Probing the Nucleon with Spin
Overview of the talk

• This talk will be less focused on detailed nuclear physics, and more of a general overview.
  ➔ Where did our field come from, and where are we now?

• Start at the beginning (several thousand years ago) and end with an upcoming spin-physics measurement at JLab.
  ➔ all in 55 minutes or less,
  ➔ I'm going to gloss over a few details...
What is the point of our effort?
- We're trying to understand what the world is made of.
- The world is beautiful, there is pleasure in the study.
- Knowledge = control (more “practical” reason).

What do we know so far?
- Overview of Particle scattering Formalism and Jargon
  - $x, v, Q^2, W, F_1, g_2, \Theta, \ldots$ huh?
  - Polarized and unpolarized structure functions
    - (experimental meat and potatoes)

$d_2^n$: Measuring quark/gluon correlations in the nucleon
- An upcoming experiment at JLab
What is that stuff made of?

- **Anaximenes**
  (Greek philosopher: 6th century BC)
  - Air was universal, everything is air at different densities.
  - Theory later expanded to include 4 elements

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Earth ➔ Air ➔ Fire
    \\
    \\
Water
```
Alchemy

• Alchemy (practiced in one form or another for 2000 years):
  ➔ Latin dictum:
    ⇔ SOLVE ET COAGULA
    (Separate and Join together)
  ➔ Precursor to:
    ⇔ Chemistry, metallurgy, physics
  ➔ Reagents:
    ⇔ Water, Metal (and oxides), Salts, Acids, ...
    ⇔ Refinement and reduction was an important goal, but few true elemental chemicals.
Chemistry

- 1809: 47 true elements identified, patterns in chemical combination being recognized.
- Mendeleev's Periodic Table (1869)
  - arranged elements by atomic mass
  - columns (periods) have similar chemical properties (i.e. valence electron structure)
  - predicted other elements and left spaces in the table for them
- Getting pretty complicated – hints that this is a manifestation of some simpler underlying structure.
  - i.e. quantization of the atomic masses
Atomic Physics

- 1886: Radioactivity discovered (Bequerel, Curies)
- 1897: Thompson discovers atomic electrons
- 1914: Rutherford identifies discrete protons exist within nucleus
- 1922: Stern-Gerlach experiment proves angular momentum is quantized
  ➞ but “intrinsic” spin not on the table yet...
• 1925: Spin invoked to explain Zeeman splitting of atomic spectra in external magnetic field (later incorporated into Pauli's exclusion principle and the spin quantum number)
• 1925: Heisenberg wave mechanics, Schrödinger eqn
• 1928: Dirac equation
  ➡ Relativistic QM description of a spin-1/2 particle
• 1932: Chadwick discovers the neutron
  ➡ Final key to explaining the Periodic Table
1930s on:

- dozens and dozens of strongly interacting fermion states (spin 1/2, 3/2, 5/2...) have been identified
  - $\Delta, \Theta, \Lambda, \Sigma...$ (Baryons)

- dozens and dozens of strongly interacting bosons (spin 0, 1, ...) have been identified
  - $\sigma, \rho, \omega, \eta, ...$ (Mesons)

That's a lot of "elementary" particles...

- Remind you of the Periodic Table?
- Something more is going on here
Scattering Experiments

- Most of these particles discovered by smashing subatomic particles into a target and measuring what comes out.

- Time to define some technical terms so we can talk about how scattering experiments are done...
"Unpolarized deep inelastic cross sections"

- **Cross section** measures the probability you'll find an electron of energy $E'$ scattered into a solid angle $d\Omega$:

$$\frac{d^2 \sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)$$

- **F's are Structure Functions.** They encode our (lack of) knowledge about the target nucleon.

$Q^2 = 4$-momentum transfer squared of the virtual photon.

$\nu = $ energy transfer.

$\theta = $ scattering angle.

$x = \frac{Q^2}{2M \nu}$ fraction of nucleon momentum carried by the struck quark.
Interpreting the Cross Section

- \( W^2 = M^2 + 2Mv + Q^2 \)
  - \( M = \) nucleus
    - (or nucleon) mass
  - \( W = \) “invariant mass” after collision

- Four regions
  - Elastic scattering
    - nucleus intact
  - Quasi-elastic scattering
    - photon interacts with a single nucleon
    - nucleus breaks up
  - Resonances
    - excited nucleon states
    - nucleon substructure starting to be probed
  - Deep inelastic scattering
    - internal structure (partons) resolved
What the Structure Functions?

