Spin structure from the beginning to JLab and muonic helium

- Muon physics
- Spin structure of the nucleon
- Parity violation in electron scattering

Gordon D. Cates
October 8, 2026

University of Virginia

I have known Paul for many years

I have known Paul for many years

But there was a time when I did not know Paul.



I also did not know Paul when he was a graduate student



Here Paul is shown in May of 1969, a graduate student in Pierre Piroué's group working on an experiment studying kaon decays



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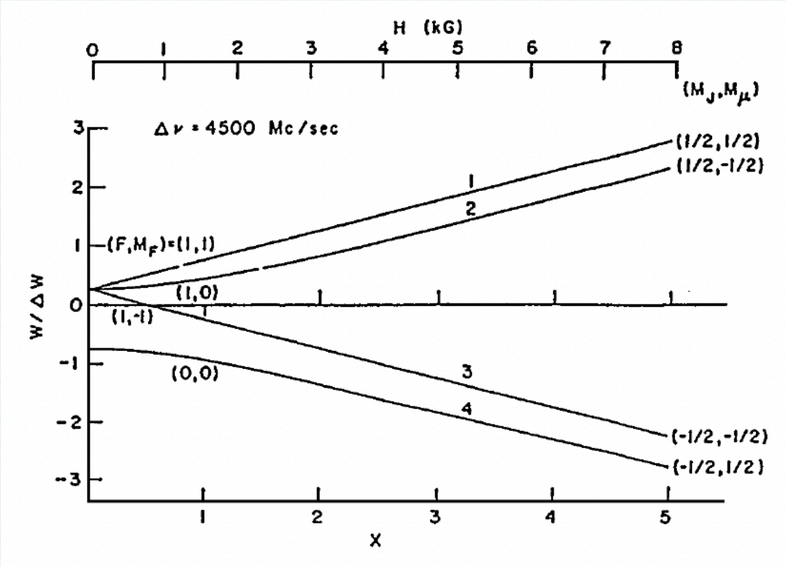


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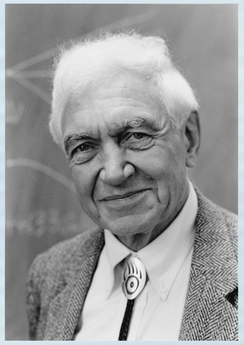


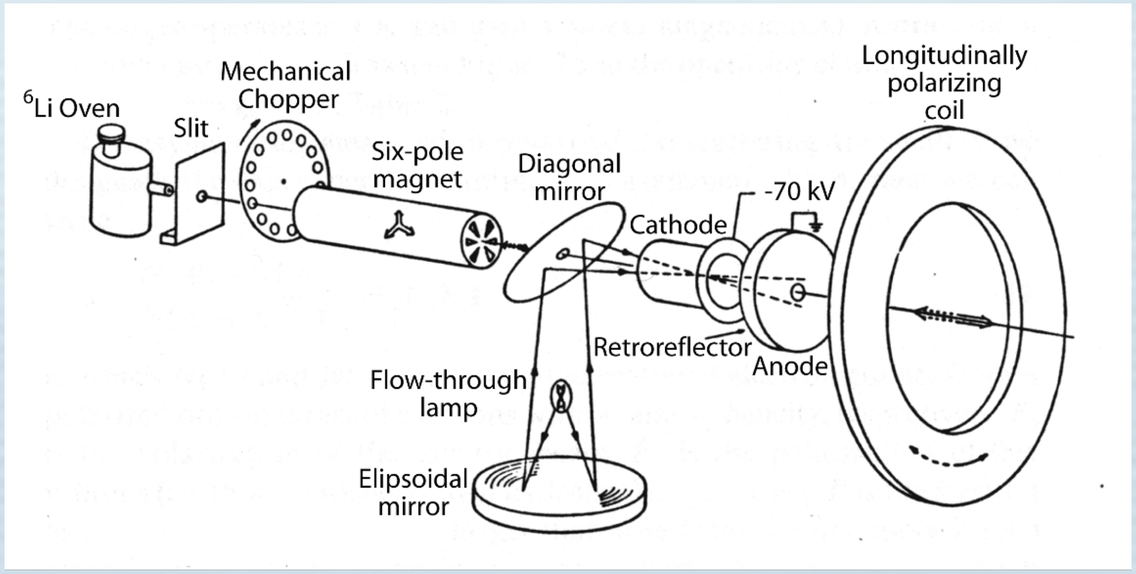
Life after graduate school

After getting his Ph.D. from Princeton in 1971, Paul went to Yale where he often collaborated with Vernon Hughes



Vernon was doing increasingly precise spectroscopy on muonium.





Vernon was also leading an effort to create the first high-energy polarized electron beam.

Paul at Yale

At Yale, at least three subjects caught Paul's interest:

- Precision measurements to study fundamental physics, at first in muonium.
- Using polarized electrons to understand the structure of the nucleon - at a time when people were still trying to understand what the heck quarks were!
- Using polarized electrons to study parity violation, which through the (Yale/SLAC) Prescott experiment, would establish the Standard Model.

Muon physics

"The Discovery of neutral muonic helium"

I'm putting this in quotes because this was the title of a talk given by Gisbert zu Putlitz (University of Heidelberg) at the "Souderfest" held at Syracuse University on the occasion of Paul's 70th birthday.

This work was published just four years after Paul got his Ph.D.

Discovery of neutral muonic helium



The experiment was performed right here at SREL before CEBAF was built.



A more recent view of the same buildings



Discovery of neutral muonic helium

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

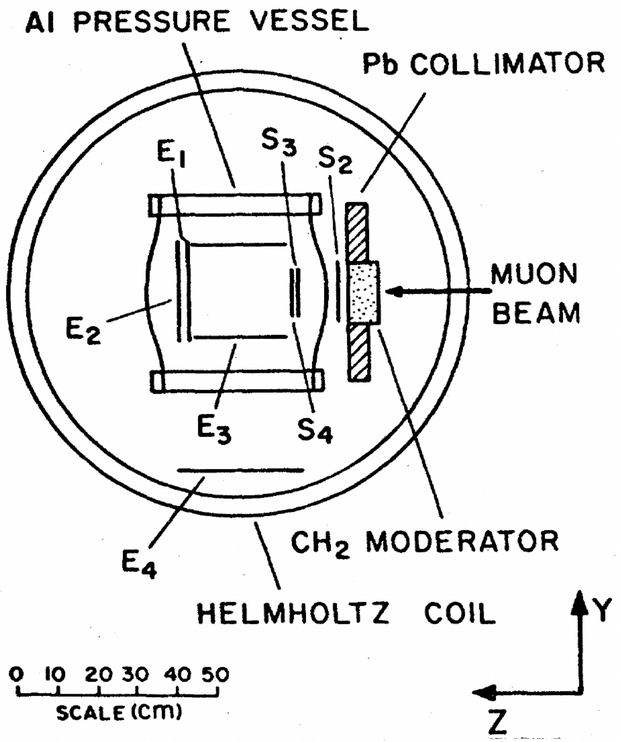


FIG. 4. Schematic diagram of apparatus to search for the precession of $(^4He\,\mu^-)^+$ and $^4He\,\mu^-e^-$. S_1 is upstream and not shown. The magnetic field points out of the paper.

Difficult expt, particularly in 1975!!!

- Expt performed at SREL (i.e.) right here in pre-CEBAF days so muon flux was quite limited.
- Polarization of the muon was quite small once it was in the ground state.
- Creating any muonic atom is challenging.

