc.
- These lie in the non perturbative range of QCD.
- Flavor and spin structure of the nucleon is not limited to *u* and *d* quarks only.
- Non-perturbative effects explained only through the generation of "quark sea".

Nonperturbative regime

- The direct calculations of these quantities form the first principle of QCD are extremely difficult, because they require non-perturbative methods.
- **Naive Quark Model** is able to provide a intuitive picture and successfully accounts for many of the low-energy properties of the hadrons in terms of the valence quarks.
- Techniques such as lattice gauge theory, QCD sum rules, and a wide variety of models have been developed to study this extremely interesting energy regime.

Chiral Constituent Quark Model

- χCQM initiated by Weinberg and developed by Manohar and Georgi to explain the successes of NQM.
- The fluctuation process describing the effective Lagrangian is

$$q^{\uparrow\downarrow} \rightarrow \mathrm{GB} + q^{'\downarrow\uparrow} \rightarrow (q\bar{q}^{'}) + q^{'\downarrow\uparrow}$$

  $q\bar{q}^{'} + q^{'}$ constitute the sea quarks.
- Incorporates *confinement* and *chiral symmetry breaking.*
- “Justifies” the idea of constituent quarks.

χCQM

- The GB field can be expressed in terms of the GBs and their transition probabilities as

$$\Phi' = \left(\begin{array}{ccc} P_\pi \frac{\pi^0}{\sqrt{2}} + P_\eta \frac{\eta}{\sqrt{6}} + P_{\eta'} \frac{\eta^{'}}{\sqrt{3}} & P_\pi \pi^+ & P_K K^+ \\ P_\pi \pi^- & -P_\pi \frac{\pi^0}{\sqrt{2}} + P_\eta \frac{\eta}{\sqrt{6}} + P_{\eta'} \frac{\eta^{'}}{\sqrt{3}} & P_K K^o \\ P_K K^- & P_K \bar{K}^0 & -P_\eta \frac{2\eta}{\sqrt{6}} + P_{\eta'} \frac{\eta^{'}}{\sqrt{3}} \end{array} \right).$$

- The chiral fluctuations $u(d) \rightarrow d(u) + \pi^{+(-)}$, $u(d) \rightarrow s + K^{+(0)}$, $u(d,s) \rightarrow u(d,s) + \eta$, and $u(d,s) \rightarrow u(d,s) + \eta^{'}$ are given in terms of the transition probabilities P_π, P_K, P_η and $P_{\eta'}$ respectively.

Pion Cloud Mechanism

- Quark sea is believed to originate from process such as virtual pion production.
- It is suggested that in the deep inelastic lepton-nucleon scattering, the lepton probe also scatters off the pion cloud surrounding the target proton. The $\pi^+(\bar{d}u)$ cloud, dominant in the process $p \to \pi^+ n$, leads to an excess of $\bar{d}$ sea.
- However, this effect should be significantly reduced by the emissions such as $p \to \Delta^{++} + \pi^-$ with $\pi^-(\bar{u}d)$ cloud. Therefore, the pion cloud idea is not able to explain the significant $\bar{d} > \bar{u}$ asymmetry.
- This approach can be improved upon by adopting a mechanism which operates in the *interior* of the hadron.

Chiral Symmetry Breaking

- The dynamics of light quarks (u, d, and s) and gluons can be described by the QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{\psi}_R \not{D} \psi_R + i\bar{\psi}_L \not{D} \psi_L - \bar{\psi}_R M \psi_L - \bar{\psi}_L M \psi_R \,,$$

  $G^a_{\mu\nu}$ is the gluonic gauge field strength tensor, D^μ is the gauge-covariant derivative, M is the quark mass matrix and ψ_L and ψ_R are the left and right handed quark fields.

