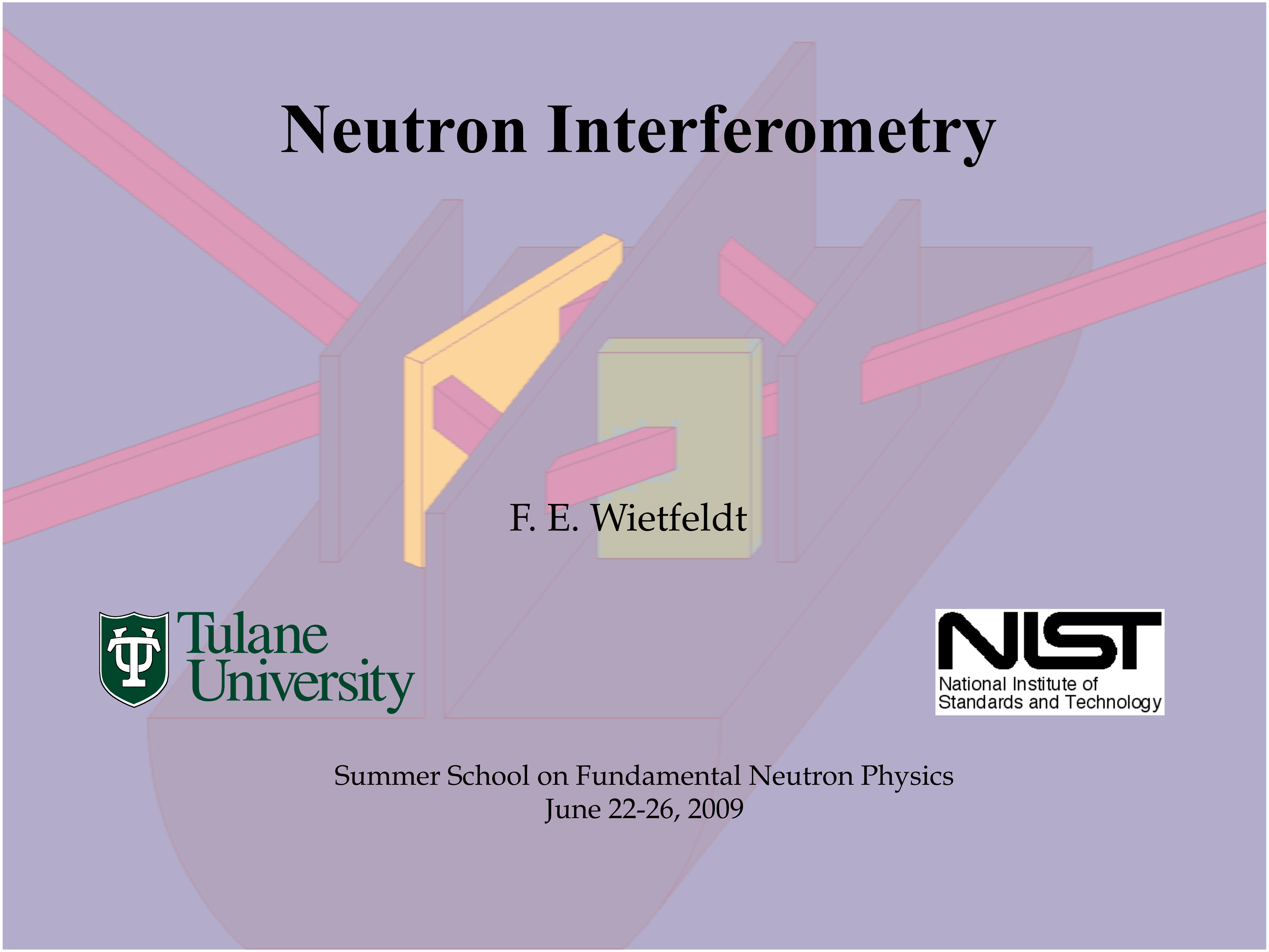


Neutron Interferometry

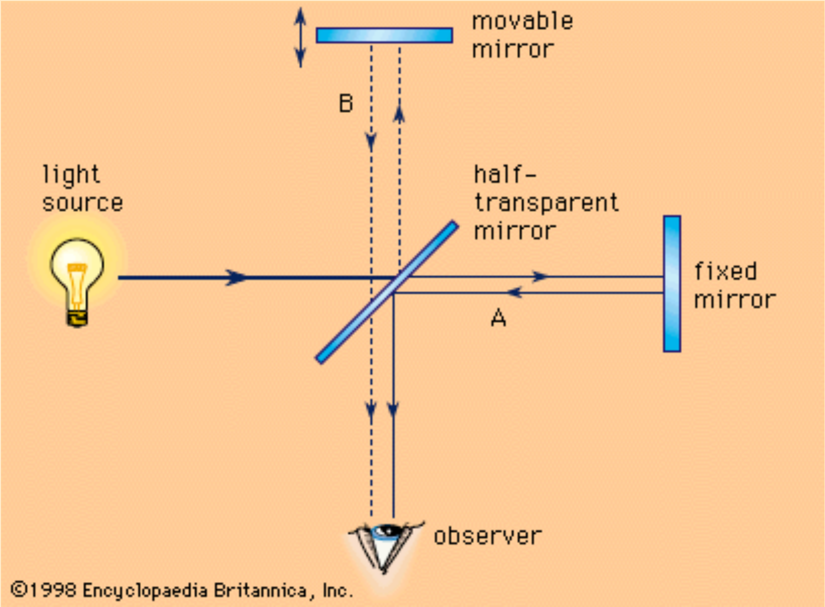
F. E. Wietfeldt

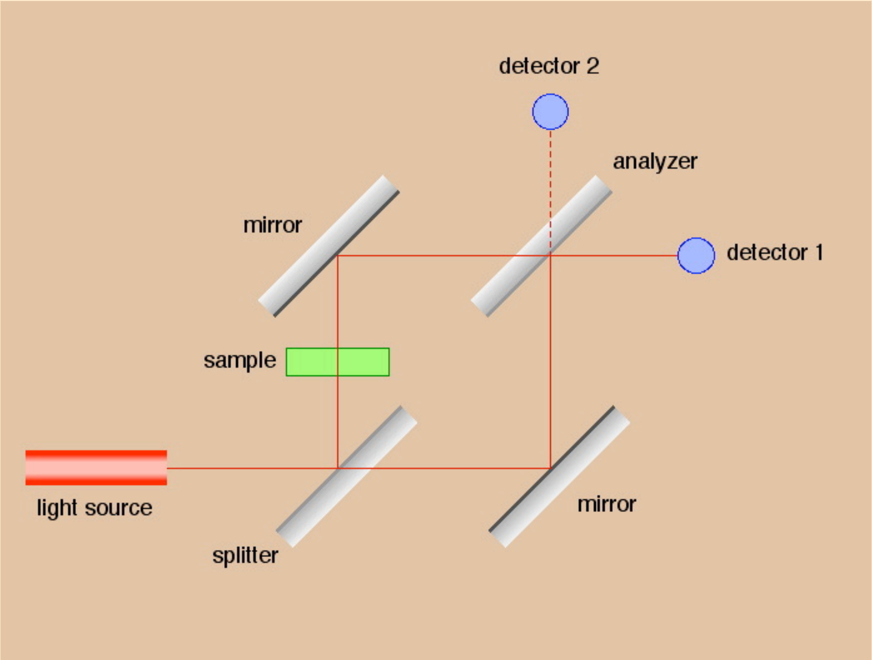
Tulane University

NIST
National Institute of Standards and Technology

Summer School on Fundamental Neutron Physics
June 22-26, 2009

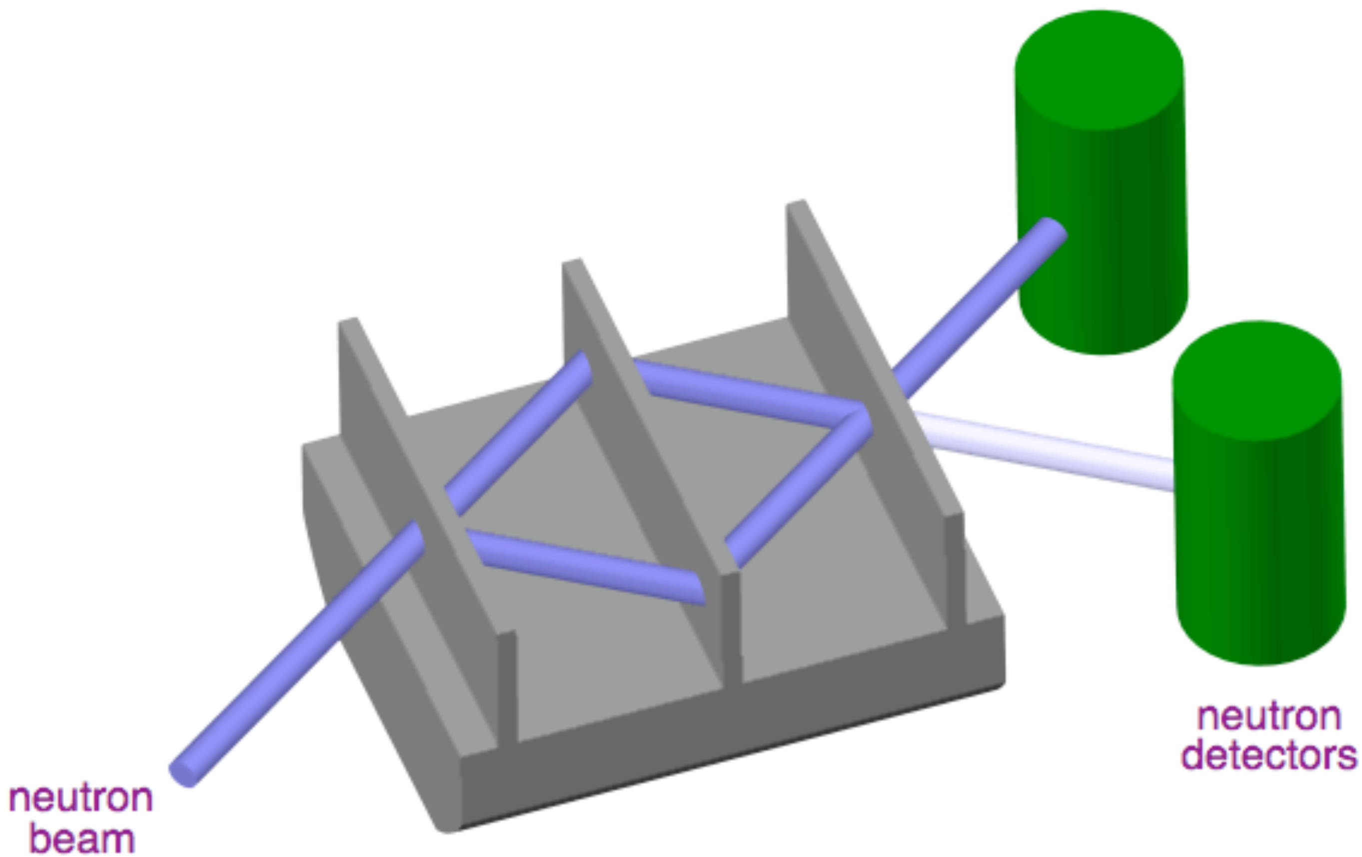
Michelson Interferometer



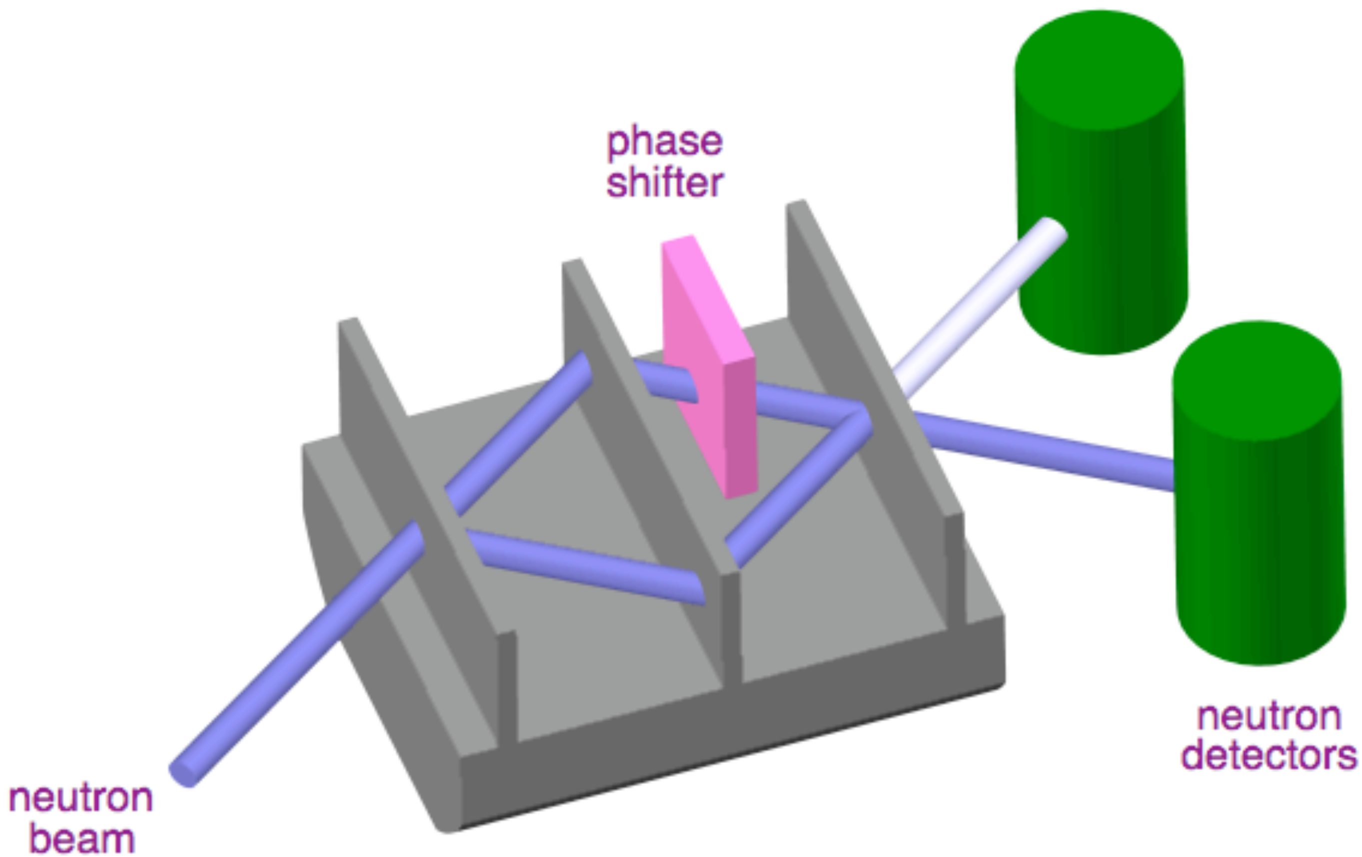


Mach-Zender Interferometer

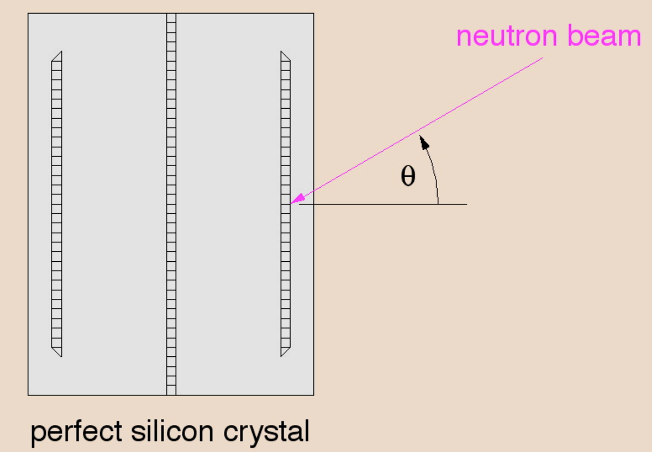
Perfect Crystal Silicon Neutron Interferometer



