An Historical Overview of Spin

With sincere thanks to:
Jian-Ping Chen, Don Crabb, Ron Gilman, Haiyan Gao, Willy Haeberli, Chris Keith, Alan Krisch, Robert Lourie, Akira Masaike, Matt Poelker, Charles Prescott, Erhard Steffens, Anatoli Zelenski

Disclaimers:
- *I am not a historian*
- *My presentation is subjective*
- *All shortcomings are my responsibility*

An Historical Perspective of Spin

P.A.M. Dirac

at

Summer studies on high-energy physics with polarized beams

Argonne National Laboratory, July 1974

- 1921: A.H. Compton suggests that the electron has a magnetic moment
- Mysterious doubling of atomic states

  Unmechanise Zweidentigkeit in German, *duplexity* in English
- Kronig suggested to Pauli that the origin might be the spin of the electron. Pauli was very hostile to the idea.
- Idea of spin also occurred to Uhlenbeck and Goudsmit. Showed it to Ehrenfest who strongly encouraged them and they wrote it up. They went to visit Lorentz and he again was hostile.
- They went back to Ehrenfest and asked to withdraw their paper. Ehrenfest said. "It is too late, I have already sent it in for publication."

1st International High Energy Spin Physics Symposium

July 1974

Spin key to explaining the physical universe: 1920-50

- 1920s: Quantum mechanics developed to describe atomic systems
- 1922: Stern-Gerlach experiment carried out with silver atoms
- 1925: Pauli exclusion principle formulated
  Uhlenbeck and Goudsmit hypothesize intrinsic spin as a property of the electron
- 1926: Thomas correctly applied relativistic calculations to spin-orbit coupling in atomic systems; resolved missing factor of two in the derived *g*-values
- 1927: Wrede, Phipps&Taylor: observed deflection of atomic hydrogen in magnetic field gradient
- 1928: Dirac equation for spin-½ particles: predicted the existence of the positron
- 1929: Mott wonders if we can observe electron spin directly: proposes scattering electrons from nuclei to measure the scattering asymmetry due to electron spin-orbit coupling

Essential role of electron spin in explaining the Periodic Table of the chemical elements established

- 1942: Shull *et al*. verifies Mott's predictions: electron spin is an experimental tool
- 1946: Schwinger suggests double scattering to determine the sign of the spin-orbit splitting
- 1949: Nuclear shell model: strong spin-orbit coupling

Essential role of proton and neutron spin in explaining the structure of atomic nuclei established

Developing Spin as an Experimental Tool: 1950-75

- 1951: Heusinkveld and Freier: first nuclear polarization scattering experiment
  Paul: proposes magnetic multipoles to focus atomic beams
- 1952: Kastler develops technique of optical pumping
- 1953: Overhauser proposes technique of dynamic nuclear polarization
- 1956: Clausnitzer, Fleischmann, Schopper make polarized ions via atomic beam method
- 1957: Wu observes parity violation in polarized ^{60}Co
- 1958: Development of atomic beam source begins in Erlangen
- 1960: Laser developed
- 1962: London proposes idea of dilution refrigerator
- 1963: Hughes at Yale begins consideration of polarized electron sources
- 1964: Gruebler, Schwandt, Haeberli develop first source of polarized H^-
- 1969: First DNP polarized proton samples with high polarization
- 1971: Sokolov-Ternov self-polarization observed at VEPP-2, Novosibirsk
  First frozen spin target developed at Rutherford Laboratory
- 1973: MRI proposed: proton spin as a medical diagnostic tool
- 1974: Yale ^{6}LI photoionization (PEGGY) source commissioned at SLAC
  First high energy polarized proton beams at Argonne ZGS

Using the Tool: 1975-1995

- 1975-76: E80 and E130 at SLAC measure spin-dependent DIS: valence quarks in proton are polarized as expected
- 1978: E122 announces parity violation at SLAC: used first GaAs source
  Derbenev and Kondratenko propose "Siberian snake" (Courant)
- 1980: Development of storage cells begins at Wisconsin
- 1981: Krisch measures large asymmetries at high p_T^2 in pp elastic scattering at the ZGS, in contradiction to the expectations from QCD
- 1984: First measurement of T_{20} in elastic eD scattering at MIT-Bates allows first separation of the three elastic form factors of deuterium
- 1985: Development of spin-exchange optical pumping of nobel gases at Princeton
- 1988: EMC data challenge the accepted understanding of the origin of nucleon spin
- 1989: Siberian snake demonstrated for first time at IUCF
  First measurements of spin-dependent electron scattering from optically pumped polarized ^{3}He gas targets at MIT-Bates
- 1991: Single-layer strained GaAsP/GaAs* produces high electron polarization
- 1992: CE-25 at IUCF: first experiment with polarized beam and target in storage ring
- 1991: Measurements with polarized electrons at the Z-pole begin at SLAC/SLC

Spin becomes routinely available at the large facilities worldwide: 1995-present

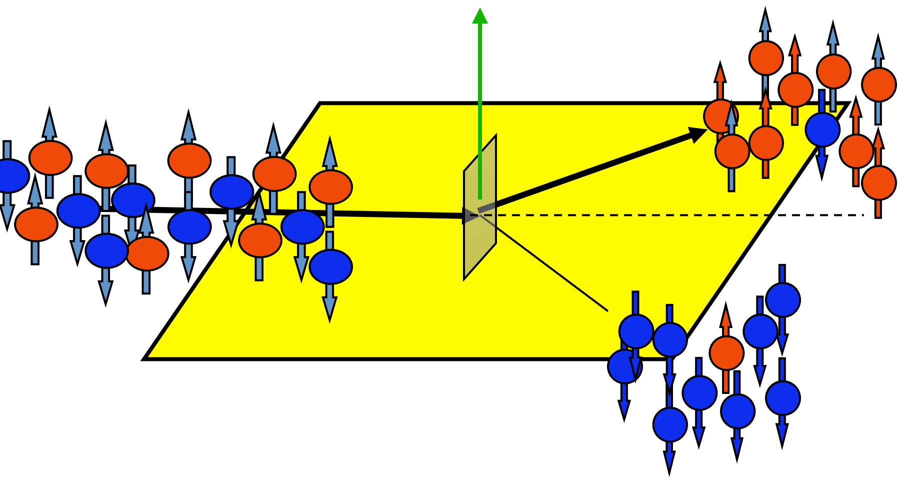
- 1995: HERMES begins data taking at HERA, DESY
  SLAC fixed target program of measurement of inclusive, spin-dependent DIS
- 1997: Intense beams of polarized protons become available via optical pumping
- 1998: Intense, highly polarized, CW, multi-GeV electron beams become available at Jefferson Lab
- 2000: Proton elastic from factor ratio as determined via recoil polarization measurement at JLab differs dramatically from cross section determination
- 2006: World's first polarized proton collider comes online at RHIC
- 2008: $G^n_E(Q^2)$ determined with precision comparable to $G^p_E(Q^2)$ using polarization techniques
- 2010: Worldwide parity-violating electron scattering program concludes that strange quarks do not have sizable contributions to the proton's elastic form-factors
- 2011: First direct measurement of contribution of gluons to proton spin using A_{LL} in dijets from RHIC
  First measurement of parity violating W-boson production at RHIC

J. Schwinger (Abstract at APS meeting 1946) suggested double-scattering to determine sign of spin-orbit splitting

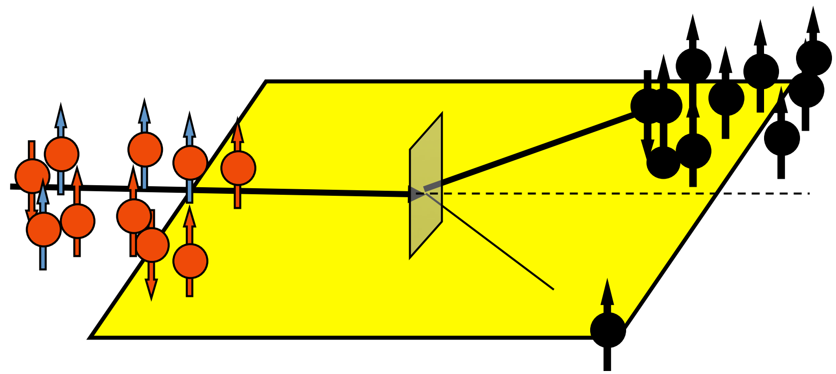
B12. Polarization of Neutrons by Resonance Scattering in Helium. JULIAN SCHWINGER, *Harvard University.*—Neutron scattering in helium exhibits an anomaly for neutron energies in the vicinity of 1 Mev, which has been attributed to a *P* resonance associated with the formation of the unstable He^5 nucleus. The energy dependence of

- Experiment is feasible only with protons rather than neutrons (Wolfenstein)
- First nuclear polarization experiment by Heusinkveld and Freier 1951

Polarizer



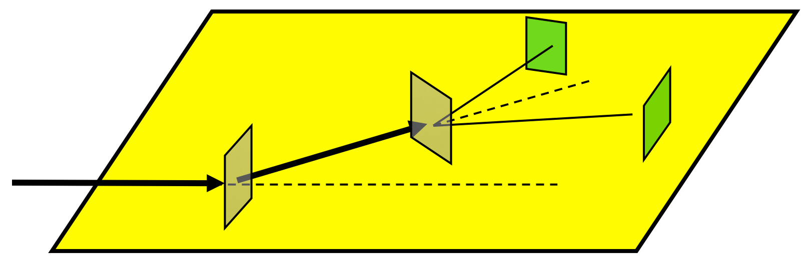
Analyzer



$$P = \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow} = \frac{9-1}{9+1} = 0.8$$

$$A = \frac{N_L - N_R}{N_L + N_R}$$

Double scattering expt:



$$PA = \frac{N_L - N_R}{N_L + N_R} = \frac{R-1}{R+1}$$

elastic scattering: P=A

P in reaction [e.g. $^3He(d,p)^4He$] = A of inverse reaction[$^4He(p,d)^3He$]

PHYSICAL REVIEW VOLUME 85, NUMBER 1 JANUARY 1, 1952

The Production of Polarized Protons and the Inversion of Energy Levels of the $P_{\frac{1}{2}}-P_{\frac{3}{2}}$ Doublet in Li^{5}*

M. HEUSINKVELD† AND GEORGE FREIER
Physics Department, University of Minnesota, Minneapolis, Minnesota

(Received September 17, 1951)

Fermi-Yang ambiguity:two sets of phase shifts identical σ.

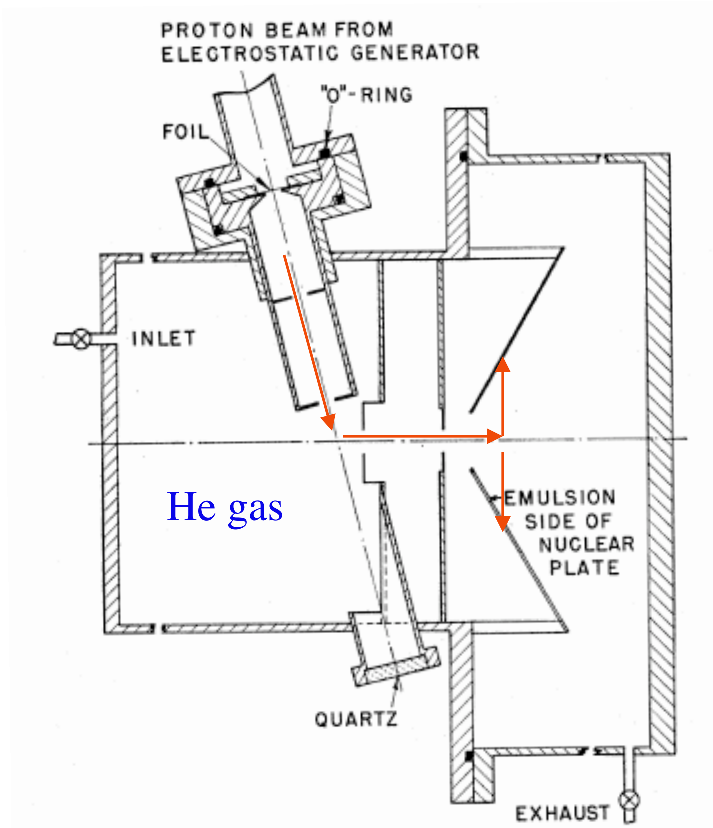


FIG. 4. Schematic diagram of double scattering chamber which uses nuclear emulsion plates as detectors of protons which have been scattered twice from He^4.

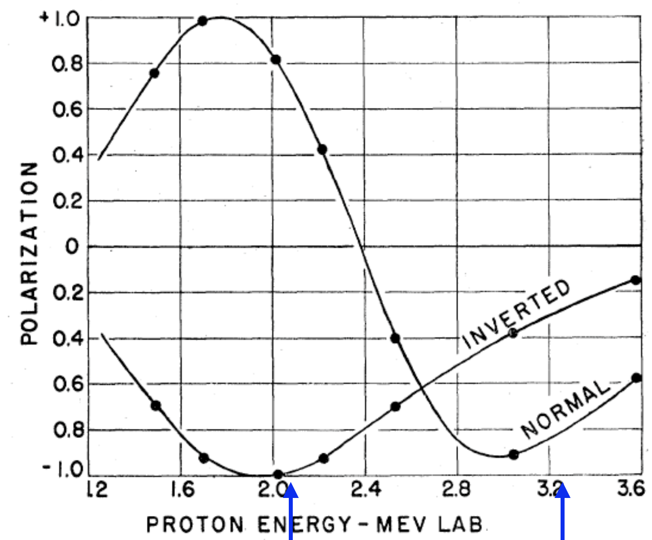


TABLE I. Ratio of proton tracks in equivalent strips in the forward and backward plates.

	No. of tracks on backward plate	No. of tracks on forward plate	Ratio—backward to forward	Theoretical ratio for ideal ray: Inverted doublet	Theoretical ratio for ideal ray: Normal doublet
3.25 Mev $\frac{1}{8}$-in. slits	364	191	1.9	2.6	1/20.2

Symposia on Polarization Phenomena in Nuclear Reactions

- Started at Basel in 1960 (Basel: first working polarized ion source and scattering experiments with polarized beam from source)
- Following every 5 years:
  - Karlsruhe (1965)
  - Madison (1970)
  - Zurich (1975)
  - Santa Fe (1980)
  - Osaka (1985)
  - Paris (1990)
  - Bloomington (1994)

PROCEEDINGS OF THE
INTERNATIONAL SYMPOSIUM ON
POLARIZATION PHENOMENA OF
NUCLEONS

Basel, July 4–8, 1960

Editors: P. HUBER and K. P. MEYER

HELVETICA PHYSICA ACTA
SUPPLEMENTUM VI

1961
BIRKHÄUSER VERLAG BASEL
UND STUTTGART

Basel Convention

In nuclear interactions the positive polarization of particles with spin $^1/_2$ is taken in the direction of the vector product $\boldsymbol{k}_i \times \boldsymbol{k}_0$, where $\boldsymbol{k}_i$ and $\boldsymbol{k}_0$ are the circular wave vectors of the incoming and outgoing particles respectively.

This agreement is called the 'Basel Convention'.

The Madison Convention for Spin-1 Particles

1. A right-handed coordinate system is assumed in which the positive z-axis is along the direction of momentum of the particles, and the positive y-axis is along $\mathbf{k}_{in} \times \mathbf{k}_{out}$ for the nuclear reaction which the polarized particles initiate, or from which they emerge.

2. Polarization effects involving spin-1 particles should be described by either spherical or Cartesian spin tensors. The components of polarization are given by p_i, p_ij (Cartesian) or t(kq) (spherical), respectively.

3. Terms used to describe the effect of initial polarization of a beam or target on the differential cross section for a nuclear reaction should include the modifiers <u>analyzing</u> or <u>efficiency</u>, denoted by T(kq) (spherical) or A(i), A(j) (Cartesian).

4. In the expression for a nuclear reaction A(b,c)D, an arrow placed over the symbol denotes a particle which is initially in a polarized state or whose state of polarization is measured, e.g. $\mathrm{A(b,\vec{c})D}$

; polarization is measured for a particle c emerging from a reaction between unpolarized particles A and b.

Polarization Phenomena in Nuclear Reactions
H.H. Barschall and W. Haeberli, eds,
The University of Wisconsin press,
Madison (1971)

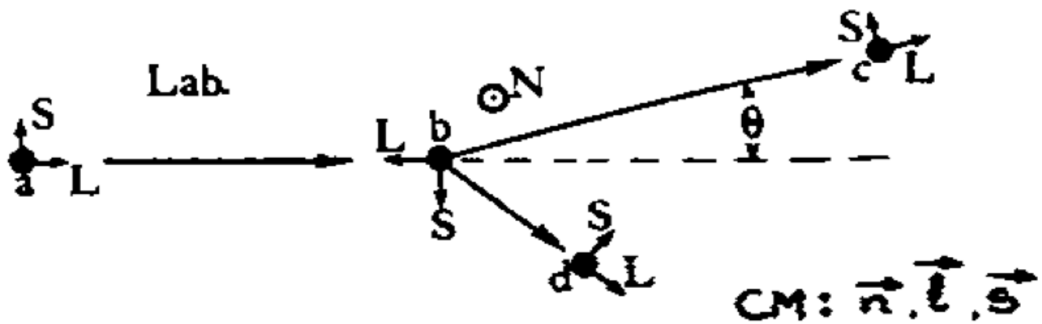
Symposia on High Energy Spin Physics

- Started at Argonne in 1974 at ANL: First polarized HE proton beam in the 12 GeV **Z**ero-**G**radient-**S**ynchrotron)
- Following, every two years:

  - Argonne (1976, 1978)
  - Lausanne (1980)
  - BNL (1982)
  - Marseille (1984)
  - Protvino (1986)
  - Minneapolis (1988)
  - Bonn (1990)
  - Nagoya (1992)
  - Bloomington (1994)

SPIN PARAMETER CONVENTION

(Ann Arbor Workshop 1977)



Reaction :

$$a + b \rightarrow c + d$$

Beam + Target → Scattered + Recoil

Spin states:

i j k l

The spin states i, j, k, l are usually denoted by

↑, →, ⊙

representing vectors along the $\vec{n}, \vec{l}, \vec{s}$ directions.

Unpolarized or unmeasured states are 0 or blank

$$\vec{N} = \frac{\vec{P}_a \times \vec{P}_c}{|\vec{P}_a \times \vec{P}_c|} \qquad \vec{S} = \vec{N} \times \vec{L}$$

Joint Symposia on Spin Physics

- Started at Amsterdam in 1996
- Following every 2 years:
  - Protvino (1998)
  - Osaka (2000)
  - BNL (2002)
  - Trieste (2004)
  - Kyoto (2006)
  - Charlottesville (2008)
  - Juelich (2010)
  - Dubna (2012)
- Next meet in Beijing, China in October 2014

Polarized Proton Sources

Sources of Polarized Ions
a review of early work

First polarized-proton sources described at the
INTERNATIONAL SYMPOSIUM ON POLARIZATION
PHENOMENA OF NUCLEONS
Basel, July 1960

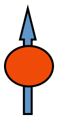
The status 40 years ago:

SOURCES OF POLARIZED IONS

BY W. HAEBERLI

ANNUAL REVIEW OF NUCLEAR SCIENCE
Vol. 17, 1967

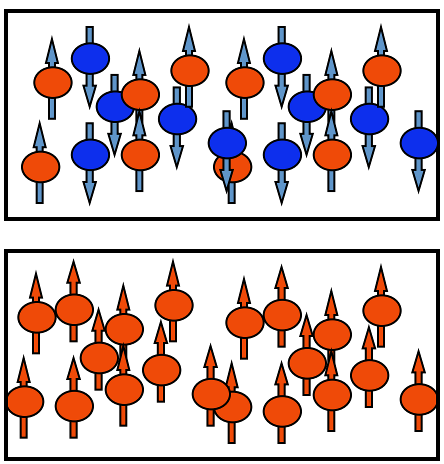
Polarizing protons is difficult ……



Associated with proton spin is a magnetic moment μ:

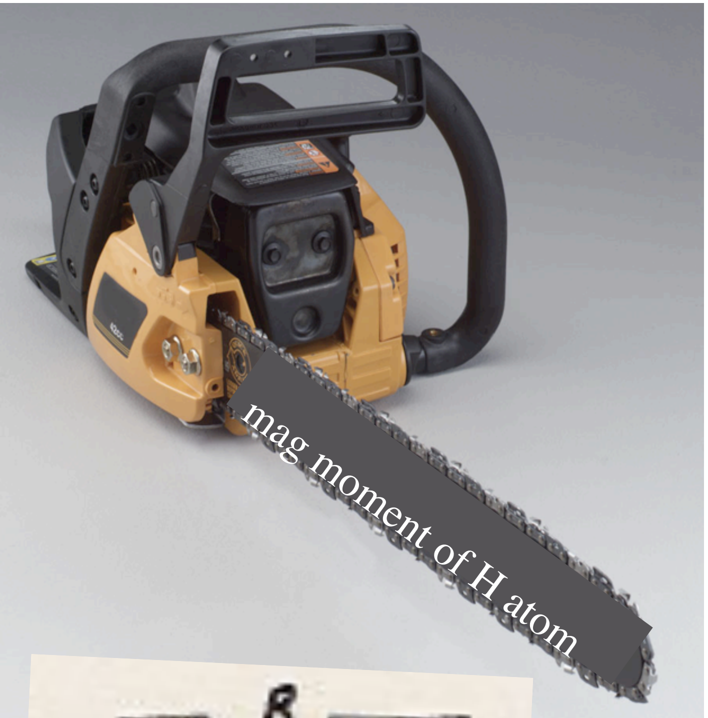
So why not use a strong magnet to line up the proton spins?

In a magnetic field spin is either up or down (space quantization)
Up-down energy difference is 2μB where $\mu_{proton} = 8.8\text{x}10^{-8}$ eV/T



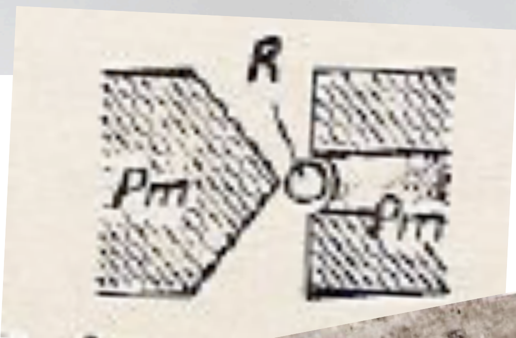
Even for 10T field (100 kG) thermal energy kT at 300K (room temp) is 14,000-times larger!
At 0.3K still 14-times. ☹

Need a better POWERTOOL!



