Spin Physics at Existing Facilities

N.C.R. Makins
University of Illinois at Urbana-Champaign

Outline

• **Spin at the Heart of Matter:**
  the restless world within the atom

• **Single-spin asymmetries:**
  a key to the spin kingdom

• **Inside the proton:**
  quark spin & orbital motion

• **A coherent picture:**
  Are we there yet?
The Strange Nature of Matter

Fields and points in empty space …

… and at every level, there is motion: pointlike particles, forever spinning and orbiting …
Orbital Shells of definite L

in atoms ...

in nuclei ...

... and within the proton? ...
Parton Distribution Functions

Look *inside* the proton with high energy beams ... ⇒ a rich substructure is revealed!

**sea quarks**: virtual quark-antiquark pairs that fluctuate in and out of the vacuum

**gluons**: the color fields of the strong force

3 constituent quarks of mass ≈ 350 MeV

many bare quarks of tiny mass ≈ 5 MeV, and gluons account for > 40% of the momentum, \(^\sim all of the mass \) ...
The Puzzle of Proton Spin

The proton: spin 1/2

Where is the other 80%? gluon spin? ORBITAL MOTION?

The quarks spins account for only 20%
Whence comes the proton spin?

\[ q(x) = q^\uparrow(x) + q^\downarrow(x) \]
\[ \Delta q(x) = q^\uparrow(x) - q^\downarrow(x) \]

Only three possibilities

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

1. **Quark polarization**
   \[ \Delta \Sigma \equiv \int dx \left( \Delta u(x) + \Delta d(x) + \Delta s(x) + \Delta \bar{u}(x) + \Delta \bar{d}(x) + \Delta \bar{s}(x) \right) \approx 20\% \text{ only} \]

2. **Gluon polarization**
   \[ \Delta G \equiv \int dx \Delta g(x) \]

3. **Orbital angular momentum**
   \[ L_z \equiv L_q + L_g \]

In friendly, non-relativistic bound states like atoms & nuclei (& constituent quark model), particles are in *eigenstates of* \( L \rightarrow \text{shells} \)

Not so for bound, relativistic Dirac particles ...

Noble “\( l \)” is *not a good quantum number*
Single-Spin Asymmetries
Single-Spin Asymmetries in Elastic pp Scattering

Analyzing Power $A_N$
left-right asymmetry

Induced Polarization $P_N$

Crab, Krisch et al, 1990
Neal & Longo, 1967
The Spin-Orbit Interaction

Particles on **left** / **right** sides head for **stronger** / **weaker** $B$

Spin $S$ // Magnetic Moment of beam polarized

$U = -\vec{\mu} \cdot \vec{B}$

**B Field** of "moving" target // $L = r \times p$ of beam particles

Let $V(r) =$ target’s potential field, in target rest frame.

**Lorentz boost** to beam frame:

$$\vec{B}' = -\gamma \frac{\vec{v}}{c^2} \times \vec{E} = \frac{\vec{p}}{mc^2} \times \frac{\vec{r} dV}{r \, dr}$$

Using $\vec{r} \times \vec{p} = \vec{l} \hbar$ and

$$U = -\vec{\mu} \cdot \vec{B}' \sim -\vec{s} \cdot \vec{B}'$$

**$\rightarrow$ spin-orbit interaction**

$$U_{s-o} = \text{const} \frac{dV}{dr} \frac{\vec{s} \cdot \vec{l}}{r}$$

**Note:** The **origin** of the underlying potential $V(r)$ doesn’t matter

**$\rightarrow$** the result follows from **relativity**

N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009
Spin-Orbit Interaction for the short-range Nuclear Force

With $\rho(r) =$ target density,

$$U_{s-o} \sim \frac{dV}{dr} \hat{s} \cdot \hat{l} \sim \frac{d\rho}{dr} \hat{s} \cdot \hat{l}$$

nuclear spin-orbit interaction active at target surfaces

SSA: $A_N$ in $p^\uparrow p \rightarrow pp$  
$\rightarrow$ sin($\theta$) term in xsec

$\vec{k}_i \rightarrow \theta \rightarrow \vec{k}_f$

$\vec{l} \cdot \vec{s} < 0$  
$\vec{l} \cdot \vec{s} > 0$

Polarized

$\vec{s} \cdot \vec{l} \sim \frac{dV}{dr} \frac{d\rho}{dr} \vec{s} \cdot \vec{l}$

$\psi_{\text{scat}} \sim (U_1 + iU_2)e^{ikr} - U_{s-o}e^{ik(r-R\theta)} + U_{s-o}e^{ik(r+R\theta)}$

$= (U_1 + iU_2 + 2iU_{s-o} \sin k\theta R)e^{ikr}$

$$\frac{d\sigma}{d\Omega} \sim |\psi_{\text{scat}}|^2 \sim U_1^2 + U_2^2 + 4U_{s-o}^2 \sin^2 k\theta R$$

$+ 4U_2U_{s-o} \sin k\theta R$

- **Interference**, between an imaginary, spin-independent term $U_2$ in volume potential and a spin-dependent spin-orbit term $U_{s-o}$

- **Surfaces** where target density has a gradient $\rightarrow$ target with structure

N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009
While many theoretical models have been suggested to explain the large spin effects found in strong interactions, models based on perturbative QCD imply that the analyzing power should be zero at high energy and large $P_T^2$.

