A Billionth of a Billionth of a Meter: Building a Microscope for the Observation of Quarks and Anti-Quarks Inside the Proton

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Saturday Physics
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A Billionth of a Billionth of a Meter: A Microscope for the Observation of Quarks & Anti-Quarks Inside the Proton

- From Atoms to Quarks
- Particle Accelerators as Microscopes
- The Weak Nuclear Force as Probe of Proton Structure
- Turning the PHENIX Spectrometer into a Microscope for Quark and Anti-Quarks
From Atoms to Quarks: What is the Substructure of Matter?

Asked early: Leukipp and Demokrit (~ 450-400 BC) ➔ atomic hypothesis!

There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

Some 2400 years & 80 generations later:

Modern experimental tools may provide quantitative answers in our lifetime!

PHENIX Experiment at Brookhaven National Lab
From Atoms to Quarks

Salt crystal \( \sim 0.1 \text{ m} \)

Na Cl \( \sim 1 \text{ billionth of a meter} = 1 \text{ nano meter} = 1 \text{ nm} \)

Na-atom \( \sim \text{ a tenth of a nm} \)

Na-Nucleus \( \sim \text{ on hundred thousandth of a nm} \)

Proton \( \sim \text{ on millionth of a nm} \)

Electron & Quark \( \sim > \text{ a billionth of a nm} \)
The Atoms of the 19\textsuperscript{th} Century: Chemical Elements

Periodic Table of the Elements

* Lanthanide Series
  - Ce
  - Pr
  - Nd
  - Sm
  - Eu
  - Gd
  - Tb
  - Dy
  - Ho
  - Er
  - Tm
  - Yb
  - Lu

* Actinide Series
  - Th
  - Pa
  - U
  - Np
  - Pu
  - Am
  - Cm
  - Bk
  - Cf
  - Es
  - Fm
  - Md
  - No
  - Lr

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The Atoms of the 19th Century:
The Sodium Atom

**Electron shell**
- 11 electrons with 1 negative elementary charge, \(-1e = -1.6 \times 10^{-19} \text{C}\), each

**Nucleus**
- 11 protons with +1e each
- 12 neutrons with no electric charge

Electrons, protons and neutrons have a well-defined intrinsic angular momentum. This is referred to as **spin**:

\[
S_{\text{electron}} = S_{\text{proton}} = S_{\text{neutron}} = \frac{1}{2} \hbar
\]

\((\hbar \rightarrow \text{Planck’s constant})\)

The spin of a particle gives rise to a small magnetic field \(\vec{B}\)!
Example for Forces Between Particle Spins: Magnetic Resonance Imaging

MRI uses force between proton and electron spins to image density of hydrogen in our bodies (e.g., water)!

- Hydrogen atom
  - Proton
  - Electron
- Magnetic Field orients & holds spins
- Energy from radio waves manipulate / flip spins

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A Microscope for Quarks and Anti-Quarks Inside the Proton
How are Electromagnetic Forces Transmitted Between Electron and Protons?

The forces in Nature

<table>
<thead>
<tr>
<th>Type</th>
<th>Intensity of Forces (Decreasing Order)</th>
<th>Binding Particle (Field Quantum)</th>
<th>Occurs In:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong Nuclear Force</td>
<td>~ 1</td>
<td>Gluons (No Mass)</td>
<td>Atomic Nucleus</td>
</tr>
<tr>
<td>Electro-Magnetic Force</td>
<td>~ 10^-3</td>
<td>Photons (No Mass)</td>
<td>Atomic Shell Electrotechnique</td>
</tr>
<tr>
<td>Weak Nuclear Force</td>
<td>~ 10^-5</td>
<td>Bosons Z°, W°, W⁻ (Heavy)</td>
<td>Radioactive Beta Desintegration</td>
</tr>
<tr>
<td>Gravitation</td>
<td>~ 10^-38</td>
<td>Gravitons (?)</td>
<td>Heavenly Bodies</td>
</tr>
</tbody>
</table>

The exchange of particles is responsible for the force.
In an atom electrons are not on uniquely defined “planet-like” orbits!

Instead they are best described by functions, $\rho(x,y,z)$, providing the probabilities that the electron will be found at a given place.
The Atoms of the 20th Century: Quarks and Leptons

Up- and down-quarks are the building blocks of all nuclear matter in the nuclei of atoms.

