Axial-vector form factors of the light, singly and doubly charmed baryons in the chiral quark constituent model

Harleen Dahiya

In Collaboration with

Suneel Dutt[1], Arvind Kumar[1] and Monika Randhawa[2]

[1]Department of Physics, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar, 144027, India
[1] University Institute of Engineering and Technology, Panjab University, Chandigarh, 160014, India

dahiyah@nitj.ac.in

DIS2023

Overview

- Internal Structure of the Hadrons
  - Quantum chromodynamics (QCD)
  - Proton Spin Problem: The Driving Question
  - Nonperturbative Regime
- Chiral Constituent Quark Model (CQM)
  - Pion Cloud Mechanism
- Axial-Vector Charges for the Spin 1/2 and Spin 3/2 Charmed Baryon Multiplets
- Results
- Scale Dependence of the Form Factors
- Summary

Internal Structure of the Hadrons

- Quantum Chromodynamics (QCD) provides fundamental description of hadronic structure and dynamics in terms of their elementary quark and gluon degrees of freedom.
- **Internal Structure:** The knowledge of internal structure provides 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

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.
- **Spin:** Quantum quantity.
  Proton's spin is sum of the spins of its three constituent quarks.
- **Size:** Spatial extension.
  Proton charge distribution given by charge radius r_p.
- **Shape:** Nonspherical charge distribution.
  Quadrupole moment of the transition $N \to \Delta$.

Fundamental Questions

- How are the static observable related to each other and how do they emerge?
- How are the sea quarks and their spins, distributed in space and momentum inside the nucleon?
- Role of orbital angular momentum of the quarks and gluons in the non-perturbative regime of QCD.
- The role played by non-valence flavors in understanding the nucleon internal structure.
- How do the quarks and gluons interact with a nuclear medium?

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 nonperturbative 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

- 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.

CQM

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

$$\begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} + \zeta\frac{\eta'}{4\sqrt{3}} - \gamma\frac{\eta_c}{4} & \pi^+ & \alpha K^+ & \gamma\bar{D}^0 \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta\frac{\eta}{\sqrt{6}} + \zeta\frac{\eta'}{4\sqrt{3}} - \gamma\frac{\eta_c}{4} & \alpha K^0 & \gamma D^- \\ \alpha K^- & \alpha\bar{K}^0 & -\beta\frac{2\eta}{\sqrt{6}} + \zeta\frac{\eta'}{4\sqrt{3}} - \gamma\frac{\eta_c}{4} & \gamma D_s^- \\ \gamma D^0 & \gamma D^+ & \gamma D_s^+ & -\zeta\frac{3\eta'}{4\sqrt{3}} + \gamma\frac{3\eta_c}{4} \end{pmatrix}$$

- The probabilities of transitions
$u(d) \rightarrow d(u) + \pi^{+(-)} = a(= |g_{15}|^2)$
$u(d) \rightarrow s + K^{-(o)} = a\alpha^2$
$u(d,s) \rightarrow u(d,s) + \eta = a\beta^2$
$u(d,s) \rightarrow u(d,s) + \eta' = a\zeta^2$
$u(d) \rightarrow c + \bar{D}^0(D^-) = a\gamma^2$

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**

Successes of CQM

- "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

Axial-Vector Charges

- The axial-vector operator constituting the quark field for the spin $\frac{1}{2}^+$ and spin $\frac{3}{2}^+$ charmed baryon multiplets can be defined as

$$A^{\mu,a} = \overline{\mathrm{q}}(\mathrm{x})\gamma^{\mu}\gamma_5\frac{\lambda^a}{2}\mathrm{q}(\mathrm{x}),$$

  $\mathrm{q}(\mathrm{x})$: flavor space quark field for the light and charm quarks $\mathrm{q} = (u, d, s, c)$.

- λ^a $(a = 1, 2, ..15)$: Gell-Mann matrices describing the flavor $SU(4)$ structure of the light and charm quarks.
  $\lambda^0(=\sqrt{\frac{2}{3}}I)$: axial-vector charge corresponding to the flavor singlet current g^0
  λ^3: flavor isovector (triplet) current g^3
  λ^8: flavor hypercharge axial-vector (octet)g^8
  λ^{15}: axial-vector charges g^{15}

SU(4) Multiplet Numerology

- Multiplet numerology for the subset of baryons belonging to $SU(4)$ flavor multiplets

$$4 \times 4 \times 4 = 20_S + 20_M + 20_M + \bar{4},$$

- The mixed symmetry 20-plet consists of $8+6+\bar{3}+3$ baryons flavor states. The spin $\frac{1}{2}^+$ baryon multiplet includes the light baryon octet at the first level, singly charmed symmetric sextet and anti-symmetric anti-triplet at the second level. The top level consists of a triplet with doubly charmed baryons.
- For the case of spin $\frac{3}{2}^+$ baryon multiplet, the symmetry 20-plet consisting of $10+6+3+1$ with the light baryon decuplet as the first level, singly charmed symmetric sextet at the second level, doubly charmed triplet at the third level and the triply charmed singlet at the top.