Our new high-precision data make it difficult to assume that this disagreement between theory and experiment will disappear because the nonzero $A_N$ is a statistical fluctuation. Perhaps one should now try to gain some new theoretical understanding of strong interactions that is consistent with this and other large and unexpected spin effects.
Single-spin asymmetries in $p^\uparrow p \rightarrow \pi X$

Analyzing Power

$$A_N = \frac{1}{P_{\text{beam}}} \frac{N_{\pi\text{left}} - N_{\pi\text{right}}}{N_{\pi\text{left}} + N_{\pi\text{right}}}$$

Huge single-spin asymmetry for forward meson production

**1991**

**FNAL E704**

**200 GeV $p^\uparrow$ beam**

Observable $\vec{S}_{\text{beam}} \cdot (\vec{p}_{\text{beam}} \times \vec{p}_{\pi})$ odd under naive Time-Reversal

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SSA’s at high-energies

T-odd observables

SSA observables $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2)$

$\Rightarrow$ odd under naive time-reversal

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

An’t come from perturbative subprocess xsec:

- $q$ helicity flip suppressed by $m_q/\sqrt{s}$
- Need $\alpha_s$-suppressed loop-diagram to generate necessary phase

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions
**SSA’s at high-energies**

**T-odd observables**

SSA observables $\sim \vec{J} \cdot (\vec{p}_1 \times \vec{p}_2) \rightarrow \text{odd under naive time-reversal}$

Since QCD amplitudes are T-even, must arise from interference between spin-flip and non-flip amplitudes with different phases

Must be a **spin-orbit structure**

- either in the fragmentation process
- or within the proton itself

At hard (enough) scales, SSA’s must arise from soft physics: T-odd distribution / fragmentation functions

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**STAR Run 6**

$p+p \rightarrow \pi^0+X$ at $\sqrt{s}=200$ GeV

Must be a spin-orbit structure either in the fragmentation process or within the proton itself

$x$-sec $\propto m_q/\sqrt{s}$

$\langle \eta \rangle = 3.7$

Can’t come from perturbative subprocess xsec:

need $\alpha_s$-suppressed loop-diagram to generate necessary phase
E704 Mechanism #1: The “Collins Effect”

Need an ordinary distribution function ... transversity

\[ q(x) \quad \Delta q(x) \]

... with a new, T-odd “Collins” fragmentation function

\[ h_1(x) \otimes H_{1\perp}(z, p_T) \]

*spin-orbit in fragmentation*

**E704 effect:**

\[ h_1(x) \otimes H_{1\perp}(z, p_T) \]
E704 Mechanism #2: The “Sivers Effect”

Need the ordinary fragmentation function $D_1(z)$

... with a new, T-odd “Sivers” distribution function $f_{1T}^\perp(x, k_T)$

Phenomenological model of Meng, Boros, Liang:
Forward π⁺ produced from orbiting valence-u quark by recombination at front surface of beam protons

Quark orbital motion!

$E704$ effect:

\[
f_{1T}^\perp(x, k_T) \otimes D_1(z)
\]
Electro-Production of Hadrons with Transverse Targets

Measure dependence of hadron production on two azimuthal angles

Electron beam defines scattering plane

Target spin transverse to beam

Azimuthal angles measured around $q$ vector ...

$\phi_S = \text{target spin orientation}$  \hspace{1cm} $\phi_h = \text{hadron direction}$
Electroproduction of Pions with Transverse Target

SIDIS xsec with \textit{transverse target} polarization has \textit{two} similar terms:

\begin{align*}
\sin(\phi^l_h + \phi^l_S) &\Rightarrow h_1 = \bullet - \bullet \otimes H_{1t}^\perp = \bullet - \bullet \\
\sin(\phi^l_h - \phi^l_S) &\Rightarrow f_{1T}^\perp = \bullet - \bullet \otimes D_1 = 
\end{align*}

\textit{both observed!}

\textit{separate Sivers and Collins mechanisms}

\begin{itemize}
  \item \((\phi^l_h - \phi^l_S) = \text{angle of hadron relative to initial quark spin}\)
  \item \((\phi^l_h + \phi^l_S) = \pi + (\phi^l_h - \phi^l_S) = \text{hadron relative to final quark spin}\)
\end{itemize}

N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009
Results from lepton beams:
Collins, Sivers, and friends
The Collins Fragmentation Function

\[ H_1^\perp(z, p_T) \]
Collins Moments for pions from $H^\uparrow$

**HERMES PRELIMINARY 2002-2005**

lepton beam asymmetry, Collins amplitudes

8.1% scale uncertainty

Magnificent agreement at very different scales!
The Collins function exists! ➔ spin-orbit correlations in π formation

Is the *Artru mechanism* responsible?

