The Curse of Spin: Lurching from One Crisis to the Next

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Thus the path of spin is strewn with the wreckage of discarded theories. The positive aspect is that better (hopefully) theories arise from the debris.
Contents

1) The Ancient World (brief)

2) The Renaissance (the European Muon Collaboration experiment)

3) The Present (new problems)
THE ANCIENT WORLD
An example: Electroweak Theory

Weak interactions were supposed to involve S-T coupling:

\[ 1 \text{ and } \frac{i}{2} [\gamma_\mu, \gamma_\nu] \]
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Eventually learned: V-A

\[ \gamma_\mu (1 - \gamma_5) \]
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Role of spin in comparing rates for \( \pi \to e\bar{\nu} \) and \( \pi \to \mu\bar{\nu} \) was crucial. Measurement of the Helicity of the neutrino was also a vital experiment in confirming this.

fig
\[
\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu
\]

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Fig. 1.8. 90% confidence level limits on the coupling constants $g_{\lambda,\lambda}^i$ from the SIN experiments.
Without this unification of Weak and Electromagnetic interactions would have been impossible!
Another example: Regge Poles

 Totally unexpected **SHRINKING** of diffraction peaks in $\frac{d\sigma}{dt}$ for elastic cross-sections

\[
A(p_1) + B(p_2) \rightarrow A(p_3) + B(p_4)
\]

\[
t = (p_1 - p_3)^2
\]
\[ \frac{d\sigma}{dt} \text{(mb/GeV}^2\text{)} \]

- ISR p-p $\sqrt{s} = 52.8$ GeV
- ISR p-\bar{p} $\sqrt{s} = 52.6$ GeV
- UA4 p-\bar{p} $\sqrt{s} = 546$ GeV
Beautiful explanation by Theory of Complex Angular Momentum: simplest version: Regge Poles———BUT
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Total failure to predict POLARIZATIONS
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Spin had a difficult birth: fine structure of hydrogen (spin-orbit coupling); Stern-Gerlach experiment; “mysterious effects too complicated to explain in an undergraduate text” etc etc
19.1 THE FINE STRUCTURE OF HYDROGEN

\[ H_{\text{magn}} = \frac{1}{m^2 c^2} \frac{1}{r} \frac{dV}{dr} \mathbf{L} \cdot \mathbf{S} \quad (18.100) \]

When the actual calculation is made with the proper Lorentz transformations for the fields, it is found that owing to purely kinematic effects we must add a term to the energy, which has the same form as (18.100) but a different coefficient. Known as the Thomas term, this contribution to the Hamiltonian is

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However, the kinematics used above is nonrelativistic. Relativistically, the electron also precesses about the nucleus (this is called the \textit{Thomas precession}) with a certain frequency. The net upshot of this precession is that the magnetic field "seen" by the electron is only half as large as the one assumed in the derivation of equation (19.2), and therefore \[ - - - - \]
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Note that a direct calculation of the spin–orbit coupling, with the usual formulations of special relativity, gives a value twice as large as (13.22), and therefore a fine-structure splitting twice too large. This is why Pauli, at the end of 1925, did not believe in the idea of spin, and called it a "Irrlehe" in a letter to Niels Bohr. However, in March 1926, L.H. Thomas remarked that the rest frame of the electron is not an inertial frame, and that a correct calculation introduces a factor of 1/2 in the formula (the Thomas precession²). This convinced Pauli of the validity of the spin-1/2 concept.

\[ \text{HERESY !} \]
THE RENAISSANCE
Deep Inelastic Scattering: a reminder

slide
Deep Inelastic Scattering in the parton model

fig
Deep Inelastic Scattering in the parton model

\[ Q^2 \equiv -q^2 = -(k - k')^2 \quad \nu \equiv E_{Lab} - E'_{Lab} \]

\[ x \equiv x_{Bjorken} = \frac{Q^2}{2M}\nu \]
The cross-sections are expressed in terms of two (unpolarized) STRUCTURE FUNCTIONS: $F_{1,2}$