- Mass terms change sign as $\psi_R \to \psi_R$ and $\psi_L \to -\psi_L$ under the chiral transformation ($\psi \to \gamma^5 \psi$), the Lagrangian no longer remains invariant. If neglected, the Lagrangian will have global chiral symmetry of the $SU(3)_L \times SU(3)_R$ group. Hadrons do not display parity doublets $\to$ the chiral symmetry is believed to be spontaneously broken around a scale of 1 GeV as

$$SU(3)_L \times SU(3)_R \to SU(3)_{L+R} \,.$$

- As a consequence, there exists a set of massless particles, referred to as the Goldstone bosons (GBs), which are identified with the observed (π, K, η mesons).
- Within the region of QCD confinement scale ($\Lambda_{QCD} \simeq 0.1 - 0.3$ GeV) and the chiral symmetry breaking scale $\Lambda_{\chi SB}$, the constituent quarks, the octet of GBs (π, K, η mesons), and the *weakly* interacting gluons are the appropriate degrees of freedom.
- The effective interaction Lagrangian in this region can be expressed as

$$\mathcal{L}_{\text{int}} = \bar{\psi}(i\not{D} + \not{V})\psi + ig_A\bar{\psi}\not{A}\gamma^5\psi + \cdots ,$$

where g_A is the axial-vector coupling constant. The gluonic degrees of freedom can be neglected owing to small effect in the effective quark model at low energy scale. The vector and axial-vector currents V_μ and A_μ are defined as

$$\begin{pmatrix} V_\mu \\ A_\mu \end{pmatrix} = \frac{1}{2}(\xi^\dagger \partial_\mu \xi \pm \xi \partial_\mu \xi^\dagger),$$

where $\xi = \exp(2i\Phi/f_\pi)$, f_π is the pseudoscalar pion decay constant ($\simeq$ 93 MeV).

- The field Φ describes the dynamics of GBs as

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} & \alpha K^0 \\ \alpha K^- & \alpha \bar{K}^0 & -\beta\frac{2\eta}{\sqrt{6}} \end{pmatrix} .$$

Expanding V_μ and A_μ in the powers of Φ/f_π, we get

$$\begin{aligned} V_\mu &= 0 + O\left((\Phi/f_\pi)^2\right) , \\ A_\mu &= \frac{i}{f_\pi}\partial_\mu\Phi + O\left((\Phi/f_\pi)^2\right) . \end{aligned}$$

- The effective interaction Lagrangian between GBs and quarks from in the leading order can now be expressed as

$$\mathcal{L}_{\rm int} = -\frac{g_A}{f_\pi}\bar{\psi}\partial_\mu\Phi\gamma^\mu\gamma^5\psi ,$$

which using the Dirac equation $(i\gamma^\mu\partial_\mu - m_q)q = 0$ can be reduced to

$$\mathcal{L}_{\rm int} \approx i\sum_{q=u,d,s}\frac{m_q + m_{q'}}{f_\pi}\bar{q}'\Phi\gamma^5 q = i\sum_{q=u,d,s} c_8\bar{q}'\Phi\gamma^5 q .$$

- $c_8 \left(= \frac{m_q + m_{q'}}{f_\pi}\right)$ is the coupling constant for octet of GBs and m_q $(m_{q'})$ is the quark mass parameter. The Lagrangian of the quark-GB interaction, suppressing all the space-time structure to the lowest order, can now be expressed as

$$\mathcal{L}_{\rm int} = c_8 \bar{\psi} \Phi \psi \,.$$

- The QCD Lagrangian is also invariant under the axial $U(1)$ symmetry, which would imply the existence of ninth GB. This breaking symmetry picks the η' as the ninth GB.
- The effective Lagrangian describing interaction between quarks and a nonet of GBs, consisting of octet and a singlet, can now be expressed as

$$\mathcal{L}_{\rm int} = c_8 \bar{\psi} \Phi \psi + c_1 \bar{\psi} \frac{\eta'}{\sqrt{3}} \psi = c_8 \bar{\psi} \left(\Phi + \zeta \frac{\eta'}{\sqrt{3}} I \right) \psi = c_8 \bar{\psi} \left(\Phi' \right) \psi \,,$$

where $\zeta = c_1/c_8$, c_1 is the coupling constant for the singlet GB and I is the 3×3 identity matrix.

