Fermilab E1039: Measuring the Seaquark Sivers Asymmetry with Polarized Drell-Yan Interaction

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Outline

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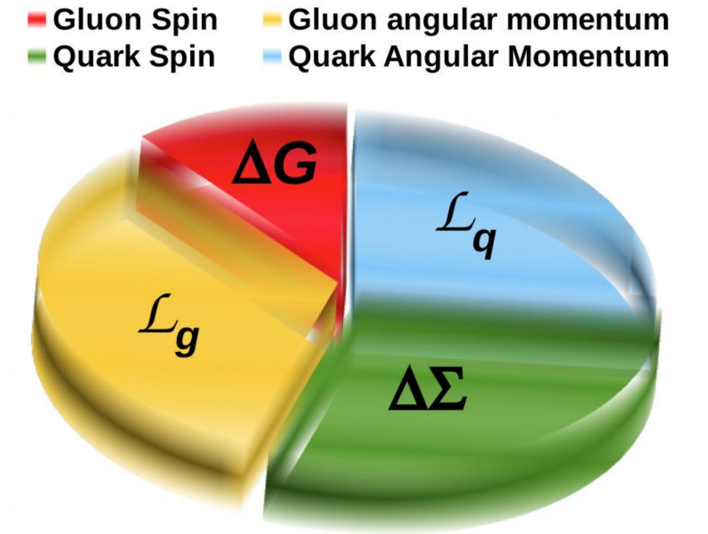
Motivation

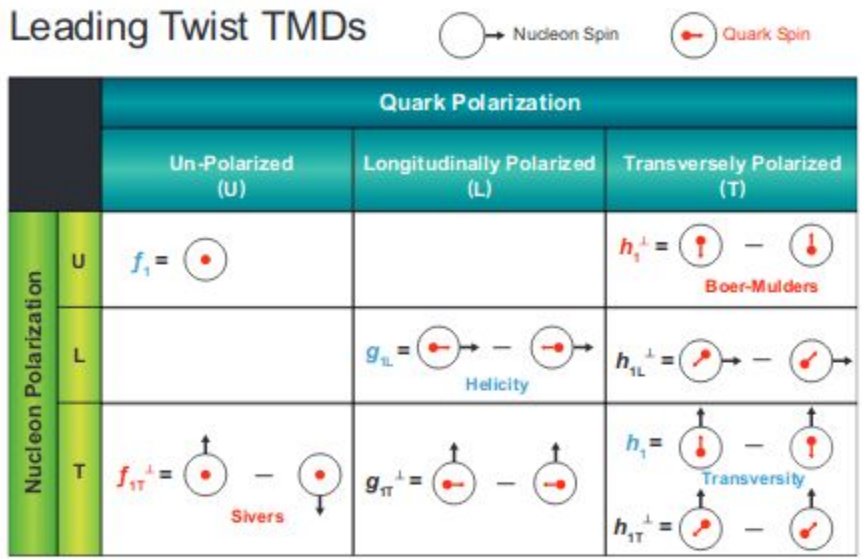
- Spin Crisis- intrinsic spins of quarks not enough.
  - Valence quarks and gluons only contribute ~50%.
- Sea quarks contribution
  - OAM of sea quarks could contribute to overall spin
- By measuring the Sivers function asymmetry, we can determine OAM of sea quarks.



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + L_{\bar{q}} + \Delta G + L_g$$

The Sivers Function

- Spin physics lets us probe structure of protons and neutrons.
- Different polarizations reveal different physics.
- E1039 will use an unpolarized beam on a transversely polarized target to gain access to the Sivers function.
- A Sivers function of zero corresponds to a zero orbital angular momentum of the sea quarks.

