The Recoil Polarization Experiments at Jefferson Lab

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Introduction

This talk limited to the use of the recoil polarization technique to obtain the ratio of the Electric and Magnetic form factors, $G_{Ep}/G_{Mp}$.

The first suggestion that double polarization would be a better way to obtain nucleon form factors in elastic $ep$ goes back to a paper by Akhiezer and Rekalo (1968). Several possible double-polarization experiments:

Pol. electron on unpol. $p(n)$, measure $p(n)$ polarization
Pol. electron on pol. $p(n)$ measure angular asymmetry of $p(n)$
unpol. electron on pol. $p$, measure $p$ polarization (never done, see Kuraev).

This talk limited to proton and large $Q^2$ range, 0.5 to 8.5 GeV$^2$, and future beyond.
Elastic Electron-Nucleon Scattering

One-photon exchange (OPEX) for elastic $eN$ scattering in QED.

\[ \Gamma^\mu = F_1(q^2)\gamma^\mu + F_2(q^2) \frac{i\sigma^{\mu\nu}q_\nu}{2M} \]

\[ Q^2 = -q^2 > 0 \]

\[ \tau \equiv \frac{Q^2}{4M^2} \]

- **Form factors:**
  - $F_1$ (Dirac): electric charge and Dirac magnetic moment
  - $F_2$ (Pauli): anomalous magnetic moment
Sachs versus Dirac and Pauli form factors

The Sachs form factors $G_E$ (electric) and $G_M$ (magnetic) are more convenient experimentally. The two sets of form factors are connected by linear relations:

$$ G_E = F_1 - \tau F_2, \quad G_M = F_1 + F_2 $$

or in the opposite direction, as we actually measure $G_E$ and $G_M$:

$$ F_1 = (G_E + \tau G_M)/(1 + \tau), \quad F_2 = (G_M - G_E)/(1 + \tau) $$

Hence, $F_2/F_1$ can be obtained directly from measured $G_E/G_M$ ratio:

$$ \frac{F_2}{F_1} = \frac{1-G_E/G_M}{\tau+G_E/G_M} $$
Rosenbluth Separation Method

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{Mott} \times \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon (1 + \tau)}
\]

\[
\epsilon \equiv \left[ 1 + 2(1 + \tau) \tan^2 \frac{\theta_e}{2} \right]^{-1}
\]

\[
\sigma_R \equiv \epsilon (1 + \tau) \frac{\sigma}{\sigma_{Mott}} = \epsilon G_E^2 + \tau G_M^2
\]

- Measure angular dependence of cross section at fixed Q^2
- In OPEX \(\epsilon\)-dependence of “reduced” cross section \(\sigma_R\) is linear, with slope \(G_E^2\) and intercept \(\tau G_M^2\).
all Rosenbluth separation data for the proton Form Factors

The results from all published Rosenbluth separation data for $G_{Ep}$ and $G_{Mp}$. The “scaling” apparent after dividing by the dipole FF, $G_D=(1+Q^2/0.71)^2$. 
Polarization Transfer Method


\[ P_t = -hP_e \sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}} \frac{r}{1 + \frac{\epsilon}{\tau}r^2} \]

\[ P_\ell = hP_e \frac{\sqrt{1-\epsilon^2}}{1 + \frac{\epsilon}{\tau}r^2} \]

\[ P_n = 0 \]

\[ r = \frac{G_E}{G_M} \]

\[ R = \mu \frac{G_E}{G_M} = -\mu \frac{P_t}{P_\ell} \sqrt{\frac{\tau(1 + \epsilon)}{2\epsilon}} \]

*\( h \) beam helicity, \( P_e \) beam polarization
Following Basle convention (1960), spin-$\frac{1}{2}$ particles with spin up scatters preferentially to the left if analyzing power, $A_y$, is positive.
Focal Plane Polarimeter, Spin Precession

\[ f^{\pm}(\theta, \varphi) = \frac{\varepsilon(\theta, \varphi)}{2\pi} \left[ 1 \pm A \gamma \left( P_{n}^{fpp} \sin \varphi - A P_{n}^{fpp} \cos \varphi \right) \right] \]

Precession angle, \( \chi_\theta = \gamma (\mu_p - 1) \Theta_B \)

\[ P_{n}^{fpp} = P_{\ell}^{tg^\dagger} \sin x_\theta \]
Calibrations at SATURNE, Saclay

The polarimeter POMME (Polarimeter Mobile a Moyenne Energy) was calibrated with polarized protons up to 2.4 GeV (3.2 GeV/c) prior to the Gep(1) experiment at Jlab.


16-parameter fit as in previous LAMPF calibration (which was limited to 800 MeV).

Note that 2.4 GeV proton kinetic energy corresponds to a $Q^2$ or 4.5 GeV$^2$, which was proposal value for GEp(1); PAC6 approved 3.5 GeV$^2$. 
The first polarimeter in the HRS, Hall A, for GEp(1)
RESULTS OF GEp(1)

Exp. 93-027, PAC6, 1997

The first JLab recoil polarization results are the filled black circles.