Powertool: H-atom

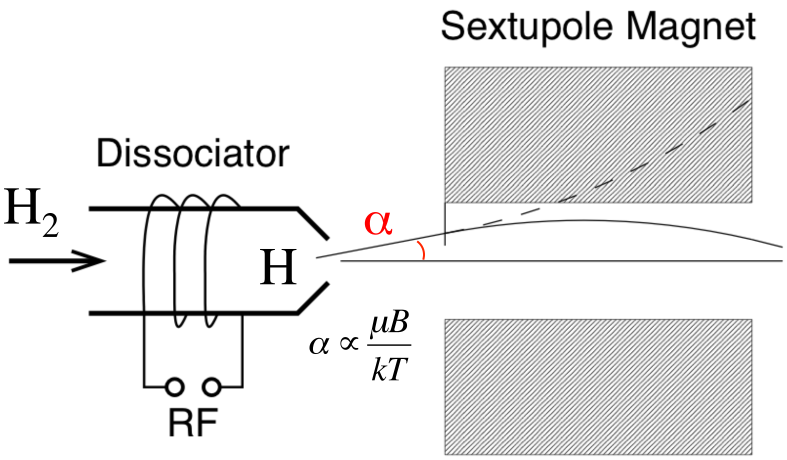
1. The electron has the same spin but 660-times larger magnetic moment than the proton.
2. H atom is neutral - suitable for deflection in inhomogenous magnetic field.
3. B-field of electron at proton is large (17.4T)

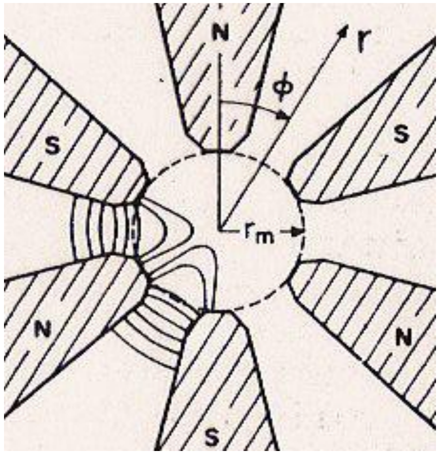


E. Wrede (Hamburg, 1927 student of Stern) and T.E. Phipps and J.E. Taylor (U. Illinois) observed deflection of H atom in magnetic field gradient of 1.0 T/cm. Splitting of 0.1 mm corresponds to mag moment of 1 Bohr Magneton 5.8×10^{-5} eV/T.

Original photogaph recovered from MPI-Heidelberg

Polarized Atomic H Beam -Principle





$$|B| \propto r^2$$

$$\vec{F}_r = \pm k\vec{r}$$

Great increase in intensity by use of multipole field, suggested by Wolfgang Paul, Bonn 1951-(Nobel 1989).

Spin-up is focussed, spin-down defocussed

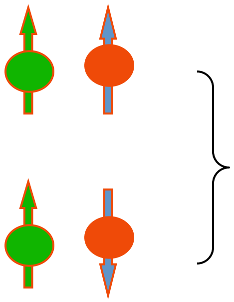
Development of atomic-beam sources in Europe starting in Erlangen (1958).

1960: good beam intensities achieved [~1.0x10^{16} H/s] but 

In STRONG magnetic field:

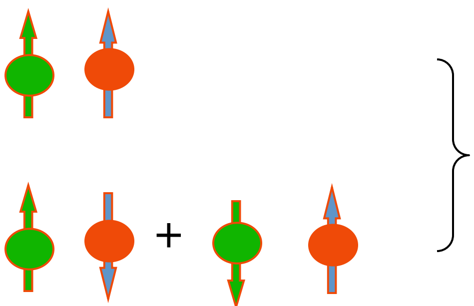
State 1

State 2



P=0! no net nuclear polarization!

In WEAK magnetic field:



"mixed state"

P = 1/2 (used in some early work)

In "weak" field e and precess (hyperfine interaction)

How weak?

Critical field = 0.05T (507 G)

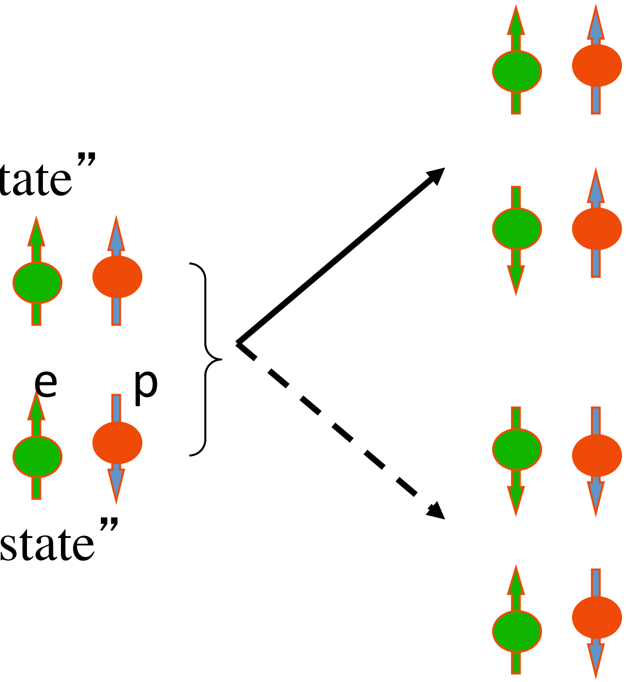
Better: RF transitions to induce spin flips (developed at Saclay)

"pure state"

State 1

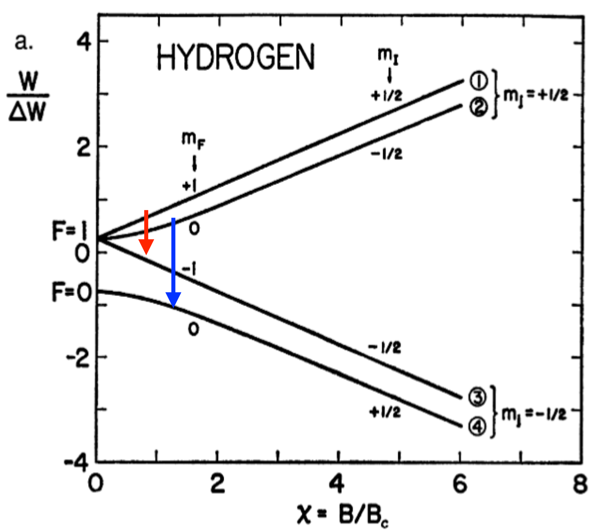
State 2

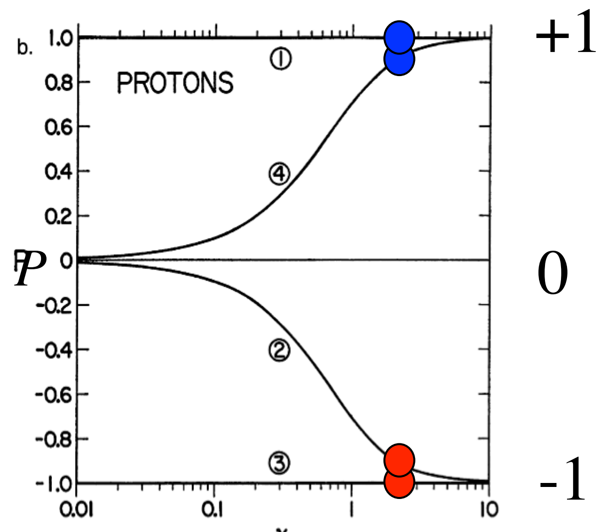
"mixed state"



"Strong-field" transition
P= +1 in strong B-field

Weak-field transition
P= -1 in weak B-field





Early Polarized Proton Ion Sources
Status 40 years ago

Ionization by electron bombardment (e.g. 200 eV)

$\sigma \sim 10^{-16}\ \mathrm{cm}^2$

First sources used weak field ionization

Improved by strong-field ionizers (Glavish, Thirion):

confine electrons in solenoid.

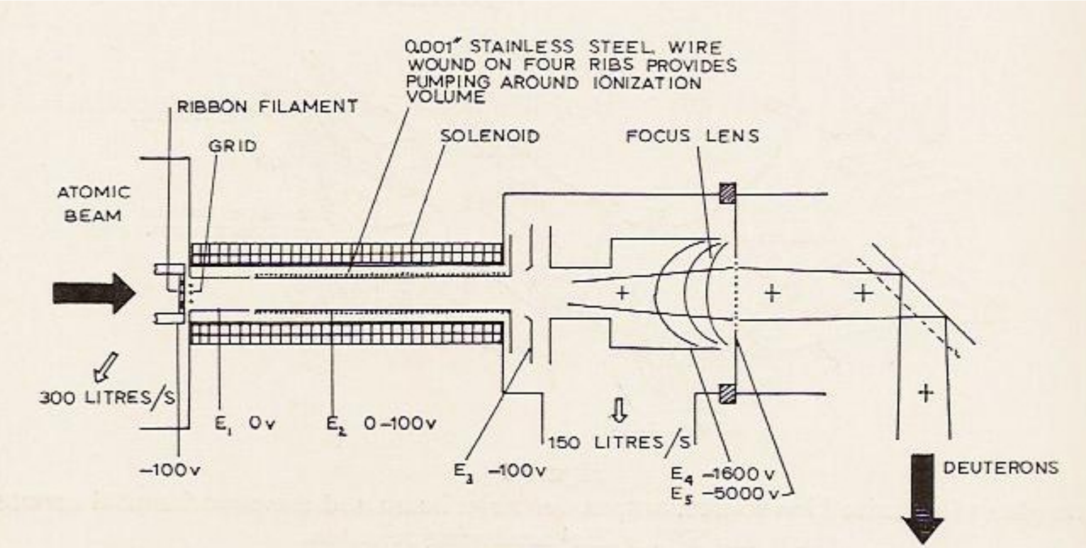


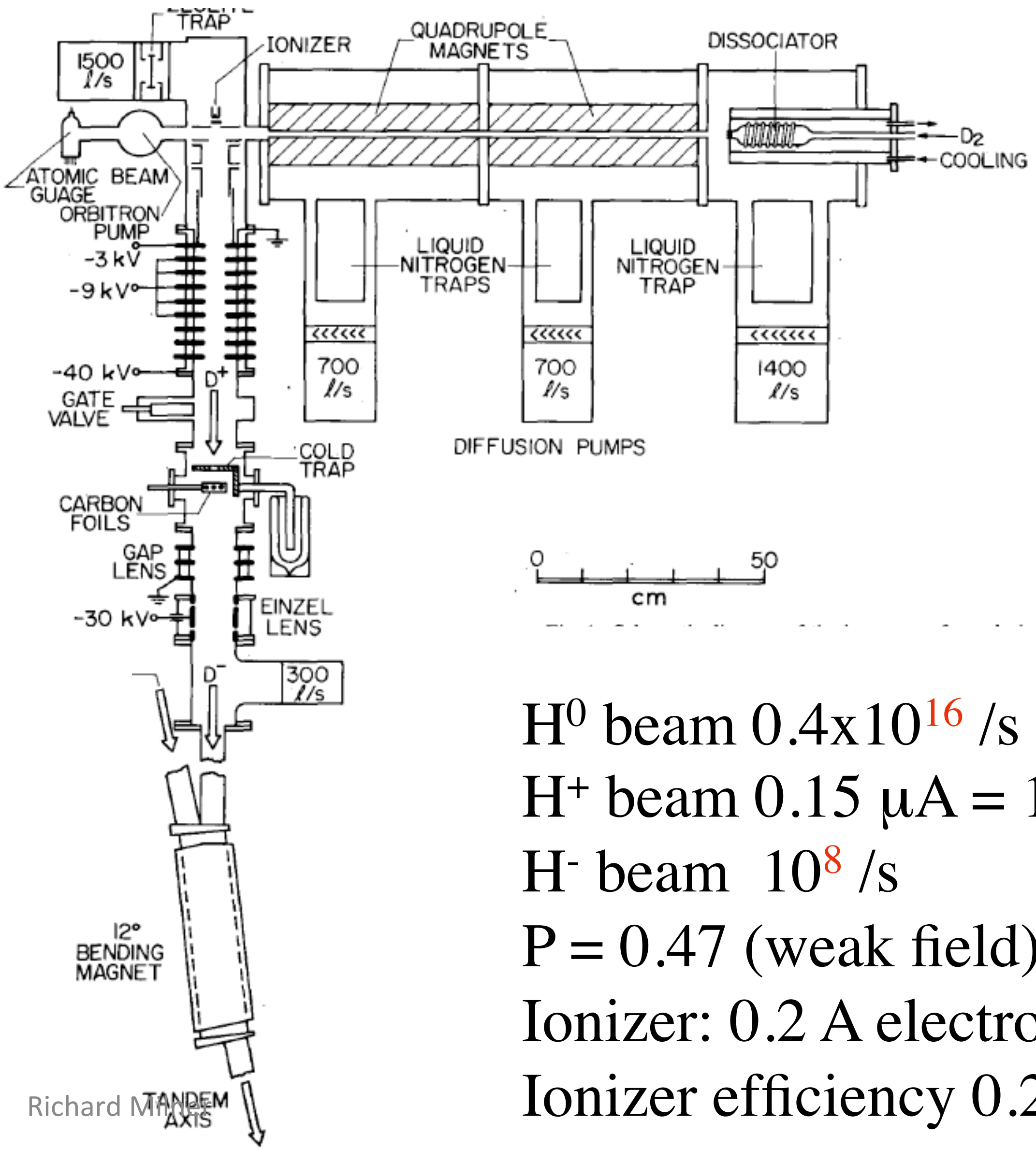
Figure 2
Strong field ionizer

0.5 μA polarized protons
P = 90%
10^{-3} Ionization efficiency

Strong-field ionizer (Glavish)

Making negative polarized H ions

First source of neg pol H (1964)
Gruebler, Schwandt, Haeberli



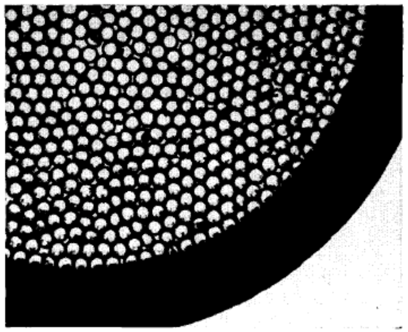


Fig. 2. Collimator of fused pyrex capillaries. The diameter of the capillaries is 0.25 mm. The transparency (fractional open area) is 65%.

H^0 beam $0.4\text{x}10^{16}$ /s

H^+ beam 0.15 μA = 10^{12} /s

H^- beam 10^8 /s

P = 0.47 (weak field)

Ionizer: 0.2 A electrons, 250 eV

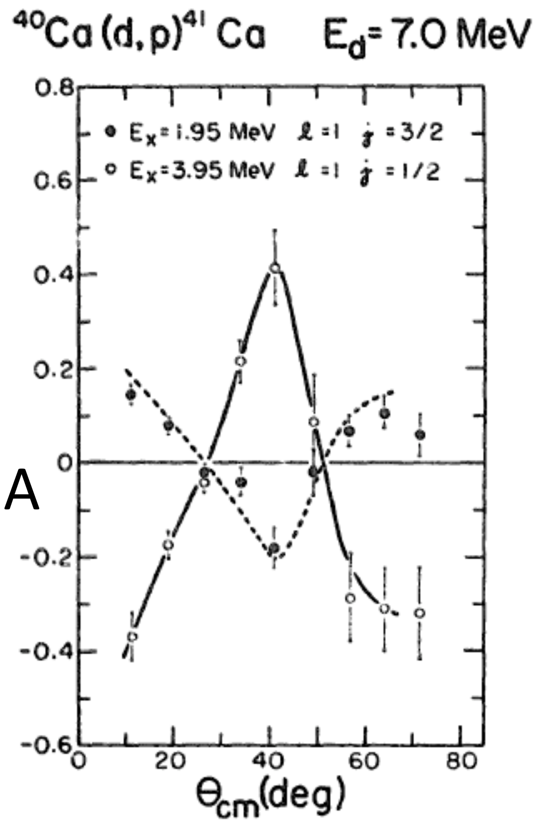
Ionizer efficiency $0.25\text{x}10^{-4}$

A feeble beam…

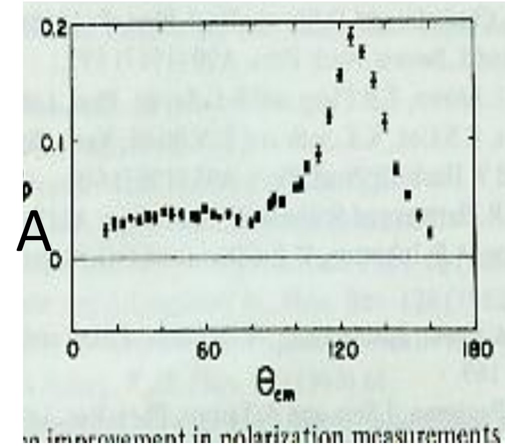
but some interesting results

d,p reaction: when neutron is captured by nucleus, which way does spin point?

Use POLARIZED deuterons!

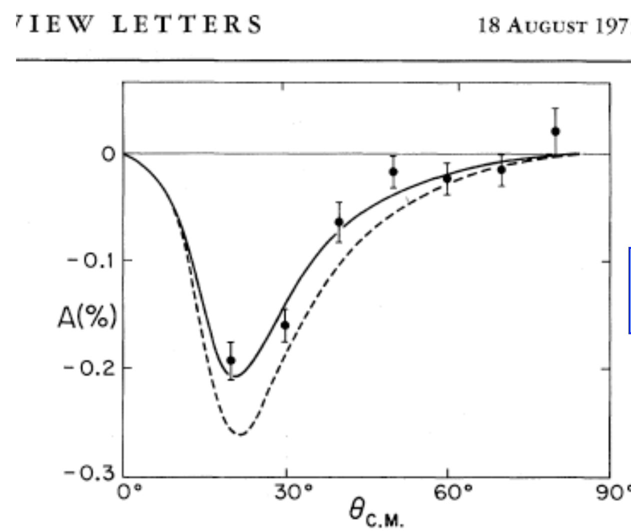


p-d and p-p scattering- is there spin dependence?



Wisc. PS2
Lamb-Shift
T.B. Clegg 12 MeV
1968

$\pm 5 x 10^{-3}$



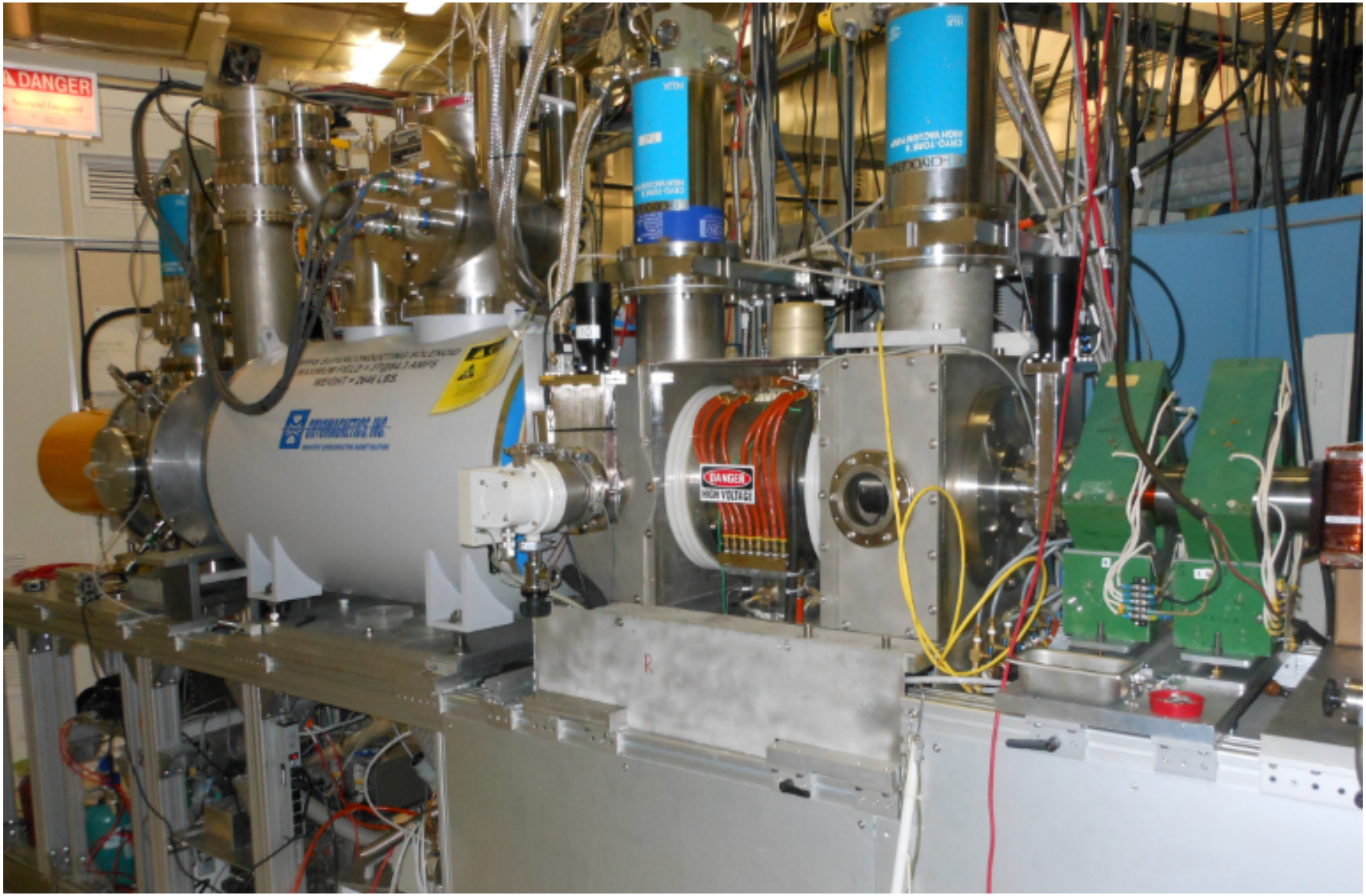
$\pm 2 x 10^{-4}$

Parity violation expts
SIN and TRIUMF

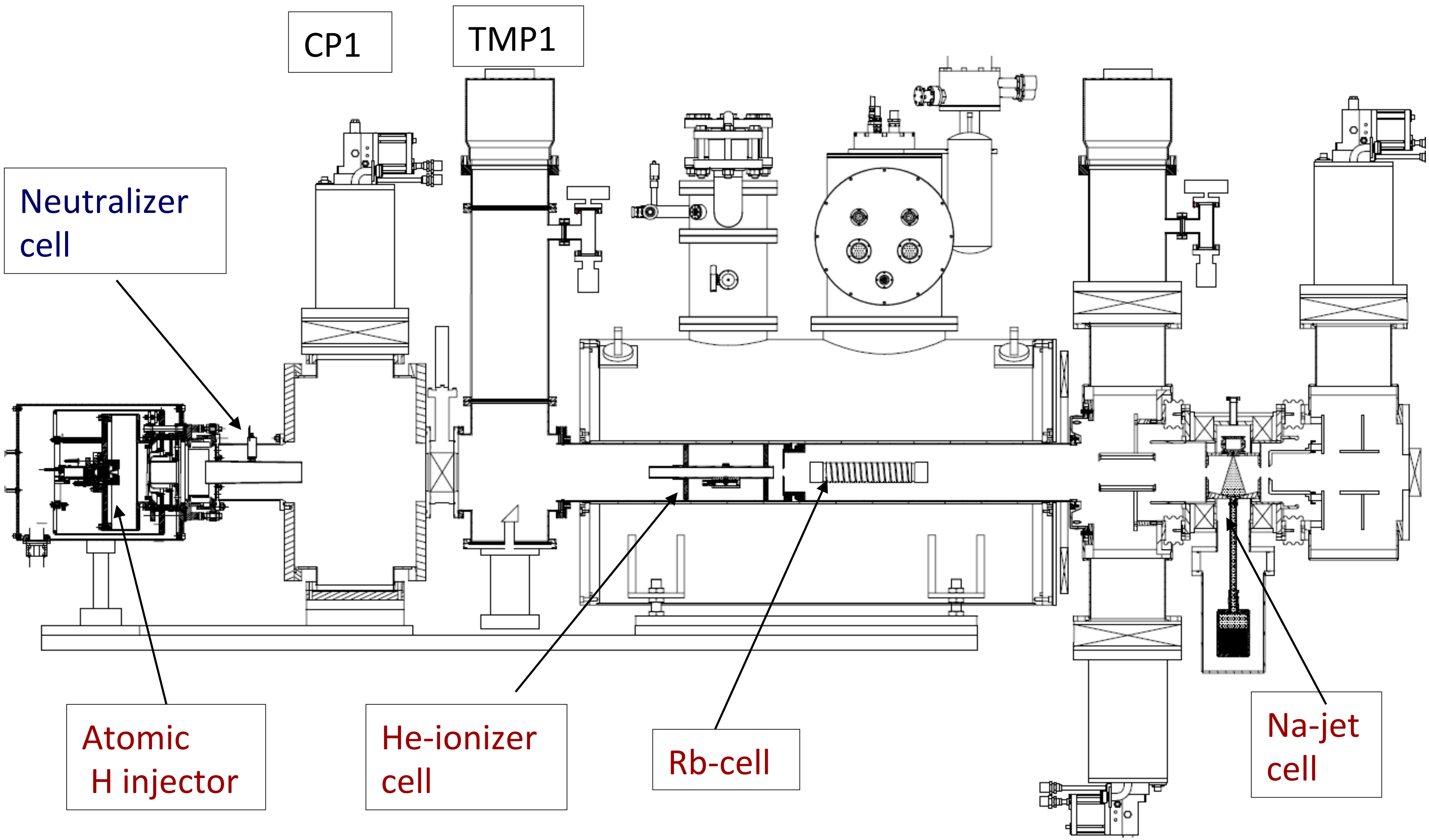
$\pm 1 x 10^{-7}$

University of Wisconsin-Madison, 1971

The RHIC OPPIS after upgrade with atomic hydrogen injector



OPPIS with atomic H injector layout



$$H^+ \xrightarrow{H2} H^0 \xrightarrow{He} H^+ \xrightarrow{Rb} H^0 \xrightarrow{Na} H^-$$

The 2013 International Workshop on Polarized Sources, Targets & Polarimetry
PSTP

Source intensity and polarization

- Reliable long-term ·operation of the source was demonstrated.
- Very high suppression of un-polarized beam component was demonstrated.
- Small beam emittance (after collimation for energy separation) and high transmission to 200 MeV.