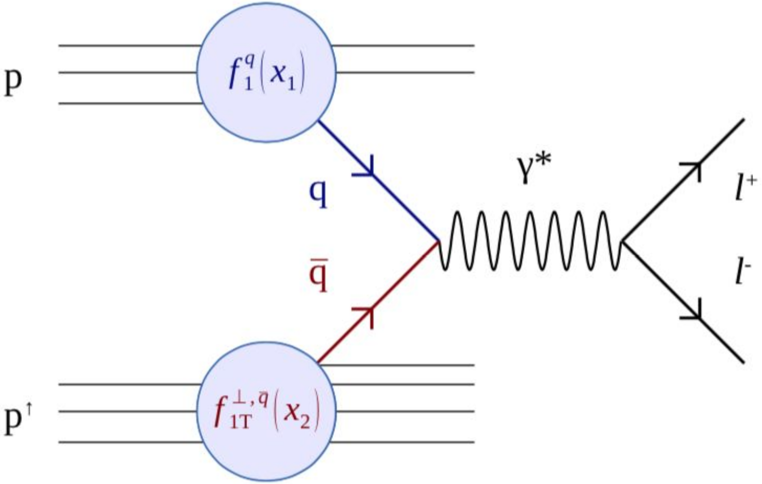


Leading Twist TMDs

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = − Boer-Mulders
L		g_{1L} = − Helicity	$h_{1L}^\perp$ = −
T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = −	h_1 = − Transversity $h_{1T}^\perp$ = −

Polarized Drell-Yan Scattering

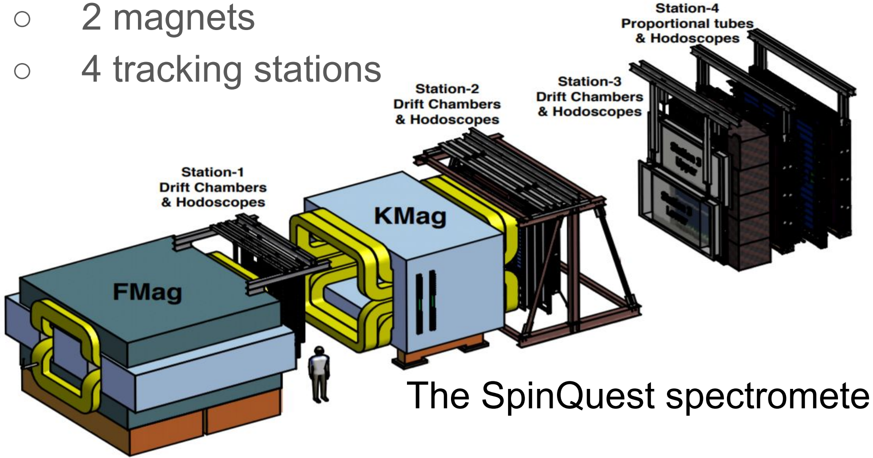
- L-R asymmetry
- No fragmentation
- Isolates valence and sea quarks
- $\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9x_b x_t}\frac{1}{s}\sum_i e_i^2\{q_i(x_b)\bar{q}_i(x_t) + \bar{q}_i(x_b)q_i(x_t)\}$
- E1039 isolates beam quarks, target antiquarks.



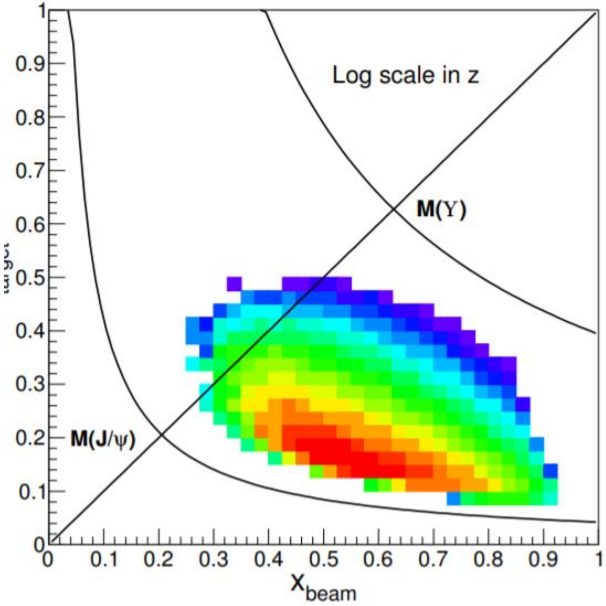
$$A_N^{DY} \propto \frac{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_{1T}^{\perp,\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2\right]}{\sum_q e_q^2\left[f_1^q(x_1)\cdot f_1^{\bar{q}}(x_2) + 1 \leftarrow\rightarrow 2\right]}$$