Spin-1/2 Axial-Vector Current

- The axial-vector current for the spin $\frac{1}{2}^+$ baryon multiplet case

$$\langle B^{\frac{1}{2}^+}(p', J_z')|A^{\mu,a}|B^{\frac{1}{2}^+}(p, J_z)\rangle = \bar{u}(p', J_z')\left[\gamma^\mu\gamma_5 G_A^a(Q^2) + \frac{q^\mu}{2M_B}\gamma_5 G_P^a(Q^2)\right]u(p, J_z)$$

M_B: baryon mass
$u(p)$ ($\bar{u}(p')$): Dirac spinors of the initial (final) baryon states
$Q^2 = -q^2$: four momenta transfer with $q \equiv p - p'$
$G_A^a(Q^2)$ and $G_P^a(Q^2)$: axial-vector and the induced pseudoscalar form factors

Spin 3/2 Axial-Vector Current

- The axial-vector current for the spin $\frac{3}{2}^+$ baryon multiplet

$$\langle B^{\frac{3}{2}^+}(p', J_z')|A^{\mu,a}|B^{\frac{3}{2}^+}(p, J_z)\rangle = \bar{u}_\rho(p', J_z')\left[\gamma^\mu\gamma_5 G_A^a(Q^2)\eta^{\rho\sigma} + \frac{q^\mu}{2M_B}\gamma_5 G_P^a(Q^2)\eta^{\rho\sigma}\right]u_\sigma(p, J_z)$$

  $u^\rho(p, J_z)$: Rarita-Schwinger spinor
  $\eta^{\rho\sigma}$: metric tensor of Minkowski space
  $u^\sigma(p, J_z)$ $(\bar{u}_\rho(p', J_z'))$: The Rarita-Schwinger spinors of the initial (final) spin $\frac{3}{2}^+$ baryon states

- A spin-1 field or Lorentz vector can be constructed from the Dirac spinor $u(p)$ and the combination of the polarization vector of the spin-1 field with the Dirac spinor of the spin $\frac{1}{2}$ field can characterize the Rarita-Schwinger spinor.

Axial-Vector Form Factors

- One can extract the axial-vector charge corresponding to the axial-vector current combinations of different quarks.

$$
\begin{aligned}
A^{\mu,0} &= \overline{u}(x)\gamma^{\mu}\gamma_5 u(x) + \overline{d}(x)\gamma^{\mu}\gamma_5 d(x) + \overline{s}(x)\gamma^{\mu}\gamma_5 s(x) + \overline{c}(x)\gamma^{\mu}\gamma_5 c(x)\,, \\
A^{\mu,3} &= \overline{u}(x)\gamma^{\mu}\gamma_5 u(x) - \overline{d}(x)\gamma^{\mu}\gamma_5 d(x)\,, \\
A^{\mu,8} &= \overline{u}(x)\gamma^{\mu}\gamma_5 u(x) + \overline{d}(x)\gamma^{\mu}\gamma_5 d(x) - 2\overline{s}(x)\gamma^{\mu}\gamma_5 s(x)\,, \\
A^{\mu,15} &= \overline{u}(x)\gamma^{\mu}\gamma_5 u(x) + \overline{d}(x)\gamma^{\mu}\gamma_5 d(x) + \overline{s}(x)\gamma^{\mu}\gamma_5 s(x) - 3\overline{c}(x)\gamma^{\mu}\gamma_5 c(x)\,.
\end{aligned}
$$

The axial-vector charges for all the members of the spin $\frac{1}{2}^+$ and spin $\frac{3}{2}^+$ baryon can be represented in terms of the explicit spin polarizations of each baryon.

$$
\begin{aligned}
g_B^0 &= \Delta u_B + \Delta d_B + \Delta s_B + \Delta c_B\,, \\
g_B^3 &= \Delta u_B - \Delta d_B\,, \\
g_B^8 &= \Delta u_B + \Delta d_B - 2\Delta s_B\,, \\
g_B^{15} &= \Delta u_B + \Delta d_B + \Delta s_B - 3\Delta c_B\,.
\end{aligned}
$$

Spin polarizations for spin 1/2 charmed baryon multiplets

- The spin polarizations for the spin $\frac{1}{2}^{+}$ baryon multiplet can be computed for the mixed symmetry 20-plet with the light baryon octet (8,0), singly charmed sextet (6,1) as well as anti-triplet ($\bar{3}$,2) and triplet (3,2) with doubly charmed baryons.