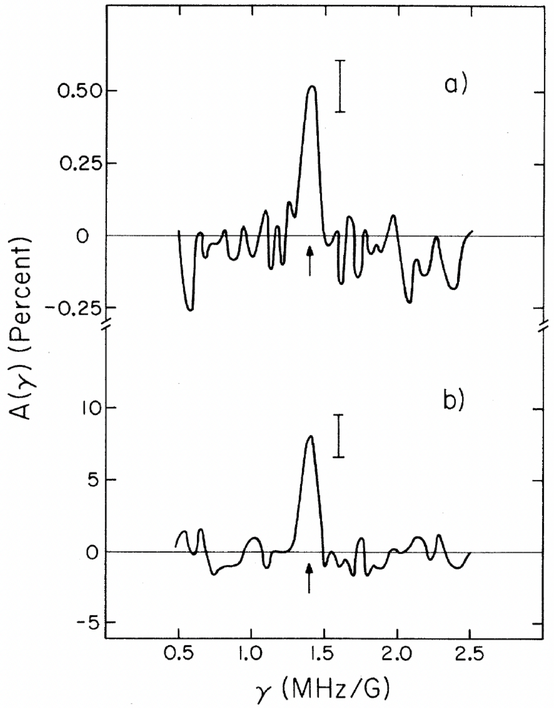


FIG. 2. Observed Larmor precession amplitudes $A(\gamma)$ versus gyromagnetic ratio $\gamma = f/B$: (a) μ^- stopped in He + 2% Xe, and forming $\alpha\mu^-e^-$ (3×10^8 μ_S); (b) μ^+ stopped in He + 2% Xe, and forming μ^+e^- (1.8×10^6 μ_S). The arrows indicate the expected gyromagnetic ratio $\gamma = 1.4$ MHz/G.

The spin structure of the nucleon

Paul participated in the original experiments that studied the spin structure of the nucleon, SLAC E80 and E130

The origins of spin-structure studies

From David Griffiths, Introduction to elementary particles

pothesis. But I think it is safe to say that by 1974 most elementary particle physicists felt queasy, at best, about the quark model. The lumps inside the proton were called *partons*, and it was unfashionable to identify them explicitly with quarks.

It was felt that verifying that the spin structure was consistent with the quark model, such as that developed by Kuti and Weiskopf, would, provide strong evidence that the partons were indeed quarks.

SLAC E80: the first measurement of the spin structure of the nucleon

Deep Inelastic Scattering of Polarized Electrons by Polarized Protons*

M. J. Alguard, W. W. Ash, G. Baum, J. E. Clendenin, P. S. Cooper, D. H. Coward, R. D. Ehrlich, A. Etkin, V. W. Hughes, H. Kobayakawa, K. Kondo, M. S. Lubell, R. H. Miller, D. A. Palmer, W. Raith, N. Sasao, K. P. Schüler, D. J. Sherden, C. K. Sinclair, and P. A. Souder

University of Bielefeld, Bielefeld, West Germany, and City University of New York, New York, New York 10031, and Nagoya University, Nagoya, Japan, and Stanford Linear Accelerator Center, Stanford, California 94305, and University of Tsukuba, Ibaraki, Japan, and Yale University, New Haven, Connecticut 06520

(Received 5 August 1976)

We report measurements of the asymmetry in deep inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. The antiparallel-parallel asymmetries are positive and large in agreement with predictions of quark-parton models of the proton. A limit is obtained on parity nonconservation in the scattering of longitudinally polarized electrons by unpolarized nucleons.

"The antiparallel-parallel asymmetries are positive and large in agreement with predictions of quark-parton models of the proton."

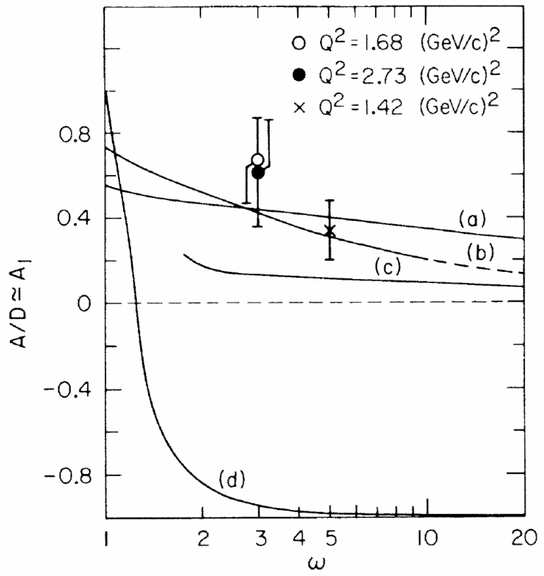


FIG. 1. Experimental values of $A/D \approx A_1$ and theoretical predictions of the virtual-photon–proton asymmetry A_1 versus ω. Theoretical curves a, b, c, and d are obtained from Refs. 5, 10, 13, and 14, respectively. For curve c the quark model with symmetry breaking is used: The model does not give values for A_1 in the range $1 < \omega < 2$, but rather gives $A_1(1) = 1$. For curve d the quantity μ^2/m_p^2 in the theory is taken equal to 0.12.

SLAC E130: the second measurement of the spin structure of the nucleon

New Measurement of Deep-Inelastic *e*-*p* Asymmetries

G. Baum, M. R. Bergström, P. R. Bolton, J. E. Clendenin, N. R. DeBotton, S. K. Dhawan, Y.-N. Guo, V.-R. Harsh, V. W. Hughes, K. Kondo, M. S. Lubell, Z.-L. Mao, R. H. Miller, S. Miyashita, K. Morimoto, U. F. Moser, I. Nakano, R. F. Oppenheim, D. A. Palmer, L. Panda,[a] W. Raith, N. Sasao, K. P. Schüler, M. L. Seely, P. A. Souder, S. J. St. Lorant, K. Takikawa, and M. Werlen

Institute of High Energy Physics, Beijing, China, and University of Bern, Bern, Switzerland, and University of Bielefeld, Bielefeld, Federal Republic of Germany, and National Laboratory for High Energy Physics, KEK, Tsukuba, Japan, and Kyoto University, Kyoto, Japan, and Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France, and Stanford Linear Accelerator Center, Stanford, California 94305, and University of Tsukuba, Ibaraki, Japan, and Yale University, New Haven, Connecticut 06520

(Received 13 July 1983)

Spin-dependent asymmetries have been measured in inclusive deep-inelastic scattering of longitudinally polarized electrons by longitudinally polarized protons. Data were obtained at a scattering angle of 10° and for incident energies of 16.2 and 22.7 GeV, which cover the kinematic range $0.18 < x < 0.70$ and $3.5 < Q^2 < 10.0$ $(\mathrm{GeV}/c)^2$. The present results provide a test of scaling and of the Bjorken and Ellis-Jaffe sum rules and are compared with various models of proton spin structure.

PACS numbers: 13.60.Hb, 13.40.Fn

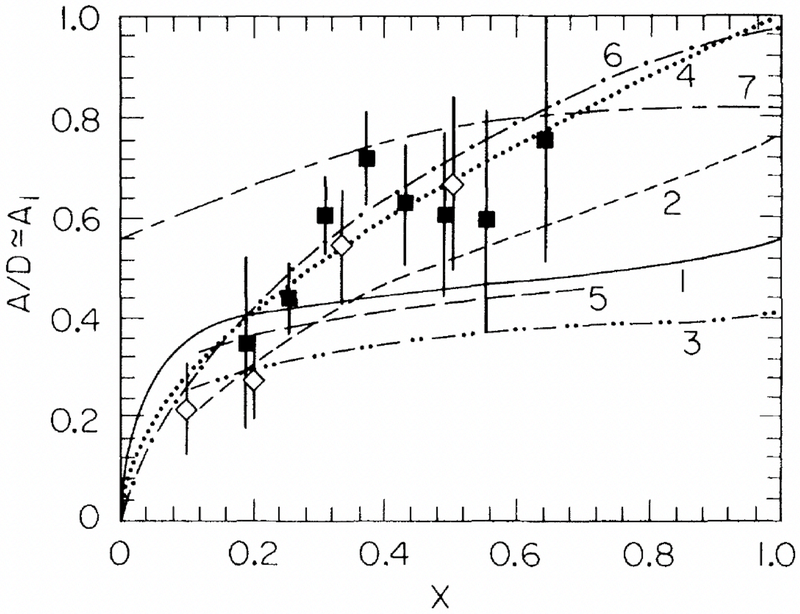


FIG. 3. Experimental values of $A/D \simeq A_1$ compared with theories for A_1: curve 1, symmetrical valence quark model (Ref. 12); curve 2, current quarks (Ref. 13); curve 3, orbital angular momentum (Ref. 14); curve 4, unsymmetrical model (Ref. 15); curve 5, MIT bag model (Ref. 16); curve 6, source theory (Ref. 17); curve 7, quark-geometrodynamics (Ref. 18).

