Sea Quark Asymmetry in Proton

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QNP2022 - The 9th International Conference on Quarks and Nuclear Physics
Outline

1. Origin of proton asymmetry
2. Exploring the Sea
3. Models
4. $\chi_{CQM}$
5. Results
6. Conclusion
Sea Quarks

- The proton picture with just three valence quarks ($uud$) fail to explain the fractional momentum carried by the constituents.
  - If there were only three valence quarks, each quark should have carried $\frac{1}{3}$ of proton’s total momentum.
  - This was found to be untrue.
  - Average fractional momentum carried by the constituents was less than $\frac{1}{3}$.

- The extra momentum was attributed to *sea quarks*. 
Gottfried Sum Rule (GSR)

- GSR suggests that if the sea is symmetric, then the value of Gottfried integral ($I_G$) = $\frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)] dx = \frac{1}{3}$.

**Gottfried Integral ($I_G$)**

\[
I_G = \frac{1}{3} \Rightarrow \text{symmetric sea } \bar{u} = \bar{d}.
\]

\[
I_G < \frac{1}{3} \Rightarrow \text{asymmetric sea } \bar{u} \neq \bar{d}.
\]

- Violation of GSR is a direct evidence of *asymmetric sea*. 
Feynman’s interpretation

- SLAC data reported $I_G = 0.20 \pm 0.04$.
- Feynman’s intuitive interpretation for proton’s asymmetric sea was as follows:
  - $u\bar{u}$ and $d\bar{d}$ pairs are produced perturbatively due to gluon splitting.
  - $u\bar{u}$ production is suppressed because proton already contains two valence up quarks \textit{(Pauli blocking)}.
  - This naturally leads to an excess of $d\bar{d}$ pairs and hence $\bar{d}$ outnumber $\bar{u}$ inside the proton.
- Observed asymmetry too large to be explained by this alone.
Deep Inelastic Scattering (DIS) experiments

- Usually addresses the difference $\bar{d} - \bar{u}$.
- Great for measuring Gottfried Integral ($I_G$).
- Can not extract individual anti-quark distribution.
Exploring the Sea

Various $DIS$ experiments were conducted and all of them reported $I_G < \frac{1}{3}$.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Gottfried Integral ($I_G$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC</td>
<td>$0.200 \pm 0.040$</td>
</tr>
<tr>
<td>EMC</td>
<td>$0.235 \pm 0.099$</td>
</tr>
<tr>
<td>NMC</td>
<td>$0.235 \pm 0.026$</td>
</tr>
<tr>
<td>HERMES</td>
<td>$0.226 \pm 0.020$</td>
</tr>
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</table>
Drell-Yan (DY) experiments

- Ratio of DY cross-section:
  \[
  \frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2} \left( 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right)
  \]

- An effective way to measure $\frac{\bar{d}}{\bar{u}}$ ratio.

- Can extract individual anti-quark distribution.
Later experiments were based on Drell-Yan (DY) process. NA51 was first dedicated DY experiment and found \(\bar{u}/\bar{d} = 0.51 \pm 0.04\) at \(x = 0.18\). NuSea reported both \(\bar{d}/\bar{u}\) and \(\bar{d} - \bar{u}\) data.

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<td>E866/NuSea</td>
<td>0.254 \pm 0.005</td>
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</table>
NuSea and SeaQuest Results

- Around $x \approx 0.3$ NuSea reported $\frac{d}{u} < 1$
- SeaQuest specifically collected data in medium to high $x$ range.
- *Disagreement* between NuSea and SeaQuest data in high $x$ region.
Theoretical attempts

- Significant $\bar{u} \, \bar{d}$ asymmetry in protons can not be explained perturbatively.
- Some *non-perturbative* models are:
  - Pion Cloud Model.
  - Chiral Constituent Quark Model ($\chi_{CQM}$)
  - Instanton Model
- Pion Cloud Model and $\chi_{CQM}$ both involve mesons in their explanations.
Pion Cloud Model