In simple Parton Model: $F_{1,2}(x)$

Including some aspects of QCD: $F_{1,2}(x, Q^2)$

Slow evolution in $Q^2$
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Slow evolution in $Q^2$

$$F_1(x, Q^2) = \frac{1}{2} \sum_{flav} e_j^2 [q_j(x, Q^2) + \bar{q}_j(x, Q^2)]$$

A key ingredient: the UNPOLARIZED parton number density $q(x)$
\[ p_i = x'_i P, s_i \]
Quite analogously, POLARIZED cross-section expressed in terms of two spin-dependent STRUCTURE FUNCTIONS: $g_{1,2}$

$$g_1(x, Q^2) = \frac{1}{2} \sum_{\text{flav}} e_j^2 [\Delta q_j(x, Q^2) + \Delta \bar{q}_j(x, Q^2)]$$
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The key ingredient here is the polarized quark density

fig
THE EMC EXPERIMENT OF 1988

\[ \Delta q = \int \Delta q(x) \, dx \] (1)

Important flavour combinations:

\[ a_3 = \Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d} \] (2)
\[ a_8 = \Delta u + \Delta \bar{u} + \Delta d - \Delta \bar{d} - 2(\Delta s + \Delta \bar{s}) \] (3)

\[ \Delta \Sigma = \sum f (\Delta q_f + \Delta \bar{q}_f) \] (4)
The EMC Experiment of 1988

Notation:

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\[ \Delta \Sigma = \sum_f (\Delta q_f + \Delta \bar{q}_f) \]

Note that \[ \Delta \Sigma = a_8 + 3(\Delta s + \Delta \bar{s}) \]
Ellis -Jaffe Theory: safe to ignore $\Delta s + \Delta \bar{s}$

$$\implies \Delta \Sigma \approx a_8 \approx 0.59$$
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$$\Rightarrow \Delta \Sigma \simeq a_8 \simeq 0.59$$

Now EMC measurement of

$$\Gamma_1^p = \int dx g_1^p(x) = \frac{1}{12} \left[ a_3 + \frac{1}{3} (a_8 + 4a_0) \right]$$

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But in naive parton model $a_0 = \Delta \Sigma$

\[\therefore\text{Gross contradiction with Ellis-Jaffe Theory}\]
Ellis-Jaffe Theory: safe to ignore $\Delta s + \Delta \bar{s}$

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Now EMC measurement of

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∴ Gross contradiction with Ellis-Jaffe Theory

Moreover, since

$$\Delta \Sigma = 2S_z^{quarks}$$

EMC seems to imply $S_z^{quarks} = 0$

and there appears to be 'A crisis in the parton model: where, oh where, is the proton’s spin?'

[Anselmino and L, Z.Phys. C41,(1988) 239]
Resolution (??)of the crisis : The Anomalous Gluon Contribution
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The Operator Product Expansion has no gluon operator contributing to the first moment of $g_1$, but Feynman diagram approach yields result:

$$a_0 = \Delta \Sigma - \frac{3\alpha_s(Q^2)}{2\pi} \Delta G'(Q^2)$$ (2)
\[ a_0 = \Delta \Sigma - \frac{3\alpha_s(Q^2)}{2\pi} \Delta G(Q^2) \]

It was thus hoped that one could have a reasonable \( \Delta \Sigma \simeq 0.6 \) and still obtain a very small \( a_0 \).
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Is this acceptable? What do we know about \( \Delta G \)?
THE PRESENT

ATTEMPTS TO MEASURE $\Delta G$

There are three ways to access $\Delta G(x)$:
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1. Polarized Deep Inelastic Scattering (DIS)—parametrize polarized quark and gluon densities and fit data on $g_1(x, Q^2)$. 
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fig world results on $\Delta G(x)$
This is a test.
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(2) $c\bar{c}$ production in DIS. Requires high energy lepton beam: COMPASS at CERN.