Rb-cell, Temp., deg. C	81	86	91	96
Linac Current, μA	295	370	410	570
Booster Input $\times 10^{11}$	4.9	6.2	7.3	9.0
Pol. %, at 200 MeV	83-84	83	80.5	78

Polarized H/D Targets

- DNP technique
- Internal gas target

Dynamical nuclear polarization

For spin-½, the degree of nuclear polarization is given by

$$P_n = \tanh(\mu B / kT)$$

For the proton, this becomes

$$P_n = \tanh(1.02 \times 10^{-7} B / T)$$

For B=10 T and T=0.01K, P_n=76%.
However, by using dynamical methods we can obtain sizable nuclear polarizations
In paramagnetic materials at lower fields and higher temperatures. Here, the magnetic coupling between electron spins and nuclear spins can transfer the polarization of electrons to nuclei.

- Overhauser predicted the saturation of the spin resonance of conduction electrons in metals could lead to a nuclear polarization comparable to the electronic polarization.
- Abragam showed that this method could be extended to non-metallic substances, in particular solids containing paramagnetic impurities.
- In 1963, Abragam and Jefferies polarized protons to about 80% in the crystal of $La_2Mg_3(NO_3)_{12}24H_20$(LMN) containing 0.2% of Neodymium.
- LMN targets were successfully operated for scattering experiments with π, K, p, n beams.

Historical evolution

- Organic materials with free radicals were desirable since these have higher concentrations of free protons and are less susceptible to radiation damage.
- In 1969, protons in butanol with a small amount of water doped with porphyrexide were polarized up to 40% at 1 K and in 2.5 T at CERN.
- Later at Argonne, protons in butanol were polarized up to 67% in a ^{3}He cryostat.
- Since 1970, polarized targets with diols and butanol cooled in ^{3}He cryostats have been widely used.
- In 1965, Schmugge and Jefferies discussed the possibility of maintaining the polarization without microwave radiation, if the nuclear spin relaxation time is long enough. This provides large access angle around the target area in less homogeneous and lower magnetic field. It was constructed first at the Rutherford Laboratory in 1971 and named the **frozen spin target**.
- Ammonia is advantageous as a target material because of the high dilution factor (0.176). In 1971, proton polarization of 70% was obtained at CERN. However, it needed to be irradiated and proton irradiation led to explosions.
- At Bonn, electron irradiation produced ≥90% polarization without explosion. Thus, ammonia irradiated in liquid argon became one of the popular polarized targets.
- LiH and LiD are useful materials since they have higher dilution factors than ammonia.
- Targets are currently operational at CERN and Jefferson Lab.

The beginning of dynamic polarization

- Initially met with great skepticism by experts in the field (Bloch, Rabi, Ramsey …), "The Overhauser Effect" was demonstrated in ^{7}Li by Carver and Slichter (1953)

1994 National Medal of Science

July 27, 1953
Dear Dr. Overhauser:

You may recall that at the Washington Meeting of the Physical Society, when you presented your paper on nuclear alignment, Bloch, Rabi, Pearsall, and myself all said that we found it difficult to believe your conclusions and suspected that some fundamental fallacy would turn up in your argument. Subsequent to my coming to Brookhaven from Harvard for the summer, I have had occasion to see the manuscript of your paper.

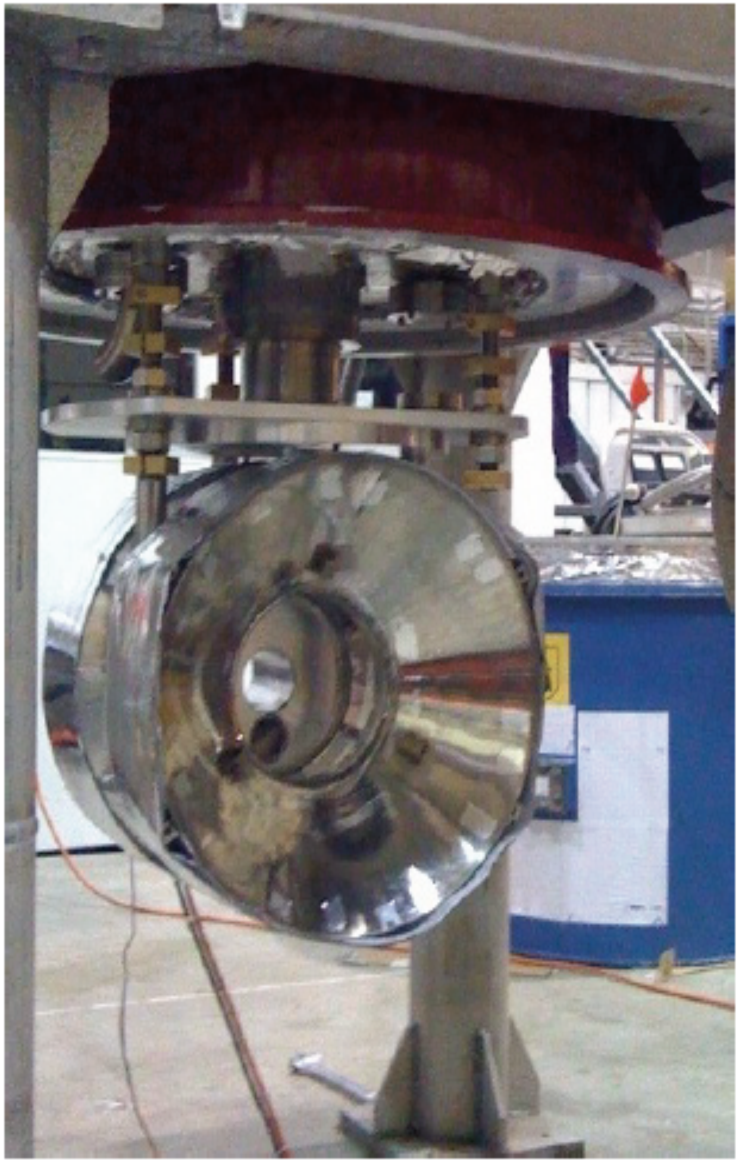
After considerable effort in trying to find the fallacy in your argument, I finally concluded that there was no fundamental fallacy to be found. Indeed, my feeling is that this provides a most intriguing and interesting technique for aligning nuclei. After considerable argument, I also succeeded in convincing Rabi and Bob Pound of the validity of your proposal and I have recently been told by Pound that he subsequently converted Pearsall shortly before Pound left for Europe.

I hope that you will have complete success in overcoming the rather formidable experimental problems that still remain. I shall be very interested to hear of what success you have with the method.

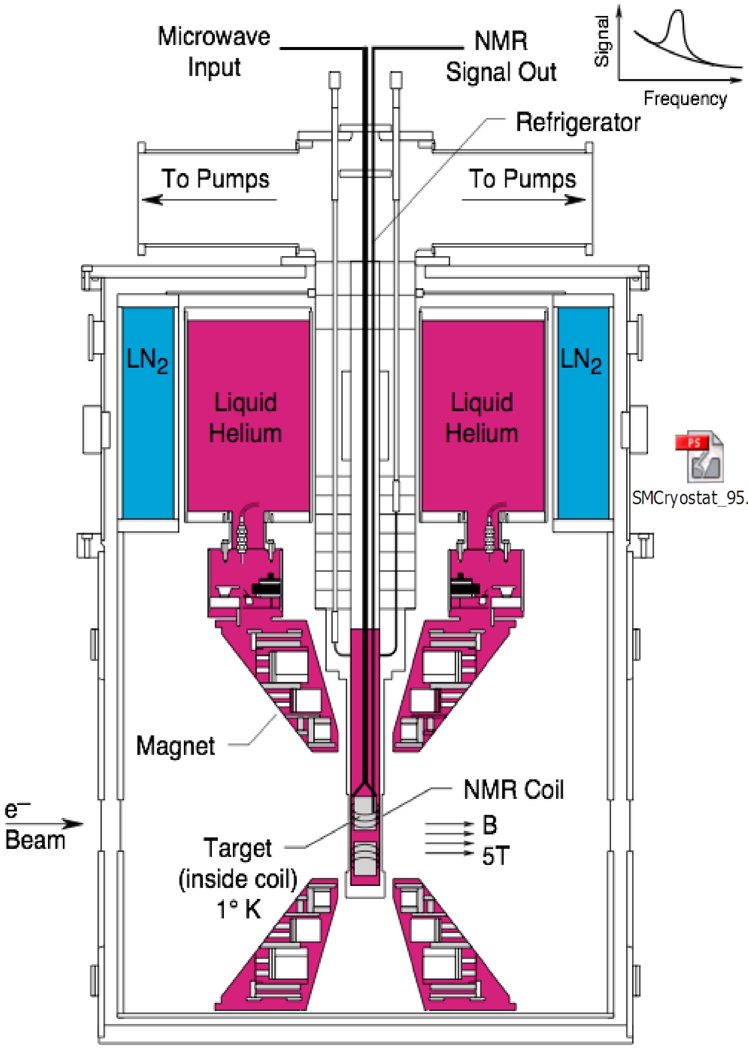
Sincerely,
Norman F. Ramsey

1 m long target for muon beams
(T. Niinikoski on the left)