Rumor has it that for E130, Vernon only wanted to use a deuterium target, but Paul pushed for a proton target. If they had only run deuterium, would the field of spin physics have even come into being?

… and somewhere in there Paul proposed the Bates ^{12}C parity experiment

And not too long after that, sort of between SLAC E80 and E130, I showed up at Yale

Parity violation in elastic scattering of polarized electrons from ^{12}C

(at the MIT-Bates Linear electron accelerator)

VOLUME 65, NUMBER 6 PHYSICAL REVIEW LETTERS 6 AUGUST 1990

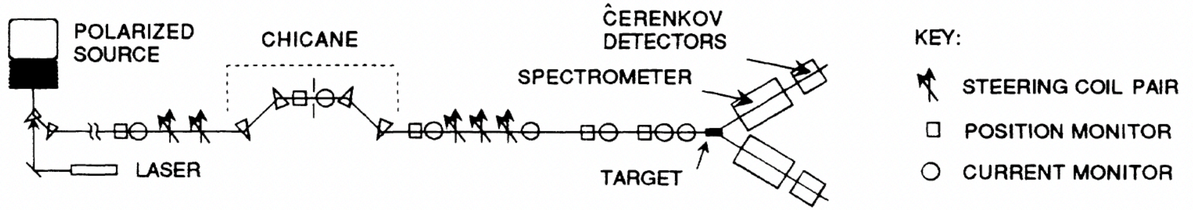
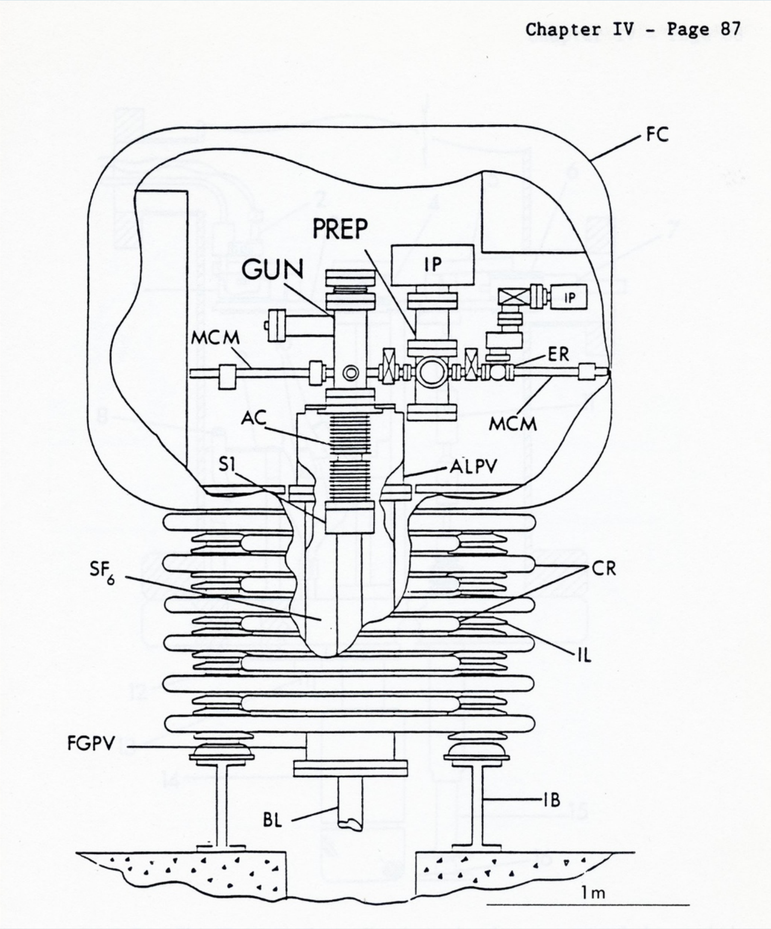


FIG. 1. Schematic diagram of the apparatus. The beam energy was measured in the chicane.

- Because ^{12}C is isoscalar and spinless, elastic scattering is described by a single form factor that cancels in the asymmetry.
- The experimental asymmetry measured was (0.60 +/- 0.14 +/- 0.02) x 10-6
- With systematics at the level of around 20 parts per billion, the Bates ^{12}C experiment paved the way for many ambitious future parity experiments.

Yes … I really did ask who was actually going to build the polarized electron source





(at Clark's Dairy in New Haven)

The Bates Carbon Experiment was proposed in 1977, as Prescott et al. got their results

A = ~100 ppm
SLAC



A = ~1 ppm
Bates

$\delta A_{systematic}$ = ~10,000 ppb
SLAC



$\delta A_{systematic}$ = ~20 ppb
Bates

By reducing systematic errors by almost a factor of 1000, the Bates Carbon experiment helped usher in what has become a hugely important subfield in electron scattering

The Bates Carbon Experiment was proposed in 1977, as Prescott et al. got their results

A = ~100 ppm SLAC	→	A = ~1 ppm Bates

1990

$\delta A_{systematic}$ = ~10,000 ppb SLAC	→	$\delta A_{systematic}$ = ~20 ppb Bates

By reducing systematic errors by almost a factor of 1000, the Bates Carbon experiment helped usher in what has become a hugely important subfield in electron scattering

Okay, back to Bates ....

- In a parity measurement, false asymmetries caused by helicity-correlated systematic effects can be death to the experiment.
- Building on techniques used in Prescott's experiment, Paul pioneered clever and subtle ways to precisely quantify the false asymmetries due to helicity-correlated changes in beam intensity, position, angle and energy. For example:

Intentionally change beam position by amounts that were small compared to the statistical fluctuations → Measure carefully the dependence of the detector rates on the position differences. → Make corrections with well understood errors. Typically about 10% of the corrections itself.

TABLE I. Corrections for experimental asymmetry A_{expt} in ppm. The raw asymmetry is 0.56 ± 0.14.

Correction	Value	Error
Energy and position monitors	0.04	± 0.006
Electronic cross talk	···	± 0.001
Transverse polarization	···	± 0.005
Nonlinearities	···	± 0.007
Phase space	···	± 0.006
Background from magnetized iron	···	± 0.010
Net asymmetry	$0.60 \pm 0.14 \pm 0.02$	

correction: 40 ppb
Error in correction: 6 ppb

The experimental legacy of the Bates Carbon Experiment

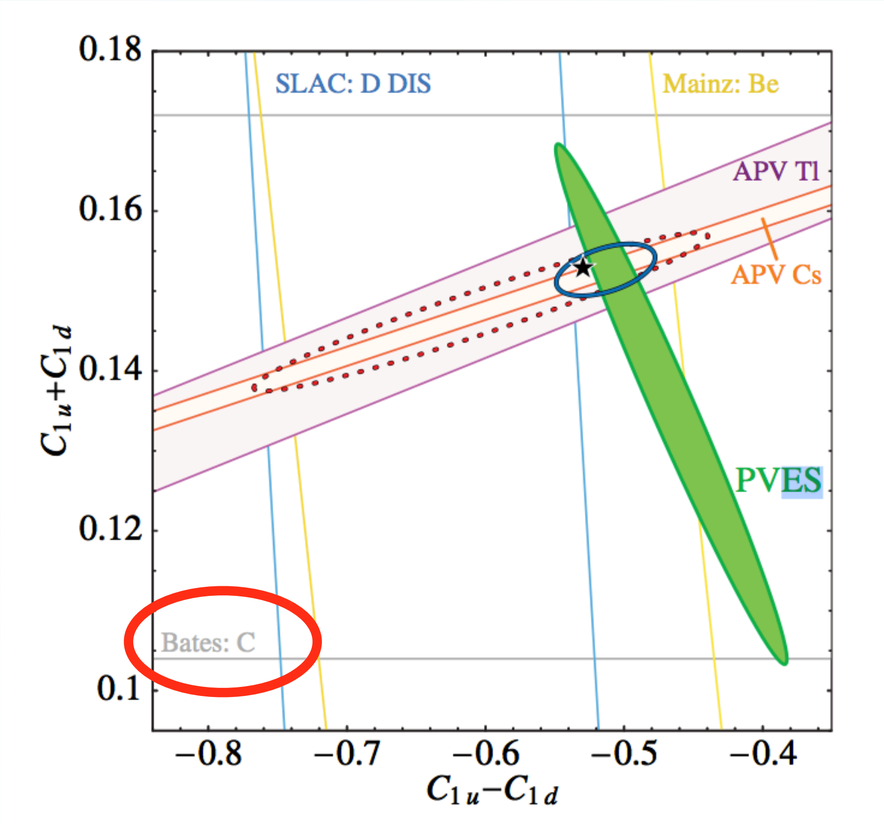


Figure that appeared on the cover of Physical Review Letters from 21 September 2007

I will forgo the discussion of the legacy of the Physics impact of the Bates experiment I will comment, however, that the impact of Bates on the field of electron scattering, was huge.

