Polarized Electron Beams and Polarimetry

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JLab Summer Detector/Computer Lectures

http://www.jlab.org/~gen/talks/polar_lect.pdf

Outline

1. Spin Physics
   - History of Spin Physics
   - Modern Studies in Spin Physics

2. Polarized Electron Beams
   - Source of Polarization
   - Electron Beam Polarimetry

Outline

Motivation

Polarized beams and targets are used to study various effects of Spin Physics.

Present Motivation

- Studying the structure of composite particles (protons etc.)
- Studying the dynamics of strong interactions
- Search for “new physics”

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History of Spin Physics

- Before 1925 - atomic spectra $\Rightarrow$ concepts of Quantum Mechanics
- 1925-1928 - Completion of QM with the concept of spin
- up to now - measuring anomalous magnetic moments
- 1956-1957 - parity violation in weak interactions
- 1955 - ... polarized proton beams
- 1975 - ... polarized muon beams
- 1975 - ... polarized electron beams
- 1987 - ... proton spin puzzle

Introduction of Spin

Ralph de Laer Kronig
early 1925 - introduced spin (unpublished)

Wolfgang Pauli
1924-1925 - exclusion principle
1927 - non-relativistic formalism

George Uhlenbeck   Samuel Goudsmit
late 1925 - introduced spin

Relativistic Description of Spin

Paul Adrien Maurice Dirac
1927 - equation for electron

Dirac's Equation

- Relativistic equation for fermions $s = \frac{1}{2}, \frac{3}{2}$
- Introduction of antiparticles
- Magnetic moment of fermions
- Basis for QED

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Magnetic Moments of Pointlike Fermions

Magnetic moment: $\mu = g\frac{q}{2m} \cdot S$,

where:

q, m, S are the particle's charge, mass and spin,

g - gyromagnetic factor.

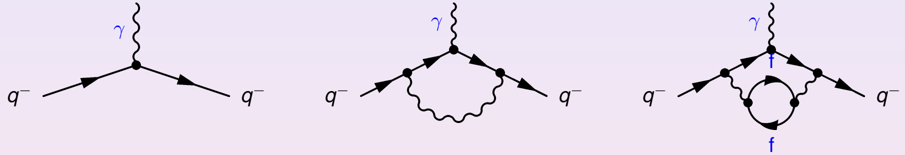
Dirac's equation with EM interaction for pointlike $S = \frac{1}{2}$: $g = 2$

Experimental values for $(g-2)/2$

- $\mathrm{e}^-, \mathrm{e}^+$: ≈ 0.001
- μ^-, μ^+: ≈ 0.001
- p : ≈ 1.79 - composite
- n : ≈ -0.91 - composite

Anomalous Magnetic Moments of Pointlike Fermions

- Interactions of EM field with itself and with vacuum
- Calculable in QED



Corrections to (g-2)/2

0	$\left(\frac{\alpha}{\pi}\right) \cdot 0.5$	$\sim \left(\frac{\alpha}{\pi}\right)^2 \cdot \left(\frac{m}{m_f}\right)^2$

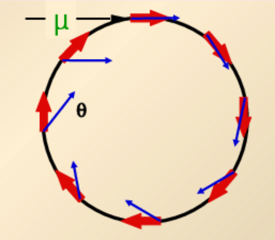
Precise measurements vs detailed calculations

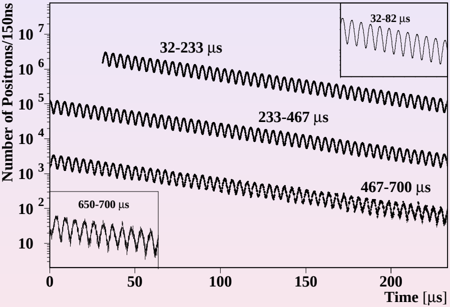
- Substructure
- Electron: test for "pure" QED
- Muon: search for "new physics": existence of heavy particles (via loops), anomalous couplings etc.

Muon Magnetic Moment

CERN (1960-1970), BNL 1990-2000 spin precession experiments

- $p + A \rightarrow .. + \pi^- \rightarrow \mu^- + \nu_\mu$, μ - polarized!
- $\vec{\mu}^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$, $\vec{p}_e \approx$ along S_μ
- Precession $\Delta\omega = \frac{g-2}{2}\frac{eB}{mc}$





World average:

$$a_\mu^{exper} - a_\mu^{theor} = 22(10) \cdot 10^{-10}$$

Remarkably accurate!

