SeaQuest Experiment at Fermilab

Spinfest 2015

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23rd July, 2015
1. Introduction
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Structure of the Proton

- The quarks in the proton exchange gluons.
- Anti-quarks are created by gluon splitting.

\[ g \rightarrow u + \bar{u}, \quad g \rightarrow d + \bar{d} \]

- The amount of \( \bar{d} \) in the proton has been thought to be the same as that of \( \bar{u} \) since the masses of \( d \) and \( u \) are almost the same.

\[ \bar{d} = \bar{u} \]

▶ “Flavor Symmetry”
Gottfried Sum

- Gottfried sum is the first experimental approach to test flavor symmetry.

\[ S_G \equiv \int_0^1 \frac{dx}{x} [F_2^p(x) - F_2^n(x)] = \frac{1}{3} + \frac{1}{3}(\bar{u}_p - \bar{d}_p) \]

\( F_2^p(x), F_2^n(x) \): structure functions of proton and neutron, respectively

- Assuming that parton distribution functions in neutron and proton have flavor symmetry:

\[ u_p(x) = d_n(x), \quad d_p(x) = u_n(x), \quad \bar{u}_p(x) = \bar{d}_n(x), \quad \bar{d}_p(x) = \bar{u}_n(x) \]

- If \( \bar{d} \) and \( \bar{u} \) in proton are symmetric, Gottfried Sum is 1/3.

- NMC experiment at CERN (1990)

\[ S_G = 0.235 \pm 0.026 < 1/3 \]

\[ \rightarrow \bar{d} \neq \bar{u} \]

Discovery of “Flavor Asymmetry”
dependence of Flavor Asymmetry

E866 experiment at Fermilab measured Bjorken $x$ dependence of $\bar{d}/\bar{u}$.

$(0.015 < x < 0.35)$

- The first measurement of $x$
dependence of flavor asymmetry.

- 70% asymmetry at maximum has been measured at $x \sim 0.2$.
  - Some theories are proposed for explaining this result (discuss one of them later).
  - They can reproduce this shape of asymmetry.

- $\bar{d} < \bar{u}$ at $x \sim 0.3$?
  - No theory can explain it.
  - Statistical errors are very large.
  - More accurate measurement is needed.
Meson Cloud Model

Meson Cloud Model can reproduce the flavor asymmetry best at present.

- A proton wave function contains virtual meson wave functions.
  \[ |p\rangle = |p_0\rangle + \alpha |n\pi^+\rangle + \beta |\Delta^{++}\pi^-\rangle + \cdots \]
  - \( p \rightarrow n + \pi^+ \): \( \pi^+ \) includes \( \bar{d} \).
  - \( p \rightarrow \Delta^{++} + \pi^- \): \( \pi^- \) includes \( \bar{u} \).
    - Probability of \( p \rightarrow n + \pi^+ \) is higher than that of \( p \rightarrow \Delta^{++} + \pi^- \).
    - It leads to \( \bar{d} > \bar{u} \).

- SeaQuest experiment will provide the new data points.
  - It will be helpful for understanding the theory of proton structure.
2. SeaQuest Experiment
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- SeaQuest is a Drell–Yan experiment at Fermi National Accelerator Laboratory (Fermilab).
- Collaboration: Japan, USA, Taiwan
- 120 GeV proton beam extracted from Main Injector is used.
- SeaQuest measures $\bar{d}/\bar{u}$ in the region $0.1 < x < 0.45$ by Drell–Yan Process.
  - Only one experiment which measures $\bar{d}/\bar{u}$ at large Bjorken $x$. 

![Image of SeaQuest and Main Injector](image-url)
Drell–Yan Process

- Drell–Yan process can directly access anti-quarks in the proton.
  - \( q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^- \)

- SeaQuest uses proton-proton and proton-deuteron Drell–Yan process.

\[
\frac{d^2\sigma}{dx_t dx_b} = \frac{4\pi\alpha^2}{9x_t x_b} \frac{1}{s} \sum e^2 [\bar{q}_t(x_t) q_b(x_b) + \bar{q}_b(x_b) q_t(x_t)]
\]

- \( x_t \ll x_b \) in SeaQuest acceptance.
- \( \bar{q}_b(x_b) q_t(x_t) \) can be ignored.
- Cross-section ratio provides \( \bar{d}/\bar{u} \):
  \[
  \frac{1}{2} \left. \frac{\sigma^{pd\rightarrow \mu^+\mu^-}}{\sigma^{pp\rightarrow \mu^+\mu^-}} \right|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]
  \]
Goal

Clarify the behavior of $\bar{d}/\bar{u}$ at large Bjorken $x$.

