Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration
University of Richmond

- Jefferson Lab’s Mission
- What we know.
- What we don’t know.
- What we measure.
- Experiments with CLAS12
- Concluding Remarks

"The Periodic Table"
What is the Mission of Jefferson Lab?

- Basic research into the quark nature of the atomic nucleus.
- Map the geography of the transition from proton-neutron picture of nuclei to one based on quarks and gluons.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
- Test the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.
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One of the seven Millennium Prize Problems from the Clay Mathematics Institute.
What Do We Know?

- The Universe is made of quarks and leptons and the force carriers.
- The atomic nucleus is made of protons and neutrons bound by the strong force.
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.

### FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e electron</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>ν_x middle neutrino</td>
<td>(0.009−2)×10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td>ν_x heaviest neutrino</td>
<td>(0.05−2)×10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td>τ tau</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

### Quarks

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<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>
</table>

### Bosons

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ 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>Z⁰</td>
<td>91.188</td>
<td>0</td>
</tr>
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### Higgs Boson

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>126</td>
<td>0</td>
</tr>
</tbody>
</table>

**The Nucleus**

- Neutrons hold their neutrons together by the strong interaction.
- Neutron and quark motions are maintained by gluons, but nucleons are held together by the strong interaction between the gluons and the quarks.
- Nuclear physics is the study of how neutrons and protons interact among themselves.
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What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.
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![Graph showing the force at different radii with 3 tons marked at the peak.](image)
What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.

- The hadronic model uses a phenomenological force fitted to data at low energy. This ‘strong’ force is the residual force between quarks.
How Well Do We Know It?

- We have a working theory of strong interactions: quantum chromodynamics or QCD (B. Abbott, et al., Phys. Rev. Lett., 86, 1707 (2001)).

- The coherent hadronic model (the standard model of nuclear physics) works too (L.C. Alexa, et al., Phys. Rev. Lett., 82, 1374 (1999)).
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What Don’t We Know?

- Matter comes in pairs of quarks or triplets.
- We are mostly triplets (protons and neutrons).
- More than 99% of our mass is in nucleons.
- Proton $\rightarrow 2$ ups $+ 1$ down.
- Neutron $\rightarrow 1$ up $+ 2$ downs.

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<tr>
<td>$\mu$ muon</td>
<td>0.106</td>
<td>$−1$</td>
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- A quiz: How much does the proton weigh?

<table>
<thead>
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<th>Leptons spin $= 1/2$</th>
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\[ m_p = 2m_{up} + m_{down} \]
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$$m_n - m_p = 1.29333205(48)\text{ MeV}/c^2 \quad \text{(exp)}$$

$$= 1.51(16)(23)\text{ MeV}/c^2 \quad \text{(th)}$$

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Hunting for Quarks
What Don’t We Know?


2. NEED TO FIGURE OUT QCD AT THE ENERGIES OF NUCLEI!!
What Do We Measure?

The Magnetic Form Factor of the Neutron ($G_n M$)

Fundamental quantity related to the distribution of magnetization/currents in the neutron. Needed to extract the distribution of quarks in the neutron.

Elastic form factors ($G_n M, G_n E, G_p M,$ and $G_p E$) provide key constraints on theory and the structure of hadrons.

Part of a broad effort to understand how nucleons are 'constructed from the quarks and gluons of QCD'.

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What is a Form Factor?

- Start with the cross section.

\[
\frac{d\sigma}{d\Omega} = \frac{\text{scattered rate/solid angle}}{\text{incident rate/surface area}}
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For elastic scattering use the Rutherford cross section.

\[
\frac{d\sigma}{d\Omega} = \frac{Z_{\text{tgt}}^2}{Z_{\text{beam}}^2} \alpha^2 \left(\frac{\hbar c}{E}\right)^2 \frac{1}{16E^2 \sin^4(\theta/2)} \left(1 - \beta^2 \sin^2 \theta \right)^2 (\text{Mott cross section})
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where \(Q^2\) is the 4-momentum transfer.
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- Cross section for elastic scattering by point particles with spin.
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- What happens when the beam is electrons and the target is not a point?
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where \( Q^2 \) is the 4-momentum transfer.