Interactions with Spin: Symmetries

	1	2	3	4
	$R \Rightarrow \bullet \Leftarrow R$	$L \Leftarrow \bullet \Rightarrow L$	$L \Leftarrow \bullet \Leftarrow R$	$R \Rightarrow \bullet \Rightarrow L$
Parity-conjugated	$L \Leftarrow \bullet \Rightarrow L$	$R \Rightarrow \bullet \Leftarrow R$	$R \Rightarrow \bullet \Rightarrow L$	$L \Leftarrow \bullet \Leftarrow R$

- Rotational symmetry - 4 potentially different processes
- Parity conservation: $\sigma_{LL} = \sigma_{RR}, \ \sigma_{LR} = \sigma_{RL}$

Parity is non-conserving in weak interactions

Typical Experiments with Polarization

Beam, target polarizations $\mathcal{P}_b$, $\mathcal{P}_t$,
Beam polarization is flipped periodically

Parity violating

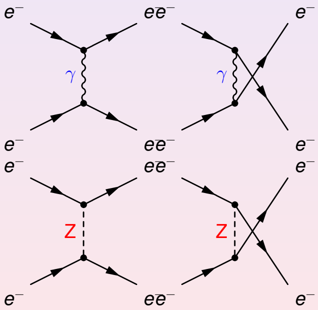
- Ex: $\mathcal{P}_b \neq 0, \mathcal{P}_t = 0$
- Measured:
  $A = \frac{N_L - N_R}{N_L + N_R} = \mathcal{P}_b \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$

Parity conserving

- Ex: $\mathcal{P}_b \neq 0, \mathcal{P}_t \neq 0$
- Measured:
  $A = \frac{N_{LL} - N_{RL}}{N_{LL} + N_{RL}} = \mathcal{P}_b \mathcal{P}_t \frac{\sigma_{LL} - \sigma_{RL}}{\sigma_{LL} + \sigma_{RL}}$

Parity Violation in Electron Scattering

Møller Scattering



$$A = \frac{N_L - N_R}{N_L + N_R} = \mathcal{P}_b \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

$$\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \propto G_F Q^2 (1 - 4\sin^2\theta_W)$$

$A \sim 10^{-3} - 10^{-6}$ - very small!

- 1978, SLAC - polarized $\vec{e}^-$ beam
- 1978 $\vec{e}^- D$ scattering (DIS) $\Rightarrow \sin^2\theta_W$
- 2003, SLAC $\vec{e}^- e^-$ Møller scattering $\Rightarrow \sin^2\theta_W$
- 1989-2006 $\vec{e}^-$ p/He elastic $\Rightarrow$ strange formafactors (Bates, JLab, Mainz)

Deep Inelastic Scattering

CERN (1987), muon beam "Proton Spin Crisis":

- Quark contribution to proton spin $\Delta q \sim 15\%$ against $\sim 75\%$ expected from quark models
- Studied at CERN, SLAC, DESY, JLab with polarized muon/electron beams and polarized target

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How to Make Polarized Electrons?

Two methods are currently used:

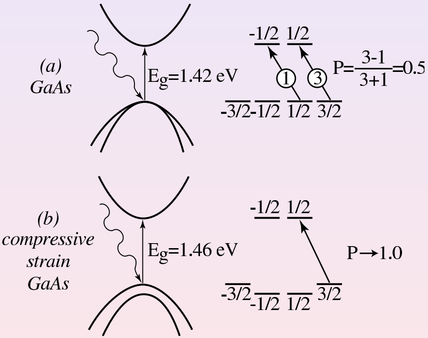
- Linac's injectors: polarized photoeffect
- Storage rings: gradual polarization by Sokolov-Ternof effect

Polarized Electron Guns

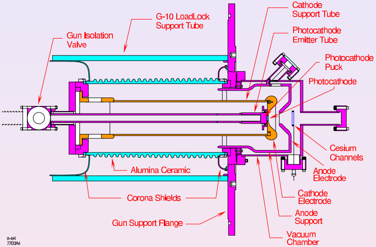
- High polarization $> 50\%$
- High current $> 100\mu$A
- Fast polarization flipping > 10Hz
- Stability against the helicity flip