Electrons make up the shell of atoms.

Forces:
- Electromagnetic $\rightarrow$ Photon
- Strong Nuclear $\rightarrow$ Gluon
- Weak Nuclear $\rightarrow$ $Z^0$, $W^+$, $W^-$

<table>
<thead>
<tr>
<th>Elementary Particles</th>
<th>Force Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks</td>
<td></td>
</tr>
<tr>
<td>u (up)</td>
<td>g (gluon)</td>
</tr>
<tr>
<td>c (charm)</td>
<td></td>
</tr>
<tr>
<td>t (top)</td>
<td></td>
</tr>
<tr>
<td>d (down)</td>
<td></td>
</tr>
<tr>
<td>s (strange)</td>
<td>$\gamma$ (photon)</td>
</tr>
<tr>
<td>b (bottom)</td>
<td></td>
</tr>
<tr>
<td>Leptons</td>
<td>W (boson)</td>
</tr>
<tr>
<td>$\nu_e$ (electron neutrino)</td>
<td></td>
</tr>
<tr>
<td>$\nu_\mu$ (muon neutrino)</td>
<td></td>
</tr>
<tr>
<td>$\nu_\tau$ (tau neutrino)</td>
<td></td>
</tr>
<tr>
<td>e (electron)</td>
<td>Z (boson)</td>
</tr>
<tr>
<td>$\mu$ (muon)</td>
<td></td>
</tr>
<tr>
<td>$\tau$ (tau)</td>
<td></td>
</tr>
</tbody>
</table>

3 $\rightarrow$ I II III $\leftarrow$ Generations
An Exotic Lepton Always Close: 
Muons Produced from Cosmic Rays

Primary Cosmic Rays: protons, helium nuclei

The Muon

Mass \( \text{= } 206 \) times the electron mass
Electric charge = electron charge
Mean life \( \text{= } 2.2 \) µs

Rate \( \text{~ } 1 \) muon/second in 4x4 square inch

\[
p + N^7 \Rightarrow \pi^+ + X \Rightarrow \mu^+ + \nu_\mu + X
\]
The Structure of Nuclei and of Protons and Neutrons

atom ~ $10^{-10}$ m

nucleus ~ $10^{-14}$ m

Proton/neutron ~ $10^{-15}$ m

electron < $10^{-18}$ m

quark < $10^{-18}$ m

A Microscope for Quarks and Anti-Quarks Inside the Proton
The Proton, a Complex System of Quarks, Anti-Quarks and Gluons

- **Valence quarks**: 2 up-, 1 down-quark
- **Gluons**: the force carriers of the strong nuclear force.
- **“Sea-quarks”**: quark-anti-quark pairs that can be formed from a gluon for a short time and annihilate again.

1 Fermi m = 1 Fm \(\sim 10^{-15}m\)
Gluons Split in Quark-Anti-Quark Pairs Abundantly Inside Protons and Neutrons

In a force field particle-anti-particle pairs are created and annihilate again.

This can take place even if the energy density is not sufficiently high to provide the energy needed for the masses of the pair

\[ \Delta t \Delta E \geq \frac{\hbar}{2} \] (Heisenberg’s Uncertainty relation)
Electron–Positron Annihilation and Positron Emission Tomography (PET)

Positron emitting radioactive isotopes and gamma rays from Electron-positron annihilation are used for medical imaging.
Quark and Gluon Momentum Distributions

Constituents Particles of the Proton:
quarks = u, d, s  and gluons

\[ q(x) = \text{quark momentum distribution} \]
Probability to observe a quark q with relative momentum x.

\[ G(x) = \text{gluon momentum distribution} \]
Probability to observe a gluon with relative momentum x.

Relative quark momentum:
\[ x = \frac{p_{\text{quark}}}{p_{\text{proton}}} \]
Quark and Gluon Spin Distributions

Constituents Particles of the Proton:
quarks = u, d, s and gluons

\[ \Delta q(x) = \text{quark spin distribution} \]
Probability to observe a quark with relative momentum \( x \) contributing to the proton spin.

\[ \Delta G(x) = \text{gluon spin distribution} \]
Probability to find gluon with relative momentum \( x \) contributing to the proton spin.