Perfect Crystal Silicon Neutron Interferometer



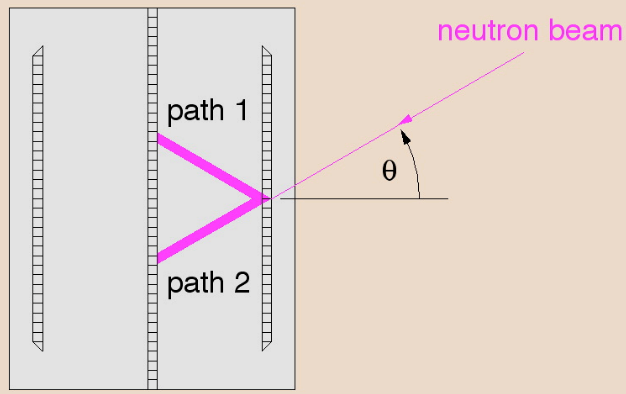
Perfect Crystal LLL Neutron Interferometer



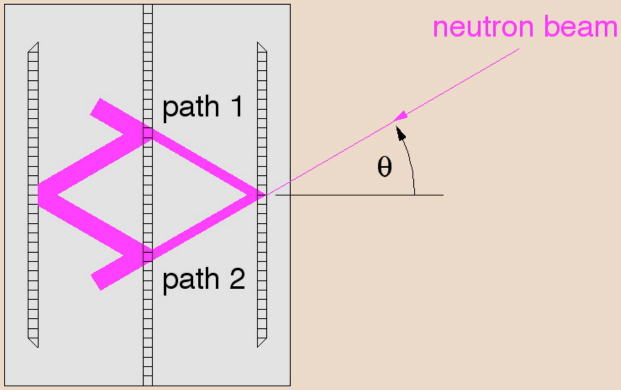
Bragg condition: $n\lambda = 2d\sin\theta$

d = lattice spacing

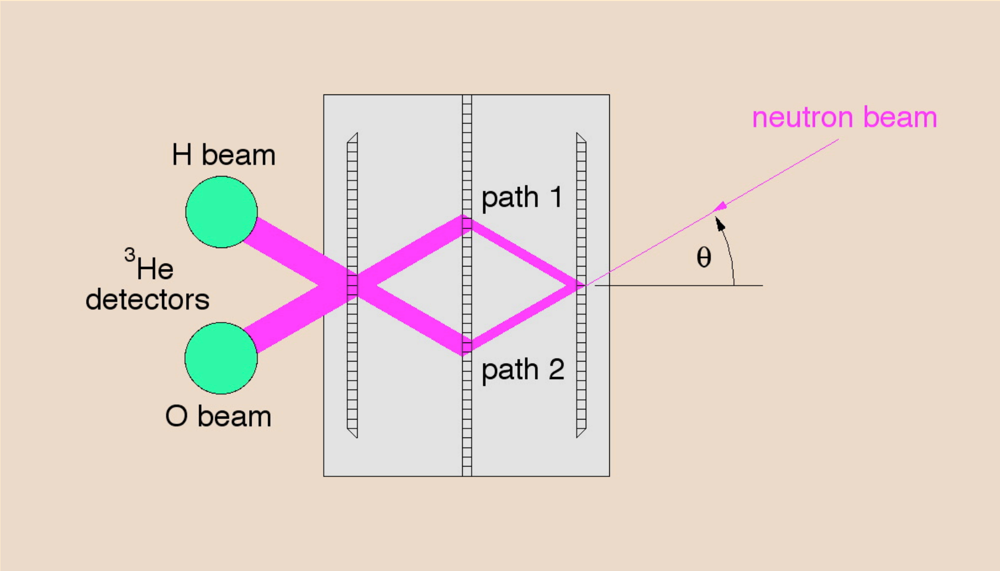
Perfect Crystal LLL Neutron Interferometer



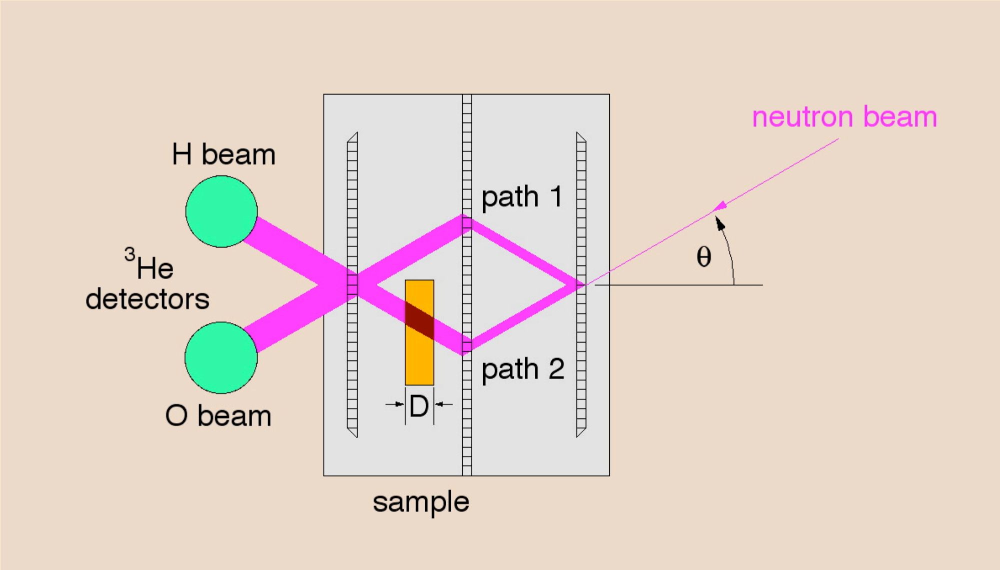
Perfect Crystal LLL Neutron Interferometer



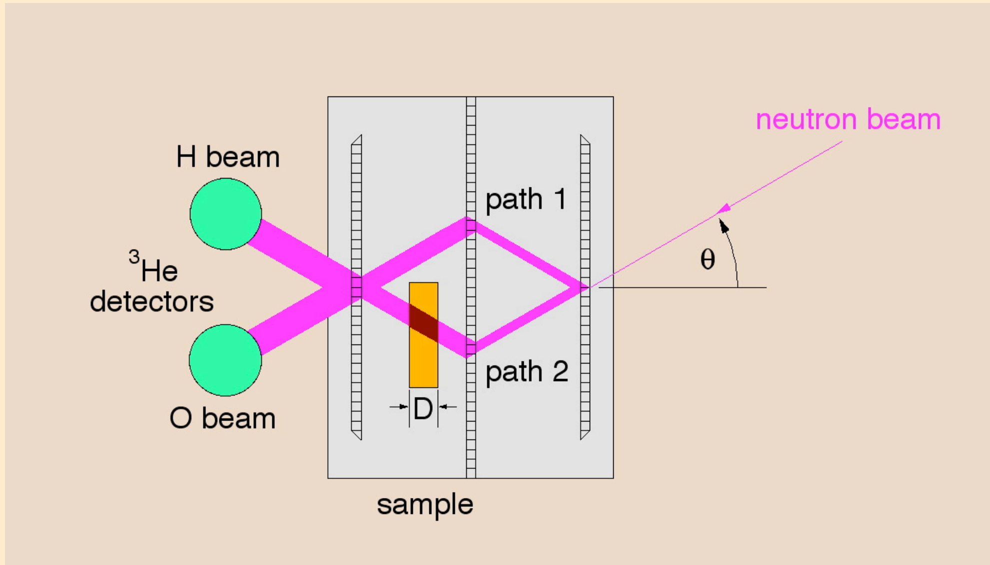
Perfect Crystal LLL Neutron Interferometer

