Exploring the Structure of the Proton

Jerome I. Friedman
MIT
SLAC Starts Operation in 1966

- CIT-MIT-SLAC Collaboration designed and constructed spectrometer complex to study structure of proton, utilizing ELASTIC SCATTERING

- Electron ideal probe:
  - Structure known: “point particle”
  - Interaction understood: QED

In 1950’s, Hofstadter used Elastic e-p scattering to measure the proton’s form factor & r.m.s. radius
What were the models of the proton at that time?

• **Nuclear Democracy**  - Bootstrap Model
  – The S Matrix era - “Old Physics”

• **Quark Model of Gell-Mann & Zweig**
  – Quarks are the building blocks of the highly successful SU(3) classification scheme
“OLD PHYSICS”

NUCLEAR DEMOCRACY
BOOTSTRAP MODEL

Particles are composites of one another

\[ p = \pi^+ + n + \ldots \]
\[ n = \pi^- + p + \ldots \]

Particles have diffuse substructures and no elementary building blocks
**QUARK MODEL (1964)**

* 3 TYPES

**UP, DOWN, STRANGE**

* SPIN 1/2

* FRACTIONAL CHARGES

\( \text{up}(+2/3), \text{down}(-1/3), \text{strange}(-1/3) \)

\[ p = (u,u,d) \quad n = (d,d,u) \]
Are Quarks Real?

MANY UNSUCCESSFUL SEARCHES
- Accelerators, Cosmic rays, Terrestrial environment
  Sea water, Meteorites, Air, etc.

FRACTIONAL CHARGES
- Considered by many to be unreasonable

GENERAL POINT OF VIEW IN 1966
Quarks most likely just mathematical representations
Useful but NOT real!

Particles have diffuse substructures and no elementary building blocks
Implementation of Quark Model

“...the idea that mesons and baryons are made primarily of quarks is hard to believe.”
M. Gell-Mann 1966

“Additional data are necessary and very welcome to destroy the picture of elementary constituents.”
J. Bjorken 1967

“I think Professor Bjorken and I constructed the sum rules in the hope of destroying the quark model.”
K. Gottfried 1967

“Of course the whole quark idea is ill founded.”
J.J. Kokkedee 1969
Stanford Linear Accelerator
Magnetic Form Factor of Proton

Extended earlier measurements at CEA & DESY
1967 MIT-SLAC begins Inelastic Program
\[ e + p \Rightarrow e + \text{Anything} \]

**Inelastic vs. Elastic Scattering**

- Elastic scattering provides information about the charge and magnetic moment distributions averaged over time.
- Inelastic scattering can provide a "snapshot" of the structure.

\[ \Delta t \approx \frac{\hbar}{\Delta E} \]

\( \Delta E \) is energy lost by electron.

\[ \Delta E = 2 \text{ GeV} \quad \Delta t = 3 \times 10^{-25} \text{ sec} \]

for \( v = c \)

motion during "snapshot" is

\[ \approx 10^{-14} \text{ cm.} \]

DEEP INELASTIC SCATTERING REQUIRED FOR LARGE \( \Delta E \)
MIT - SLAC Group

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M. Sogard
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Increasing $q^2$

(a) $E = 7.000$ GeV $\theta = 6^\circ$
(b) $E = 16.049$ GeV $\theta = 6^\circ$
(c) $E = 17.696$ GeV $\theta = 10^\circ$

$W$ (GeV)
Two Major Surprises

• Bjorken Scaling of Structure Functions

• Weak $q^2$ dependence of cross sections
INVARIENTS

\[ \nu = \frac{p \cdot q}{M} = E - E' \]

\[ q^2 = - (p - p')^2 = 4 E E' \sin^2 \frac{\Theta}{2} \]

\[ w^2 = 2M\nu + M^2 - q^2 \]
**Bjorken Scaling**

\[ \nu = \Delta E \text{ for } e \]
\[ q^2 = (\Delta p)^2 - (\Delta E)^2 \]

