Asymmetries of quark sea in nucleon

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Outline

1. Internal structure of the baryons
2. Chiral Constituent Quark Model
3. Sea Quark Distribution
4. Gottfried Sum Rule
5. Results
6. Summary and Conclusions

Naive Quark Model

- **Internal Structure:** The knowledge of internal structure of nucleon in terms of 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.
- **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.

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.
- 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 $\Delta s = 0$)

Flavor Structure

- Several interesting facts revealed regarding the flavor distribution functions.
- The conventional expectation that the quark sea perhaps can be obtained through the perturbative production of the quark-antiquark pairs by gluons produces nearly equal numbers of $\bar{u}$ and $\bar{d}$.
- 1991 NMC result: Asymmetric nucleon sea ($\bar{d} > \bar{u}$)
  Confirmed by E866 and HERMES
  Gottfried Sum Rule: $I_G = \frac{1}{3} + \frac{2}{3}\int_0^1 [\bar{u}(x) - \bar{d}(x)]dx = 0.254 \pm 0.026$
- Confirmed by the Drell-Yan experiments measuring a large quark sea asymmetry ratio $\bar{d}/\bar{u}$. Study of the quark sea is intrinsically a nonperturbative phenomena and it is still a big challenge to perform these calculations from the first principles of QCD.

Quark Sea

- Flavor and spin structure of the nucleon is not limited to u and d quarks only.
- The measured quark sea asymmetry established that the study of the structure of the nucleon is intrinsically a nonperturbative phenomena.
- Non-perturbative effects explained only through the generation of “quark sea”

Non-perturbative regime

- 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.
- The direct calculations of these quantities form the first principle of QCD are extremely difficult: they require non-perturbative methods.
- 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.

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 $p \rightarrow \pi^+ n$, leads to an excess of $\bar{d}$ sea.
- However, this effect should be significantly reduced by the emissions such as $p \rightarrow \Delta^{++} + \pi^-$ 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 Constituent Quark Model

- χCQM initiated by Weinberg and developed by Manohar and Georgi to explain the successes of NQM.
- "Quark sea" generation $q_{\pm} \rightarrow GB^0 + q^{'}_{\mp} \rightarrow (q\bar{q}^{'}) + q^{'}_{\mp}$
- Incorporates *confinement* and *chiral symmetry breaking.*
- “Justifies” the idea of constituent quarks and scope of the model extended in the context of **“proton spin crisis”**

Methodology

- "Quark sea" generation $q_{\pm} \rightarrow GB^0 + q'_{\mp} \rightarrow (q\bar{q}') + q'_{\mp}$
- $\mathcal{L} = g_8 \bar{q} \left(\Phi + \zeta \frac{\eta'}{\sqrt{3}} I \right) q = g_8 \bar{q} \left(\Phi' \right) q$
- $\Phi' = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} & \alpha K^0 \\ \alpha K^- & \alpha \bar{K}^0 & -\beta \frac{2\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} \end{pmatrix}$
- $\Phi' = \begin{pmatrix} \phi_{uu} u\bar{u} + \phi_{ud} d\bar{d} + \phi_{us} s\bar{s} & \varphi_{ud} u\bar{d} & \varphi_{us} u\bar{s} \\ \varphi_{du} d\bar{u} & \phi_{du} u\bar{u} + \phi_{dd} d\bar{d} + \phi_{ds} s\bar{s} & \varphi_{ds} d\bar{s} \\ \varphi_{su} s\bar{u} & \phi_{sd} s\bar{d} & \phi_{su} u\bar{u} + \phi_{sd} d\bar{d} + \phi_{ss} s\bar{s} \end{pmatrix}$

