Studying Nuclear Structure with Electron Scattering

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Outline

Introduction

Electron Scattering Experiments

Structure of the Proton

Nucleons in the Nucleus

Summary

Smaller, smaller

- Quest for basic building blocks of the universe
- The concept of *atom* by Greeks
  - *atom*: indivisible, fundamental building block
- *Modern* atoms are composed of *nuclei* and *electrons*
- *Nucleus* is composed of *protons* and *neutrons*
  - Oxygen atom (O) has 8 electrons and a nucleus with 8 *protons* and 8 *neutrons*
- *Nucleons* (protons and neutrons) are composed of quarks, gluons
  - In naïve quark model, proton has 2 u quarks and 1 d quark.

Observing *atoms*, or anything else

- Optical microscope
  - Send light to the object
  - Re-emitted light is focused/magnified by lenses
  - Human eye detects the light
  - Image recognized in the brain
  - Resolution: λ of visible light (1000 angstrom or 100 nm)
- Electron microscope
  - Send electron beam to the object
  - Scattered electrons are focused/magnified by coils
  - Phosphor screen detects scattered electrons
  - Human eye sees the image
  - Resolution: λ of electron matter wave (typically 0.2 nm)

Observing *Nucleus*

- Size of the nucleus: a few fm (femto meter, or *fermi*, 1 fm = 10^{-15}m)
- Requires electron beam at higher energies (100's of MeV)

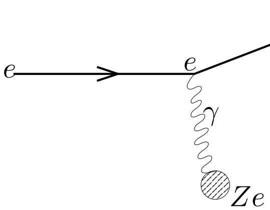
$$\hbar c = 197\text{MeV} \cdot \text{fm}$$

- Electron beam is prepared by *accelerators*
- Focusing/bending electrons are done by *magnets*
- Sophiscated detector system for the electrons.
- Observe number of scattered electrons as a function of angle and energy
- Reconstruction of *image* from the cross section

Why use electrons?

- One of *elementary* particles
  - point-like *without* internal structure
  - stable particle
  - well-known properties (mass, charge, spin *etc*)
  - well-known interaction with other elementary particles (*e.g.* quarks)
- Relatively easy to prepare (compare to other leptons or quarks)
- Easy to detect
- In general, experiments are quite *clean* compared to those with hadron beams

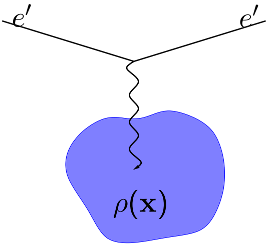
Electron Scattering from a Point Charge



- Rutherford-*like* scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{point}} \equiv \left(\frac{d\sigma}{d\Omega}\right)_{\mathsf{Mott}} = \frac{(Z\alpha)^2\cos^2\frac{\theta}{2}}{4E^2\sin^4\frac{\theta}{2}}$$

Probing the Nucleus



- Fermi's Golden Rule

$$\frac{d\sigma}{d\Omega} = \frac{2\pi}{\hbar} \left|\mathcal{M}_{fi}\right|^2 D_f$$

- $\mathcal{M}_{fi}$: scattering amplitude
- D_f: density of the fi nal states (or *phase factor*)

Potential Scattering Amplitude

$$\mathcal{M}_{fi} = \int \psi_f^* V(\mathbf{x}) \psi_i \, d^3\mathbf{x}$$
$$= \int e^{-i\mathbf{k}_f \cdot \mathbf{x}} V(\mathbf{x}) e^{i\mathbf{k}_i \cdot \mathbf{x}} \, d^3\mathbf{x}$$
$$= \int e^{i\mathbf{q} \cdot \mathbf{x}} V(\mathbf{x}) \, d^3\mathbf{x}$$

- Plane wave approximation for incoming and outgoing electrons
- Born approximation (interact only once)