**Scattering**
\[ \frac{d^2 \sigma}{d\Omega dE} = \sigma_M \left( W_2 + 2W_1 \tan^2 \theta/2 \right) \]

Q.E.D. (understood)

Target (unknown)

**Scaling Bjorken (1967)**

For \( \nu \to \infty \) \( q^2 \to \infty \)

With \( \omega = \frac{2M\nu}{q^2} \) held fixed

\[ \nu W_2 (\nu, q^2) \to F_2 (\omega) \]
\[ 2MW_1 (\nu, q^2) \to F_1 (\omega) \]
Experimental Test of Scaling

$W > 2.6$ GeV

$2 < q^2 < 20$ (GeV)$^2$
Test of Scaling 2

\[ q^2 \text{ (GeV/c)}^2 \]

\[ \nu W_2 \]

\[ + 6^\circ \quad \square 18^\circ \]
\[ \times 10^\circ \quad \triangle 26^\circ \]

\[ \omega = 4 \]
Comparison of e-Carbon & e-p Scattering

Carbon Target
$E_0 = 194$ MeV
$\theta = 135^\circ$

Elastic Peak

EXPERIMENTAL SPECTRUM WITHOUT RADIATIVE CORRECTIONS
INCIDENT ELECTRON ENERGY = 10.0 GeV
SCATTERING ANGLE = 6.0 DEGREES
e-p Cross-sections divided by Mott Cross-section

1968
- $W = 2$ GeV
- $W = 3$ GeV
- $W = 3.5$ GeV

MOMENTUM TRANSFER $q$

FORM FACTOR $G(q^2) = \int \rho(r) e^{iqr} d^3r$

point distribution function $\rho(r) = \delta(r)$

$G(q^2) = 1$

"POINT-LIKE" $\Rightarrow$ WEAK $q^2$ DISTRIBUTION

Results suggested "point-like" Constituents
Non-Constituent Models proposed to explain Scaling

"OLD PHYSICS"

Vector Dominance

Resonance Models

Veneziano N’s and Δ’s

Regge Poles

Diffraction Models
Later data sets (after 1970)

\[ e + p \rightarrow e + \text{Anything} \]
\[ e + d \rightarrow e + \text{Anything} \]

* More statistics – greater range of angles
* Extracted Neutron cross-section and Structure Functions

Impulse Approximation used to obtain Neutron results

\[ \sigma_n = \sigma_d - \sigma_p \]

Applied "Smearing" Corrections to eliminate Fermi Motion
Scaling Observed in Deuteron and Neutron Scattering
n / p Scattering

\[ \frac{\sigma_n}{\sigma_p} \]

\[ x = 1/\omega \]

- This Experiment
- \(18^\circ, 26^\circ, 34^\circ\)
- \(6^\circ, 10^\circ\)
### COMPARISON OF $\sigma_n/\sigma_p$ WITH MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_n/\sigma_p$ at $x \approx 0.85$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction</td>
<td>1</td>
</tr>
<tr>
<td>Resonance</td>
<td>$\sim 0.7$</td>
</tr>
<tr>
<td>Regge</td>
<td>$\sim 0.6$</td>
</tr>
<tr>
<td>Duality</td>
<td>0.47</td>
</tr>
<tr>
<td>Parton (Bare Nucleon + Pions)</td>
<td>0.10</td>
</tr>
<tr>
<td>Quark</td>
<td>$\geq 0.25$</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.30 ± 0.03</td>
</tr>
</tbody>
</table>
• Many attempts were made to use "Old Physics" models to explain results without success.

• But **Quark model** was not regarded as valid by most physicists.

?  

• Theoretical contribution that helped resolve puzzle:
  – R. Feynman -- Parton Model
Parton Model *(Feynman 1968)*

1) Electrons scatter from bound constituents (partons)

2) Partons recoil and interact internally, producing known particles, $\pi'$ s, $K'$ s, etc.

