The Seaquest Experiment

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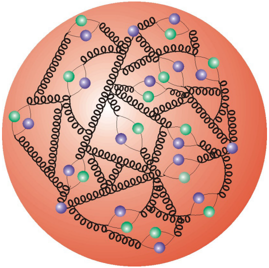
The Proton

- Discovered by Rutherford in his gold foil experiment
- Thought to be fundamental particle for a long time.
- Now understood to be a far more complicated object.
- There are many gaps in our understanding of the Proton's structure, and the SeaQuest experiment is aiming to better understand two of them: the EMC effect and quark flavor asymmetry.



Source: physics.stackexchange.org

Constituent Quark Model

- Anomalous Magnetic moment: $\mu = 5.58\mu_B$. Implies that the proton is a consituent particle.
- Color charge: Δ^{++} Baryon is *uuu* and spin $\frac{3}{2}$ which makes it totally symmetric. This means that there must be an $SU(3)$ symmetry to make it overall antisymmetric.
- This symmetry is assigned to the "Color Charge" and is described in Quantum Chromodynamics
- In low energy experiments, the proton is treated as being made of the three quarks *uud* and nothing else.
- At high energies, this model breaks down, as there scattered particle interacts with individual quarks.

Formalism - Particle Scattering

- Quantum Field Theory treats scattering as if a "virtual" particle was exchanged. (Could be γ, g, W, Z, etc)
- 4-vectors for scattered particle are k,k, and virtual particle is $q = k' - k$.
- $Q^2 = q_\mu q^\mu > 0$. Momentum transfer: If $E, E' >> m_l$, then $Q^2 \approx 4EE' \sin^2(\theta/2)$.
- $\nu = E - E'$ is the energy loss of the lepton.
- $y = \nu/E$ is the energy fraction.
- W^2 is the squared mass of the recoiling system

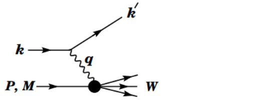


Figure 16.1: Kinematic quantities for the description of deep inelastic scattering. The quantities k and k' are the four-momenta of the incoming and outgoing leptons, P is the four-momentum of a nucleon with mass M, and W is the mass of the recoiling system X. The exchanged particle is a γ, $W^{\pm}$, or Z; it transfers four-momentum $q = k - k'$ to the nucleon.

Source: Particle Data Group, LBL

Types of Scattering: Coulomb Scattering

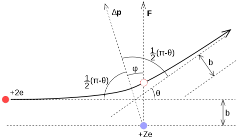
- At low energies, dominant scattering mode is the electromagnetic potential.
- The Scattering cross section is given by Rutherford's Formula:

$$\frac{d\sigma}{d\Omega} = (\frac{Z_1 Z_2 e^2}{4\pi\epsilon_0 E \sin^2\theta/2})^2 \quad (1)$$

- At this scale, nothing about the structure of the proton can be seen.

- Spin-1/2 Electron: Use Mott scattering:

$$\frac{d\sigma}{d\Omega} = (\frac{Z_1 Z_2 e^2 \cos\theta/2}{4\pi\epsilon_0 E \sin^2\theta/2})^2 \quad (2)$$



Source: wikipedia.org

Deep Inelastic Scattering

- First performed at SLAC in 1969
- Electron-Proton Scattering at 7-18 GeV
- Elastic Scattering predicts σ falls off as $\frac{1}{Q^2}$ compared to σ_{MOTT}, but SLAC observed almost no dependence on Q^2.
- Concluded that it must be scattering(incoherently) from point particles.
- At high energies(> 1GeV), particles may scatter with the quarks themselves.
- At high enough energies, the proton itself may be completely destroyed afterwards.

Formalism - Bjorken "x" Parameter

- If a parton(quark or gluon) carries some fraction x of the nucleon's 4-momentum, then the inelastic part of the scattering scales with the parameter

$$x = \frac{Q^2}{2M_p\nu} \tag{3}$$

- This is the "Bjorken x parameter" named after Bjorken.
- Used to parameterize a variety of form factors for nucleons, due to weak dependence on Q^2 for inelastic processes.

James Bjorken
Source: fnal.gov

Formalism - Parton Distribution Function

- Using the x parameter, we can identify the structure of the partons using parton distribution functions (pdfs).
- Each flavor of quark gets its own pdf.
- Each pdf $q(x)$ describes the number density of quarks of flavor q at momentum fraction x.