Transition probabilities

- $$\begin{aligned} \phi_{uu} &= \phi_{dd} = \frac{1}{2} + \frac{\beta}{6} + \frac{\zeta}{3}\,, \quad \phi_{ss} = \frac{2\beta}{3} + \frac{\zeta}{3}\,, \quad \phi_{us} = \phi_{ds} = \phi_{su} = \phi_{sd} = -\frac{\beta}{3} + \frac{\zeta}{3}\,, \\ \phi_{du} &= \phi_{ud} = -\frac{1}{2} + \frac{\beta}{6} + \frac{\zeta}{3}\,, \quad \varphi_{ud} = \varphi_{du} = 1\,, \quad \varphi_{us} = \varphi_{ds} = \varphi_{su} = \varphi_{sd} = \alpha\,. \end{aligned}$$
- The parameter $a(=|g_8|^2)$ denotes the transition probability of chiral fluctuation of the splittings $u(d) \to d(u) + \pi^{+(-)}$, whereas $\alpha^2 a$, $\beta^2 a$ and $\zeta^2 a$ respectively denote the probabilities of transitions of $u(d) \to s + K^{-(o)}$, $u(d,s) \to u(d,s) + \eta$, and $u(d,s) \to u(d,s) + \eta^{'}$.
- The quark sea content of the baryon can be calculated in χCQM by substituting for every constituent quark $q \to \sum P_q q + |\psi(q)|^2$, where $\sum P_q$ is the transition probability of the emission of a GB from any of the q quark and $|\psi(q)|^2$ is the transition probability of the q quark.

Octet baryons

- For p(uud)
  $\bar{u} = a(2\phi^2_{uu} + \phi^2_{du} + \varphi^2_{du})$, $\bar{d} = a(2\phi^2_{ud} + 2\varphi^2_{ud} + \phi^2_{dd})$ and
  $\bar{s} = a(2\phi^2_{us} + 2\varphi^2_{us} + \phi^2_{ds} + \varphi^2_{us})$
- For $\Sigma^+(uus)$
  $\bar{u} = a(2\phi^2_{uu} + \phi^2_{su} + \varphi^2_{su})$, $\bar{d} = a(2\phi^2_{ud} + 2\varphi^2_{ud} + \phi^2_{sd} + \varphi^2_{sd})$ and
  $\bar{s} = a(2\phi^2_{us} + 2\varphi^2_{us} + \phi^2_{ss})$
- For $\Sigma^0(uds)$
  $\bar{u} = a(\phi^2_{uu} + \phi^2_{du} + \phi^2_{su} + \varphi^2_{du} + \varphi^2_{su})$, $\bar{d} = a(\phi^2_{ud} + \phi^2_{dd} + \phi^2_{sd} + \varphi^2_{ud} + \varphi^2_{sd})$
  and $\bar{s} = a(\phi^2_{us} + \phi^2_{ds} + \phi^2_{ss} + \varphi^2_{us} + \varphi^2_{ds})$
- For $\Xi^0(uss)$
  $\bar{u} = a(\phi^2_{uu} + 2\phi^2_{su} + 2\varphi^2_{su})$, $\bar{d} = a(\phi^2_{ud} + \varphi^2_{ud} + 2\phi^2_{sd} + 2\varphi^2_{sd})$ and
  $\bar{s} = a(\phi^2_{us} + \varphi^2_{us} + 2\phi^2_{ss})$

$x-$dependence in χCQM

- $$F_2^B(x) = x \sum_{u,d,s} e_q^2 [q^B(x) + \bar{q}^B(x)]\,,$$
  $$F_1^B(x) = \frac{1}{2x} F_2^B(x)\,,$$
  where e_q is the charge of the quark q ($e_u = \frac{2}{3}$ and $e_d = e_s = -\frac{1}{3}$). In terms of the quark distribution functions, the structure function F_2 for any baryon can be expressed as
  $$F_2^B(x) = \frac{4}{9} x(u^B(x) + \bar{u}^B(x)) + \frac{1}{9} x(d^B(x) + \bar{d}^B(x) + s^B(x) + \bar{s}^B(x))\,.$$
- $x-$dependence is phenomenologically incorporated $\bar{u}^B(x) = \bar{u}^B(1-x)^{10}$, $\bar{d}^B(x) = d^B(1-x)^7$, $\bar{s}^B(x) = s^B(1-x)^8$.
- Flavor structure of the baryon is given as
  $$q^B(x) = q^B_{\rm val}(x) + \bar{q}^B(x)\,,$$
  where $q = u, d, s$.

