SPIN

NEUTRON INTERFEROMETRY

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(retired)

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& Curators' Professor Emeritus
The University of Missouri, Columbia, MO

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2 LECTURES on 4 EXPERIMENTS

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1. Observation of Gravitationally-Induced Quantum Interference
The COW and Subsequent Experiments

2. Observation of the Effect of the Earth's Rotation on the Quantum Mechanical Phase of the Neutron
The Sagnac Effect

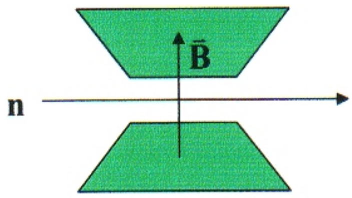
✓ ***3. First Observation of the Scalar Aharonov-Bohm Effect***
Neutrons come to the rescue again!

✓ ***4. First Observation of the Topological Aharonov-Casher Effect***
Do neutrons see Electric Charge?

Fundamental Neutron Physics Workshop
Institute for Nuclear Theory
The University of Washington, Seattle, WA

May 3,4, 2007

Spinor Symmetry



$$\psi^{II} \rightarrow \psi^{I} e^{-iHt/\hbar} = \psi^{I} e^{-i\vec{\mu}\vec{B}t/\hbar} = \psi^{I} e^{-i\mu\vec{\sigma}\vec{B}t/\hbar} = \psi^{I} e^{-i\vec{\sigma}\vec{\alpha}/2}$$

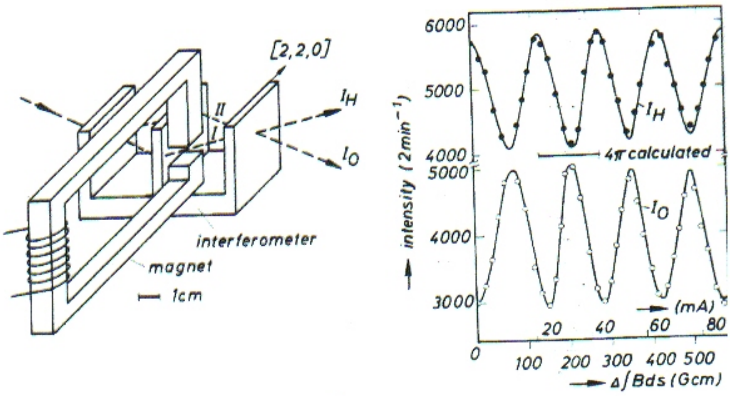
$$|\alpha| = \frac{2\mu Bt}{\hbar} = gBt \cong \frac{2\mu B\ell}{\hbar\ v}$$ ... Larmorangle

$$\psi(\alpha) = \begin{pmatrix} e^{-\alpha/2} & 0 \\ 0 & e^{\alpha/2} \end{pmatrix} \begin{pmatrix} \psi^{I}_{\uparrow}(0) \\ \psi^{I}_{\downarrow}(0) \end{pmatrix}$$

Theory: H.J.Bernstein, Phys.Rev.Lett. 18(1967)1102,
Y.Aharonov, L.Susskind, Phys.Rev. 158(1967)1237

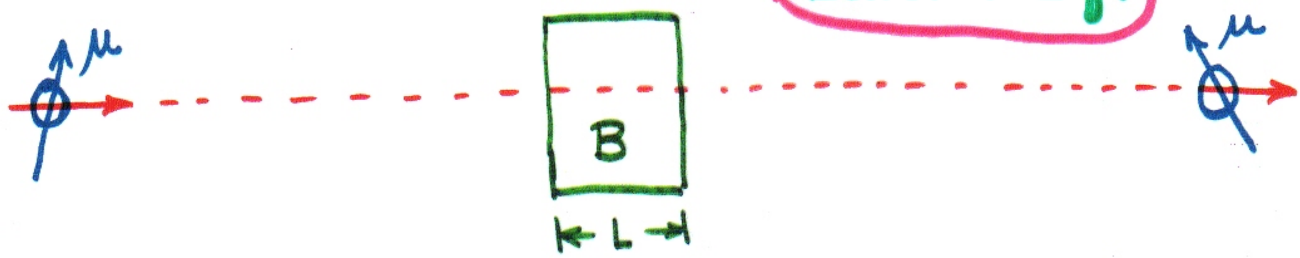
$$\psi(2\pi) = -\psi(0)$$
$$\psi(4\pi) = \psi(0)$$

$$I_0 \propto \left|\psi^{I}_{0}(0) + \psi^{I}_{0}(\alpha)\right|^2 = \frac{I_0(0)}{2}\left(1+\cos\frac{\alpha}{2}\right)$$



Experiment: H.Rauch, A.Zeilinger, G.Badurek, A.Wilfing, W.Bauspiess, U.Bonse, Phys.Lett. 54A(1975)425
S.A.Werner, R.Colella, A.W.Overhauser, C.F.Eagen, Phys.Rev.Lett. 35(1975)1053
A.G.Klein, G.I.Opat, Phys.Rev. D11(1976)523
E.Klempt, Phys.Rev. D13(1975)3125
M.E.Stoll, E.K.Wolff, M.Mehring, Phys.Rev. A17(1978)1561

$-1 = e^{i\pi}$
Euler's Eq.



For a 2π phase shift

$\lambda BL = 272$ Å · gauss · cm

For B = 165 gauss, $\mathcal{E} = \mu B = 1$ neV.

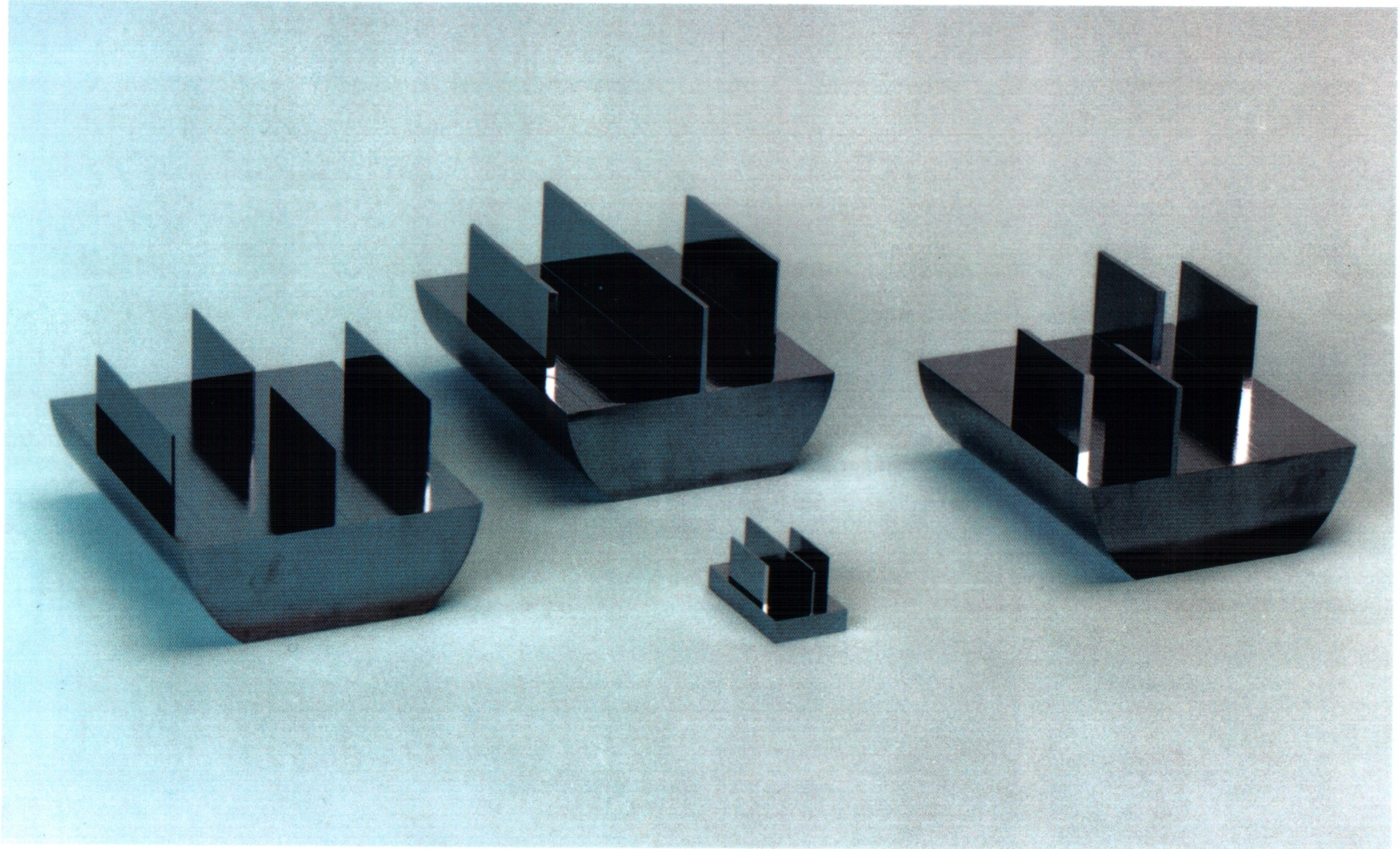
gravitational energy = mgh = 1 neV for h = 1cm

$$\mu B = mgh$$

for $h = 1$ cm
$mgh = 1$ neV

for $B = 165$ gauss
$\mu B = 1$ neV

Sam Werner



SCALAR AB EFFECT

with Longitudinally Polarized Neutrons

W.-T. Lee, O. Motrunich, B.E. Allman & S.A. Werner

Phys. Rev. Lett. 80, 3165 (1998).

B.E. Allman, W.-T. Lee, O. Motrunich & S.A. Werner

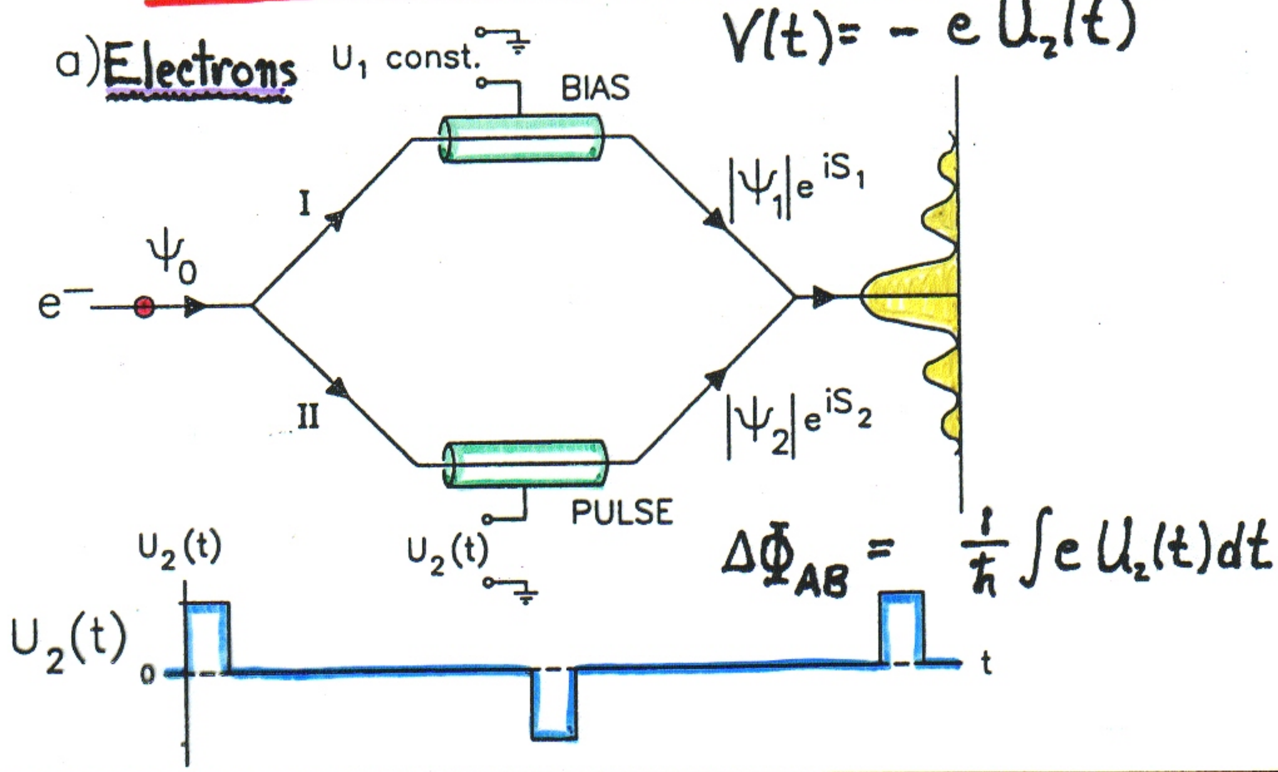
Phys. Rev. A60, 4272 (1999).

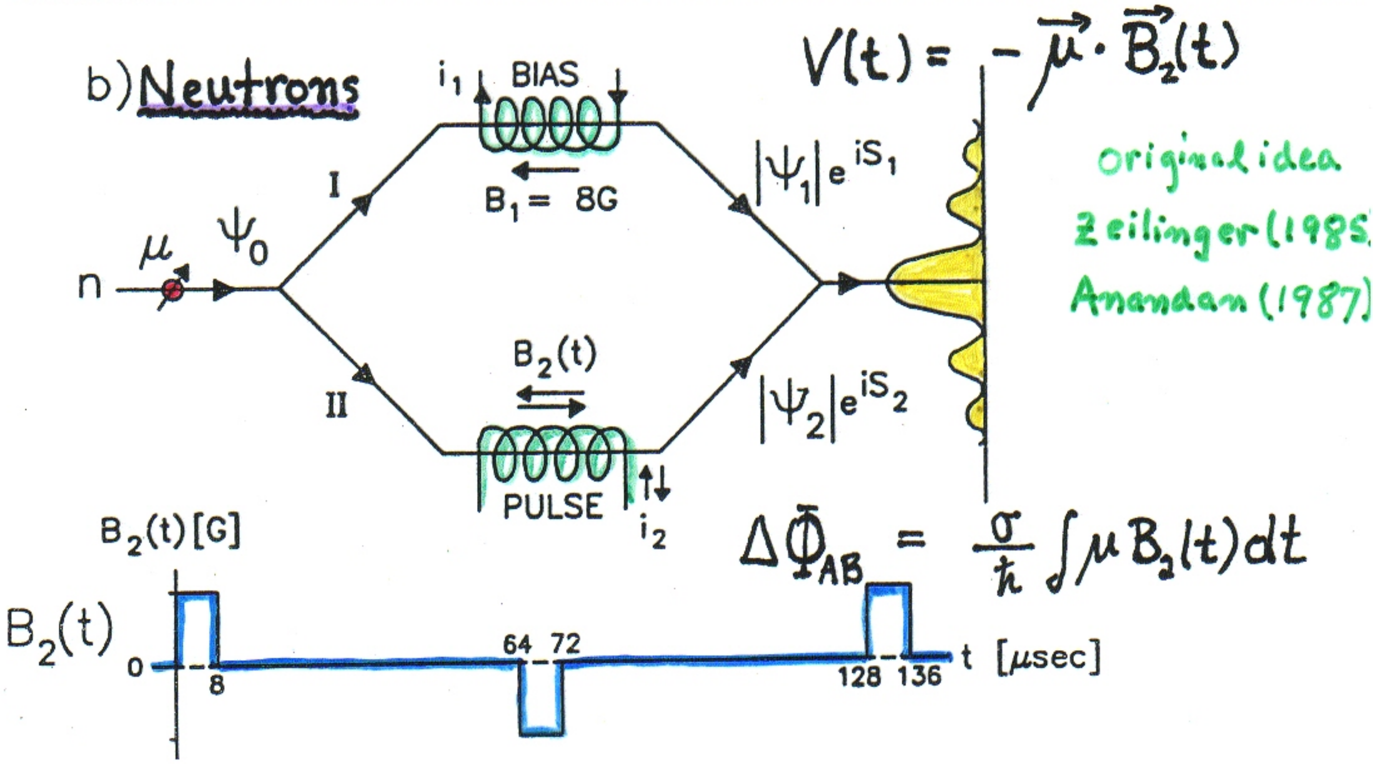
Work supported by

NSF Physics Division

SCALAR AB EFFECT

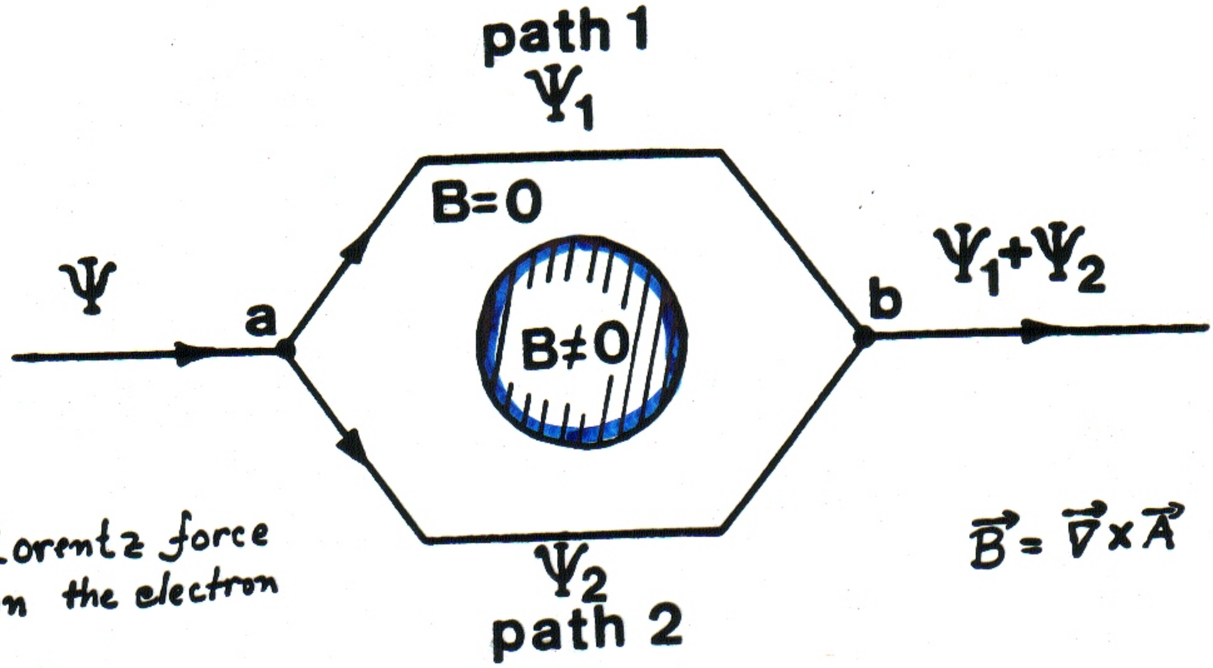
Melbourne - Missouri Collaboration





Aharonov-Bohm Effect

Electrons: Phys. Rev. 115, 485 (1959)



No Lorentz force on the electron

$\vec{B} = \vec{\nabla} \times \vec{A}$

Hamiltonian: $\mathcal{H} = \dfrac{(\vec{p} - \frac{e}{c}\vec{A})^2}{2m}$.