Experimental Layout

- Fermilab main injector beam
  - 120 GeV
  - 10^{13} protons per 4 second spill, 10^{18} per year
- Detector is the existing E906 spectrometers.
  - 2 magnets
  - 4 tracking stations



The SpinQuest spectrometer



Detector sensitivity

Target

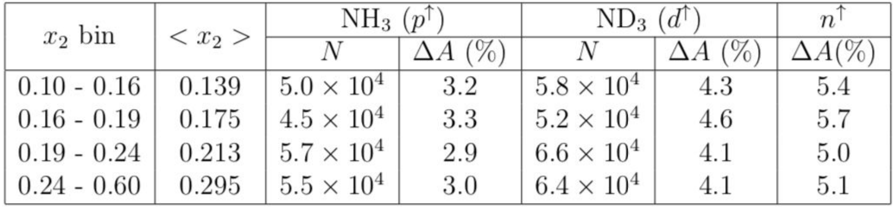
- We will be using a target made up of ammonia beads (NH_3 or ND_3)
- Dynamic Nuclear Polarization
- Polarization will be done with a 5T magnet, ^{4}He evaporation refrigerator 140 GHz microwave source and a 15000 m^3/hr pumping system.
- For proton we are assuming 80% polarization, for deuteron, 32%.

$$A_N(p_{\text{beam}} + p^{\uparrow}_{\text{trg}} \to \text{DY}) \propto \frac{N_L^{DY} - N_R^{DY}}{N_L^{DY} + N_R^{DY}} \propto \frac{f_{1T}^{\perp,\bar{u}}(x_t)}{f_1^{\bar{u}}(x_t)}$$

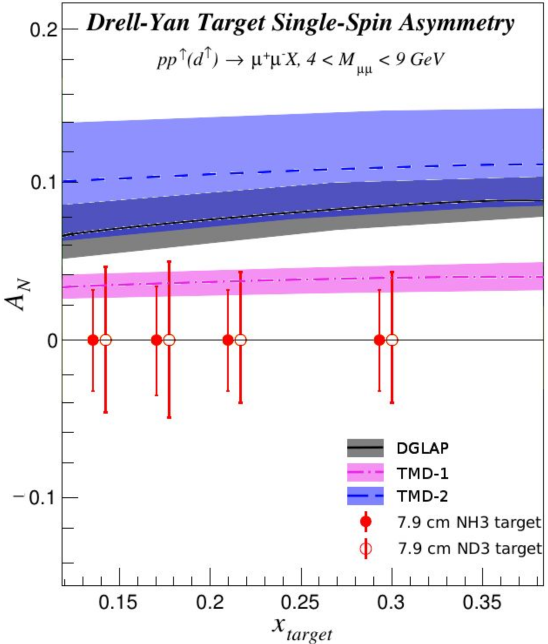
Error estimates

- Systematic: 6.5%
    - **Target: 5.7%**
        - **Dilution: 3%**
        - **Density: 1%**
        - **Polarization: 2.5%**
        - **Packing Fraction: 2%**
        - **Polarization Homogeneity: 2%**
        - **Uneven Decay: 3%**
    - Beam: 2.5%
        - Relative Luminosity: 1%
        - Drifts: 2%
        - Scraping/Dead Time: 1%
    - Detector: 1.8%
        - DAQ: 1.5%
        - Detector: 1%