The Gottfried integrals

- The Gottfried integral I_G^{pn} in terms of the sea quarks

$$I_G^{pn} = \int_0^1 \frac{F_2^p(x) - F_2^n(x)}{x} dx = \frac{1}{3} + \frac{2}{3} \int_0^1 \left[\bar{u}^p(x) - \bar{d}^p(x)\right] dx \,.$$

- Normalization conditions used

$$\int_0^1 u^p_{\rm val}(x)dx = 2\,, \quad \int_0^1 d^p_{\rm val}(x)dx = 1\,, \int_0^1 s^p_{\rm val}(x)dx = 0\,,$$

$$\int_0^1 u^n_{\rm val}(x)dx = 1\,, \int_0^1 d^n_{\rm val}(x)dx = 2\,, \int_0^1 s^n_{\rm val}(x)dx = 0\,,$$

$$\int_0^1 \bar{d}^n(x)dx = \int_0^1 \bar{u}^p(x)dx\,, \quad \int_0^1 \bar{u}^n(x)dx = \int_0^1 \bar{d}^p(x)dx\,,$$

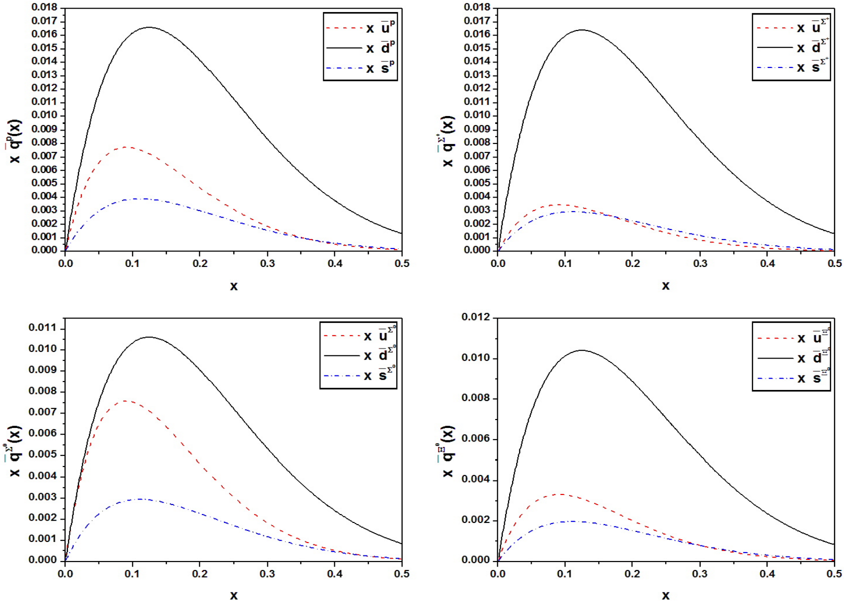
$$\int_0^1 \bar{s}^n(x)dx = \int_0^1 \bar{s}^p(x)dx\,.$$