Canonical Momentum: $\vec{p} = m\vec{v} + \frac{e}{c}\vec{A} \Rightarrow -i\hbar\vec{\nabla}$

Phase difference $= \Delta\beta = \frac{1}{\hbar}\oint \vec{p}\cdot d\vec{r}$

$$\boxed{\Delta\beta = \frac{e}{\hbar c}\,\Phi}$$ "A-B effect"

Φ = magnetic flux.

Recent experiment: Tonomura, et al., Phys. Rev. Lett. 56, 792 (1986).

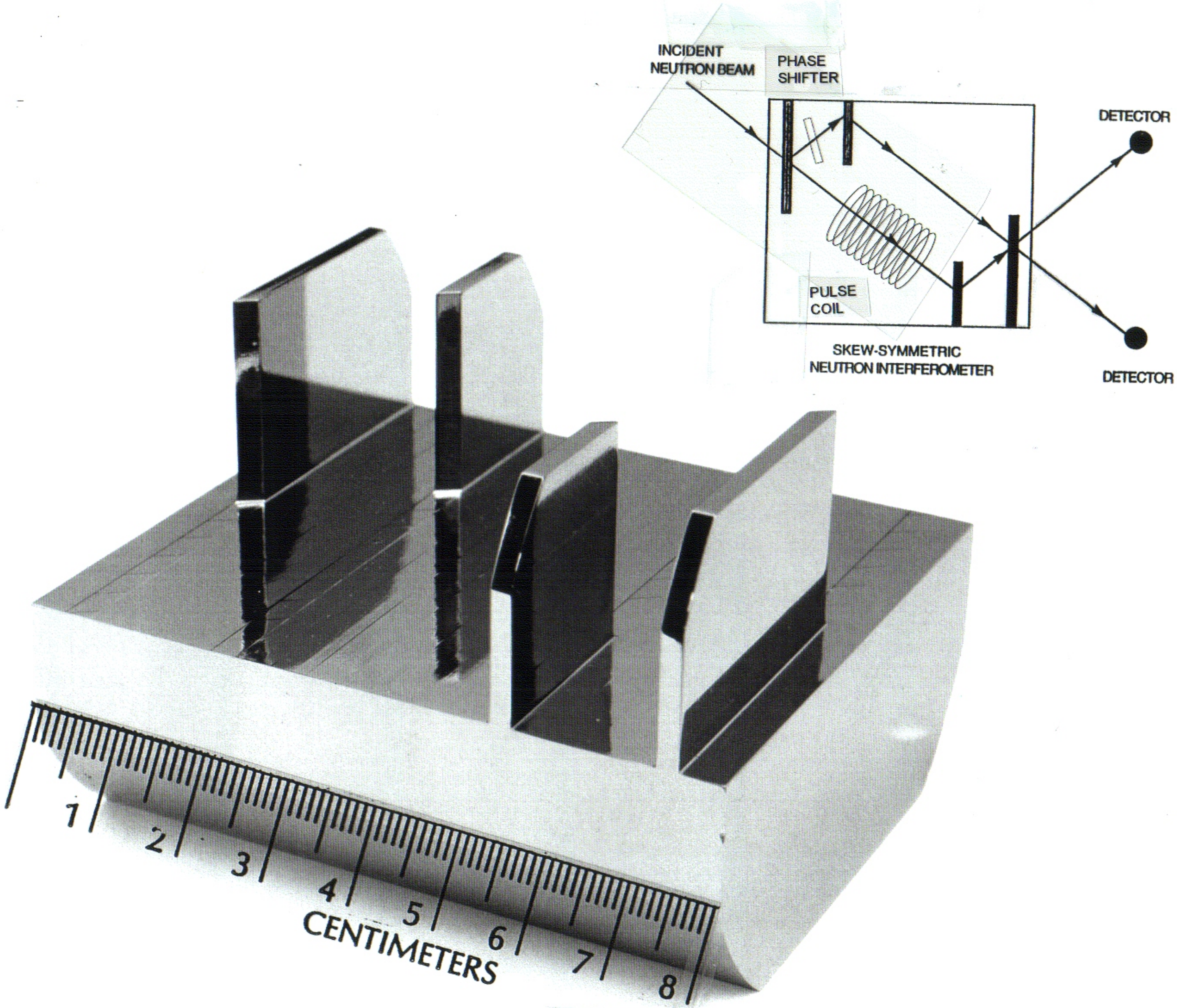
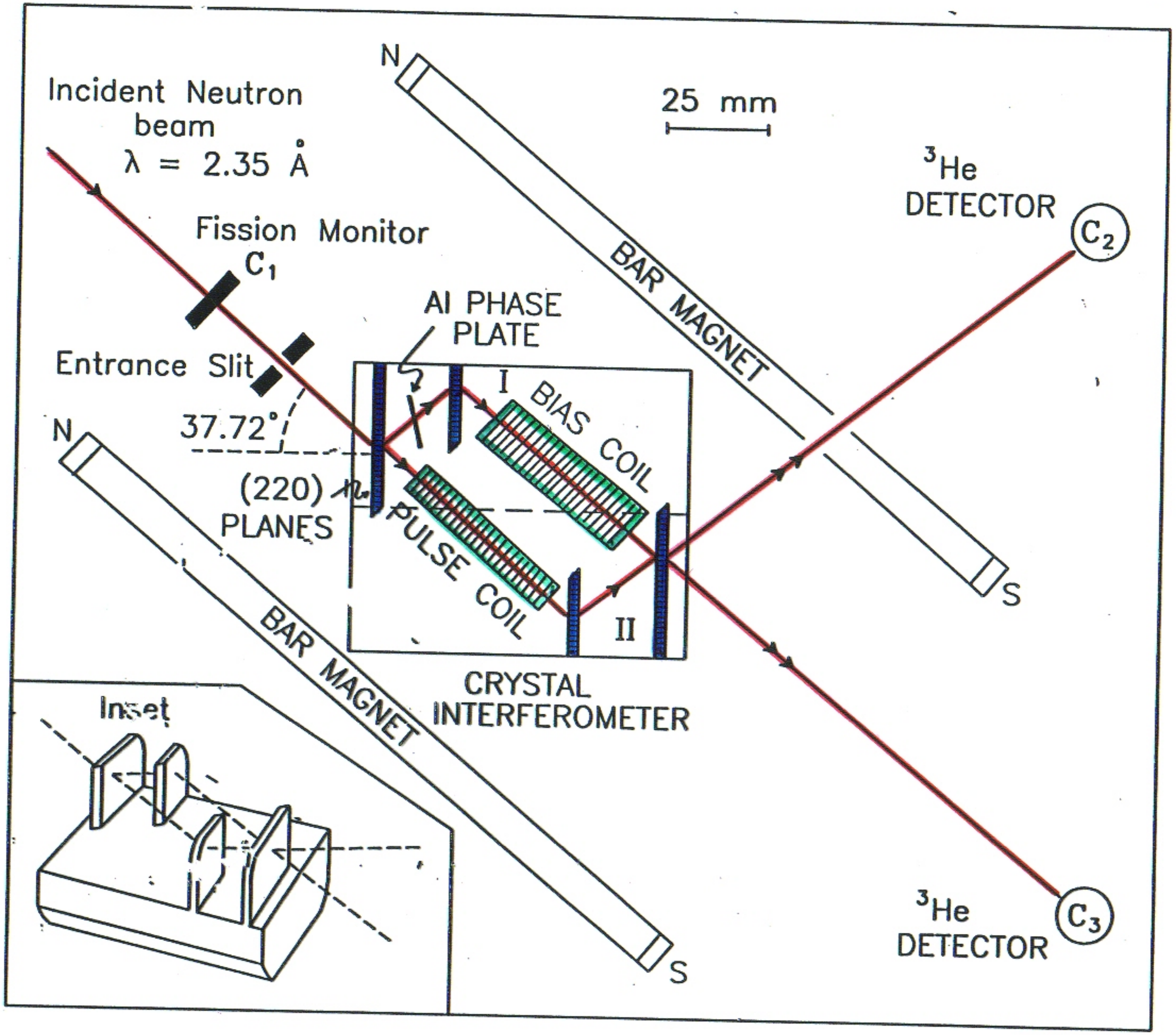
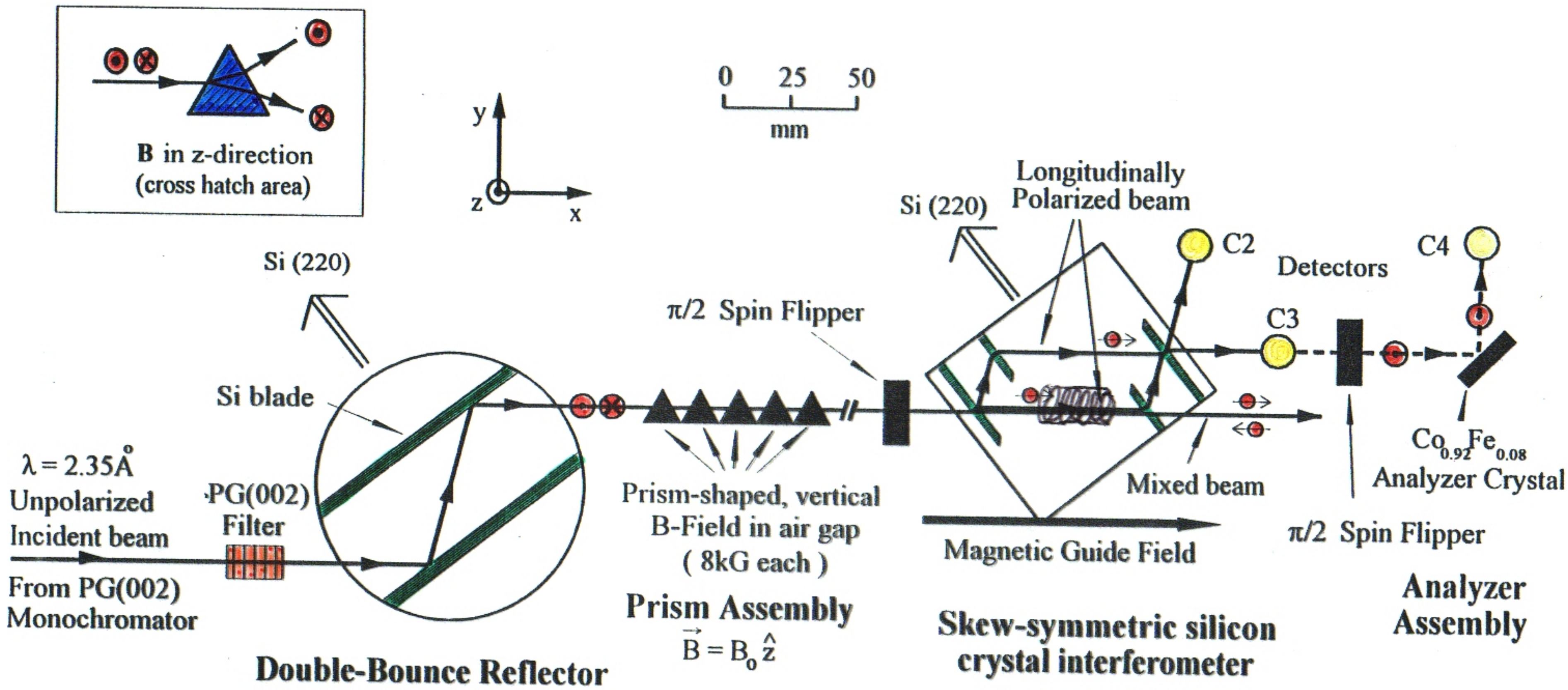

INCIDENT NEUTRON BEAM
PHASE SHIFTER
DETECTOR
PULSE COIL
SKEW-SYMMETRIC NEUTRON INTERFEROMETER
DETECTOR
1
2
3
4
5
6
7
8
CENTIMETERS

Fig. 2

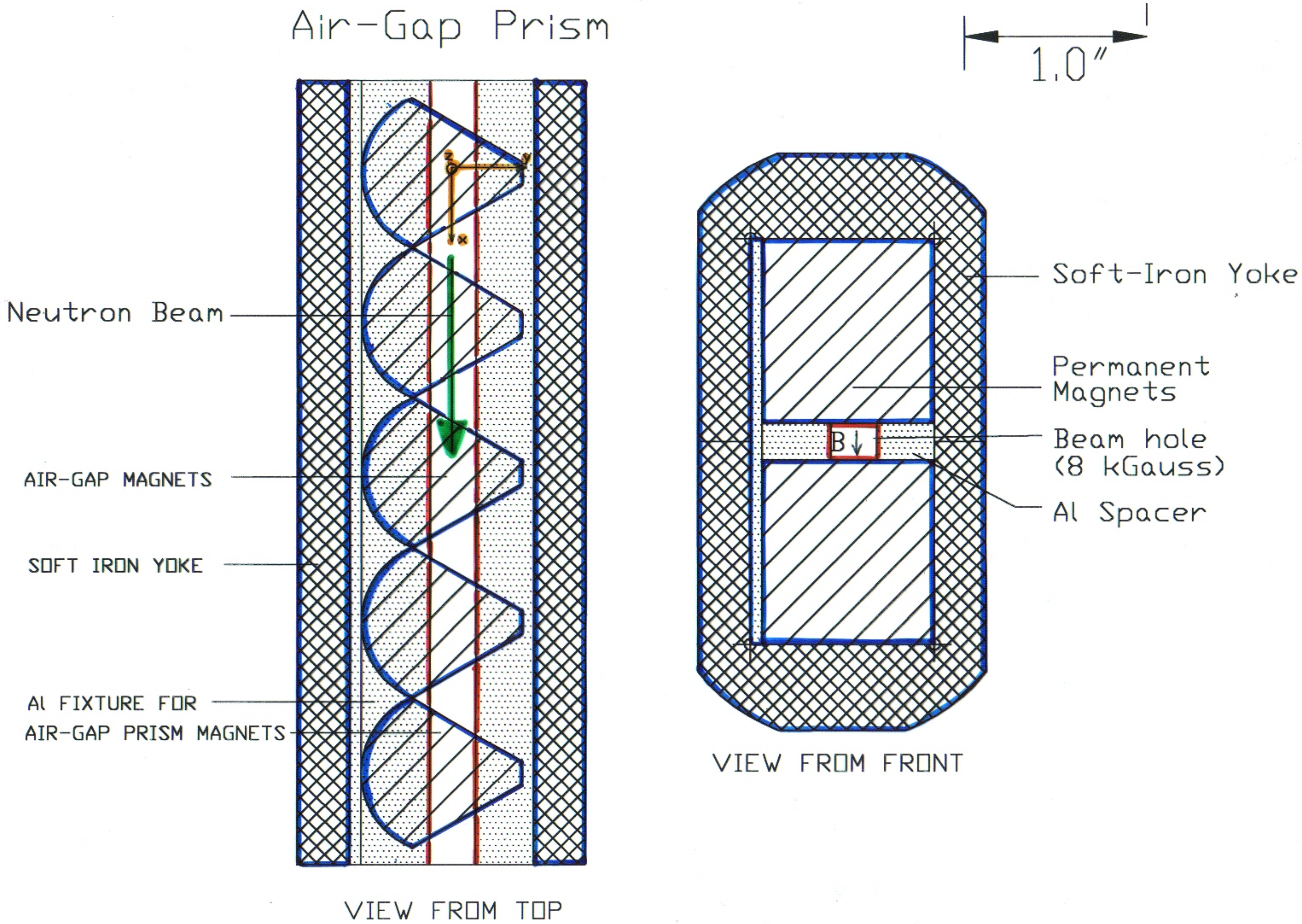


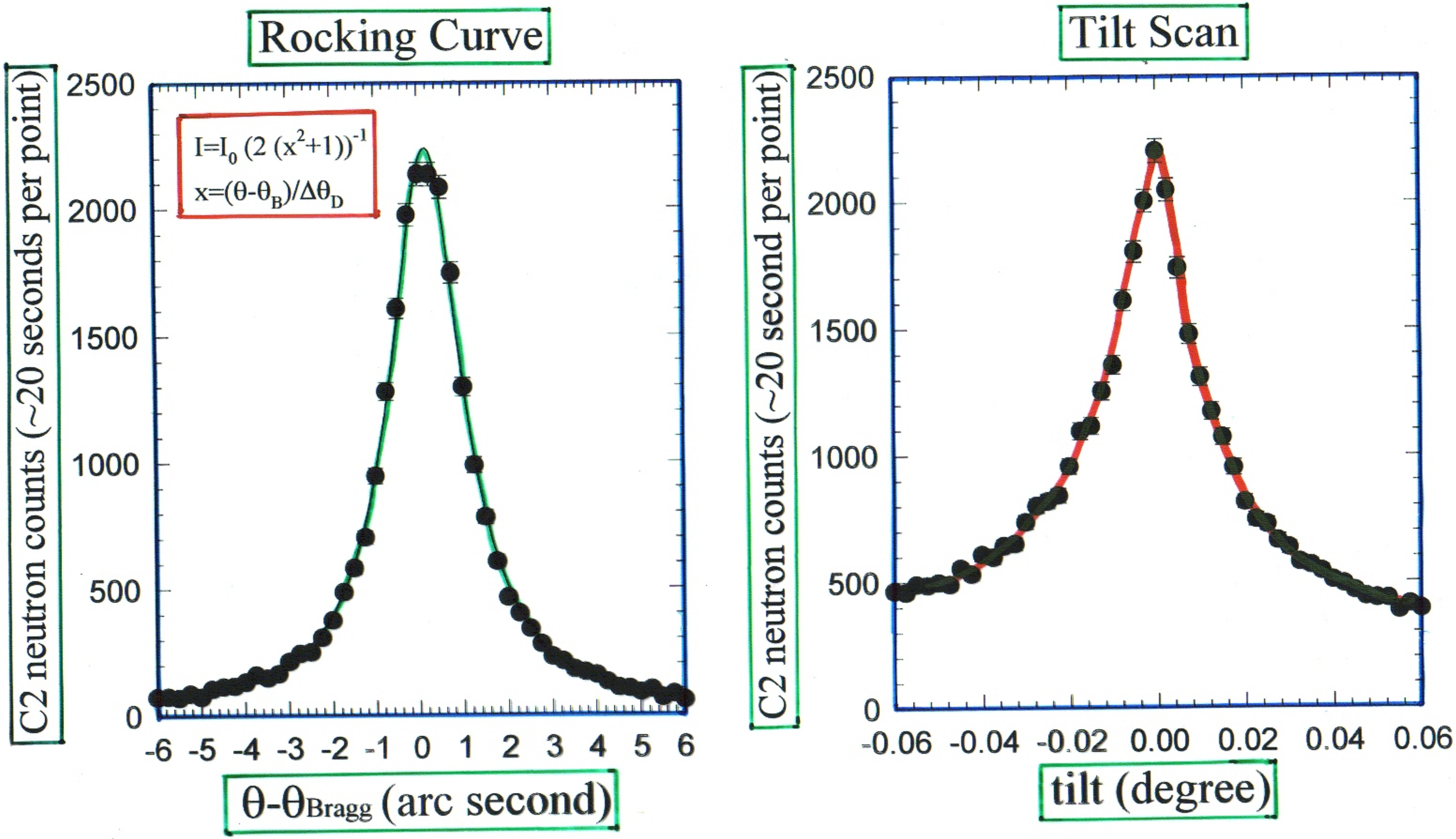
Incident Neutron beam
λ = 2.35 Å
Fission Monitor
C_1
Entrance Slit
37.72°
(220) PLANES
AI PHASE PLATE
I
BIAS COIL
PULSE COIL
II
CRYSTAL INTERFEROMETER
N
BAR MAGNET
S
N
BAR MAGNET
S
25 mm
^{3}He DETECTOR
C_2
^{3}He DETECTOR
C_3
Inset