- Statistical: $\Delta A_N = \frac{1}{f}\frac{1}{P}\frac{1}{\sqrt{N}}$

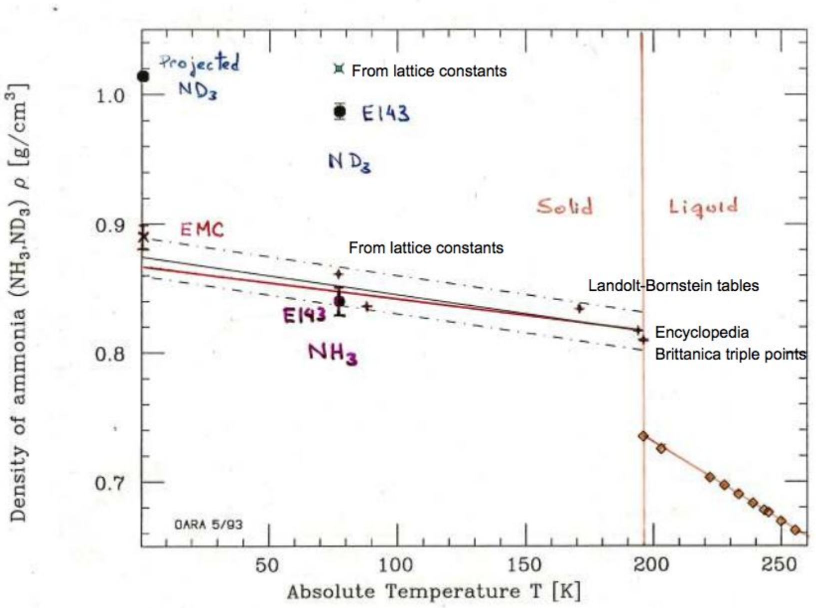


x_2 bin	$< x_2 >$	$\mathrm{NH_3}$ ($p^\uparrow$)		$\mathrm{ND_3}$ ($d^\uparrow$)		$n^\uparrow$
		N	ΔA (%)	N	ΔA (%)	ΔA(%)
0.10 - 0.16	0.139	5.0×10^4	3.2	5.8×10^4	4.3	5.4
0.16 - 0.19	0.175	4.5×10^4	3.3	5.2×10^4	4.6	5.7
0.19 - 0.24	0.213	5.7×10^4	2.9	6.6×10^4	4.1	5.0
0.24 - 0.60	0.295	5.5×10^4	3.0	6.4×10^4	4.1	5.1



Target Error: Packing Fraction+Density

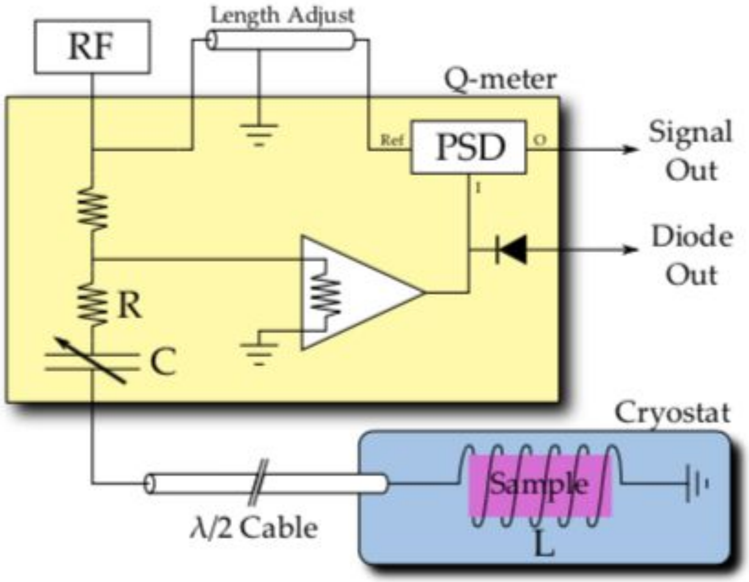
- Archimedes' Principle
- Submerge in liquid nitrogen, measure displacement.
- Density of ammonia changes based on temperature, so packing fraction will change in liquid helium bath compared to liquid nitrogen.
- Very little data on density of ammonia at low temperatures.
- Create sealed, pre-measured targets.