Lund String Model
The Sivers Function

$f_{1T}^\perp(x, k_T)$

$L_\theta$ within the proton
Sivers Moments for pions from $H^\uparrow$ Data

**HERMES PRELIMINARY 2002-2005**

lepton beam asymmetry, Sivers amplitudes
- 8.1% scale uncertainty

**COMPASS final 2003-04 D$^\uparrow$**

brief sample of current results

N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009
The Leading-Twist Sivers Function: Can it Exist in DIS?

A T-odd function like $f_{1T}^T$ must arise from interference ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?

Brodsky, Hwang, & Schmidt 2002

It looks like higher-twist ... but no, these are soft gluons = “gauge links” required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are final (or initial) state interactions ... and may be process dependent! new universality issues e.g. Drell-Yan
Global Fit to Sivers Asymmetries

E. Boglione, Transversity2008
Anselmino et al, arXiv:0805.2677

antiquark orbital $L \neq 0$ favoured!

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Phenomenology: Sivers Mechanism

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ stronger for oncoming quarks

We observe $\langle \sin(\phi^l_h - \phi^l_S) \rangle_{\pi^+ > 0}$
(and opposite for $\pi^-$)

∴ for $\phi^l_S = 0$, $\phi^l_h = \pi/2$ preferred

Model agrees!

Jet Shadowing

Parton energy loss considerations suggest quenching of jets from "near" surface of target

⇒ quarks from "far" surface should dominate

Opposite sign to data ...

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The Boer-Mulders function

\[ h_1^{⊥}(x, k_T) \]

... now correlated with the quark’s own spin ...

L_q within the proton
First charge-separated data on $<\cos(2\Phi)>_{uu}$

$h_{1}^{+}(x, k_T) \otimes H_{1}^{+}(z, p_T) \rightarrow \cos(2\phi)$ modulation

deuterium $\approx$ hydrogen values $\rightarrow$ indicate Boer-Mulders functions of same sign for u and d quarks (both negative & similar magnitudes)
A Coherent Picture?

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$
  $\rightarrow$ same as $g_{1,u}$ and $g_{1,d}$ in NR limit

- **Sivers**: $f_{1T,u} < 0 \quad f_{1T,d} > 0$
  $\rightarrow$ relat$^n$ to **anomalous magnetic moment**
  
  
  $f_{1T,q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$

  values achieve $\kappa^{p,n} = \sum_q e_q \kappa_q$ with $u,d$ only

- **Boer-Mulders**: should follow that $h_{1,u} \quad$ and $h_{1,d} < 0$ ?
  $\rightarrow$ relat$^n$ to **tensor magnetic moment**
  $\rightarrow$ possible analogue to Sokolov-Ternov?

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**but these TMDs are all independent**

\[
\langle \vec{s}_u \cdot \vec{s}_p \rangle = +0.5 \quad \langle \vec{l}_u \cdot \vec{s}_p \rangle = +0.5 \quad \langle \vec{s}_u \cdot \vec{l}_u \rangle = 0
\]

*Burkardt PRD72 (2005) 094020; Barone et al PRD78 (1008) 045022; N.C.R. Makins, Spin Physics Symposium, U Michigan, Nov 14, 2009*
Lattice QCD
Transverse spin on the lattice

Compute quark densities in **impact-parameter space** via GPD formalism

*nucleon coming out of page ...*

spatial shifts → infer \( L_q \) direction via chromodynamic lensing

\[ \begin{align*}
L_u > 0 & \quad \text{Sivers} \\
L_d < 0 & \quad \text{Boer-Mulders}
\end{align*} \]

Expected picture from relativistic quark models
→ no disconnected graphs, evolution applied via Ji, Hoodbhoy

\[
\Delta G(Q_0^2=0.4) = 0
\]

\[
\Delta G(Q_0^2=0.4) = 0.1
\]

\[ J_u \]

\[ J_d \]

\[ L_u \]

\[ L_d \]

→ lattice shows \( L_u < 0 \) and \( L_d > 0 \) in longitudinal case at expt al scales!

Evolution might explain disagreement with quark models, but not with lattice calculations of transverse spin.

Are disconnected graphs – sea quarks – the reason for apparent \( L_u \) & \( L_d \) sign change from longitudinal to transverse?
With spin around, there’s never a dull moment 😊

Congratulations, Prof. Krisch, and Thank You!

the Spin Kids

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