Form Factor and Charge Distribution

Using Coulomb potential from a charge distribution $\rho(\mathbf{x})$,

$$V(\mathbf{x}) = -\frac{Ze^2}{4\pi\varepsilon_0}\int \frac{\rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\, d^3\mathbf{x}'$$

$$\begin{aligned}
\mathcal{M}_{fi} &= -\frac{Ze^2}{4\pi\varepsilon_0}\int e^{i\mathbf{q}\cdot\mathbf{x}}\int \frac{\rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\, d^3\mathbf{x}'\, d^3\mathbf{x} \\
&= -\frac{Ze^2}{4\pi\varepsilon_0}\int e^{i\mathbf{q}\cdot\mathbf{R}}\left[\int \frac{e^{i\mathbf{q}\cdot\mathbf{x}'}\rho(\mathbf{x}')}{|\mathbf{R}|}\, d^3\mathbf{x}'\right] d^3\mathbf{R} \\
&= -\frac{Ze^2}{4\pi\varepsilon_0}\int \frac{e^{i\mathbf{q}\cdot\mathbf{R}}}{\mathbf{R}}\, d^3\mathbf{R}\int e^{i\mathbf{q}\cdot\mathbf{x}'}\rho(\mathbf{x}')\, d^3\mathbf{x}' \\
F(\mathbf{q}) &= \int e^{i\mathbf{q}\cdot\mathbf{x}'}\rho(\mathbf{x}')\, d^3\mathbf{x}'
\end{aligned}$$

Form Factor and Cross Section

- For point-like particle, $\rho(\mathbf{x}') = \delta(\mathbf{x}')$ and $F(\mathbf{q}) = 1 \rightarrow$ Rutherford-*like* scattering

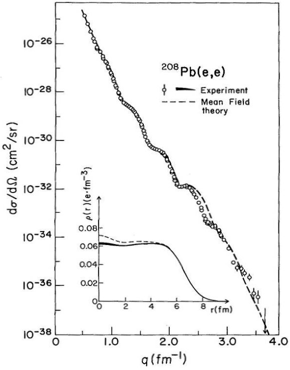
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{point}} \equiv \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{(Z\alpha)^2 \cos^2 \frac{\theta}{2}}{4E^2 \sin^4 \frac{\theta}{2}}$$

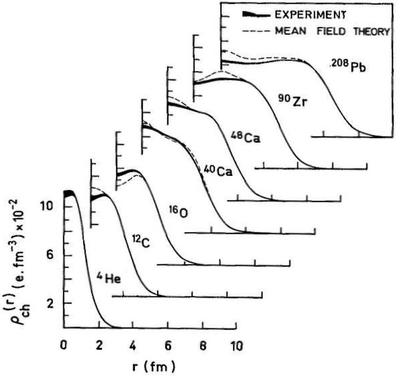
- Scattering from a charge distribution

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} |F(\mathbf{q})|^2$$

Charge Distribution in the Nucleus

- Measurement of $F(\mathbf{q})$ (from cross section)
- Inverse Fourier transform gives $\rho(\mathbf{x})$





Probing Inside the Proton

- For a target with *non-zero* spin - form factors for *charge* and *magnetization*

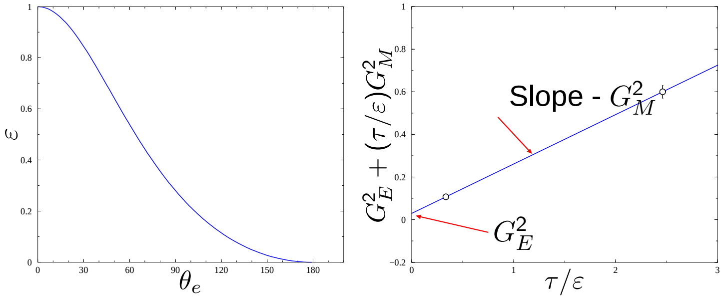
$$\frac{d\sigma}{d\Omega}_{\text{lab}} = \left(\frac{\alpha^2 E'^2 \cos^2 \frac{\theta}{2}}{4E^3 \sin^4 \frac{\theta}{2}} \right) \left[(G_E^p)^2 + \frac{\tau}{\varepsilon} (G_M^p)^2 \right] \left(\frac{1}{1+\tau} \right)$$

$$\tau \equiv \frac{Q^2}{4M^2}, \quad \frac{1}{\varepsilon} = 1 + 2(1+\tau) \tan^2 \frac{\theta}{2}$$