The Gottfried Integrals

- Gottfried integrals in terms of the sea quarks

$$
\begin{aligned}
I_G^{\Sigma^+\Sigma^0} &\equiv \int_0^1 \frac{F_2^{\Sigma^+}(x) - F_2^{\Sigma^0}(x)}{x} dx \\
&= \frac{1}{3} + \frac{2}{9}\int_0^1 \left[4\bar{u}^{\Sigma^+}(x) + \bar{d}^{\Sigma^+}(x) - 4\bar{u}^{\Sigma^0}(x) - \bar{d}^{\Sigma^0}(x)\right] dx\,, \\
I_G^{\Sigma^0\Sigma^-} &\equiv \int_0^1 \frac{F_2^{\Sigma^0}(x) - F_2^{\Sigma^-}(x)}{x} dx \\
&= \frac{1}{3} + \frac{2}{9}\int_0^1 \left[4\bar{u}^{\Sigma^0}(x) + \bar{d}^{\Sigma^0}(x) - 4\bar{d}^{\Sigma^+}(x) - \bar{u}^{\Sigma^+}(x)\right] dx\,, \\
I_G^{\Xi^0\Xi^-} &\equiv \int_0^1 \frac{F_2^{\Xi^0}(x) - F_2^{\Xi^-}(x)}{x} dx = \frac{1}{3} + \frac{2}{3}\int_0^1 \left[\bar{u}^{\Xi^0}(x) - \bar{d}^{\Xi^0}(x)\right] dx\,.
\end{aligned}
$$

- A flavor symmetric sea leads to the Gottfried sum rule $I_G = \frac{1}{3}$ with $\bar{u}^B$=$\bar{d}^B$.


x $\bar{u}^p$
x $\bar{d}^p$
x $\bar{s}^p$
x $\bar{q}^p(x)$
x
x $\bar{u}^{\Sigma^+}$
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x $\bar{s}^{\Sigma^+}$
x $\bar{q}^{\Sigma^+}(x)$
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x $\bar{u}^{\Sigma^0}$
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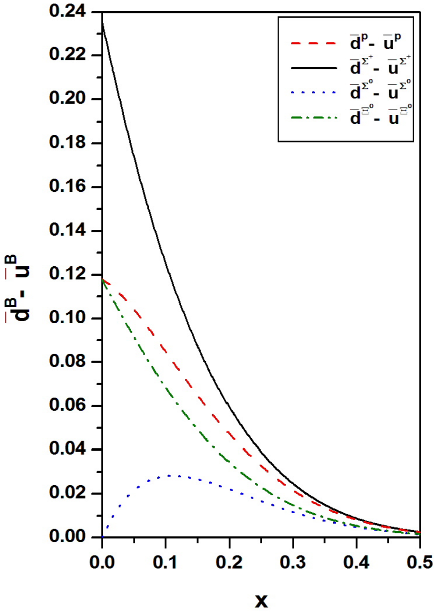
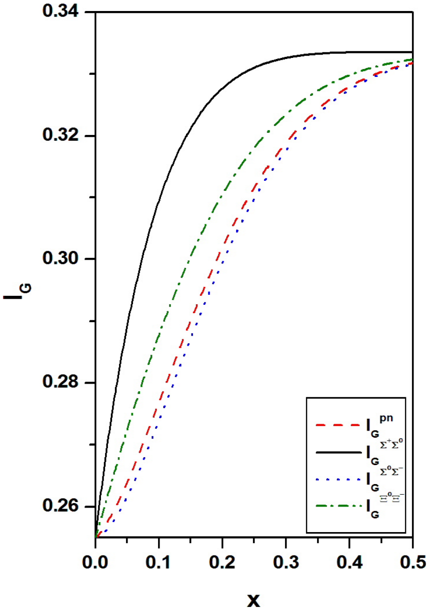
x $\bar{s}^{\Sigma^0}$
x $\bar{q}^{\Sigma^0}(x)$
x
x $\bar{u}^{\Xi^0}$
x $\bar{d}^{\Xi^0}$
x $\bar{s}^{\Xi^0}$
x $\bar{q}^{\Xi^0}(x)$
x

