JLab measurement of the ratio of the nucleon structure functions, $F_2^n/F_2^p$, from electron DIS off $^3$H and $^3$He at large Bjorken $x$ (MARATHON Experiment) *

Tong Su
Kent State University

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Deep Inelastic Scattering and Quark Parton Model

- Deep Inelastic Scattering:

\[
\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4(\theta/2)} \left[ \frac{F_2(\nu, Q^2)}{\nu} \cos^2(\theta/2) + \frac{2F_1(\nu, Q^2)}{M} \sin^2(\theta/2) \right]
\]

\[
R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 M}{F_1 \nu} \left( 1 + \frac{\nu^2}{Q^2} \right) - 1
\]

\[
\nu = E - E'
\]

\[
Q^2 = 4EE' \sin^2(\theta/2)
\]

- Quark-Parton Model (QPM) interpretation in terms of quark probability distributions \( q_i(x) \) (large \( Q^2 \) and \( \nu \)):

\[
F_1(x) = \frac{1}{2} \Sigma e_i^2 q_i(x) \quad F_2(x) = x_i \Sigma e_i^2 q_i(x)
\]

- Bjorken \( x \): fraction of nucleon momentum carried by struck quark:

\[
x = \frac{Q^2}{2M \nu}
\]
\[ \frac{F_2^n}{F_2^p} \text{ and } d/u \]

- Assume isospin symmetry

\[
\begin{align*}
  u^p(x) &= d^n(x) \equiv u(x) & \bar{u}^p(x) &= \bar{d}^n(x) \equiv \bar{u}(x) \\
  u^n(x) &= d^p(x) \equiv d(x) & \bar{d}^p(x) &= \bar{u}^n(x) \equiv \bar{d}(x) \\
  s^n(x) &= s^p(x) \equiv s(x) & \bar{s}^p(x) &= \bar{s}^n(x) \equiv \bar{s}(x)
\end{align*}
\]

- Proton and neutron structure functions:

\[
\begin{align*}
  F_2^p &= x \left[ \frac{4}{9}(u + \bar{u}) + \frac{1}{9}(d + \bar{d}) + \frac{1}{9}(s + \bar{s}) \right] \\
  F_2^n &= x \left[ \frac{4}{9}(d + \bar{d}) + \frac{1}{9}(u + \bar{u}) + \frac{1}{9}(s + \bar{s}) \right]
\end{align*}
\]

- Nachtmann inequality

\[ 1/4 \leq \frac{F_2^n}{F_2^p} \leq 4 \]
Early SLAC data

- SLAC, End Station A
- SLAC Measurements, End Station A, 1968-1972
- $F_{2n}^n/F_{2p}^p$ extracted from proton and deuterium deep inelastic data using Hamada-Johnston potential in a Fermi-smearing model.
SLAC/CERN Data Interpretation in QPM

- Nachtmann inequality satisfied
- For $x \rightarrow 0 : F_2^n/F_2^p \rightarrow 1$: Sea quarks dominate with:
  
  $$u + \bar{u} = d + \bar{d} = s + \bar{s}$$

- For $x \rightarrow 1 : F_2^n/F_2^p \rightarrow 1/4$: High momentum parton in proton (neutron) are up (down) quarks, and:
  
  $$s + \bar{s} = 0$$

- For medium and high $x$, safe to assume that (with $d$ and $u$ denoting now quark plus antiquark distributions):
  
  $$\frac{F_2^n}{F_2^p} = \frac{[1 + 4(d/u)]}{[4 + (d/u)]}$$
Half a century later

- $F_2^p$ has been precisely measured

- $F_2^n$ not well known at large $x$
- Data inconclusive due to uncertainties in deuterium nuclear corrections
$F_2^n$ uncertains translates directly to uncertainty on $d/u$, $d(x)$…

- A. Accardi, L.T. Brady, W. Melnitchouk, J.F. Owens, N. Sato

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$F_2^n/F_2^p$ from Theory

$F_2^n/F_2^p$, $d/u$ ratios and $A_1$ for $x \to 1$

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<th>$A_1^n$</th>
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Extract $F_2^n / F_2^p$ from A=3 nuclei

- Instead of dealing with the nuclear correction in deuterium, MARATHON proposed a new way to extract $F_2^n / F_2^p$ from Tritium and Helium-3 DIS data by taking advantage of the mirror symmetry of the A=3 nuclei.

- Define the EMC type ratio:

$$R_{3H} = \frac{F_2^{3H}}{2F_2^n + F_2^p} \quad R_{3He} = \frac{F_2^{3He}}{F_2^n + 2F_2^p}$$

- Super Ratio:

$$\mathcal{R} = \frac{R_{3He}}{R_{3H}}$$

- Solve for the nucleon $F_2$ ratio and calculate $R^*$ (expected to be very close to unity) using a theory model:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{3He} / F_2^{3H}}{2(F_2^{3He} / F_2^{3H}) - \mathcal{R}}$$
The JLab MARATHON Experiment

- MARATHON took data in the period January-April, 2018 at Jefferson Lab.
- It used the 2 High Resolution Spectrometers (HRS) of Hall A and a cryogenic high pressure gas target system of 3H, 3He, 2H, and 1H (25 cm long cells of 1.25 cm diameter).
- It used a 10.6 GeV electron beam with 20 μA beam current.
- The electron scattering angle varied between 17 and 36 deg.
- The scattered electron momentum was fixed at 3.1 GeV/c for the Left-HRS and at 2.9 GeV/c for the Right-HRS.
**MARATHON $^2\text{H}/^1\text{H}$ DIS Calibration Data**

- MARATHON measured the ratio of d/p DIS yield at low Bjorken $x$ values with *high precision*. The *accuracy* of the d/p results is essentially dominated by the gas target uncertainties.