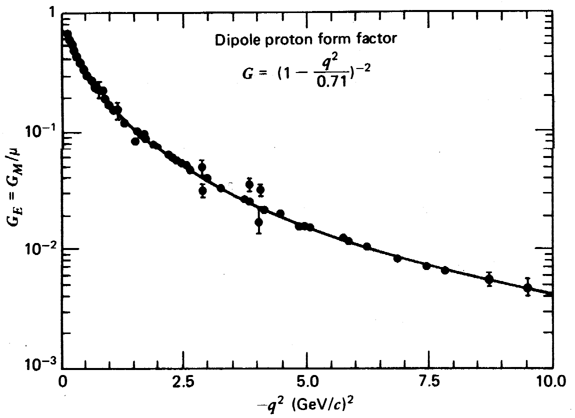
G_E^p distribution of charge inside the proton

G_M^p distribution of magnetization inside the proton

Rosenbluth Separation



Electric and Magnetic Form Factor of the Proton



- Conclusion: $G_E^p(Q^2) = G_M^p(Q^2)/\mu_p$

New Method to Measure Proton Form Factors

- Use of *polarized* electron beam
- Measure polarization *transfer* to the proton

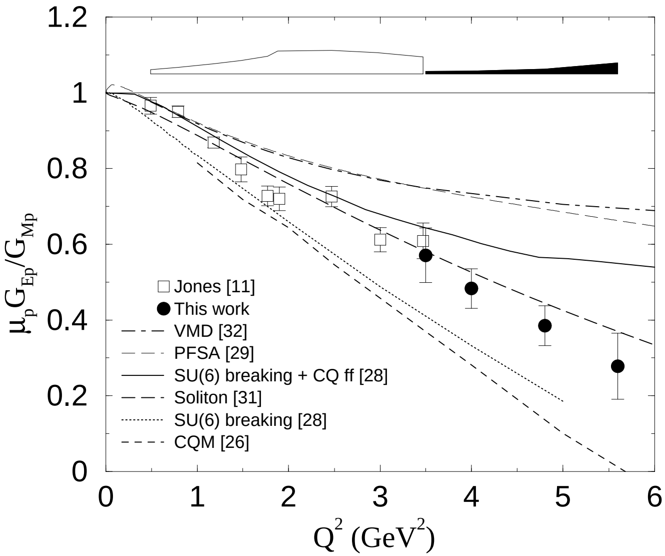
$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E^p G_M^p \tan\frac{\theta}{2}$$

$$I_0 P_l = \frac{(E+E')}{M}\sqrt{\tau(1+\tau)}(G_M^p)^2 \tan^2\frac{\theta}{2}$$

$$I_0 = (G_E^p)^2 + \frac{\tau}{\varepsilon}(G_M^p)^2$$

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{(E+E')}{2M}\tan\frac{\theta}{2}$$

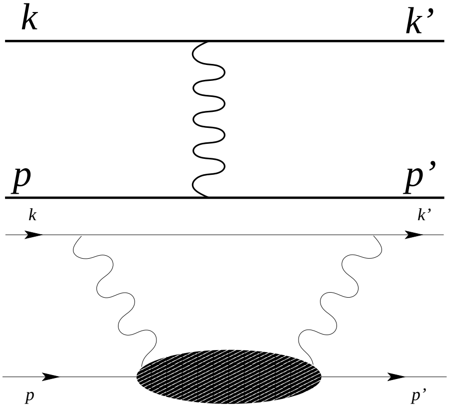
Surprise!