THE FORM FACTOR!
Why Should You Care?

- The chain of reason.

\[ \frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow_{\text{QCD, Constituent quarks}} \]

Experiment \hspace{1cm} Comparison \hspace{1cm} Theory

The form factors are the meeting ground between theory and experiment.

- The Fourier transform of the form factors are related to the charge and current distributions within the neutron.
Why Should You Care Even More?

- The old picture of the neutron (and proton).
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What We’ll Learn - Flavor Decomposition

- With all four EEFFs we can unravel the contributions of the $u$ and $d$ quarks.
  \[ F_u^{1(2)} = 2F_p^{1(2)} + F_n^{1(2)} \quad F_d^{1(2)} = 2F_n^{1(2)} + F_p^{1(2)} \]
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- Agreement with Nambu-Jona-Lasinio model encouraging - no parameter fits to the EEFFs.


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The JLab program will double our reach in $Q^2$ to $\approx 8 \text{ GeV}^2$. 

Evidence of di-quarks? $d$-quark scattering probes the diquark.
What We’ll Learn - Dyson-Schwinger Eqs

- Equations of motion of quantum field theory.
  - Infinite set of coupled integral equations.
  - Inherently relativistic, non-perturbative, connected to QCD.
  - Deep connection to confinement, dynamical chiral symmetry breaking.
  - Infinitely many equations, gauge dependent → Choose well!

- Recent results (Cloët et al).
  - Model the nucleon dressed quark propagator as a quark-diquark.
  - Damp the shape of the mass function $M(p)$.

![Graph showing the dependence of $M(p)$ on $p$](image1)

Cloët et al
PRL 111, 101803 (2013)

![Graph showing the dependence of $\mu_p G_E/p G_M$ on $Q^2$](image2)

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Hunting for Quarks

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Position of zero in $\mu_p G_E^p/G_M^p$ and $\mu_n G_E^n/G_M^n$ sensitive to shape of $M(p)$!
Based on connections between light-front dynamics, it's holographic mapping to anti-de Sitter space, and conformal quantum mechanics.

Recent paper by Sufian et al. (Phys. Rev. D95, 01411 (2017)) included calculations of the electromagnetic form factors that include higher order Fock components $|qqqq\bar{q}\rangle$.

Obtain good agreement with all the form factor data with only three parameters, e.g. $\mu_n G_E^n / G_M^n$. 

![Graph showing comparison of LFHQCD and world data for $\mu_n G_E^n / G_M^n$ vs. $Q^2$. The graph includes data points and curves for LFHQCD with different values of $r$.]
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### The JLab Lineup

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Method</th>
<th>Target</th>
<th>(Q^2(\text{GeV}^2))</th>
<th>Hall</th>
<th>Beam Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>(G_M^p) *</td>
<td>Elastic scattering</td>
<td>(LH_2)</td>
<td>7 – 15.5</td>
<td>A</td>
<td>24</td>
</tr>
<tr>
<td>(G_E^p/G_M^p)</td>
<td>Polarization transfer</td>
<td>(LH_2)</td>
<td>5 – 12</td>
<td>A</td>
<td>45</td>
</tr>
<tr>
<td>(G_M^n)</td>
<td>(E - p/e - n) ratio</td>
<td>(LD_2, LH_2)</td>
<td>3.5 – 13.0</td>
<td>B</td>
<td>30</td>
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<td>A</td>
<td>25</td>
</tr>
<tr>
<td>(G_E^n/G_M^n)</td>
<td>Double polarization asymmetry</td>
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<td>A</td>
<td>50</td>
</tr>
<tr>
<td>(G_E^n/G_M^n)</td>
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<td>4 – 7</td>
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* Data collection is complete.