Successes of χCQM

- "Proton spin problem" including quark spin polarizations, orbital angular momentum of quarks etc.
- Quark flavor distributions, fraction of a particular quark (antiquark) present in a baryon, flavor structure functions, the Gottfried integral and the meson-baryon sigma terms.
- Magnetic moments of octet and decuplet baryons including their transitions and the Coleman-Glashow sum rule.
- Axial-vector form factors of the low lying octet baryons, singlet (g_0^A) and nonsinglet (g_3^A and g_8^A) axial-vector coupling constants.
- The spin independent (F_1^N and F_2^N) and the spin dependent g_1^N structure functions, longitudinal spin asymmetries of nucleon (A_1^N).

Contd...

- Hyperon β decay parameters including the axial-vector coupling parameters F and D.
- Magnetic moments of octet baryon resonances well as Λ resonances .
- Charge radii and quadrupole moment of the baryons.
- The model is successfully extended to predict the important role played by the small intrinsic charm content in the nucleon spin in the SU(4) χCQM and to calculate the magnetic moment and charge radii of charm baryons including their radiative decays.

Transition Magnetic Moments

- The transition magnetic moments for the the spin $\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$ transitions from the radiative decays $B_i \rightarrow B_f + \gamma$, where B_i and B_f are the initial and final baryons.
- The magnetic moment of a given baryon in the χCQM receives contribution from the valence quark spin, sea quark spin and sea quark orbital angular momentum

$$\mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm Total} = \mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm V} + \mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm S} + \mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm O}.$$

- $$\mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm V} = \sum_{q=u,d,s} \Delta q\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V} \mu_q$$
$$\mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm S} = \sum_{q=u,d,s} \Delta q\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm S} \mu_q$$
$$\mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm O} = \sum_{q=u,d,s} \Delta q\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V} \mu(q_+ \rightarrow)$$

- $\mu_q = \frac{e_q}{2M_q}$ ($q = u, d, s$) is the quark magnetic moment in the units of μ_N (nuclear magneton), $\Delta q\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V}$ and $\Delta q\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm S}$ are the valence and sea quark spin polarizations respectively, $\mu(q_+ \rightarrow)$ is the orbital moment for any chiral fluctuation, e_q and M_q are the electric charge and the mass, respectively, for the quark q.

- The spin structure of a decuplet to octet transition matrix element is defined as

$$\left\langle B_{\frac{1}{2}^+}, S_z = \frac{1}{2} \middle| \mathcal{N}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right) \middle| B_{\frac{3}{2}^+}, S_z = \frac{1}{2} \right\rangle .$$

- The number operator measures the number of quarks with spin up (↑) or down (↓) in the transition $\frac{3}{2}^+ \to \frac{1}{2}^+$

$$\mathcal{N}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right) = \sum_{q=u,d,s} \left(N_{q^{\uparrow}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)} + N_{q^{\downarrow}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)} \right) .$$

- This can be used to calculate the quark spin polarizations (for $q = u, d, s$) for a given transition

$$\Delta q\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right) = N_{q^{\uparrow}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)} - N_{q^{\downarrow}\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)} .$$

Valence transition magnetic moments for $\frac{3}{2}^+ \to \frac{1}{2}^+$ transitions.