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
p	0.939	-0.335	-0.024	-0.001	0.579	1.274	0.652	0.583
n	-0.335	0.939	-0.024	-0.001	0.579	-1.274	0.652	0.583
Σ^+	0.911	-0.144	-0.264	-0.001	0.502	1.055	1.295	0.506
Σ^0	0.385	0.385	-0.264	-0.001	0.505	0.0	1.298	0.509
Σ^-	-0.144	0.911	-0.264	-0.001	0.502	-1.055	1.295	0.506
Λ	0.005	0.005	0.841	-0.001	0.85	0.0	-1.672	0.854
Ξ^0	-0.215	0.0	1.154	-0.001	0.938	-0.215	-2.523	0.942
Ξ^-	0.0	-0.215	1.154	-0.001	0.938	0.215	-2.523	0.942

Table: The quark spin polarization and the axial coupling constants for spin $\frac{1}{2}^+$ octet baryons (8,0) within $SU(4)$ representation in the chiral quark constituent model.

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
Σ_c^{++}	0.908	-0.15	-0.03	-0.249	0.479	1.058	0.818	1.475
Σ_c^{+}	0.377	0.379	-0.03	-0.249	0.477	-0.002	0.816	1.473
Σ_c^{0}	-0.15	0.908	-0.03	-0.249	0.479	-1.058	0.818	1.475
$\Xi_c^{\prime +}$	0.439	-0.09	0.559	-0.249	0.659	0.529	-0.769	1.655
$\Xi_c^{\prime 0}$	-0.09	0.439	0.559	-0.249	0.659	-0.529	-0.769	1.655
Ω_c^{0}	-0.03	-0.03	1.149	-0.249	0.84	0.0	-2.358	1.836

Table: The quark spin polarization and the axial coupling constants for singly charmed spin $\frac{1}{2}^+$ baryons (6,1) within $SU(4)$ representation in the chiral quark constituent model

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
Λ_c^+	0.02	0.02	-0.003	0.893	0.93	0.0	0.046	-2.642
Ξ_c^+	0.026	-0.007	0.033	0.893	0.945	0.033	-0.047	-2.627
Ξ_c^0	-0.007	0.026	0.033	0.893	0.945	-0.033	-0.047	-2.627
Ξ_{cc}^{++}	-0.187	0.029	0.004	1.216	1.062	-0.216	-0.166	-3.802
Ξ_{cc}^+	0.029	-0.187	0.004	1.216	1.062	0.216	-0.166	-3.802
Ω_{cc}^+	0.004	0.004	-0.235	1.216	0.989	0.0	0.478	-3.875

Table: The quark spin polarization and the axial coupling constants for double charmed spin $\frac{1}{2}^+$ baryons (3,2) within $SU(4)$ representation in the chiral quark constituent model.

- For the case of spin$-\frac{1}{2}^+$ charmed baryons, we observe the following relations between the isospin partners with the interchange of $u \longleftrightarrow d$