Rondon, 1993

Target Error: Polarization

- Measured using Nuclear Magnetic Resonance
- 3 probes over length of target
- NMR precise to within 1%, but uncertainty between probes.
- Proton bombardment can cause uneven decay, making this measurement less accurate the longer we use one sample.

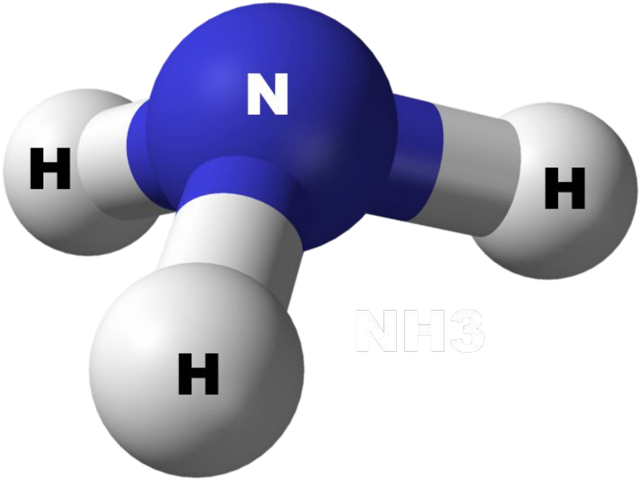


Target Error: Dilution

- Dilution factors well known for individual chemicals.
- Other objects in beam path create uncertainty (Helium, Aluminium, plastic)
- Uncertainty in the dilution will likely be around 2-3%
- Could add an additional physics channel to measure single muon channel.

Dilution factor of
Deuterium target

$$f = \frac{N_D \sigma_{D,H}}{N_N \sigma_N + N_D \sigma_D + \Sigma N_A \sigma_A}$$



Elastic Proton-Proton Asymmetry as a Check

- Elastic scattering asymmetry well understood
- By measuring asymmetry, can have an additional measurement which can be used to check either polarization or dilution.
- Would be used if data did not align with our expectations to check conditions of target.

E1039 Collaboration

Contact Spokespersons: Kun Liu (liuk@fnal.gov) - LANL and Dustin Keller (dustin@jlab.org) - UVA

More information: https://wiki.shanti.virginia.edu/display/SeaQuest/

Schedule/Status:

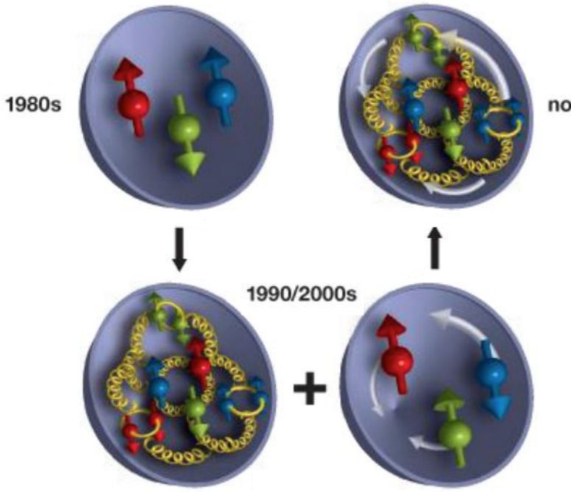
Starting March 2019: Commissioning starts