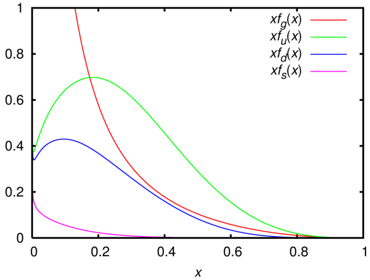


Figure: CTEQ Parton Distribution Functions

Form Factors and Structure Functions

- "What is the distribution of parameter X?"
- Can have form factors for spin, electric charge, etc.
- $F_2(x) = \sum_i e_i^2 x q_i(x)$ where $q_i(x)$ is the pdf for quark flavor i.
- $F(x)$ is essentially the Fourier transform of the electric charge distribution into x-space.
- So it's essentially the momentum distribution within the nucleon.

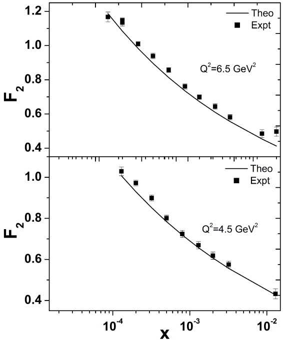


Figure: HERA structure functions arXiv:1409.0397 [hep-ph]

The Parton Model

- DIS Studies of F_2 at low x show more structure than expected.
- Conclusion: In addition to the valence quarks and gluons, there are lots and lots of "sea quarks," $q\bar{q}$ pairs residing at low x.
- These quarks pop into and out of existence rapidly, and can only be seen with high energy(= penetrate deep into the nucleon) collisions.

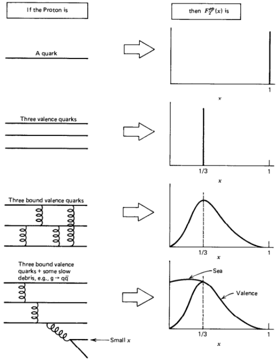


Fig. 9.7 The structure function pictured corresponding to different compositions assumed for the proton.

Source: Halzen and Martin, p. 201

Proton Spin Crisis

- Parton model leads to more questions
- Only <1/3 of the spin of the proton is due to the quarks according to work by the European Muon Collaboration
- EMC (1987): "total quark spin constitutes a rather small fraction of the spin on the nucleon."[1]
- $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g \tag{4}$$
- RHIC is currently probing spin structure of proton to figure out gluon polarization.

EMC Effect

- EMC shot muons at d and Fe Targets in 1983.
- Measured the $F_2(x)$ for the proton in each nucleus.
- Found that the $F_2^{FE}(x)/F_2^d(x)$ decreases with x.
- As F_2 is the FT of charge distribution, this implies that nucleons are LARGER in Fe!

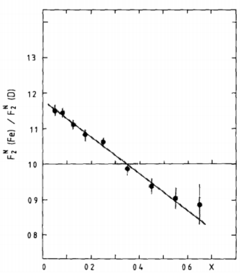


Figure: EMC Effect [2]

Further EMC effect work

EMC effect was later studied in low x region, where "shadowing" was discovered"

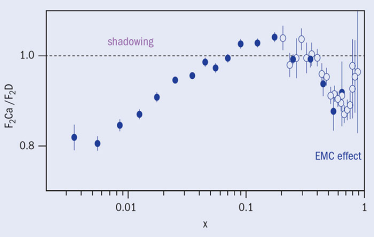


Figure: EMC effect in Calcium. Open circles: SLAC, closed: NMC Source: CERN

Quark Flavor Asymmetry

- New Muon Collaboration was an upgrade to the EMC that once again performed Deep Inelastic Scattering but at 90 GeV and 280 GeV at H and D.
- Their 1991 results conflicted with theory, either abandon $n - p$ charge symmetery, or abandon quark flavor symmetry.
- Charge symmetry violations not discovered, so $\int [\bar{d}(x) - \bar{u}(x)] dx = .148 \pm .039$ [3].
- This is weird, and sparked off a lot of theoretical discussion of why that would be. Ex: Pauli Blocking, Instanton Model, Meson Cloud, Hybrid Model, Chiral Quark,...