Relative quark momentum

\[ x = \frac{p_{\text{quark}}}{p_{\text{proton}}} \]
Decomposition of the Proton Spin: Quark Spin + Gluon Spin + Orbital Angular Momentum

Origin of the Proton Spin:
add all quark spin contributions $\Delta q(x) \rightarrow \Delta \Sigma$
add all gluon spin contributions $\Delta G(x) \rightarrow \Delta G$

\[
\frac{1}{2} \hbar = \frac{1}{2} \hbar \Delta \sum + \hbar \Delta G + \hbar L_z
\]

$\chi = \frac{p_{\text{quark}}}{p_{\text{proton}}}$

Quark Spin
Gluon Spin
Orbital Angular momentum
Experimental Method: Scattering of High Energy Particles on Target Material Under Study

Ernest Rutherford: Scattering experiments lead to the discovery of the atomic nucleus, 1911

J.J. Thomson
Atomic Plum Pudding Model

Observation of α-particles at large angles

source of α-particles (He-nuclei)

α-particles

scintillating screen

target Au-foil

Observation of α-particles at large angles

Rate [cps]

Thomson

Rutherford

180° angle

A Microscope for Quarks and Anti-Quarks Inside the Proton
Discovery of Quark Structure in Protons Through Electron-Proton Scattering at SLAC

Nobel Prize 1990 for
Jerome Friedman, Henry Kendall and Richard Taylor

A Microscope for Quarks and Anti-Quarks Inside the Proton
Quark Spin Distributions from the COMPASS Experiment at CERN, Switzerland


$\Delta u$ is positive and contributes about $+0.69 \hbar$

$\Delta d$ is negative and contributes about $-0.33 \hbar$

The total quark spin contribution, $\Delta \Sigma = 0.3 \hbar$

Next steps:
- Measure gluon spin contribution
- Probe anti-quark distributions directly
Measurement of Spin-Dependent Anti-Quark Distributions in PHENIX at RHIC

The Relativistic Heavy Ion Collider is located at Brookhaven National Laboratory on Long Island.
How Can we Probe Proton Spin Structure at RHIC?

At ultra-relativistic energies the proton represents a jet of quarks and gluons.

Use the weak nuclear force ($W^+/-$-bosons) to directly probe anti-quarks!

\[ p + p \rightarrow W^\pm \rightarrow \mu^\pm + \nu \]

\[ m_W = 80 \times m_{\text{proton}} \]

\rightarrow high energy muons!

Error projections from computer simulations, the future error band from Ws at RHIC is red!

$A_L \approx x \Delta \bar{u}$

$A_L \approx x \Delta \bar{d}$
The Experimental Challenge in PHENIX

Only 1 (useful) W-boson in
1 billion p-p collisions

Must operate at 5-10 million p-p collisions per second!

PHENIX has 350,000 readout channels
10 MHz corresponds to about
5 TeraByte/second detector data

All raw data are kept for 4 micro sec.
after this only selected data can be
written to tape (0.5 GigaByte/second)

Need to develop new detectors +
fast online computers to find high
energy muons from W-boson
decay in less than 4 micro seconds!!
The W-Trigger Upgrade in PHENIX

(I) Develop fast processor boards to identify high energy muons in 4 micro seconds.

(II) Develop fast readout electronics for existing muon tracking chambers

(III) Develop additional fast tracking detectors, RPCs, for timing and background rejection

89 physicists from 18 institutions in the US, Japan, Korea and China:

KEK, Kyoto, RIKEN, Rikkyo, LANL, U. New Mexico, Seoul National University (JSPS funded)

UIUC, RBRC, UC Boulder, ISU, CIAE/PKU, Columbia University, GSU, UC Riverside, Korea University, ACU, Muhlenberg College, Hanyang University (NSF funded)

Construction: September 2005 to January 2012
The Construction Project

- RPCs in Urbana (NSF)
- RPCs in PHENIX (NSF)
- FPGA based level-1 trigger processors
- muTr trigger electronics (JSPS)
- SS 310 absorbers for background rejection
Assembly in the RPC Factory at BNL

 Cosmic RPC test stand
Installation in the PHENIX Spectrometer

PHENIX RPC-1 north (~ 3m)  PHENIX RPC-3 north (diameter ~ 10 m)
Ready for Data Taking in 2013!

W trigger efficiency

W trigger rejection

PHENIX 2kHz Bandwidth