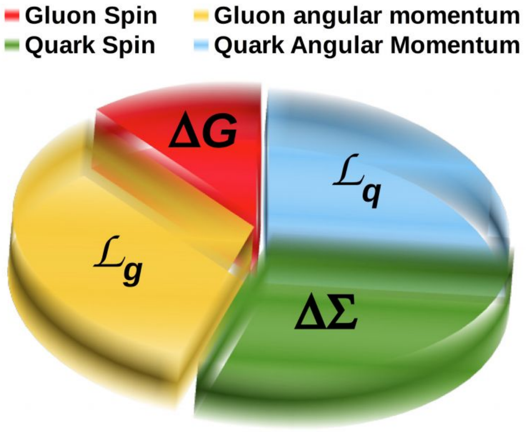
May 2019: LHe liquefier installation

Summer 2019-2021: Experiment runs

The Spin Crisis

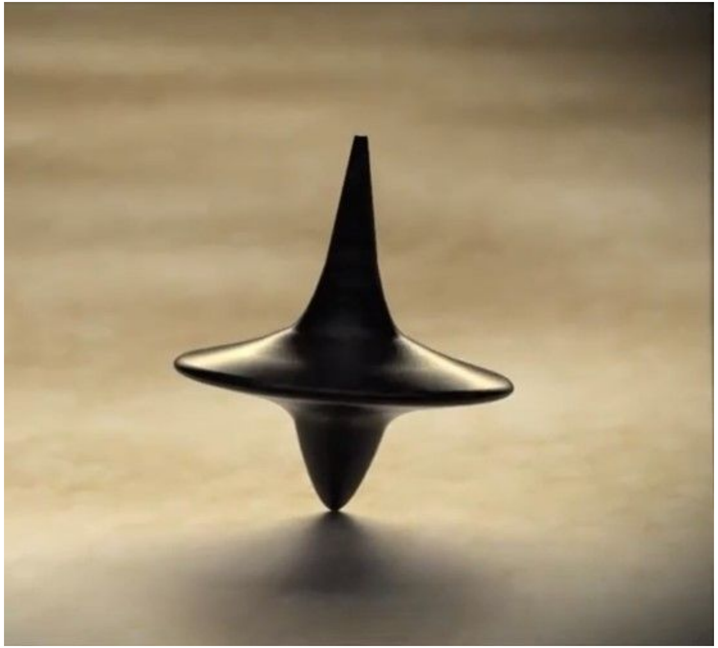
- Spin of nucleon was expected to be made up entirely of intrinsic spin of quarks.
- 1987 experiment by European Muon Collaboration showed contribution is consistent with zero.
- Search for other contributions (Gluon spin, orbital angular momentum).
- Many experiments (SLAC, CERN, JLAB, RHIC) and hundreds of papers confirm this.



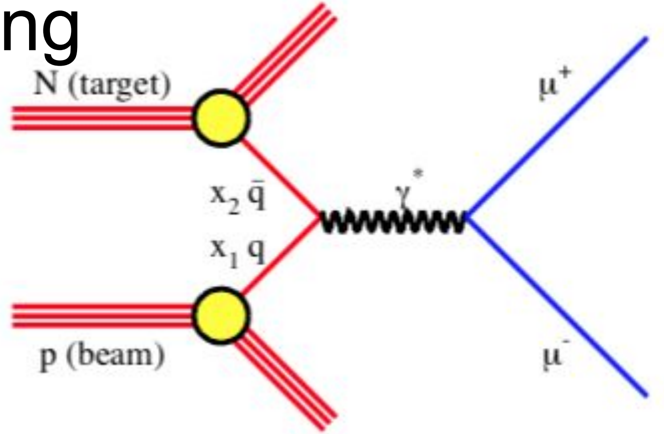


Quark Orbital Angular Momentum

- Valence quarks contribute essentially no orbital angular momentum.
- Sea quarks are believed to contribute about half the total angular momentum of nucleon.
- If OAM of sea quarks is zero, Sivers function vanishes.