Paul is generous (and prolific) with ideas, particularly when working with young people

After graduating from Yale, I moved to Princeton where I began learning about optical pumping and spin exchange from Will Happer, and together with Art McDonald, starting working with polarized ^{3}He.

Based on my new research directions, Paul made two suggestions:

- Pursue an idea first suggested by C. S. Wu for measuring the induced pseudo scalar coupling g_p
  - We started working on that quite quickly.
- Measure the spin structure of the neutron using 3He at SLAC
  - We held off on this figuring that if Vernon Hughes got kicked out of SLAC, we wouldn't have a chance.

The experiment from C. S. Wu Paul suggested



Use the spin dependence of the reaction:

$$\mu^- + {}^3\mathrm{He} \longrightarrow {}^3\mathrm{H} + \nu_\mu$$

To determine the induced pseudo scalar coupling g_p.

The differential capture rate can be written

$$\frac{d\Gamma}{d\cos\theta} \approx \tfrac{1}{2}\Gamma_0(1 + A_v P_v \cos\theta)$$

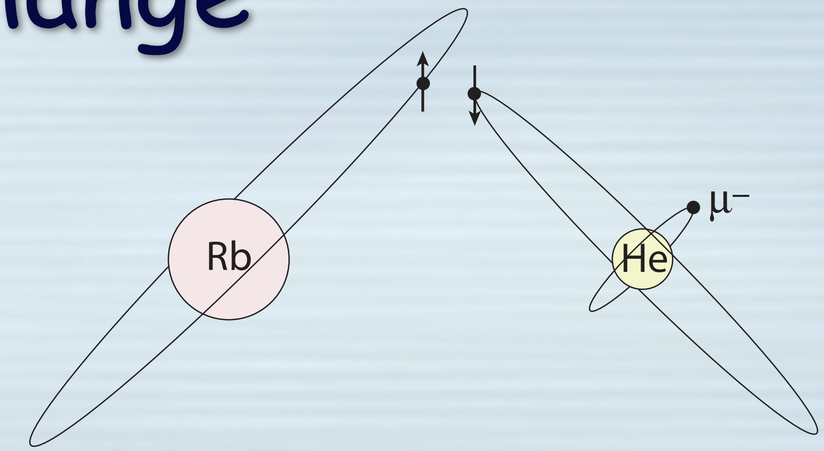
Where Γ_0 is the spin-averaged capture rate,
$P\nu$ is the polarization of the muon, and
θ is the angle between the muon polarization and the direction of the triton.

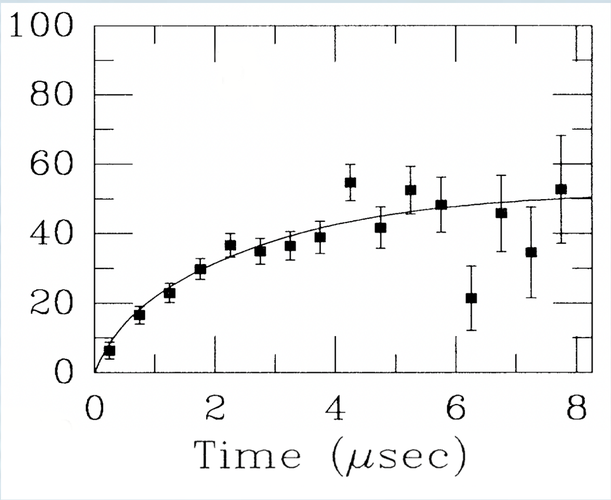
g_p can be determined quite accurately from the vector analyzing power A_ν

Her experiment failed because the polarization of the stopped muon was only a few percent.

We developed a way to achieve much higher muon polarization using optical pumping and (electronic) spin exchange

- Stop muons in He to form muonic helium.
- Muonic He is hydrogen with a He/muon pseudo nucleus
- Maintain a dense vapor of optically pumped Rb.
- Rapid spin-exchange takes place between the hydrogenic Rb and the hydrogenic muonic He.
- Polarization is quickly shared with the muonic He pseudo nucleus.

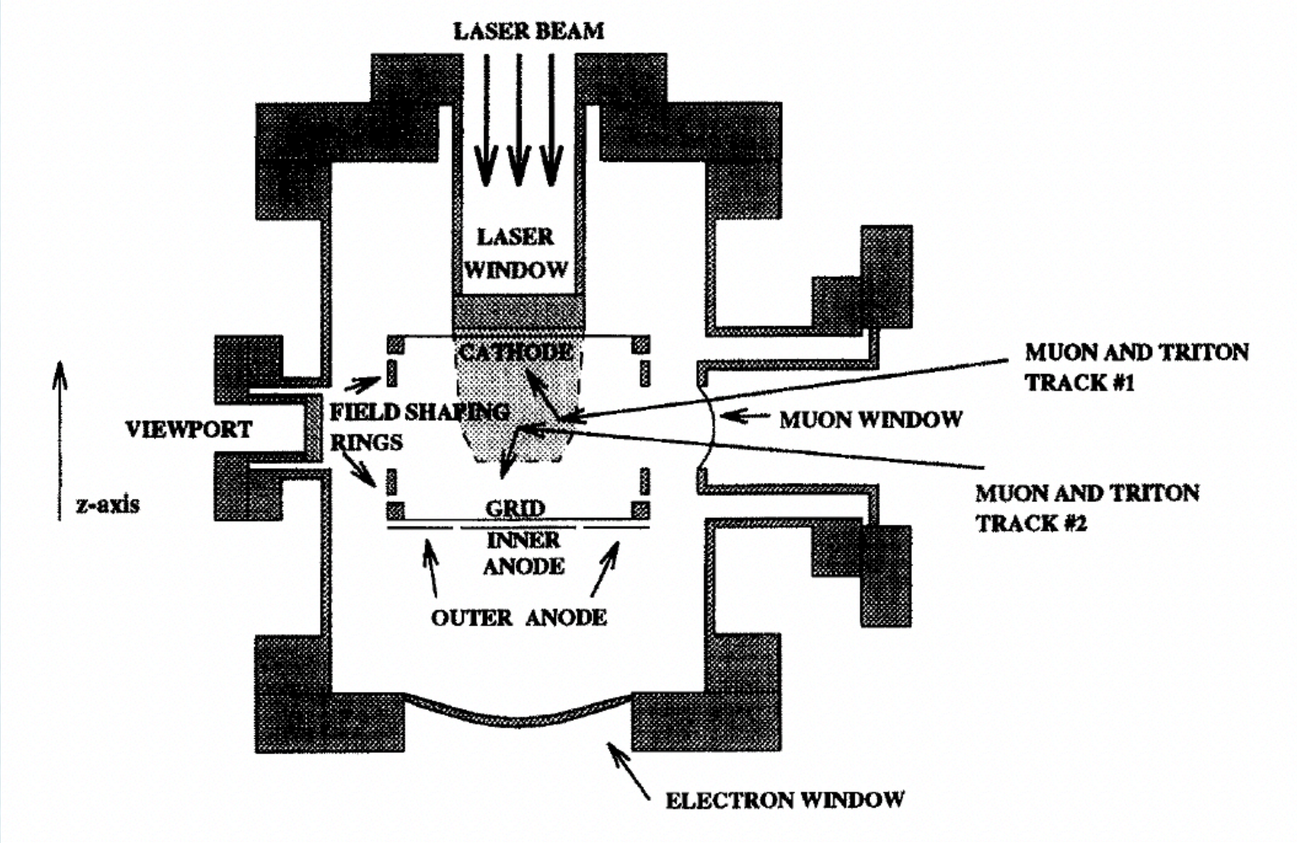




VOLUME 70, NUMBER 6 PHYSICAL REVIEW LETTERS 8 FEBRUARY 1993

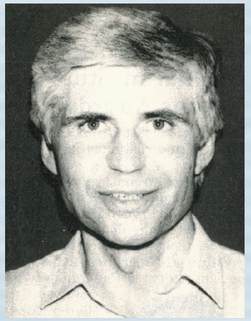
Highly Polarized Muonic He Produced by Collisions with Laser Optically Pumped Rb

We even made a rough measurement of the vector analyzing power



- Muonic 3He is formed inside a unity-gain ion chamber.
- Polarized through interactions with optically pumped Rb
- Directional information derived from the shape of the signal from the triton.
- Measured the vector analyzing power to be 0.59 +/- 0.13

This work was done in collaboration with Otto Hausser's research group.