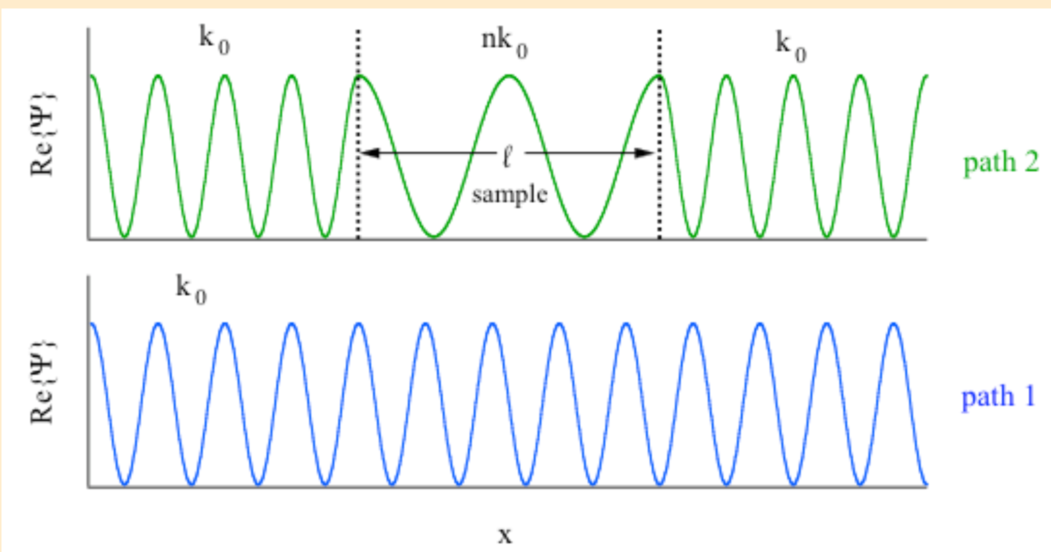


Nuclear Phase Shift



Nuclear Phase Shift



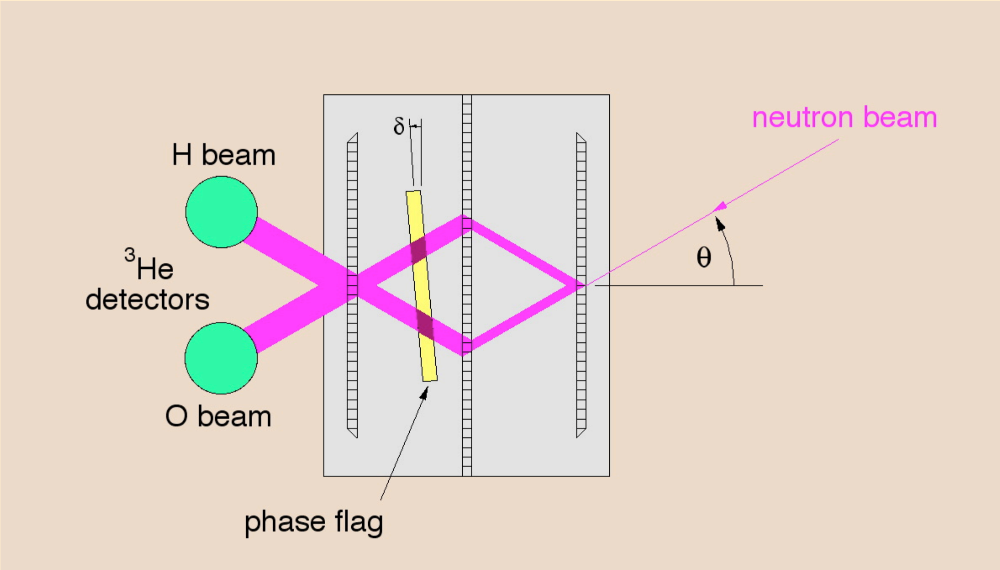


index of refraction: $n = 1 - \frac{Nb\lambda^2}{2\pi}$

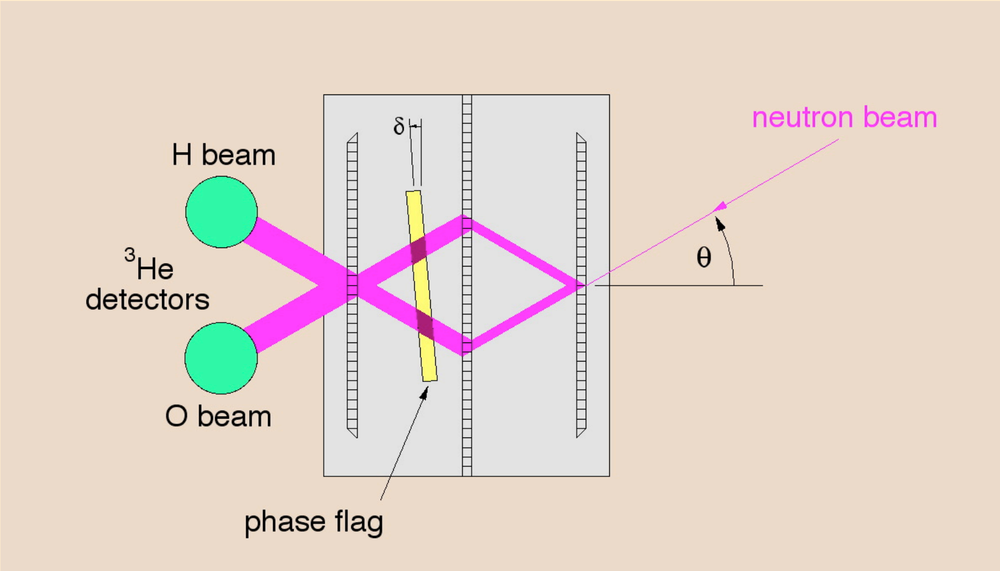
relative phase shift:

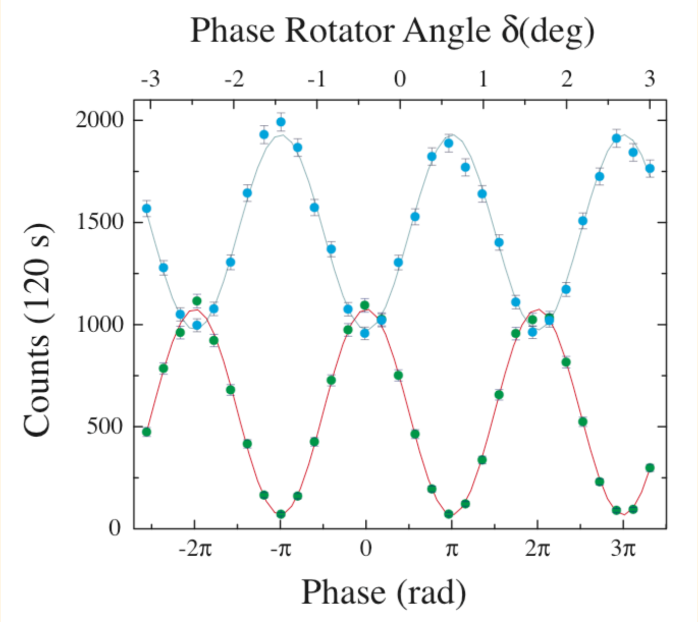
$$\Delta\chi = k_0\ell - nk_0\ell = Nb\lambda\frac{D}{\cos\theta}$$

Interferogram



Interferogram



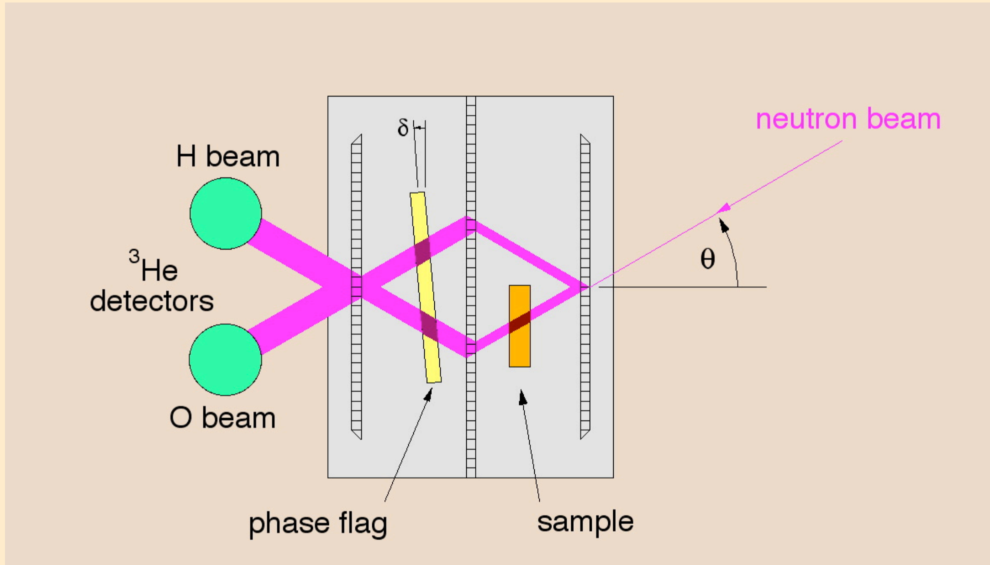


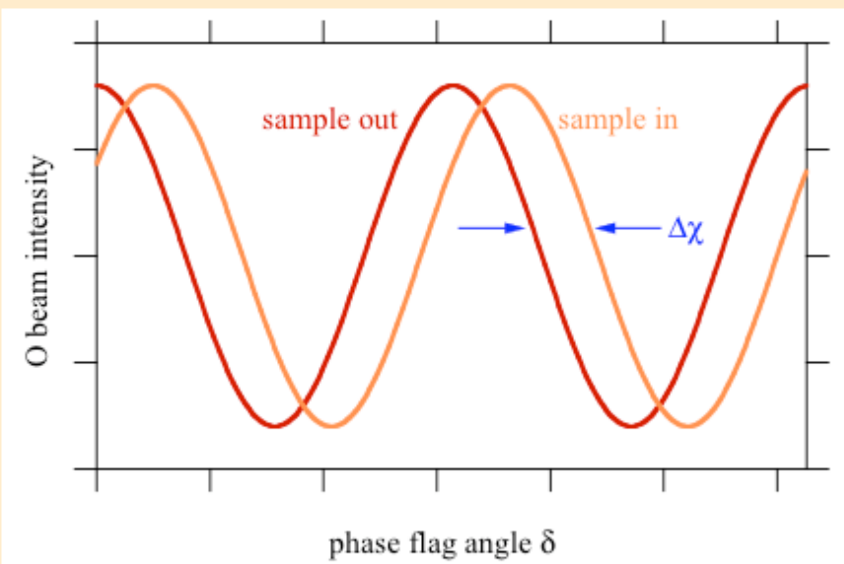
O beam: $I_O = A\left[1 + f\cos(\chi_2 - \chi_1)\right]$

H beam: $I_H = B - Af\cos(\chi_2 - \chi_1)$

contrast $f = \dfrac{C_{max} - C_{min}}{C_{max} + C_{min}}$ (O-beam)

Precision Phase Shift Measurement



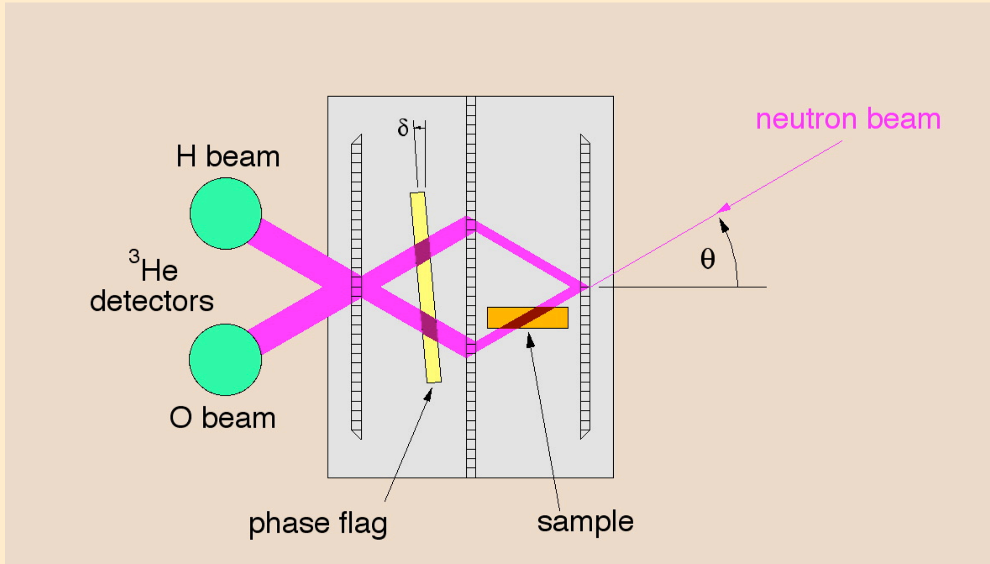


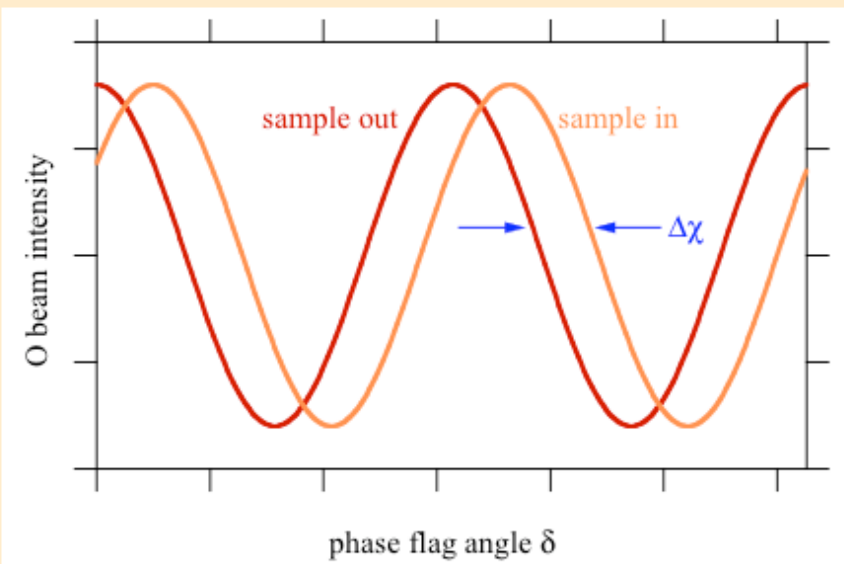
$$\Delta\chi = Nb\lambda \frac{D}{\cos\theta}$$

Example: aluminum sample,

$$\lambda = 2.70\dot{\text{A}},\ \langle 111 \rangle \text{ reflection:}$$
$$D = \ 100\ \mu\text{m} \ \Rightarrow \Delta\chi = 2\pi$$