**PAC approval for 229 days of running in the first five years.**
How Do We Measure $G_M^n$ on a Neutron? (Step 1)

- Start at your local mile-long, high-precision, 12-GeV electron accelerator.
- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.
- Electrons do up to five laps, are extracted, and sent to one of three experimental halls.
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How Does CEBAF Do That?

Accelerate your electrons to high energy.

What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each hall beam buckets are about 2 picoseconds long and arrive every 2 nanoseconds.
How Do We Measure $G_M^n$ on a Neutron? (Step 2)

- Add one 45-ton, $80$-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
- CLAS covers a large fraction of the total solid angle at forward angles.
- Has about 62,000 detecting elements in about 40 layers.
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- Add one 45-ton, $80$-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.

Other layers measure energy, time-of-flight, and particle identification.

Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.

Scatter electrons off protons and deuterons (proton+neutron).
A CLAS12 Event

[Diagram showing various components of a CLAS12 event, including drift chambers, Cherenkov detectors, and calorimeters, with arrows indicating Time-of-flight measurements.]
A Simulated CLAS12 Event - Drift Chamber close-up
A Simulated CLAS12 Event - Drift Chamber close-up
A Real CLAS12 Event - Building the Drift Chambers
A Real CLAS12 Event - Building the Drift Chambers

Jerry Gilfoyle
Hunting for Quarks
A Real CLAS12 Event - Building the Drift Chambers
A Simulated CLAS12 Event - Calorimeter close-up
A Simulated CLAS12 Event - Calorimeter close-up
A Simulated CLAS12 Event - Calorimeter close-up
A Simulated CLAS12 Event - Calorimeter close-up
A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Time-of-Flight close-up
A Simulated CLAS12 Event - Summary
A Simulated CLAS12 Event - Cherenkov close-up

Cherenkov Counter will go here.

155 cm
A Simulated CLAS12 Event - Cherenkov close-up
A Simulated CLAS12 Event - Cherenkov close-up
A Simulated CLAS12 Event - Cherenkov close-up

- Cherenkov Light
- Electron Calorimeters
- Mirrors

Calorimeters
Elliptical Mirrors
Hyperbolical Mirrors
Photomultiplier and Magnetic Shielding
Winston Cones

Light

MIRRORS

Electron
Simulated CLAS12 Events

Forward Detector

Central Detector

EC/PCAL
DC
HTCC
Solenoid
FTOF
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)
Putting It All Together - 3

6/24/2017
How Do We Measure $G^n_M$ on a Neutron? (Step 3)

- Where’s my target?
  
  Use a dual target cell with liquid hydrogen and deuterium.

- How bad do the protons mess things up? They help!

\[ R = \frac{d\sigma}{d\Omega}(D(e, e'n)) \frac{\sigma}{d\Omega}(D(e, e'p)) = a(Q^2) \frac{G^n_E^2 + \tau G^n_M^2}{1 + \tau} + 2\tau G^n_M^2 \tan^2\left(\frac{\theta}{2}\right) \]

- The ratio is less vulnerable to corrections like acceptance, efficiencies, etc.

- Use the dual target to perform *in situ* detector calibrations.
How Do We Measure $G_M^n$ on a Neutron? (Step 4)

- Quasi-elastic event selection: Apply a maximum $\theta_{pq}$ cut to eliminate inelastic events plus a cut on $W^2$ (J.Lachniet thesis).

- Use the $ep \rightarrow e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.
How Do We Measure $G_M^n$ on a Neutron? (Step 5)

Analyzing the data - CLAS12 computing requirements.