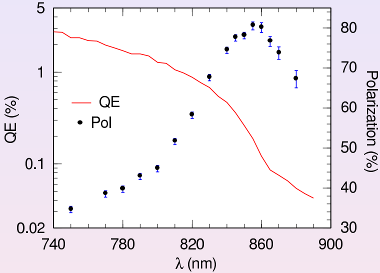
GaAs guns

- GaAs wafer
- Optical pumping by circularly polarized light
- Electron extraction into vacuum from the Cs and O_2 treated surface
- Super-lattice cathodes $\mathcal{P} > 85\%$



Electron Gun at JLab





- $\sim$ 100 kV electron extraction
- Lifetime depends on the full charge extracted
- QE decrease
- Very high vacuum needed (ion bombardment kill the cathode)
- Laser spot can be moved to recover QE

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Requirements for Polarimetry

In precise PV experiments the systematic error is dominated by polarimetry!

- Typical systematics error $> 1.5\%$
- In some special cases $\sim 0.5\%$
- Requirements for future experiments $< 0.5\%$

Methods Used for Electron Polarimetry

Spin-dependent processes with a known analyzing power.

Atomic Absorption

$\vec{e}^{\,-}$ ~50 keV decelerated to ~13 eV

$\vec{e}^{\,-}(13eV) + Ar \rightarrow \vec{Ar}^{*} + e^{-}$, $\vec{Ar}^{*} \rightarrow Ar + (h\nu)_{\sigma}$

Atomic levels: $(3p^5 4p)^3 D_3 \rightarrow (3p^6 4s)^3 P_2$ 811.5nm fluorescence

Potential $\sigma_{syst} \sim$ 1%. Only relative so far, invasive, diff. beam

Spin-Orbital Interaction

Mott scattering, 0.1-10 MeV: $e^{-}\uparrow + Z \rightarrow e^{-} + Z$ σ_{syst} ~3%, ⇒1% (?) invasive, diff. beam

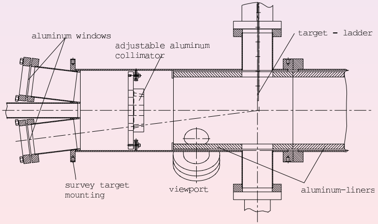
Spin-Spin Interaction

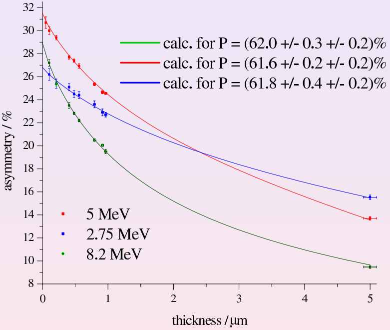
- Møller scattering: $\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^{-} + e^{-}$ at >0.1 GeV, $\sigma_{syst} \sim$ 3-4% , ⇒ 0.5% Mostly invasive, diff. beam
- Compton scattering: $\vec{e}^{\,-} + (h\nu)_{\sigma} \rightarrow e^{-} + \gamma$ at >0.5 GeV ~ 1-2%, ⇒0.5%. non-invasive, same beam

Mott Polarimetry

0.1-10 MeV: $e^- \uparrow + Au \rightarrow e^- + Au$ Analyzing power $\sim$ 1-3%:

- Nucleus thickness: phase shifts
- Spin rotation functions
- Electron screening, rad. corr.
- No energy loss should be allowed
- Single arm - background
- Extrapolation to zero target thickness





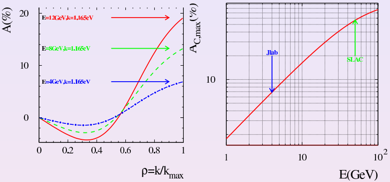
- $e^- \uparrow < 5\ \mu A$ - extrapolation needed

JLab: $\sigma(\mathcal{P})/\mathcal{P} = 1\%(Sherman) \oplus 0.5\%(other)$ (unpublished) $\oplus \sigma(extrapol)$

$$\frac{N_{\uparrow\uparrow}-N_{\uparrow\downarrow}}{N_{\uparrow\uparrow}+N_{\uparrow\downarrow}} = A\cdot\mathcal{P}_b\mathcal{P}_t$$

Compton

$\vec{e}^{\,-} + (h\nu)_\sigma \rightarrow e^- + \gamma$ QED.