But sadly, the DOE pulled the plug once we were working at TRIUMF

Paul's other suggestion

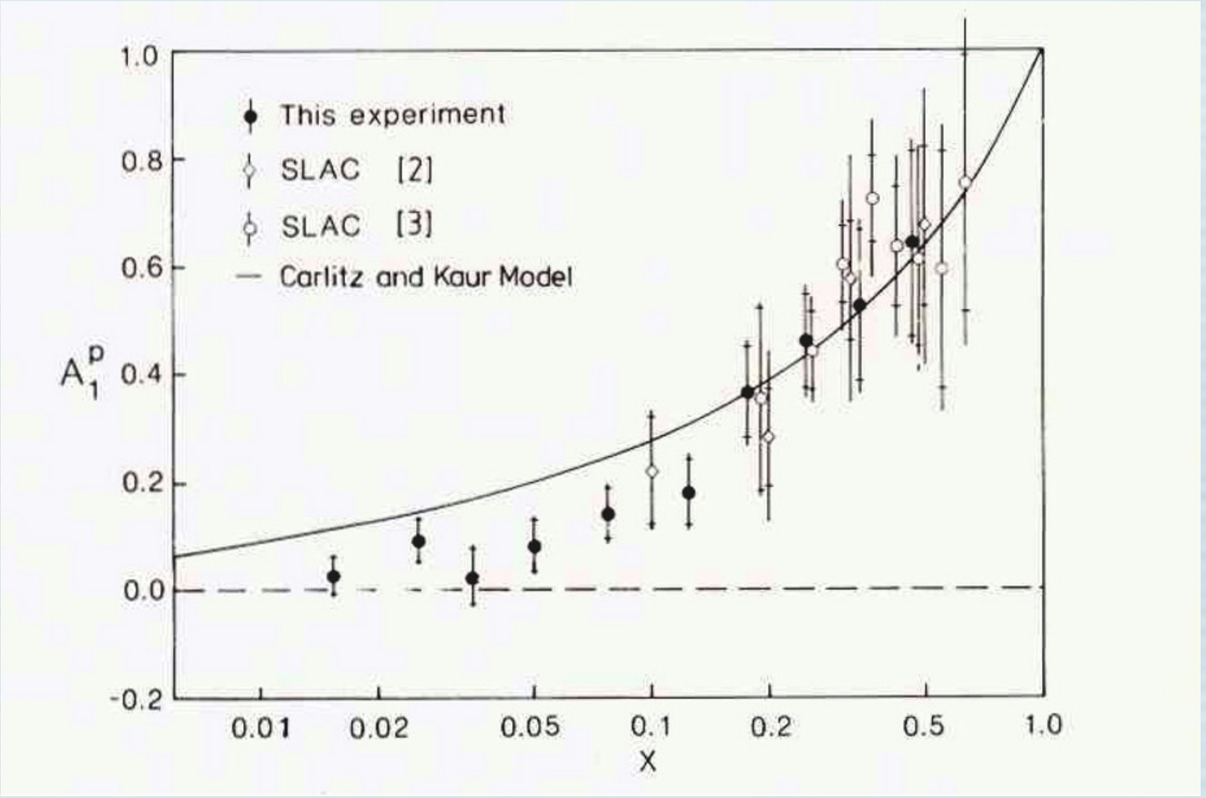
(on the spin structure of the neutron)

Paul's other suggestion arose because of the proton spin crisis

In an experiment led by Vernon Hughes, the European Muon Collaboration (EMC) greatly improved the data on A_1^p.

The spin structure function

$$g_1^{p(n)}(x, Q^2) \approx A_1(x, Q^2) F_1(x, Q^2)$$



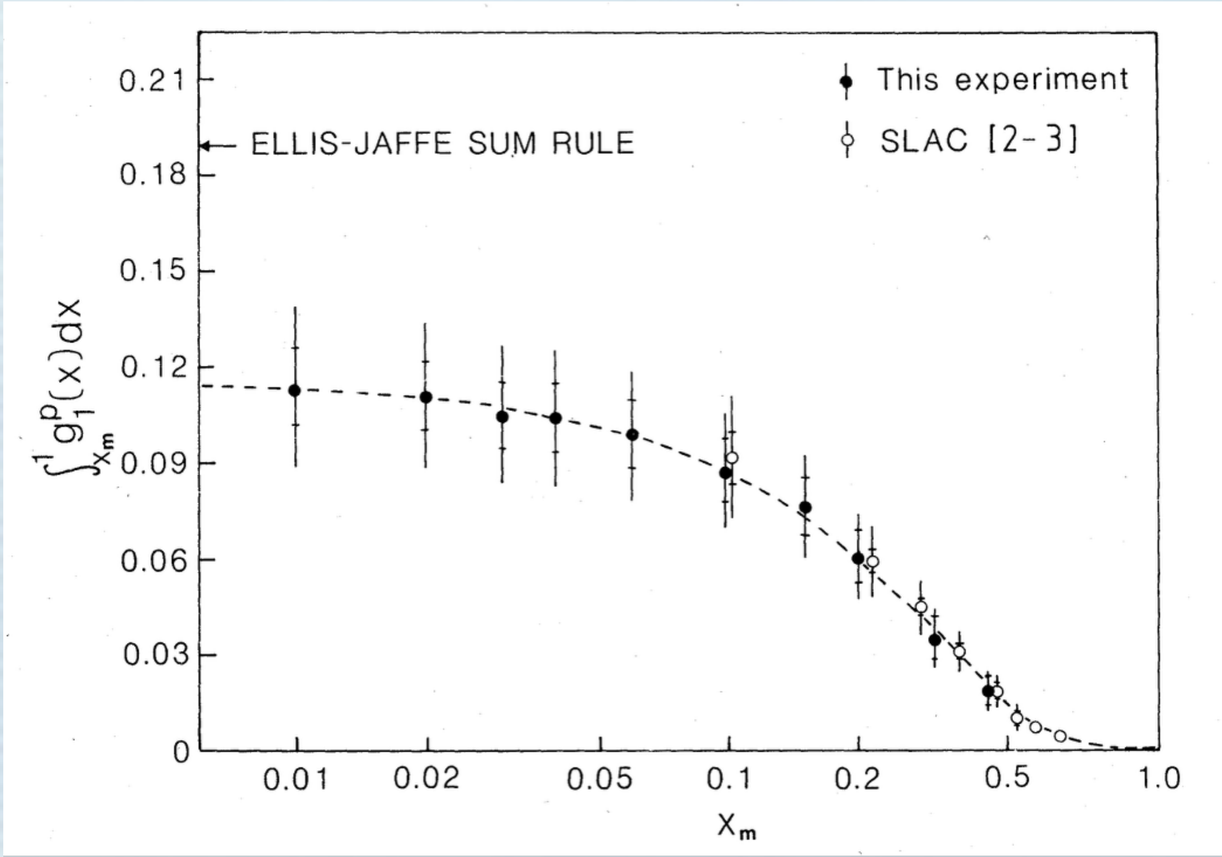
The proton spin crisis

The new data clearly showed a violation of the Ellis-Jaffe Sum Rule

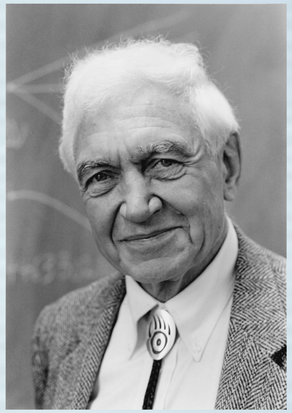
The first moment of the spin structure function:

$$\Gamma_1^{p(n)}(x,Q^2) \equiv \int_0^1 g_1^{p(n)}(x,Q^2)\,dx$$

Without going into too much detail, the EMC results clearly showed that rather little of the spin of the proton was due to the spins of the quarks, a very surprising result