Unpolarized Drell-Yan Scattering



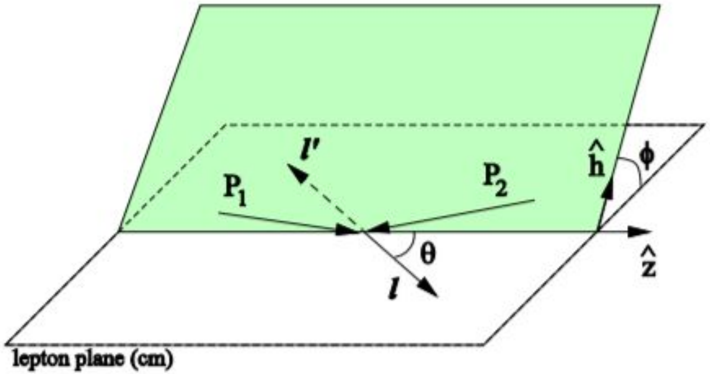
- Hadron-Hadron collisions
- Quark-Antiquark annihilation creates virtual photon
- Decays into two leptons
- In nucleon experiments, antiquark must come from sea quarks.

$$\frac{d\sigma}{dx_1 dx_2} = \frac{4\pi\alpha^2}{9 s x_1 x_2} \sum_i e_i^2 (q_i^B(x_1, Q^2)\bar{q}_i^T(x_2, Q^2) + \bar{q}_i^B(x_1, Q^2) q_i^T(x_2, Q^2)$$

u-quark dominates due to charge

Polarized Drell-Yan Scattering

- Drell-Yan has an angular dependence on lepton plane.
- Polarization controls this angle, letting us measure asymmetry.
- By using a transverse polarization, we measure the Sivers function.



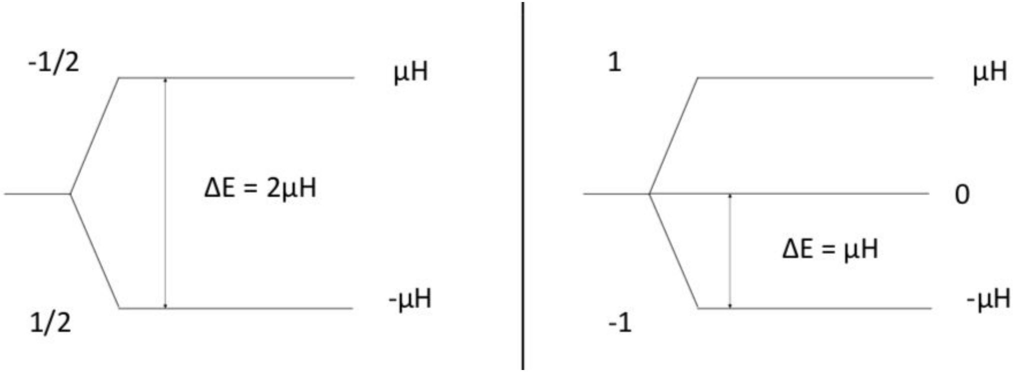
$$\left(\frac{1}{\sigma}\right)\left(\frac{d\sigma}{d\Omega}\right)=\left[\frac{3}{4\pi}\right]\left[1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi\right]$$

Brute-force Polarization

- Probability of polarization determined by temperature and magnetic field
- For T=1K and B=5T
    - Electron Polarization 99.76%
    - Proton Polarization 0.5108%
    - Deuteron Polarization 0.1046%
    - Neutron Polarization -0.35%
- Need something else to reach 80% and 32%

$$P_{TE}^{\frac{1}{2}} = \tanh\frac{\Delta E}{2kT}$$

$$P_{TE}^{1} = \frac{4\tanh\frac{\Delta E}{2kT}}{3+\tanh^2\frac{\Delta E}{2kT}}$$



Dynamic Nuclear Polarization

- Target doped with paramagnetic centers (electrons)
- Electrons polarized in low temp/high B field
- Microwaves transfer polarization
- Relaxation time for electrons on scale of ms, protons on scale of minutes/hours