Descent into the Proton

A Journey Inside an Elementary Particle

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Zooming in on the World around us
Atoms

19th century chemistry confirms: there are only 92 different ‘elements’, from hydrogen H to uranium U.

Everything around us is built from combinations of these elements.

Democritus, Greek philosopher ~ 400 B.C:

“All matter is made up of very small indivisible elements”

He called them ‘atomos’.

Descent into the Proton

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Today: we can make atoms visible

Size of the smallest atom (hydrogen):

0.000 000 000 1 m (meter)

= 10^{-10} m = 1 Angstrom

How is it possible to see such tiny structures?
Scattering Experiments

Our vision: the eye collects light reflected from objects and our brain processes the information.

Use this principle:
Shoot a ray of light or particles at an object.
Measure the scattered rays with a detector.

Resolution of the probe (light, particle) is important:
The wavelength must be smaller than the size of the structure to probe.

Light: wavelength 4000 – 7000 Angstrom, too large to see an atom.
Better: X-rays, electrons

Electrons

What is electric current?
In wires there seems to be a flow of very small quantities of negative electric charge carried by tiny particles.

They are called electrons e⁻.

In fact these 'quanta' can be extracted from metals by heating them up → cathode rays.

Basic properties of electrons, measured around 1900:

Electric charge is -e. e = 1.6 × 10⁻¹⁹ C is called the fundamental charge.

Mass = 1/2000 u = 511 keV. 1 u is the mass of the hydrogen atom.

J. J. Thomson (1897): Electrons are small parts of atoms. The first 'subatomic' particle was discovered.
Taking a Look inside an Atom

Atoms are neutral. If they contain electrons there must be an equal amount of positive charge. How does an atom look on the inside?

Compare the following two "scattering experiments":

Professional scientist, closed lab, do not attempt!

1) Shooting at a bag of beans

2) Bag of equal weight but stuffed with cotton and a few small lead beads

Obviously the possible scattering angles of the bullets are different in both cases.

1) Only small angles possible.
2) Some bullets are scattered at large angles.

In 1911 E. Rutherford did this famous experiment with $\alpha$-particles instead of bullets. His target were gold atoms.

Rutherford's result was similar to the second scenario!

The positive charge in an atom and most of its mass is concentrated in a tiny, very dense center, the nucleus.
The Nucleus

More than 99% of the mass of an atom is in the nucleus, which is more than 10,000 times smaller than the atom, about 1 - 10 fm (Fermi).

1 fm = $10^{-5}$ Angstrom = $10^{-15}$ m.

A cloud of electrons orbits the nucleus, held in place by the mutual attraction of the electric charges.

Most of the atom is just empty space!

But with a strong electromagnetic field present.

Nuclei are made up of two particles:
- **Protons** $p$: positive charge $+e$, mass $\approx 1u$
- **Neutrons** $n$: neutral, roughly the same mass as $p$

Protons and neutrons are kept together by a new force: the strong force.

Quantum mechanics tells us that electrons can not be localized. Only a probability can be given for their current position.

⇒ Atomic orbitals.

Atoms: A Modern View

Rutherford, Bohr

Heisenberg

Schroedinger

Quantum mechanics tells us that electrons can not be localized. Only a probability can be given for their current position.

⇒ Atomic orbitals.
**Particles**

We distinguish particles by their ...

- **participation in strong interactions**
  - YES: they are called *hadrons*  
    - e.g. proton, neutron  
  - NO: they are called *leptons*  
    - e.g. electron

- **spin**
  - = Quantized angular momentum  
    - (can take values \(0, \frac{1}{2}, 1, \frac{3}{2}, 2, \text{ etc}\))  
  - Electrons, protons, neutrons: spin \(\frac{1}{2}\ h\)

- **electric charge**
  - positive or negative  
    - usually in multiples of \(e\)

- **mass**
  - usually measured in electronvolts (eV)  
    - \(1 \text{ u} \approx 0.939 \text{ GeV (Gigaelectronvolts, Giga = Billion)}\)

**Particles with integer spin**
- are called *bosons*.

**Particles with half-integer spin**
- are called *fermions*.

**Electrons, protons and neutrons are fermions.**

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**The Hadron Zoo**

In 1940 only 5 elementary particles were known: proton, neutron, electron, muon and positron. With the advent of accelerators at the end of the decade a big 'zoo' of hadrons was discovered.