$\frac{3}{2}^+ \to \frac{1}{2}^+$ transition	Valence transition magnetic moments
$\mu(\Delta \to p)_{\rm V}$	$\frac{2\sqrt{2}}{3}\mu_u - \frac{2\sqrt{2}}{3}\mu_d$
$\mu(\Sigma^{*+} \to \Sigma^+)_{\rm V}$	$\frac{2\sqrt{2}}{3}\mu_u - \frac{2\sqrt{2}}{3}\mu_s$
$\mu(\Sigma^{*0} \to \Sigma^0)_{\rm V}$	$\frac{\sqrt{2}}{3}\mu_u + \frac{\sqrt{2}}{3}\mu_d - \frac{2\sqrt{2}}{3}\mu_s$
$\mu(\Sigma^{*0} \to \Lambda)_{\rm V}$	$\sqrt{\frac{2}{3}}\mu_u - \sqrt{\frac{2}{3}}\mu_d$
$\mu(\Sigma^{*-} \to \Sigma^-)_{\rm V}$	$\frac{2\sqrt{2}}{3}\mu_d - \frac{2\sqrt{2}}{3}\mu_s$
$\mu(\Xi^{*0} \to \Xi^0)_{\rm V}$	$\frac{2\sqrt{2}}{3}\mu_u - \frac{2\sqrt{2}}{3}\mu_s$
$\mu(\Xi^{*-} \to \Xi^-)_{\rm V}$	$\frac{2\sqrt{2}}{3}\mu_d - \frac{2\sqrt{2}}{3}\mu_s$

Sea quark transition magnetic moments for $\frac{3}{2}^+ \to \frac{1}{2}^+$ transitions.

$\frac{3}{2}^+ \to \frac{1}{2}^+$ transition	Sea quark transition magnetic moments
$\mu(\Delta \to p)_S$	$-\frac{2\sqrt{2}}{3}\left(P_\pi + P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u + \frac{2\sqrt{2}}{3}\left(P_\pi + P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_d$
$\mu(\Sigma^{*+} \to \Sigma^+)_S$	$-\frac{2\sqrt{2}}{3}\left(2P_\pi + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u - \frac{2\sqrt{2}}{3}\left(P_\pi - P_K\right)\mu_d$ $+\frac{2\sqrt{2}}{3}\left(P_K + \frac{4}{3}P_\eta + \frac{2}{3}P_{\eta'}\right)\mu_s$
$\mu(\Sigma^{*0} \to \Sigma^0)_S$	$-\frac{\sqrt{2}}{3}\left(3P_\pi - P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u - \frac{\sqrt{2}}{3}\left(3P_\pi - P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_d$ $+\frac{2\sqrt{2}}{3}\left(P_K + \frac{4}{3}P_\eta + \frac{2}{3}P_{\eta'}\right)\mu_s$
$\mu(\Sigma^{*0} \to \Lambda)_S$	$-\sqrt{\frac{2}{3}}\left(P_\pi + P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u + \sqrt{\frac{2}{3}}\left(P_\pi + P_K + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_d$
$\mu(\Sigma^{*-} \to \Sigma^-)_S$	$-\frac{2\sqrt{2}}{3}\left(P_\pi - P_K\right)\mu_u - \frac{2\sqrt{2}}{3}\left(P_\pi + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_d$ $+\frac{2\sqrt{2}}{3}a\left(P_K + \frac{4}{3}P_\eta + \frac{2}{3}P_{\eta'}\right)\mu_s$
$\mu(\Xi^{*0} \to \Xi^0)_S$	$-\frac{2\sqrt{2}}{3}\left(2P_\pi + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u - \frac{2\sqrt{2}}{3}\left(P_\pi - P_K\right)\mu_d$ $+\frac{2\sqrt{2}}{3}\left(P_K + \frac{4}{3}P_\eta + \frac{2}{3}P_{\eta'}\right)\mu_s$
$\mu(\Xi^{*-} \to \Xi^-)_S$	$-\frac{2\sqrt{2}}{3}\left(2P_\pi + \frac{P_\eta}{3} + \frac{2}{3}P_{\eta'}\right)\mu_u - \frac{2\sqrt{2}}{3}\left(P_\pi - P_K\right)\mu_d$ $+\frac{2\sqrt{2}}{3}\left(P_K + \frac{4}{3}P_\eta + \frac{2}{3}P_{\eta'}\right)\mu_s$