- In the figure, we have shown the variation of the sea quark distributions $x\bar{u}(x)$, $x\bar{d}(x)$ and $x\bar{s}(x)$ with the Bjorken scaling variable x for $p(uud)$, $\Sigma^+(uus)$, $\Sigma^0(uds)$ and $\Xi^0(uss)$.
- One can easily find out that

$$\bar{d}^p(x) > \bar{u}^p(x) > \bar{s}^p(x), \quad \bar{d}^{\Sigma^+}(x) > \bar{u}^{\Sigma^+}(x) \approx \bar{s}^{\Sigma^+}(x),$$
$$\bar{d}^{\Sigma^0}(x) > \bar{u}^{\Sigma^0}(x) > \bar{s}^{\Sigma^0}(x), \quad \bar{d}^{\Xi^0}(x) > \bar{u}^{\Xi^0}(x) > \bar{s}^{\Xi^0}(x),$$

- As the sea quarks do not contribute at higher values of x, therefore we have taken the region $x = 0 - 0.5$. Beyond this x region the contribution of the sea quarks should be completely dominated by the valence quarks. The difference between the various sea distributions is observed to be maximum at $x \approx 0.1$. As the value of x increases, the difference between the sea contributions decreases.


0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$\bar{d}^B - \bar{u}^B$
$\bar{d}^p - \bar{u}^p$
$\bar{d}^{\Sigma^+} - \bar{u}^{\Sigma^+}$
$\bar{d}^{\Sigma^o} - \bar{u}^{\Sigma^o}$
$\bar{d}^{\Xi^o} - \bar{u}^{\Xi^o}$
0.0
0.1
0.2
0.3
0.4
0.5
x


0.34
0.32
0.30
0.28
0.26
I_G
I_G^{pn}
$I_G^{\Sigma^+\Sigma^0}$
$I_G^{\Sigma^0\Sigma^-}$
$I_G^{\Xi^0\Xi^-}$
0.0
0.1
0.2
0.3
0.4
0.5
x

- These quantities not only provide important constraint on a model that attempts to describe the origin of the quark sea but also provide a direct determination of the presence of significant amount of quark sea in the low x region.
- When x is small $\bar{d}^B(x) - \bar{u}^B(x)$ asymmetries are large implying the dominance of sea quarks in the low x region.
- At the values $x > 0.3$, $\bar{d} - \bar{u}$ tends to 0 implying that there are no sea quarks in this region.
- The case of Σ^0 is particularly interesting because of its flavor structure which has equal numbers of u, d and s quarks in its valence structure.
- Unlike the other octet baryons, where the $\bar{d}(x) - \bar{u}(x)$ asymmetry decreases continuously with the x values, the asymmetry in this case first increases and then for values of $x > 0.1$ it decreases.

- The Gottfried sum rules for the case of Σ^+, Σ^0, and Ξ^0 should read $I_G^{\Sigma^+\Sigma^0} = \frac{1}{3}$, $I_G^{\Sigma^0\Sigma^-} = \frac{1}{3}$ and $I_G^{\Xi^0\Xi^-} = \frac{1}{3}$ if the quark sea was symmetric.
- However, due to the $\bar{d}(x) - \bar{u}(x)$ asymmetry in the case of octet baryons, a lower value of the Gottfried integrals is obtained.
- The quality of numerical agreement can be assessed only after the data gets refined.

Application Potential

The present calculations suggest few important points

- Decomposition of various measurable quantities into the contributions from valence and sea components.
- Contribution of strange quarks in the nucleon which do not appear explicitly in most quark model descriptions of the nucleon and the role played by non-valence flavors in understanding the nucleon internal structure.
- What is the role played by non-valence flavors in understanding the nucleon internal structure?

Summary and Conclusions

- The results obtained for the quark distribution functions reinforce our conclusion that χCQM is able to generate qualitatively as well as quantitatively the requisite amount of quark sea.
- This phenomenological analysis strongly suggests an important role for the quark sea at low value of x.
- New experiments aimed at measuring the flavor content of the other octet baryons are needed for profound understanding of the nonperturbative properties of QCD.
- At leading order, the model envisages constituent quarks, the Goldstone bosons (π, K, η mesons) as appropriate degrees of freedom.