Structure Function Separations
and the Determination of Parton Spin

By Michael Riordan
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My Participation in Electron-Nucleon Scattering

- **1967–68**: Senior thesis with Jerry Friedman, analyzing results of SLAC Expt. 4A, elastic $e - p$ scattering, with grad student Paul Kirk.
- **1969–70**: Joined Friedman-Kendall group as first-year MIT grad student and worked on SLAC Expt. 49B, deep inelastic $e - p$ and $e - d$ scattering, using 8 GeV Spectrometer at 18°, 26° and 34°.
- **1970–73**: Analyzed E49B data at SLAC on IBM 360/91 computer and participated in follow-on SLAC Expt. 87 while writing Ph.D. dissertation on combined E49 results (adviser Jerry Friedman).
- **1973–75**: Worked as MIT postdoc with Arie, Jerry and Henry analyzing results of E87 and doing combined E49/E87 analysis.
- **1985–87**: Worked with Arie as Univ. of Rochester staff scientist on SLAC Expts. 139 and 140 (The “R Experiment”) while finishing manuscript for my 1987 book, *The Hunting of the Quark*. 
Two Cautionary Quotes on Quarks

• “The idea that mesons and baryons are made primarily of quarks is difficult to believe, since we know . . . that they are mostly, if not entirely, made up out of one another. The probability that a meson consists of a real quark pair rather than two mesons or a baryon and anti-baryon must be quite small.”
   — Murray Gell-Mann, Rochester Conference, Berkeley, 1966

• “If such quark particles existed, at least one of them would have to be stable. . . . A search for new particles of this type has so far proved unsuccessful. In view of this failure and the difficulty of inventing a mechanism which would bind a quark and an anti-quark, or three quarks, . . . we will not discuss the quark model further.”
Three Pivotal 1969 Papers


The 1990 Nobel Prize in physics for the experimental discovery of quarks was awarded based largely on the last two papers.
MIT-SLAC's "Marsden Moment"
Inelastic e–N Scattering Cross Sections

\[ \frac{d^2 \sigma}{d\Omega d\nu} = \sigma_{\text{Mott}} [W_2(\nu, q^2) + 2W_1(\nu, q^2)\tan^2(\theta/2)] \]

or, equivalently,

\[ \frac{d^2 \sigma}{d\Omega d\nu} = \Gamma_T [\sigma_T(\nu, q^2) + \varepsilon\sigma_L(\nu, q^2)] \]

where:

- energy transfer \( \nu = E - E' \)
- momentum transfer \( q^2 = 4EE'\sin^2(\theta/2) \)
- virtual-photon polarization \( \varepsilon = [1 + 2(1 + \nu^2/q^2)\tan^2(\theta/2)]^{-1} \)
- hadronic final-state mass \( W = [M^2 + 2M\nu - q^2]^{1/2} \)
- Bjorken scaling variable \( \omega = 2M\nu/q^2 = 1/x \) (Feynman)
\[ R = \sigma_L / \sigma_T = (W_2 / W_1)(1 + \nu^2 / q^2) - 1 \]

Callan-Gross (1969) current-algebra predictions:
- **spin-1/2:** \( \sigma_L = 0 \) \( \rightarrow \) \( R = 0 \) (in Bjorken limit)
- **spin-0:** \( \sigma_T = 0 \) \( \rightarrow \) \( R \) approaches infinity

Or, more generally, for finite \( \nu \) and \( q^2 \):
\[ R = a(x) + b(x)q^2 / \nu^2 \]

If pure spin-1/2 partons, \( a(x) = 0 \) and \( b(x) = 1 \), or
\[ R = q^2 / \nu^2 \]
8 GeV and 20 GeV Spectrometers
The 8 GeV Spectrometer

- able to roll out in minutes to much greater angles than the 20 GeV Spectrometer
- designed to measure elastic e-p scattering and enable structure-function separations
- its solid-angle acceptance $\Delta\Omega\Delta p$ remained unchanged at all scattering angles
- detectors discriminated electrons from background pions with high efficiency
- greater angles $\theta$ meant greater $q^2$, proportional to $\sin^2(\theta/2)$, but counting rates plummeted (prop. to $q^{-4}$)
E4B Separations of $\sigma_L$ and $\sigma_T$

Average value of $R = \sigma_L / \sigma_T = 0.18 \pm 0.10$

Consistent with $R = q^2 / \nu^2$ (spin-$\frac{1}{2}$)

G. Miller et al., Phys. Rev. D5 (1972) 528
Bjorken Scaling of $\nu W_2 = F_2(\omega)$

$W_2$ extracted from $d^2\sigma/d\Omega dv$ assuming $R = \sigma_L/\sigma_T = 0.18$
- scaling works better if $\nu W_2$ plotted versus $\omega' = 1 + W^2/q^2$

G. Miller et al., Phys. Rev. D5 (1972) 528
Scaling of $\nu W_2$ at $\omega = 4$

Using inelastic $e - p$ scattering cross sections at $6°, 10°, 18°, 26°$

$W_2$ again extracted from $d^2\sigma/d\Omega d\nu$ assuming $R = 0.18$
Second-Generation Experiments