Drell-Yan Processes

- Leading order process: quark from beam proton annihilated sea antiquark, produces $l\bar{l}$ pair.
- Lepton's won't interact as strongly as the quarks, so DY is a good probe of sea quarks.
- Proton and Deuteron cross section ratio [4]:

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}(1 + \frac{\bar{d}(x)}{\bar{u}(x)}) \quad (5)$$

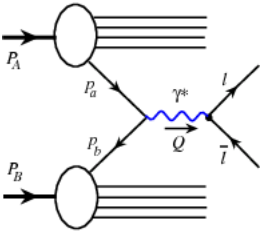


Figure: Drell-Yan Process

Why Drell-Yan?

- Parton motion through hot nuclear matter is well studied(eg. at the LHC)
- Less is known about cold nuclear matter
- Products of DY are leptons, so less energy loss as they exit the nucleon.
- Fixed targets simplify math and allow study of the target in isolation.

E-866/NuSea

- 800 GeV/c Proton Beam on Hydrogen and Deuterium Targets at Fermilab
- Drell-Yan Process, measured 2μ flux with magnetic mass spectrometer.
- Measured at $.015 < x < .35$
- Nothing in theory explains the < 1 ratio at larger x.

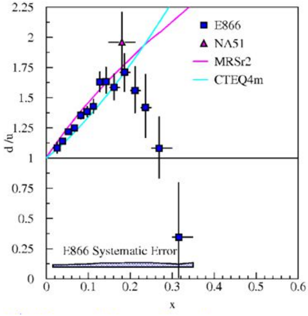


Figure: Flavor Asymmetry

Fermilab E-772

- E-772 was another Drell-Yan experiment done at Fermilab, which looked at the structure functions in different nuclei
- It had inconclusive results, so EMC effect so far has not been observed for Drell-Yan/ Sea quark experiments.

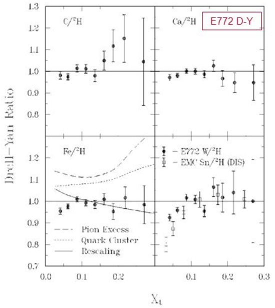


Figure: E-772 Data showing no EMC effect in Drell-Yan Experiments

E-906/Seaquest Proposal

- Want to measure flavor asymmetry at high x. $(.1 < x < .45)$.
- Major Changes: Lower energy beam (120 GeV)$\rightarrow$ 7x DY σ.
- J/Ψ production leads to single μ decays. Lower energy beam has 7x less single muon rate.
- Put together: 50x higher statistics than NuSea.

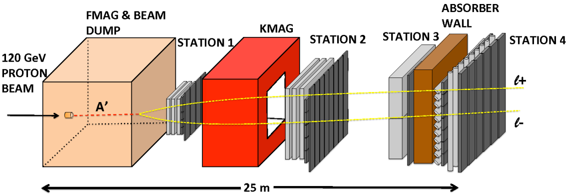


Figure: Seaquest Spectrometer

Targets

- For EMC effect, several targets are used.
- LH_2, LD_2, Fe, C, W, Empty Flask, and Empty Position
- Flasks for LH_2 and LD_2 correspond to $7-15\%$ of the interaction length (20"). Made of Steel, with Ti window for beam to go through.
- Arranged on a rotating table that can change targets in $30s$.

Beam Properties

- Seaquest receives 5 seconds of every minute of Fermilab's beam, called a "spill"
- Fermilab Main Injector: beam broken into 6 "trains"
- Each "train" has 83 "buckets," 1-2 ns in length that arrive at 53 MHz (every 18.9 ns).
- Each "bucket" has 4×10^4 120 GeV/c protons[5].

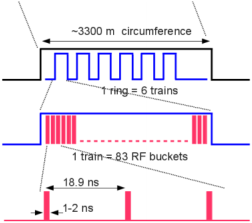


Figure 4.3: The beam structure of the Main Injector proton beam. Protons are erated to 8 GeV at the Booster. The protons are then injected from the Booster Main Injector. The Main Injector typically holds six Booster injections (trains), an train holds 83 RF buckets. The protons are accelerated to 120 GeV in the Main In and then sent to the experimental hall by the slow extraction system. The protons in 1-2 ns-long RF bucket spaced by 18.9 ns at the SeaQuest experimental hall.