Given that the nucleon has no INTRINSIC charm, the $c\bar{c}$ are produced via 'gluon-photon fusion'.

fig
Photon-Gluon fusion

\[ q = c \]

"OPEN CHARM"

cross section difference in charmed meson production

→ theory well understood

→ experiment challenging

\[ q = u, d, s \]

"HIGH \( p_T \) HADRON PAIRS"

cross section difference in 2+1 jet production in COMPASS:

events with 2 hadrons with high \( p_T \)

→ experiment "easy"

→ theory more difficult
Detecting BOTH charmed particles would be an absolutely clean signal for the mechanism!

But the intensity is too low—factor of 30 in rate lost in detecting second charmed meson—so rely on single charm production. Also on back-to-back jets—much less clean.

Figure shows some of the COMPASS results
Figure 3: Comparison of the $\Delta G/G$ measurements from COMPASS (present work), SMC [14], and HERMES [23]. The horizontal bar on each point represents the range in $x_g$. The curves show various parametrizations from NLO fits in the $\overline{MS}$ scheme at $\mu^2 = 3$ (GeV/c)$^2$: GRSV2000 [20] (3 curves, please see text for details), AAC03 [24], and LSS05 sets 1 and 2 [25].
Suggests very small $\Delta G$ compatible with result quoted above
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(3) $A_{LL}$ with polarized protons: uniquely at RHIC.

Several reactions:

$\vec{p} + \vec{p} \rightarrow \pi^0 + X$ (needs Fragmentation Functions)

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Dominant partonic reactions:

$g + g \rightarrow g + g$: dominates at smaller $p_T^2$

$\vec{g} + \vec{q} \rightarrow g + q$: dominates at larger $p_T^2$
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Nice test: PQCD describes cross-sections quite well. Fig
\( \pi^0 \) Cross Section

- Data points extend from 1 to 20 GeV/c in pT.

- pQCD calculation with KKP FF describes the data well over all measured pT region. (range of \( 10^9 \))

- The cross section of other channel, for example charged pion, is also useful to test pQCD.
Results: $A_{LL}$ is SMALL!

Fig
\[ \int L dt = 2.7 pb^{-1} \]

\[ P \approx 0.45 \]

Run 5 (Preliminary)

GRSV-max

GRSV-std

Scaling error of 40% is not included.
Consistent with ZERO gluon polarization
Consistent with ZERO gluon polarization

THE SPIN CRISIS

IS STILL WITH US!
Expect more definite statement on $A_{LL}$ very soon: much improved accuracy

fig
Prospects for Run5 (first long pp run) and Run6 (ongoing)

Run5 improvements:
- $P_b \sim 45\%$ ($\sim 40\%$ in Run4) $L = 3/\text{pb} \ (0.3/\text{pb in Run4})$
  $\text{FoM (Run5)/FoM(Run4)} = 16$
- Acceptance: 3/4 BEMC complete ($1/2$ in Run4)
- Two complementary jet triggers permit assessment of trigger bias due to $q$ vs. $g$ jet differences in shape, multiplicity, hardness in $z$.

Potential to discriminate between several $A_{LL}$ predictions based on DIS parametrizations
Hadronic reactions like

\[ p^\uparrow + p \rightarrow \pi + X \]

\( p^\uparrow \): transversely polarized proton
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Asymmetry under reversal of direction of polarization

\[ A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \]
TRANSVERSE SINGLE-SPIN ASYMMETRIES

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Partonic mechanism:

fig
In collinear Parton Model $A_N \approx 0$
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To get an idea of the size, at parton level

$$\tilde{a}_N = \alpha_s \frac{m_q}{\sqrt{s}} f(\theta^*)$$

where $f(\theta^*)$ is of order 1
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THE DATA STRONGLY CONTRADICT THIS!
Large asymmetry in pion production
Asymmetry persists to high energy
No asymmetry in proton production at the AGS (not shown)
How to extricate QCD from this mess???
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1) Include intrinsic transverse momentum $k_T$ of partons.

