Opportunities in Nucleon and Nuclear Physics
Probing the Structure of Matter

Donal Day
February 27, 2009
Opportunities

- Spin structure of the neutron and proton
- Superfast quarks

- Exposure to wide range of laboratory skills
  - Superconducting magnets
  - Vacuum technology
  - NMR (RF circuitry: 10 to 300 MhZ)
  - Microwave circuitry (140GHz)
  - DAQ
  - Particle tracking and identification

- Healthy infrastructure
- Summer opportunities in lab and at JLAB
Group Effort

Faculty
  • Donal Day & Donald Crabb
  • Oscar Rondon (Principal Scientist)

Research Associates (Post Doc)
  • Narbe Kalantarian
  • Hovhannes Baghdasaryan

Graduate Students
  • James Maxwell
  • Jonathan Mulholland
  • Vahe Mayman
  • Kang Kang Li (Kovacs)

Undergraduates
  • Will Levine
  • Ilya Krifman

Recent Graduates
  • Nadia Fomin, Ph.D in December 07, now at U. of Tennessee
  • Jon Mellor, M.S. in 06, now with Peace Corps
  • Josh Pierce, Ph.D in October 07 now at Oak Ridge National Lab
  • Justin Wright, M.S. now with US Army

Recent Post Doc
  • Karl Slifer, tenure track at UNH
At most fundamental level strongly interacting matter consists of light pointlike quarks and powerful gluon fields.

- Proton (Neutron) is built from two (one) up quarks, a (two) down quarks and an infinite number of quark-antiquark pairs and gluons.

- The theory that describes the interactions among these "partons" is called Quantum Chromodynamics (QCD).

- Atomic nuclei, being composed of protons and neutrons, are likewise systems of bound quarks and gluons.

- Major aim of nuclear experiments through the next decade is to take detailed "snapshots" of this structure at various levels of resolution.
Electron Scattering - The Basics

- Visible light: $\lambda \sim 0.4 - 0.7 \, \mu m$
  $E_\gamma \sim 0.5 - 1 \, eV$

- X-ray: $\lambda \sim 0.03 - 3 \, nm$
  $E_\gamma \sim 1 - 100 \, KeV$

Multi-Gev electrons allow $\Delta r \approx 10^{-\, m}$
How to gain access to the details of the structure?
Use spin observables since they often result from interference between amplitudes

Spin Observables require the use of polarized beams and polarized targets

Very schematically
some operator $\mathcal{O} = \mathcal{O}_{\text{Big}} + \mathcal{O}_{\text{Small}}$

unpolarized crosssection: $d\sigma \propto |\langle f | \mathcal{O}_{\text{Big}} | i \rangle |^2 + |\langle f | \mathcal{O}_{\text{Small}} | i \rangle |^2$

while spin observables contain terms like:

$\langle f | \mathcal{O}_{\text{Big}} | i \rangle^* \langle f | \mathcal{O}_{\text{Small}} | i \rangle$

which is linear in a small quantity but with a large coefficient

For the form factors: $\mathcal{O} \propto \frac{G_E}{G_M}$ instead of $\mathcal{O} \propto G_E^2 + G_M^2$

We specialize in one critical aspect of these techniques: Polarized targets
Block Diagram of Polarized Target

- Magnet
- Target Coil
- Refrigerator
- Target Material
- Microwave Generator
- Cryogenics $^4\text{He}$
- Magnet Power Supply

- Polarization Detection System
  \[ P_{\text{DYN}} = \varepsilon P_{\text{T.E.}} \]

- Nuclear Resonance Oscillator
  \[ \nu_n = 213\text{MHz for Protons} \]
  \[ \nu_n = 32\text{MHz for deuterons} \]

- Electron Frequency
  \[ \nu_e \pm \nu_n = 140\text{GHz} \]

- Temperature
  \[ T \leq 1\text{K} \]

- Magnetic Field
  \[ B = 5.0\text{T} \]
Solid Polarized Targets

- *frozen(doped) NH3*
- *$^4$He evaporation refrigerator*
- *5T polarizing field*
- *remotely movable insert*
- *dynamic nuclear polarization*

![Diagram](image.png)
Deep Inelastic Scattering

\[ \frac{d\sigma}{d\Omega dE'} = \sigma_M \left[ \frac{F_2(x, Q^2)}{\nu} + \frac{2F_1(x, Q^2)}{M} \tan^2(\theta/2) \right] \]

* Spin averaged structure function \( F_1 \) and \( F_2 \) depend on
  - 4-momentum transfer squared \( Q^2 \).
  - Bjorken \( 0 < x < 1 \) interpreted as fraction of nucleon momentum carried by struck quark
Nucleon Spin Structure Functions

Polarized electron-polarized nucleon scattering

\[ A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \]

\[ = f \left[ g_1(x, Q^2) [E + E' \cos \theta] - \frac{Q^2}{\nu} g_2(x, Q^2) \right] \]

\[ A_{\perp} = \frac{\sigma^{\downarrow\leftarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\downarrow\leftarrow} + \sigma^{\uparrow\leftarrow}} \]

\[ = f E' \sin(\theta) \left[ g_1(x, Q^2) + \frac{2E}{\nu} g_2(x, Q^2) \right] \]

In the 1980s, experiments at CERN and SLAC showed that only a small fraction of the nucleon spin is carried by the quarks. Since then, many experiments have been done to solve this "spin crisis". Our current understanding of nucleon spin is that it is the sum of the spins of the valence quarks and the q and the qbar sea quarks, the orbital angular momenta of quarks and the spins of gluons.
High density configurations

A single nucleon, $r = 1 \text{ fm}$, has a volume of $4.2 \text{ fm}^3$
$197 \times 4.2 \text{ fm}^3 \approx 830 \text{ fm}^3$
$60\%$ of the volume is occupied – very closely packed!

Potential between two nucleons

Nucleon separation is limited by the short range repulsive core

Even for a $1 \text{ fm}$ separation, the central density is about $4x$ nuclear matter

Comparable to neutron star densities!

High enough to modify nucleon structure?

To which nucleon does the quark belong?
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• Healthy infrastructure
• Summer opportunities in lab and at JLAB
• Group effort – always someone to get help from
Our students actually do things – in fact, because of their training, they lead

Jonathan Mulholland, Anusha Liyanage (Hampton student) & Oscar Rondon

Jonathan Mulholland & Kangkang Kovacs (Li)