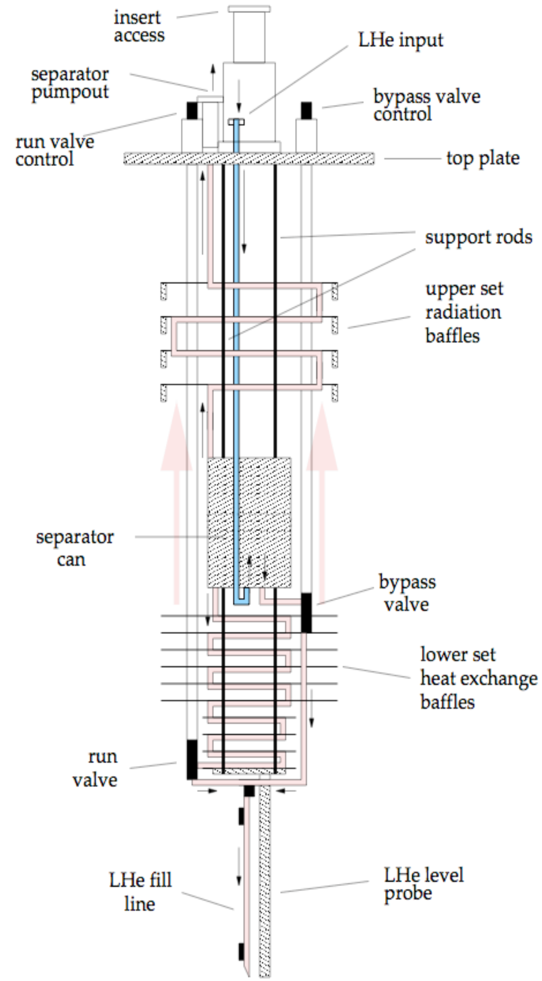
5T magnet for Hall A/C polarized target



UVA/SLAC/JLAB Target



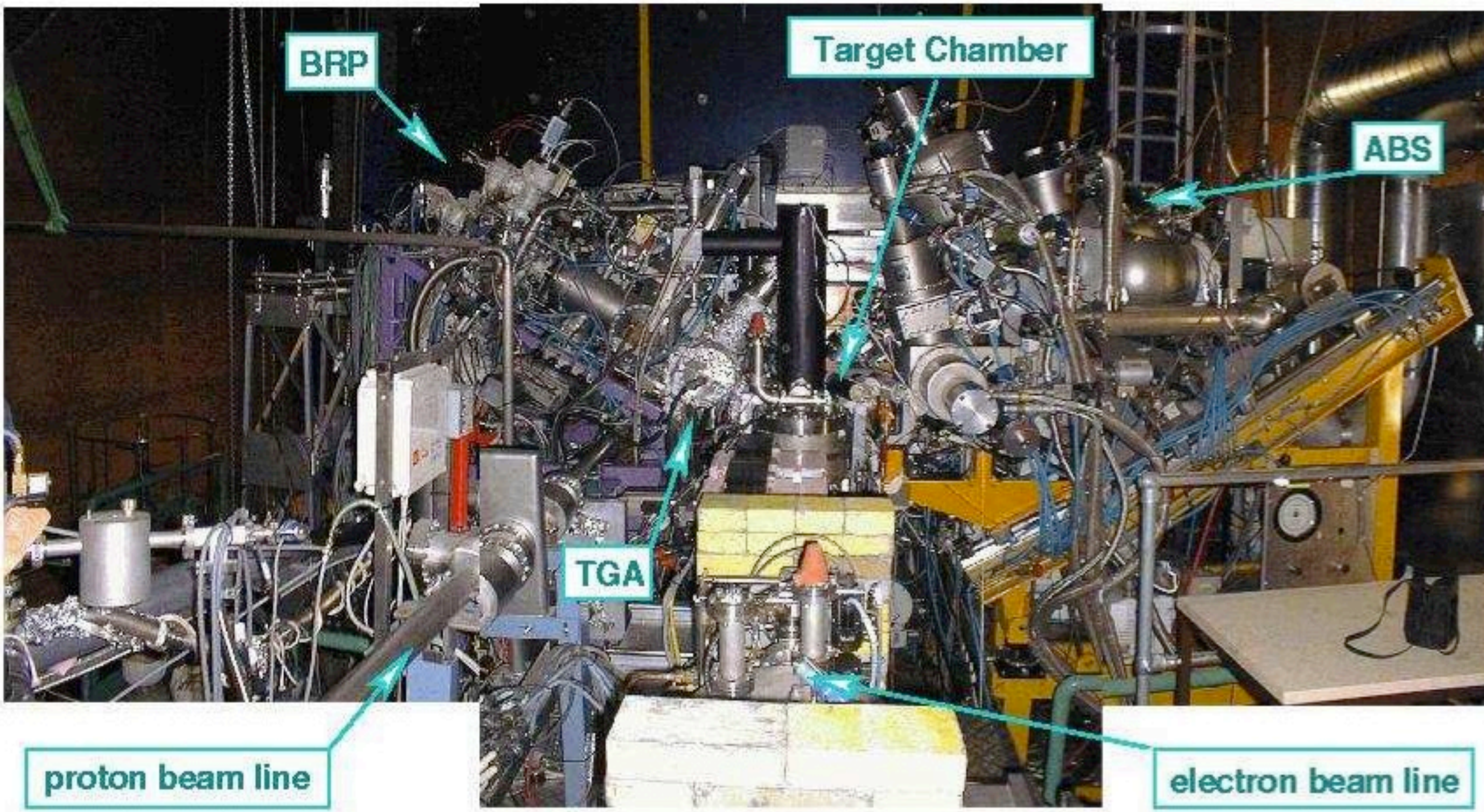
SMCryostat_95.ps

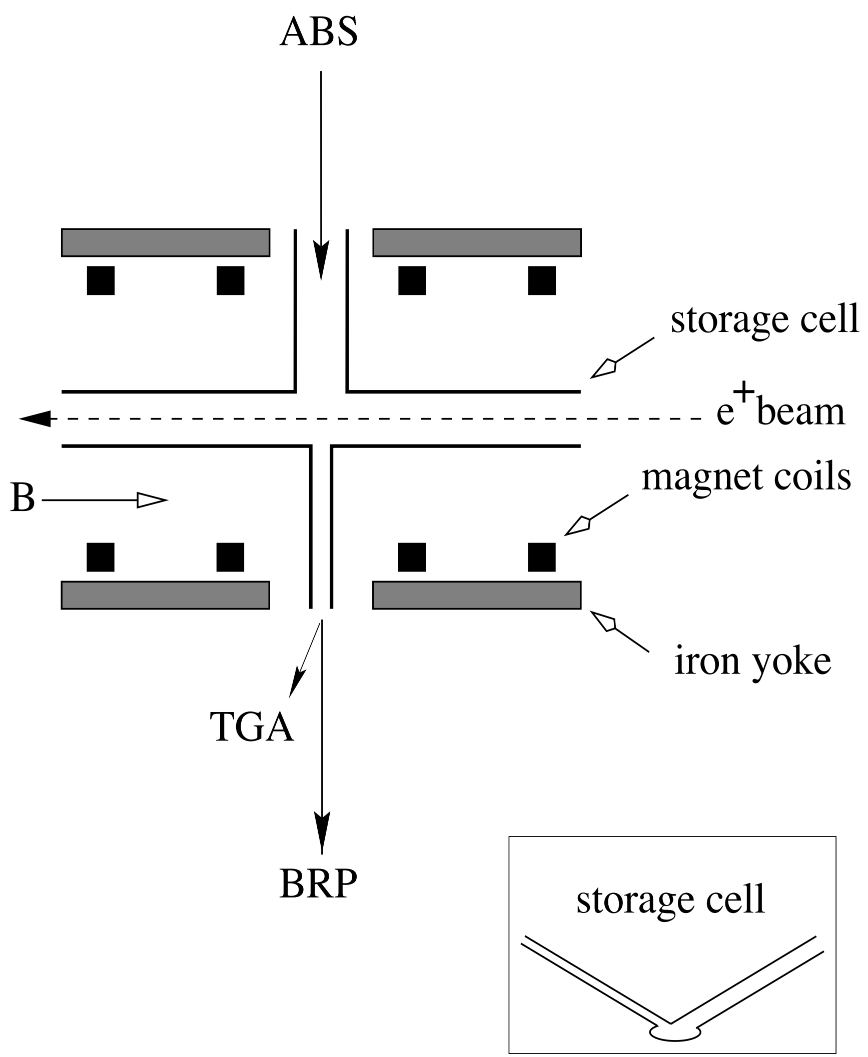


Polarizing Magnets- Split Pair

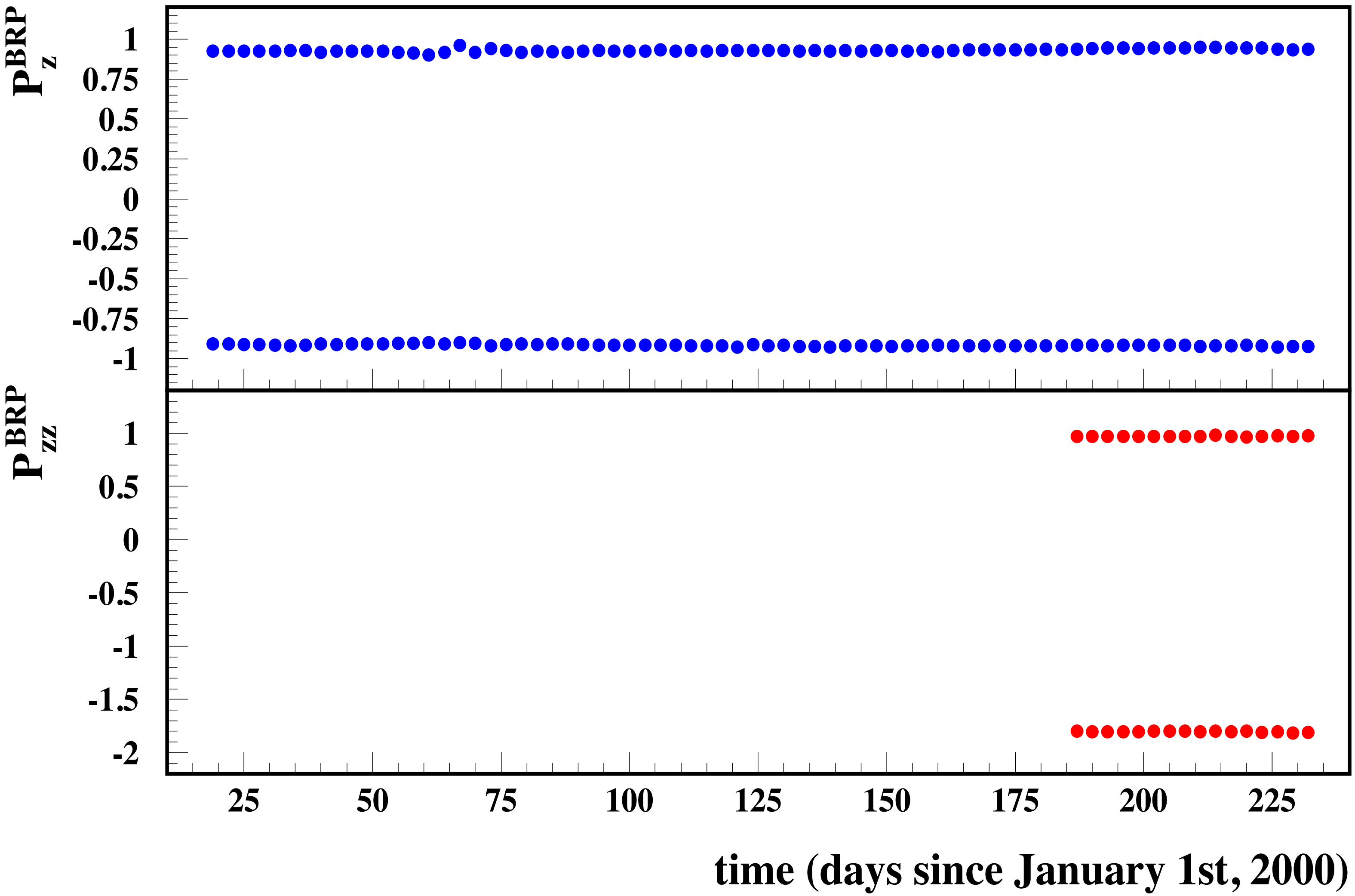
UVA/SLAC/JLAB Target

HERMES Polarized H/D Internal Gas Target




ABS
storage cell
e+beam
B
magnet coils
iron yoke
TGA
BRP
storage cell

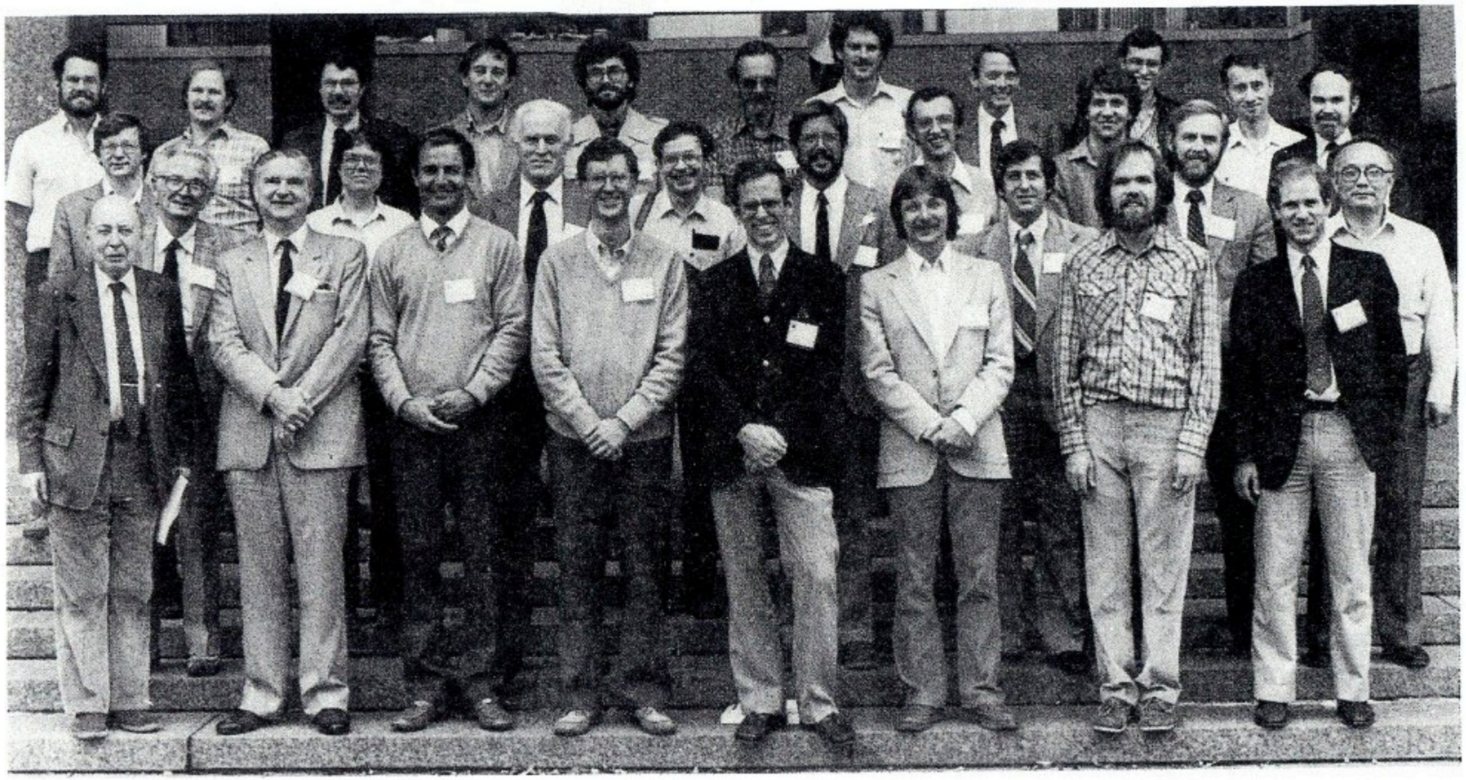
Performance



Polarized ^{3}He Gas Targets

- 1963: metastability exchange optical pumping technique invented by Colegrove, Schearer, and Walters
- 1965-75: experiments with polarized beams and targets using this technique pursued at many laboratories worldwide; polarizations limited to ≤20% because of use of discharge lamps
- 1983: development of high power lasers at 1.083 μm at Ecole Normale Superiore, Paris yielded polarizations of order 70% and high polarization rates
- 1988: development of high density, high polarization gas target of polarized 3He for electron scattering at Harvard
- 1990-93: series of experiments at MIT-Bates using both MEOP and spin-exchange optical pumping techniques
- The spin exchange technology is now the standard for external electron beams: SLAC, JLab
- MEOP employed with compression at Mainz; used as internal gas target at IUCF, AmPs, HERMES

Workshop on Polarized ^{3}He Beams and Targets
Princeton, October 22-24, 1984



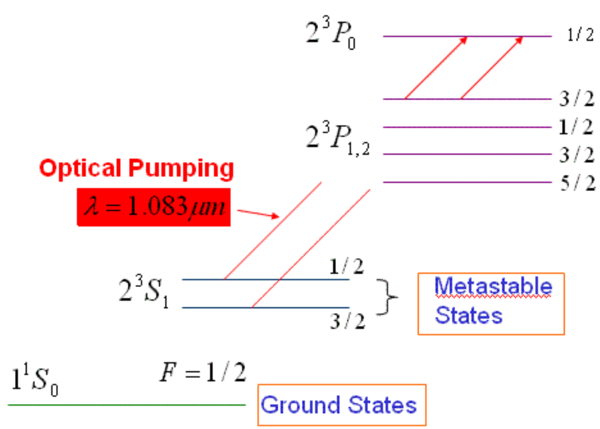
FRONT(L-R): E.P. Wigner, R.J. Slobodrian, F.P. Calaprice, S.D. Baker, T.B. Clegg, R.D. McKeown, M.S. Dewey, T. Chupp

MIDDLE: M.M. Lowry, R. Sherr, J. Powelson, J.M. Daniels, J. Dupont-Roc, D.P. May, R. Roy, J.G. Alessi, J.D. Brown, A.B. McDonald, S. Oh

BACK: M. Schneider, R.T. Kouzes, R.W. Dunford, R.G. Milner, C. Rioux, W.H. Moore, R. Knize, W. Happer, J, Giroux, F. Laloë, D.E. Murnick

$^3\vec{He}$ Targets Pioneered at MIT-Bates in Probing the neutron structure

Metastability-exchange optical pumping

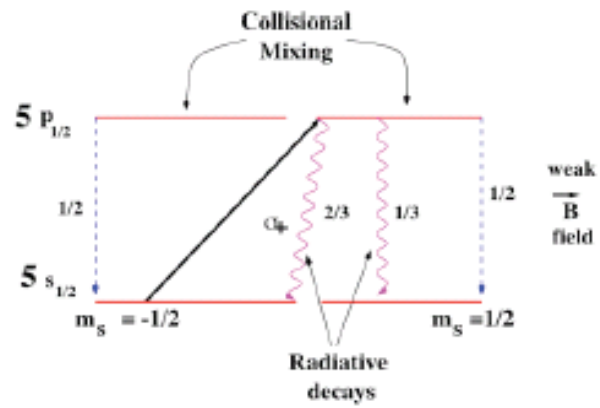


C.E.Woodward *et al.*, PRL **65**, 698 (1990)

H. Gao *et al.*, PRC **50,** R546 (1994)

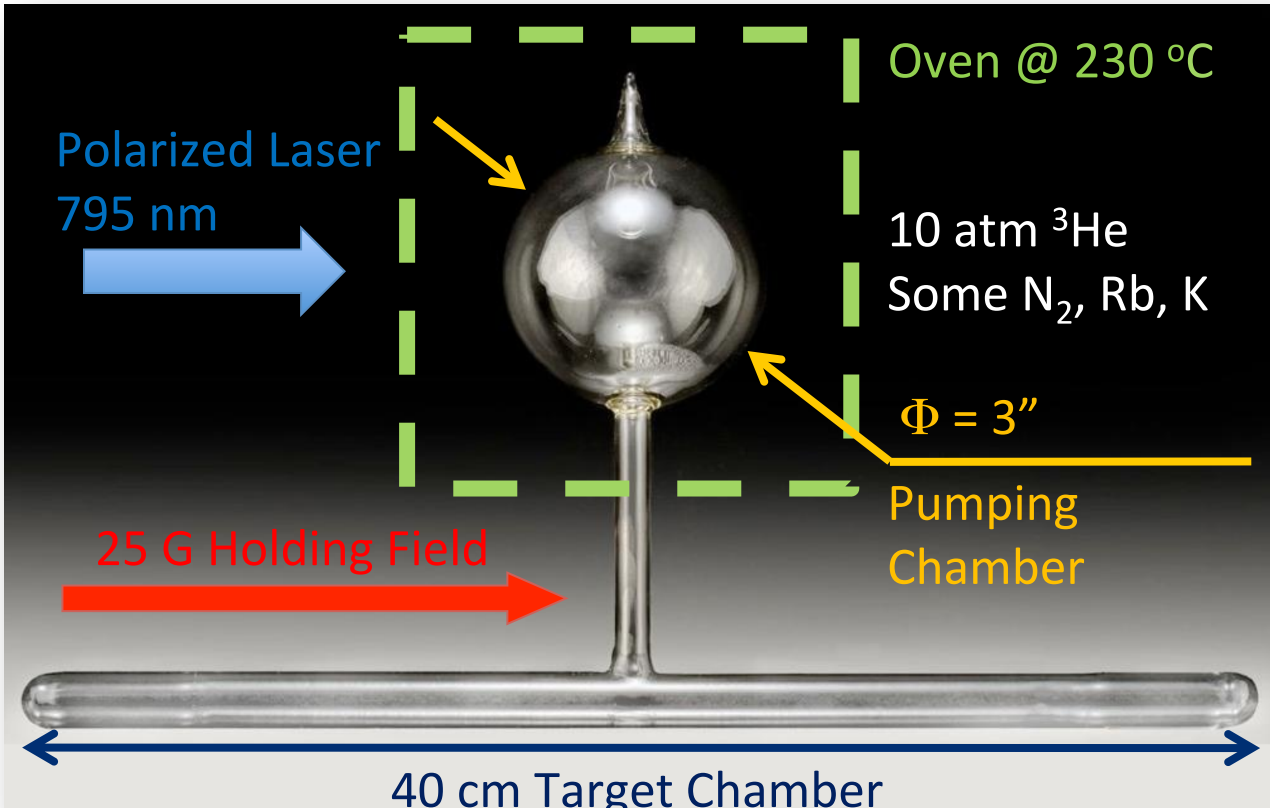
J.-O. Hansen *et al.,* PRL74, 654 (1995)

Spin-exchange optical pumping



A.K.Thompson *et al*., PRL**68**, 2901(1992)

Polarized ^{3}He Target in Jefferson Lab Hall A

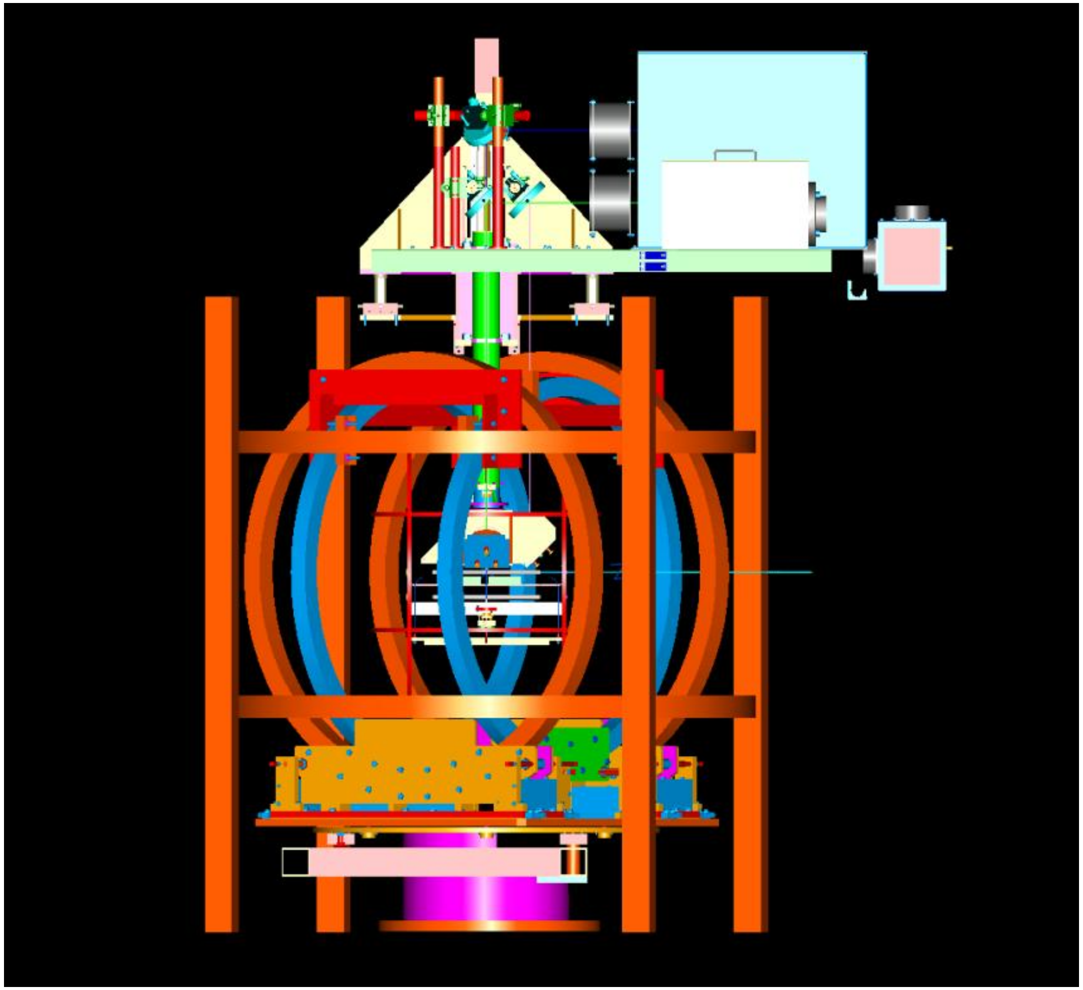


- 10 atm ^{3}He, Rb/K alkali mixture
- Luminosity with 15 μA electron beam
  - $L(n) = 10^{36}$ cm^2/s

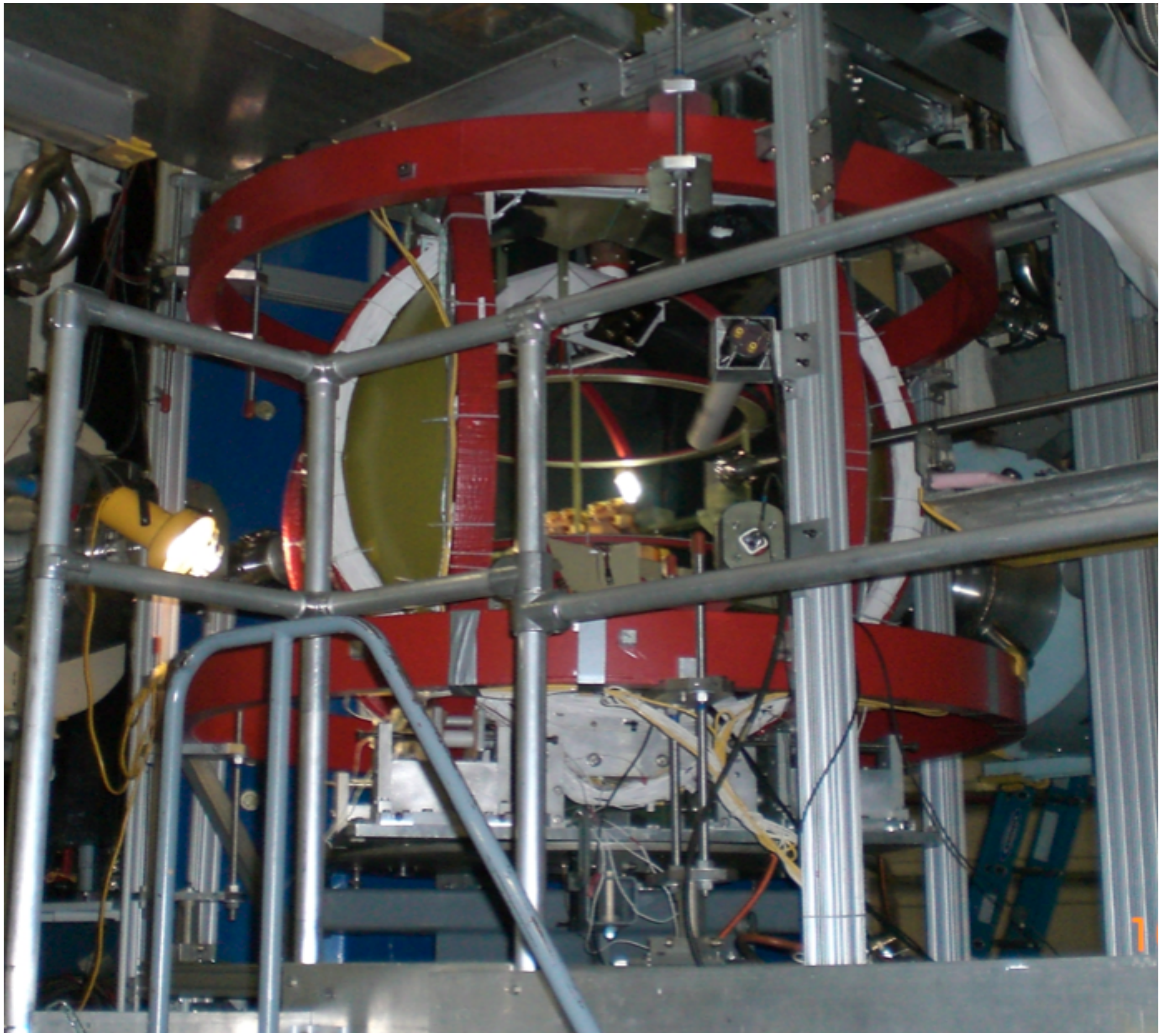
World Record

Polarized ^{3}He Target Setup

Three sets of Helmholtz coils to provide polarization in 3D.



Polarized ^{3}He Set-up in Hall A



Polarized Electron Sources

1963
Gibbs Laboratory
Yale University

Vernon started the search
For a polarized electron source
Specifically intended for high
Energy electron scattering
Experiments.

Vernon hires Bill Raith and
Gunter Baum

They settle on photoionization
of a spin-polarized alkali atomic
beam (potassium) and begin work

PHYSICAL REVIEW LETTERS

VOLUME 15 — 5 JULY 1965 — NUMBER 1

POLARIZED ELECTRONS FROM A POLARIZED ATOMIC BEAM*

R. L. Long, Jr., W. Raith, and V. W. Hughes
Gibbs Laboratory, Yale University, New Haven, Connecticut

(Received 25 May 1965)

A source of polarized electrons would have many uses in atomic, nuclear, and elementary-particle physics for the study of the spin dependence of interactions. Although polarized electrons are available from beta decay[1] and can also be produced by Mott scattering,[2] these sources of polarized electrons are not particularly convenient or useful as regards intensity, degree of polarization, energy variability, or suitability for injection into an accelerator. Many conceivable schemes for producing polarized electrons have been discussed.[2,3] All experiments which sought to utilize the electronic polarization in ferromagnetic materials have had negative results.[4] Utilization of optical pumping[5] and of elastic scattering of electrons with energies in the keV range from heavy atoms[6] are presently under investigation. In this Letter we report on the successful production of polarized electrons by photoionization of a polarized atomic beam of alkali atoms. We believe that this method can provide useful sources of polarized electrons.