Conceptually no problem; but makes serious calculations horrendous.
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a) **SIVERS**: Number density of quarks with momentum $xP + k_T$ depends on polarization $\mathcal{P}$ of parent hadron:

$$ q(x, k_T) = A + B_S \mathcal{P} \cdot (xP \times k_T) $$
\textbf{BUT} can show this violates Parity and Time Reversal invariance \textbf{IF}

\[ \text{hadron} \rightarrow \text{quark} + X \]

is treated as an \textit{independent} reaction——as it is in the parton model.
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Number density of hadrons with momentum \( P_h = \frac{1}{z} p + k_T \) depends on polarization \( \mathcal{P} \) of fragmenting quark.
$D(z, P_h) = A + B_C \cdot (p \times P_h)$
\[ D(z, P_h) = A + B_C \cdot \mathcal{P} \cdot (p \times P_h) \]

Again, vanishes if fragmentation

\[ q \rightarrow hadron + X \]

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is treated as an independent reaction, as it is in the parton model.

So again lose universality.
\begin{equation}
D(z, P_h) = A + B_C \cdot \mathcal{P}(p \times P_h)
\end{equation}

Again, vanishes if fragmentation

\[ q \rightarrow \text{hadron} + X \]

is treated as an independent reaction, as it is in the parton model.

So again lose universality.

Moreover, can’t calculate $B_S$ or $B_C$ so need to introduce new functions phenomenologically, for each flavour of quark and antiquark. Ugly!
THE LATEST PROBLEM
One of the oldest and supposedly best understood reactions:

\[ \text{electron} + \text{proton}(p) \rightarrow \text{electron} + \text{proton}(p') \]

Measurement of the ELECTROMAGNETIC FORM FACTORS OF THE PROTON
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As always, assume ONE PHOTON Exchange

fig
The photon-proton vertex is given by:
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\[ \bar{u}(p')\left[\gamma_\mu F_{1e}^m(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}\kappa F_{2e}^m(Q^2)\right]u(p) \]

\[ q = p' - p \quad \kappa = \text{anomalous magnetic moment} \]
\[ Q^2 = -q^2 \]

\( F_{1,2} \) Dirac em form factors. Sachs more convenient:

\[ G_E = F_1 - \kappa\tau F_2 \quad G_M = F_1 + \kappa F_2 \]

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

\[ G_E(0) = 1 \]
\[ G_M(0) = \text{total magnetic moment}(\mu) = 2.79 \]
Diff. cross-section in the LAB: ROSENBLUTH

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)'_{\text{Mott}} \left[ \frac{G_E^2 + \tau G_M^2}{1 + \tau} + 2\tau G_M^2 \tan^2(\theta/2) \right]
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Both $G_E$ and $G_M$ drop with increasing $Q^2$

Long standing experimental assertion that

$G_M(Q^2) \approx \mu G_E(Q^2)$
New cross-section measurements are consistent with this:

fig
HOWEVER

A totally new kind of measurement: Polarization transfer to the proton from a longitudinally polarized electron colliding with an unpolarized target:
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LONGITUDINAL polarization of the recoil proton:

\[ P_L \propto \left[ \frac{E + E'}{M} \right] \sqrt{\tau(1 + \tau)} G_M^2 \tan^2(\theta/2) \]
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TRANSVERSE (in scattering plane) polarization of the recoil proton:

\[ P_T \propto -2\sqrt{\tau (1 + \tau)} G_E G_M \tan(\theta/2) \]
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Size consistent with comparison of electron-proton with positron-proton

Exact calculation would require evaluation of Feynman graph:

fig
Not possible. Can do approximate calculation of simplest two photon graph:

fig
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Mainly affects Rosenbluth extraction and suggests polarization results for $G_E/G_M$ are correct!

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What about famous prediction of perturbative QCD:

$$G_E/G_M \rightarrow \text{constant as } Q^2 \rightarrow \infty \quad ????
SUMMARY

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(c) We are facing the realization that what is arguably the best-understood of all reactions i.e. electron-proton elastic scattering, has, in fact, been significantly misunderstood.