Note the small error bars, almost entirely statistical.

V. Punjabi et al, PR C 71, 055202
How do we know that we understand the precession?

Zero crossing of $P_n^{fp}$:

$$P_n^{fp} = P_{\ell}^{tg} \sin \chi_\theta$$

Showing the normal component at the FPP as a function of precession angle $\chi_\theta$.

Open circle: data from GEp(1).
Dashed line: fit to data.
Dots: calculated from COSY.

$P_n^{fp}$ fit crosses 0 at $\chi_\theta=178.4^0$, instead of $180^0$.
Ideal $\chi_\theta$ for experiment is of course $90^0$. 
Analyzing power from GEp(1)

$P_\perp$ and $P_\parallel$ are measured: we can either obtain $G_E$ and $G_M$ separately. But requires knowing absolute analyzing power and beam polarization, or obtain ratio $G_E/G_M$ AND absolute analyzing power $A_y$ (must know beam polarization for $A_y$).

Second solution was first proposed by V. Punjabi and CFP in 1997 (PAC6).

$A_y$ determines the error bars as

$$\Delta P_\perp^{fpp} = \Delta P_\parallel^{fpp} = \sqrt{2/\epsilon A_y^2 N}$$

$N$: #events, $A_y$ analyzing power, $\epsilon$ efficiency.
Results of GEp(2)

Exp.99-007, PAC15, 1999

As published, Gayou et al., in PRL 88, 092301 (2002).

Has been reanalyzed since and published, Puckett et al., P.R. C 85 (2012), 045203.
Analyzing powers from GEp(2)

Note apparent “scaling”:

Maximum of $A_y$ appears at a nearly constant transverse momentum $p_T$.

Confirms scaling observed in Dubna calibration.
Results of 2001 Dubna calibration

Was necessary to get GEp(3) experiment approved by PAC.

Determine best thickness of CH$_2$ analyzer.

Observation “scaling” of $A_y$ versus $1/p$. And $A_y$ at a nearly constant transverse momentum $p_T$, a second “scaling”.

GEP(3) in Hall C
2007-8

The double polarimeter built for GEP(3) in the Hall C HMS spectrometer.

Pink boxes, $CH_2$ analyzer
Blocks (50 gcm$^{-2}$)

Pale blue: 2 drift chambers per polarimeter for tracking.
Double FPP in HMS

Two Focal Plane chambers

Trigger Scintillators

First Pair FPP Chambers

First CH2 Analyzer

Second CH2 Analyzer

Second Pair FPP Chambers
$\mu_p G_{E_p}/G_{M_p}$ from all double Polarization Experiments

Recent Rosenbluth data including:

Other polarization results (cyan, or aqua marine), including recoil polarization and beam-target asymmetry results.
Higher momentum $p$-$CH_2$ analyzing power $A_y$

$A_y$ from GEp(3), to proton momentum of 5.4 GeV/c

The scaling in $1/p$. Hydrogen as an analyzer would be twice as good.

$A_y$ vs. $p_t = p \sin(\theta)$ in GEp(3)

All data: $A_y^{\text{max}}$ versus $1/p$

Will measure $A_y$ to 7.5 GeV/c at JINR (Dubna) in Fall of 2014 (Piskunov et al.).
Negative effect of inelastic contribution

Current polarimeters detect charged particles (no identification). Single track events have max Ay; contamination from multi-particle final states degrade Ay. In future, better tracking resolution and crude measurement of energy behind the polarimeters will increase effective Ay: HCal in SBS for GEp(5).

\[ f^\pm(\vartheta, \varphi) = \frac{\varepsilon(\vartheta, \varphi)}{2\pi} \left[ 1 \pm A_y P_t^{fpp} \sin \varphi - A_y P_n^{fpp} \cos \varphi \right] \]

\[ P_t^{fpp} \text{ and } P_n^{fpp} \text{ are the polarization components at the FPP} \]

Physical Asymmetries are obtained from difference distributions.
Super Bigbite Spectrometer for GEp(5)
CH\textsubscript{2} analyzer

GEANT3 simulation of the proton momentum vs polar angle from 50 gcm\textsuperscript{-2} block of CH\textsubscript{2}, for 7 GeV/c incident momentum (by Yang Wang, WM)
green: elastic pC, single particle.
violet: elastic pp (and pn), single particle
blue, inelastic, all final states.
effective analyzing power can be improved by selecting the energy of the emerging particles.
In GEp(5) with a hadron calorimeter of the COMPASS type.
Expected error bars for GEp(5)
CONCLUSIONS

Recoil polarization experiments became possible with Jlab; had been tested at Bates at $Q^2<0.5$ GeV$^2$ in 1996.

Results of recoil polarization experiments were unexpected, showing an irreducible difference from cross section results with Rosenbluth separation results.

It is now commonly assumed that the difference is due to incomplete radiative corrections to cross section, with double virtual photon exchange the single prime candidate. The size of the two-photon exchange has yet to be determined experimentally; the $e^+/e^-$ cross section ratio should resolve the puzzle (although this ratio is quite sensitive to radiative corrections too).