Non-Dispersive Geometry



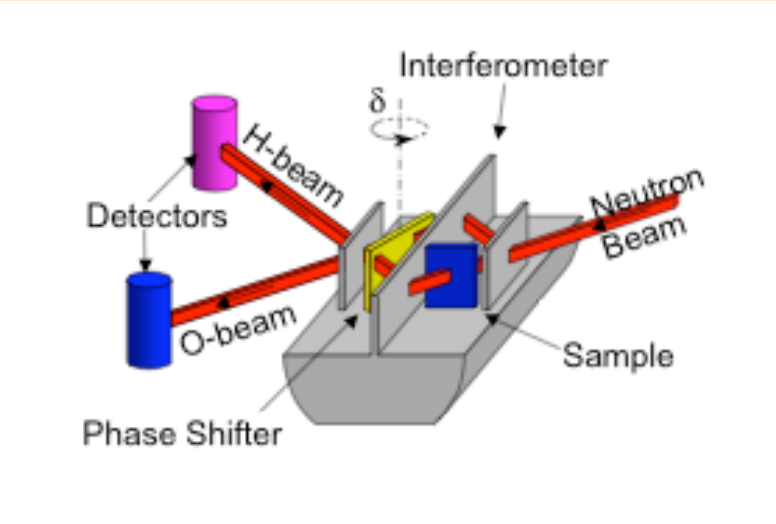


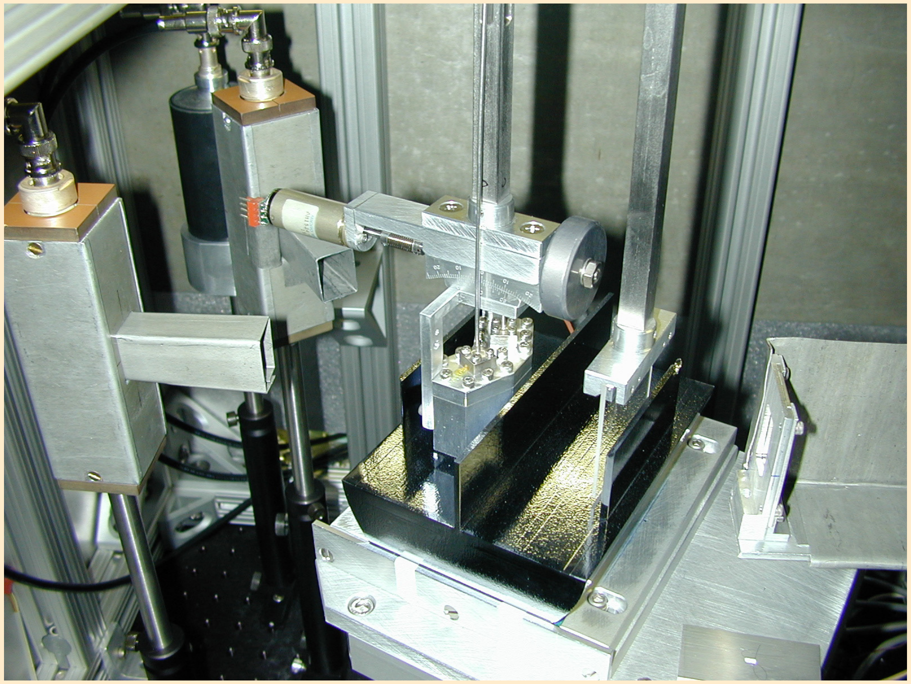
path length $\ell = \dfrac{D}{\sin\theta}$

$$\Delta\chi = 2Nb\,d\,D$$

independent of λ

Perfect Crystal LLL Neutron Interferometer





PHYSICAL REVIEW A VOLUME 58, NUMBER 2 AUGUST 1998

Precision neutron-interferometric measurement of the coherent neutron-scattering length in silicon

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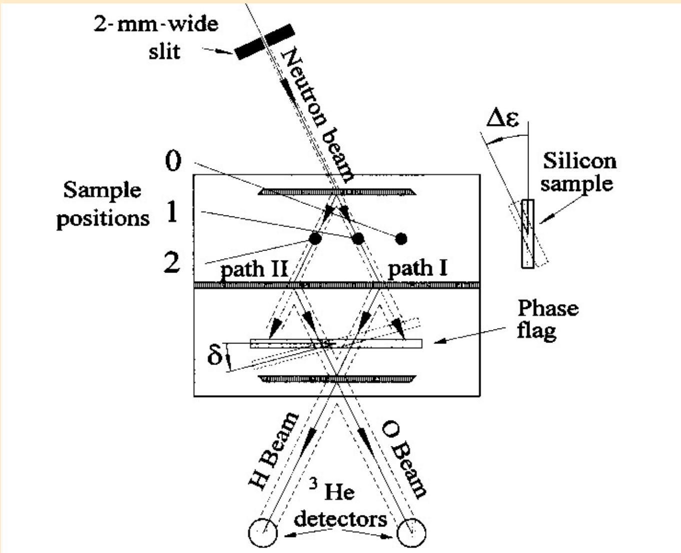
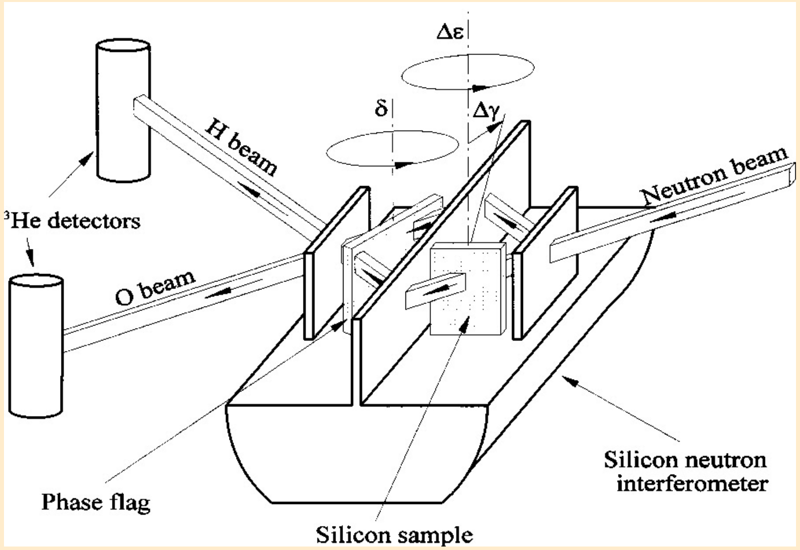
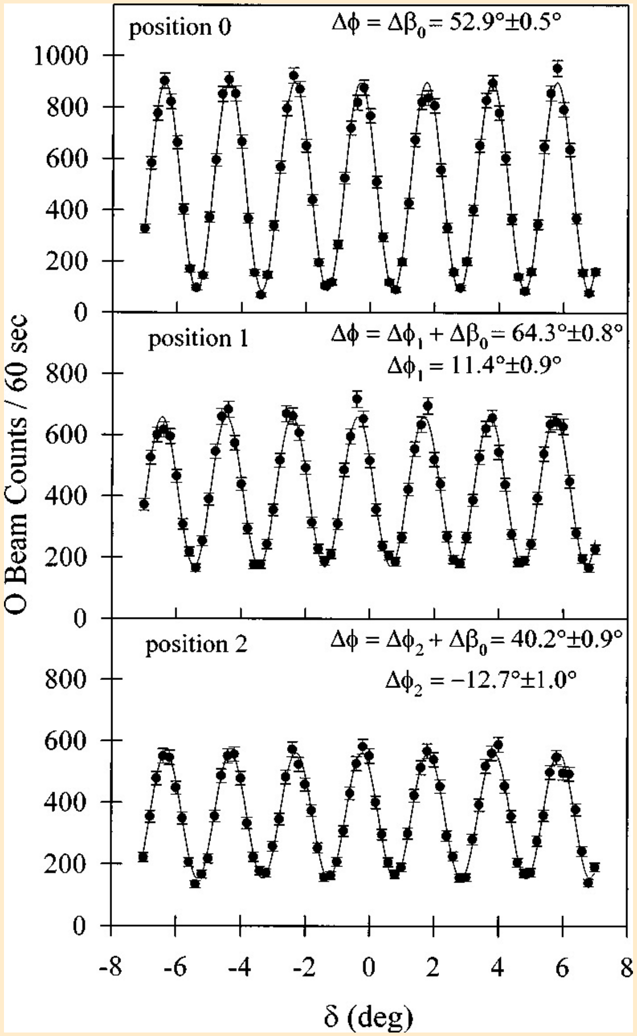
(Received 15 August 1997)

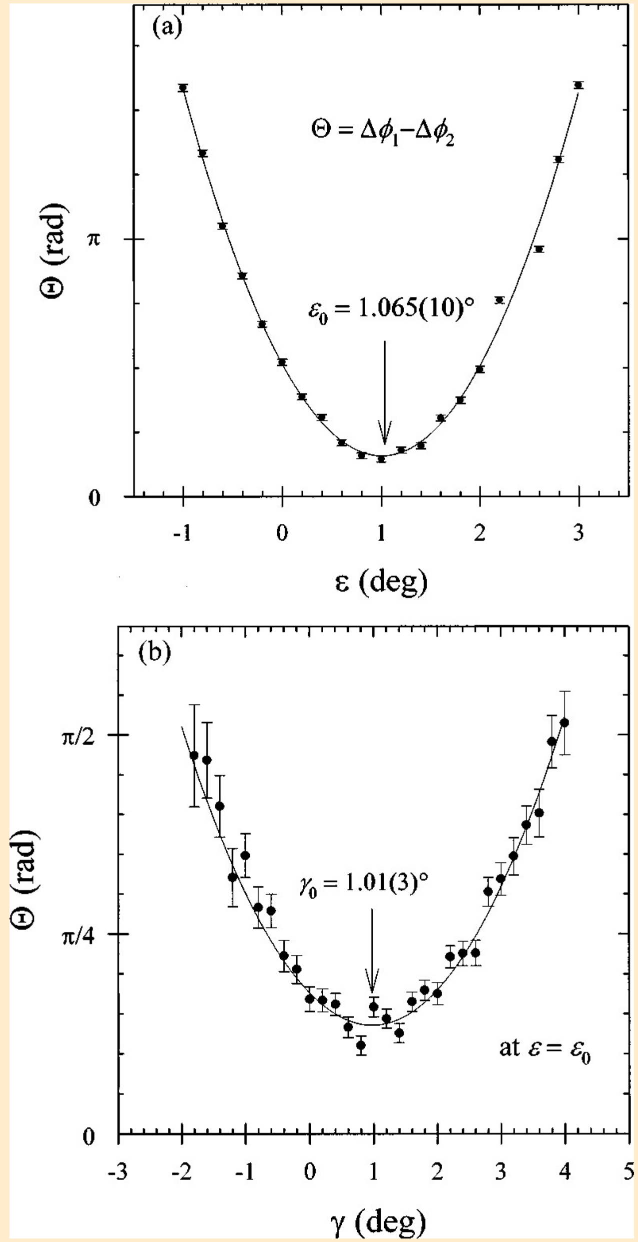
The neutron-interferometry (NI) technique provides a precise and direct way to measure the bound, coherent scattering lengths b of low-energy neutrons in solids, liquids, or gases. The potential accuracy of NI to measure b has not been fully realized in past experiments, due to systematic sources of error. We have used a method which eliminates two of the main sources of error to measure the scattering length of silicon with a relative standard uncertainty of 0.005%. The resulting value, $b=4.1507(2)$ fm, is in agreement with the current accepted value, but has an uncertainty five times smaller. [S1050-2947(98)04808-2]