- The "F's" in the unpolarized cross section are Structure Functions:
  \[
  \frac{d^2 \sigma}{d \Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)
  \]

- They encode information about the internal structure of the target nucleon
  - You can measure them,
  - You can compute them,
  - But what do they mean?

- The Parton Model
  - Assume hadrons composed of free particles called 'partons'
  - $F_1$ (and $F_2$) reflect the probability of finding a parton (ie. quark) with momentum fraction 'x'
Interpreting the Structure Functions

\[
\frac{d^2 \sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)
\]

\[F_2^A\]

Low \(Q^2\)

Excited Nuclear States

Elastic Peak

\[F_2^A\]

Moderate \(Q^2\)

Quasielastic Peak

Inelastic Resonances

Elastic Peak

\[F_2^A\]

High \(Q^2\)

Inelastic Resonances

Quasielastic Peak

Elastic Peak

Bjorken Scaling

NMC Collaboration

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\(Q^2 \text{ GeV}^2\)

\(F_2^p\)
What happened to $F_1$?

- **Callan-Gross Relation**
  - If the point-like partons are spin 0, then
    $$2x F_1(x)/F_2(x) = 0$$
  - If they are spin $\frac{1}{2}$, then
    $$2x F_1(x)/F_2(x) = 1$$

- So,
  $$2x F_1(x) = F_2(x)$$
  
  the partons are spin $\frac{1}{2}$
So, we've got it cased now?

- The partons in the nucleon look like quarks
  - quarks are point-like, spin $\frac{1}{2}$ particles
  - a proton is a spin $\frac{1}{2}$ particle
    - therefore you expect to have two quarks with spin $+\frac{1}{2}$ and one with spin $-\frac{1}{2}$
    - (quark spin sum) $\frac{1}{2} + \frac{1}{2} - \frac{1}{2} = +\frac{1}{2}$ (proton spin)

- CERN designed an experiment to explicitly measure the quark contribution to the proton spin (1987)
  - naïve expectation: 100%
  - after relativistic corrections: 75%
  - measured: $12 \pm 16\%$

The “Proton Spin Crisis”
Spin Crisis (Puzzle) still not fully understood

- Total spin = $\frac{1}{2} \Delta \Sigma + \Delta G + L_z$
  - $\Delta \Sigma$ = quark spin (including sea quarks now)
  - $\Delta G$ = gluon spin
  - $L_z$ = orbital angular momentum of gluons and quarks

- Sea quarks were supposed to solve the puzzle but measurements indicate a very small contribution < 5%

- $(L_z$ is extremely hard to measure)

- Understanding the gluon contribution is now underway
  - But how do we probe the gluon field?
    - they don't respond to an electromagnetic probe
    - we can't manipulate gluons directly, but we *can* manipulate the nucleon spin
Spin Crisis (Puzzle) still not fully understood

- There's more going on inside the nucleon than we thought
  - gluons are a big part of it

- How can we get a handle on the quark/gluon interactions?
  - by manipulating the nucleon spin
\[ \frac{d^2 \sigma}{dE'd\Omega} (\downarrow \uparrow - \uparrow \downarrow) = \frac{4\alpha^2}{MQ^2} \frac{E'}{\nu E} \left[ (E + E' \cos \theta)g_1(x, Q^2) - \frac{Q^2}{\nu}g_2(x, Q^2) \right] = \Delta \sigma_\parallel \]

\[ \frac{d^2 \sigma}{dE'd\Omega} (\downarrow \Rightarrow - \uparrow \Rightarrow) = \frac{4\alpha^2 \sin \theta}{MQ^2} \frac{E'^2}{\nu^2 E} \left[ \nu g_1(x, Q^2) + 2Eg_2(x, Q^2) \right] = \Delta \sigma_\perp \]

\( Q^2 \) = 4-momentum transfer squared of the virtual photon.
\( \nu \) = energy transfer.
\( \theta \) = scattering angle.
\( x = \frac{Q^2}{2M\nu} \) fraction of nucleon momentum carried by the struck quark.
What are $g_1$ and $g_2$?

