JLab Measurements of the Few-Body Elastic Form factors

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Few-Body Form Factors (FFs)

- Extracted from cross section measurements of elastic electron scattering from light nuclei (A=2,3,4).
- They determine the nuclear charge and magnetization distributions and their associated radius.
- Are sensitive probes of:
  - Nucleon-nucleon potential
  - Meson-exchange currents
  - Multi-quark component in nuclear wave function
  - Three-body force effects (A=3,4)
- Expected to uncover, at large $Q^2$, a possible transition in the description of elastic scattering, from meson-nucleon to quark-gluon degrees of freedom.
Elastic Electron-Deuteron Scattering

• Charge, Quadrupole and Magnetic Form Factors:

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E'}{4E^3 \sin^4(\frac{\theta}{2})} \left[ A(Q^2) \cos^2(\frac{\theta}{2}) + B(Q^2) \sin^2(\frac{\theta}{2}) \right]
\]

\[
A(Q^2) = F_C^2(Q^2) + \frac{8}{9} \tau^2 F_Q^2(Q^2) + \frac{2}{3} \tau F_M^2(Q^2)
\]

\[
B(Q^2) = \frac{4}{3} \tau (1 + \tau) F_M^2(Q^2)
\]

\[
\tau = Q^2 / 4M^2 \quad Q^2 = 4EE' \sin^2(\theta / 2)
\]

• Tensor Polarization from polarized e-d scattering:

\[
\tilde{t}_{20} = \sqrt{2} \frac{y(2 + y)}{1 + 2y^2} \quad y = \frac{2}{3} \tau \frac{F_Q}{F_C}
\]

• Half a century of experimental and theoretical work!
Elastic Electron-Helium/Tritium Scattering

- $^3$He and $^3$H Charge and Magnetic Form Factors:

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2 E'}{4E^3 \sin^4\left(\frac{\theta}{2}\right)} \left[ A(Q^2)\cos^2\left(\frac{\theta}{2}\right) + B(Q^2)\sin^2\left(\frac{\theta}{2}\right) \right]$$

$$A(Q^2) = \frac{F_C^2(Q^2) + \tau\mu^2 F_M^2(Q^2)}{1 + \tau}$$

$$B(Q^2) = 2\tau\mu^2 F_M^2(Q^2)$$

$$Q^2 = 4EE'\sin^2(\theta/2)$$

$$\tau = Q^2 / 4M^2$$

- $^4$He Charge Form Factor:

$$\frac{d\sigma}{d\Omega} = \frac{Z^2\alpha^2 E' \cos^2\left(\frac{\theta}{2}\right)}{4E^3 \sin^4\left(\frac{\theta}{2}\right)} F_C^2(Q^2)$$

- Half a century of experimental and theoretical work!
Non-Relativistic Impulse Approximation (IA)

- Few-Body FFs are, simplistically in the IA, convolutions of the nuclear wave functions with the nucleon form factors.
- **Deuteron**
  - Ground state is solved using the Schrödinger equation with a realistic $N-N$ potential.
  - All calculations are complemented by Meson Exchange Currents (MEC).
- **Helium-Tritium**
  - Ground state is solved using the coupled Faddeev equations ($^3\text{He},^3\text{H}$) or Faddeev-Yakubovski equations ($^4\text{He}$) with a realistic $N-N$ potential, or
  - Variational or Green’s Functions Monte Carlo Methods.
  - All calculations are complemented by MEC and selected diagrams of Three-Body Force Effects (3BFE).
“Few-body form factors are the observables of choice for testing the $N-N$ interaction and the associated current operator” (Laura Marcucci et al.)
Relativistic Approaches

Deuteron

- **Propagator Dynamics**: Ground state is solved using three-dimensional reductions of Bethe-Salpeter (BS) equation [also called as Relativistic Impulse Approximation (RIA)]:
  - Quasi-potential approximation: Gross spectator equation or Blankenbeckler-Sugar equation
  - Equal-time approximation: Wallace-Mandelzweig equation
  - Both methods are complemented by the $\rho \pi \gamma$ interaction current
- **Hamiltonian Dynamics**: Based on Hilbert space Quantum Mech. with instant, point or light form dynamics (LFD) quantization.