The principles of the atomic beam method have been discussed in detail.[7] The first experimental attempt to use this method was made by Friedmann.[8] Ground-state alkali atoms with the electronic magnetic quantum number $m_J = +\frac{1}{2}$ are selected by deflection in a strong inhomogeneous magnetic field. The selected atoms having an electronic polarization P_a close to unity enter the photoionization region where there is a weaker magnetic field H along the axis of propagation. They change adiabatically into the states characteristic of H for which the electronic polarization P is smaller than P_a due to the hfs coupling of the electronic spin and the nuclear spin I:

$$P = P_a f(H),$$

where

$$f(H) = (2I+1)^{-1} \sum_{m=-I+\frac{1}{2}}^{I+\frac{1}{2}} [x + m(I+\tfrac{1}{2})^{-1}] \times [x^2 + 2xm(I+\tfrac{1}{2})^{-1} + 1]^{-1/2},$$

and

$$x = (g_J - g_I)\mu_0 H/\Delta W$$

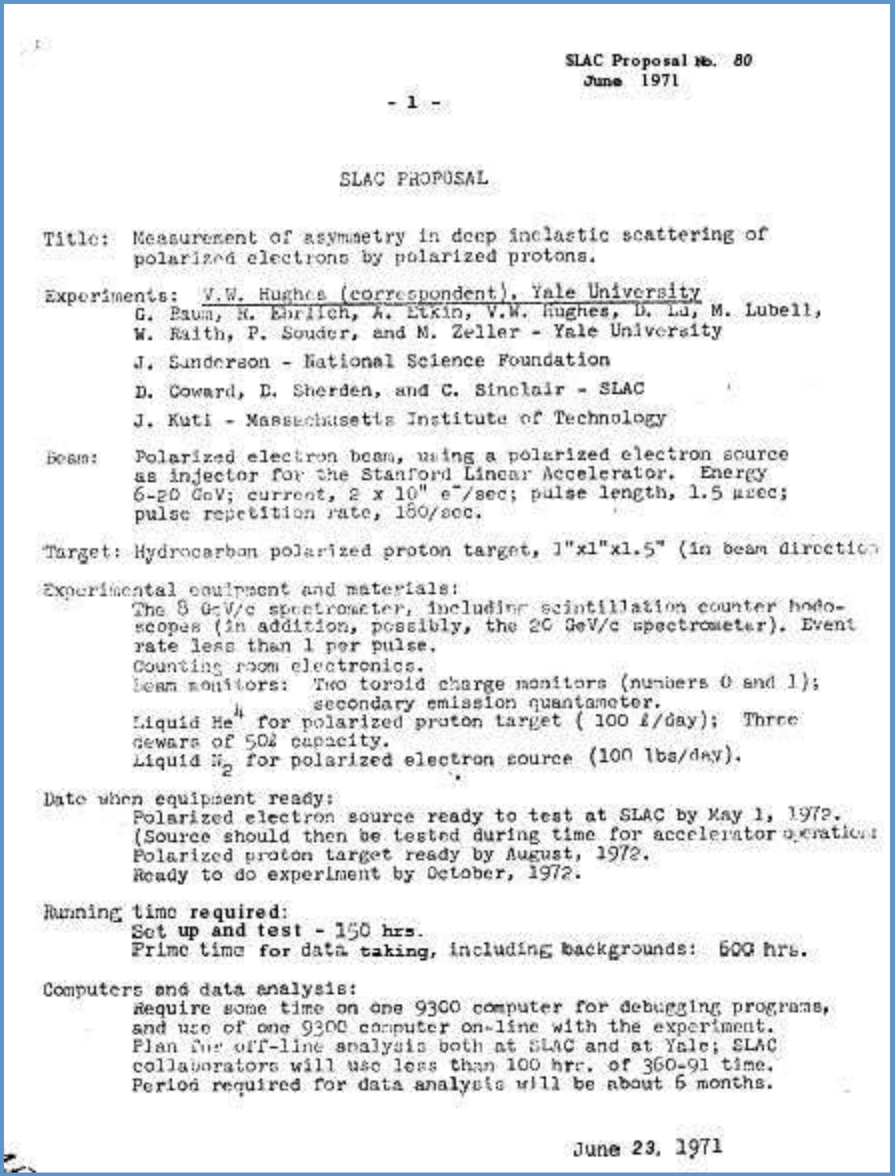
(ΔW = hfs energy interval; μ_0 = Bohr magneton; g_J and g_I are the electronic and nuclear g values).[9] Photoionization is predominantly an electric dipole transition and the spin-orbit interaction in the final state is not large enough to cause a spin flip for the outgoing electron during the time it spends in the field of the positive ion[10]; hence, the polarization of the photoelectrons should be equal to the electronic polarization P of the atoms. Potassium was chosen as the alkali atom because of its relatively small hfs interaction and relatively low photoionization threshold energy corresponding to

1

1960-1970:A new generation of accelerators was coming

The "Monster" project at Stanford was underway

SLAC construction photo
1963



SLAC Proposal No. 80
June 1971

- 1 -

SLAC PROPOSAL

Title: Measurement of asymmetry in deep inelastic scattering of polarized electrons by polarized protons.

Experimenters: V.W. Hughes (correspondent), Yale University
G. Baum, H. Ehrlich, A. Etkin, V.W. Hughes, D. Lu, M. Lubell, W. Raith, P. Souder, and M. Zeller - Yale University

J. Sanderson - National Science Foundation

D. Coward, D. Sherden, and C. Sinclair - SLAC

J. Kuti - Massachusetts Institute of Technology

Beam: Polarized electron beam, using a polarized electron source as injector for the Stanford Linear Accelerator. Energy 6-20 GeV; current, 2 x 10" e⁻/sec; pulse length, 1.5 μsec; pulse repetition rate, 180/sec.

Target: Hydrocarbon polarized proton target, 1"x1"x1.5" (in beam directio[n]

Experimental equipment and materials:
The 8 GeV/c spectrometer, including scintillation counter hodoscopes (in addition, possibly, the 20 GeV/c spectrometer). Event rate less than 1 per pulse.
Counting room electronics.
Beam monitors: Two toroid charge monitors (numbers 0 and 1); secondary emission quantameter.
Liquid He^4 for polarized proton target (100 ℓ/day); Three dewars of 50ℓ capacity.
Liquid N_2 for polarized electron source (100 lbs/day).

Date when equipment ready:
Polarized electron source ready to test at SLAC by May 1, 1972.
(Source should then be tested during time for accelerator operation)
Polarized proton target ready by August, 1972.
Ready to do experiment by October, 1972.

Running time required:
Set up and test - 150 hrs.
Prime time for data taking, including backgrounds: 600 hrs.

Computers and data analysis:
Require some time on one 9300 computer for debugging programs, and use of one 9300 computer on-line with the experiment. Plan for off-line analysis both at SLAC and at Yale; SLAC collaborators will use less than 100 hrs. of 360-91 time. Period required for data analysis will be about 6 months.

June 23, 1971

E80 Proposal
June 23, 1971

PEGGY Source

Polarized H target

SLAC 8 and 20 GeV Spectrometers

600 hours

Ready by October 1972

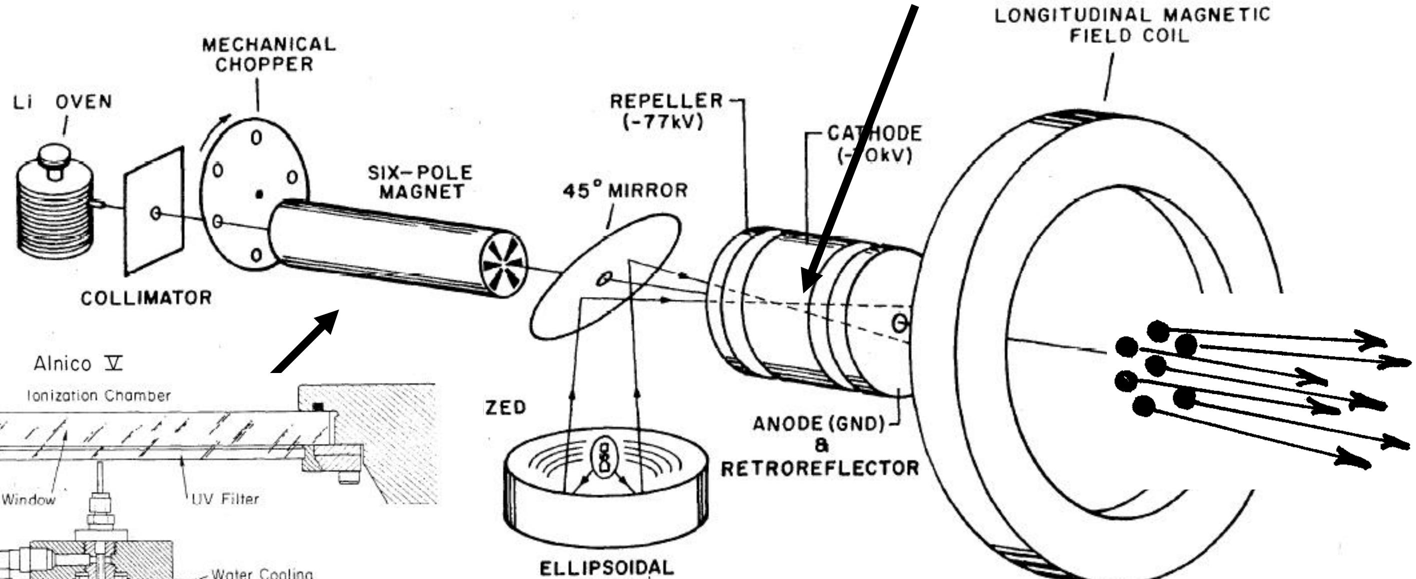
PEGGY

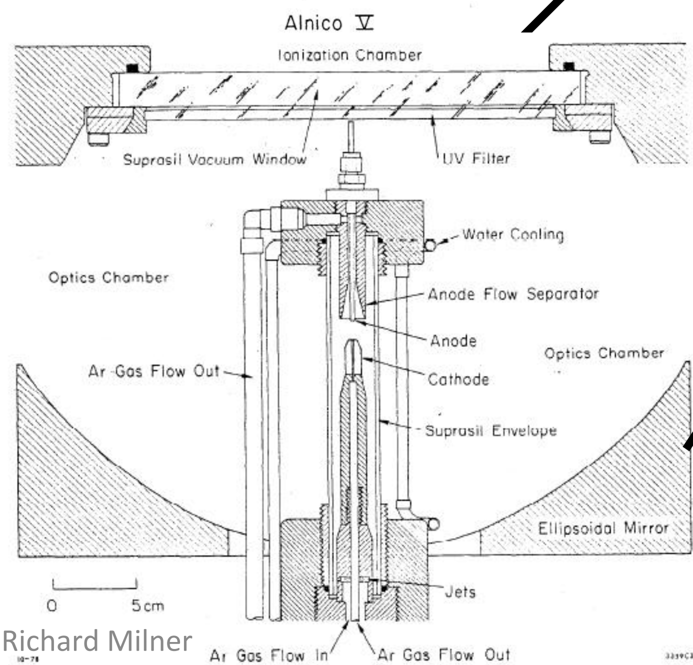
commissioned at SLAC in Nov 1974

750 gm Li-6 at 875 C

~175 hours

Mag field 215 gauss





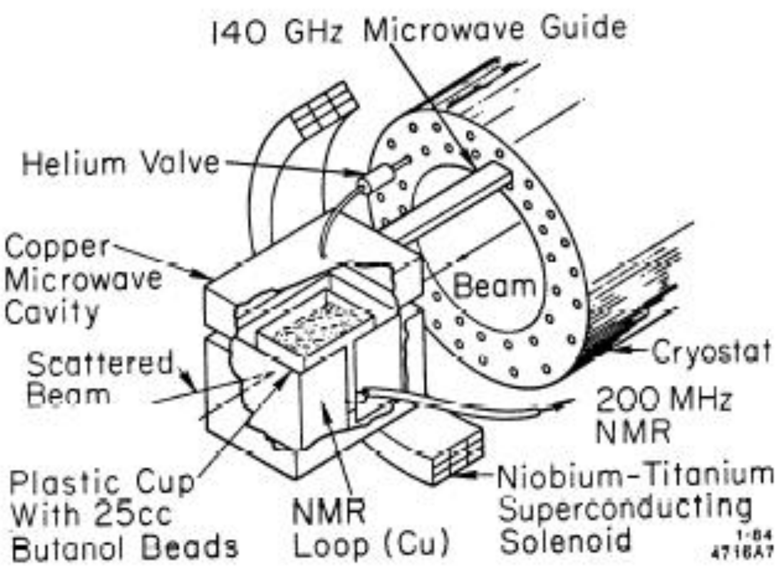
2 x 10^9 es/pulse at 180 pulses/sec

Pol = ±90 %

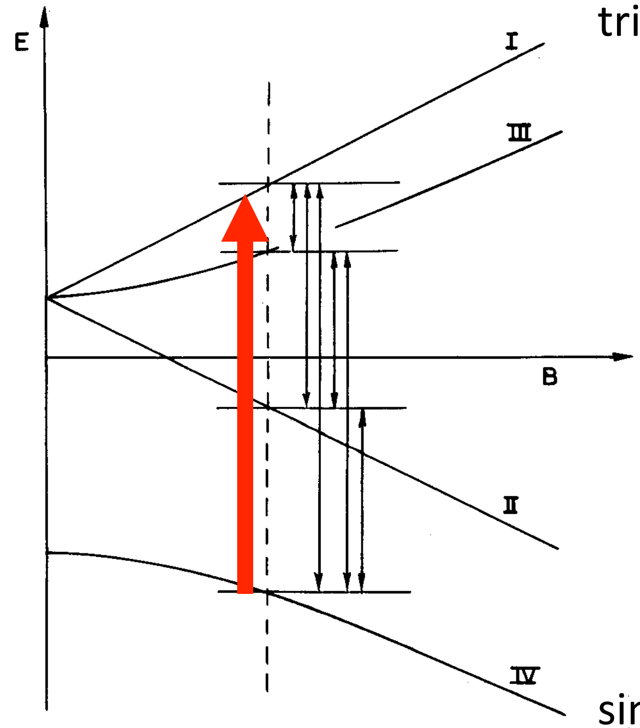
High Polarization, but intensity only 1/500 of SLAC beam !

Slow reversal of spin ~ 1 min

E80 Polarized Proton Target (1975)



hydrogen atom levels



triplet

singlet

Breit-Rabi Diagram

25 cm^3 butanol doped with porphyrexide

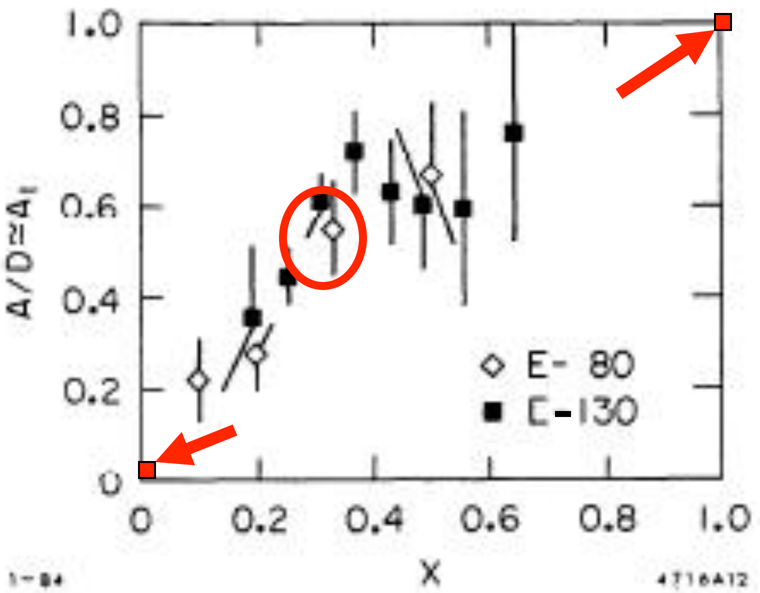
1 deg K

50 Kgauss

75 % proton polarization , but ~85% non-polarized materials

Radiation damage: 3 x 10^{14} e's/cm^2 -- -> frequent replacing

E80 (1975) and E130 (1976)



Simplest model: static quarks in SU(6) wave function*

$$|proton\uparrow\rangle = \frac{1}{\sqrt{18}}\Big[2|u^{\uparrow}d^{\downarrow}u^{\uparrow}\rangle + 2|u^{\uparrow}u^{\uparrow}d^{\downarrow}\rangle + 2|d^{\downarrow}u^{\uparrow}u^{\uparrow}\rangle - |u^{\uparrow}u^{\downarrow}d^{\uparrow}\rangle - |u^{\uparrow}d^{\uparrow}u^{\downarrow}\rangle - |u^{\downarrow}d^{\uparrow}u^{\uparrow}\rangle - |d^{\uparrow}u^{\downarrow}u^{\uparrow}\rangle - |d^{\uparrow}u^{\uparrow}u^{\downarrow}\rangle - |u^{\downarrow}u^{\uparrow}d^{\uparrow}\rangle\Big].$$

Predicts $A_p = 5/9$

and $A_n = 0$

at x = 1/3

*J. Kuti and V. Weisskopf, Phys. Rev. **D**4, 3418 (1971)

Proposal 138 in 1980

Vernon proposes another polarized electron – polarized target run --- E138

- new GaAs polarized electron source
- New polarized target technologies – NH_3 and ND_3 --- which withstood radiation damage much better
- Longitudinal and transverse target polarization

BUT SLAC was committed to building a new kind of collider – SLC
the SLAC LINEAR COLLIDER

E138 was not accepted, so Vernon left SLAC and went to CERN
and the European Muon Collaboration (EMC)

SLAC would re-enter this arena in 1991-----but before this part of the story,
we must go back to 1972 and the electroweak unification saga....

E95 Proposal - 1972

SLAC Proposal E95

EXPERIMENTAL TEST FOR AN ELECTROMAGNETIC AXIAL-VECTOR CURRENT OF HADRONS IN INELASTIC SCATTERING OF POLARIZED ELECTRONS

Experimenters: C.Y. Prescott (Spokesman); W. Atwood; E. Bloom;
H. DeStaebler; S. Stein; R. Taylor; D. Trines:
SLAC - Group A
and
D. Coward; D. Sherden: SLAC Spectrometer Facilities Group
and
G. Baum; R. Ehrlich; V. W. Hughes;
M.Lubell; W. Raith; M. Zeller:
Yale University

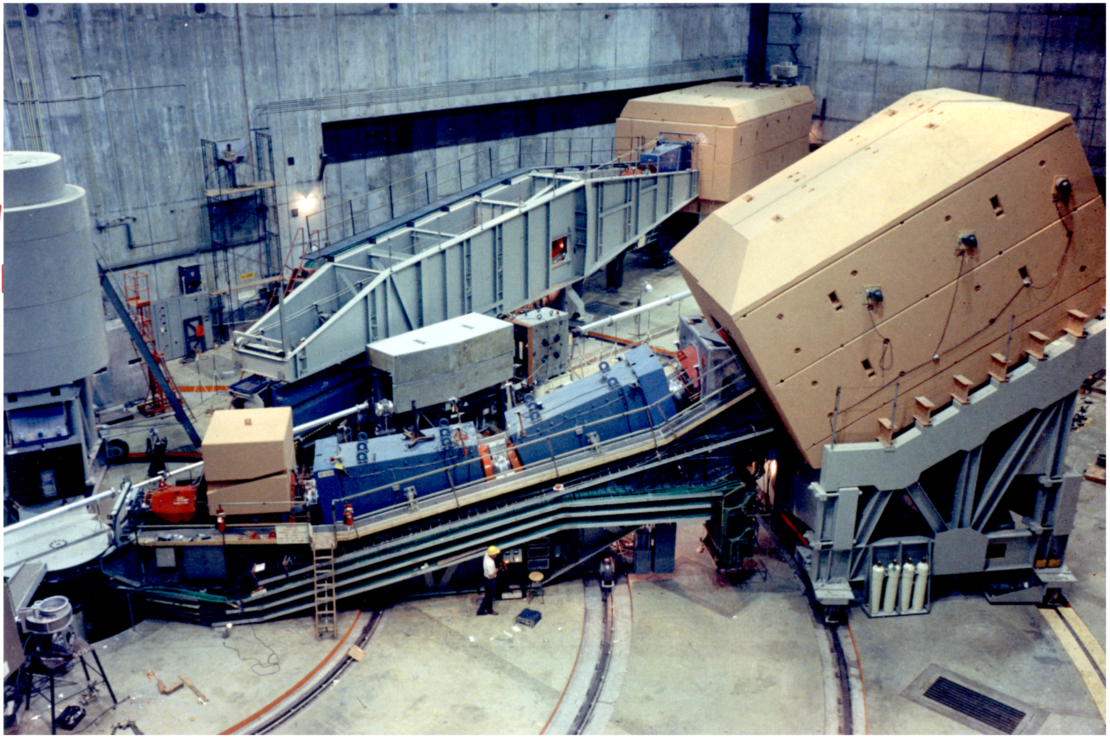
12°, an asymmetry of .004 corresponds to a parity violation of .03 of a maximal violation. This provides a good test of parity violation in electromagnetism, but is not sufficiently sensitive to observe parity violating effects arising from neutral weak currents.

4) The orientation of the electron spin relative to the momentum

End Station A

E95 ran in 1976 and published a limit
$A_{LR} < 8 \times 10^{-4}$
at $Q^2 = 1.2$ GeV/c^2

Even before E95 was underway, Charlie Sinclair and I were discussing ways to reach the weak level, as defined in the Weinberg-Salam model



We needed to increase the counting rate by

~10000!

July 1973

Search for a new source

DATE: July 20, 1973

TO : Distribution

FROM : Charlie Sinclair

SUBJECT: Discussion of PEGGY Status and a Possible Alternative Polarized Electron Source.

A meeting was held on 18 July 1973 with D. Coward, E. Garwin, R. Miller, R. Koontz, R. Neal, W. Panofsky, and C. Sinclair in attendance. The status of the polarized electron source, PEGGY, presently in testing at Yale, was reviewed, and the possibilities of an alternative source were discussed.

Dave Coward reviewed the status of the PEGGY tests, as obtained from a phone conversation with Mike Lubell on 7/18. After an initial test in May, when a yield of 5×10^7 electrons of unknown polarization/pulse was obtained (a factor of 20 below design), a mirror misalignment was found

C. Sinclair to Distribution
Discussion of PEGGY Status...

July 20, 1973
Page 2

Roger Miller feels that a lower limit to the time between hardware arrival at SLAC and any possible accelerated beam is six weeks. The potential pitfalls in this time estimate are too numerous to list. Thus it was universally agreed that SLAC must operate on the presumption that there will be no polarized e- beam in 1973.

Given the realities of the PEGGY situation, it is prudent to imagine that PEGGY might not perform acceptably in the forseeable future, and investigate possible alternative methods of obtaining a polarized electron source.

These possible alternatives include photo emission from EuO or field emission from EuS covered W needles, as pointed out to Pief in a memo from W. Spicer.

These solutions, like the Yale source, involve a number of distinct technical difficulties, and if it were decided to pursue one of these methods, it would involve a sizeable commitment on SLAC's part. Among the possible problems with these sources, we noted the following:

1. The emittance is dominated by the large magnetic fields used. SLAC

Neutral Currents Discovered!
Gargamelle
CERN - 1973

434 *Donald Perkins*

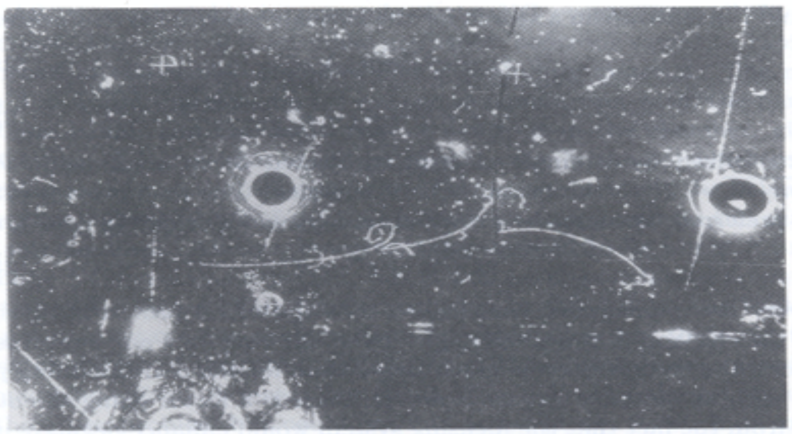


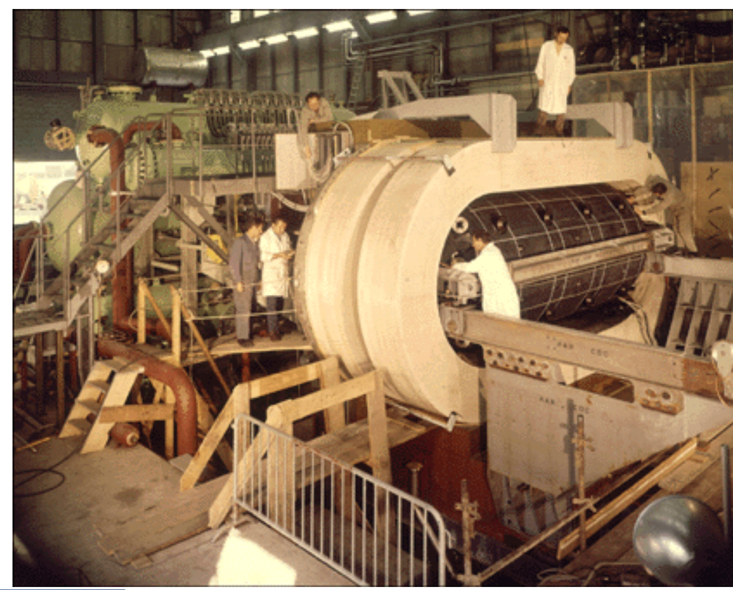
Fig. 25.3. First bubble-chamber photograph of the neutral-current process $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.

