Sea Quark Asymmetry in Proton

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Outline

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)

$I_G = \frac{1}{3} \Rightarrow$ symmetric sea $\bar{u} = \bar{d}$.

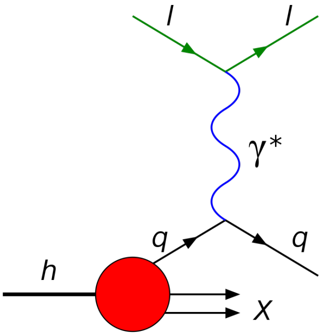
$I_G < \frac{1}{3} \Rightarrow$ asymmetric sea $\bar{u} \neq \bar{d}$.

- 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 (*Pauli blocking*).
  - This naturally leads to an excess of $d\bar{d}$ pairs and hence $\bar{d}$ outnumbers $\bar{u}$ inside the proton.
- Observed asymmetry too large to be explained by this alone.

Deep Inelastic Scattering (DIS) experiments



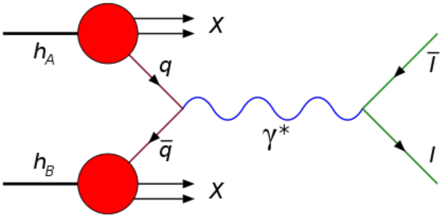
- Usually addresses the difference $\bar{d} - \bar{u}$.
- Great for measuring Gottfried Integral (I_G).
- Can not extract individual anti-quark distribution.

Exploring the Sea

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

Experiment	**Gottfried Integral** (I_G)
SLAC	0.200 ± 0.040
EMC	0.235 ± 0.099
NMC	0.235 ± 0.026
HERMES	0.226 ± 0.020

Drell-Yan (DY) experiments



- Ratio of *DY* cross-section :

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right)$$

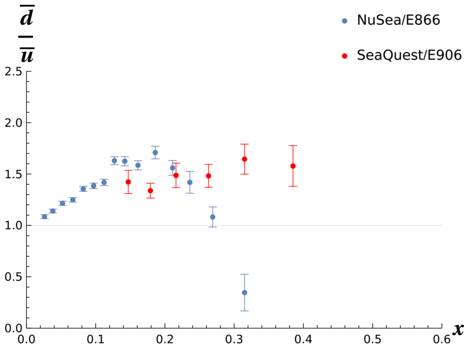
- An effective way to measure $\frac{\bar{d}}{\bar{u}}$ ratio.
- Can extract individual anti-quark distribution.

Exploring the Sea

- Later experiments were based on Drell-Yan *(DY)* process.
- NA51 was first dedicated DY experiment and found $\frac{\bar{u}}{\bar{d}} = 0.51 \pm 0.04$ at $x = 0.18$
- NuSea reported both $\frac{\bar{d}}{\bar{u}}$ and $\bar{d} - \bar{u}$ data.

Experiment	**Gottfried Integral** (I_G)
E866/NuSea	0.254 ± 0.005

NuSea and SeaQuest Results



- Around $x \approx 0.3$ NuSea reported $\frac{\bar{d}}{\bar{u}} < 1$
- 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 (χ_{CQM})
  - Instanton Model
- Pion Cloud Model and χ_{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.

χCQM

- In χ_{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 π^+ and π^- 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, η and η'.

Justification for using χ_{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.

Mass term in $\mathcal{L}_{QCD}$

- QCD Lagrangian describes the dynamics of light quarks (*up*, *down* and *strange*) and gluons.
  - $\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + i\bar{\psi}_R \not{D} \psi_R + i\bar{\psi}_L \not{D} \psi_L - \bar{\psi}_L M \psi_R - \bar{\psi}_R M \psi_L$
- It is not invariant under chiral transformation ($\psi \to \gamma^5 \psi$) 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.

Spontaneous Chiral Symmetry Breaking

- 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 $\approx 1GeV$.
- As a result an *octet* of GBs is generated, comprising of π, K and η mesons.
- $\mathcal{L}_{QCD}$ also invariant under axial $U(1)$ symmetry, when this is broken, a ninth GB η' is also generated.

Quark-GB Interaction

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

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

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*
  - ε
  - $\varepsilon\lambda^2$
  - $\varepsilon\kappa^2$
  - $\varepsilon\xi^2$

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 χ_{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

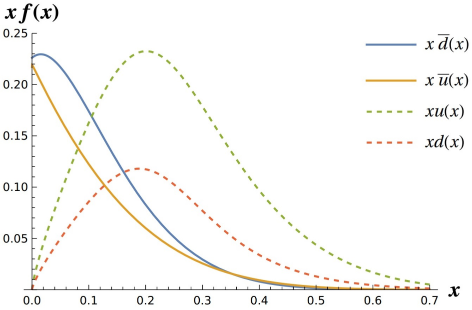
$$\bar{u}(x) = 0.2211x^{-0.999}(1-x)^{7.4}(1+2.0876x)$$

Gottfried Integral (I_G) $\quad 0.015 \leq x \leq 0.45$

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

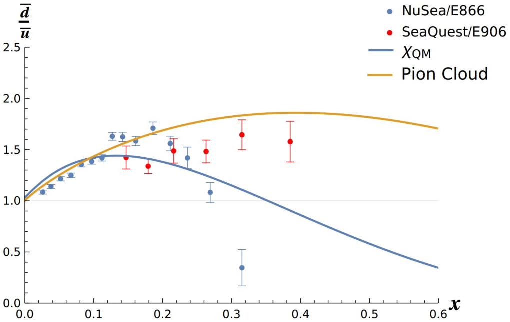
$$I_G = \frac{1}{3} + \frac{2}{3}\int_{0}^{1}[\bar{u}(x) - \bar{d}(x)]dx = 0.210$$

Parton momentum distribution



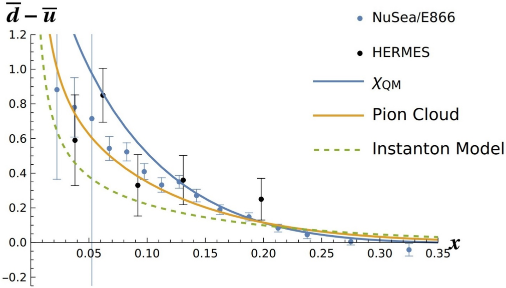
- Clear dominance of valence quark distribution for $x > 0.3$
- Sea quark distribution completely overshadows valence distribution at low x.
- *Excess of $\bar{d}$* over $\bar{u}$ when $x < 0.3$

$\bar{d}(x)/\bar{u}(x)$ 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 χ_{CQM} in the low x region is due to their distinct mechanisms.

Conclusion

- In χ_{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.