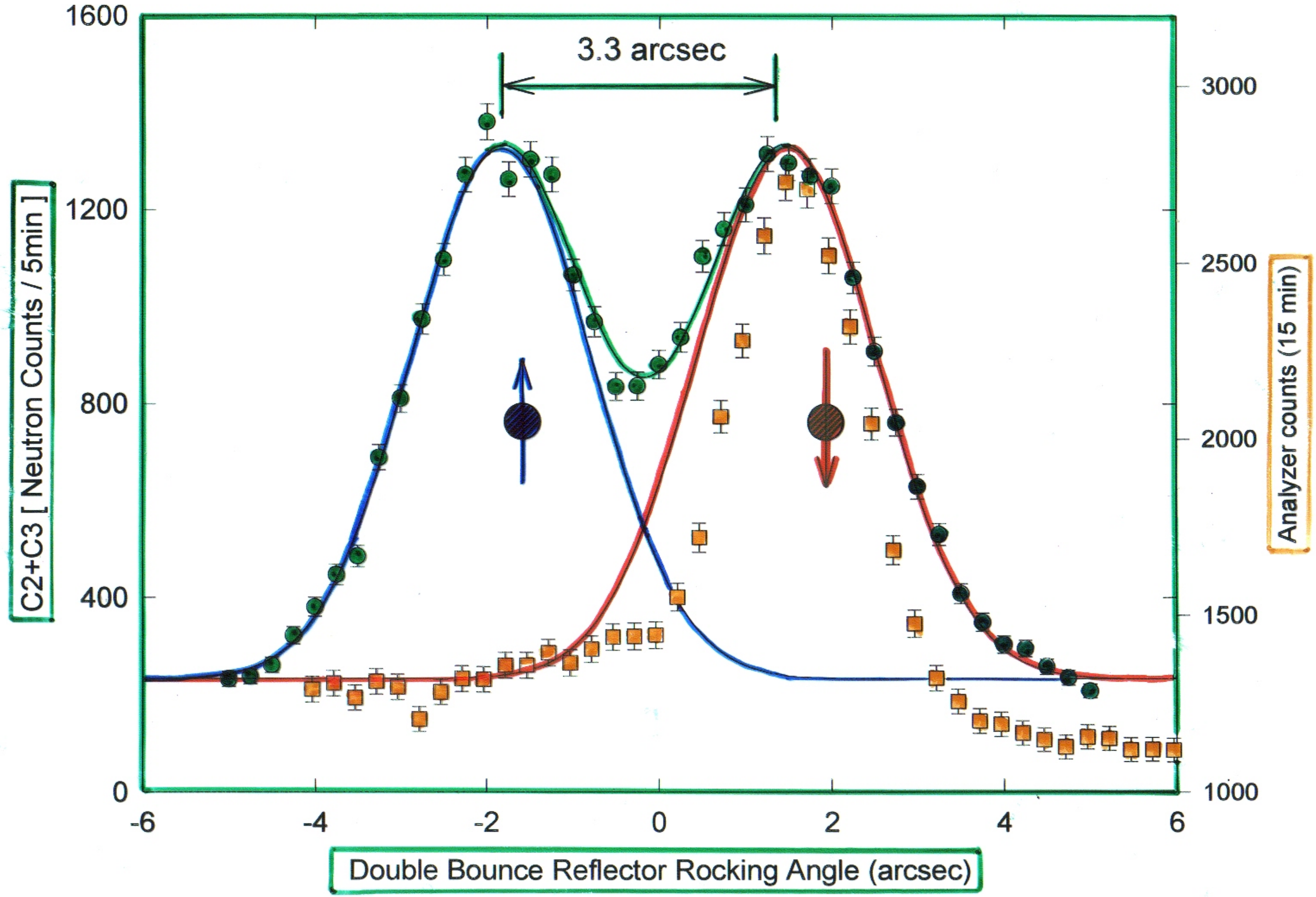
B in z-direction
(cross hatch area)
y
z
x
0 25 50
mm
Si (220)
Longitudinally
Polarized beam
C2
Detectors
C4
Si (220)
π/2 Spin Flipper
C3
Si blade
λ = 2.35Å
Unpolarized
Incident beam
PG(002)
Filter
Prism-shaped, vertical
B-Field in air gap
(8kG each)
Mixed beam
Co0.92Fe0.08
Analyzer Crystal
Magnetic Guide Field
π/2 Spin Flipper
From PG(002)
Monochromator
Prism Assembly
B = B0 ẑ
Skew-symmetric silicon
crystal interferometer
Analyzer
Assembly
Double-Bounce Reflector

Air-Gap Prism



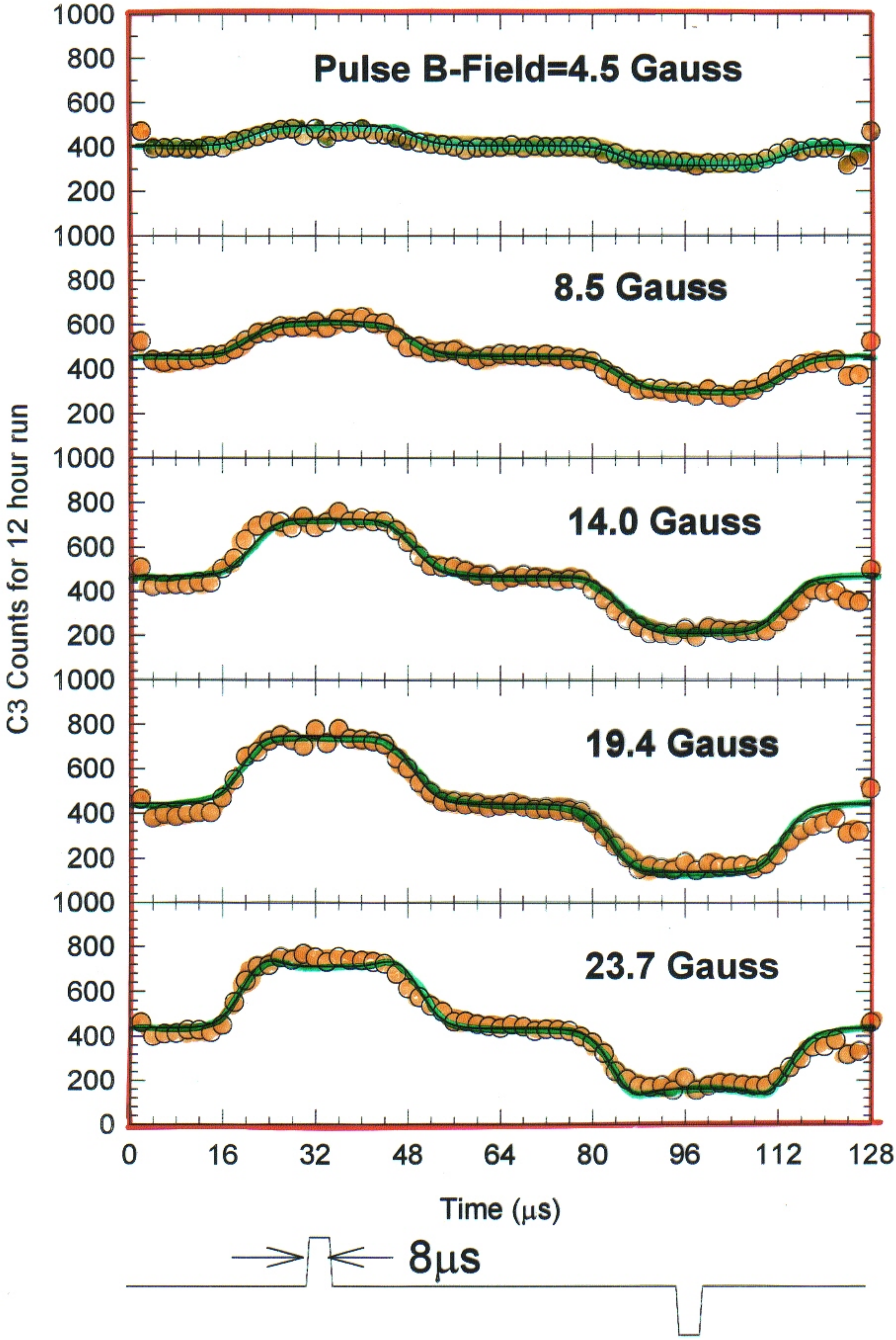


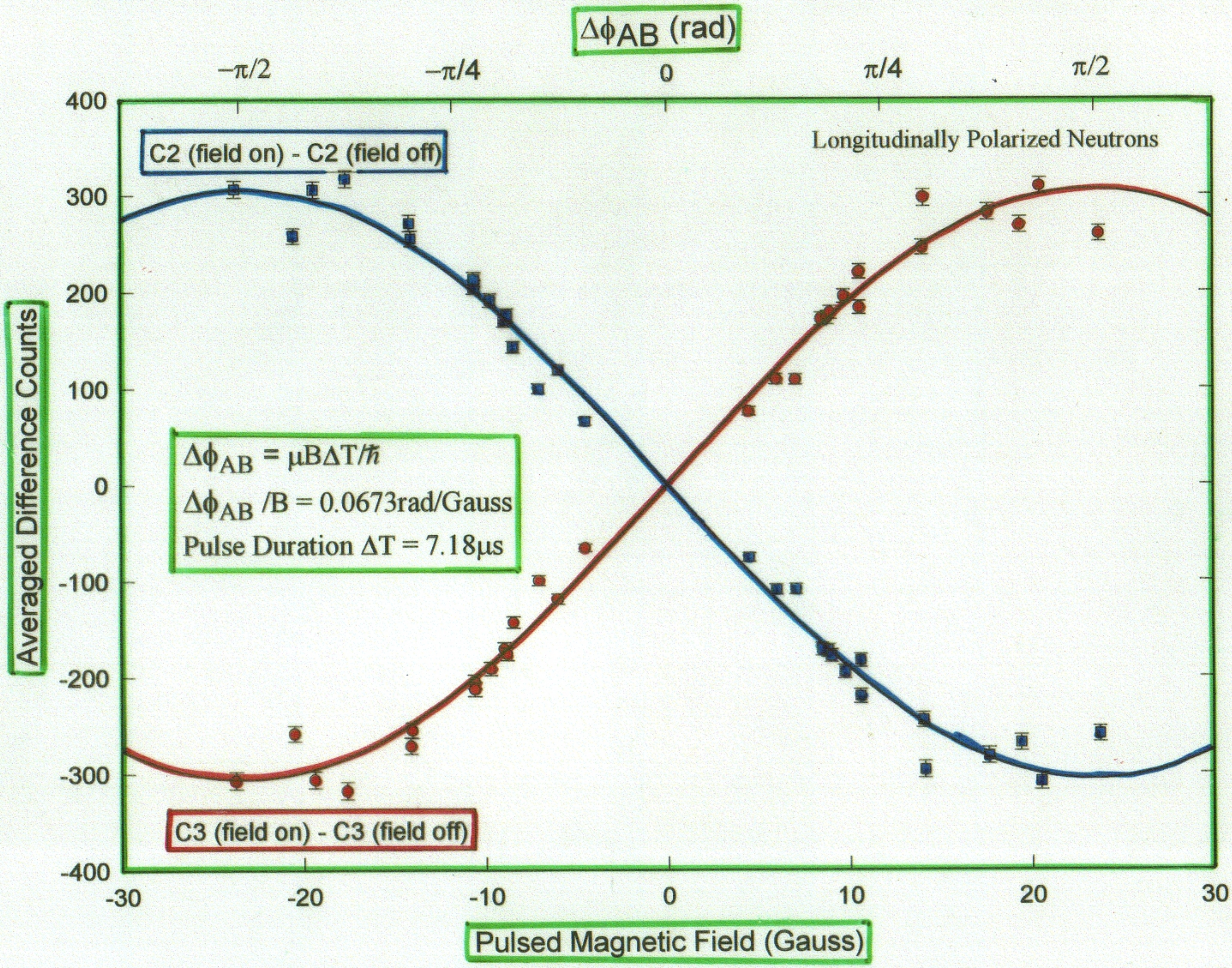
Rocking Curve
C2 neutron counts (~20 seconds per point)
2500
2000
1500
1000
500
0
I=I0 (2 (x2+1))-1
x=(θ-θB)/ΔθD
-6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6
θ-θBragg (arc second)
Tilt Scan
C2 neutron counts (~20 second per point)
2500
2000
1500
1000
500
0
-0.06 -0.04 -0.02 0.00 0.02 0.04 0.06
tilt (degree)



3.3 arcsec
C2+C3 [Neutron Counts / 5min]
Analyzer counts (15 min)
Double Bounce Reflector Rocking Angle (arcsec)
1600
1200
800
400
0
3000
2500
2000
1500
1000
-6
-4
-2
0
2
4
6

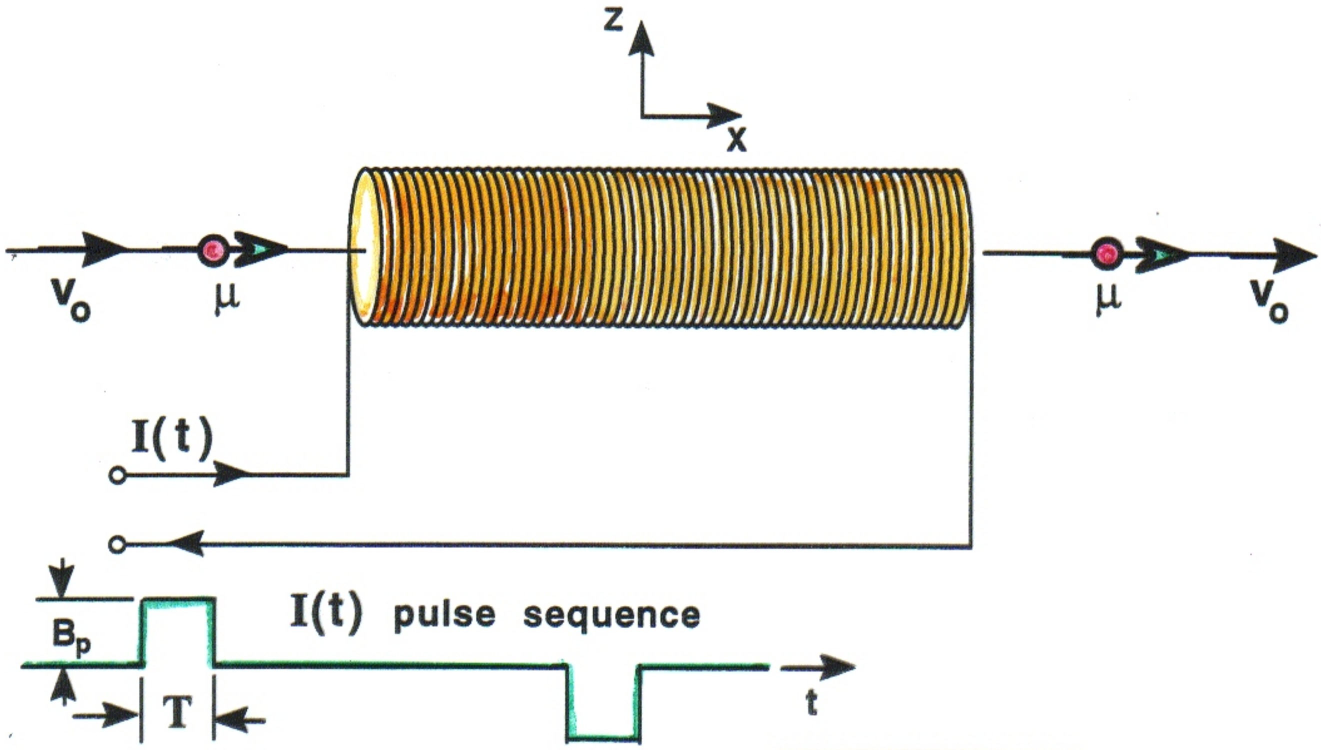
Time of Flight Data





Allman, Cimmino, Klein, Opat, Kaiser, Werner, Phys. Rev. Lett. ***68*** *(1992).*
Lee, Motrunich, Allman, Werner, Phys. Rev. Lev. ***80*** *(1998).*

SCALAR AB EFFECT WITH LONGITUDINALLY POLARIZED NEUTRONS



SCALAR POTENTIAL $V = -\mu B_p$

$E_o = 14.7$ meV, $\lambda = 2.35$ Å
$v_o = 1.68$ mm/μs
$\mu = 6.03$ peV/gauss
$T = 8$ μs

Neutrons which are inside the solenoid when the pulse is on and leave after it is turned off experience no force and no torque. That is,

$$F = \nabla(\mu \cdot B) = 0$$

$$\tau = \mu \times B = 0$$

Thus, for these neutrons, their velocity and polarization are not affected by the pulsed magnetic field. However, there is a change of phase

$$\Delta\Phi_{AB} = -\mu B_p T/\hbar$$

This is a strictly Quantum Mechanical effect, and can only be observed by interferometry.