Gargamelle finds one ν_μ e^- event!

(two more by 1976)

First Z^0 seen in UA1 in 1983

Charlie Baltay



E122 Letter of Intent – July 1974

DATE: July 26, 1974

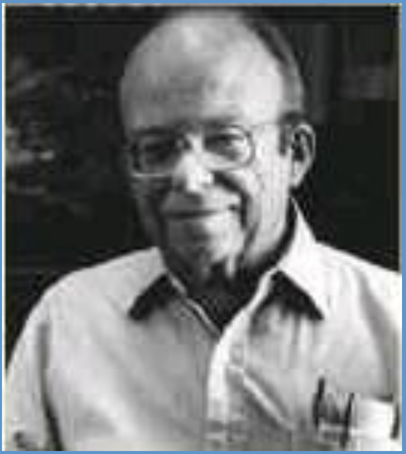
TO : W. K. H. Panofsky

FROM : Charles Sinclair, Charles Prescott

SUBJECT: INTENT TO SUBMIT PROPOSAL

For some time, now, we have been studying the possibilities for observing parity violating $\vec{\sigma}\cdot\vec{p}$ terms in inelastic scattering of polarized electrons off unpolarized targets. Such experiments, if convincingly able to demonstrate asymmetries at the 10^{-4} level, are both timely and of fundamental importance. Measurement of such small asymmetries is an extremely difficult experimental task. Our studies of the prospects for seeing such small effects have led us to two conclusions.

First, proof of observation of parity violation requires elimination of systematic effects, correlated to spin reversal, which lead to false asymmetries. Checks must be carried out systematically on-line and will require running times comparable to those of the measurements of interest. Any proposal which counts individual electrons implies, at SLAC's duty cycle, lengthy runs to obtain sufficient statistical accuracy to reach the 10^{-4} level. A better approach is to achieve high counting rates for electrons so that 10^{-4} asymmetries



Pief

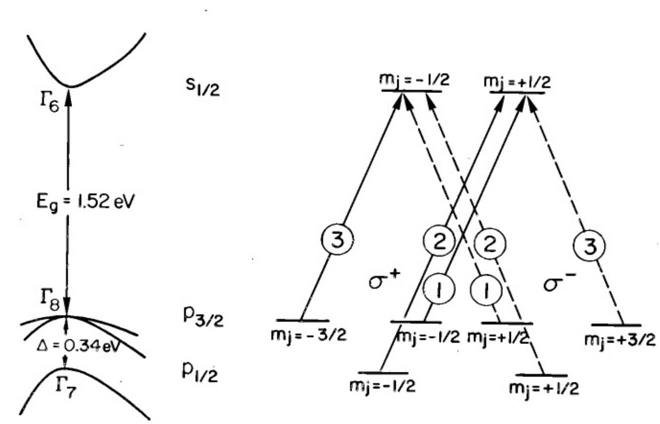
GOAL: to test the Weinberg – Salam model

The Promise of Gallium Arsenide 1974

Gallium Arsenide was well known to have polarized internal electrons when optically pumped by circularly polarized light
(Ekimov and Sakarov, JETP Letters 13, 495 (1971))

Bell and Spicer had shown that the conduction band electrons could be photoemitted by adding Cs-O monolayers to the surface.

Ed Garwin knew of these works and the need for a source at SLAC.



Ed Garwin

Bill Spicer

Gallium Arsenide proposed

Garwin, Pierce, and Siegmann
1974

Ed Garwin visited ETH Zurich in 1974, and while there proposed to develop a polarized electron source using gallium arsenide. The first source was built and demonstrated by Dan Pierce at ETH Zurich (now at NIST).

The density of electrons in GaAs is high, promising large available currents. GaAs as a source of polarized electrons appeared ideal for SLAC, but first, the principles had to be demonstrated.

Ed Garwin

H. C. Siegmann

Dan Pierce

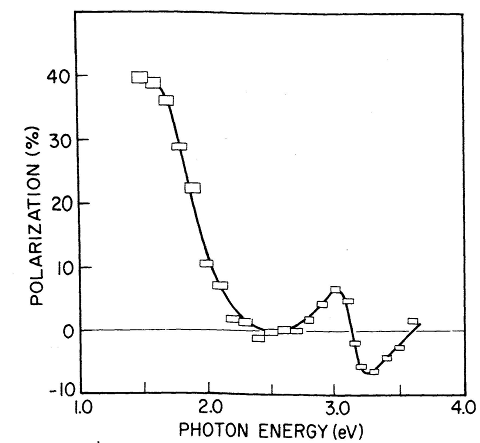


FIG. 6. Spectrum of spin polarization from GaAs + CsOCs at $T \le 10$ K [the same sample and conditions as curve (a) of Fig. 5]. Note the high value of $P = 40\%$ at threshold ($\hbar\omega \sim 1.5$ eV) and positive and negative peaks

Flashlamp-pumped Dye laser

Charles Sinclair is shown here with the high-power laser used with the PEGGY II polarized electron source. (Photo by Joe Faust.)

GaAs cathode

20 mm dia

E122 Proposal - Test of Weinberg-Salam Model

June 1975

SLAC Proposal E-122

A TEST OF PARITY VIOLATION IN THE INELASTIC SCATTERING OF POLARIZED ELECTRONS AT THE LEVEL OF THE WEAK INTERACTION

EXPERIMENTERS: SLAC, Groups A and SFG: W. Ash; W. Atwood; R. Cottrell; H. DeStaebler; H. Pessard; C. Prescott*; L. Rochester; D. Sherden; C. Sinclair*; R. Taylor

Yale University: M. Bergstrom; R. Ehrlich; V. Hughes; M. Lubell; K. Kondo; N. Sasao; P Souder

University of Bielefeld: G. Baum; B. Raith, P. Schuler

* Spokesman

BEAM: Solid State Polarized Electron Source, (under development) 10^{11} e⁻/pulse (10 ma peak 1.6 usec), 50% polarized, 180 pps.

TARGET: 30 cm LD_2

EQUIPMENT: 8 GeV/c and 20 GeV/c spectrometers, modified for high counting rates; Counting House electronics and computers.

RUNNING TIME: 300 hours at 200 pps and 100 hours checkout at 30 pps

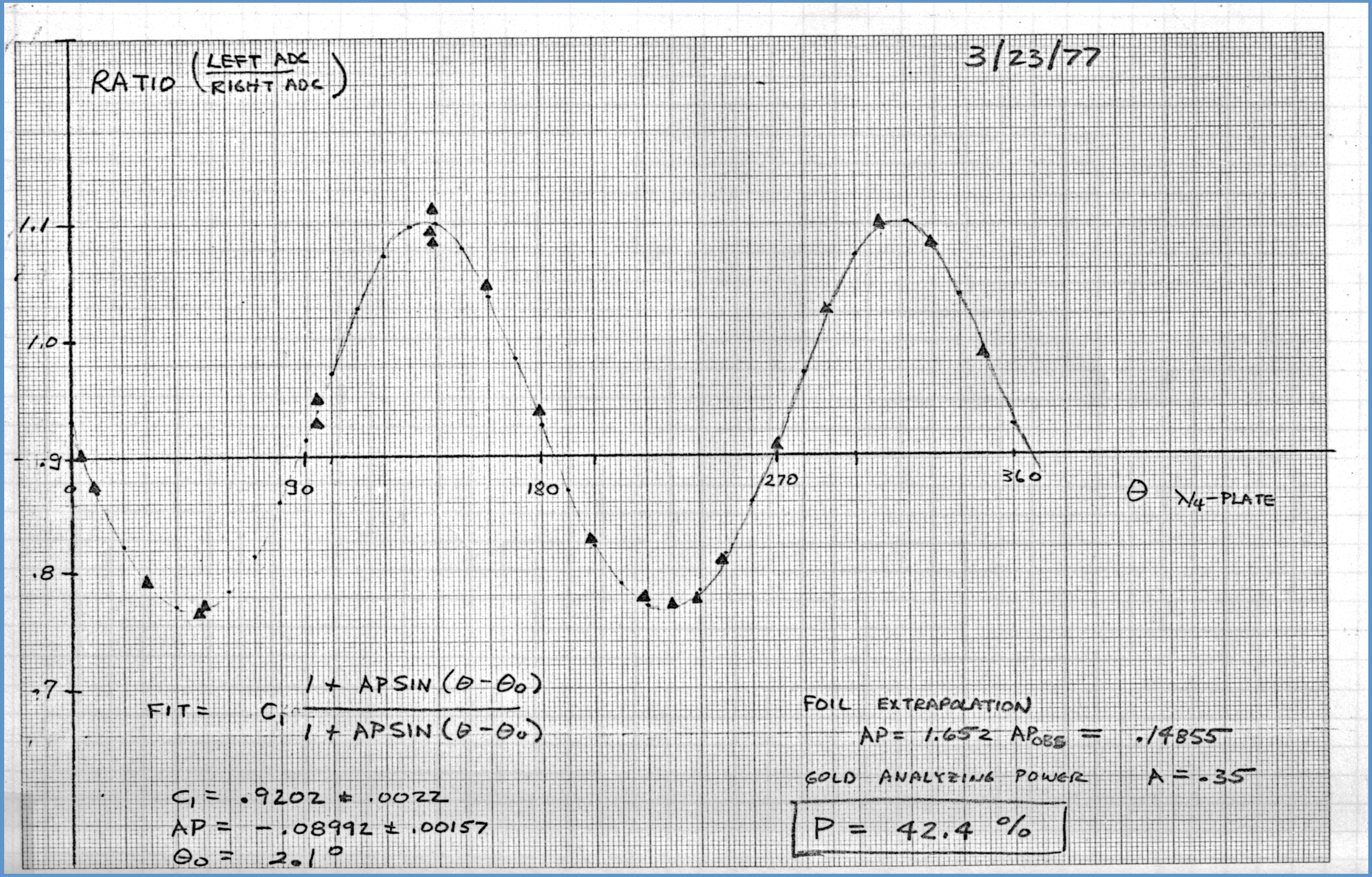
100 hours at 19.42 GeV

100 hours at 16.18 GeV

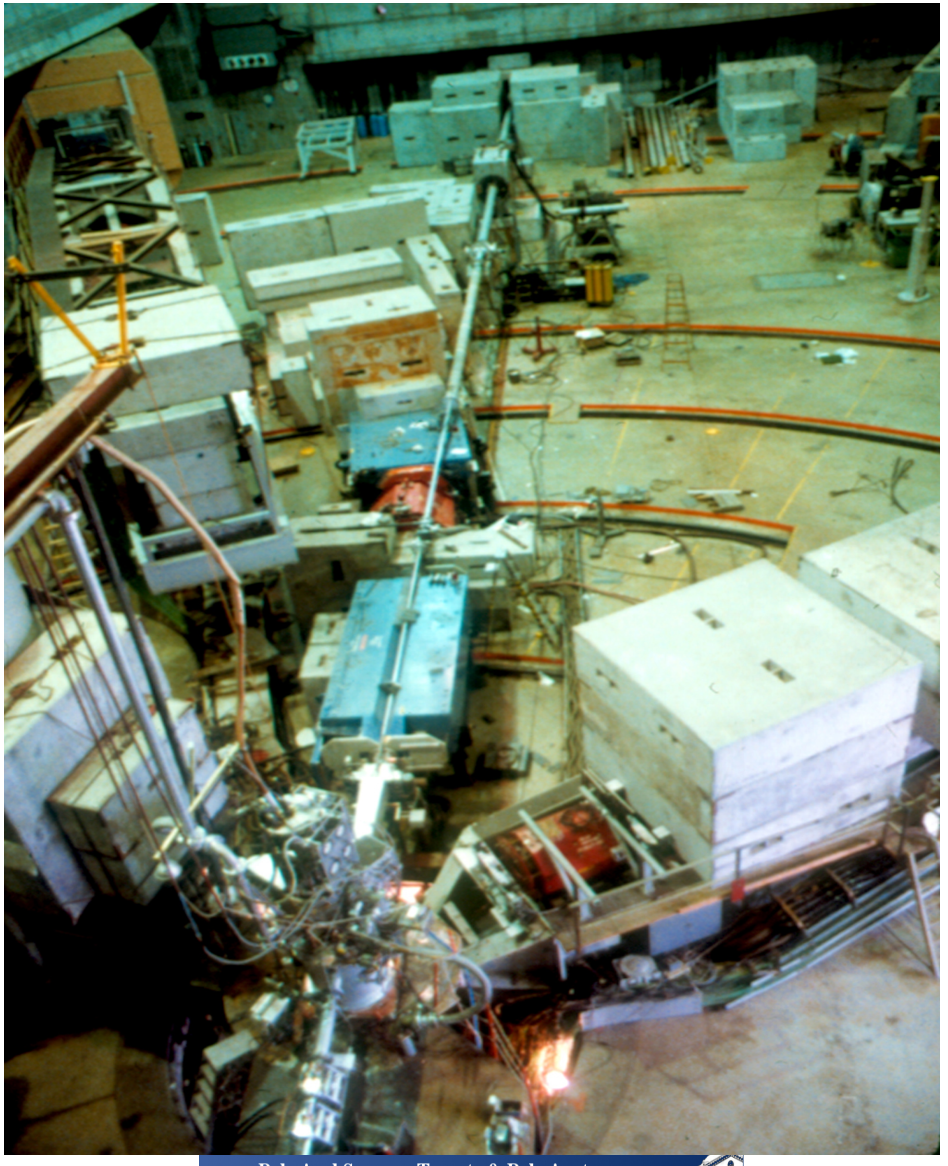
100 hours at 17.80 GeV

Source Works!!

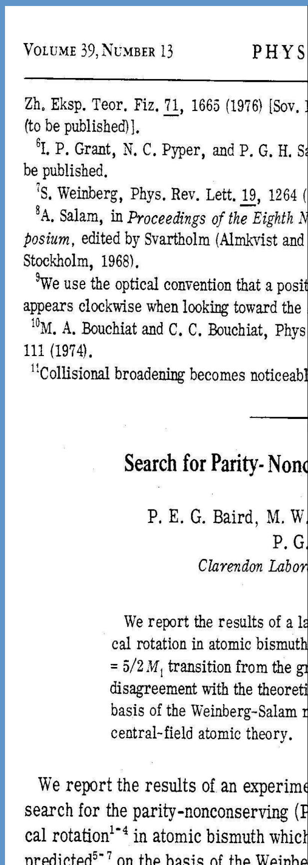
Mott Analyzer at 120 KeV



Building the Experiment
1977- 1978



1977
Atomic Parity Violation measures 0 !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[8]A. Salam, in *Proceedings of the Eighth*
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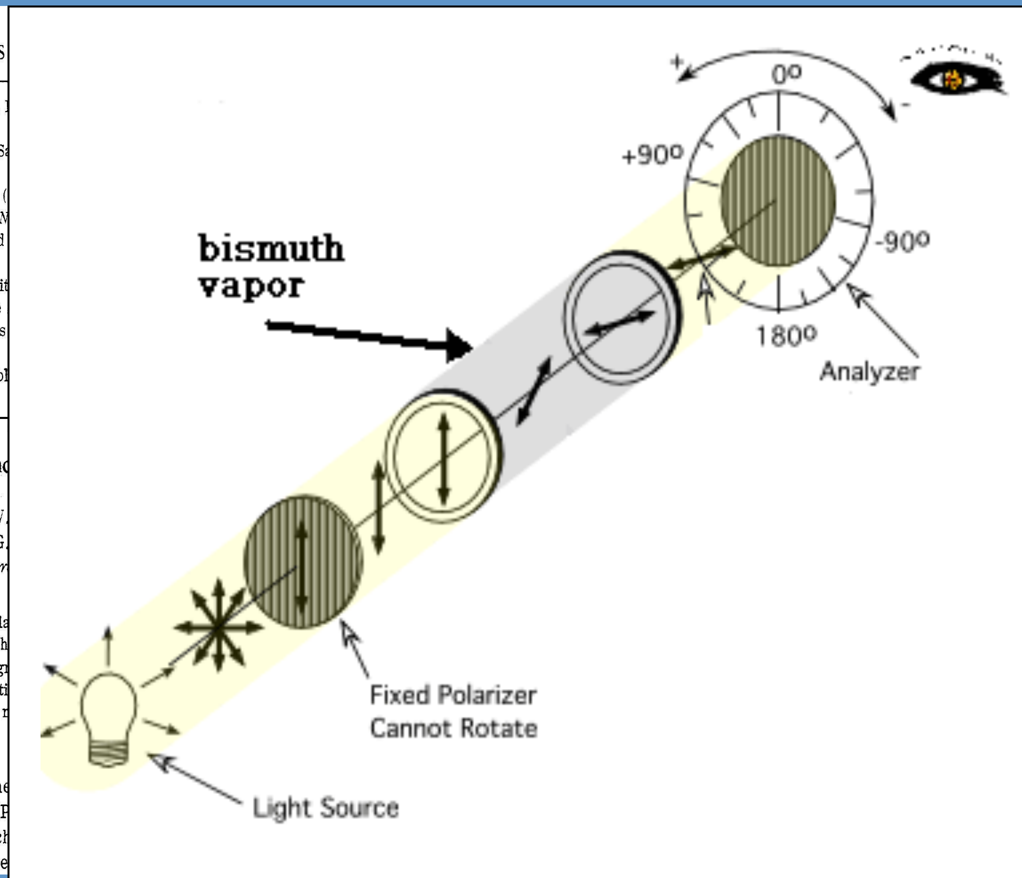
[10]M. A. Bouchiat and C. C. Bouchiat, Phys
111 (1974).
[11]Collisional broadening becomes noticeabl

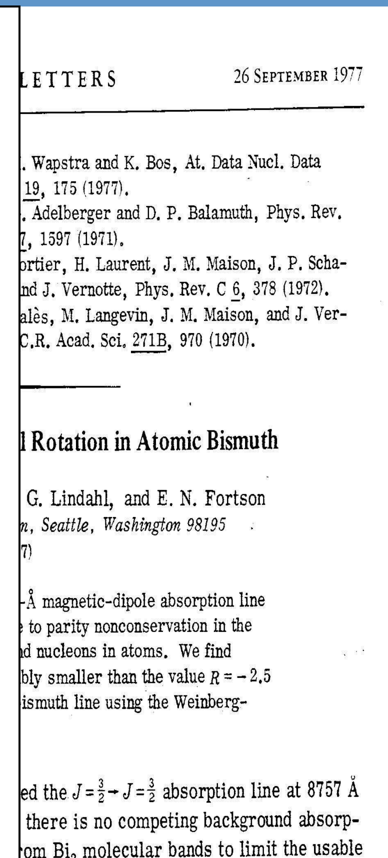
Search for Parity-Non

P. E. G. Baird, M. W
P. G
Clarendon Labor

We report the results of a la
cal rotation in atomic bismuth
= 5/2 M_1 transition from the g
disagreement with the theoreti
basis of the Weinberg-Salam
central-field atomic theory.

We report the results of an experime
search for the parity-nonconserving (P
cal rotation[1-4] in atomic bismuth which
predicted[5-7] on the basis of the Weinbe

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l Rotation in Atomic Bismuth

G. Lindahl, and E. N. Fortson
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7)

-Å magnetic-dipole absorption line
to parity nonconservation in the
d nucleons in atoms. We find
bly smaller than the value $R = -2.5$
ismuth line using the Weinberg-

ed the $J=\frac{3}{2} \rightarrow J=\frac{3}{2}$ absorption line at 8757 Å
there is no competing background absorp-
om Bi_2 molecular bands to limit the usable

$\mathrm{Im}(E_1/M_1) = (+2.7 \pm 4.7)\mathrm{x}10^{-8}$ $\mathrm{Im}(E_1/M_1) = (-0.7 \pm 3.2) \times 10^{-8}$

Theory: $\approx -30 \times 10^{-8}$

A Model of Leptons

Steve Weinberg - 1967

By 1977 many of the issues of neutral currents were being resolved in neutrino scattering. But one issue remained…. The assignment of the right-handed electron into a singlet or a doublet.