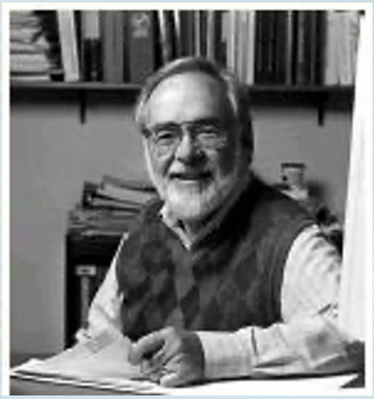
SLAC E142 is Born



Yes Vernon got kicked out of SLAC (they were worrying about SLC)

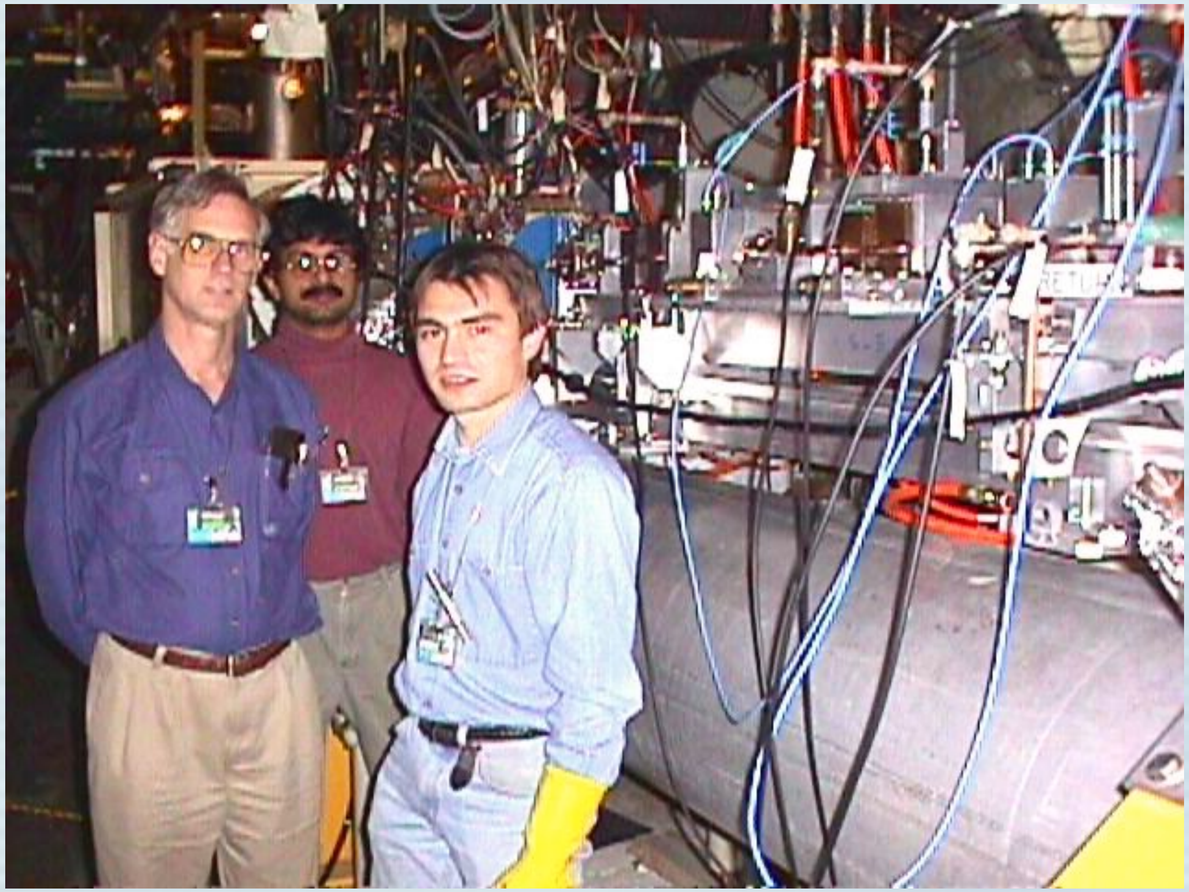
But Vernon's son Emlyn took a post-doc at SLAC





With encouragement from Prescott (which is like a letter of transit if you know the movie Casablanca), Emlyn started building a collaboration to study the neutron (later expanded to include the proton).

SLAC E142 is Born as was SLAC E154

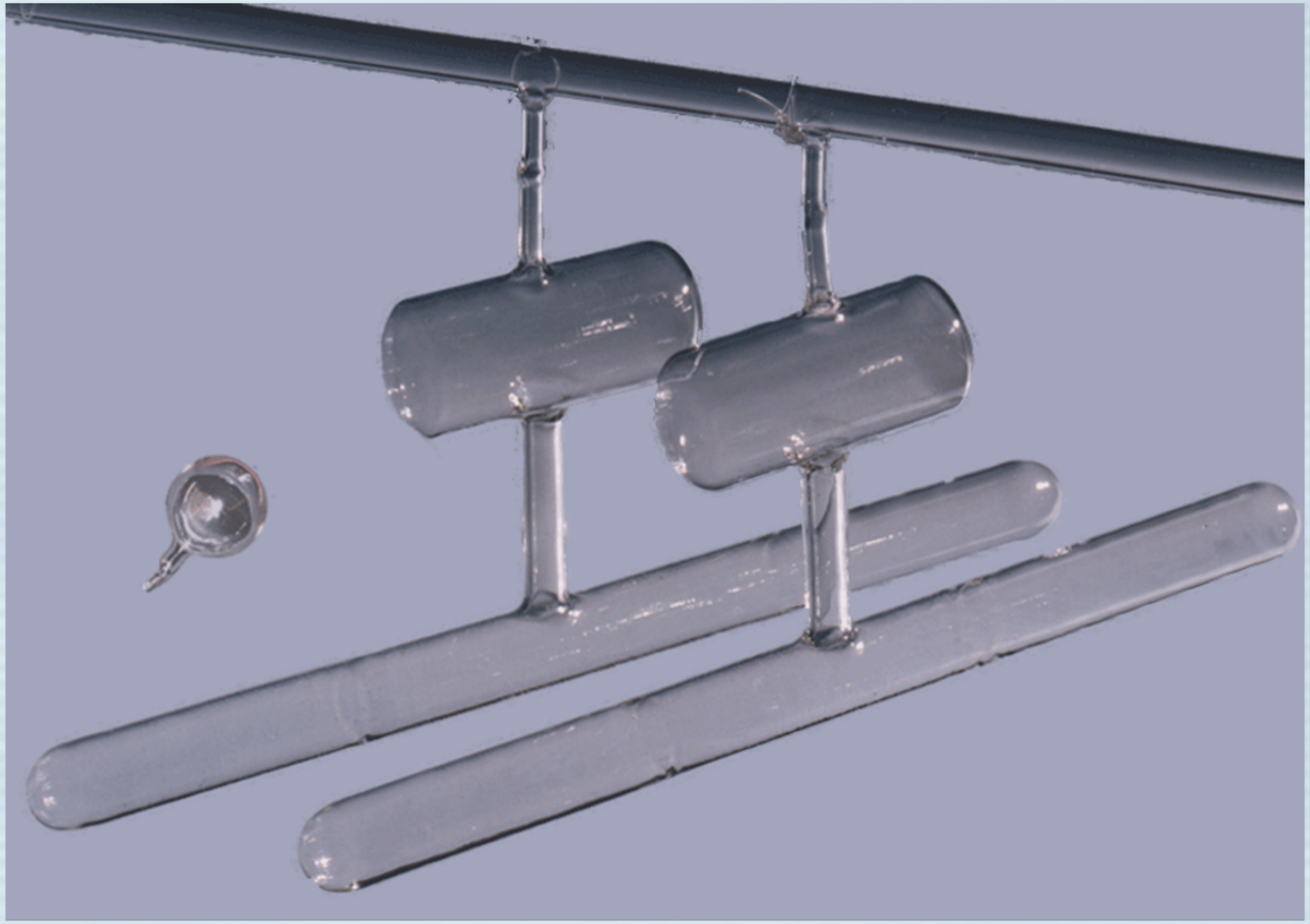


This photo is actually slightly later from a test run for E158

Paul was a battle-hardened veteran of both E80 and E130 and understood all this stuff way better than any of us. He became part of the core group in the experiment.