- The magnetic moment contribution of the angular momentum of a given sea quark

$$\langle L_q \rangle = \frac{M_{\rm GB}}{M_q + M_{\rm GB}} \text{ and } \langle L_{\rm GB} \rangle = \frac{M_q}{M_q + M_{\rm GB}} \,.$$

- The general orbital moment for any quark q is given as

$$\mu(q^{\uparrow} \rightarrow q^{'\downarrow}) = \frac{e_{q'}}{2M_q}\langle L_q \rangle + \frac{e_q - e_{q'}}{2M_{\rm GB}}\langle L_{\rm GB} \rangle \,.$$

- The magnetic moment arising from all the possible transitions of a given valence quark to the GBs is obtained by multiplying the orbital moment of each process to the probability for such a process to take place.

- The orbital moments of u, d and s quarks after including the transition probabilities P_π, P_K, P_η and $P_{\eta'}$ as well as the masses of GBs M_π, M_K and M_η can be expressed as

$$[\mu(u^\uparrow \rightarrow)] = \left[\frac{3P_\pi M_u^2}{2M_\pi(M_u+M_\pi)} - \frac{P_K(M_K^2-3M_u^2)}{2M_K(M_u+M_K)} + \frac{P_\eta M_\eta}{6(M_u+M_\eta)} + \frac{P_{\eta'} M_{\eta'}}{3(M_u+M_{\eta'})}\right]\mu_u\,,$$

$$[\mu(d^\uparrow \rightarrow)] = -\left[\frac{3P_\pi(M_\pi^2-2M_d^2)}{2M_\pi(M_d+M_\pi)} - \frac{P_K M_K}{(M_d+M_K)} - \frac{P_\eta M_\eta}{6(M_d+M_\eta)} - \frac{P_{\eta'} M_{\eta'}}{3(M_d+M_{\eta'})}\right]\mu_d\,,$$

$$[\mu(s^\uparrow \rightarrow)] = -\left[\frac{P_K(M_K^2-3M_s^2)}{M_K(M_s+M_K)} - \frac{2P_\eta M_\eta}{3(M_s+M_\eta)} - \frac{P_{\eta'} M_{\eta'}}{3(M_s+M_{\eta'})}\right]\mu_s\,.$$

- The orbital contribution to the magnetic moment of the decuplet to octet transition $\mu\left(B_{\frac{3}{2}^+} \rightarrow B_{\frac{1}{2}^+}\right)_{\rm O}$ for the baryon the type $B(Q_1Q_2Q_3)$

$$\Delta Q_1\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V}\mu(Q_1^\uparrow \rightarrow) + \Delta Q_2\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V}\mu(Q_2^\uparrow \rightarrow) + \Delta Q_3\left(\frac{3}{2}^+ \rightarrow \frac{1}{2}^+\right)_{\rm V}\mu(Q_3^\uparrow \rightarrow).$$

- Input parameters: transition probabilities P_π, P_K, P_η, $P_{\eta'}$ and masses of GBs M_π, M_K, M_η.
- Hierarchy followed by the probabilities of fluctuations of a constituent quark into pions, K, η and $\eta^{'}$

$$P_{\eta'} < P_\eta < P_K < P_\pi \,.$$

- The transition probabilities are fixed by the experimentally known spin and flavor distribution functions measured from the DIS experiments. A detailed analysis leads to the following probabilities:

$$P_{\eta'} = 0.03\,, \quad P_\eta = 0.04\,, \quad P_K = 0.06\,, \quad P_\pi = 0.12\,.$$

- The on mass shell mass values can be used for the orbital angular momentum contributions characterized by the masses of quarks and GBs (M_q and M_{GB}).