- In PCM, proton can momentarily exist as a virtual pion and a baryon.
  - \( |p\rangle = (1 - a - b)|p_0\rangle + a|n\pi^+\rangle + b|\Delta^{++}\pi^-\rangle \)
- It is more probable for proton to exist as \( |n\pi^+\rangle \) than \( |\Delta^{++}\pi^-\rangle \)
  - \( uud \rightarrow (udd)(\bar{d}u) \rightarrow uud \)
  - \( uud \rightarrow (uuu)(\bar{u}d) \rightarrow uud \)
- \( a > b \) causes excess of \( \bar{d} \).
- There are other baryons but generally neutron and delta considered.
\[ \chi_{CQM} \]

- In \( \chi_{CQM} \), valence quark \( q \) can transition into a Goldstone Boson (GB) and a valence quark \( q' \) (different flavor).
  - \( q^{\pm} \rightarrow GB + q'^{\pm} \)
- Valence up and down quarks can transition with maximum probability into a \( \pi^+ \) and \( \pi^- \) GB.
  - \( u \rightarrow \pi^+ d \rightarrow (u\bar{d})(d) \)
  - \( d \rightarrow \pi^- u \rightarrow (d\bar{u})(u) \)
- Two valence up quarks in proton causes excess of \( \bar{d} \).
- Other GBs are \( K \), \( \eta \) and \( \eta' \).
Justification for using $\chi_{CQM}$

- Successfully explains the "proton spin problem".
- Can account for baryon magnetic moments.
- Calculates charge radii and quadrupole moment of baryons.
- Incorporates *chiral symmetry breaking* and *confinement*, two key features of *QCD*.
- Mechanism involving GBs operate in the *interior* of proton.
QCD Lagrangian describes the dynamics of light quarks (up, down and strange) and gluons.

\[ \mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G^{\mu\nu}_a + i \bar{\psi}_R \gamma^\mu \psi_R + i \bar{\psi}_L \gamma^\mu \psi_L - \bar{\psi}_L M \psi_R - \bar{\psi}_R M \psi_L \]

It is not invariant under chiral transformation \( (\psi \rightarrow \gamma^5 \psi) \) due to presence of mass terms.

At high energies mass terms can be neglected and Lagrangian has a \( SU(3)_L \times SU(3)_R \) global chiral symmetry.
At low energies mass terms can no longer be neglected and chiral symmetry is *spontaneously broken* as:

\[ SU(3)_L \times SU(3)_R \rightarrow SU(3)_{L+R} \]

This happens at \( \approx 1 \text{GeV} \).

As a result an *octet* of GBs is generated, comprising of \( \pi, K \) and \( \eta \) mesons.

\( L_{QCD} \) also invariant under axial \( U(1) \) symmetry, when this is broken, a ninth GB \( \eta' \) is also generated.
Quark-GB Interaction

- Interaction between the quarks and nonet of GBs is the basis of $\chi_{CQM}$. It is described by $L_{int} = g_8 \bar{\psi} \varphi' \psi$.
  - $g_8 :=$ Coupling constant for octet of GBs.
  - $\varphi' :=$ GB field in terms of nonet and their transition probabilities.

$$\varphi' = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \kappa \frac{\eta}{\sqrt{6}} + \frac{\xi \eta'}{\sqrt{3}} \\ -\frac{\pi^0}{\sqrt{2}} + \frac{\kappa \eta}{\sqrt{6}} + \frac{\xi \eta'}{\sqrt{3}} \\ \frac{\pi^+}{\sqrt{2}} + \frac{\kappa \eta}{\sqrt{6}} + \frac{\xi \eta'}{\sqrt{3}} \\ -\kappa^2 \frac{\eta}{\sqrt{6}} + \frac{\xi \eta'}{\sqrt{3}} \\ \lambda K^+ \\ \lambda K^0 \\ \lambda K^0 \\ -\frac{\kappa \eta}{\sqrt{6}} + \frac{\xi \eta'}{\sqrt{3}} \end{pmatrix}$$
Probability Parameters

**Transition**
- \( u(d) \rightarrow \pi^{+(-)} + d(u) \)
- \( u(d) \rightarrow K^{+(0)} + s \)
- \( u(d, s) \rightarrow \eta + u(d, s) \)
- \( u(d, s) \rightarrow \eta' + u(d, s) \)