• Measure inelastic e-p and e-d scattering cross-sections with much higher counting statistics
• What are the parton properties (charge and spin)?
• E49A: 6° and 10° by MIT and SLAC Group A, 1970
• E49B: 18°, 26° and 34° by MIT and SLAC SFG, 1970
• 1.5° and 4° by SLAC Group A, 1971
• E87: 15°, 19°, 26° and 34° by MIT and SLAC SFG, 1972 — measuring “threshold” behavior as x → 1
• 50° and 60° by SLAC Group A on 1.6 GeV Spectrometer
E49 Separated Values of $R_p = \sigma_L/\sigma_T$

Dashed line represents the Callan-Gross (spin-1/2) prediction that $R_p = q^2/\nu^2$. Good fit except at low $x$. 
E49B Average Values of $\Delta = R_d - R_p$

These data are everywhere consistent with $R_p = R_d = R_n$. 
As you know, I am very anxious to see the data on \( R \) . . .

I am only thinking the conventional thoughts, that the behavior of \( R \) versus \( \nu \) and \( x \) can tell us whether the charged partons of which protons are made are purely spin \( \frac{1}{2} \) (in which case the scaling law is that \( \nu R \) is a function solely of \( x \) . . .), or there are some scalar partons (in which case \( R \) itself should scale, \( R \) itself should be a function only of \( x \)).

We are all betting (hoping for simplicity) that there are no other charged partons than quarks, and that it is \( R' = (\nu^2/q^2)R \) which depends only on \( x \), not on \( \nu \) for large \( \nu \).
Thank you very much for your detailed description of R. I have no questions as the results were so completely described. It is still possible, I take it, that the spin $\frac{1}{2}$ parton view is correct (so $\nu R_p$ scales), but that for small $x$ the scaling law breaks down because $q^2$ is not large enough. Thus I can only expect scaling to work for $\nu R$ as long as $q^2$ is large. I am therefore trying to go along continuing to suppose all charged partons are $\frac{1}{2}$ integral, and the rise with $\nu$ from scaling at small $x$, large $\nu$, is due to a mixture of systematic or radiation errors there, and the fact that $q^2$ is not high enough.

I take it from your paper that $R = a/q^2$ with constant $a'$ fits the data fairly well.

Thank you very much for sending me your results.

Sincerely,

Richard P. Feynman
Scaling Fits to $\nu R_p$ versus $\nu$ or $q^2$

Extraction of $R = g_L / g_T$ from Deep Inelastic e-p and e-d Cross Sections

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The quantity $R = g_L / g_T$ is extracted for the proton, neutron, and neutrino from deep inelastic $e-p$ and $e-d$ scattering cross sections measured in recent experiments at Stanford Linear Accelerator Center. For $\omega < 5$ the kinematic behavior of $\nu R_p$ is consistent with scaling, indicative of spin-1/2 constituents in a parton model of the proton. We also find that within large statistical errors, $R_d$ and $K_n$ are consistent with being equal to $R_p$.

FIG. 1. Values of $\nu R_p$ plotted with their statistical errors versus $Q^2$ for fixed values of $\omega$. The solid lines represent least-square fits of the form $\nu R_p = a + b \nu = a + (\omega/2M) b Q^2$, and the dashed lines represent $R_p = Q^2/\nu^2$. 
Tests of Scaling of $\nu W_2$ and $W_1$

- based on E49A and E49B deep inelastic e-p scattering data on both the 20 GeV and 8 GeV Spectrometers
- normalization factor of 1.02 applied to E49A data before separating structure functions.
- no assumptions about $R_p$
- first suggestions of possible scaling violations


Fig. 1. Proton structure functions versus $Q^2$ for fixed $\omega$. The symbols $\cdot$ and $\square$ represent $W \geq 2.6$ GeV and 2.6 GeV data respectively. Only statistical errors are shown. Note that the scales have suppressed zeros.
Further Tests of Scaling of $\nu W_2$

- based on E49B and E87 inelastic e-p experiments on only the 8 GeV Spectrometer
- solid indications of the pattern of scaling violations required by QCD theories (Gross & Wilczek, Politzer, 1973)
Scaling Violations in $2MW_1$

- SLAC Experiment 89 using 1.6 GeV Spectrometer to detect deep inelastic electron scattering at 50° and 60°
- SLAC Group A experiment led by Stanford grad student Bill Atwood
- at such large angles, differential cross sections begin to be dominated by $W_1$
- clear evidence of scaling violations:
  “The observed breaking could . . . correspond to the logarithmic scale breaking expected in asymptotically free theories or theories with anomalous dimensions.”
Epilogue: The Mid-1980s

1990 Reunion in Stockholm

“The three prizewinners were the key persons in a research team which in a series of investigations found clear signs that there exists an inner structure in the protons and neutrons of the atomic nucleus.”

— Cecilia Jarlskog, Nobel Prize ceremony
Finally Back “in Print”!
Simon & Schuster, 1987  Plunkett Lake Press, 2018