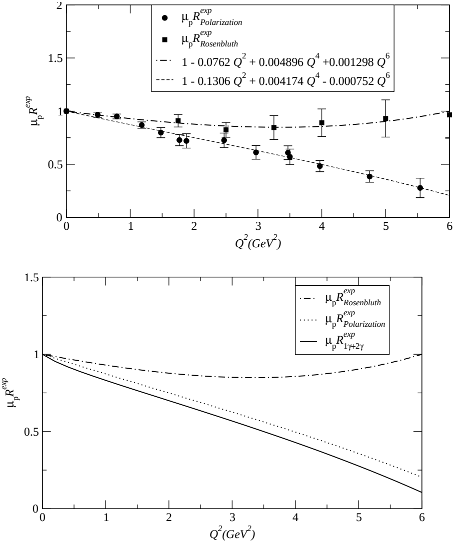
1.2
1
0.8
0.6
0.4
0.2
0
$\mu_p G_{Ep}/G_{Mp}$
Jones [11]
This work
VMD [32]
PFSA [29]
SU(6) breaking + CQ ff [28]
Soliton [31]
SU(6) breaking [28]
CQM [26]
0
1
2
3
4
5
6
Q^2 (GeV^2)

Why?

- Same object, two different way of looking
- Current smoking gun $\longrightarrow$ Rosenbluth separation
  - Initial assumption: Born approximation (one photon exchange)
  - At large Q^2, two photon exchange needs to be considered

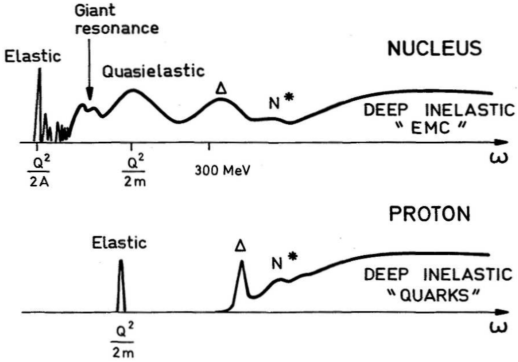


One Possibility



Protons Inside the Nucleus

- *Quasi*-elastic scattering - scattering from the bound protons inside the nucleus
- Useful tool to investigate nucleon properties inside the nucleus



Cross Section

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_{\text{Mott}} \left[\frac{Q^4}{q^4} R_L(q,\omega) + \frac{Q^2}{2q^2} \frac{1}{\varepsilon} R_T(q,\omega) \right]$$

- $R_L(q,\omega)$, $R_T(q,\omega)$: Response functions
- Analogy of G_E^p and G_M^p of the free proton
- $R_L(q,\omega)$ characterizes charge interaction in the nucleus.
- Coulomb Sum

$$S_L(q) = \int_{\omega_{\text{el}}^+}^{\infty} d\omega \frac{R_L(q,\omega)}{Z \tilde{G_E}^2(Q^2)}$$

$$\tilde{G_E}^2(Q^2) = \left([G_E^p(Q^2)]^2 + (N/Z)[G_E^n(Q^2)]^2\right) \frac{1+Q^2/4M^2}{1+Q^2/2M^2}$$

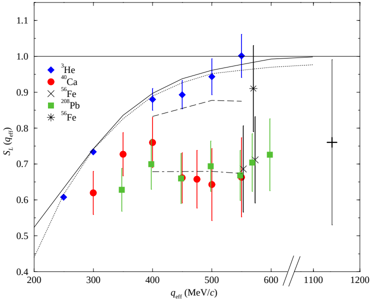
Coulomb Sum Rule

- By defi nition, $S_L(q) = 1$ for the free proton
- Saturation of the Coulomb Sum

  $S_L(q) \rightarrow 1$ at suffi ciently large q
- Deviation of the Coulomb Sum Rule
  - at small q – Nucleon-nucleon long-range correlations and Pauli blocking
  - at large q – Short range correlations and modification of the free nucleon electromagnetic properties inside the nuclear medium
- Nuclear density dependence (^{4}He to ^{208}Pb)
- Related to chiral symmetry restoration in dense nuclear medium