$$
\begin{array}{lllll}
\Delta u_p = \Delta d_n, & g^0_p = g^0_n, & g^3_p = -g^3_n, & g^8_p = g^8_n, & g^{15}_p = g^{15}_n, \\
\Delta u_{\Sigma^+} = \Delta d_{\Sigma^-}, & g^0_{\Sigma^+} = g^0_{\Sigma^-}, & g^3_{\Sigma^+} = -g^3_{\Sigma^-}, & g^8_{\Sigma^+} = g^8_{\Sigma^-}, & g^{15}_{\Sigma^+} = g^{15}_{\Sigma^-}, \\
\Delta u_{\Xi^0} = \Delta d_{\Xi^-}, & g^0_{\Xi^0} = g^0_{\Xi^-}, & g^3_{\Xi^0} = -g^3_{\Xi^-}, & g^8_{\Xi^0} = g^8_{\Xi^-}, & g^{15}_{\Xi^0} = g^{15}_{\Xi^-}, \\
\Delta u_{\Sigma_c^{++}} = \Delta d_{\Sigma_c^0}, & g^0_{\Sigma_c^{++}} = g^0_{\Sigma_c^0}, & g^3_{\Sigma_c^{++}} = -g^3_{\Sigma_c^0}, & g^8_{\Sigma_c^{++}} = g^8_{\Sigma_c^0}, & g^{15}_{\Sigma_c^{++}} = g^{15}_{\Sigma_c^0}, \\
\Delta u_{\Xi_c'^+} = \Delta d_{\Xi_c'^0}, & g^0_{\Xi_c'^+} = g^0_{\Xi_c'^{+0}}, & g^3_{\Xi_c'^+} = -g^3_{\Xi_c'^0}, & g^8_{\Xi_c'^+} = g^8_{\Xi_c'^0}, & g^{15}_{\Xi_c'^+} = g^{15}_{\Xi_c'^0}, \\
\Delta u_{\Xi_c^+} = \Delta d_{\Xi_c^0}, & g^0_{\Xi_c^+} = g^0_{\Xi_c^0}, & g^3_{\Xi_c^+} = -g^3_{\Xi_c^0}, & g^8_{\Xi_c^+} = g^8_{\Xi_c^0}, & g^{15}_{\Xi_c^+} = g^{15}_{\Xi_c^0}, \\
\Delta u_{\Xi_{cc}^{++}} = \Delta d_{\Xi_{cc}^+}, & g^0_{\Xi_{cc}^{++}} = g^0_{\Xi_{cc}^+}, & g^3_{\Xi_{cc}^{++}} = -g^3_{\Xi_{cc}^+}, & g^8_{\Xi_{cc}^{++}} = g^8_{\Xi_{cc}^+}, & g^{15}_{\Xi_{cc}^{++}} = g^{15}_{\Xi_{cc}^+}.
\end{array}
$$

- We also have the same contribution of the strange quark polarizations in the light and charmed baryons lying in the same multiplets between each of the octet, sextet, anti-triplet and triplet. We have

$$\begin{aligned}
&\Delta s_p = \Delta s_n \,, \\
&\Delta s_{\Sigma^+} = \Delta s_{\Sigma^0} = \Delta s_{\Sigma^-} \,, \\
&\Delta s_{\Xi^0} = \Delta s_{\Xi^-} \,, \\
&\Delta s_{\Sigma_c^{++}} = \Delta s_{\Sigma_c^+} = \Delta s_{\Sigma_c^0} \,, \\
&\Delta s_{\Xi_c'^+} = \Delta s_{\Xi_c'^0} \,, \\
&\Delta s_{\Xi_c^+} = \Delta s_{\Xi_c^0} \,, \\
&\Delta s_{\Xi_{cc}^{++}} = \Delta s_{\Xi_{cc}^+} \,.
\end{aligned}$$

- Further, the charm quark polarization contributes equally for the entire octet, sextet, anti-triplet and triplet baryons since the number of charmed quarks are same in the constituent structure. We have

$$\begin{aligned}
&\Delta c_p = \Delta c_n = \Delta c_{\Sigma^+} = \Delta c_{\Sigma^0} = \Delta c_{\Sigma^-} = \Delta c_{\Lambda} = \Delta c_{\Xi^0} = \Delta c_{\Xi^-} \,, \\
&\Delta c_{\Sigma_c^{++}} = \Delta c_{\Sigma_c^+} = \Delta c_{\Sigma_c^0} = \Delta c_{\Xi_c'^+} = \Delta c_{\Xi_c'^0} = \Delta c_{\Omega_c^0} \,, \\
&\Delta c_{\Lambda_c^+} = \Delta c_{\Xi_c^+} = \Delta c_{\Xi_c^0} \,, \\
&\Delta c_{\Xi_{cc}^{++}} = \Delta c_{\Xi_{cc}^+} = \Delta c_{\Omega_{cc}^+} \,.
\end{aligned}$$

Spin polarizations for spin 3/2 charmed baryon multiplets

- The spin polarizations for the spin $\frac{3}{2}^+$ symmetric 20-plet with the light baryon decuplet (10,0), singly charmed sextet (6,1), doubly charmed triplet (3,2) and triply charmed singlet (1,3).