- Red points show the expected statistical errors of all the data of SeaQuest.
  (Magnitudes are set to 1.)
- SeaQuest will obtain $\times 50$ more statistics than E866 experiment.
  
  - Beam energy: 800 GeV (E866) $\rightarrow$ 120 GeV (SeaQuest)
    - $\sigma_{DY} \propto 1/s \cdots \times 7$ signals
    - $\sigma_{J/\psi} \propto s \cdots \times 1/7$ main backgrounds
First long run of data taking was done (Run 2).
  - Data analyzed and shown in this presentation are taken in Run 2.

Integrated number of protons:
\[ \sim 0.8 \times 10^{18} \]
It is \( \sim 20\% \) of final number of protons.

SeaQuest will take \( 3.8 \times 10^{18} \) protons by July 2016.
3. Experimental Setup
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Proton Beam

- Beam energy: 120 GeV
  - Center of mass energy $\sqrt{s} = 15$ GeV
- 5 seconds of the beam is provided every 60 seconds.
  - The other 55 seconds of the beam is used for a neutrino experiment at Fermilab.

Beam bunch

- Frequency: 53 MHz (comes every 19 ns)
- One bunch contains 40k protons on average.
- Duty Factor (indicates stability of beam intensity $I$) $\equiv \langle I \rangle^2 / \langle I^2 \rangle$: 30% in Run 2 $\rightarrow$ 45% in Run 3
Measures momenta of dimuons from Drell–Yan process.

- **Targets:** proton, deuteron, carbon, iron and tungsten
- **Four Tracking “Stations”**
  - Hodoscopes for Trigger.
  - Drift Chambers or Proportional Tubes for Tracking.
- **Two Dipole Magnets**
  - Focuses the muons and dumps the beam (1st magnet).
  - Determines muon momenta (2nd magnet).
“Trigger Road”
- A rough decision on the Drell–Yan muons pass.
- It is determined by Hodoscopes of St. 1, 2, 3 and 4.
  ex. \( (H_1, H_2, H_3, H_4) = (13, 13, 15, 15) \) ··· each number is paddle ID

“Trigger Road Set”
- A set of trigger roads enabled in trigger decision.

Dimuon Trigger
- At least one accepted positive muon and one accepted negative muon are required.
- Drell–Yan rate (mass \( \geq 4 \text{ GeV}/c^2 \)): a few Hz
- Random coincidence is dominant: \( \sim 1 \text{ kHz} \)
4. Analysis and Results
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Dimuon Mass

- Data set: approximately 5% of final data set are analyzed
  - July 25th - Sept. 3rd, 2014
- The distribution shapes of Drell–Yan, $J/\psi$ and $\psi'$ events were estimated with simulation.
- Shape of random backgrounds was estimated using real data.
- Experimental data were reasonably well fitted.
  - Detectors and tracking tools work as expected.
- Drell–Yan events are dominant at mass $\geq 4.2$ GeV
Cross-section Ratio

Cross-section Ratio Preview

Cross-section ratio of $\sigma^{pd}$ and $\sigma^{pp}$

- dimuon mass $\geq 4.2$ GeV
- The result of cross-section ratio is consistent with the E866 result at small $x$.
- Systematic error is being investigated and reduced.
  - Main cause of this is beam intensity dependence.
Flavor Asymmetry Preview

- $\bar{d}/\bar{u}$ is derived from cross-section ratio using the formula:
  
  $$\frac{1}{2} \frac{\sigma^{pd}}{\sigma^{pp}} \bigg|_{x_b \gg x_t} \approx \frac{1}{2} \left[ 1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)} \right]$$

- Systematic error of $\bar{d}/\bar{u}$ is still large but is being investigated and reduced.

- The results of $\bar{d}/\bar{u}$ are consistent with the E866 results at small Bjorken $x$.

- We need more statistics to clarify the behavior at large Bjorken $x$.
  - 20 times more data will be used finally.
  - Data taking and quality assurance of the data are in progress.
5. Summary

- Bjorken $x$ dependence of flavor asymmetry of anti-quark is important to understand the structure of the proton.
- SeaQuest measures flavor asymmetry of anti-quarks in the proton at large $x$ ($0.1 < x < 0.45$).
- 20% of final number of protons have already been taken.
- 5% of final data set were analyzed.
- Dimuon mass was reconstructed well.
  - Detectors and tracking tools work as expected.
- Cross-section ratio is consistent with that of E866 at small $x$.
  - Systematic error is large because of beam intensity dependence of cross-section ratio.
  - We are investigating it and reducing the systematic error.
- Flavor asymmetry is consistent with that of E866 at small $x$.
  - In order to clarify the behavior at large $x$, we need more data. It is in progress.