Original idea for Neutron SAB experiment
A. Zeilinger (1985)
J. Anandan (1989) ...

PHYSICAL REVIEW LETTERS

VOLUME 80 13 APRIL 1998 NUMBER 15

Observation of Scalar Aharonov-Bohm Effect with Longitudinally Polarized Neutrons

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[1]*Department of Physics and Astronomy and Research Reactor Center, University of Missouri–Columbia, Columbia, Missouri 65211*
[2]*Physics Department, Princeton University, Princeton, New Jersey 08544*
[3]*School of Physics, University of Melbourne, Parkville, 3052 Australia*
(Received 7 November 1997)

We have carried out a neutron interferometry experiment using longitudinally polarized neutrons to observe the scalar Aharonov-Bohm effect. The neutrons inside the interferometer are polarized parallel to an applied pulsed magnetic field $\mathbf{B}(t)$. The pulsed B field is spatially uniform so it exerts no force on the neutrons. Its direction also precludes the presence of any classical torque to change the neutron polarization. [S0031-9007(98)05764-0]

PACS numbers: 03.65.Bz, 42.50.–p

One distinction that sets quantum mechanics apart from classical mechanics is the treatment of a potential. In classical mechanics, the presence of a potential can be inferred only from the motion of the particles under the influence of the force it generates. The motion of particles through a region of uniform potential is, therefore, no different from that in empty space. In quantum mechanics, however, particles passing through a potential, uniform or not, acquire a quantum mechanical phase shift through their interaction with the potential. For instance, the phase shift acquired by electrons passing through a region of space containing a magnetic vector potential **A** and a scalar electric potential V is given by the action integral

$$\Delta\Phi = \frac{1}{\hbar}\left[\int\left(m\mathbf{v} + \frac{e}{c}\mathbf{A}\right)\cdot d\mathbf{r} - \int eV(t)\,dt\right]. \quad (1)$$

This phase shift can be detected by interferometric techniques, as first pointed out clearly by Aharonov and Bohm (AB) [1]. The vector AB effect arises from the vector potential $\mathbf{A}(\mathbf{r})$ in the spatial part of the action integral, while the scalar AB effect comes from the potential $V(t)$ in the temporal part. However, the experimental realization of the scalar Aharonov-Bohm (SAB) effect has proven to be challenging due to the technical difficulties in electron interferometry. The forces acting on the electrons render the experiment by Mateucci and Pozzi [2] inconclusive. A SAB neutron interferometry experiment, the analog of the electron experimental idea, was first suggested by Zeilinger [3] and later by Anandan [4], and subsequently carried out by Allman *et al.* using unpolarized incident neutron [5]. In this experiment, the magnetic moments $\boldsymbol{\mu}$ of unpolarized thermal neutrons were subjected to a spatially uniform, but time-dependent magnetic induction $\mathbf{B}(t) = B(t)\hat{\mathbf{z}}$. The scalar interaction $E = -\boldsymbol{\mu}\cdot\mathbf{B}(t)$ produces a quantum mechanical phase shift that is measurable by neutron interferometry. In this experiment, a spin-independent phase shifter was used to establish separate control over the phase shifts for the spin-up and the spin-down neutron states. However, the use of unpolarized neutrons gave rise to the interpretational objection that each neutron experiences a classical torque [6], $\boldsymbol{\tau} = \boldsymbol{\mu}\times\mathbf{B}(t)$, and, therefore, the observed phase shift is not strictly SAB, but an effect also observable by classical polarimetry [7]. We have now carried out a similar SAB experiment, but using neutrons polarized along the $\mathbf{B}(t)$ field. In this arrangement, there is neither a classical torque nor (as before) a classical force exerted on the neutrons.

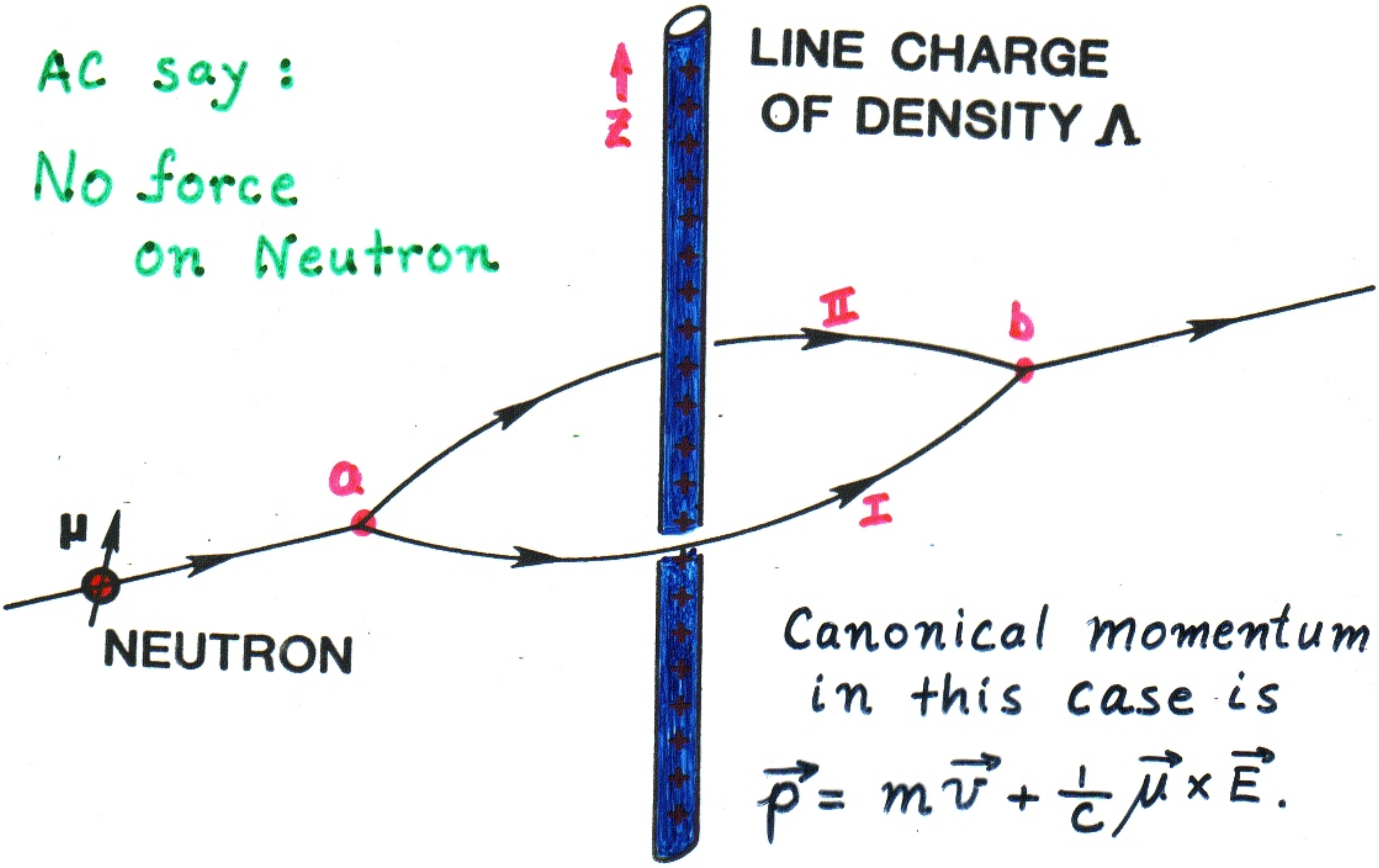
The experimental setup is shown schematically in Fig. 1. The setup consists of two main parts: the neutron polarizer and the neutron interferometer. The neutron polarizer includes a double-bounce neutron reflector made from a perfect silicon crystal and a magnetic prism assembly. The principle behind the polarizer is birefringence; i.e., the polarization dependence of the neutron

Topological Quantum Effects for Neutral Particles

Y. Aharonov[a] and A. Casher
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel
(Received 21 May 1984)

We derive the effective Lagrangian which describes the interaction between a charged particle and a magnetic moment in the nonrelativistic limit. It is shown that neutral particles with a magnetic moment will exhibit the Aharonov-Bohm effect in certain circumstances. We suggest several types of experiments.

AC say:
No force on Neutron



Canonical momentum in this case is

$$\vec{p} = m\vec{v} + \frac{1}{c}\vec{\mu}\times\vec{E}.$$

$$\Delta\phi_{AC} = \sigma\,\frac{4\pi\mu\Lambda}{\hbar c}$$

$$\sigma = \pm 1$$

Independent of the closed trajectory around the line charge.

∴ TOPOLOGICAL

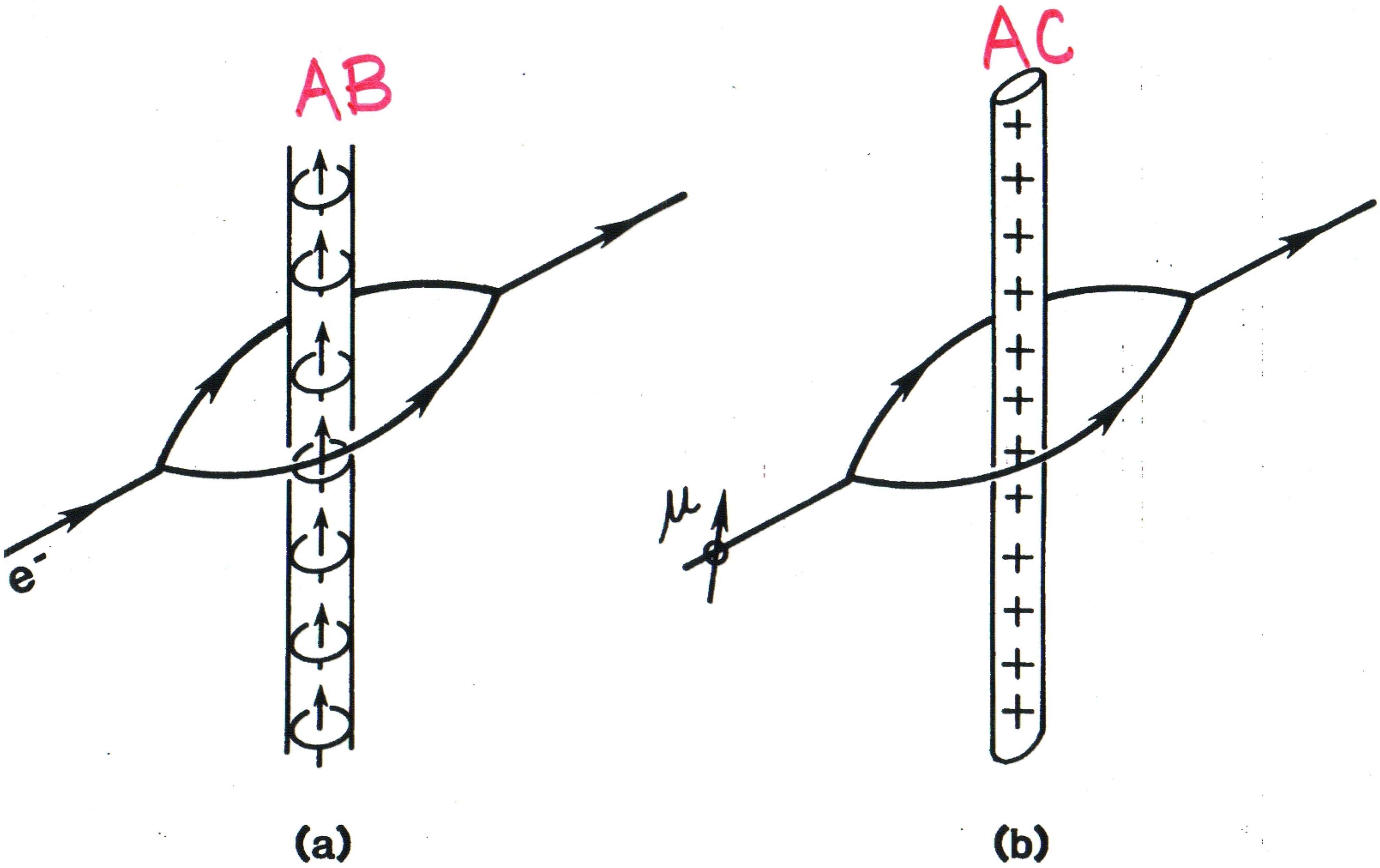
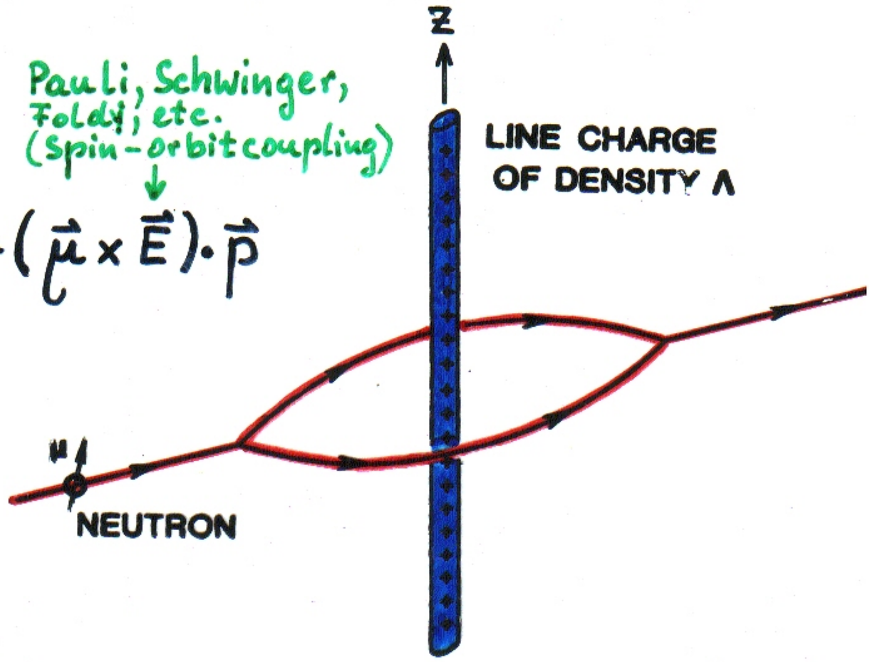


Fig. 8

Aharonov - Casher Effect



Hamiltonian:

Pauli, Schwinger, Foldy, etc. (Spin-orbit coupling)

$$\mathcal{H} = \frac{p^2}{2m} - \frac{1}{mc}(\vec{\mu} \times \vec{E}) \cdot \vec{p}$$

$$\vec{v} = \dot{\vec{r}} = \frac{\partial \mathcal{H}}{\partial \vec{p}}$$

Canonical momentum:

$$\vec{p} = m\vec{v} + \frac{1}{c}\vec{\mu} \times \vec{E}$$

Phase shift:

$$\Delta\phi_{AC} = \frac{1}{\hbar}\oint \vec{p} \cdot d\vec{s} = \frac{1}{\hbar c}\oint \vec{\mu} \times \vec{E} \cdot d\vec{s}$$

$$d\vec{s} = dr\,\hat{r} + r\,d\varphi\,\hat{\varphi} + dz\,\hat{z}$$

$$\vec{\mu} = \mu\hat{z}\sigma, \ \sigma = \pm 1, \quad \vec{E} = \frac{2\Lambda}{r}\hat{r}$$

$$\vec{\mu} \times \vec{E} = \frac{2\Lambda\mu\sigma}{r}\hat{\varphi}$$

Note: $\frac{1}{c}\vec{\mu} \times \vec{E} = \vec{p}_{dm}$ ... is a solenoidal vector field

$$\Delta\phi_{AC} = \frac{1}{\hbar c} 2\Lambda\mu\sigma \oint \frac{\hat{\varphi}}{r} \cdot d\vec{s} = \frac{1}{\hbar c} 2\Lambda\mu\sigma \int_0^{2\pi} d\varphi$$

$$\boxed{\Delta\phi_{AC} = \sigma \frac{4\pi\Lambda\mu}{\hbar c}}$$

"AC-effect"