PACS number(s): 03.75.Dg, 07.60.Ly, 61.12.−q





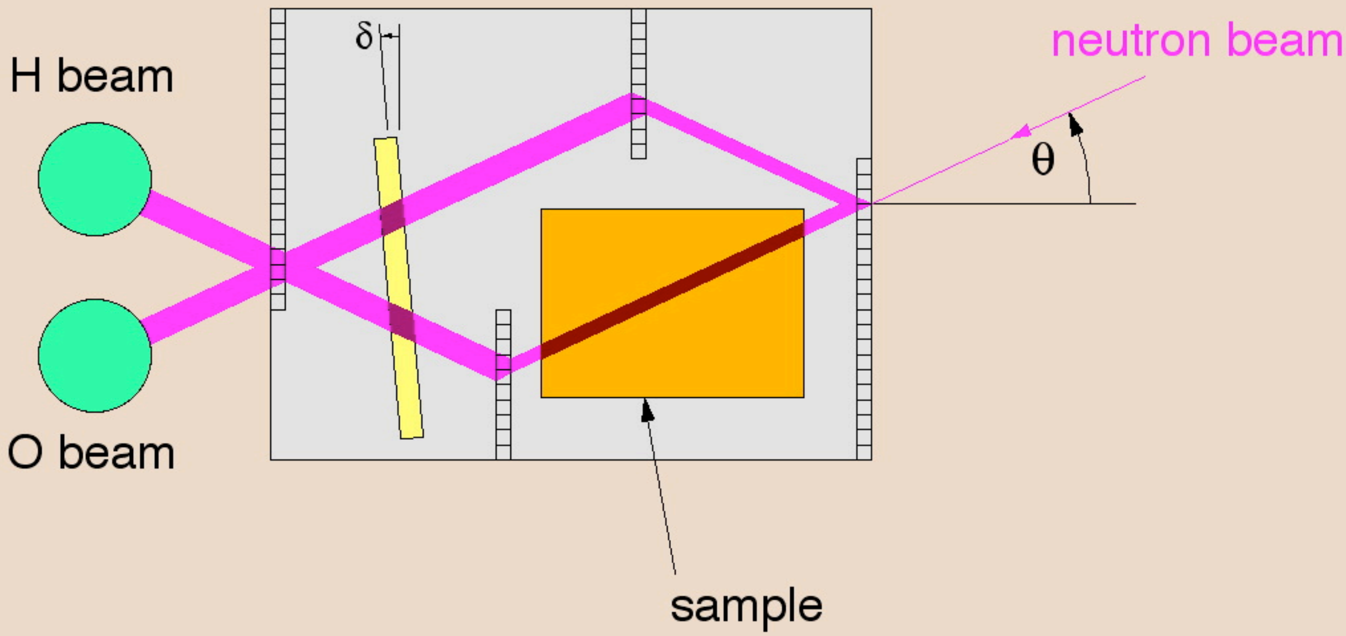




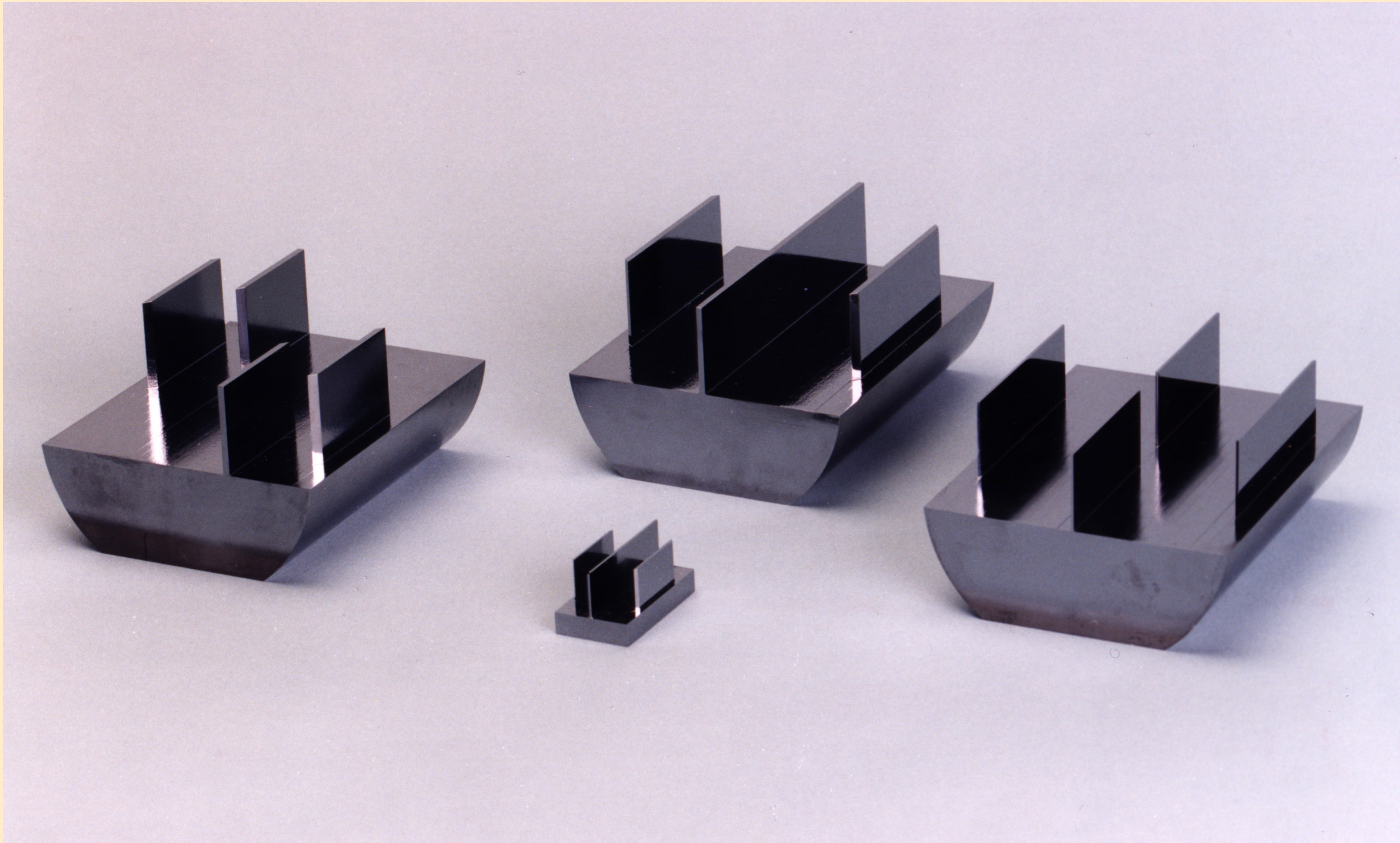
net phase shift: $\Theta\left(\varepsilon_0,\gamma_0\right)=248\pi+0.455(7)$ radians

$b_{\mathrm{coh}}=4.15041(21)$ fm

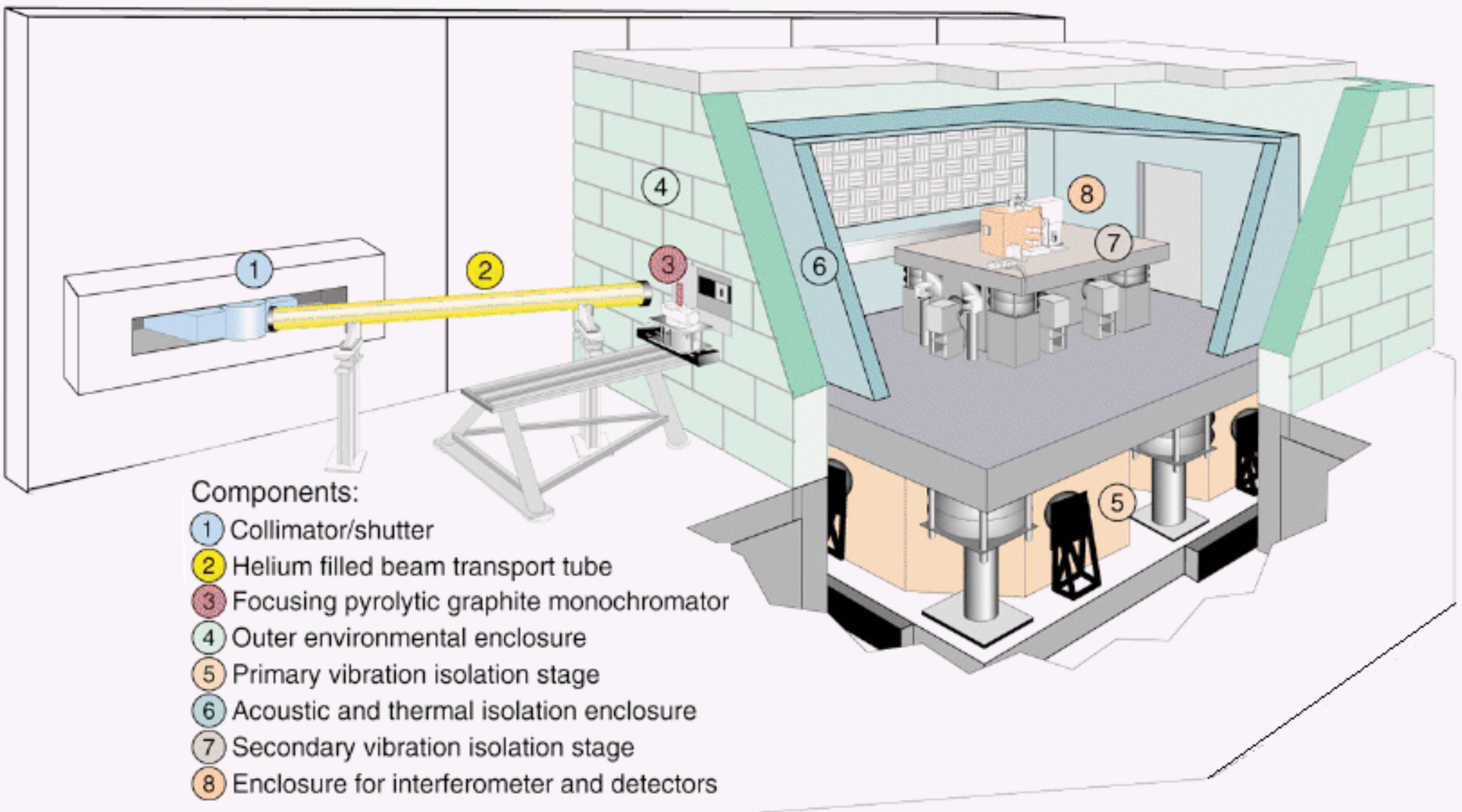
Skew-Symmetric Neutron Interferometer



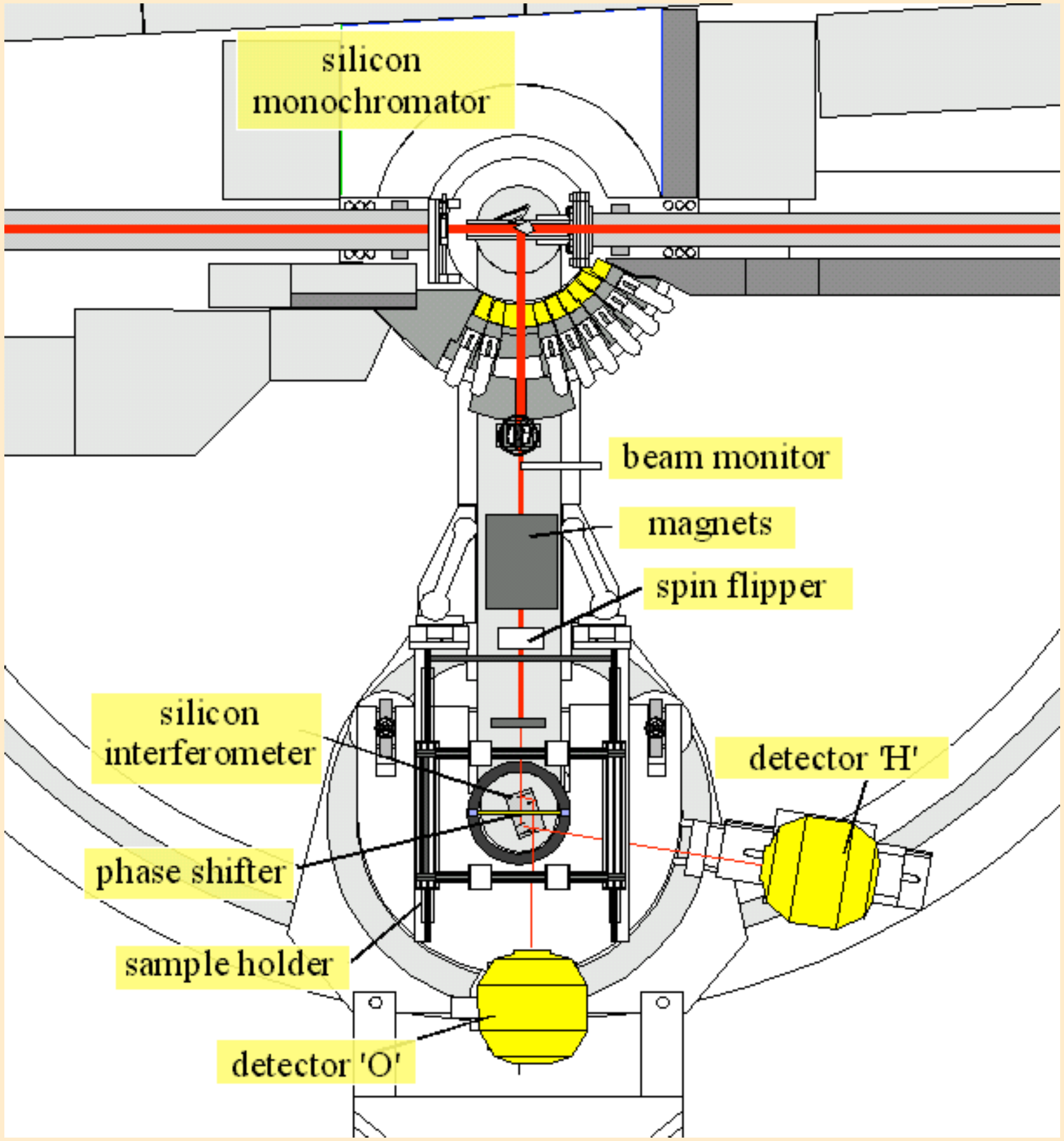
NIST perfect crystal silicon interferometers