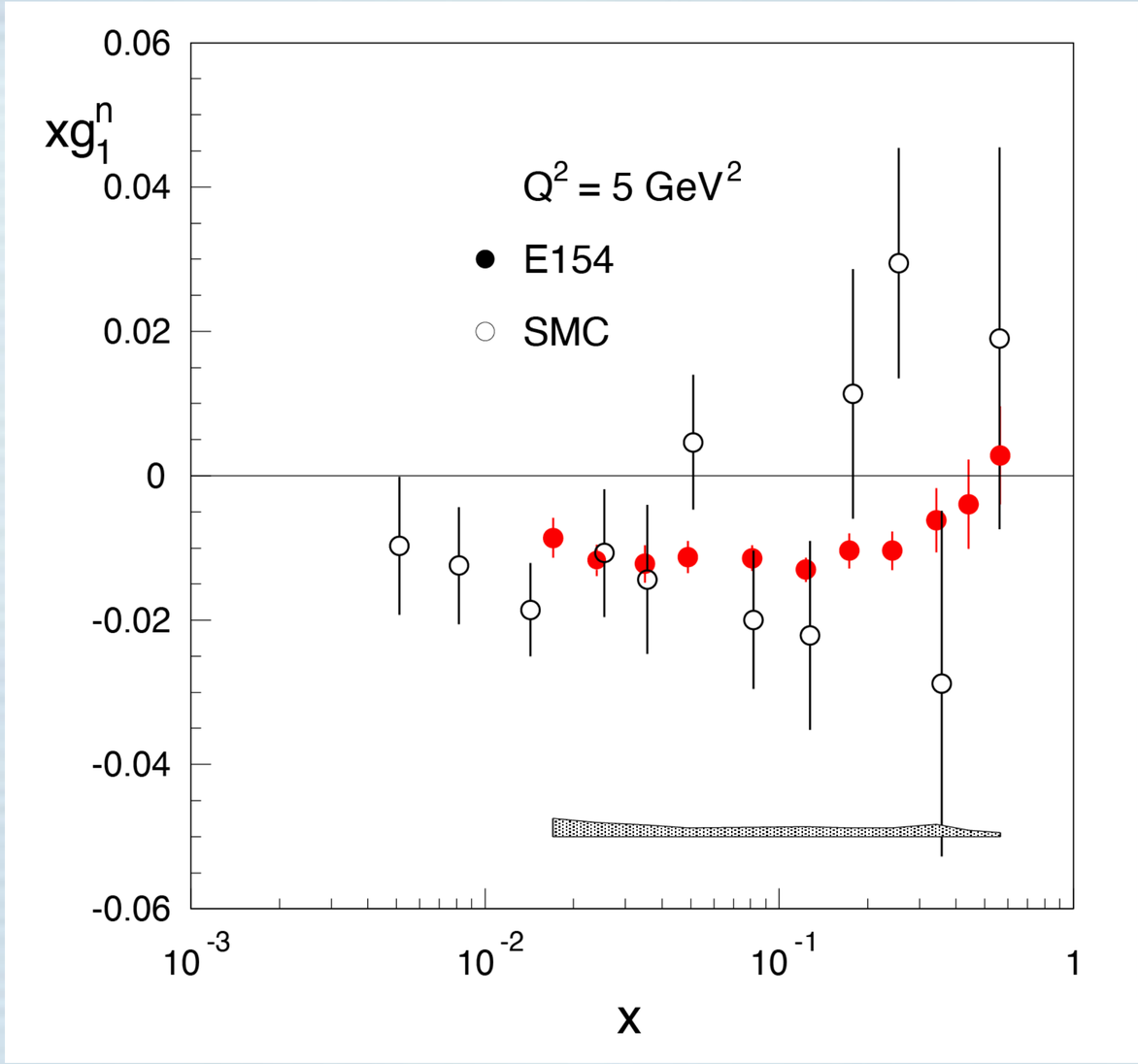
The E142 polarized ^{3}He target was the first large-volume high-pressure target of its type

- Quite a bit of physics needed to be sorted out to scale up to the size and pressure required for E142.
- While the target cells themselves were built by my group at Princeton, many people were central to the effort including Tim Chupp, Emlyn Hughes and others.
- Paul actually brought a critical aspect of fabricating the targets that he learned from Otto Hausser at TRIUMF.

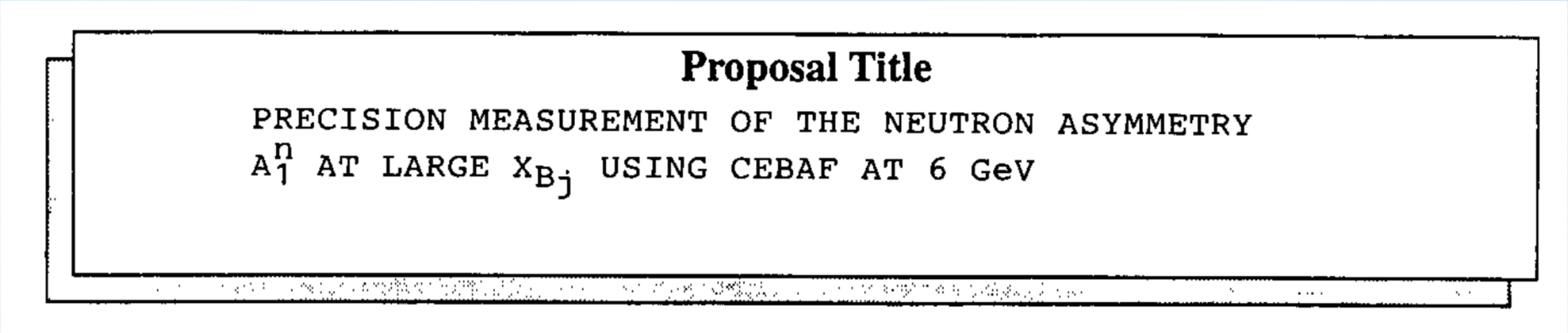


SLAC E154 results compared with SMC neutron

To this day, I believe that the SLAC E154 results are the most accurate over much of the kinematic range covered by the experiment.