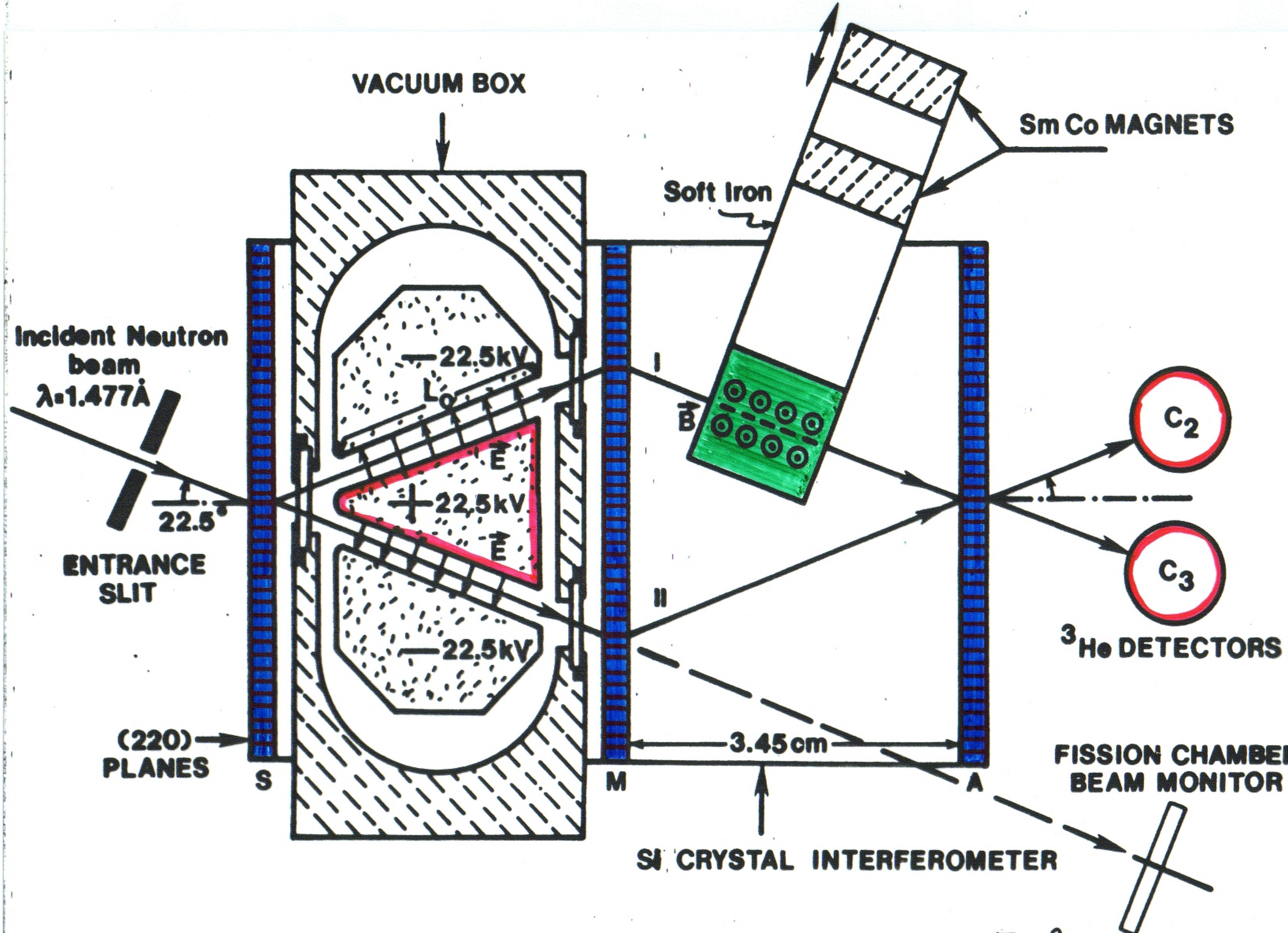

VACUUM BOX
Sm Co MAGNETS
Soft Iron
Incident Neutron
beam
λ=1.477Å
−22.5kV
L_0
I
$\vec{B}$
$\vec{E}$
+22.5kV
$\vec{E}$
22.5°
ENTRANCE
SLIT
II
−22.5kV
C_2
C_3
^{3}He DETECTORS
(220)
PLANES
S
M
3.45cm
A
FISSION CHAMBER
BEAM MONITOR
Si CRYSTAL INTERFEROMETER

Fig. 2

Predicted AC-phase shift for an electrode system with length L

$$\Delta\phi_{AC} = \sigma \frac{4\pi\mu\Lambda}{\hbar c} = \sigma \frac{2VL\mu}{\hbar c D}$$

$\sigma = \pm 1$

using Gauss' law

$$\Lambda = \frac{2EL}{4\pi} = \frac{2VL}{4\pi D}$$

For our experimental setup with $V = 45\,kV$ (= 150 statvolts), $D = 0.154\,cm$ and $L = 2.53\,cm$

$$\boxed{\Delta\phi_{AC} = 1.50\sigma \text{ millirad.}}$$

NEUTRON POLARIZATION

$$I = I(\uparrow) + I(\downarrow)$$

$$I(\uparrow) = \tfrac{1}{2} I_0 \left(1 + \cos(\alpha + \beta)\right)$$

$$I(\downarrow) = \tfrac{1}{2} I_0 \left(1 + \cos(\alpha - \beta)\right)$$

α = spin-independent phase shift (nuclear, gravit
β = spin-dependent phase shift (magnetic field)

$$\beta = \beta_E + \beta_B$$

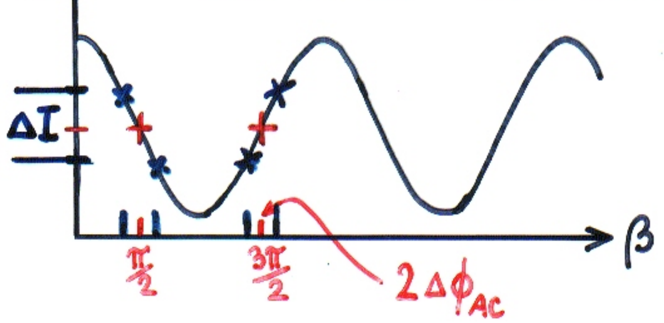
$$\beta_B = \frac{2\pi \mu B \ell \lambda m}{h^2}$$

($B\lambda\ell = 272$ G.Å.cm for 4π)

$$\beta_E = \Delta\phi_{AC} = \frac{2\mu E L}{\hbar c}$$

$$\boxed{I = I_0 (1 + \cos\alpha \cos\beta)}$$

Must set $\alpha = 0$ (mod 2π)

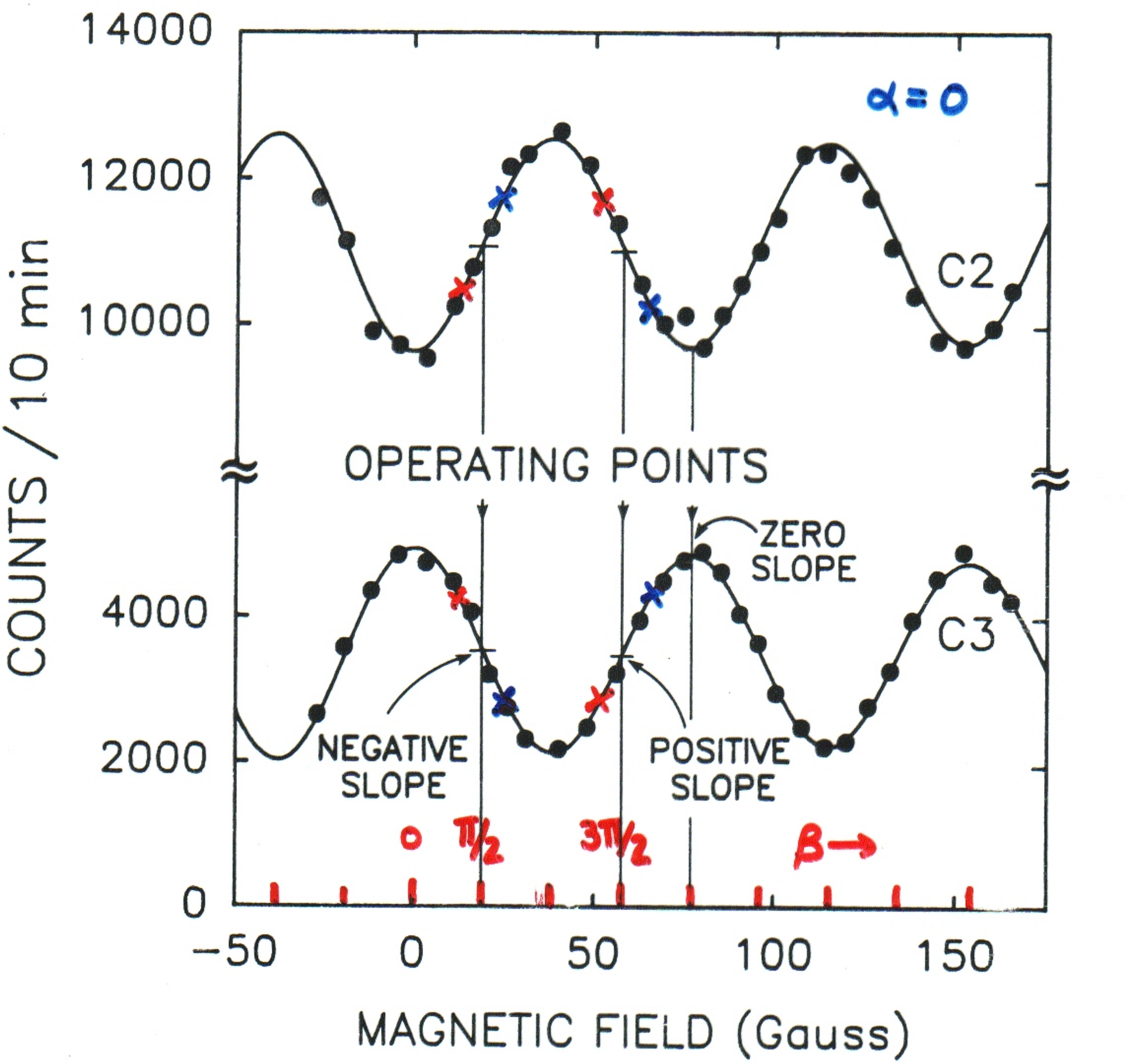


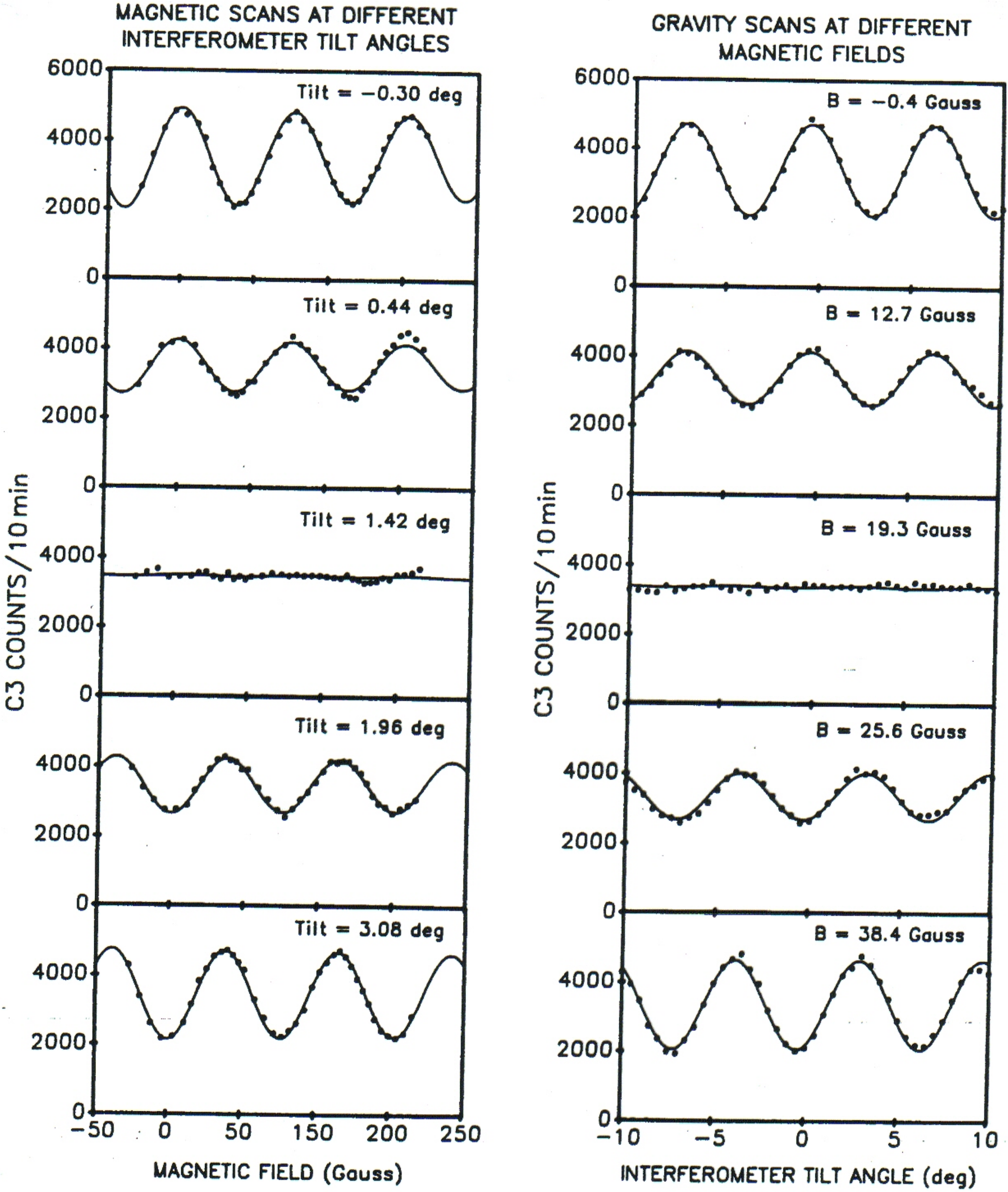
$$\boxed{\frac{\Delta I}{I} \approx \frac{1}{1000}}$$

PHASE SHIFT DUE TO SPIN PRECESSION

$$C_3 = A + B\cos\alpha \cdot \cos\beta$$

MAGNETIC SCAN AT TILT ANGLE = −0.30 deg





MAGNETIC SCANS AT DIFFERENT INTERFEROMETER TILT ANGLES
Tilt = −0.30 deg
Tilt = 0.44 deg
Tilt = 1.42 deg
Tilt = 1.96 deg
Tilt = 3.08 deg
C3 COUNTS/10 min
MAGNETIC FIELD (Gauss)
GRAVITY SCANS AT DIFFERENT MAGNETIC FIELDS
B = −0.4 Gauss
B = 12.7 Gauss
B = 19.3 Gauss
B = 25.6 Gauss
B = 38.4 Gauss
C3 COUNTS/10 min
INTERFEROMETER TILT ANGLE (deg)

Fig. 11

Table III

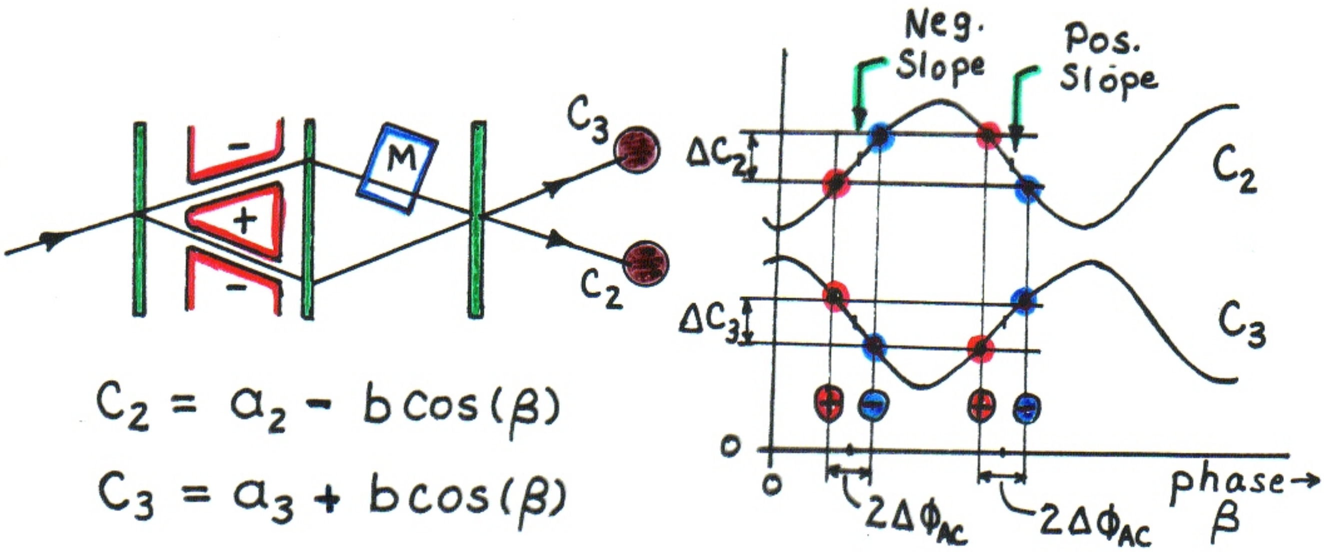
This table summarizes the total accumulated neutron counts for positive (+)and negative (-) voltage polarity for the four operating conditions of the bias magnetic field. There were approximately 1700 voltage cycles for each operating condition, taking approximately 35 days each.