Magnetic moments in units of μ_N for the $B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}$ transitions.

$B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}$ Transition	Data [?]	$\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)_V$	$\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)_S$	$\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)_O$	$\left(B_{\frac{3}{2}^+} \to B_{\frac{1}{2}^+}\right)$
$\Delta \to p$	-3.43	2.83	-0.60	1.65	3.87
$\Sigma^{*+} \to \Sigma^+$	4.45	2.49	-0.54	0.65	2.60
$\Sigma^{*0} \to \Sigma^0$	$--$	1.08	-0.24	-0.18	0.67
$\Sigma^{*0} \to \Lambda$	3.69	2.45	-0.52	1.42	3.35
$\Sigma^{*-} \to \Sigma^-$	< 0.85	-0.33	-0.05	-0.99	-1.37
$\Xi^{*0} \to \Xi^0$	< 5.39	2.50	-0.31	0.65	2.83
$\Xi^{*-} \to \Xi^-$	< 5.39	-0.33	-0.31	-1.00	-1.64

- The orbital part is contributing with the same sign as that of the valence part except in the case of $\Sigma^{*0} \rightarrow \Sigma^0$ transition.
- The sea part has opposite sign as that of the valence quarks except in the case of $\Sigma^{*-} \rightarrow \Sigma^-$ and $\Xi^{*-} \rightarrow \Xi^-$ transitions.
- The orbital part dominates over the sea part making the total magnetic moments even higher than the valence part. $\Delta \rightarrow p$, $\Sigma^{*+} \rightarrow \Sigma^+$, $\Sigma^{*0} \rightarrow \Lambda$ and $\Xi^{*0} \rightarrow \Xi^0$ transitions.
- In the $\Sigma^{*0} \rightarrow \Sigma^0$ transition, the total magnetic moments are much lower than the valence part owing to the same sign of sea and orbital part.
- The valence, sea and orbital parts have the same sign in $\Sigma^{*-} \rightarrow \Sigma^-$ and $\Xi^{*-} \rightarrow \Xi^-$ and all these contributions add up to give a much higher magnetic moment.

- Experimental data is available for $\Delta \to p$, $\Sigma^{*+} \to \Sigma^+$, and $\Sigma^{*0} \to \Lambda$ transitions.
- The empirical estimate for the magnetic moment of the $\Delta \to p + \gamma$ transition can be made from the helicity amplitudes, $A_{\frac{1}{2}} = -0.135 \pm 0.005$ GeV$^{-\frac{1}{2}}$ and $A_{\frac{3}{2}} = -0.250 \pm 0.008$ GeV$^{-\frac{1}{2}}$ as inputs in the decay rate.
- The extracted magnetic moment $\mu_{\Delta \to p} = 3.46 \pm 0.03\ \mu_N$. Our predicted value of 3.87 μ_N is very close to the experimental results.
- The sea quarks perhaps provide the dominant dynamics of the constituents in the nonperturbative regime of QCD. A further precise measurement of these magnetic moments, therefore, would have great importance for the understanding of χCQM.

Summary: Application Potential of the model

The present calculations suggest few important points

- The sea quarks and the orbital angular momentum of the sea quarks perhaps provide the dominant dynamics of the constituents in the low-energy regime of QCD.
- The constituent quarks and weakly interacting Goldstone bosons provide the appropriate degree of freedom in the nonperturbative regime of QCD.
- A further precise measurement of these magnetic moments, therefore, would have important implications for the χCQM.

Long term

Understanding the spin structure of the baryon will help to resolve the most challenging problems facing subatomic physics which include

- What happens to the spin in the transition between current and constituent quarks in the low energy QCD?
- How can we distinguish between the *current quarks* and the *constituent quarks*?
- How is the spin of the baryon built out from the intrinsic spin and orbital angular momentum of its quark and gluonic constituents?
- What is the role played by non-valence flavors in understanding the baryon internal structure?

Thank You