Spin structure at JLab



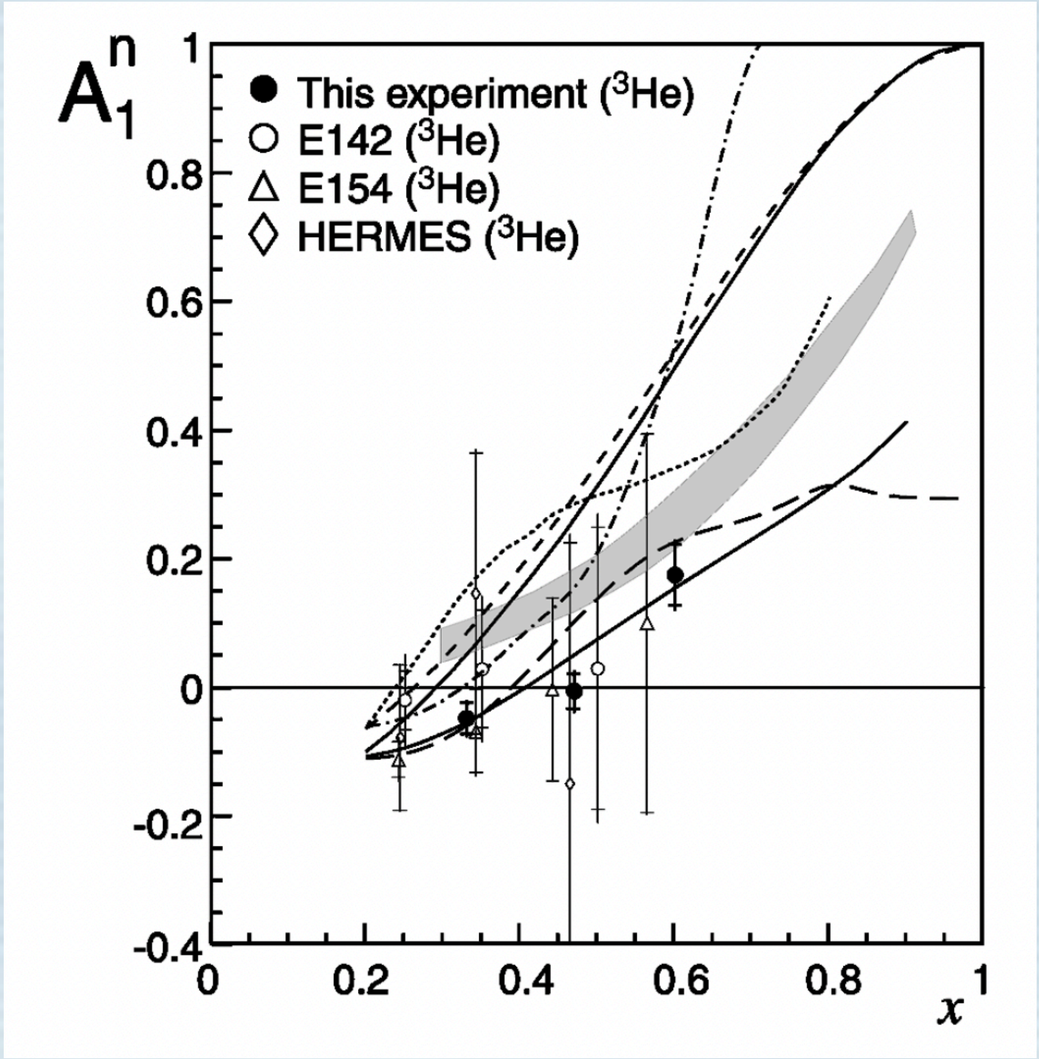
Proposal Title

PRECISION MEASUREMENT OF THE NEUTRON ASYMMETRY A_1^n AT LARGE X_{Bj} USING CEBAF AT 6 GeV

Starting in 1994, Zein-Eddine Meziani and Paul Souder, recognizing the strength of JLab for spin structure measurements in the quark valence region, proposed measuring A1n accurately as high as x = 0.63

Spin structure at JLab

- The experiment eventually ran as E99-117
- It was the first time A1n was seen to turn to a positive value.
- This was the thesis experiment of Prof. Xiaochao Zheng.



High-x physics at JLab at 12 GeV

I found this document in my files while preparing for this talk. It reads like a menu for much of the spin-structure work that has been done at JLab.

It looks like it may have been part of preparations for the 12 GeV white paper. While I don't want to claim that all of the ideas listed here originated with Paul, it is just yet another example of the depth of his thinking on these issues.

Physics Issue at High Bjorken-x

P. A. Souder

December 22, 1999

1 Introduction

There are a number of possible measurements that can be made for high x kinematics when spin degrees of freedom are included. These experiments would not be feasible without recent developments in polarized beams and targets and a 12 GeV JLab or equivalent facility.

A partial list that comes to mind includes the following:

1. A_1^n
2. g_2^n
3. $^3\mathrm{He}/^3\mathrm{H}$
4. eP parity
5. eD parity
6. R
7. $A_1^p,\ g_2^p$

Paul's impact on physics and physicists

- Seminal contributions to many fields, and I barely touched on parity violation!
- A brilliant, incredibly creative and imaginative physicist.
- Has perhaps the deepest understanding of physics of anyone with whom I have had the pleasure of working.
- A patient and nonjudgmental mentor (once you figure out his style)
- Generous with his ideas (which are numerous!)
- It is no wonder so many people have sought him out as a friend, mentor and collaborator over the years.

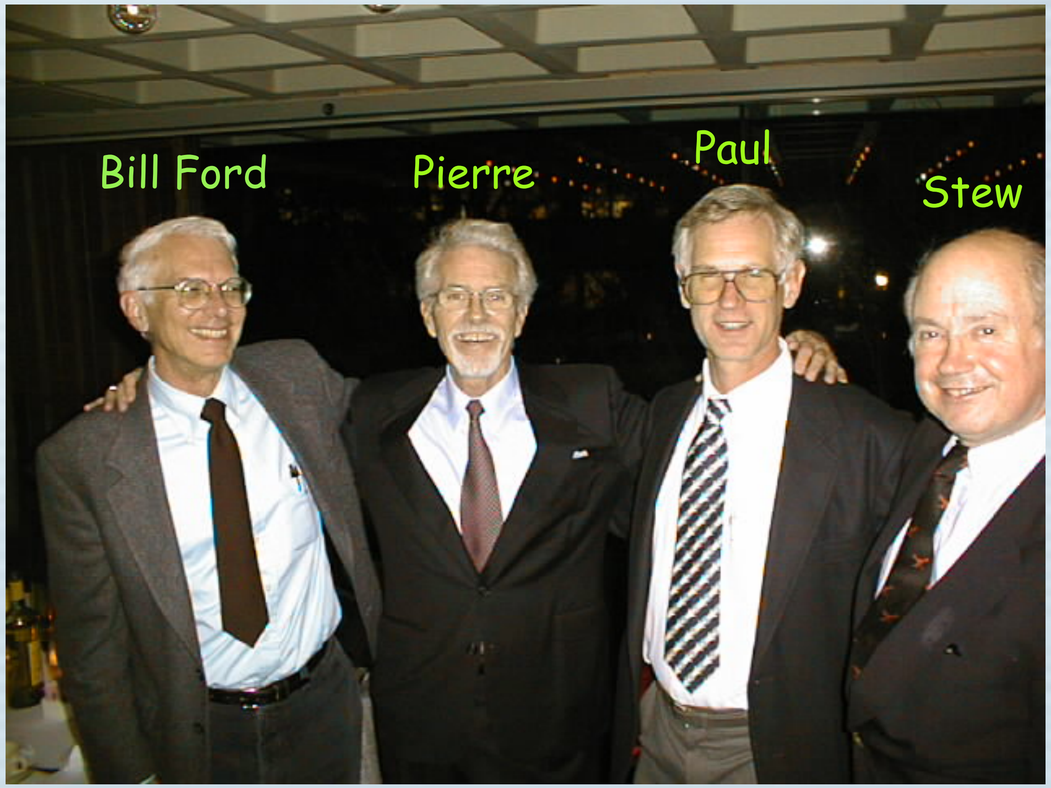


Photo from symposium on the occasion of Pierre Piroué's 70th birthday (~2001)

Interpreting this result within the quark parton model

In the quark parton model, the spin structure function

$$g_1(x,Q^2) = \tfrac{1}{2} \sum_{flavors} e_i^2 [q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)]$$

If we further define the spin fraction

$$\Delta q_i = \int_0^1 [q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)] dx$$

We can then write the first moment of the spin structure function

$$\Gamma_1^p(x,Q^2) \equiv \int_0^1 g_1^p(x,Q^2)\, dx = \tfrac{1}{2}[\tfrac{4}{9}\Delta u + \tfrac{1}{9}\Delta d + \tfrac{1}{9}\Delta s]$$

What carries the spin of the proton?

From experiment: $\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s = 2\Gamma_1^p$

From the Bjorken Sum Rule: $\Delta u - \Delta d = \frac{g_A}{g_V}$

From SU(3) and baryon decay data: $\Delta u + \Delta d - 2\Delta s = 3F - D$

When we put the numbers in, we find that rather little of the spin of the proton is due to the spins of the quarks.