Helium-3/Tritium

- Quasi-potential propagator calculation was recently completed (Gross, Pinto, and Stadler), no inclusion of $\rho \pi \gamma$ current yet.
- LFD calculations have started, no MEC inclusion yet (Baroncini, Kievsky, Pace, and Salme).
Quark-Gluon Approaches

- **Deuteron**
  - Addition of quark-cluster admixtures in the ground-state wave function
  - Dimensional-Scaling Quark Model (DSQM)
  - Perturbative QCD (pQCD)
  - DSQM/pQCD prediction: $F_d = [A(Q^2)]^{1/2} \sim (Q^2)^{-6.1}$

- **Helium-Tritium**
  - Addition of quark-cluster admixtures in the ground-state wave function
  - DSQM/pQCD:
    - $^3$He/$^3$H Form Factor prediction: $[A(Q^2)]^{1/2} \sim (Q^2)^{-9.1}$
    - $^4$He Form Factor prediction: $[A(Q^2)]^{1/2} \sim (Q^2)^{-12.1}$
DSQM

$^3\text{He}$
Deuteron Form Factors
RIA + [ρπγ current]

Thick Dots: Gross Equation
Tripole nucleon F3

Solid: Gross Equation
Dipole nucleon F3

Dots: Blankenbeckler-Sugar Equation

Dashes: Wallace-Mandelzweig Equation
Deuteron Quark Scaling?

Deuteron Form Factor

\( F_d(Q^2)[(Q^2)^5] \)

\( Q^2 \) \( [(GeV/c)^2] \)

JLab Hall A

SLAC E101
Jefferson Lab Helium Experiment E04-018
The Jefferson Lab Hall A Collaboration

- Measurement of the charge and magnetic form factors of $^3$He and charge form factor of $^4$He, via elastic scattering.
- Used the two Hall A High Resolution Spectrometers (HRS) to detect scattered electrons and recoil nuclei in coincidence.
- Electrons were identified using a gas threshold Cherenkov counter and a lead-glass segmented E-M Calorimeter.
- Helium nuclei were identified using double-arm TOF, and recoil scintillator ADC signals.
- Normalization checked with elastic coincidence $e-p$ scattering.
- Full Monte Carlo simulation of the double-arm experiment, which provided the effective coincidence $\Delta\Omega$ solid angle, with radiative and Landau energy losses, multiple scattering, etc.
JLab Hall A Helium Form Factor Setup

DETECTORS
Cherenkov, Calorimeter, 2 Scintillator planes, and Drift Chamber set

Electron Spectrometer

Detector Hut

Hadron Spectrometer

Dipole

Q3

Q2

Q1

Beamline

Scattering Chamber

DETECTORS
Two Scintillator planes, and Drift Chamber Set
JLab E04-018 Hall A Collaboration


Argonne, Cal. State, Duke, Florida International, INFN, JLab, Kent State, Kentucky, Longwood, MIT, Rutgers, Seoul, Smith, St. Norbert, UST China, Temple, Virginia, William and Mary, Yerevan

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Electron-Recoil TOF Spectrum

$^3\text{He}$ elastic
$Q^2 = 30 \text{ fm}^{-2}$

Electron-Recoil TOF Spectrum

$^4\text{He}$ elastic
$Q^2 = 34 \text{ fm}^{-2}$
Elastic e-He Cross Section Determination

\[
\frac{d\sigma}{d\Omega}(E, \theta_e) = \frac{N_{e'r}}{N_e N_t (\Delta\Omega)_{\text{eff}}} F(Q^2) \prod_i C_i
\]