Experimental Condition	C_2 (+)	C_3 (+)	C_2 (-)	C_3 (-)	$C_2(+) + C_3(+)$	$C_2(-) + C_3(-)$	$C_2(+) - C_2(-)$	$C_3(+) - C_3(-)$
(1) Null	20,660,214 ±4,545	6,016,395 ±2,453	20,665,350 ±4,546	6,015,752 ±2,453	26,676,609 ±5165	26,681,102 ±5,165	-5136 ±6,428	+643 ±3,469
(2) Positive Slope	19,367,164 ±4,401	6,098,373 ±2,469	19,353,702 ±4,399	6,106,392 ±2,471	25,465,538 ±5,046	25,460,094 ±5,045	+13,462 ±6,223	-8,019 ±3,494
(3) Negative Slope	18,584,314 ±4,311	5,830,053 ±2,415	18,594,300 ±4,312	5,821,810 ±2,413	24,414,368 ±4,941	24,416,110 ±4,941	-9,986 ±6,097	+8,243 ±3,413
(4) Zero Slope	18,119,184 ±4,257	7,912,480 ±2,813	18,117,466 ±4,256	7,916,111 ±2,814	26,031,664 ±5,102	26,033,578 ±5,102	+1,718 ±6,020	-3,631 ±3,979

FINAL RESULTS

DIFFERENCE COUNTS / CYCLE

EXPERIMENTAL CONDITION	$C_2(+) - C_2(-)$	$C_3(+) - C_3(-)$	$\langle \Delta C \rangle$
POSITIVE SLOPE 3539 CYCLES 74 DAYS	$+7.66 \pm 2.48$	-4.80 ± 1.39	5.49 ± 1.21
NEGATIVE SLOPE 3654 CYCLES 76 DAYS	-5.43 ± 2.36	$+4.66 \pm 1.32$	4.84 ± 1.15



$$C_2 = a_2 - b\cos(\beta)$$

$$C_3 = a_3 + b\cos(\beta)$$

$$\langle \Delta C \rangle = W_2 |\Delta C_2| + W_3 |\Delta C_3| \qquad (W_2 = 0.24,\ W_3 = 0.76)$$

$b = 1234 \pm 15$ COUNTS/CYCLE

POSITIVE SLOPE: $\Delta\phi_{AC} = \dfrac{\langle \Delta C \rangle}{2b} = 2.22 \pm 0.49$ mra

NEGATIVE SLOPE: $\Delta\phi_{AC} = \dfrac{\langle \Delta C \rangle}{2b} = 1.96 \pm 0.46$ mrac

FINAL RESULT
AC PHASE SHIFT

THEORY

$$\Delta\Phi_{AC} = 1.52 \text{ mrad.}$$

EXPERIMENT

$$\Delta\Phi_{AC} = 2.11 \pm 0.34 \text{ mrad.}$$

Phys. Rev. Lett. 63, 380 (1989)

ICAP-XII · Ann Arbor (Aug. 1990)
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Observation of the Topological Aharonov-Casher Phase Shift by Neutron Interferometry

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The phase shift predicted by Aharonov and Casher for a magnetic dipole diffracting around a charged electrode has been observed for the case of thermal neutrons, using a neutron interferometer containing a 30-kV/mm vacuum electrode system. The judicious use of the Earth's gravitational field introduces a spin-independent phase shift which enables unpolarized neutrons to be used. A supplementary magnetic bias field of the correct magnitude allows first-order sensitivity to be achieved; even so, the theoretically predicted phase shift is only 1.50 mrad for the geometry and conditions of the experiment. We observe a phase shift of 2.19 ± 0.52 mrad.

PACS numbers: 41.70.+t, 03.65.−w, 42.50.−p

The well-known topological interference effect of Aharonov and Bohm (AB) concerns a phase shift for electrons diffracting around a tube of magnetic flux.[1] The effect has been observed and measured in a series of investigations culminating in the experiments of Tonomura *et al.*[2] More recently, an extension of the Aharonov-Bohm effect was presented by Aharonov and Casher (AC).[3] They predict that a neutral particle possessing a magnetic dipole moment (e.g., a neutron) should experience an analogous phase shift when diffracted around a line of electric charge. The situation may be visualized by referring to Fig. 1. In Fig. 1(b) the AB flux tube of Fig. 1(a) has been replaced by an equivalent line of magnetic dipoles. Between Figs. 1(b) and 1(c) the role of charge and magnetic dipole have been interchanged, resulting in the AC configuration. In this sense the AC effect is an electrodynamic and quantum-mechanical dual of the AB effect. The differences between the two effects were recently discussed by Goldhaber who also comments on new theoretical aspects of the AC effect.[4] The purpose of this paper is to describe a neutron interferometry experiment in which we have detected the AC phase shift for the first time.[5]

In this experiment, carried out at the University of Missouri Research Reactor (MURR), the AC configuration was realized using a Bonse-Hart single-crystal neutron interferometer[6] schematically shown in Fig. 2. Dynamical Bragg diffraction in the perfect silicon crystal splits the neutron beam in the interferometer plate S, reflects each of the resulting beams in plate M, and recombines them in plate A. As pointed out by Aharonov and Casher, their phase shift depends on the lineal charge density Λ enclosed by the beam paths, but not on any details of the geometry of the beam paths relative to the line charge. In this sense the effect is topological. Consequently, a series of line charges can be used, as long as they are enclosed by the beam paths, thereby amplifying the expected phase shift. Thus, instead of a line charge, a charged prism-shaped electrode system was placed between the splitter (S) and mirror (M) plates of the interferometer. The charged central metallic electrode is identical to a continuous series of line charges residing on its surfaces, perpendicular to the plane of the interferometer beam paths shown in Fig. 2.

The canonical momentum for a neutron having magnetic moment μ, mass m, and velocity $\mathbf{v}$, in an electric field $\mathbf{E}$ is

$$\mathbf{p} = m\mathbf{v} + \frac{\mu}{c} \times \mathbf{E}. \qquad (1)$$

For a neutron diffracting around a line charge, one obtains the AC phase shift (in cgs units) by evaluating the line integral of $\mathbf{p}$, namely

$$\Delta\Phi_{AC} = \frac{1}{\hbar} \oint \mathbf{p} \cdot d\mathbf{r} = \sigma \frac{4\pi\mu\Lambda}{\hbar c}, \qquad (2)$$

where $\sigma = \pm 1$ depending on whether the neutron spin is up or down with respect to the plane of the neutron motion. For an electrode, Gauss's law allows us to replace the lineal charge density Λ by $2VL/4\pi D$, where V is the potential difference between the electrodes, D is their separation, and L is the effective path length shown in Fig. 2. In terms of these quantities, for $V = 45$ kV ($= 150$ statvolts), $D = 0.154$ cm and $L = 2.53$ cm (corrected for end effects, an 8% effect), we find

$$\Delta\Phi_{AC} = 1.50\sigma \text{ mrad}. \qquad (3)$$

The neutron counting rates in detectors C_2 and C_3 are given by

$$C_2 = a_2 - b_2 \cos\Delta\Phi, \qquad (4)$$

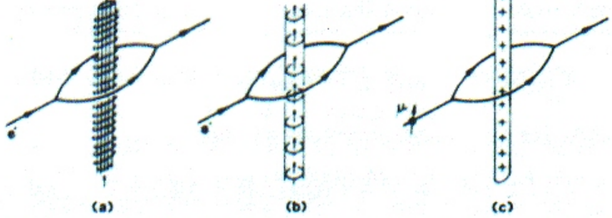
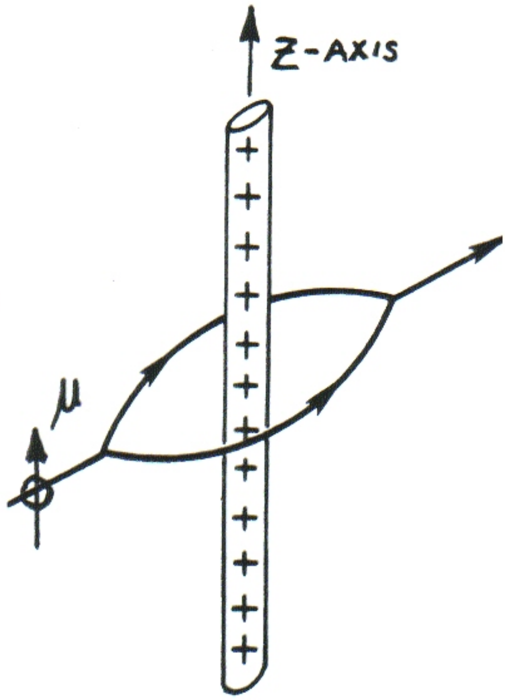


FIG. 1. Duality between the Aharonov-Bohm topology and the Aharonov-Casher topology.

NO FORCE ON NEUTRON



$$\mathcal{H} = \frac{p^2}{2m} - \frac{1}{mc}(\vec{\mu}\times\vec{E})\cdot\vec{p}\,.$$

$$\dot{\vec{r}} = \frac{\partial \mathcal{H}}{\partial \vec{p}} = \vec{p}/m - (\vec{\mu}\times\vec{E})/mc\,.$$

Thus,

$$\text{(A)} \quad m\vec{a} = \dot{\vec{p}} - \frac{1}{c}\frac{d}{dt}(\vec{\mu}\times\vec{E})\,.$$

But,

$$\dot{\vec{p}} = -\frac{\partial \mathcal{H}}{\partial \vec{r}} \approx \frac{1}{mc}\vec{\nabla}[(\vec{\mu}\times\vec{E}\cdot m\vec{v}]\,.$$

And,

$$\frac{d}{dt} = \vec{v}\cdot\vec{\nabla}\,. \qquad (\vec{E} \text{ is static})$$

Therefore,

$$m\vec{a} = \frac{1}{c}\left\{\vec{\nabla}[(\vec{\mu}\times\vec{E})\cdot\vec{v}] - \vec{v}\cdot\vec{\nabla}(\vec{\mu}\times\vec{E})\right\}.$$

or,

$$\text{(B)} \quad \boxed{m\vec{a} = -\frac{1}{c}(\vec{\mu}\cdot\vec{\nabla})(\vec{v}\times\vec{E})\,.}$$

But,

$$\vec{\mu}\cdot\vec{\nabla} = \mu\frac{\partial}{\partial z} \qquad (\vec{\mu} \text{ along z-axis})$$

And,

$$\vec{E} = \vec{E}(x, y)\,.$$

Thus,

$$\text{(C)} \quad \boxed{m\vec{a} = 0\,. \quad \text{in AC geometry to order } 1/c.}$$

NEUTRON INTERFEROMETRY AND COHERENCE
A Symposium In Honor of SAMUEL A. WERNER

Front Row: Mohanna Yethiraj, Muhammad Arif, Tony Klein, Sam Werner, Alberto Cimmino, Helmut Rauch, Hal Lee
Back Row: Helmut Kaiser, David Jacobson, Paul Huffman, Fred Wietfeldt, Yugi Hasegawa, Wolfgang Treimer, Ken Littrell, Brendan Allman, Bill Hamilton

ICNS 2005. December 1, 2005. Sydney, Australia

The Neutron

When a pion an innocent proton seduces
With neither excuses
Abuses
Nor scorn
For its shameful condition
Without intermission
The proton produces:
A neutron is born.
        What love have you known
        O neutron full grown
        As you bominate into the vacuum alone?
Its spin is a half, and its mass is quite large
-About one AMU - but it hasn't a charge;
Though it finds satisfaction in strong interaction
It doesn't experience coulombic attraction
        But what can you borrow
        Of love, joy or sorrow
        O neutron, when life has so short a tomorrow?

Within its
Twelve minutes
Comes disintegration
Which leaves an electron in more disolation
And also another ingenuous proton
For other unscrupulous pions to dote on
At last, a neutrino;
Alas, one can see no
Fulfilment for such a leptonic bambino -
No loving, no sinning
Just spinning and spinning -
Eight times through the globe without ever beginning...
A cycle mechanic
No anguish or panic
For such is the pattern of life inorganic.
        O better
        The fret a
        Poor human endures
        Than the neutron's dichotic
        Robotic
        Amours.

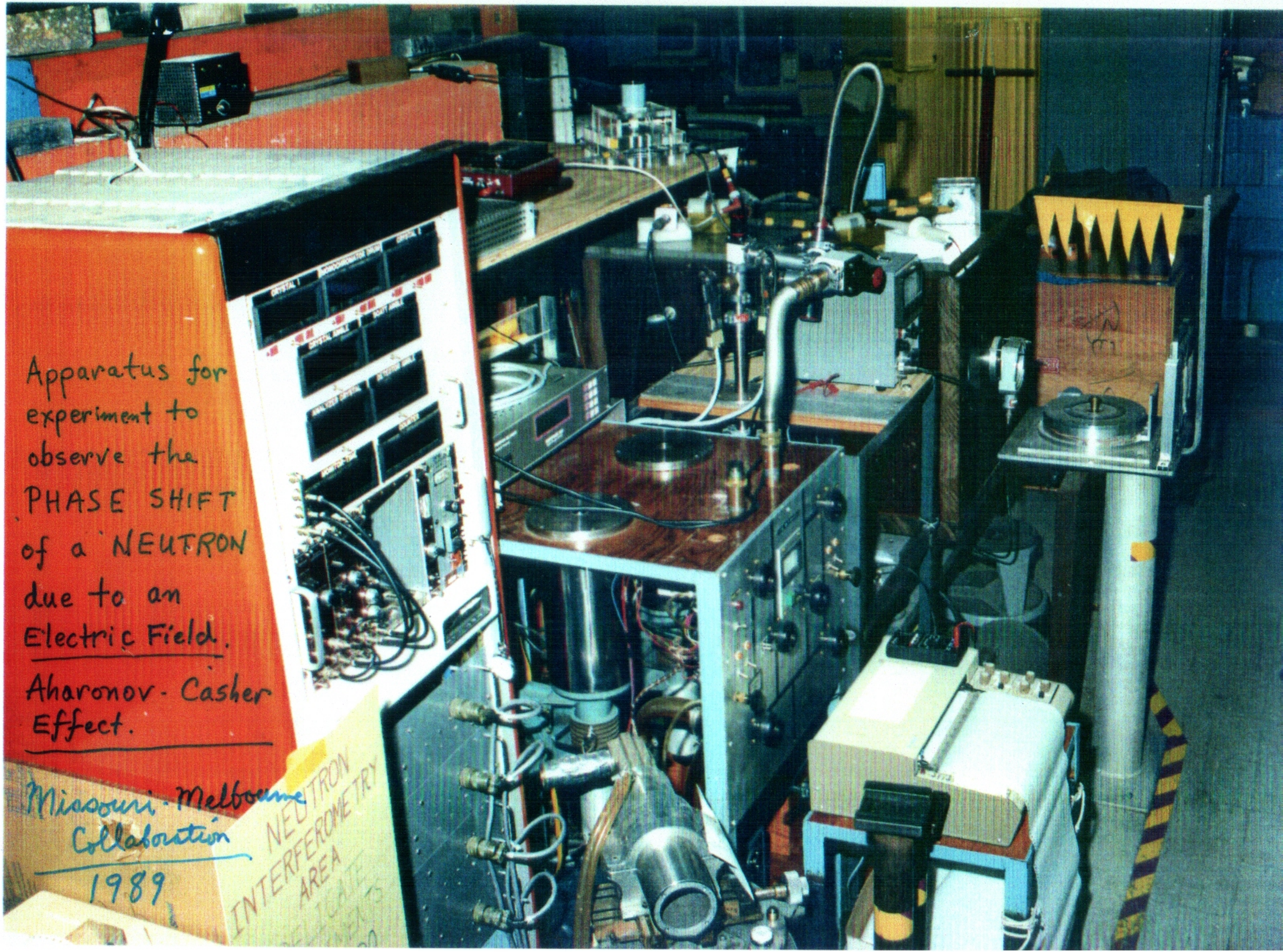
- with acknowledgements.

Table 1.4 Neutron interferometry experiments (1974–1999)

- First test of perfect Si-crystal interferometer with neutrons: Vienna (1974)
- Observation of gravitationally induced quantum interference: Michigan, Missouri (1975, 1980, 1988, 1993, 1996)
- Observation of the change of sign of the wavefunction of a fermion due to precession of 360° in a magnetic field: Michigan, Vienna–Grenoble, Melbourne (1975, 1976, 1978)
- Observation of the effect of the Earth's rotation on the quantum mechanical phase of the neutron (Sagnac effect): Missouri (1980)
- Measurement of the energy-dependent scattering length of ^{149}Sm in the vicinity of a thermal nuclear resonance: Missouri (1982)
- Charge dependence of the four-body nuclear interaction in (n–^{3}He versus n–^{3}H): Vienna–Grenoble (1979, 1985)
- Search for nonlinear terms in the Schrödinger equation: MIT (1981)
- Search for the Aharonov–Bohm effect for neutrons with a magnetized-single-crystal-of-Fe-inside interferometer: MIT (1981)
- Measurement of the longitudinal coherence length of a neutron beam: Missouri (1983)
- Observation of the coherent superposition of spin states ('Wigner phenomenon') with both static and RF spin flippers: Vienna–Grenoble (1983, 1984)
- Neutron interferometric search for quaternions in quantum mechanics: Missouri (1984)
- Sagnac effect using a laboratory turntable—shows phase shift due to rotation is linear in ω: MIT (1984)
- Observation of acceleration-induced quantum interference: Dortmund–Grenoble (1984)
- Experiment on the null Fizeau effect (stationary boundaries) for thermal neutrons in moving matter: Missouri–Melbourne (1985)
- Observation of the neutron Fizeau effect with moving boundaries of moving matter: Dortmund–Grenoble (1985)
- Double RF coil experiment—analogue of the magnetic Josephson experiment: Vienna–Grenoble (1986)
- Precision measurement of the bound-coherent neutron scattering lengths of ^{235}U, ^{238}U, V, Eu, Gd, Th, Kr, H, D, Si, Bi, etc.: Vienna–Grenoble, Missouri, NIST (1975–1999)
- Observation of a motion-induced phase shift of neutron de Broglie waves passing through matter near a nuclear resonance (^{149}Sm): Missouri–Melbourne (1988)
- Observation of stochastic versus deterministic absorption of the neutron wavefunction: Vienna–Grenoble (1984, 1987, 1990)
- Observation of the topological Aharonov–Casher phase shift: Missouri–Melbourne (1989)
- Test of possible non-ergodic memory effects: Vienna–Grenoble (1989)
- Observation of the effects of spectral filtering in neutron interferometry: Missouri–Vienna (1991)
- Counting statistics experiments—particle number/phase uncertainty: Vienna (1990, 1992)
- Observation of the neutron phase echo effect: Missouri–Vienna (1991)
- Coherence effects in time-of-flight neutron interferometry: Missouri–Vienna (1992)
- Observation of the scalar Aharonov–Bohm effect: Missouri–Melbourne (1992, 1993, 1998)
- Spectral modulation and squeezed states in neutron interferometry: Missouri–Vienna (1994)
- Observation of multiphoton exchange amplitudes by interferometry: Vienna–Missouri (1995)
- Test of a Jamin-type interferometer: Kumatori–Kyoto (1996)
- Observation of the topological phase by coupled loop interferometers: Vienna–Berlin (1996)
- Quantum beat experiments with spin-echo and a Jamin-type interferometer: Kumatori–Kyoto (1998)
- Experimental separation of geometric (Berry) and dynamical phases by neutron interferometry: Bombay–Missouri–Vienna (1997, 1998)

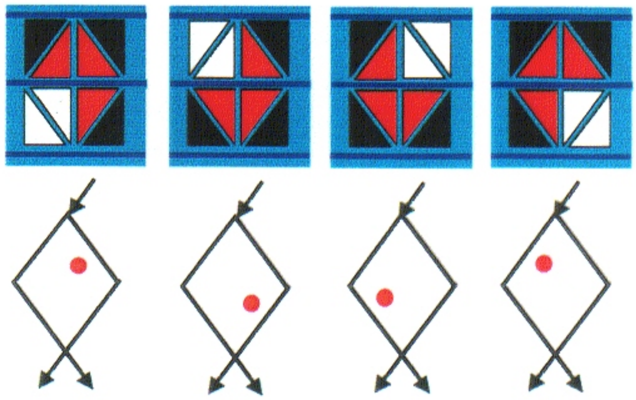
(2000-2006)

- Neutron-Electron scattering length, mean square charge radius of the neutron (NIST, Tulane)
- Phase Contrast Imaging (Melbourne, NIST, Dortmund, Vienna)
- Contextuality in Quantum Mechanics (Vienna)
- Reciprocal Space Imaging (NIST, MIT)
- Very high precision scattering lengths of H, D, He-3, few nucleon physics (NIST, Indiana, UNC)
- Bell's Inequality Experiments (Vienna)
- Hidden Observables in Quantum Mechanics (Vienna)


Apparatus for experiment to observe the PHASE SHIFT of a NEUTRON due to an Electric Field.
Aharonov - Casher Effect.
Missouri - Melbourne Collaboration
1989
NEUTRON INTERFEROMETRY AREA

Topological character of the AC effect

The phase shift $\Delta\Phi_{AC}$ should be independent of the position of the lineal charge distribution within the neutron interference loop. One of the many possible configurations consists in grounding cyclically one electrode pair. The position of the resulting, effective lineal charge distribution is then indicated below. For uniform inter-electrode gap, the expected phase shift is $0.75\times\Delta\Phi_{AC}$, in all four cases.

