Taking snap-shots of the nucleon

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How do we take pictures of small things?

• Use e/m waves:
  • Resolution is limited by wave-length:
  • For visible light ~ 500 nm
  • X-rays ~ 1 nm

• But particle waves have much finer resolution:

\[ \lambda = \frac{h}{p} \]

50 KeV electrons have a wavelength of 0.005 nm!

electron and neutron scattering to image VERY small things
Electron Microscope

About 100-200 times better resolution than an optical microscope
Bigger (and more expensive) “Electron Microscope” : particle accelerator

\[ pc = 6000 \text{ MeV} \]

\[ \lambda = \frac{hc}{pc} = 5 \times 10^{-16} \text{ m} \]
Resolution of the probe

\[ \lambda = \frac{\hbar}{Q^2} = \frac{\hbar}{\sqrt{Q^2}} \]

- \( Q^2 = 0 \)
- \( Q^2 = \infty \)

Low \( Q^2 \): large distance
Elastic scattering off nucleon

Intermediate \( Q^2 \)
- scattering off constituent quarks
- confinement
- resonance excitations

Large \( Q^2 \): short distance
"free" quarks
incoherent "elastic" scattering off quarks
DIS
Momentum distribution

Form factor: $F(q)$

Fourier Transform

Spatial Distribution

$\rho(r)$
It’s a Ball, No it is a pretzel: Must be a proton: NY Times 05/06/03
Quark structure of the nucleon

- Three $u$ and $d$ valence quarks
- Also gluons and a “sea” of $q, \bar{q}$ pairs
- Strong interaction between quarks
- Governed by QCD
- Mediated by gluons
- Gluons interact with other gluons: self coupling
The Science Problem?

Quantum Chromodynamics (QCD) in the confinement regime:
How does it work?

• What do we know?

  QCD works in the perturbative (weak) regime
  Many experimental tests led to this conclusion, example:
  Nucleon as a laboratory
  ➔ Proton is not pointlike (Nobel Prize: Hofstadter); Elastic electron scattering
  ➔ Quarks and gluons/Partons are the constituents; Deep Inelastic electron Scattering (Nobel prize: Friedman, Kendall and Taylor, 1991).

  Theory celebrated recently
  but
  Confinement in QCD is still a puzzle and among the 10 top problems in Physics! (Gross, Witten,....)

Strings 2000
The incoming electron interacts with the:

- electric charge of the target particles
- And the magnetic moment of the charged particle
  - Proton or neutron magnetic moment is due to spins of quarks, orbital motion of quarks, etc.

- 4 form factors:

- $G(E)p$, $G(M)p$, $G(E)n$ and $G(M)n$

- $G(E)n$ is the hardest to measure
Jefferson Lab Hall A
Hall A GEn experiment (E02-103)

- **Electron Arm**
- **Polarized $^3$He target**
- **neutron arm**

$$^3\text{He}\left(\vec{e}, \, e'n\right)$$

- BigBite - large acceptance spectrometer, measures $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID
Our Previous MRI project: large wire-chamber tracker for Bigbite spectrometer in Hall A

• MRI grant  ~  $ 0.45 M , Completed in 2005
• Used by more than 7 highly ranked experiments.
• Strong Undergraduate and graduate student participation.
Hall A GEn experiment (E02-103): improves the resolution of neutron change distribution by more than a factor of 2
High $Q^2$ form factor measurements with Jefferson lab 12 GeV beam: Improving resolution much further

$GEp$, $GEN$ and $GMP$ measurements with Super-Bigbite spectrometer in Hall A
GAS ELECTRON MULTIPLIER (GEM)

Thin metal-coated polymer foil chemically pierced by a high density of holes. On application of a voltage gradient, electrons released on the top side drift into the hole, multiply in avalanche and transfer the other side. Proportional gains above $10^3$ are obtained in most common gases.

SIGNAL READOUT

Electrons are collected on patterned readout boards. A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination. All readout electrodes are at ground potential.

Applications of GEM chambers

• PARTICLE PHYSICS: TRACKING, CHERENKOV LIGHT, CALORIMETRY
• ASTROPHYSICS
• NUCLEAR PHYSICS: NEUTRON DETECTION
• MEDICAL DIAGNOSTICS: PET, PORTAL IMAGING
• NATIONAL SECURITY: RADIATION DETECTION
What can you do with a nuclear/particle physics PhD in addition to research/academia?

The skills you acquire (Radiation detection, analysis and interpretation of large data sets etc.) are in high demand in many areas

- **Medical Physics:** radiation oncology and medical imaging
- **National security:** many opportunities at national labs and private companies
- **Wall-street**
BigBite Spectrometer: Optimization is the Key to New Physics

Two experiments have been completed using the high performance wire chamber detector package in BigBite. In E02-13, the electrical nature of the neutron is studied. The neutron is a neutral particle where the net charge of the quark composition is zero, yet the interior local charge density is not. The question to be answered is what is the distribution and origin of the electrical charge in the interior of the neutron and how is it manifested by QCD and the orbital motion of the quarks? This Jefferson Lab experiment made precision charge measurements in the neutron interior down to distances of $1.0 \times 10^{-14}$ m, which is about 1/8 the size of the neutron radius.

In E04-007, the creation of a very low energy neutral pions (called threshold pions) is studied. Due to the quark-antiquark structure of the neutral pion, the electroproduction of the pion by the scattering of electrons from the proton depends sensitively on chiral symmetry breaking. This symmetry breaking is related to the fact that the quarks are not massless. In addition, the dependence of the scattering on beam polarization is directly related to higher order two step processes in the production of neutral pion. Several new highly rated experiments using the BigBite wire chamber detector package are now scheduled and tranversity is currently scheduled to begin in October 2008.

The success of these experiments is largely due to the “BigBite” spectrometer with a high luminosity wire chamber detector package, which yields a figure-of-merit up to 100 times higher than that based on available standard equipment. The spectrometer, which weighs 20 tons, also has an acceptance of 100 msr, which is 15 times larger than that for the standard spectrometer. The detector package of BigBite is based on three low mass, and highly segmented drift chambers for high rates (20 MHz), which can be optimized for the detection of low energy protons to high energy electrons. A team of 10 undergraduate students, 3 graduate students and a research scientist, which was led by the University of Virginia Grant PI’s Richard Lindgren and Nilanga Liyanage and Jlab’s Bogdan Wojtsekhowski constructed the detector of the spectrometer in three years. The detector development was supported by NSF MRI Award No. 0216351.