<table>
<thead>
<tr>
<th></th>
<th>Cores</th>
<th>Disk (TBytes)</th>
<th>Tape (TByte/year)</th>
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</thead>
<tbody>
<tr>
<td>DAQ</td>
<td></td>
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<td>1,270</td>
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<tr>
<td>Calibration</td>
<td>173</td>
<td>508</td>
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<tr>
<td>Reconstruction</td>
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<tr>
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<td>318</td>
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<tr>
<td>Reconstruction Studies</td>
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<tr>
<td>Physics Analysis</td>
<td>607</td>
<td>889</td>
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<tr>
<td>Sum</td>
<td>11,520</td>
<td>2,223</td>
<td>7,938</td>
</tr>
</tbody>
</table>

We'll collect 5-10 TByte/day!

Intel Many-Integrated CoProcessor computer
Anticipated Results

\[ \frac{G^n_M}{\mu_n G^D_n} \]

\( Q^2 \) (GeV\(^2\))

Red - J.Lachniet et al.
Green - Previous World Data
Black - CLAS12 anticipated
Blue - Hall A anticipated (with systematic uncertainties)

Anticipated
Statistical uncertainties only

Miller
Guidal et al.
Cloet et al.
By measuring all four EEFFs we have an opportunity to unravel the contributions of the $u$ and $d$ quarks.


$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n$$

$$F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p$$

- $u$ and $d$ are different.
- AND different from the proton and neutron form factors.
- Evidence of di-quarks, $s$ quark influence, ...?
Concluding Remarks

- JLab is a laboratory to test and expand our understanding of quark and nuclear matter, QCD, and the Standard Model.
- We continue the quest to unravel the nature of matter at greater and greater depths.
- Lots of new and exciting results are coming out.
- A bright future lies ahead in the 12 GeV Era.
Additional Slides
What’s going on now?

Alignment and commissioning of the silicon vertex tracker (SVT).
Check alignment with Type1 cosmic ray tracks

Type 1 tracks.
Check alignment with Type 1 cosmic ray tracks.

Type 1 tracks.
Students from Richmond (and one from Surrey) visit JLab CLAS12 detector.
Life on the Frontiers of Knowledge

Jerry Gilfoyle

Hunting for Quarks
How Do We Measure $G_M^n$ on a Neutron? (Step 1)

- Start at your local mile-long, high-precision, 12-GeV electron accelerator.

- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.

- Electrons do up to five laps, are extracted, and sent to one of three experimental halls.

- All three halls can run simultaneously.
How Do We Measure $G^n_M$ on a Neutron? (Step 2)

- Add one 45-ton, $50$-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS).

- CLAS covers a large fraction of the total solid angle.

- Has about 35,000 detecting elements in about 40 layers.
Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.

Other layers measure energy, time-of-flight, and particle identification.

Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.
A CLAS Event
How Do We Measure $G_M^n$ on a Neutron? (Step 3)

- Where’s my target?
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$$R = \frac{\frac{d\sigma}{d\Omega}(D(e, e'n))}{\frac{d\sigma}{d\Omega}(D(e, e'p))} = a(Q^2) \left( \frac{G_E^n + \tau G_M^n}{1 + \tau} \frac{G_E^n + \tau G_M^n}{1 + \tau} + 2\tau G_M^n \tan^2(\frac{\theta}{2}) \right)$$

- The ratio is less vulnerable to corrections like acceptance, efficiencies, etc.

- Use the dual target to perform in situ detector calibrations.
Overlapping measurements of $G_M^n$ scaled by the dipole are consistent.
Results - Comparison with Existing Data

Comparison of the ratio of the magnetic form factors $G_M^n/\mu_n G_D$ as a function of $Q^2 (\text{GeV}^2)$ with existing data.

- **CLAS**
- **Lung**
- **Kubon**
- **Anklin**
- **Arnold**
- **Xu**
- **Anderson**

Legend:
- Green band - Diehl
- Solid - Miller
- Dashed - Guidal

Systematic Uncertainty

Data points are shown along with error bars representing systematic uncertainties.
Results - Comparison with Existing Data

Systematic Uncertainty

- CLAS
- Kubon
- Anklin
- Green band - Diehl
- Lung
- Bartel
- Arnold
- Solid - Miller
- Xu
- Anderson
- Dashed - Guidal

\[ G_{M/n}^n / \mu_n G_D \]

\[ Q^2 (\text{GeV}^2) \]
The electron beam energy at JLab (CEBAF) has been doubled from 6 GeV to 12 GeV.