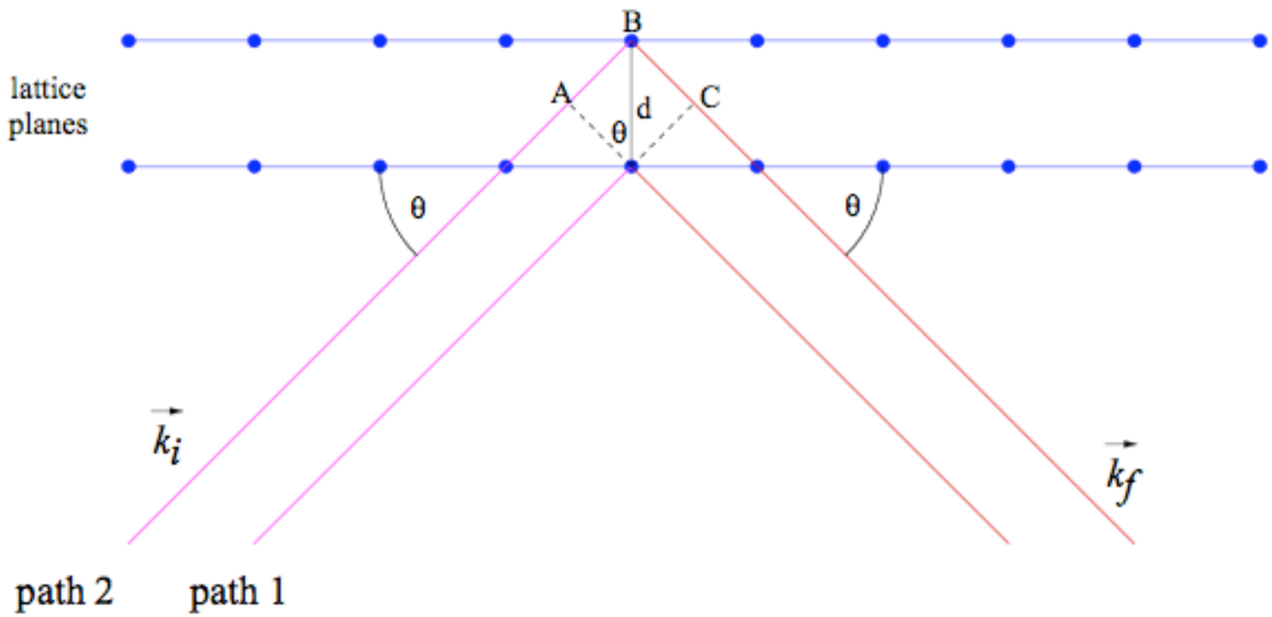
Neutron Interferometer and Optics Facility



S18 Neutron Interferometer at the Institut Laue-Langevin



"Geometric" Bragg Reflection

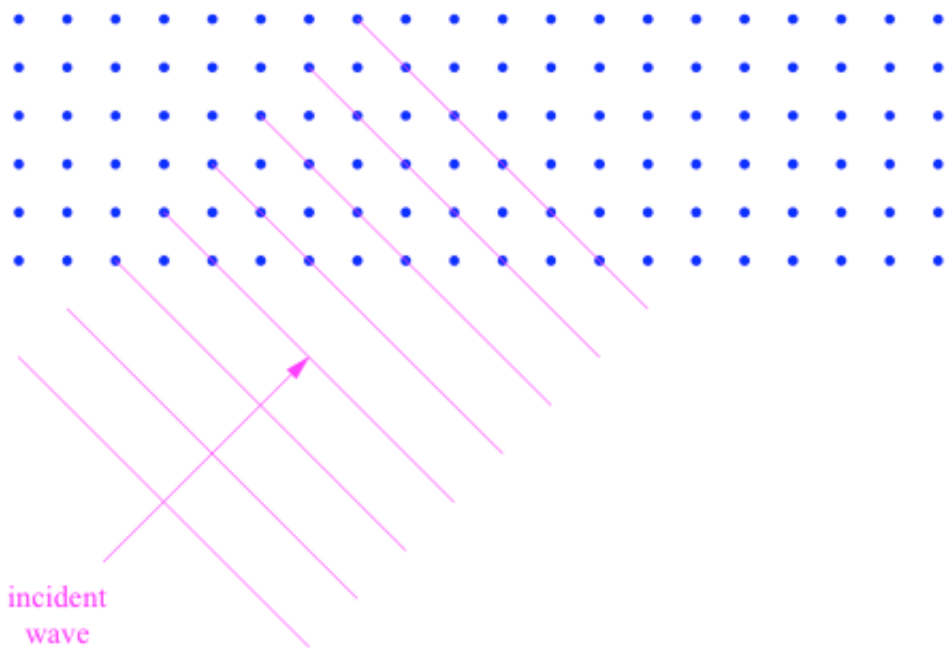


path 2 travels addition distance $\overline{AB} + \overline{BC} = 2d \sin\theta$

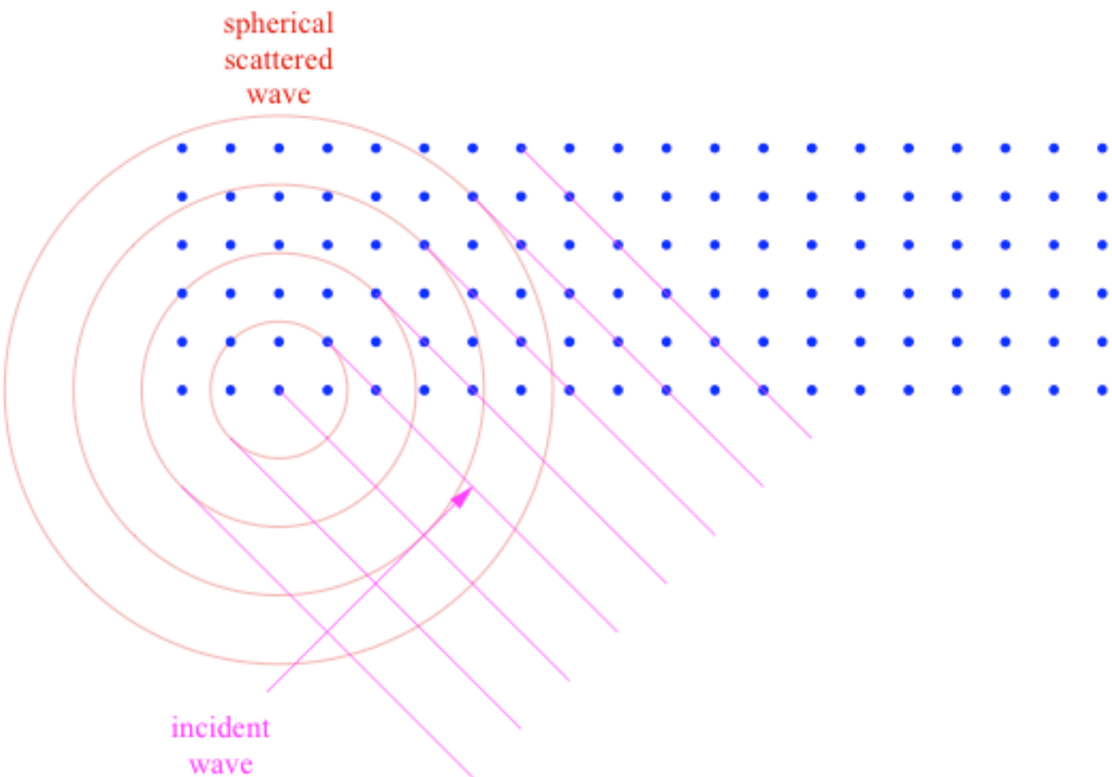
relative phase shift: $\Delta\phi = \dfrac{2d \sin\theta}{\lambda} \times 2\pi$

condition for constructive interference: $n\lambda = 2d \sin\theta$ (Bragg's Law)