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
Δ^{++}	2.17	-0.36	-0.073	-0.004	1.733	2.53	1.956	1.749
Δ^{+}	1.326	0.483	-0.073	-0.004	1.732	0.843	1.955	1.748
Δ^{0}	0.483	1.326	-0.073	-0.004	1.732	-0.843	1.955	1.748
Δ^{-}	-0.36	2.17	-0.073	-0.004	1.733	-2.53	1.956	1.749
$\Sigma^{\star+}$	1.422	-0.264	0.866	-0.004	2.02	1.686	-0.574	2.036
$\Sigma^{\star 0}$	0.579	0.579	0.866	-0.004	2.02	0.0	-0.574	2.036
$\Sigma^{\star-}$	-0.264	1.422	0.866	-0.004	2.02	-1.686	-0.574	2.036
$\Xi^{\star 0}$	0.675	-0.169	1.805	-0.004	2.307	0.844	-3.104	2.323
$\Xi^{\star-}$	-0.169	0.675	1.805	-0.004	2.307	-0.844	-3.104	2.323
Ω^{-}	-0.073	-0.073	2.744	-0.004	2.594	0.0	-5.634	2.61

Table: The quark spin polarization and the axial coupling constants for spin $\frac{3}{2}^+$, decuplet baryons (10,0) within SU (4) representation in the chiral quark constituent model.

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
$\Sigma_c^{\star++}$	1.445	-0.241	-0.05	0.966	2.12	1.686	1.304	-1.744
$\Sigma_c^{\star+}$	0.602	0.602	-0.05	0.966	2.12	0.0	1.304	-1.744
$\Sigma_c^{\star0}$	-0.241	1.445	-0.05	0.966	2.12	-1.686	1.304	-1.744
$\Xi_c^{\star+}$	0.697	-0.146	0.889	0.966	2.406	0.843	-1.227	-1.458
$\Xi_c^{\star0}$	-0.146	0.697	0.889	0.966	2.406	-0.843	-1.227	-1.458
$\Omega_c^{\star0}$	-0.05	-0.05	1.828	0.966	2.694	0.0	-3.756	-1.17

Table: The quark spin polarization and the axial coupling constants for spin $\frac{3}{2}^+$, sextet baryons (6,1) within SU (4) representation in the chiral quark constituent model.

Baryon	Δu_B	Δd_B	Δs_B	Δc_B	g_B^0	g_B^3	g_B^8	g_B^{15}
$\Xi_{cc}^{\star++}$	0.72	-0.123	-0.027	1.936	2.506	0.843	0.651	-5.238
$\Xi_{cc}^{\star+}$	-0.28	0.877	-0.027	1.936	2.506	-1.157	0.651	-5.238
$\Omega_{cc}^{\star+}$	-0.027	-0.027	0.912	1.936	2.794	0.0	-1.878	-4.95
$\Omega_{ccc}^{\star++}$	-0.004	-0.004	-0.004	2.906	2.894	0.0	0.0	-8.73

Table: The quark spin polarization and the axial coupling constants for spin $\frac{3}{2}^+$, triplet baryons (3,2) and singlet (1,3) baryons within SU (4) representation in the chiral quark constituent model.

- For the case of spin$-\frac{3}{2}^+$ light and charmed baryons we observe the following relations between the isospin partners with the interchange of $u \longleftrightarrow d$