**Probability**
- \( \varepsilon \)
- \( \varepsilon \lambda^2 \)
- \( \varepsilon \kappa^2 \)
- \( \varepsilon \xi^2 \)

**Hierarchy of Probabilities**

*Transition probability* is inversely proportional to the mass of GB and scales as \( \frac{1}{M_{GB}^2} \). This sets the constraint \( \varepsilon > \varepsilon \lambda^2 > \varepsilon \kappa^2 > \varepsilon \xi^2 \).
Calculating Asymmetry

\[\bar{u} = \varepsilon \left( \frac{7}{4} + \frac{\kappa^2}{12} + \frac{\xi}{3} + \frac{\xi^2}{3} + \frac{\kappa}{6} + \frac{\kappa \xi}{6} \right)\]

\[\bar{d} = \varepsilon \left( \frac{11}{4} + \frac{\kappa^2}{12} - \frac{\xi}{3} + \frac{\xi^2}{3} - \frac{\kappa}{6} - \frac{\kappa \xi}{3} \right)\]

\(\bar{u} \bar{d} \) asymmetry

Taking \(\varepsilon = 0.114\), \(\kappa = 0.45\) and \(\xi = -0.75\) we obtain

\(\bar{u} - \bar{d} = -0.118\) and \(\bar{u}/\bar{d} = 0.652\)
Incorporating $x$ dependence in $\chi_{CQM}$

- Parton distributions can not be calculated from the first principles yet and are determined experimentally.
- To make anti-quark distribution $\bar{u}$ and $\bar{d}$ $x$-dependent, we have multiplied it with a function of form $(Nx)^a(1 - x)^b(1 + Cx)$.
- Parameters $N$, $a$, $b$ and $C$ are chosen such that $\frac{\bar{d}(x)}{\bar{u}(x)}$ and $\bar{d}(x) - \bar{u}(x)$ are consistent with experimental data from NuSea, SeaQuest and HERMES.
Explicit sea quark distribution functions.

**Probability density: down sea quark**

\[
\bar{d}(x) = 0.3391(1.5x)^{-1}(1 - x)^{10}(1 + 12.0569x)
\]

**Probability density: up sea quark**

\[
\bar{u}(x) = 0.2211x^{-0.999}(1 - x)^{7.4}(1 + 2.0876x)
\]

**Gottfried Integral** \((I_G)\) \(0.015 \leq x \leq 0.45\)

\[
I_G = \frac{1}{3} + \frac{2}{3} \int_{x_{\text{min}}}^{x_{\text{max}}} [\bar{u}(x) - \bar{d}(x)]dx = 0.256
\]

\[
I_G = \frac{1}{3} + \frac{2}{3} \int_0^1 [\bar{u}(x) - \bar{d}(x)]dx = 0.210
\]
Parton momentum distribution

- Clear dominance of valence quark distribution for \( x > 0.3 \)
- Sea quark distribution completely overshadows valence distribution at low \( x \).
- *Excess of \( \bar{d} \) over \( \bar{u} \) when \( x < 0.3 \)
**$ar{d}(x)/ar{u}(x)$ compared to SeaQuest and NuSea data**

- $\frac{\bar{d}(x)}{\bar{u}(x)} \geq 1$ in the region $x \leq 0.35$
- $\frac{\bar{d}(x)}{\bar{u}(x)} < 1$ for $x > 0.35$. This is valence quark dominated region.
- Ratio peaks at $x = 0.133$ then gradually decays.
- No model has yet explained why the ratio drops below unity at high $x$. 
$\bar{d}(x) - \bar{u}(x)$ compared to HERMES and NuSea data

- $\bar{d}(x) - \bar{u}(x)$ is consistent with other models in that it does not change sign in $0.30 < x < 0.35$
- The difference between $PCM$ and $\chi_{CQM}$ in the low $x$ region is due to their distinct mechanisms.
In $\chi_{CQM}$, GBs generated due to spontaneous chiral symmetry breaking are the basis of sea quark asymmetry in proton. Sea quarks carry most of proton’s momentum at low $x$ and $\bar{d}$ outnumbers $\bar{u}$ in this region. For $x > 0.3$ proton’s momentum is mostly carried by valence quarks.
Thank You.