- The “$g$’s” play a role analogous to the “$F$’s” in the unpolarized cross section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \left( \frac{2}{M} F_1(x, Q^2) \sin^2 \frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2 \frac{\theta}{2} \right)$$

- $F$ encodes information about the momentum structure of the nucleon

- $g_1$ and $g_2$ encode information about the spin structure of the target nucleon

- The Parton Model
  - $g_1$ reflects the difference in probabilities between quarks with spin aligned parallel and anti-parallel to the nucleon spin
  - $g_2$ ??
$g_2$ and Quark-Gluon Correlations

QCD allows the helicity exchange to occur in two principle ways:

- **twist-2**
  - Carry one unit of orbital angular momentum
  $$g_2(x, Q^2) = g_{2WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$

- **twist-3**
  - Couple to a gluon

**a twist-2 term (Wandzura & Wilczek, 1977):**

$$g_{2WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 g_1(y, Q^2) \frac{dy}{y}$$

**a twist-3 term with a suppressed twist-2 piece (Cortes, Pire & Ralston, 92):**

$$\bar{g}_2(x, Q^2) = -\int_x^1 \frac{\partial}{\partial y} \left( \frac{m_q}{M} h_T(y, Q^2) + \xi(y, Q^2) \right) \frac{dy}{y}$$

- transversity
- quark-gluon correlation

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Moments of Structure Functions

\[ \Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2) \, dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + \cdots \]

leading twist  
higher twist

\[ \mu_2^{p,n}(Q^2) = \left( \pm \frac{1}{12} g_A + \frac{1}{36} a_8 \right) + \frac{1}{9} \Delta \Sigma + \text{pQCD corrections} \]

\[ g_A = 1.257 \quad \text{and} \quad a_8 = 0.579 \quad \text{are the triplet and octet axial charge, respectively} \]

\[ \Delta \Sigma = \text{singlet axial charge} \]

(Extracted from neutron and hyperon weak decay measurements)

\[ g_A = \Delta u - \Delta d \]
\[ a_8 = \Delta u + \Delta d - 2\Delta s \]
\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s \]

pQCD radiative corrections
Moments of Structure Functions (continued)

\[ \mu_4(Q^2) = \frac{M^2}{9} \left[ a_2(Q^2) + 4d_2(Q^2) + 4f_2(Q^2) \right] \]

Twist - 2   Twist - 3   Twist - 4  
(TMC)

where \( a_2, d_2 \) and \( f_2 \) are higher moments of \( g_1 \) and \( g_2 \)

e.g. \[ d_2(Q^2) = \int_0^1 x^2 [2g_1(x, Q^2) + 3g_2(x, Q^2)] \, dx = 3\int_0^1 x^2 \bar{g}_2(x, Q^2) \, dx \]

\[ a_2(Q^2) = \int_0^1 x^2 g_1(x, Q^2) \, dx \]

• To extract \( f_2, d_2 \) needs to be determined first.

• Both \( d_2 \) and \( f_2 \) are required to determine the color polarizabilities
Color “polarizabilities”

How does the gluon field respond when a nucleon is polarized?

Define color magnetic and electric polarizabilities (in nucleon rest frame):

\[ \chi_{B,E} 2M^2 \vec{S} = \langle PS|\vec{O}_{B,E}|PS \rangle \]

where

\[ \vec{O}_B = \psi^\dagger g \vec{B} \psi \]
\[ \vec{O}_E = \psi^\dagger \vec{\alpha} \times g \vec{E} \psi \]

\[ \chi_E^n = (4d_2^n + 2f_2^n)/3 \]
\[ \chi_B^n = (4d_2^n - f_2^n)/3 \]

\( \chi_E \) and \( \chi_B \) represent the response of the color \( \vec{B} \) & \( \vec{E} \) fields to the nucleon polarization.
Model evaluations of $d_2$
World Data on $\bar{d}_2$

(nucleon elastic contribution suppressed)
The Experiment

- A 4.6 and 5.7 GeV polarized electron beam scattering off a polarized $^3$He target
- Measure unpolarized cross section for $^3\text{He}(e, e')$ reaction $\sigma_0^{^3\text{He}}$ in conjunction with the parallel asymmetry $A^{^3\text{He}}_\parallel$ and the transverse asymmetry $A^{^3\text{He}}_\perp$ for $0.23 < x < 0.65$ with $2 < Q^2 < 5\text{ GeV}^2$.