$$
\begin{array}{lllll}
\Delta u_{\Delta^{++}} = \Delta d_{\Delta^-}, & g^0_{\Delta^{++}} = g^0_{\Delta^-}, & g^3_{\Delta^{++}} = -g^3_{\Delta^-}, & g^8_{\Delta^{++}} = g^8_{\Delta^-}, & g^{15}_{\Delta^{++}} = g^{15}_{\Delta^-}, \\
\Delta u_{\Delta^+} = \Delta d_{\Delta^0}, & g^0_{\Delta^+} = g^0_{\Delta^0}, & g^3_{\Delta^+} = -g^3_{\Delta^0}, & g^8_{\Delta^+} = g^8_{\Delta^0}, & g^{15}_{\Delta^+} = g^{15}_{\Delta^0}, \\
\Delta u_{\Sigma^{*+}} = \Delta d_{\Sigma^{*-}}, & g^0_{\Sigma^{*+}} = g^0_{\Sigma^{*-}}, & g^3_{\Sigma^{*+}} = -g^3_{\Sigma^{*-}}, & g^8_{\Sigma^{*+}} = g^8_{\Sigma^{*-}}, & g^{15}_{\Sigma^{*+}} = g^{15}_{\Sigma^{*-}}, \\
\Delta u_{\Xi^{*0}} = \Delta d_{\Xi^{*-}}, & g^0_{\Xi^{*0}} = g^0_{\Xi^{*-}}, & g^3_{\Xi^{*0}} = -g^3_{\Xi^{*-}}, & g^8_{\Xi^{*0}} = g^8_{\Xi^{*-}}, & g^{15}_{\Xi^{*0}} = g^{15}_{\Xi^{*-}}, \\
\Delta u_{\Sigma_c^{*++}} = \Delta d_{\Sigma_c^{*0}}, & g^0_{\Sigma_c^{*++}} = g^0_{\Sigma_c^{*0}}, & g^3_{\Sigma_c^{*++}} = -g^3_{\Sigma_c^{*0}}, & g^8_{\Sigma_c^{*++}} = g^8_{\Sigma_c^{*0}}, & g^{15}_{\Sigma_c^{*++}} = g^{15}_{\Sigma_c^{*0}}, \\
\Delta u_{\Xi_c^{*+}} = \Delta d_{\Xi_c^{*0}}, & g^0_{\Xi_c^{*+}} = g^0_{\Xi_c^{*0}}, & g^3_{\Xi_c^{*+}} = -g^3_{\Xi_c^{*0}}, & g^8_{\Xi_c^{*+}} = g^8_{\Xi_c^{*0}}, & g^{15}_{\Xi_c^{*+}} = g^{15}_{\Xi_c^{*0}}, \\
\Delta u_{\Xi_{cc}^{*++}} = \Delta d_{\Xi_{cc}^{*+}}, & g^0_{\Xi_{cc}^{*++}} = g^0_{\Xi_{cc}^{*+}}, & g^3_{\Xi_{cc}^{*++}} = -g^3_{\Xi_{cc}^{*+}}, & g^8_{\Xi_{cc}^{*++}} = g^8_{\Xi_{cc}^{*+}}, & g^{15}_{\Xi_{cc}^{*++}} = g^{15}_{\Xi_{cc}^{*+}}.
\end{array}
$$

- The contribution of the strange quark polarizations is again same in the multiplets between each of the decuplet, sextet and triplet of the baryons. We have

$$
\begin{aligned}
&\Delta s_{\Delta^{++}} = \Delta s_{\Delta^{+}} = \Delta s_{\Delta^{0}} = \Delta s_{\Delta^{-}} \,, \\
&\Delta s_{\Sigma^{*+}} = \Delta s_{\Sigma^{*0}} = \Delta s_{\Sigma^{*-}} \,, \\
&\Delta s_{\Xi^{*0}} = \Delta s_{\Xi^{*-}} \,, \\
&\Delta s_{\Sigma_c^{*++}} = \Delta s_{\Sigma_c^{*+}} = \Delta s_{\Sigma_c^{*0}} \,, \\
&\Delta s_{\Xi_c^{*+}} = \Delta s_{\Xi_c^{*0}} \,, \\
&\Delta s_{\Xi_c^{+}} = \Delta s_{\Xi_c^{0}} \,, \\
&\Delta s_{\Xi_{cc}^{*++}} = \Delta s_{\Xi_{cc}^{*+}} \,.
\end{aligned}
$$

- The charm quark polarization gives the same contribution for the entire decuplet, sextet and triplet baryons and we have

$$
\begin{aligned}
&\Delta c_{\Delta^{++}} = \Delta c_{\Delta^{+}} = \Delta c_{\Delta^{0}} = \Delta c_{\Delta^{-}} = \Delta c_{\Sigma^{*+}} = \Delta c_{\Sigma^{*0}} = \Delta c_{\Sigma^{*-}} = \Delta c_{\Xi^{*0}} = \Delta c_{\Xi^{*-}} = \Delta c_{\Omega^{-}} \,, \\
&\Delta c_{\Sigma_c^{*++}} = \Delta c_{\Sigma_c^{*+}} = \Delta c_{\Sigma_c^{*0}} = \Delta c_{\Xi_c^{*+}} = \Delta c_{\Xi_c^{*0}} = \Delta c_{\Omega_c^{*0}} \,, \\
&\Delta c_{\Xi_c^{+}} = \Delta c_{\Xi_c^{0}} = \Delta c_{\Xi_{cc}^{*++}} = \Delta c_{\Xi_{cc}^{*+}} \,.
\end{aligned}
$$