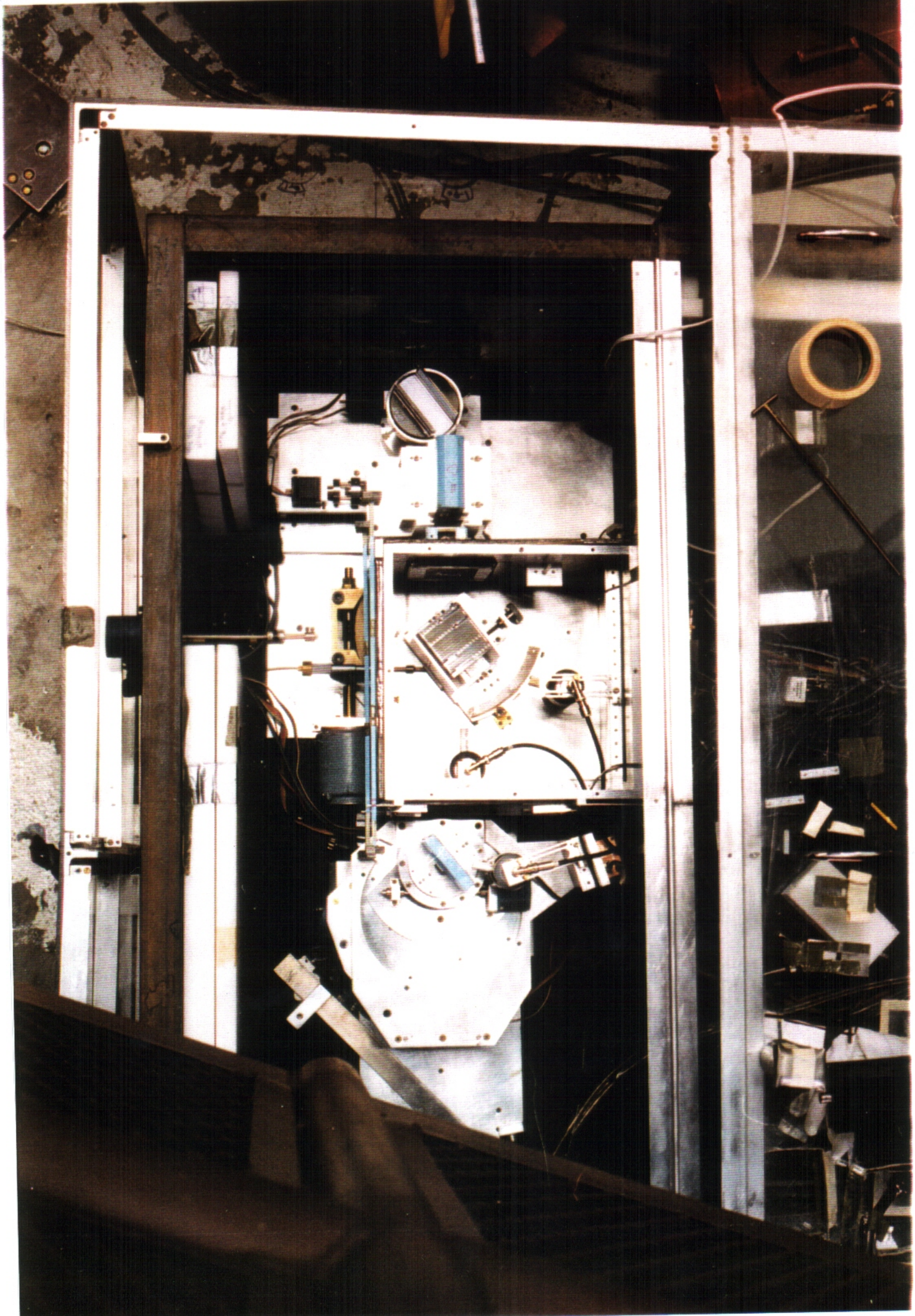


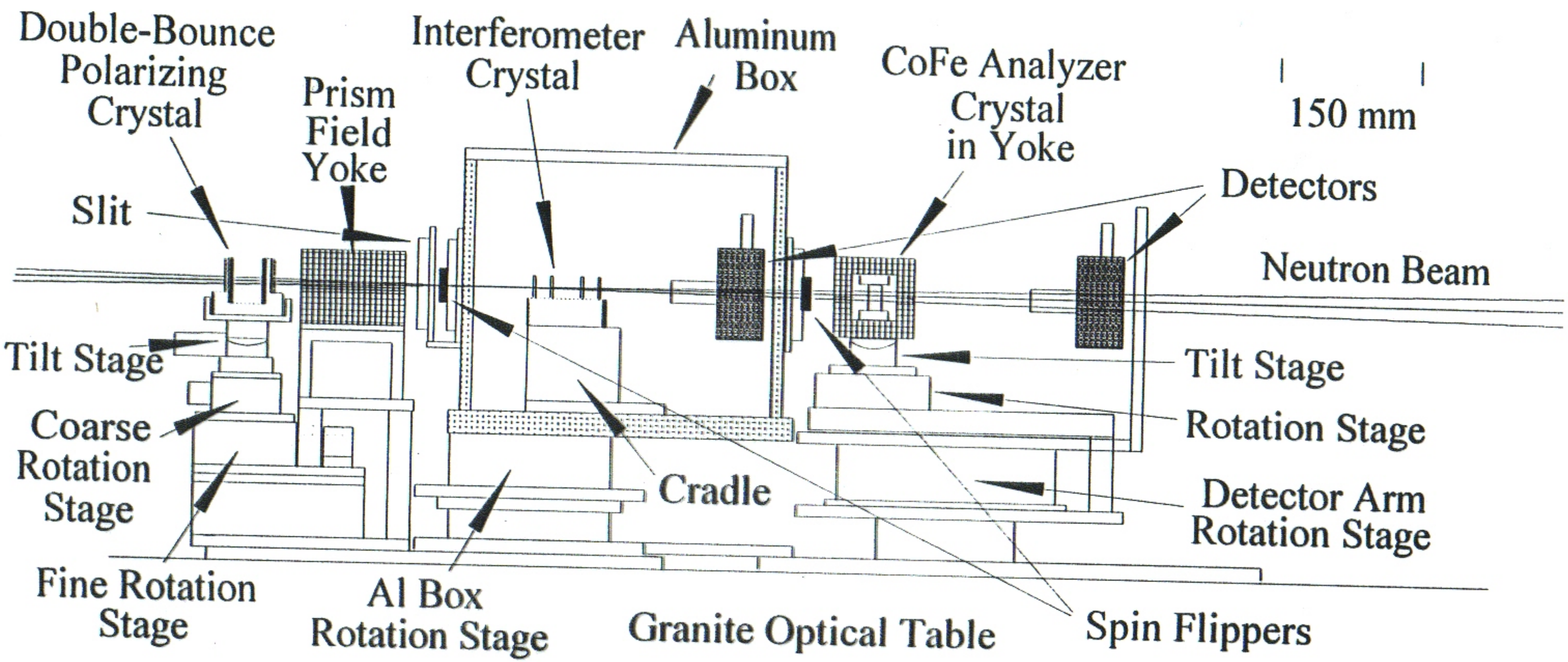
Conclusions

We plan to perform a high precision AC experiment, to improve on the accuracy of the previous measurement and to highlight the topological nature of the effect. AC-type phase shifts have been measured accurately in several atom interferometry experiments. However, they have failed to demonstrate the topological character of the effect. We intend to show this aspect by placing several electrodes in the interferometer, and to charge them cyclically to effectively change the position of the line charge. We have developed and presented results of an adjustable magnetic bias configuration that can be applied from outside the interferometer.

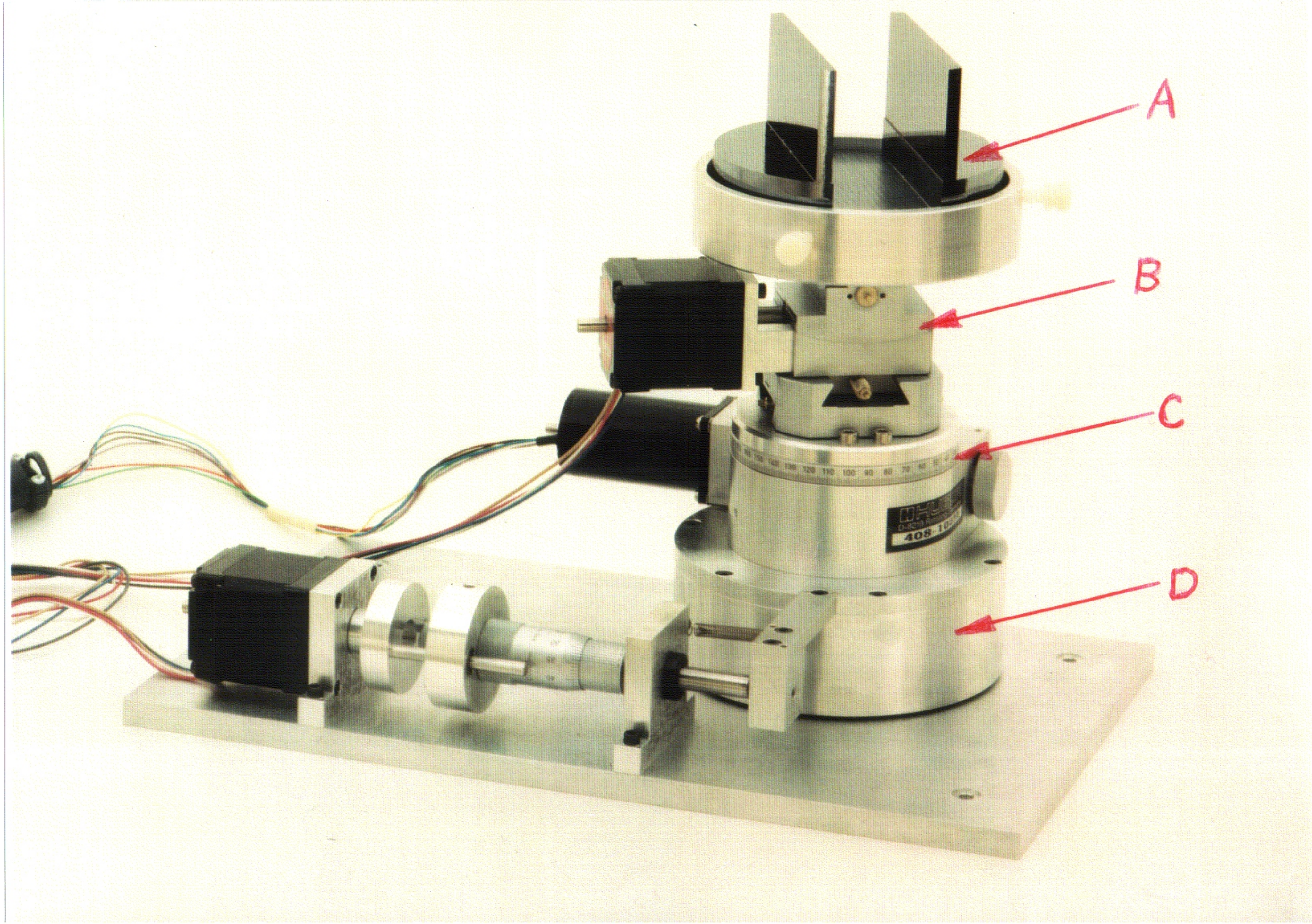
References

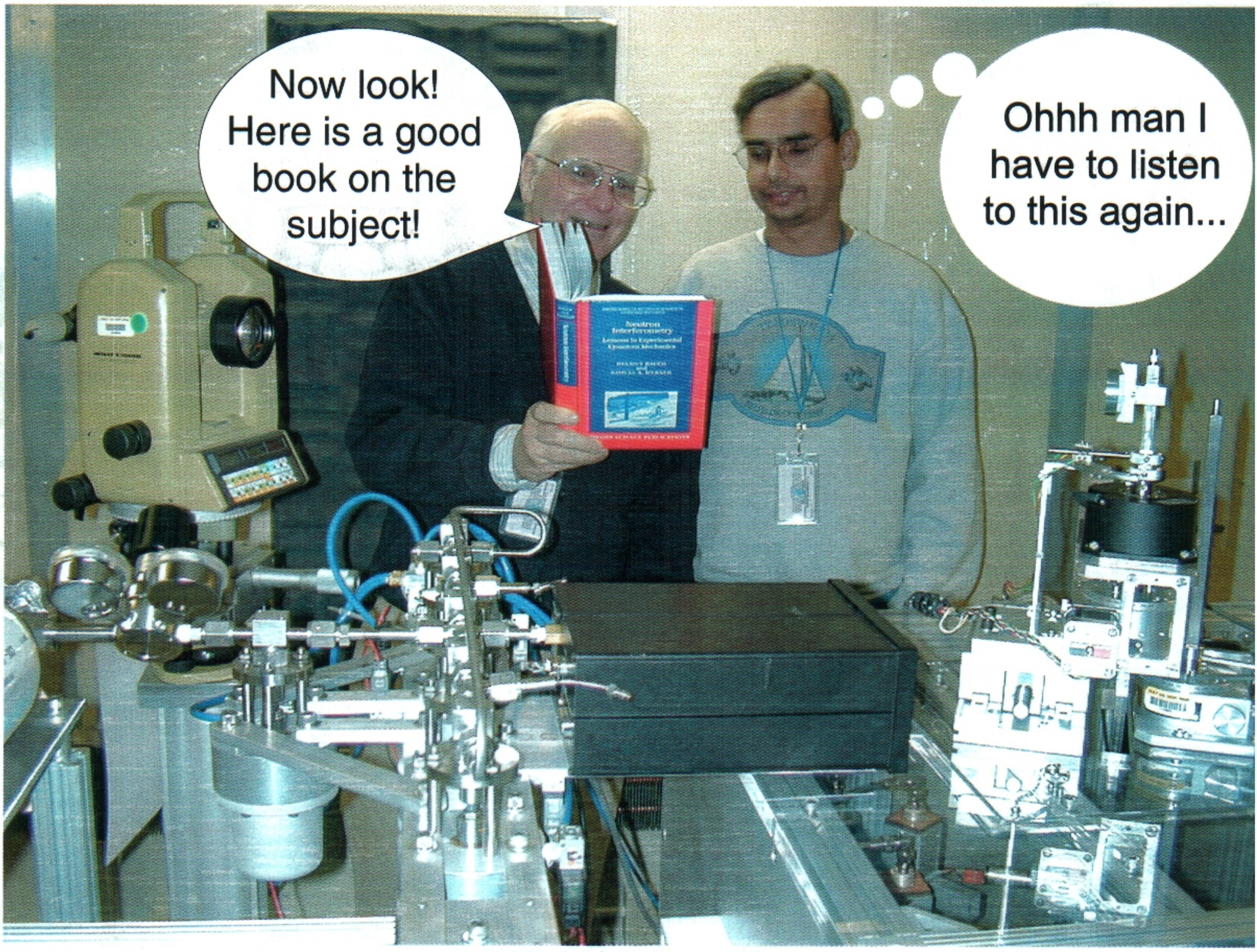
1. Y. Aharonov and D.Bohm, *Phys. Rev.* **115** (1959) 485.
2. M. Peshkin and A. Tonomura, "The Aharonov-Bohm Effect", Lecture Notes in Physics, Vol. **3450**, (Springer-Verlag, Berlin, 1989), p39.
3. Y. Aharonov and A. Casher, *Phys. Rev. Lett.* **53** (1984) 319.
4. R.G. Chambers, *Phys. Rev. Lett.* **5** (1960) 3.
5. A. Tonomura et al., *Phys. Rev. Lett.* **56** (1986) 792.
6. A. Cimmino et al., *Phys. Rev. Lett.* **63** (1989) 3803.
7. B.E. Allman et al., *Nucl. Instr. Meth.* **A412** (1998) 392.
8. A.G. Klein and S.A. Werner, Methods of Experimental Physics, Vol. **23A**, D.L. Price and K. Skjold (Eds.), Ch.4, (Academic Press, New York 1986).
9. B.E. Allman et al., *Phys. Rev. Lett.* **72** (1992) 2409.
10. W-T. Lee et al., *Phys. Rev. Lett.* **80** (1998) 3165.
11. K. Sangster et al., *Phys. Rev.* **A 51** (1995) 1776.
12. A. Görlitz, et al., *Phys. Rev.* **A 51** (1995) R4305.
13. N.F. Ramsey, *Phys. Rev.* **A 48** (1993) 80.