- The d/p ratio data, are in excellent *agreement* with the SLAC benchmark data, taken at *similar kinematics*, by the SLAC/MIT Nobel prize winning group, with the 8 GeV/$c$ Spectrometer.

- The MARATHON $F_2^n/F_2^p$ calibration values have been determined from the $^1\text{H}$ and $^2\text{H}$ data using the standard formula $F_2^n/F_2^p = [(F_2^d/F_2^p)/R^*] - 1$, where $R^*$ is the deuteron EMC-type ratio $R^* = F_2^d / [F_2^p + F_2^n]$, calculated from a theoretical model by S. Kulagin and R. Petti, which is, at low $x$, in very good agreement with data extracted from the JLab BoNuS experiment.

- The d/p $F_2^n/F_2^p$ values in the vicinity of $x=0.3$ have been used to normalize the $F_2^n/F_2^p$ obtained from the $^3\text{H}/^3\text{He}$ ratio data.
d/p DIS cross section ratio ($W^2 > 4 \text{ GeV}^2$)

MARATHON (preliminary) vs SLAC Bodek et al.

Error bars contain statistical, random ptp, and scale errors added in quadrature.
Circles: JLab Hall B BoNuS Experiment

Curve: S. Kulagin and R. Petti (MARATHON Kinematics, 2018)
MARATHON vs SLAC/Bodek et al.

MARATHON Using Kulagin-Petti Model (10.6 GeV)

SLAC/Bodek et al. Using Kulagin-Petti Model (10.4 GeV)

PRELIMINARY
MARATHON $^3\text{H}/^3\text{He}$ DIS Data

- The super-ratio $R^*$ model for $^3\text{H}$ and $^3\text{He}$ that was used (among several available models) was developed, for the actual MARATHON kinematics, by Kulagin and Petti in the summer of 2018, using the $A=3$ spectral functions by the Rome group (E. Pace, G. Salmè et al.).

- $F^n_2/F_2^p$ as calculated from the measured $^3\text{H}/^3\text{He}$ ratio was compared to $F^n_2/F_2^p$ as calculated from the measured d/p MARATHON ratio. In order to match the values of the two measurements in the vicinity of $x=0.3$, the $^3\text{H}/^3\text{He}$ ratio must be scaled down (normalized) by 2.8%.

- Note that the MARATHON measured values and the Kulagin-Petti $F^n_2/F_2^p$ predicted values are in excellent agreement!
The $R(3\text{He})$ and $R(3\text{H})$ Ratios

Red: $R(3\text{He}) = \frac{F_2^{3\text{He}}}{2F_2^p + F_2^n}$
Green: $R(3\text{H}) = \frac{F_2^{3\text{H}}}{F_2^n + 2F_2^p}$
Blue: $R^* = R(3\text{He})/R(3\text{H})$

A=$3$ Spectral Functions by Rome Group (G. Sialmè et al.)
Tritium to Helium DIS Cross Section Ratio

- JLab MARATHON (No Normalization)
- JLab MARATHON Normalized by 2.8\% \(\downarrow\)
- Kulagin-Petti Model Using Rome A=3 Spectral Functions

\( \frac{^3\text{H}}{^3\text{He}} \) vs. Bjorken \( x \)

PRELIMINARY
Summary

- The MARATHON d/p DIS measurements agree very well with the seminal SLAC Bodek *et al.* measurements and provide an excellent normalization for the 3H/3He DIS data.
- MARATHON has provided high quality $F_2^n/F_2^p$ data at medium and large values of Bjorken $x$ that are free of the deuteron structure uncertainties present in the SLAC data from d/p DIS.
- There is no need to iterate the $F_2^n/F_2^p$ extraction process, as the Kulagin and Petti input model agrees very well with the data!
- Next to be done is the extraction of LT (Leading Twist) $F_2^n/F_2^p$ in order to determine the $d/u$ ratio… Stay tuned …!
- Note: MARATHON has provided for the 1st time data for the EMC effect of $^3$H, and new large-$x$ and large-$W^2$ data for the EMC effect of $^3$He. The isoscalarity correction factor uses the MARATHON $F_2^n/F_2^p$ (following talks by M.Nycz and T.Hague).
The JLab MARATHON Tritium Collaboration


**More than 140 Collaborators**

**Red-Boldfaced Names:** Tritium Program grad students; **starred:** MARATHON Ph.D. students

**Blue-Boldfaced Names:** Tritium Program postdoctoral associates
Thanks

• Thanks to all fellow graduate students and postdocs for their hard work and dedication in preparing, running and analyzing the experiment.

• Thanks to the Accelerator and Hall A Scientific and Technical Staff of JLab, and the Lab Management for their outstanding support of the MARATHON project.

• Special thanks to Roy Holt and David Meekins for making a reality, for (only) the third time in the US, a tritium target for electronuclear physics.

• Special thanks to Doug Higinbotham for managing the Tritium Program.

• Thanks to all theory colleagues who embraced the experiment since its inception and contributed to the development of the proposal and to the analysis of the experimental data.
Thanks !