- The magnitude of charm quark polarization for different spin$-\frac{1}{2}^+$ and spin$-\frac{3}{2}^+$ light and charmed baryon multiplets is directly related to the number of charm quarks in the baryon and this observation is reflecting from the results as well. The value remains same within the baryons in the same multiplets but varies between the different multiplets having distinct values of hypercharge. We have

$$\Delta c_{(8,0)} < \Delta c_{(6,1)} < \Delta c_{(\bar{3},2)} < \Delta c_{(3,2)} \,,$$
$$\Delta c_{(10,0)} < \Delta c_{(6,1)} < \Delta c_{(3,2)} < \Delta c_{(1,3)} \,.$$

- For a low and moderate momentum transfer $Q^2 \leq 1$, the dipole form of parametrization has been conventionally used to analyse the vector and axial-vector form factors

$$G_B^j(Q^2) = \frac{g_B^j(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}, \tag{1}$$

where $g_A^0(0)$, $g_A^3(0)$, $g_A^8(0)$ and $g_A^{15}(0)$ are the axial-vector coupling constants at zero momentum transfer.

- M_A: axial mass
  M_A extracted from measurement of flux-averaged neutral-current elastic differential cross section at MiniBooNE experiment is $M_A = 1.39 \pm 0.11$ GeV at $Q^2 = 0$
  From MINOS and T2K, the values of M_A are found to be $1.23^{+0.13}_{-0.09}$ and $1.26^{+0.21}_{-0.18}$ GeV.
  $M_A = 1.10^{+0.13}_{-0.15}$ GeV extracted by employing NuWro Monte Carlo generator method (*np*–*nh* contribution) to the MiniBooNE experiment data.

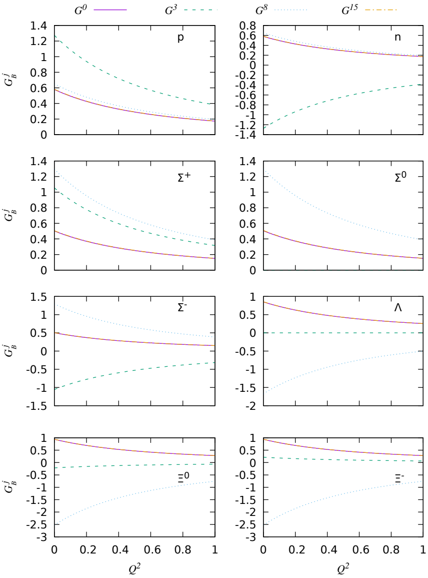

Figure: The axial-vector charges for the spin $\frac{1}{2}^+$ mixed symmetry 20-plet with the light baryon octet (8,0) plotted as function of Q^2 (in units of GeV^2).

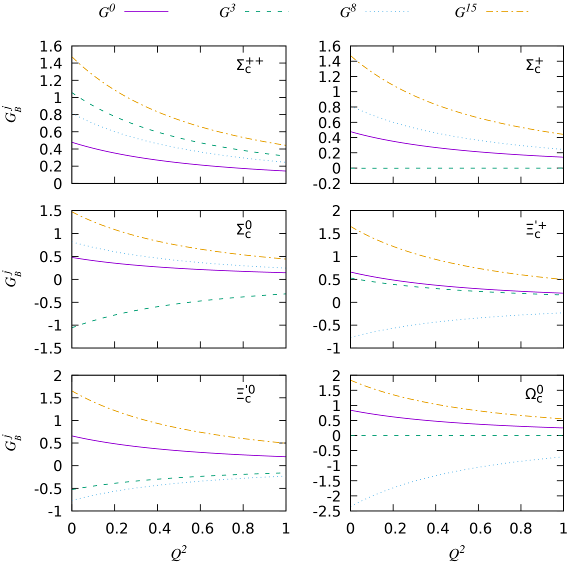

Figure: The axial-vector charges for the spin $\frac{1}{2}^+$ mixed symmetry 20-plet with the singly charmed sextet (6,1) plotted as function of Q^2 (in units of GeV^2).