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \qquad (e)_r$$

Parity is violated

or

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \qquad \begin{pmatrix}E^0\\ e\end{pmatrix}_r$$

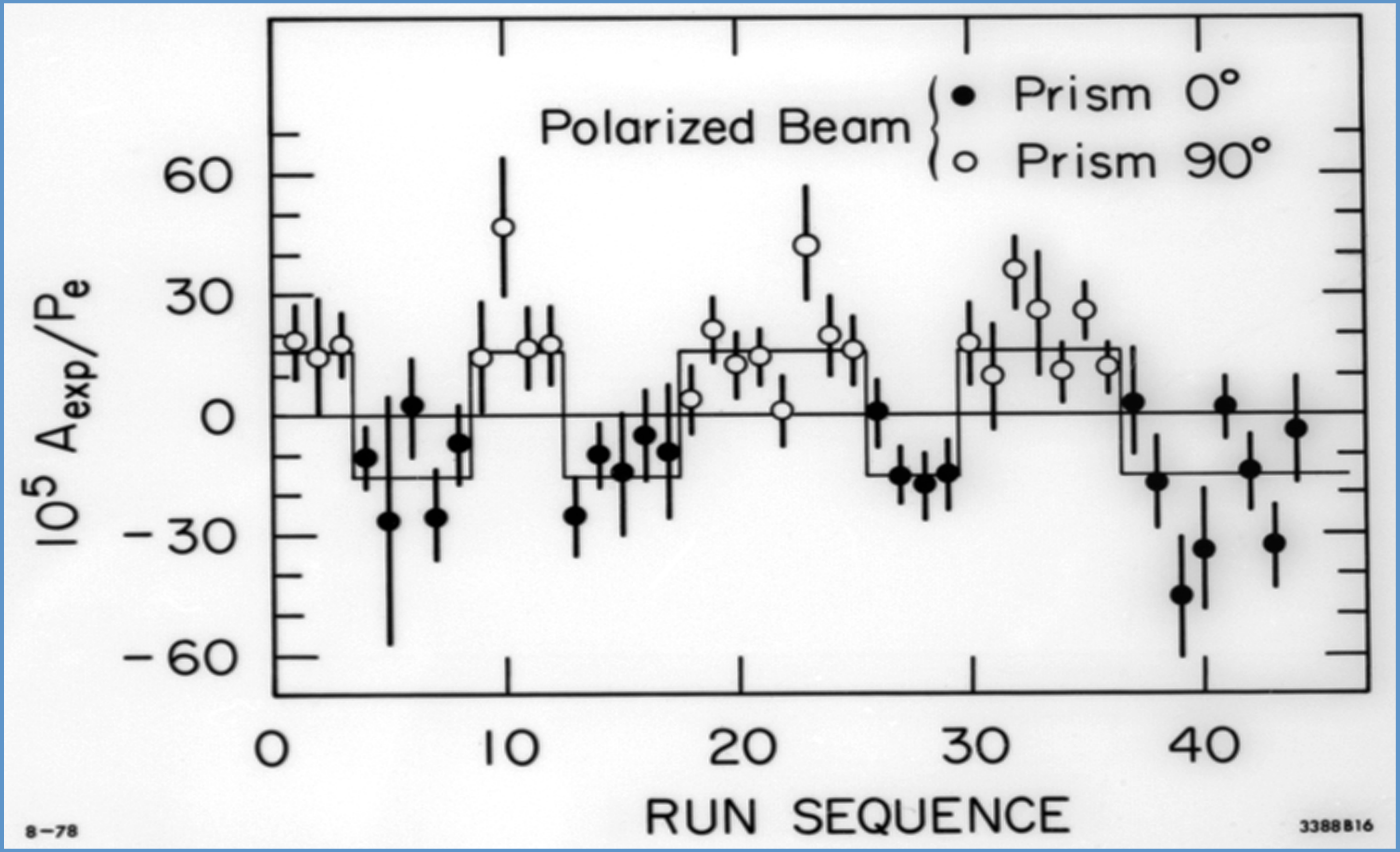
Parity is conserved

"hybrid model"

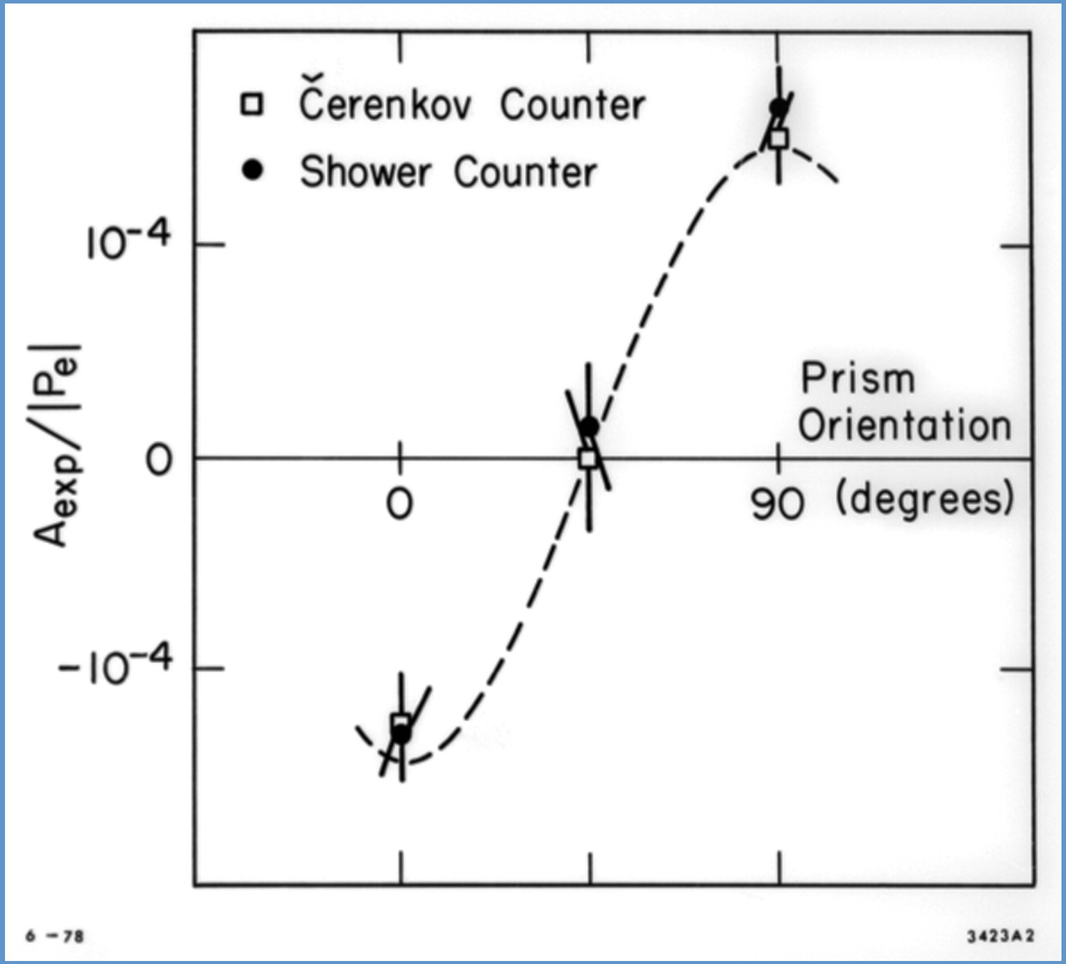
$g_l = T_{3l} - q \sin^2\Theta w$ and $g_r = T_{3r} - q \sin^2\Theta w$

At SLAC, the laser-driven GaAs source works; Polarized electrons are accelerated in December 1977.

Running E122
March 1978



Prism Orientation



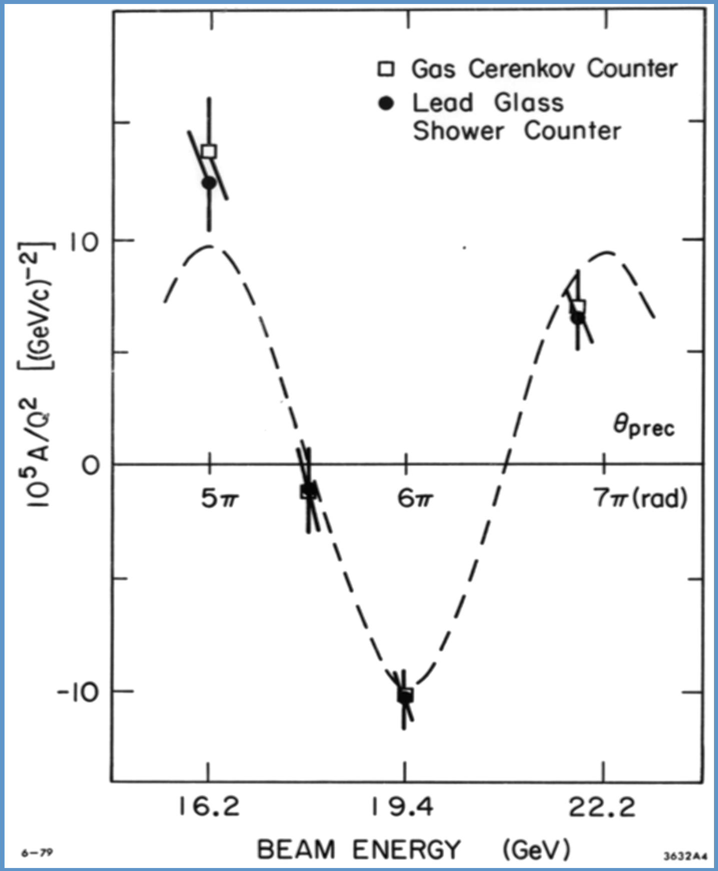
E122 Announces Parity Violation June 1978

g-2 precession

in the ESA beamline.

The statistical significance exceeded 10 sigma. Consistency checks and null texts were fully satisfied.

$\sin^2 \Theta_w = 0.224 \pm .02$



These results confirm Weinberg's Model
left handed doublet and right handed singlet
AND
agrees with GRAND UNIFICATION

Polarimetry

Elastic scattering cross section

In the one-photon exchange approximation, the cross section is a product of the Mott cross section and the form factor functions

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2}\frac{1}{\sin^4\frac{\theta}{2}}\cdot\cos^2\frac{\theta}{2}\cdot\frac{E'}{E}$$

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

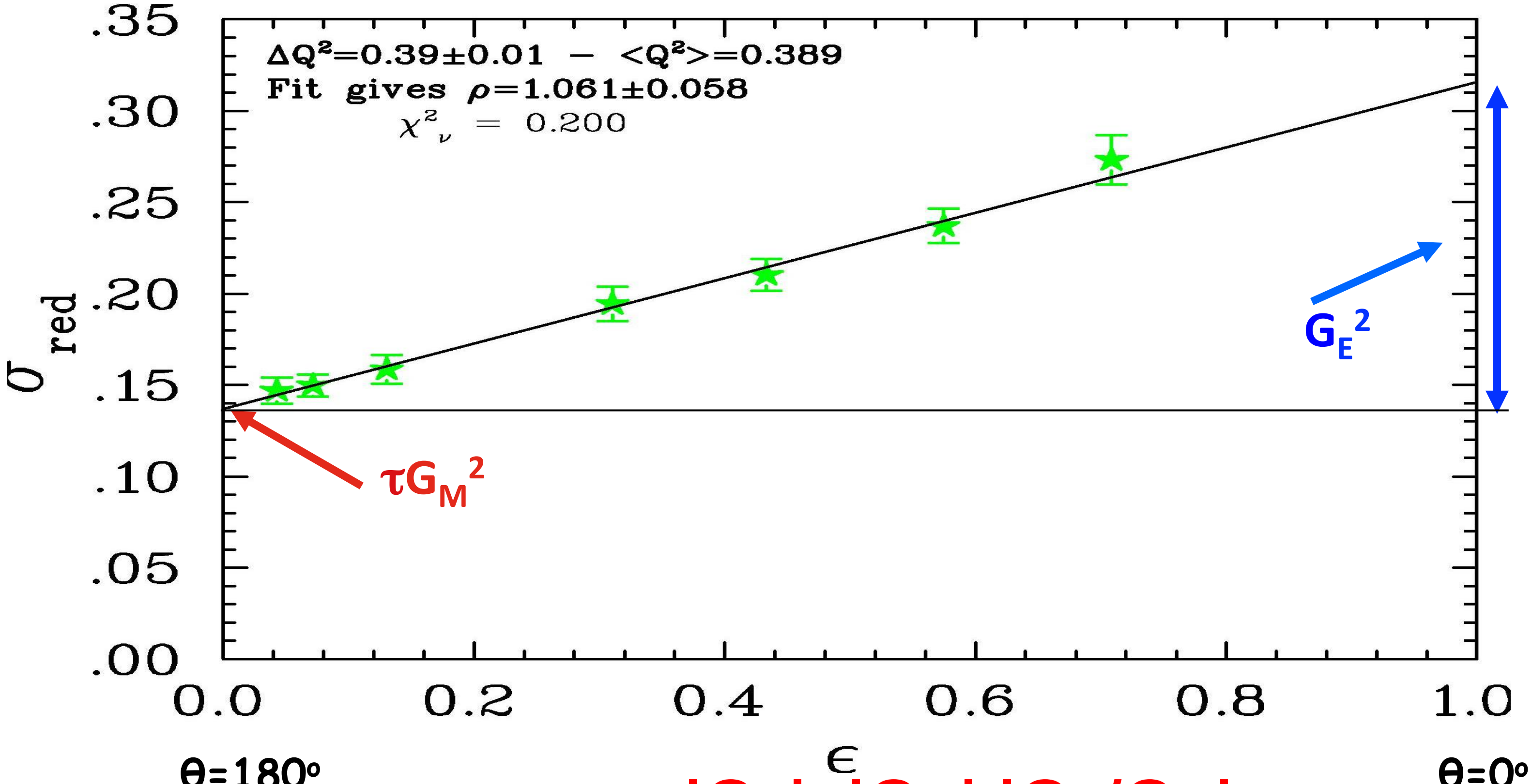
$$\tau = \frac{Q^2}{4M_p^2}$$

ε =relative flux of longitudinally polarized virtual photons

Form Factors from Cross section (Rosenbluth Method)

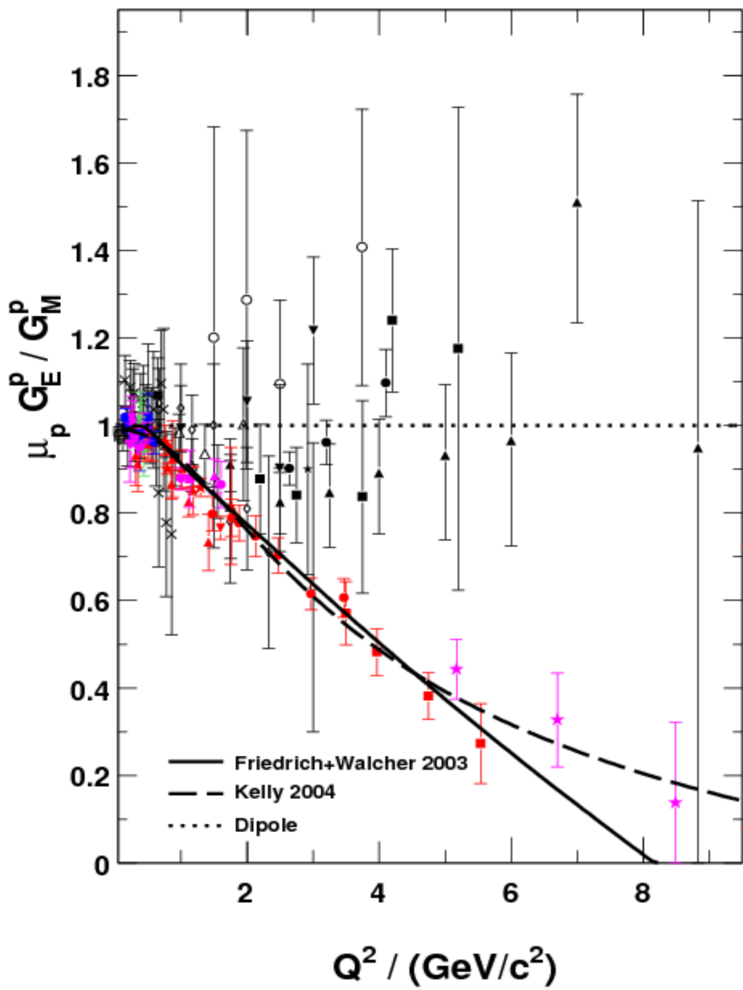
One can define the reduced cross section σ_{red}

$$\sigma_{red} = \varepsilon G_E^2 + \tau G_M^2$$



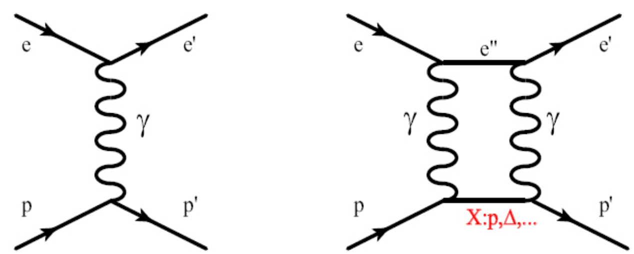
→ **Determine $|G_E|, |G_M|, |G_E/G_M|$**

Proton Form Factor Ratio



Jefferson Lab 2000

- All Rosenbluth data from SLAC and JLab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Contribution of multi-photon exchange widely accepted explanation of discrepancy



Dramatic discrepancy!

>800 citations

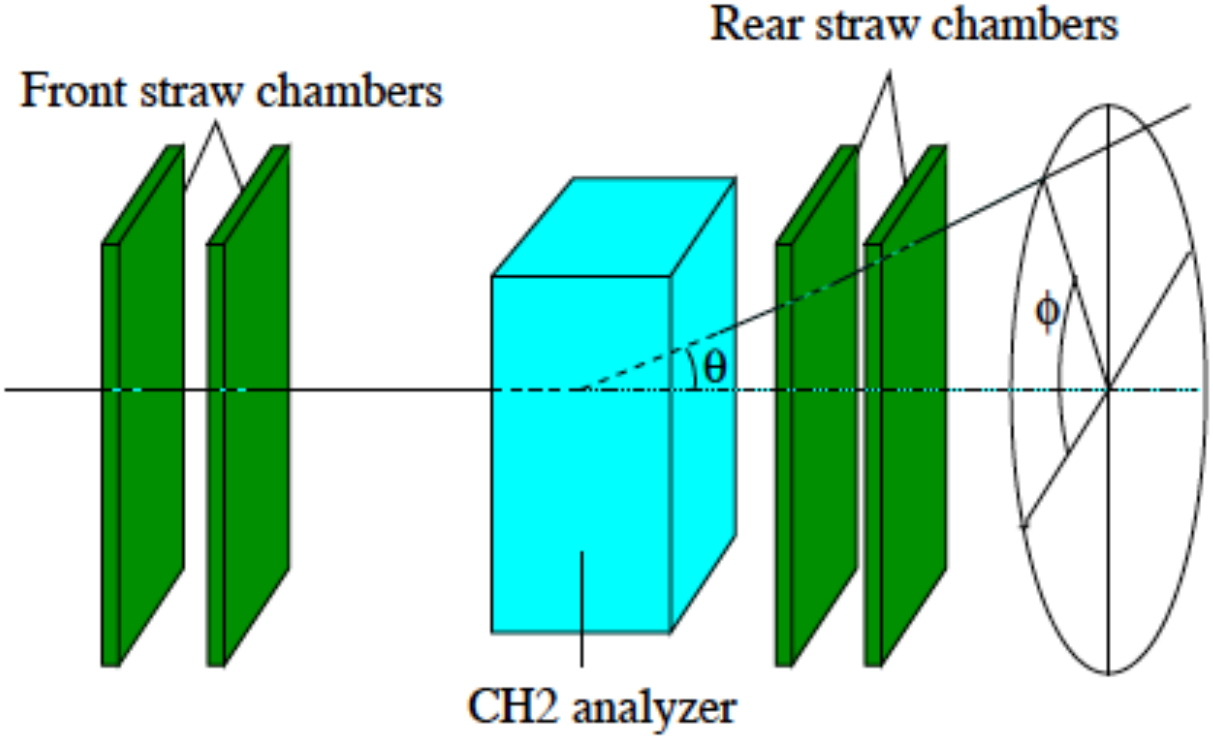


FIG. 1. (color online) Layout of the Focal Plane Polarimeter.

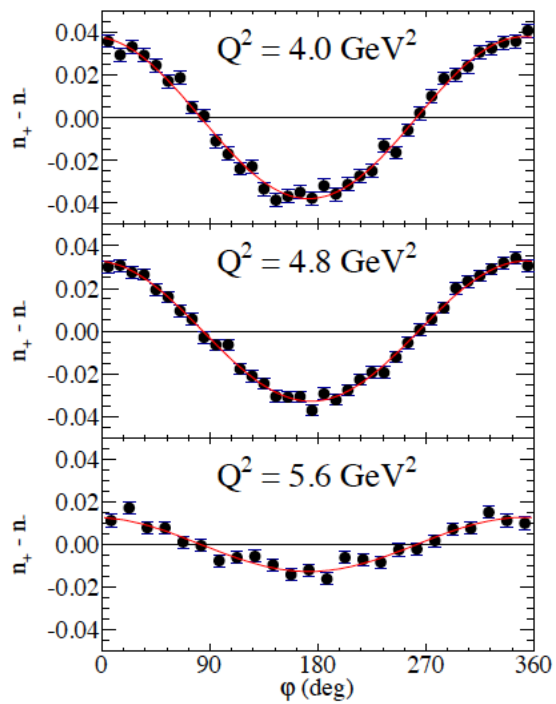
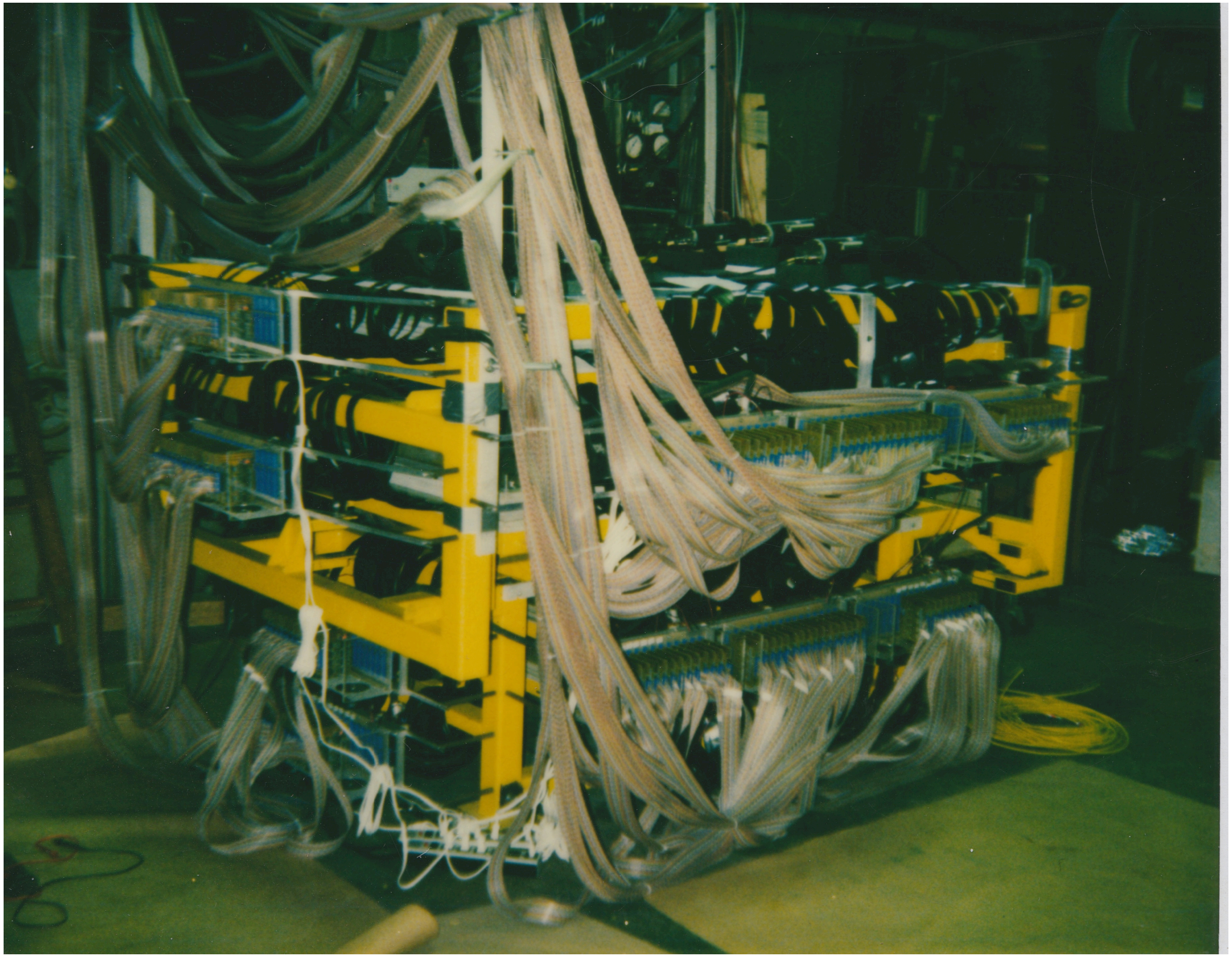


FIG. 6. (color online) Focal-plane helicity-difference asymmetry $n_+ - n_- \equiv (N_{bins}/2)\left[N^+(\varphi)/N_0^+ - N^-(\varphi)/N_0^-\right]$, where N_{bins} is the number of φ bins and $N^{\pm}(\varphi)$, $N_0^{\pm}$ are defined as in equation (4), for the three highest Q^2 points from GEp-II. Curves are fits to the data. See text for details.