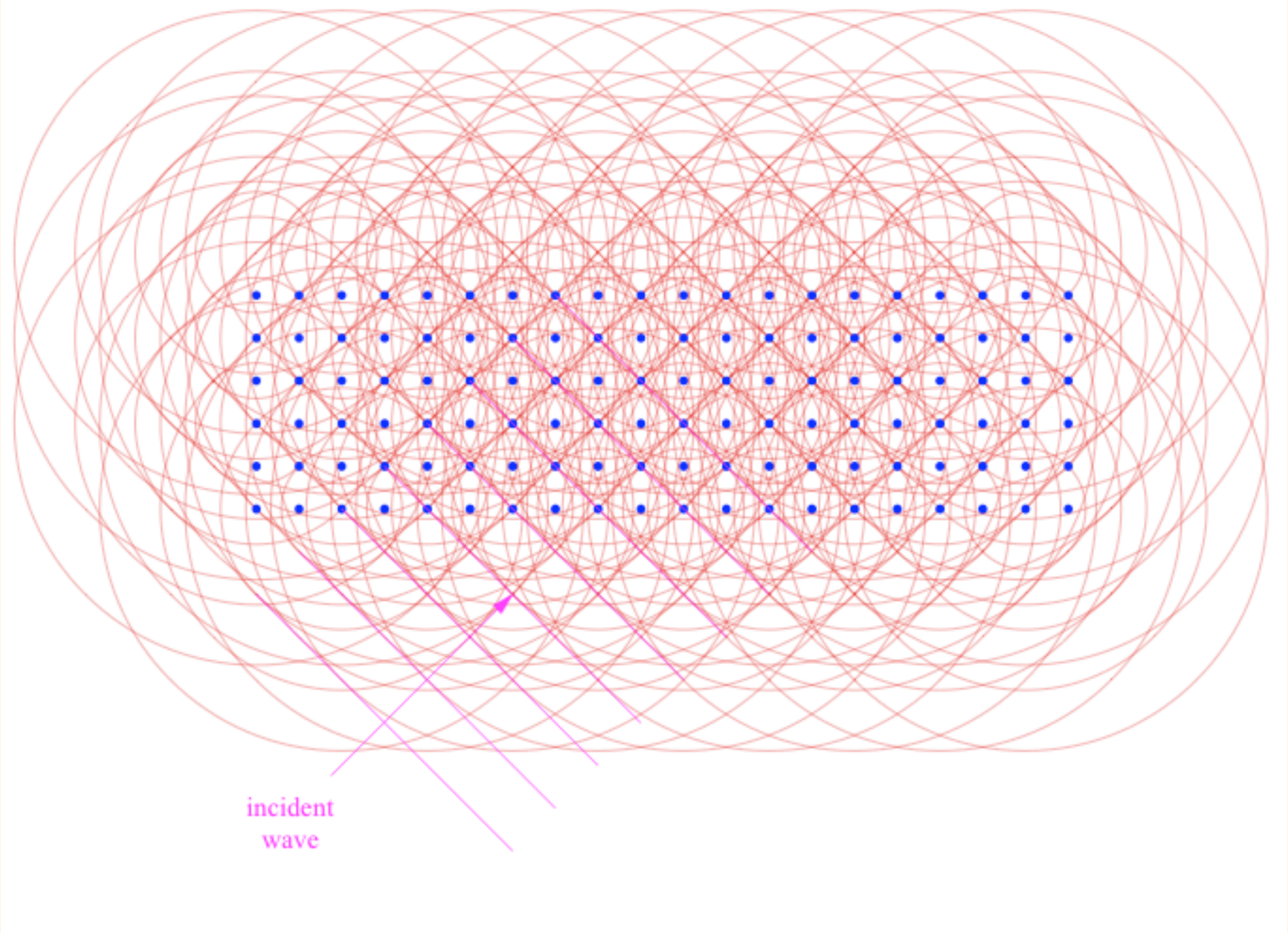
Kinematic Bragg Diffraction



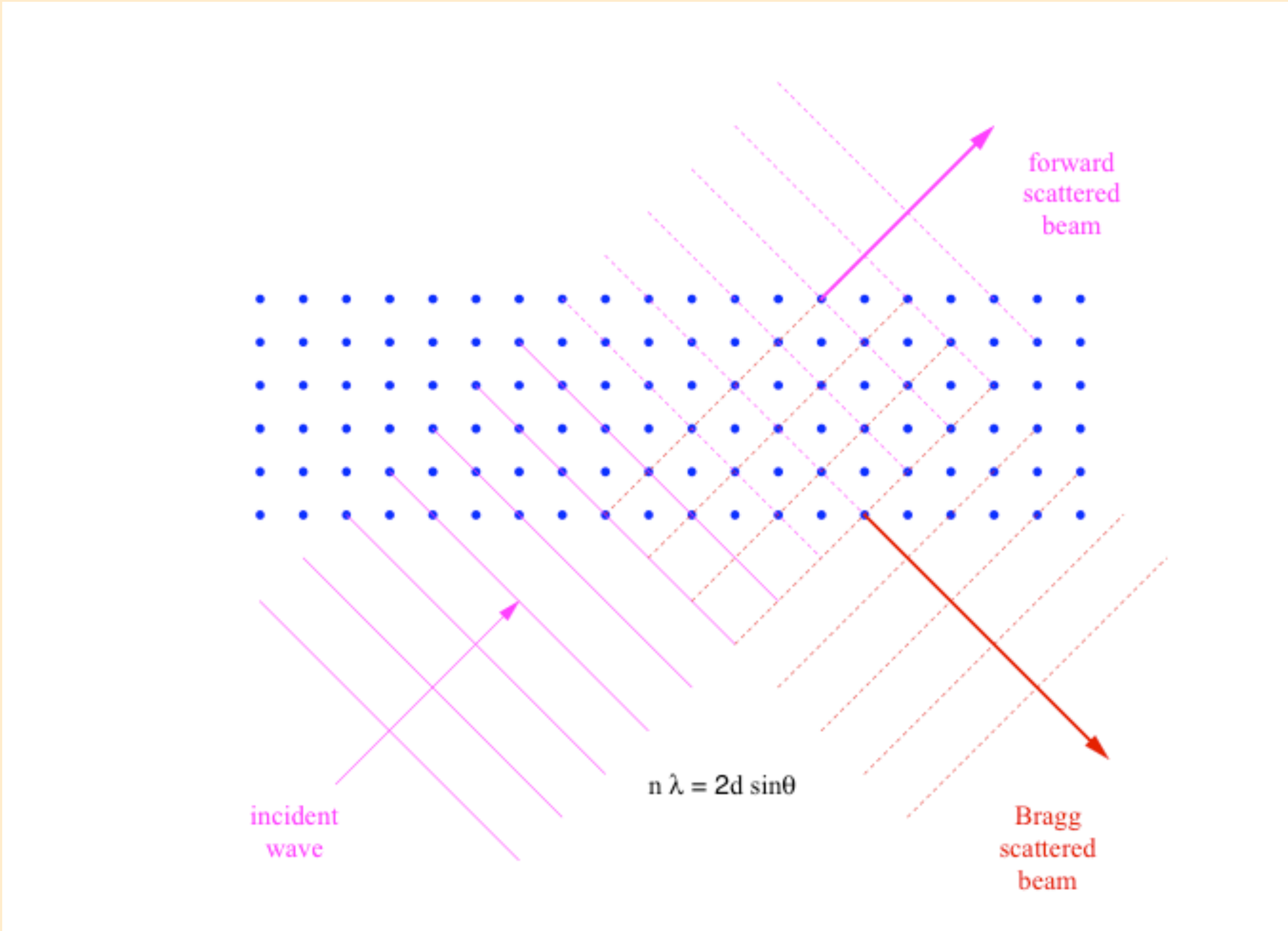
Kinematic Bragg Diffraction



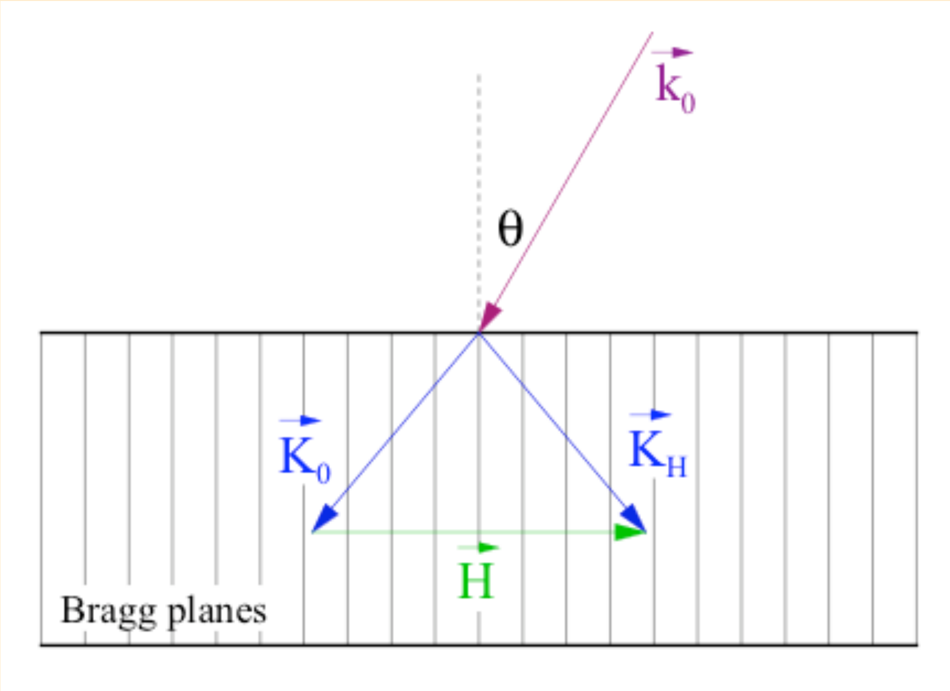
Kinematic Bragg Diffraction



Kinematic Bragg Diffraction



Dynamical Diffraction Theory



$\vec{H}$ = Bragg vector

$$\left|\vec{H}\right| = \frac{2\pi n}{d}$$

$\vec{K}_0$ = internal forward scattered wave

$\vec{K}_H$ = internal Bragg scattered wave

Bragg condition:

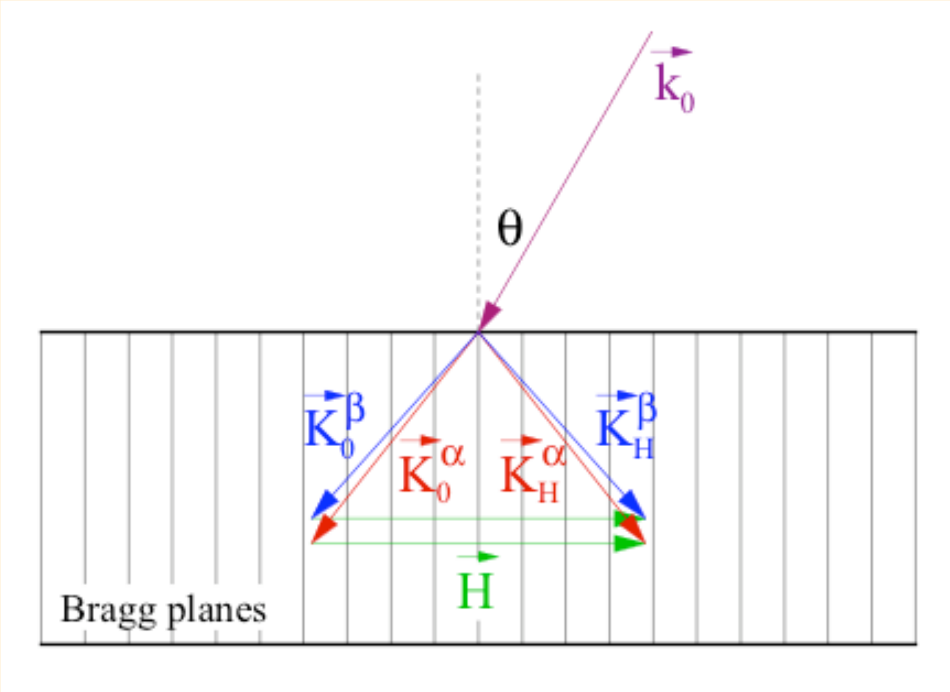
$$\vec{K}_H - \vec{K}_0 = \vec{H}$$

Solve Schrödinger Eqn. inside crystal:

$$\left(\nabla^2 + k_0^2\right)\Psi(\vec{r}) = v(\vec{r})\Psi(\vec{r})$$

$$\text{with} \quad v(\vec{r}) = 4\pi\sum_i b_i \delta\left(\vec{r} - \vec{r}_i\right) = \sum_n v_{H_n} e^{i\vec{H}_n \cdot \vec{r}}$$

Dynamical Diffraction Theory

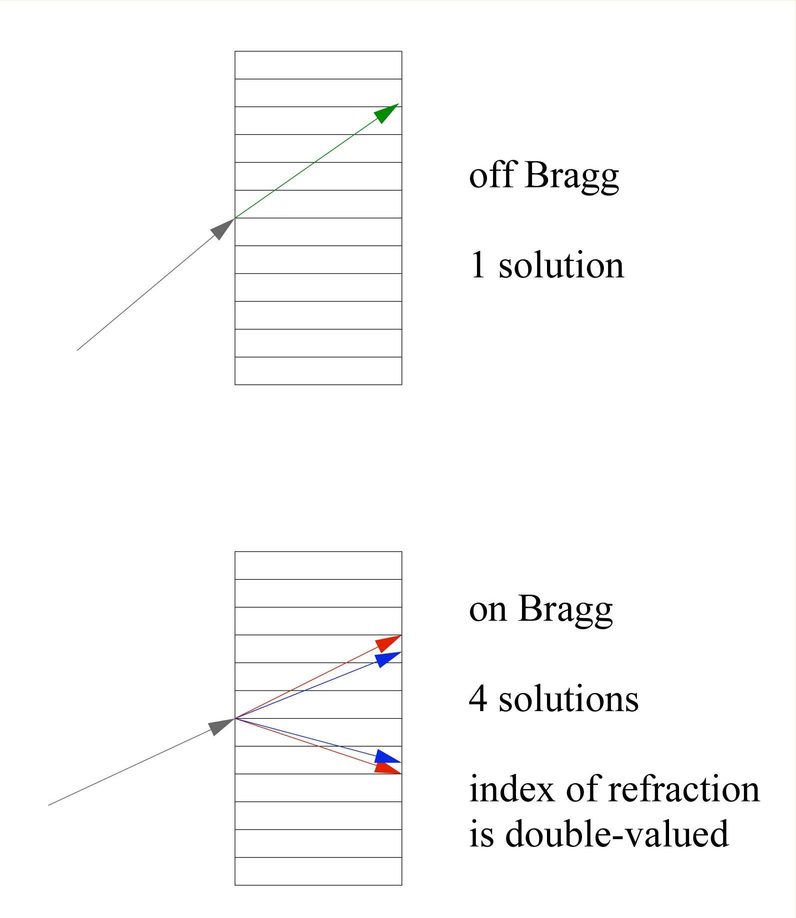


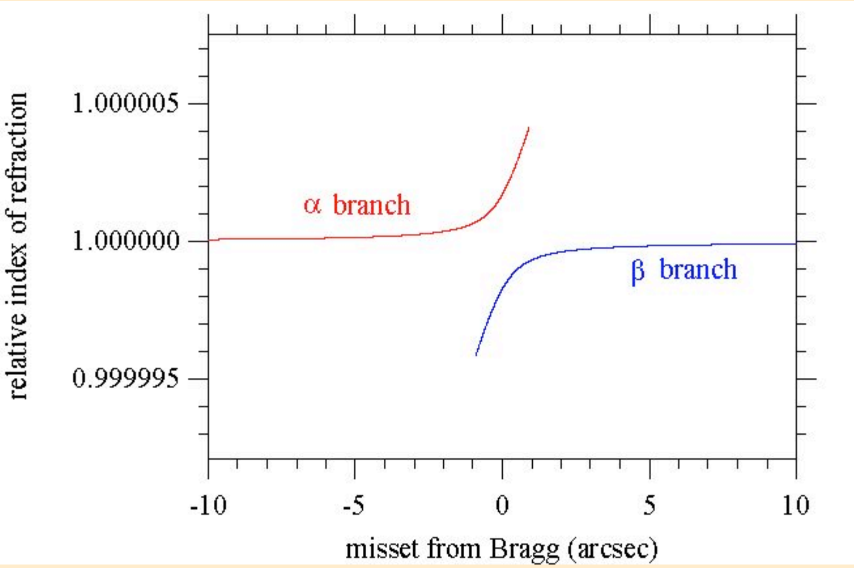
Dispersion Equation: $$\left(K^2 - K_0^2\right)\left(K^2 - K_H^2\right) = v_H^2$$