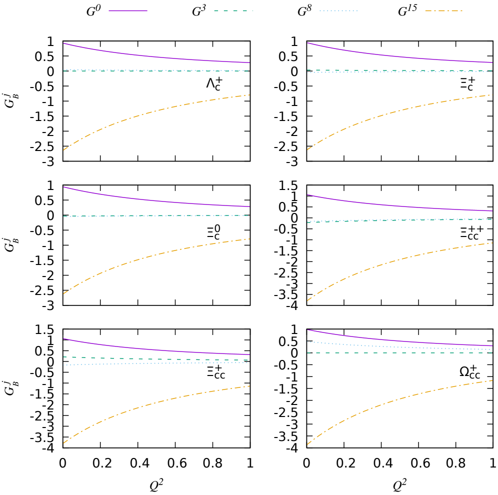

Figure: The axial-vector charges for the spin $\frac{1}{2}^+$ mixed symmetry 20-plet with the anti-triplet $(\bar{3},2)$ and triplet $(3,2)$ with doubly charmed baryons plotted as function of Q^2 (in units of GeV^2).

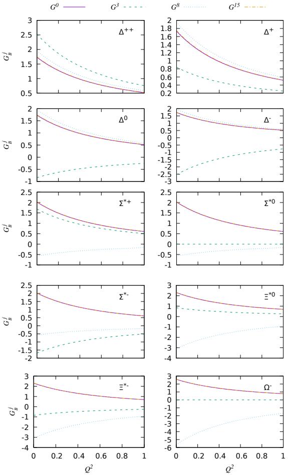

Figure: The axial-vector charges for the spin $\frac{3}{2}^+$ symmetric 20-plet with the light baryon decuplet (10,0) plotted as function of Q^2 (in units of GeV^2).

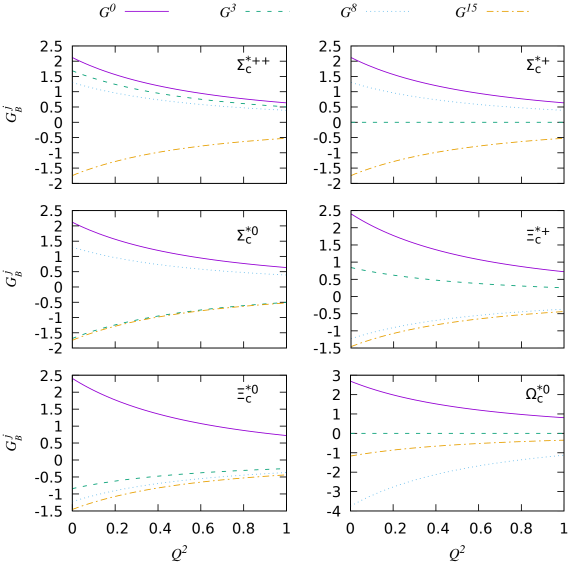

Figure: The axial-vector charges for the spin $\frac{3}{2}^+$ symmetric 20-plet with the singly charmed sextet (6,1) plotted as function of Q^2 (in units of GeV^2).

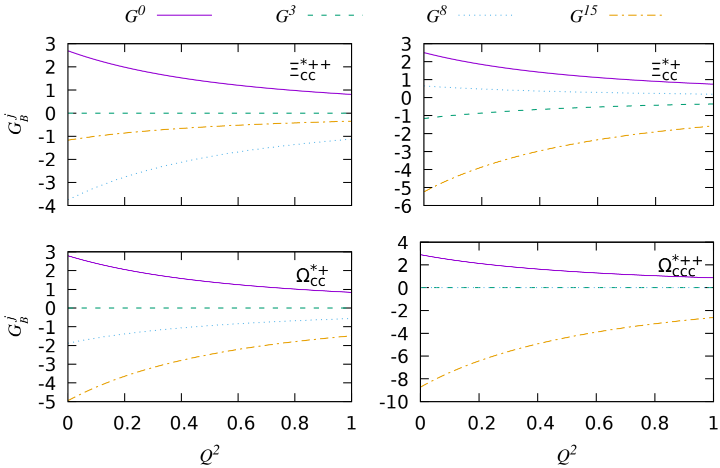

Figure: The axial-vector charges for the spin $\frac{3}{2}^+$ symmetric 20-plet with the doubly charmed triplet (3,2) and triply charmed singlet (1,3) plotted as function of Q^2 (in units of GeV^2).

Summary

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

- Our results confirm the presence of intrinsic strange and charm quarks in the light baryons and the other non-constituent quark contributions in the charmed baryons.
- The understanding of pivotal role played by SU(3) symmetry breaking will lead to crucial hints in understanding the fundamental structure of the baryons in the nonperturbative QCD regime.
- The phenomena of chiral symmetry breaking will have far-reaching implications in terms of the elementary degrees of freedom of the composite particles.
- Lattice calculations and future experiments at EIC will not only have the possibility to illuminate the complicated issue of spin structure but also impose significant and decisive restraints in different kinematic regions.