They could be grouped into one of two categories:

- ❖ Heavier baryons, whose total number is always conserved.  
  - E.g. protons, neutrons

- ❖ Lighter mesons, which can decay into particles which are not hadrons.  
  - E.g. pions, kaons

Remember: hadrons are subject to the strong force, like the proton

Too many! Maybe hadrons are not elementary particles after all?
Gell-Mann & Zweig (1964): the systematics of hadrons could be understood if hadrons consisted of combinations of smaller, more fundamental particles. Those must be fermions (spin-$\frac{1}{2}$) and have fractional charges.

Gell-Mann called them quarks. Nobody believed them.

Deep-Inelastic Scattering (DIS)

How could this hypothesis be tested? A new Rutherford experiment with better resolution!

Introducing: deep-inelastic scattering (DIS), shoot electrons at protons with $E_{cm} > 1$ GeV

Measurement: deflection angle $\theta$
final electron energy $E'$

$\theta$ and $E'$ can be rewritten as two quantities known as $x$ and $Q^2$.

$x = \text{fraction of the proton energy carried by what is hit inside the proton.}$
$Q^2 = \text{resolution of the photon.}$

E.g. proton as a whole: $x=1$.

If it consisted of three equal parts with the same energy, each of those would have $x = 1/3$. 
Deep-Inelastic Scattering (DIS)

DIS scattering formula:
(cross section as function of $\theta$ and $E'$)

$$\frac{d\sigma}{dE'd\Omega} = \left(\frac{\alpha h}{2E \sin^2(\theta/2)}\right)^2 \left[ \frac{2F_1(x,Q^2)}{M} \sin^2(\theta/2) + \frac{2MxF_2(x,Q^2)}{Q^2} \cos^2(\theta/2) \right]$$

"Structure functions" $F_1$ and $F_2$ know about the structure of the proton.

Different predictions had been made.

For the quark model (i.e. proton is a loose collection of point-like spin-$\frac{1}{2}$ fermions):

1) $F_1$, $F_2$ don't depend on $Q^2$ (Bjorken scaling)

2) $F_1$, $F_2$ are not independent: $2xF_F = F_2$ (Callan-Gross relation)

The Discovery of Quarks

The verdict (SLAC, 1968)
SLAC = Stanford Linear Accelerator Center

The Winner is …the Quark Triplet!
Quarks

3 different quarks were initially found: Up, Down and Strange. Three more were found later on.

We know that there are only six quarks in 3 generations:

\[
\begin{array}{ccc}
\text{up} & \text{down} & \text{top} \\
\text{charm} & \text{strange} & \text{bottom} \\
\end{array}
\]

+ their six antiquarks

Increasing mass from 0.002 GeV (up) to 174 GeV (top).

Quark Chromodynamics

How do quarks interact and bind together?

Experimental result: each quark seems to exist in three varieties. The strange new feature was called color.

Each quark has one of three colors: 'red', 'green' or 'blue' (+ 3 anti colors for antiquarks)

1972: the theory of Quantum Chromodynamics is born:

Quarks interact through a new kind of particle, called the gluon. The gluon transmits the strong force, just as photons transmit the electromagnetic force.
**Gluons**

Color is the 'charge' for the strong force, i.e. gluons couple to this color charge.

(just as photons couple to electric charge to transmit the electromagnetic force)

Gluons themselves also carry color. Thus gluons couple to themselves!

This is a direct result of the Yang-Mills theory.

There are 8 different color charges possible for a gluon (3 color)x(3 anti-color)-'white'

**Hadrons = Bound States**

Experimental fact: all hadrons are color neutral.

I.e. the color of the quarks and gluon inside has to add up to 'white'.

- **Meson** = quark + antiquark
- **Baryon** = 3 quarks

Those quarks are called the valence quarks of a hadron.

E.g. the valence quark structure of the proton is \( uud \)
**Asymptotic Freedom**

Puzzle: if the strong force is “strong”, why does the quark model (i.e. hadron = loose collection of quarks) work in deep-inelastic scattering?


The strength of the color coupling increases further away from the color charge.

Strength of a charge is not really constant in quantum field theories, it depends on energy.

At high energies (or when very close) quarks and gluons (partons) interact weakly.

At low energies (or when far apart) quarks and gluons interact strongly.

Running of the strong coupling: theory vs experiment.
Confinement

QCD exhibits another fantastic feature: confinement. No free color charge can exist in the vacuum (remember hadrons are all color neutral).

Quarks and gluons have never been observed in the vacuum.

Confinement has not yet been fully understood.