- **Standard Terms**
  - Number of electron-nucleus TOF coincidence events
  - Number of incident electrons
  - Number of target nuclei
  - Effective solid angle with radiative corrections
  - \(Q^2\)-only-dependent part of radiative corrections

- **Multiplicative Corrections \(C_i\)**
  - Computer dead time
  - Detector inefficiencies
  - Absorption of recoil nuclei in target and windows
  - Beam-induced target density reduction
Monte Carlo Simulation Model

- Landau Ionization energy loss for incident electrons, scattered electrons and recoil nuclei.
- Internal and external bremsstrahlung radiation energy loss for incident and scattered electrons (Mo and Tsai formalism).
- Multiple scattering for incident electrons, scattered electrons and recoil nuclei.
- Ray-tracing of scattered electrons and recoil nuclei in the two High Resolution Spectrometers of Hall A.
- Model weights scattering events with their cross section probability.
- Effective solid angle for $N_{suc}$ successful events reaching electron and recoil detectors out of $N_{trial}$ trial events from the electron $\Delta\theta \cdot \Delta\varphi$ phase space:

$$\left( \Delta\Omega \right)_{eff} = \Delta\theta \cdot \Delta\varphi \frac{N_{suc}}{N_{trial}}$$
Elastic e-p Halls A and C Cross Sections vs Fit

Fit: Arrington et al.

JLab Data / Fit

Epsilon

Christy (2008)
Dutta (2003)
Niculescu (1999)
Hall A
Electron “Elastic” Scattering from 3He clusters in 4He !!

**Strength of “elastic” e-He3 “peak is very comparable to e-He4 peak. Strong evidence for A=3 clustering in He4 (possibly in all nuclei?)!!**

[DC (Drift Chamber) HRS position is proportional to particle momentum]
Possible JLab experiment using the HRS and BigBite Hall A Spectrometers. JLab Letter of Intent using the tritium target for the 12 GeV DIS experiment. (Submitted in May 2013; well received, will proceed with full proposal.)
Possible JLab experiment using the HRS and BigBite Hall A Spectrometers. JLab Letter of Intent using the tritium target for the 12 GeV DIS experiment. (Submitted in May 2013; well received, will proceed with full proposal.)
Deuteron Form Factors

Curves: Relativistic Propagator and Hamiltonian Dynamics, and selected non-relativistic with relativistic corrections

B: **MOST** Sensitive Observable!!
Possible MAMI Measurement
Deuteron Magnetic Form Factor

A1 Facility
Spectrometer A

0.6-1.6 GeV beam
80 μA current
10 cm target
410 W cooling
1 MeV resolution
160 deg.

Add Calorimeter

Bonus: THRESHOLD inelastic scattering data for FREE
Have submitted a Note of Expression of Interest to MAMI
Summary

- $^4$He $F_C$ data exhibit a second diffraction minimum at $Q^2=52$ fm$^{-2}$, ruling out, for the JLab accessible $Q^2$ range, applicability of quark counting rules/pQCD.
- $^3$He $F_C$ data point to another diffraction minimum just over $Q^2=60$ fm$^{-2}$; incompatible with quark counting rules/pQCD.
- $^3$He $F_M$ seems to possess a second diffraction minimum in the vicinity of $Q^2=50$ fm$^{-2}$.
- JLab Hall A data *significantly* disagree with SLAC data ($^4$He $F_C$) and Saclay data ($^3$He $F_M$).
- Standard Model IA, with inclusion of MEC and 3BFE fails to describe well (YET!) all few-body form factor data.
- Strong evidence for $^3$He-cluster configurations in $^4$He!!
- JLab (MAMI) would be the ideal place to extend the triton $F_C$ and $F_M$ (deuteron B) measurements to higher $Q^2$ …
“Diamonds are Forever and Form Factors are Eternal”

Bogdan Wojtsekhowksi (JLab)

Spring 2009 APS Meeting Talk
Denver, Colorado