  - Asymmetries measured by BigBite at a single angle: $\theta = 45^\circ$
  - Absolute cross sections measured by L-HRS
- Determine $d_2^n$ using the relation

$$
\tilde{d}_2(x, Q^2) = x^2[2g_1(x, Q^2) + 3g_2(x, Q^2)]
= \frac{M Q^2}{4\alpha^2} \frac{x^2 y^2}{(1-y)(2-y)} \sigma_0 \left[ \left( \frac{3}{(1-y) \sin \theta} + \frac{4}{y} \tan \frac{\theta}{2} \right) A_\perp + \left( \frac{4}{y} - 3 \right) A_\parallel \right]
$$

where,

- $A_\perp = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\downarrow}}{2\sigma_0}$
- $A_\parallel = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\downarrow}}{2\sigma_0}$
- $A^{^3\text{He}}_\parallel = \frac{\Delta_\parallel}{P_t P_\perp}$
- $A^{^3\text{He}}_\perp = \frac{\Delta_\perp}{P_t P_\perp}$
- $\Delta_\perp = \frac{(N^{\downarrow\uparrow} - N^{\uparrow\downarrow})}{(N^{\downarrow\uparrow} + N^{\uparrow\downarrow})}$
- $\Delta_\parallel = \frac{(N^{\downarrow\uparrow} - N^{\uparrow\downarrow})}{(N^{\downarrow\uparrow} + N^{\uparrow\downarrow})}$
Kinematics of the measurement

- Two beam energies 4.6 and 5.7 GeV (4 pass, 5 pass)

- BigBite fixed at single scattering angle ($\theta=45^\circ$) (data divided into 10 bins during analysis)

- Avoid resonance region as much as possible.
Floor configuration for this experiment

Beam Polarization: 75%
Beam Current: 15 microA
Non-focusing, Large acceptance, Open geometry

$\frac{\Delta p}{p} = 1 - 1.5\% \, (\text{@ 1.2 T}) \, \sigma(W) = 50 \, \text{MeV}$

Angular resolution 1.5 mr, extended target resolution 6 mm

Large solid angle: $\sim 64 \, \text{msr}$

Detector package:

$\Rightarrow$ 3 MWDCs, scintillator plane,

Pb-glass pre-shower + shower

$\Rightarrow$ Gas Cherenkov (new)
• MC simulation by Degtyarenko et al. (tested in Halls A and C)
• Online cuts include:
  ➔ BB magnet sweeps particles with \( p < 200 \text{ MeV}/c \)
  ➔ GeN BB trigger: shower+pre-shower+scint
    ➔ provide ~10:1 online hadron rejection (or better)
  ➔ ~550—600 MeV threshold on shower
  ➔ 4—5 p.e. threshold on Cherenkov
    ➔ heavily suppress random background
    ➔ negl. pion contamination (~100 Hz knock-ons)
• Total estimated trigger rate (GeN trig + Cherenkov): 2—5 kHz

**Background Rates**

- \( e^- \) 2-5 kHz
- \( e^+ \) <1 kHz
- \( p^- \) 90 kHz
- \( p^+ \) 90 kHz
- \( p \) 50 kHz
- \( n \) 50 kHz

Removed via online cuts
Projected $x^2 g_2(x,Q^2)$ results

- $g_2$ for $^3$He is extracted directly from $L$ and $T$ spin-dependent cross sections measurements within the same experiment.
- The nuclear corrections will be applied to the moments not to the structure functions.
- SLAC E155x $g_2$ data points at high $x$ are evolved from $Q^2$ as large as 16 GeV$^2$ to 5 GeV$^2$
Expected Error on $d_2$
Summary of Experiment

- We will precisely measure the neutron $d_2^n$ at $Q^2 \approx 3.0 \text{ GeV}^2$.
  - Determine asymmetries in conjunction with an absolute cross section measurement over the region ($0.23 < x < 0.65$)
  - Also, measure $Q^2$ evolution of $x^2 g_2$ over the same $x$ region

- Provide a benchmark test for theory (lattice QCD).
  - we can achieve a statistical uncertainty of $\Delta d_2^n = 5 \times 10^{-4}$
    - four times better than existing world average!

- Dramatically improve our knowledge of $g_2^n(x)$
  - double the data points for $x > 0.2$, all with better precision

- The nature of the this quantity (clean measurement, clean calculation) makes the $d_2^n$ an excellent way to precisely probe the strength and character of quark-gluon interactions in the nucleus.