How should we view the sea: threatening or calm?

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What are the origins of the Sea?

Conventional thought:
- Gluon splitting leads to sea
- Sea is flavor symmetric since splitting is flavor independent
- Unfortunately this picture doesn’t agree with observations
Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3 \text{ GeV}^2$. The predicted extrapolations are uniquely determined by the requirement of a valence-like structure of all parton distributions at some low resolution scale . . . .

Gluck, Reya, Vogt,
ZPC 53, 127 (1992)
Evidence for a turbulent sea (II)

- Gottfried Sum Rule (NMC)

\[ \int_0^1 [F_2^p(x) - F_2^n(x)] \, dx = \frac{1}{3} \]

if and only if

\[ \int_0^1 [\bar{d}(x) - \bar{u}(x)] \, dx \neq 0 \]
Evidence for a turbulent sea (III)

- Drell-Yan
  NA51 at CERN

\[ \bar{d} > \bar{u} \text{ at } x = 0.18 \]
Evidence for a turbulent sea (IIIb)

- Drell-Yan
  NA51 at CERN
  \[ \bar{d} > \bar{u} \text{ at } x = 0.18 \]

- E866/NuSea (Fermilab)
  \[ \bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35 \]

- Knowledge of sea dist. are data driven

- Sea quark distributions are difficult for Lattice QCD*

*but significant progress is being made by the lattice community

Paul E Reimer,
Drell-Yan Cross Section—Sensitivity to Sea Quarks

- Point-like scattering of spin-1/2 particles
- Convoluted of beam and target parton distributions

\[
\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{x_b x_t s} \sum_{q \in \{u, d, s, \ldots\}} e_q^2 \left[ \bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t) \right]
\]
Drell-Yan Cross Section—
Sensitivity to Sea Quarks

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- u-quark dominance
  \((2/3)^2 \text{ vs. } (1/3)^2\)
- Acceptance limited
  (Fixed Target, Hadron Beam)

<table>
<thead>
<tr>
<th>Beam</th>
<th>Sensitivity</th>
<th>Experiment</th>
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<tr>
<td>Hadron</td>
<td>Beam quarks target antiquarks</td>
<td>Fermilab, J-PARC RHIC (forward acpt.)</td>
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<tr>
<td>Anti-Hadron</td>
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<td>J-PARC, GSI-FAIR Fermilab Collider</td>
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<tr>
<td>Meson</td>
<td>Beam antiquarks Target quarks</td>
<td>COMPASS, J-PARC</td>
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Drell-Yan Cross Section—Sensitivity to Sea Quarks

Cross Section
- Point-like scattering of spin-1/2 particles
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u-quark dominance
\((2/3)^2\) vs. \((1/3)^2\)

Acceptance limited
(Fixed Target, Hadron Beam)

\[
\frac{\sigma_{pd}}{2\sigma_{pp}} = \frac{1}{2} \left[ 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right]
\]

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1 June 2018
Drell-Yan Cross Section—Next-to-leading order $\alpha_s$

- Responsible for up to 50% of the cross section
SeaQuest Experiment

Main Injector 120 GeV

Tevatron 800 GeV

Fixed Target Beam
E906/SeaQuest Status

- Data with $^1$H, $^2$H, C, Fe and W targets
- Acceptance from below $J/\psi$ to $\approx 8$ GeV
- Completed data recording summer 2017
- Recorded $1.8 \times 10^{18}$ “live” protons on target
  - 1/3 of requested integrated luminosity

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Solid Iron
Focusing Magnet, Hadron absorber and beam dump

4.9m
Mom. Meas. (KTeV Magnet)

Station 1:
Hodoscope array MWPC tracking

Station 2 and 3:
Hodoscope array Drift Chamber tracking

Liquid $H_2$, $d_2$, and solid targets (Fe, C, W)

25m

Hadron Absorber (Iron Wall)

Station 4:
Hodoscope array Prop tube tracking

Drawing: T. O’Connor and K. Bailey

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21 June 2016
Data From FY2014—target-dump separation

- Entire beam interacts upstream of first SeaQuest Spectrometer tracking chamber
- Spatial resolution poor along beam axis
- Resolve target vs beam dump

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![Data From FY2014—target-dump separation](image)
Monte Carlo describe data well

Resolution better than expected

- $\sigma_M(J/\psi) \sim 180$ MeV
- $\sigma_M(D-Y) \sim 220$ MeV

- $J/\psi - \psi'$ separation
- Lower $J/\psi$ mass cut (more Drell-Yan events)

On going work

- Previous optimization valued CPU time
- Reconstruction efficiency
  - Spectrometer Rate Dependence
  - Background subtraction
SeaQuest Cross Section Ratio

- Low-x overlap region consistency?
- There is a kinematic difference between SeaQuest and E866
  - $x_{1}^{SQ} > x_{1}^{E866}$
- LO calculations still slightly low

$3.5 \times 10^{17}$ live protons, 20% of final data set

Preliminary
Iteratively ask, “What ratio of $\bar{d}/\bar{u}$ is needed to reproduce the observed cross section ratio.

Caveats:
- Leading order only—so far
- Correct method -> global fit
- Large $x_{\text{beam}} \bar{d}/\bar{u}$
- . . .

Low-x overlap region consistency?

SeaQuest Leading Order $\bar{d}/\bar{u}$

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3.5 x 10^{17} live protons, 20% of final data set

Paul E Reimer,
21 June 2016
SeaQuest E906 Status

Plot based on first $0.3 \times 10^{18}$ protons
SeaQuest has recorded $1.8 \times 10^{18}$ protons
Acceptance improvements so later protons are “worth” more

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Fermilab E772 Data

- No clear EMC effect
- No evidence for nuclear pion enhancement

SeaQuest Seaquark EMC Effect

Parton distributions in nuclei are different than in nucleons!!

- No antiquark enhancement apparent.
- 10% of anticipated statistical precision
- Increased detector acceptance at large-x to come.
SeaQuest Seaquark EMC Effect

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E-1039: Correlation between unpolarized quarks and nucleon transverse polarization

Do sea quarks have orbital angular momentum?
– Non-zero Sivers distribution ⇒ non-zero quark orbital momentum:

\[ f_{1T} = \frac{1}{2} \]

Requires Transversely polarized target

Status
– Funding from DOE/Nuclear Physics with support from HEP
– Installation beginning!!
– Commissioning fall 2018
– Production data FY19-20.
Projected Statistical Precision with a Polarized Target

Drell-Yan Target Single-Spin Asymmetry

$pp^\uparrow \rightarrow \mu^+\mu^-X$, $4 < M_{\mu\mu} < 9$ GeV

Statistics precision shown for two calendar years of running:

Protons on target = $2.7 \times 10^{18}$
$L = 7.2 \times 10^{42}$/cm$^2$

$A_N$

$X_{\text{target}}$

Sun and Yuan, 2013
Anselmino et al. 2009
**Take Away Thoughts**

**The Proton’s Sea is Turbulent**

- Drell-Yan can select sea quark distributions
- SeaQuest extends the reach of previous sea quark measurements to larger $x_{Bj}$
  - Preliminary results indicate
  - 5x more data recorded

- Sea quarks show no sign of the EMC effect

- Drell-Yan Sivers Function and sea quark orbital angular momentum will be probed with polarized target
  $$f_{1T} =$$