Figure: Fermilab Main Injector [5]

Cherenkov Veto

- A secondary emission chamber and ion chamber monitor beam intensity over the course of a spill.
- Bucket level analysis -¿ need faster counter
- Beam produces Cherenkov light in Ar/CO_2 mixture
- Counted with a photomultiplier tuber (PMT).

Early Seaquest Results

No EMC effect observed in the Sea Quarks so far[6]

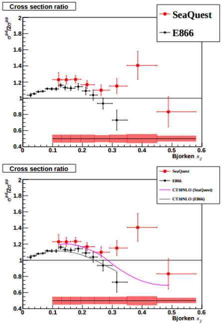


Figure 6.1: Cross section ratio as a function of Bjorken x. The SeaQuest result is plotted in red and the E866 result is plotted in black. The error bars represent the statistical uncertainty, and the error band at the bottom represent the systematic uncertainty. The position of the error band was arbitrary chosen. The systematic uncertainty of E866 is less than 1% and is not shown. In the bottom figure, also the predictions calculated with CT10NLO PDF parameterizations for SeaQuest (magenta line) and E866 (gray line) are drawn.

Figure: Run II and III Seaquest Results [5]

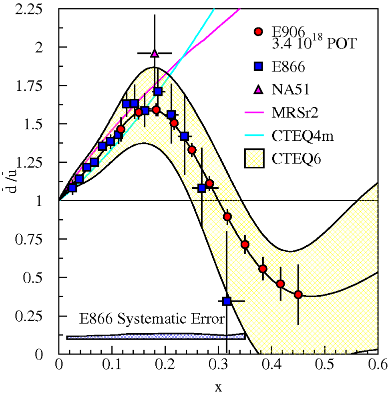


Figure: Expected Seaquest Results

Dark Sector Probe

- "Dark Sector" is a family of particles that don't couple to the four fundamental forces.
- SQ may produce dark photons in the iron target [7].
- Dark photons go straight through the magnetic field before decaying (with some probability for dimuons).
- Can anaylze the kinematics to search for peaks in intensity from this "displaced vertex."

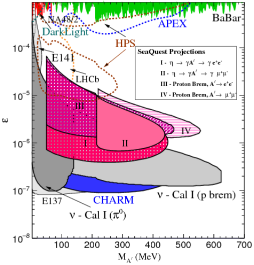


Figure: Parameter Search space for the coupling ϵ between SM and DS

Future Goals for Seaquest

- Seaquest ran run V in 2016 and expects results out later this year.
- Future Fermilab Drell-Yan experiments will look into spin-polarization of Sea Quarks.
- E-1027 is polarized beam, E-1039 is polarized targets.

Summary

- There are a number of unexplained features of the Proton structure
- The proton seems to have a volume that depends on the nucleus its in (EMC effect)
- The sea quarks within the proton exhibit flavor asymmetry
- Seaquest builds on previous experiments to explore a larger parameter space for quantifying these asymetries.
- Seaquest has had two Physics runs, and is still taking data

References I

[1] J. Ashman, et al., [European Muon Collaboration], A Measurement of the Spin Asymmetry and Determination of the Structure Function g(1) in Deep Inelastic Muon-Proton Scattering, Phys. Lett. B206 364, 1988

[2] J.J. Aubert et al., The ratio of the nucleon structure functions F2N for iron and deuterium, Phys. Lett. 123B, 275 (1983)

[3] The New Muon Collaboration, P. Amaudruz eZ nZ., Phys. Rev. Lett. 66, 2712 (1991); M. Arneodo eZ nZ., Phys. Rev. D 50, R1 (1994)

[4] R. Towell,"MEASUREMENT OF THE ANTIQUARK FLAVOR ASYMMETRY IN THE NUCLEON SEA," , Thesis, University of Texas,1999

[5] Shou Miyasaka, "Probing Flavor Asymmetry of Anti-quarks in the Proton by Drell-Yan Experiment SeaQuest," Thesis, Tokyo Institute of Technology, 2016

References II

[6] Michelle M. Medeiros, "The Seaquest Experiment," Talk given at 2016 Fermilab Users Meeting, June 15 2016.

[7] arXiv:1509.00050v2 [hep-ph]