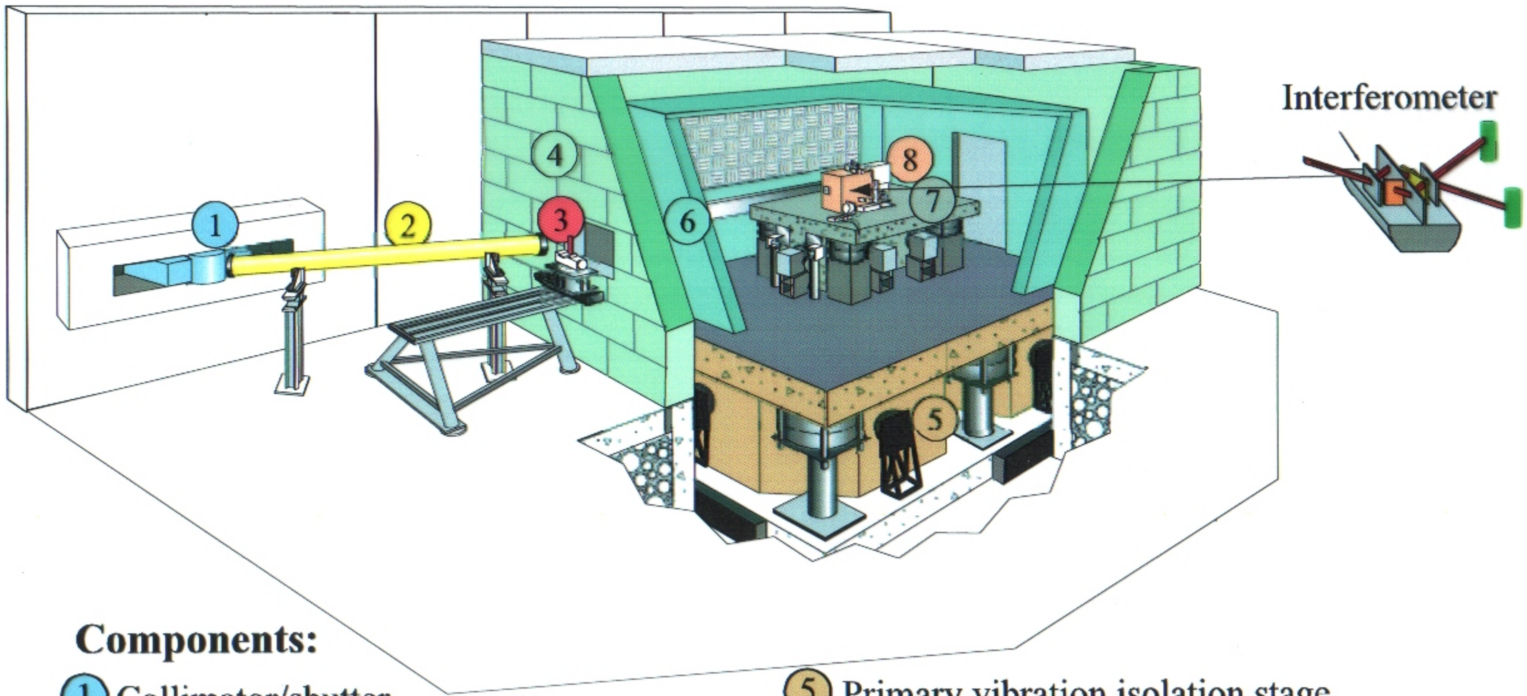
Double-Bounce Polarizing Crystal
Prism Field Yoke
Interferometer Crystal
Aluminum Box
CoFe Analyzer Crystal in Yoke
150 mm
Slit
Detectors
Neutron Beam
Tilt Stage
Coarse Rotation Stage
Tilt Stage
Rotation Stage
Cradle
Detector Arm Rotation Stage
Fine Rotation Stage
Al Box Rotation Stage
Granite Optical Table
Spin Flippers


A
B
C
D


Now look! Here is a good book on the subject!
Ohhh man I have to listen to this again...

NIST

Neutron Interferometer and Optics Facility



Components:

1. Collimator/shutter
2. Helium filled beam transport tube
3. Focusing pyrolytic graphite monochromator
4. Outer environmental enclosure
5. Primary vibration isolation stage
6. Acoustic and thermal isolation enclosure
7. Secondary vibration isolation stage
8. Enclosure for interferometer and detectors

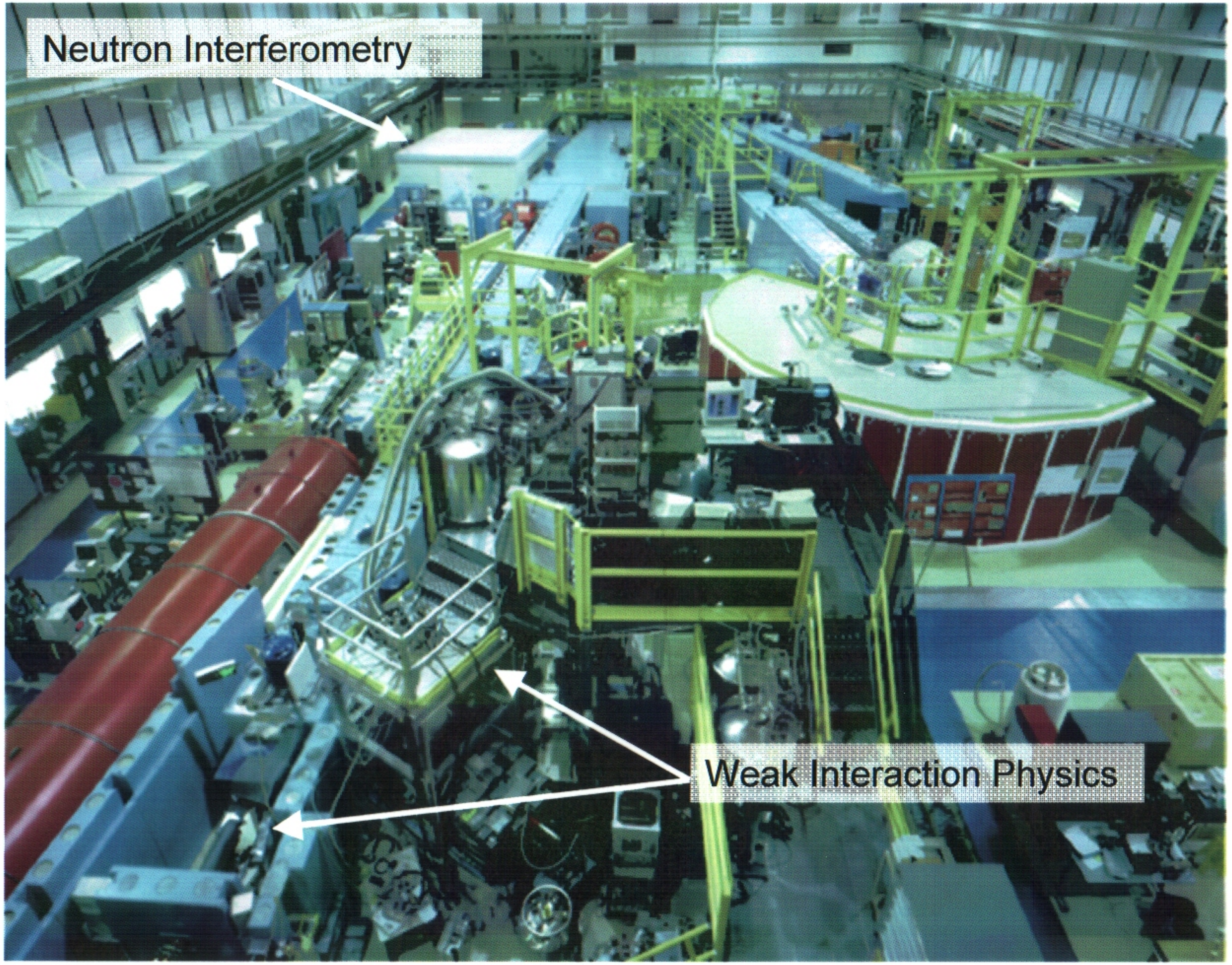
Vibration Isolation = 10^{-7}g

Translation = Less than a μm

Rotation = Less than a mrad

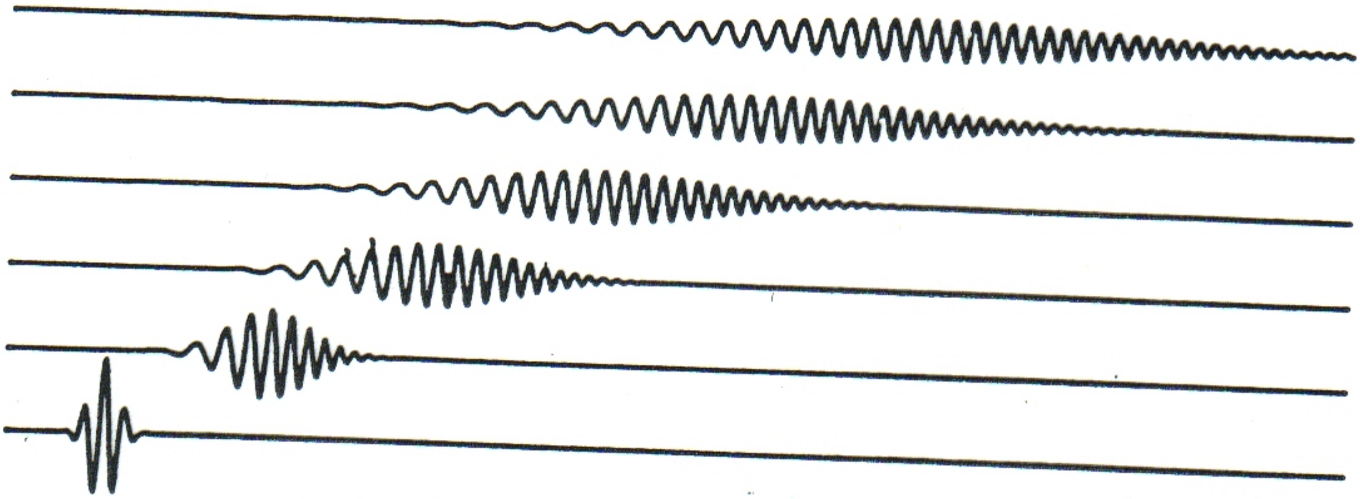
Temperature = 0.1 C

Cold Neutron Guide Hall



Neutron Wave Packet

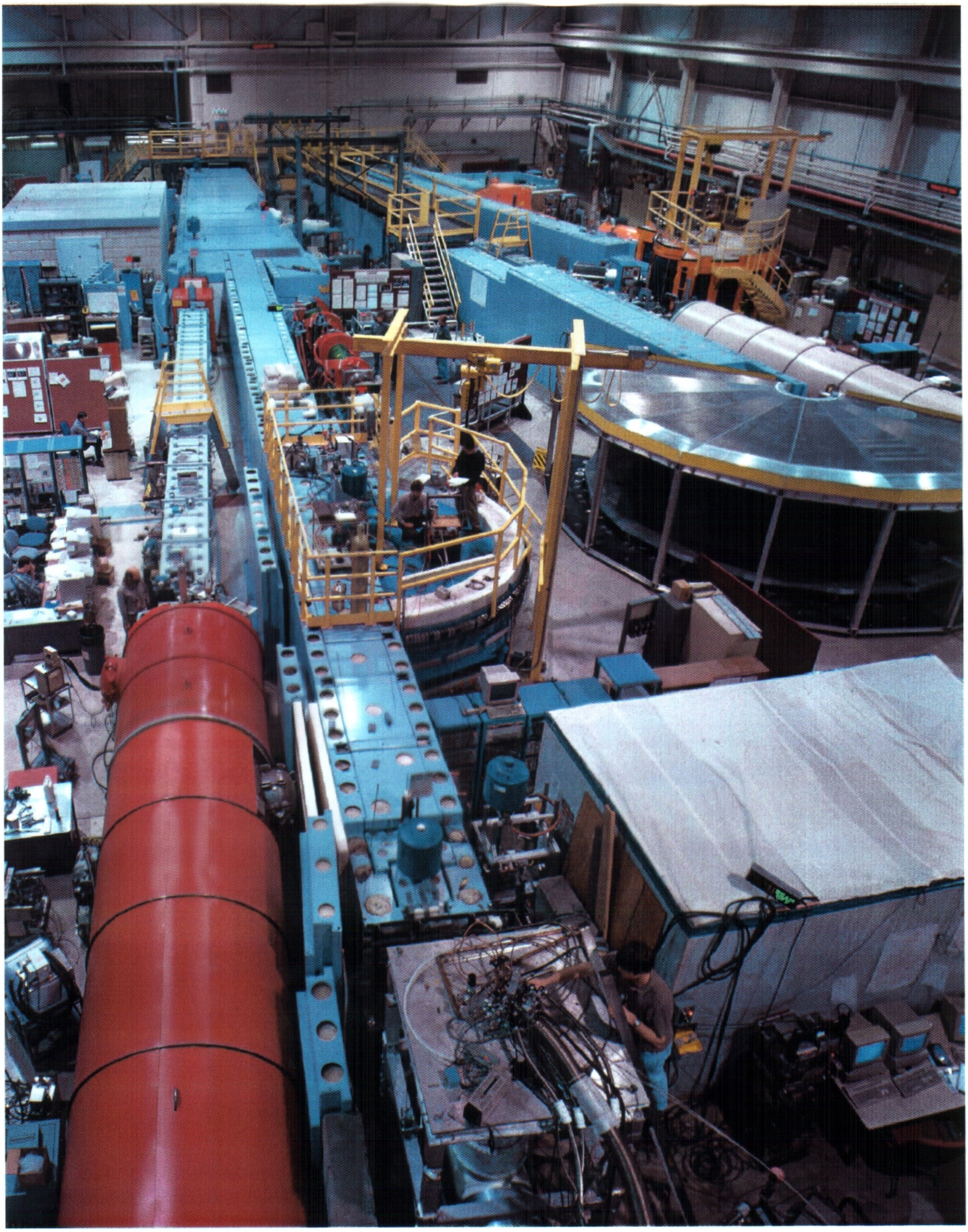
evolving in space & Time



Spatial Width:

$$\sigma_x^2(t) = \sigma_x^2(0) + \left(\frac{\hbar t}{2m\,\sigma_x(0)}\right)^2$$

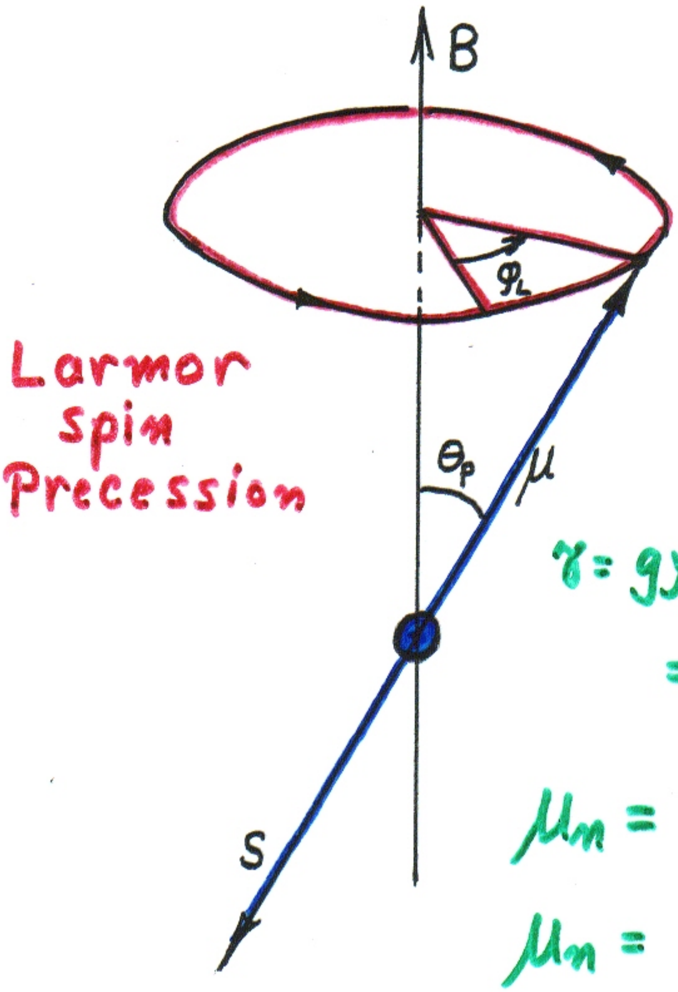
$$\sigma_x \sigma_k \geq \frac{1}{2}$$



8

Neutron Interferometry Group 1985
MURR . Columbia , MO

Classical Spin Precession



$$\vec{\mu} = -\gamma \vec{S}$$

$$\gamma = \frac{2\mu_n}{\hbar}$$

$$\varphi_L = \omega_L t = \gamma B t$$

γ = gyromagnetic ratio

$= 1.83 \times 10^4$ rad/s/G

$\mu_n = 6.02 \times 10^{-12}$ eV/G

$\mu_n = g_n \mu_N$, $g_n = -1.913$

$$\text{Torque} = \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$

$$\frac{d\vec{\mu}}{dt} = -\gamma \vec{\mu} \times \vec{B} \quad \text{(Eq. of Motion)}$$

$$\text{Potential Energy} = V = -\vec{\mu} \cdot \vec{B}$$

Precession Rate is independent of the polar angle θ_p.

Quantum Mechanics

$$\psi(\varphi_L = 2\pi) = -\psi(\varphi_L = 0)$$

Why is there this change of sign?

Neutrons are Fermions. $S = 1/2$.

$$V = -\vec{\mu}\cdot\vec{B} = -\mu_n\,\vec{\sigma}\cdot\vec{B}$$

Pauli Spin Matrices:

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Wave function:

$$\psi = \cos\frac{\theta_p}{2}\, e^{-i\varphi_L/2}\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \sin\frac{\theta_p}{2}\, e^{i\varphi_L/2}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Note factor of $1/2$ in phases.

Get classical eqs. of motion for:

$$\langle\vec{\mu}\rangle = \mu_n \langle \psi^* \vec{\sigma}\, \psi \rangle$$