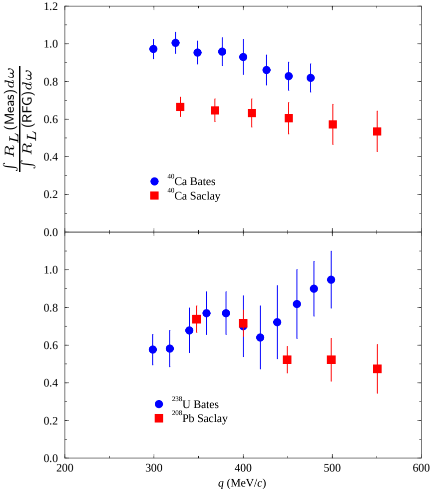
Measurements

- For the past twenty years, a large experimental program at Bates, Saclay and SLAC
- Limited kinematic coverage in q and ω due to machine limitations



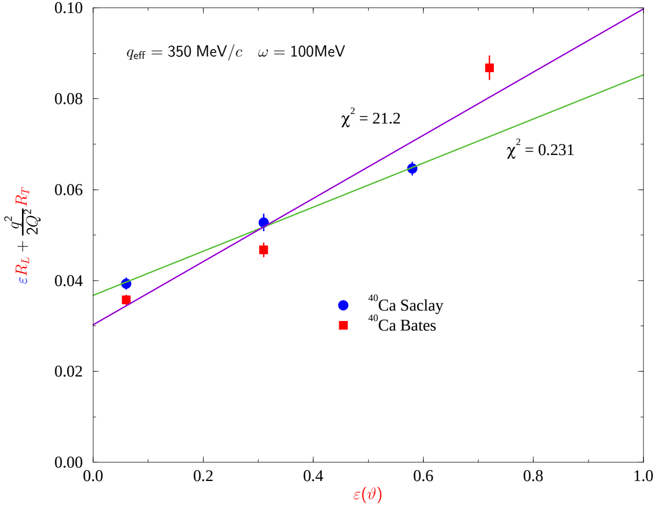
❇ The fi gure does NOT include all the existing data. Especially, MIT Bates results are not included.

Controversy

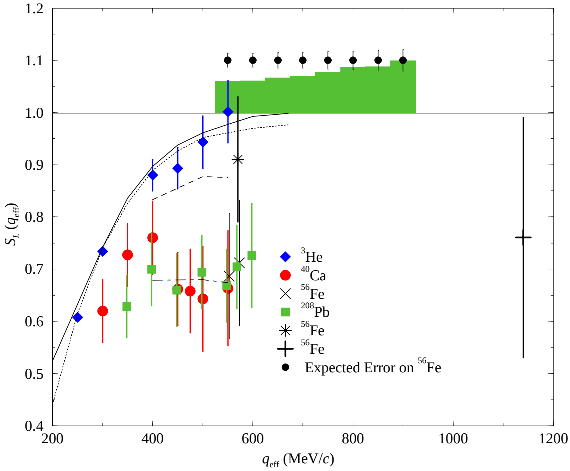


- Early data shows significant quenching of the CSR.
- With the addition of forward angle data, Bates claims no significant quenching.
- Saclay new analysis claims that quenching persists.

Saclay(France) vs. MIT(US)



New Proposed Experiment at JLab



Summary

- Electron Scattering Experiments
  - One of the main tools in nuclear physics research
  - Charge density of the nucleus - Comparison with theoretical model
  - Structure of the proton (charge and magnetization)
- New challenge
  - Surprising results on G_E^p/G_M^p from JLab
  - Two photon exchange effect - more study in theory and experiment
- Nucleons inside the nucleus
  - Change *or* no change, that is the question.
  - Controversial results on the Coulomb Sum
  - Proposed experiment will give a definitive answer
- Probing quarks
  - Existence and interaction of quarks
  - Study of the quark spins