Halls A, B and C will be upgraded to accommodate the new physics opportunities.

A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.
JLab 12 GeV Upgrade - New Detectors

The CEBAF Large Acceptance Spectrometer at Jefferson Lab

- Drift Chambers
  - 35,000 wires
  - $\sigma_r = 350$ $\mu$m

- Superconducting Toroidal Magnet
  - $B_{0} = 1.7$ T

- Cerenkov Counters
  - 216 channels
  - 99.5\% efficiency over 50 m$^2$ area

- Electromagnetic Shower Calorimeters
  - 1700+ channels
  - $\varepsilon/E = 10\% E^{0.5}$

- Time of Flight Counters
  - 500+ channels, 145 ps resolution

- Electron beam direction
Rutherford Trajectories

Rutherford trajectories for different impact parameters
What is an Angle?
What is an Angle?

\[ d\theta = \frac{ds}{|\vec{r}|} \]
Solid Angle
Solid Angle

\[
\theta \quad \frac{\theta + d\theta}{\theta + d\theta} \\
\phi \quad \frac{\phi + d\phi}{\phi + d\phi}
\]
Solid Angle

\[
\begin{align*}
\theta & \quad \theta + d\theta \\
\theta + d\theta & \quad \phi + d\phi
\end{align*}
\]
Solid Angle

\[ \theta, \theta + d\theta, \phi, \phi + d\phi \]
Solid Angle

\[ dA = r \sin \theta \, d\theta \, d\phi \]

\[ d\Omega = \frac{dA}{r^2} = \sin \theta \, d\theta \, d\phi \]
Solid Angle

\[ dA = r \, d\theta \times r \sin \theta \, d\phi = r^2 \sin \theta \, d\theta \, d\phi \]
Solid Angle

\[ dA = r \, d\theta \times r \sin \theta \, d\phi = r^2 \sin \theta \, d\theta \, d\phi \]

\[ d\Omega = \frac{dA}{r^2} = \sin \theta \, d\theta \, d\phi \]
Rutherford Scattering Results From Rutherford

H. Geiger and E. Marsden, Phil. Mag., 25, p. 604 (1913)
alphas on gold

Huffman et al., PRC 22, 1522 (1980)
H. Geiger and E. Marsden, Phil. Mag., 25, p. 604 (1913)

alphas on gold

Huffman et al., PRC 22, 1522 (1980)

$^6\text{Li} + ^{208}\text{Pb}$

$E_{\text{lab}} = 73.7$ MeV
Plots showing the dependence of differential cross section $d\sigma/d\Omega$ on the scattering angle $\theta_s$ for two different energies. The left plot is for $E_{cm} = 23.65$ MeV, $^4\text{He} + ^{197}\text{Au}$ (Blue). The right plot is for $E_{cm} = 27.95$ MeV, $^4\text{He} + ^{197}\text{Au}$ (Green). The curve represents Rutherford scattering.
Plotting the Homework (no. 10)

$E_{cm} = 23.65 \text{ MeV}, ^4\text{He} + ^{197}\text{Au} \text{ (Blue)}$

$E_{cm} = 27.95 \text{ MeV}, ^4\text{He} + ^{197}\text{Au} \text{ (Green)}$

Curve - Rutherford scattering

$E_{cm} = 23.65 \text{ MeV}, ^4\text{He} + ^{197}\text{Au} \text{ (Blue)}$

$E_{cm} = 27.95 \text{ MeV}, ^4\text{He} + ^{197}\text{Au} \text{ (Green)}$