It has been named one of the outstanding mathematical problems of our time. The Clay Foundation will pay you $1,000,000 if you prove it!

http://www.claymath.org/

| Potential energy of two quarks: Coulomb-like at small distances, linear at large distances. |
| | |
| *V(r) \propto a/r + br* |
| |
| **Gluons moving over large distances form 'flux tubes' between quarks which act like rubber bands.** |
| |
| **Breaking of a flux tube: create a new qq pair, never single quarks** |
| |
| **To pull this quark-antiquark pair apart you need to spend more and more energy.** |
QCD Vacuum

Modern interpretation of a vacuum:
Constant fluctuations of particles coming into existence and annihilating again

D. Leinweber (Adelaide)

A Modern Perspective

From modern DIS experiments:
Accurate parton distributions ($\sim F_2$)

Parton distribution $f(x)$ gives probability that a quark or gluon has a fraction $x$ of the proton's energy.

Parton distributions tell us: there is an unlimited number of quarks and gluons in a proton at any given time. All but the three valence quarks come from quantum fluctuations.

1972: Proton = uud
2008: Proton = uud + gluons + $q$-antiquark pairs
The Spin Puzzle

The spin (i.e. quantized angular momentum) of a proton is \( \frac{1}{2} \). This spin should be “made” by the spins of the quarks inside.

"Spin crisis": All quarks inside a proton only account for 20% of the proton spin.

How can you find out? A polarized Rutherford experiment.

Currently going on: RHIC Spin

The Relativistic Heavy Ion Collider is also the world’s only polarized proton collider.

In our modern view of the proton, there are more sources of spin:

\[
\langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle = \frac{1}{2}
\]

Just measured at RHIC: \( \langle S_g \rangle \) is rather small as well.

Proton spin must come from orbital angular momentum!

Ongoing research, right here at the Cyclotron!
Proton Tomography

We are just starting to understand the 3-D structure of the proton.

Wigner distributions of up quarks in a fast moving proton.

(computed by Ji et al.)

Proton moving this way, look from the top.

Experiment of choice: deeply-virtual Compton scattering (proton stays intact, very rare)

The End

The animation *Secret Worlds: The Universe Within* can be found on the website of the National High Magnetic Field Laboratory at Florida State University.

http://micro.magnet.fsu.edu/primer/java/scienceopticsu/powersof10/

Credit: Florida State University. A Java plugin for the browser is necessary to watch the animation.
The Standard Model

What we have described so far is called the Standard Model of Particle Physics.

The fermions (quarks and leptons) are the building blocks of matter. A set of bosons are the force carriers for the electromagnetic, weak and strong interactions.

Compare the interactions:

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrally Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>W⁺⁻, Z⁰</td>
<td>γ</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength at</td>
<td>(10^{-18} \text{ m})</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>(3\times10^{-17} \text{ m})</td>
<td>(10^{-41})</td>
<td>(10^{-4})</td>
<td>60</td>
</tr>
</tbody>
</table>

The 4th force in nature, gravity, is usually not considered to be a part of the Standard Model. It is EXTREMELY weak.

6 fermions and 6 leptons come in 3 identical generations (only masses are different) Plus they have antiparticles.

Leptons and quarks feel the weak force. Only quarks have color charges and feel the strong force.
Quarks are confined into colorless objects, the hadrons.

Hadrons can be quark-antiquark systems (mesons) or 3 quark systems (baryons)

Of the 24 quarks and leptons in the Standard Model, only 3 are necessary to build atoms and all chemical elements: u, d, e⁻

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>p</td>
<td>antiproton</td>
<td>uud</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>Λ</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>Ω⁻</td>
<td>omega</td>
<td>sss</td>
<td>-1</td>
<td>1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

Mesons q̅q
Mesons are bosonic hadrons
These are a few of the many types of mesons.

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<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>pion</td>
<td>u̅d</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>K⁻</td>
<td>kaon</td>
<td>s̅u</td>
<td>-1</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>ρ⁺</td>
<td>rho</td>
<td>u̅̅d</td>
<td>+1</td>
<td>0.776</td>
<td>1</td>
</tr>
<tr>
<td>B⁰</td>
<td>B-zero</td>
<td>d̅b</td>
<td>0</td>
<td>5.279</td>
<td>0</td>
</tr>
<tr>
<td>η_c</td>
<td>eta-c</td>
<td>e̅c</td>
<td>0</td>
<td>2.980</td>
<td>0</td>
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