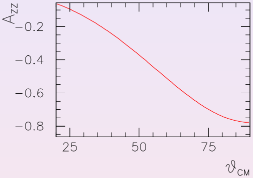
- Detecting the γ at 0 angle
- Detecting the e^-
- Strong $\frac{dA}{dk'}$ - good $\sigma E_\gamma/E_\gamma$
- $A \propto kE$ at $E < 20$ GeV
- $T \propto 1/(\sigma\cdot A^2) \propto 1/k^2 \ \times\ 1/E^2$
- $\mathcal{P}_{laser} \sim 100\%$
- Non-invasive measurement

Syst. error 3→50 GeV:

$\sim 1. \rightarrow 0.5\%$

Møller

$\vec{e}^{\,-} + \vec{e}^{\,-} \rightarrow e^- + e^-$ QED.



$A(E) = -\frac{7}{9}$

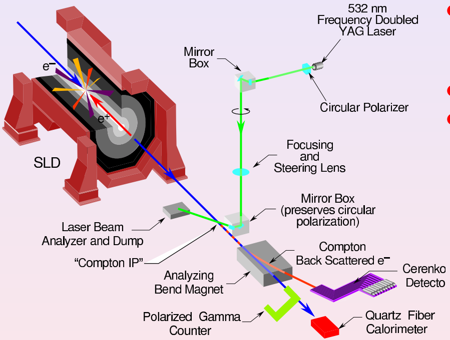
$\sigma_{lab} \sim 180\,\frac{mb}{ster}$

- Detecting the e^- at $\theta_{CM} \sim 90^\circ$
- $\frac{dA}{d\theta_{CM}}|_{90^\circ} \sim 0$ - good systematics
- Beam energy independent
- Coincidence - no background
- Ferromagnetic target $\mathcal{P}_T \sim 8\%$

Syst. error $\sim 3\%$ typically, (0.5%)

Compton Polarimeters: Best Accuracy at High Energy

SLAC SLD



Beam:

45.6 GeV

$3.5 \cdot 10^{10}$e$^-$ $\times$120 Hz $\sim$ 0.7 μA

Laser:

- 532 nm, 50 mJ at 7 ns $\times$ 17 Hz
- Crossing angle 10 mrad

Detector:

- e$^-$ 17-30 GeV gas Cherenkov
- γ detector - calorimeter

Stat: 1% in 3 min

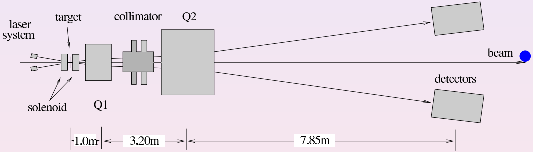
source	$\sigma(\mathcal{P})/\mathcal{P}$ SLD 1998	ILC Goal
Laser polarization	0.10%	0.10%
Analyzing power	0.40%	0.20%
Linearity	0.20%	0.10%
Electronic noise	0.20%	0.05%
total	0.50%	0.25%

M.Woods, JLab Polarimetry workshop, 2003

Møller Polarimeter with Saturated Iron foil

JLab, Hall C, M. Hauger *et al.*, NIM A **462**, 382 (2001)

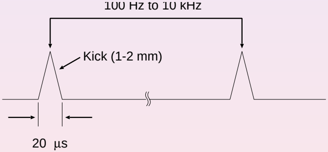
- External $B_Z \sim 4\ T$
- Target 4-10 μm, perp. to beam
- $\mathcal{P}_t$ not measured
- Important: annealing, etc.



source	$\sigma(A)/A$
optics, geometry	0.20%
target	0.28%
Levchuk effect	0.30%
total	0.46%
$\Rightarrow$ 100 μA	?

Tests for high current

- Beam $\sigma_X \approx 50\mu$m $> r = 12\mu$m
- At 20μA - accidentals/real$\approx$0.4
- $\sigma_{stat} \sim$ 1% in 2h



Current Studies

- A 1μA thick half-foil
- Higher duty factor

Summary

Physics with polarized electron beams

- Studying the structure of composite particles (protons etc.)
- Studying the dynamics of strong interactions
- Search for “new physics”

Features

- Polarization $\sim 80\%$
- Polarimetry $\sigma\mathcal{P} \sim 1\%$