Bates FPP in building 20



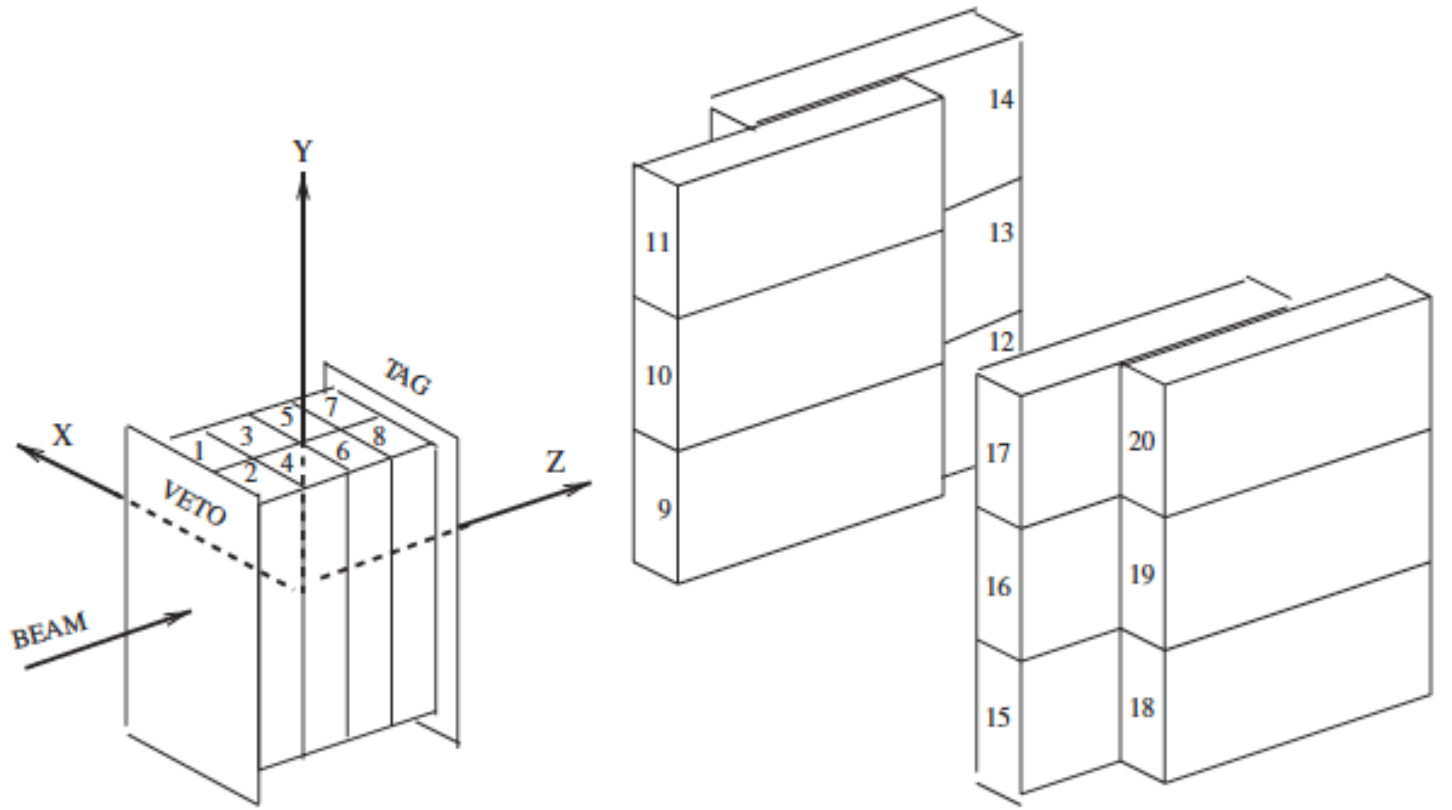


Fig. 1. Layout of the neutron polarimeter.

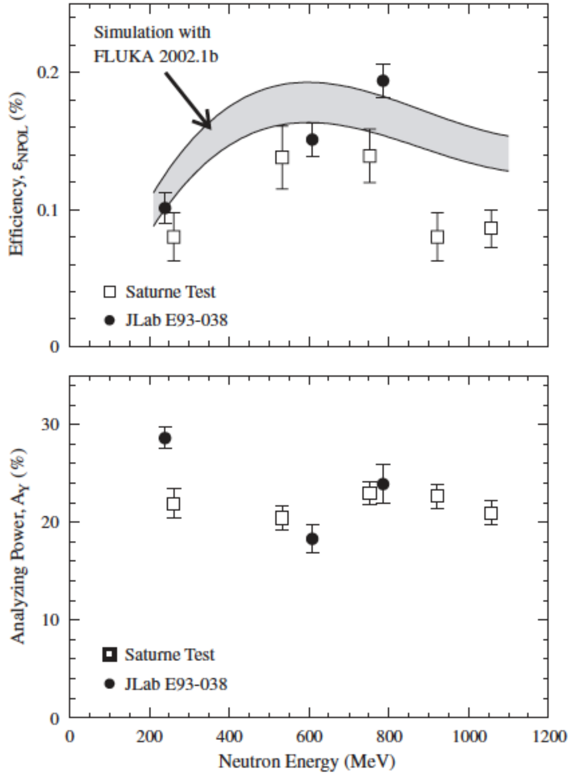


Fig. 8. Comparison of the prototype polarimeter parameters (viz., neutron polarimeter efficiency and analyzing power) measured at the Saturne National Laboratory (open boxes) with the results from E93-038 (closed circles). The gray band in the top panel shows the uncertainty in the polarimeter efficiency simulated with the FLUKA 2002.1b code. The results correspond to a velocity-ratio selection criterion $R_V > 0.95$.

$G_E^n(Q^2)$ now determined with precision comparable to $G_E^p(Q^2)$

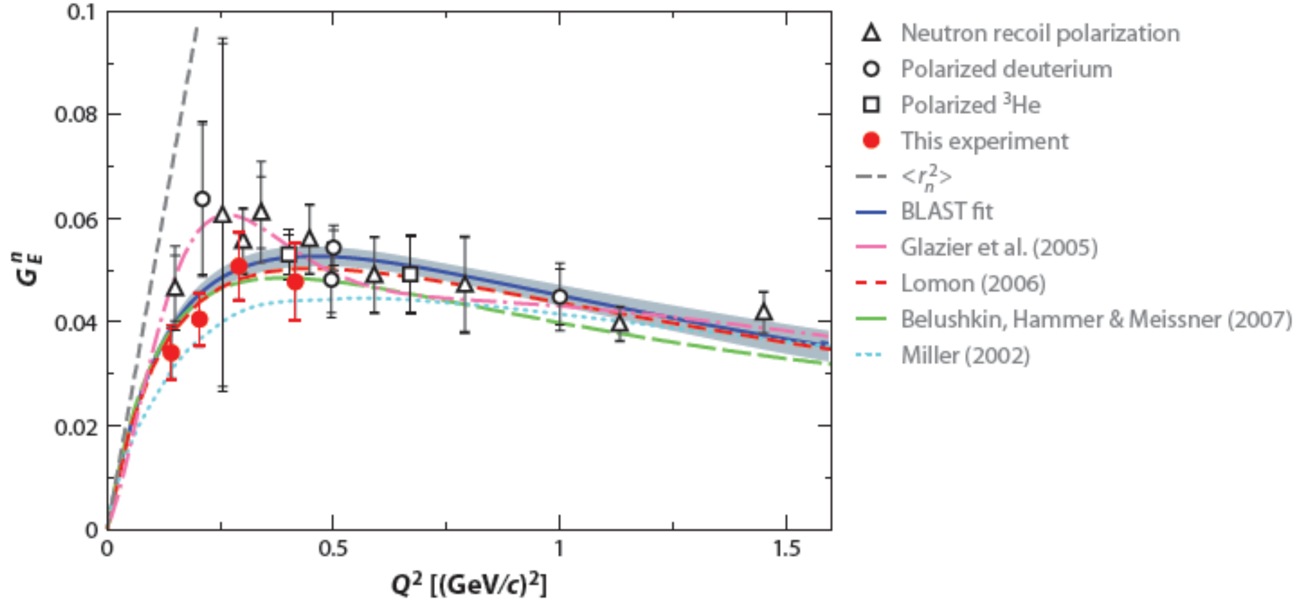
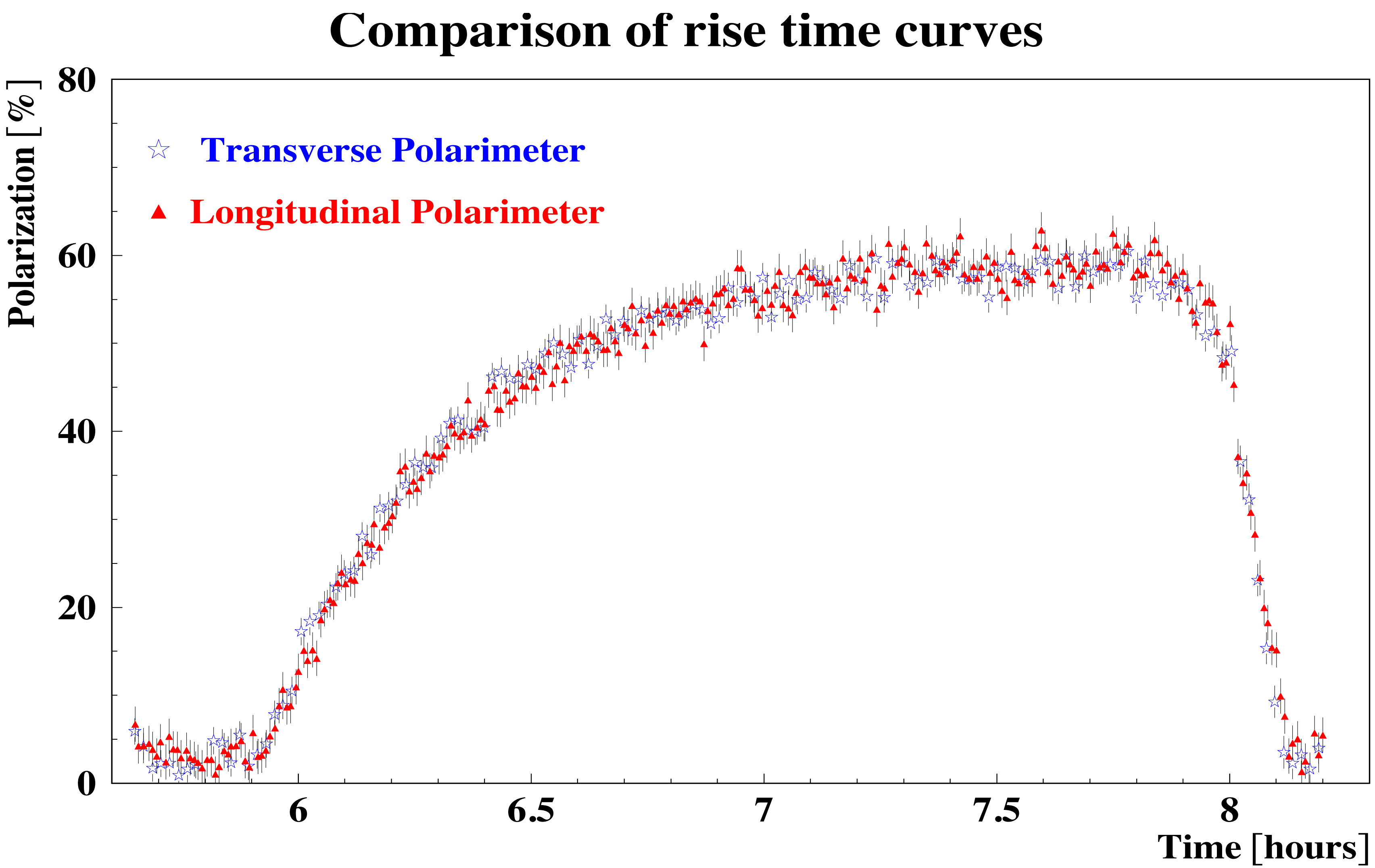


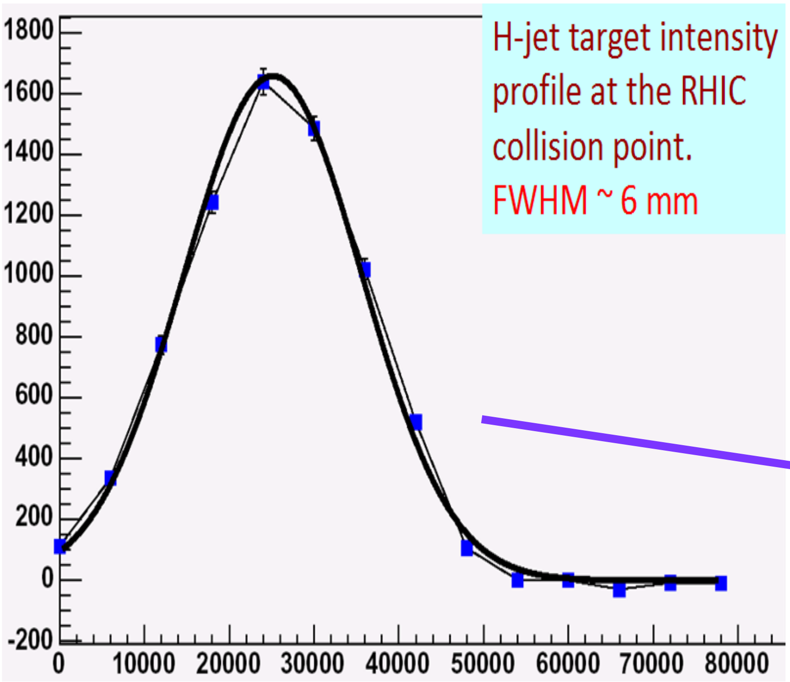
Figure 7

World data on G_E^n from double polarization experiments. The parameterization (*dashed-dotted magenta line*) (72) is based on the form introduced in Reference 27, with the ansatz of an additional bump structure around 0.2–0.4 (GeV/c)^2. Recent results based on vector meson dominance are indicated by the red dashed line (84, 107), and results based on dispersion relations are indicated by the green dashed line (108). The prediction of a light-front cloudy bag model with relativistic constituent quarks is indicated by the dotted cyan line (28). The BLAST fit is indicated by the blue line.

e+/e- polarization in HERA

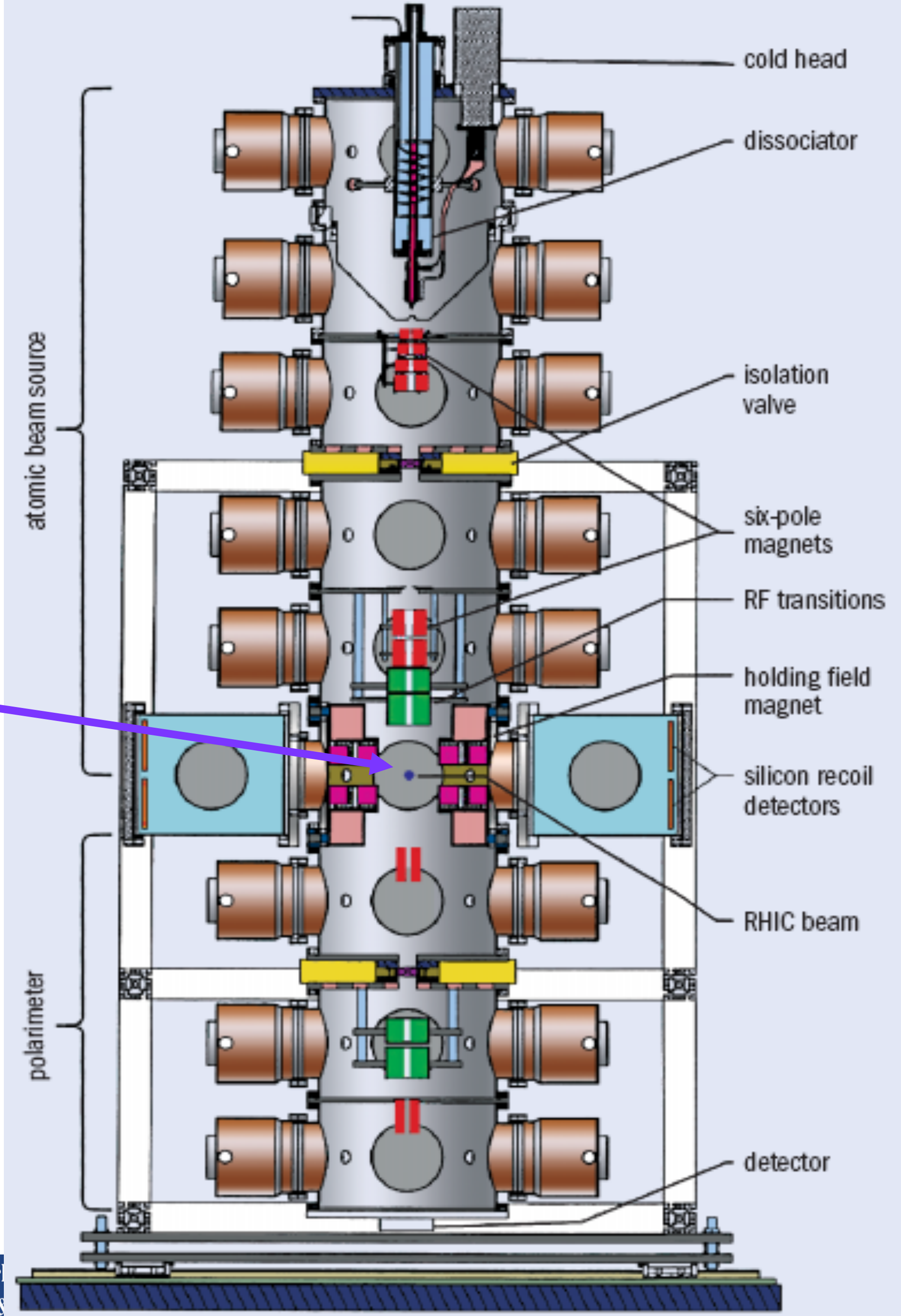


H -jet polarimeter

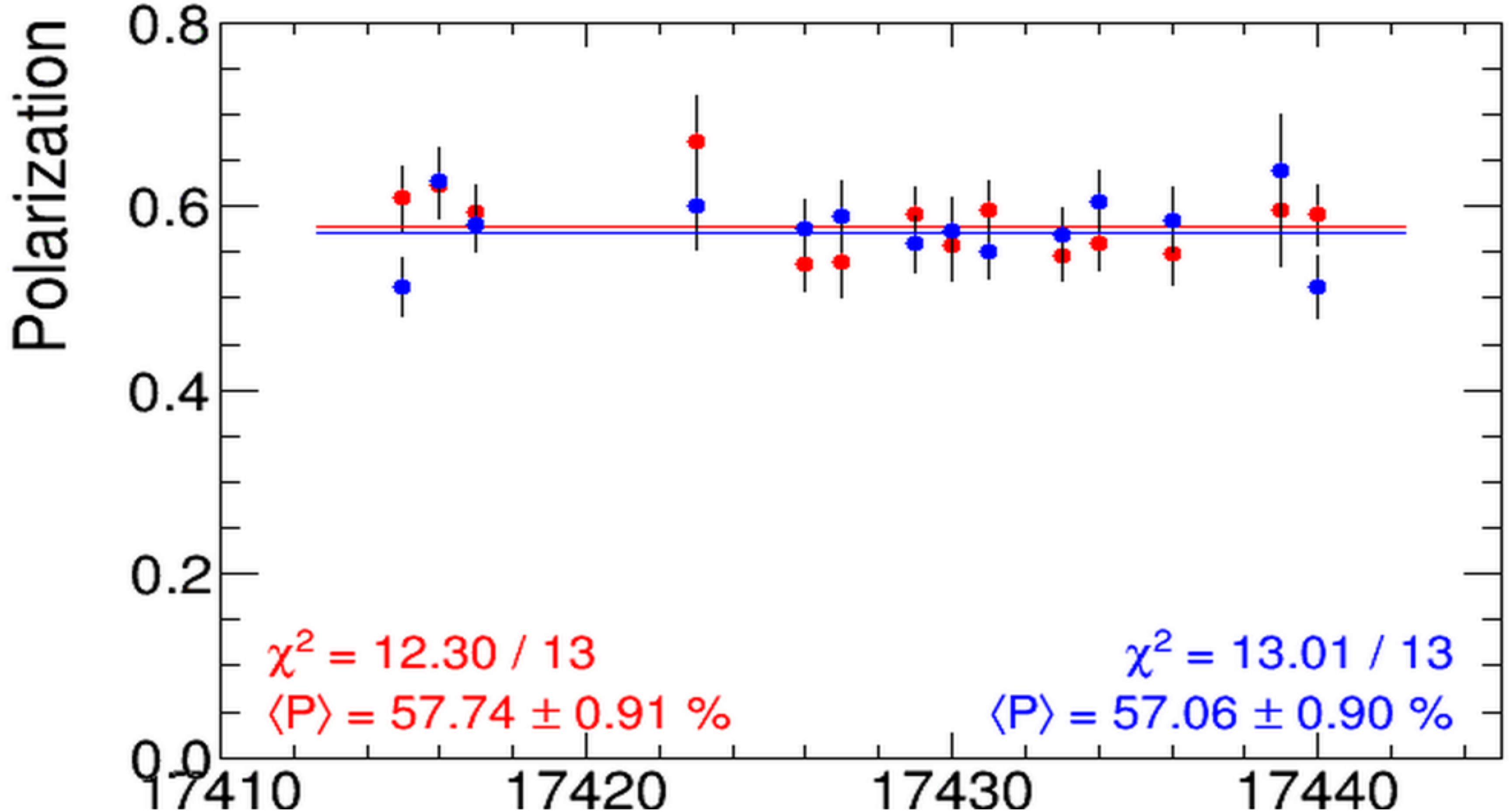


Record $12.6 \cdot 10^{16}$ atoms/s Atomic Beam intensity.

H-jet thickness at the collision point-$1.2 \cdot 10^{12}$ atoms /cm^2



Polarization measurements at 255 GeV in H-jet polarimeter, Run-2013, April-25-30



Summary

- The history of spin physics is a major aspect of the history of modern physics
- Here, I have offered a personal perspective on the major conceptual milestones, the principal technical developments, and some of the scientific results
- This ≈90 year long sojourn has yielded some of the most precise tools we have to understand and manipulate the structure of matter.
- Current activities and plans promise a bright future for the further development of physics using spin.