3) If partons are point-like, $F_2$ and $F_1$ scale in $X = q^2 / 2Mv = 1/\omega$

4) Scaling variable $x$ is fractional momentum of struck Parton

5) $F_2(x)$ is related to momentum distribution of Partons in proton
If Partons are Quarks

1) They must be spin 1/2 particles

2) They must have fractional charges consistent with the quark model
SEPARATION OF $W_1$ AND $W_2$

Requires Measurements of cross sections at constant $W$ and $q^2$ (vary $E, E', \theta$)

$$R = \frac{W_2}{W_1} \left( 1 + \frac{v^2}{q^2} \right) - 1$$

$$R = \frac{\sigma_L}{\sigma_T}$$

PARTON MODEL:

Callan - Gross

Spin $\frac{1}{2}$

$R \to 0$ as $v \to \infty$

$$F_2 = 2xF_1$$
Comparisons of forward and backward scattering answered the question:

**What is the spin of the partons?**

Spin 1/2

Spin 0
CONCLUSION:  CONSISTENT WITH QUARK MODEL IF

* QUARKS CARRY 1/2 MOMENTUM
* GLUONS CARRY OTHER HALF
Do Partons have Fractional Charges (+2/3, -1/3)?

• Comparisons of Electron Scattering and Neutrino Scattering provided the answer.

• First results came from Large Heavy Liquid Bubble Chamber “Gargamelle” (1971-1974)
EARLY NEUTRINO AND ANTI-NEUTRINO RESULTS

CERN -- Large Heavy-Liquid Bubble Chamber --

"Gargamelle" (1971 - 74)

1) Observed neutrino and anti-neutrino scattering probability increased linearly with energy

** confirmed existence of "point-like" constituents

2) Comparisons of electron and neutrino scattering

** confirmed fractional charges of constituents

STRONG VALIDATION OF QUARK MODEL
GARGAMELLE

5 meters                      12000 liters of Freon
Neutrino and Anti-neutrino Scattering

Linear rise of scattering cross sections confirmed point-like constituents in proton and neutron
Comparison of electron & neutrino scattering in the quark model (1972-1974)

\[ \int [ F_2^{\text{vn}}(x) + F_2^{\text{vp}}(x) ] dx \]

\[ \int [ F_2^{\text{en}}(x) + F_2^{\text{ep}}(x) ] dx \]

\[ = \frac{2}{(Q_u^2 + Q_d^2)} \]

\[ = \frac{2}{(2/3)^2 + (1/3)^2} \]

\[ = 3.6 \]

Experimental Value (MIT-SLAC, CERN) = 3.4 ± 0.7

VALIDATION OF QUARK MODEL
OTHER NEUTRINO RESULTS

\[ \frac{1}{2} \int \left[ F_2^{\nu p}(x) + F_2^{\nu n}(x) \right] dx = \left( \begin{array}{c} \text{Total Fraction of} \\ \text{Nucleon's Momentum} \\ \text{carried by Quarks} \end{array} \right) \]

Experimental Value (Gargamelle)  
\[ = 0.49 \pm 0.07 \]

Half of Momentum carried by Quarks as suggested by Electron Scattering results

\[ \frac{1}{2} \int \left[ F_3^{\nu p}(x) + F_3^{\nu n}(x) \right] dx = \text{Number of Valence Quarks} \]
\[ = 3 \]

Experimental Value (Gargamelle)  
\[ = 3.2 \pm 0.6 \]
Consistent with Quark Model
Partons are Quarks

- Constituents have spin 1/2

- Constituents have fractional charges consistent with quark model --- from electron and neutrino sum rules

Model of Nucleon

1. 3 valence quarks ------ p(uud), n(ddu)

2. Quark-antiquark sea ---- vacuum polarization

3. Gluons ------ neutral particles responsible for binding quarks that carry 1/2 of nucleon’s momentum