Hunting for Quarks and Gluons

Jerry Gilfoyle
University of Richmond

- What we know and don’t know about the sub-atomic world and its forces.
- What we’ll learn with Jefferson Lab (JLab).
- How we measure things - CLAS12.
- What we do.
The structure of matter.

→ Table of Elements (TOE)
What Do We Know About the Structure of Matter?

- The structure of matter.
  → Table of Elements (TOE)
- The current TOE!
  → quarks and leptons.

![Table of Elements (TOE)]

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$ (lightest neutrino)</td>
<td>$(0-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$ (electron)</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_M$ (middle neutrino)</td>
<td>$(0.009-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ (muon)</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$ (heaviest neutrino)</td>
<td>$(0.05-2) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ (tau)</td>
<td>1.777</td>
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<tr>
<td>$u$ (up)</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ (down)</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ (charm)</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ (strange)</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ (top)</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ (bottom)</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
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What Do We Know About the Structure of Matter?

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- We are made mostly of triplets of quarks.
  → protons and neutrons
  → the nucleons
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- The bosons are the force carriers.

### Table of Elements (TOE)

#### Leptons

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<tr>
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#### Quarks

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</tr>
<tr>
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<td>0.005</td>
<td>−1/3</td>
</tr>
<tr>
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<td>2/3</td>
</tr>
<tr>
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<td>0.1</td>
<td>−1/3</td>
</tr>
<tr>
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<tr>
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### FERMIONS

#### Bosons

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<th>Name</th>
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</thead>
<tbody>
<tr>
<td>$\gamma$ photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.39</td>
<td>−1</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.39</td>
<td>+1</td>
</tr>
<tr>
<td>$Z^0$</td>
<td>91.188</td>
<td>0</td>
</tr>
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### BOSONS

#### Force Carriers

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<tr>
<th>Name</th>
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<td>$g$ gluon</td>
<td>0</td>
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- The bosons are the force carriers.

More than 99% of our mass is in quark triplets.
What is the force that holds us together?

- Quarks are bound by the ‘color’ force.
- There are three kinds of ‘color’ charge.
- The quarks are never alone.
  - → confinement
- At high energy the force is weak.
  - → asymptotic freedom

Quantum Chromodynamics


QCD applies only at high energy where the color force is weak.

QCD can’t be solved at nucleon energies where we live.
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Yet!
The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
Where does mass come from?

- The proton is 2 ups + 1 down; the neutron is 1 up + 2 downs.
- A quiz: How much does the proton weigh?

![Table of Fermions]

The table above lists the properties of different fermions, including their mass, electric charge, and spin. The proton is composed of two up quarks and one down quark, contributing to its mass. The neutron is composed of one up quark and two down quarks, also contributing to its mass.
Where does mass come from?

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- A quiz: How much does the proton weigh?

\[ m_p = 2m_{up} + m_{down} \]
Where does mass come from?

- The proton is $2$ ups + $1$ down; the neutron is $1$ up + $2$ downs.
- A quiz: How much does the proton weigh?

$$m_p = 2m_{up} + m_{down} = 2(0.002 \text{ GeV} / c^2) + 0.005 \text{ GeV} / c^2$$

$$= 0.009 \text{ GeV} / c^2$$
Where does mass come from? - **UH-OH!**

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\[
= 0.939 \text{ GeV/c}^2 \quad \text{OOOPS!!!?????}
\]
How do we get out of this?

- The color charge of a quark produces a strong field, e.g. a charged particle.

\[ E = mc^2 \]

Most of the mass we see comes from the quark color fields → gluon cloud!

At JLab we probe the nucleon interior with high-momentum electrons. The momentum/wavelength (\(\lambda\)) of the electrons sample different sizes. At high momentum you probe close to the quarks → bare quark mass. At low momentum you probe the whole cloud.
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We are probing how mass emerges from QCD color fields.
How Do We Measure the Form Factors? - 1

- Build the newest US national lab Jefferson Lab (JLab) in Newport News, VA
- The accelerator CEBAF is a mile-long, racetrack-shaped, superconducting linear accelerator.
- Rapidly varying electric fields push electrons close to 12 GeV.
- Electron beam distributed to four halls.
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It’s a QCD laboratory!
How Do We Measure the Form Factors? - 2

- Build a large (3-story, 45-ton) particle detector called CLAS12 in Hall B.
- Many layers measure debris from electron-target collisions.
- Over 100,000 readouts in \(\approx 40\) layers.
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- Will collect 10-30 TByte each day.
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The usual suspects: Sarah Hu, Jessie Hess, Matthew Hayrich, Ryan Sanford, Alexander Balsamo, Chris Childs, Ben Weinstein, Michael Armstrong, Adrian Saina, Lamya Baashen, old gray-haired guy.

Software is important! We are writing code for:
- analyzing CLAS12 data and simulations.
- extracting the neutron magnetic form factor $G_M^n$ from the $eD \rightarrow e'p(n)$ and $eD \rightarrow e'n(p)$ reactions.
- measuring the neutron detection efficiency (NDE) needed for $eD \rightarrow e'n(p)$ with $ep \rightarrow e'\pi^+ n$.
- determine the CLAS12 NDE in situ.
- establish benchmarks for the CLAS12 event reconstruction resolution.
- install reconstruction unit tests.
- build CLAS12 subsystem geometry.

Ten students over last three years.
Seven presentations at national meetings.
JLab is at the frontier of our understanding of the basic properties of matter including most of the known mass.

Putting QCD on a precise quantitative basis in the nuclear energy regime.

CLAS12 is a large, complex particle detector. Software is the key element to bring it all together.

Our group is feverishly working to understand the deluge of data that has arrived!

Students are using and developing essential tools for handling complex systems with large data sets.
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