approximate: $$\left(K - K_0\right)\left(K - K_H\right) = \frac{v_H^2}{4k_0^2}$$

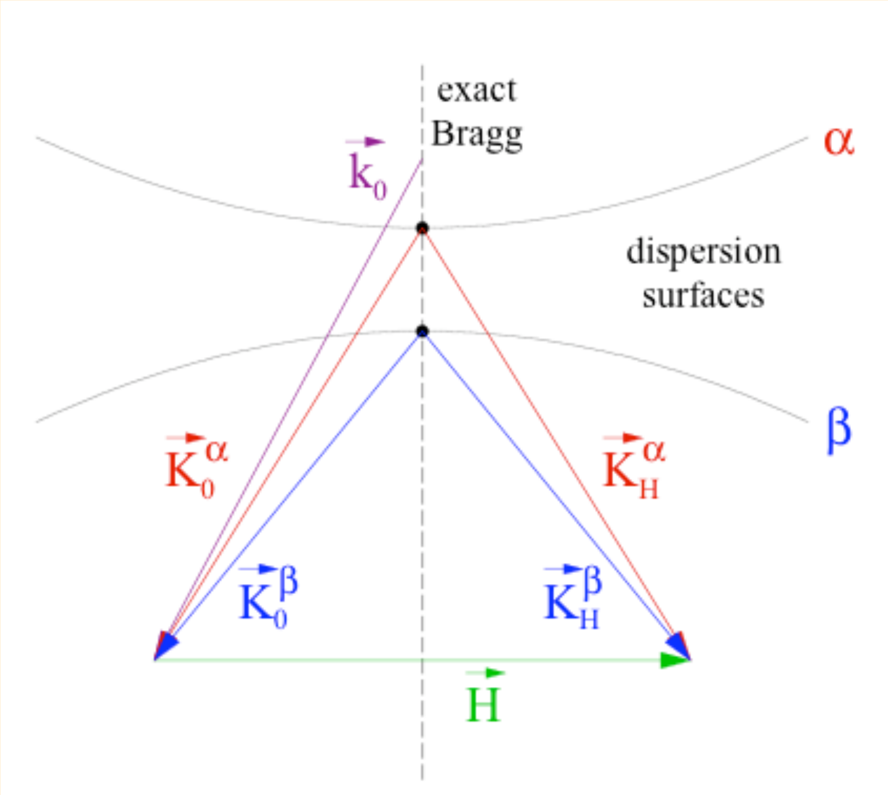
quadratic equation
2 solutions for K_0

Dynamical Diffraction Theory



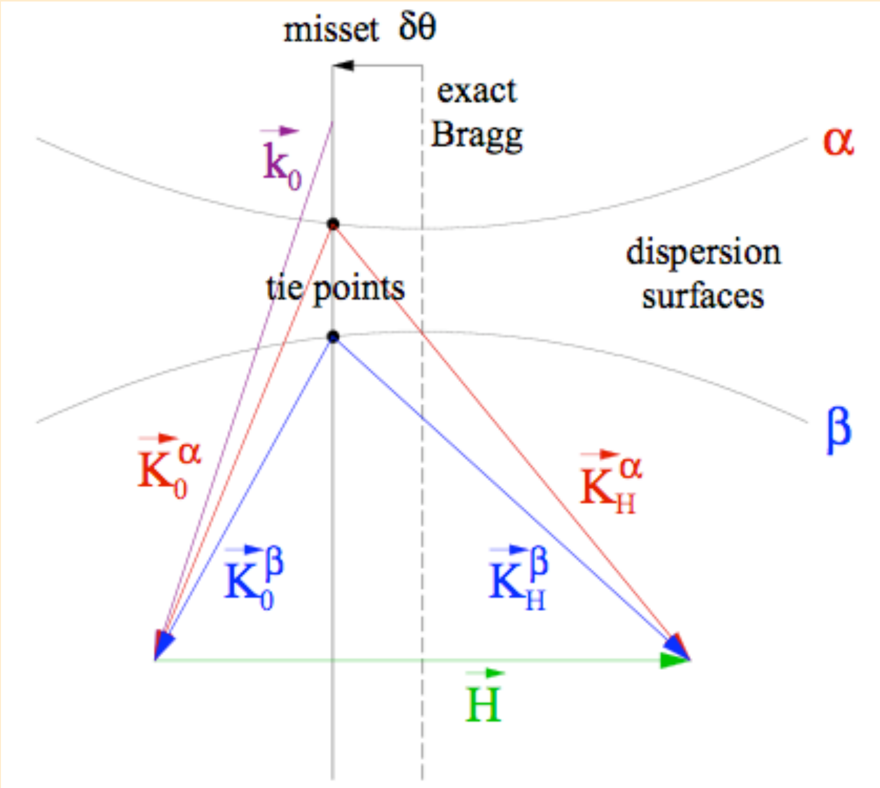


Dynamical Diffraction Theory



internal wave function: $\Psi(\vec{r}) = \psi_0^\alpha e^{i\vec{K}_0^\alpha \cdot \vec{r}} + \psi_0^\beta e^{i\vec{K}_0^\beta \cdot \vec{r}} + \psi_H^\alpha e^{i\vec{K}_H^\alpha \cdot \vec{r}} + \psi_H^\beta e^{i\vec{K}_H^\beta \cdot \vec{r}}$

Dynamical Diffraction Theory



$$\psi_0^\alpha = \frac{1}{2}\left[1 - \frac{y}{\sqrt{1+y^2}}\right]A_0$$

$$\psi_0^\beta = \frac{1}{2}\left[1 + \frac{y}{\sqrt{1+y^2}}\right]A_0$$

$$\psi_H^\alpha = -\frac{1}{2}\left[\frac{1}{\sqrt{1+y^2}}\right]A_0$$

$$\psi_H^\beta = +\frac{1}{2}\left[\frac{1}{\sqrt{1+y^2}}\right]A_0$$

$$y = \frac{k_0 \sin 2\theta_B}{2v_H}\delta\theta$$

misset parameter

internal wave function: $\Psi(\vec{r}) = \psi_0^\alpha e^{i\vec{K}_0^\alpha \cdot \vec{r}} + \psi_0^\beta e^{i\vec{K}_0^\beta \cdot \vec{r}} + \psi_H^\alpha e^{i\vec{K}_H^\alpha \cdot \vec{r}} + \psi_H^\beta e^{i\vec{K}_H^\beta \cdot \vec{r}}$

Dynamical Diffraction Theory

Transmitted wave: $$\Psi_{\text{trans}}(\vec{r}) = \psi_{\text{tr }0}\, e^{i\vec{k}_0\cdot\vec{r}} + \psi_{\text{tr H}}\, e^{i\vec{k}_H\cdot\vec{r}}$$

$$\psi_{\text{tr }0} = \left[\cos\Phi - \frac{iy}{\sqrt{1+y^2}}\sin\Phi\right] e^{i(\phi_1-\phi_0)} A_0$$

$$\psi_{\text{tr H}} = \left[\frac{-iy}{\sqrt{1+y^2}}\sin\Phi\right] e^{-i(\phi_1+\phi_0)} A_0$$

with

$$\phi_0 = \frac{\nu_0 D}{\cos\theta_B} \quad , \quad \phi_1 = \frac{\nu_H D}{\cos\theta_B}$$

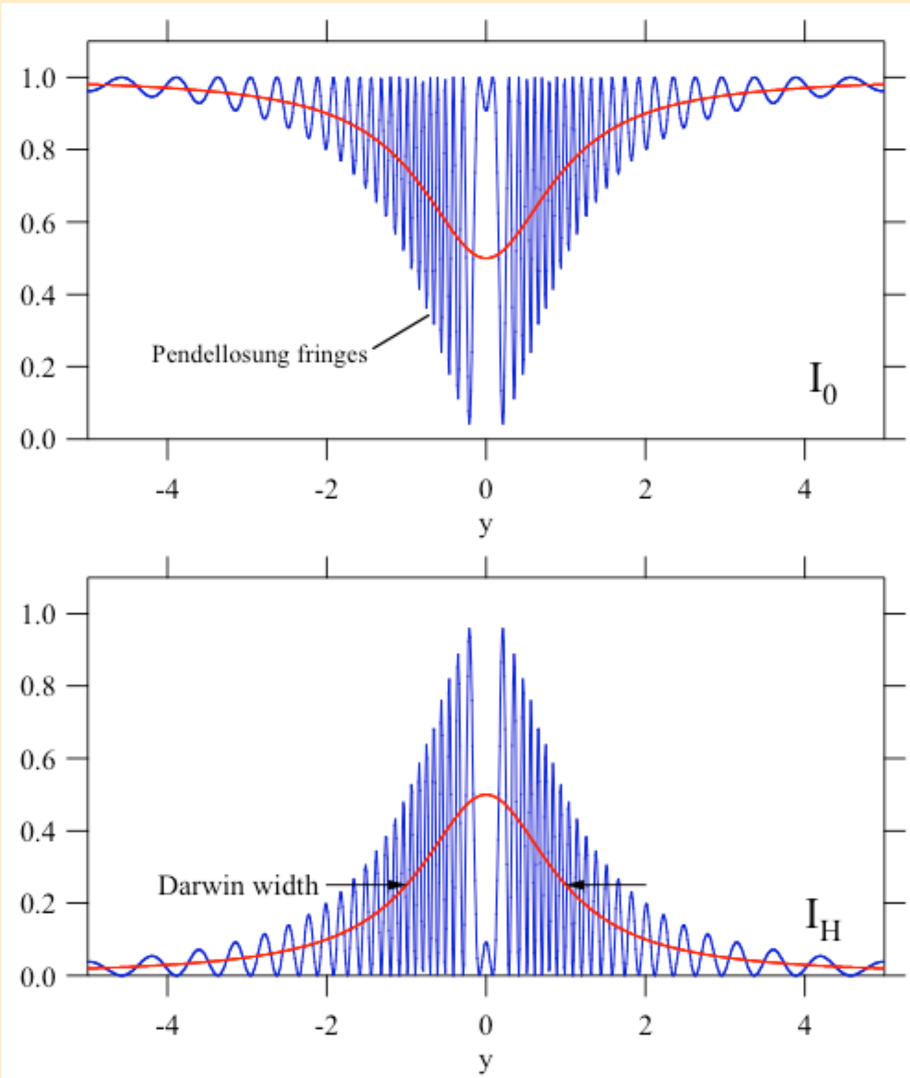
$$\Phi = \left(\nu_H \frac{1}{\sqrt{1+y^2}}\right)\frac{D}{\cos\theta_B}$$

Transmitted intensities:

$$I_0 = \left|\psi_{\text{tr }0}\right|^2 = A_0^2\left[\cos^2\Phi + \frac{y^2}{1+y^2}\sin^2\Phi\right]$$

$$I_H = \left|\psi_{\text{tr H}}\right|^2 = A_0^2\left[\frac{1}{1+y^2}\sin^2\Phi\right]$$

Transmitted Intensities



For the (111) reflection in Si at λ=2.70 Å:

$$\boxed{y = 1 \quad \rightarrow \quad 0.9 \text{ arcsec}}$$

Some Consequences of Dynamical Diffraction

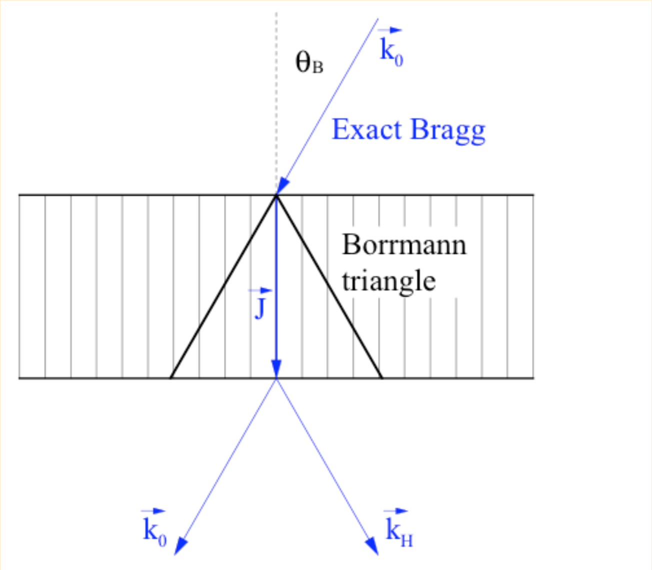
- Pendellösung interference

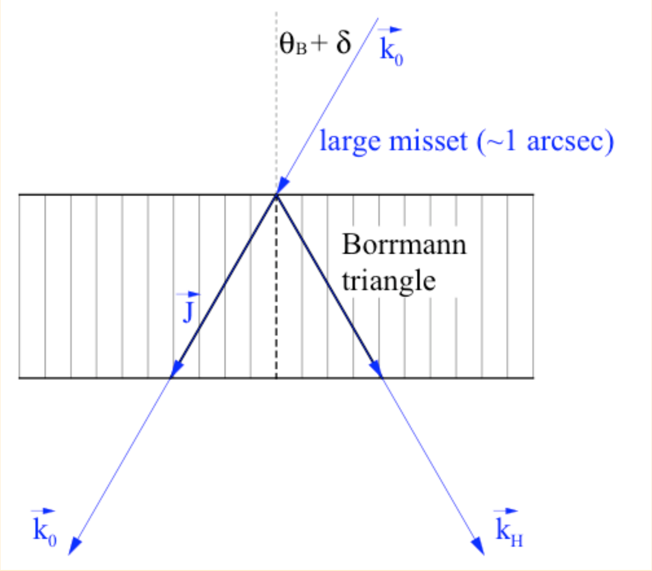
$$\Phi = \left(\nu_H \frac{1}{\sqrt{1+y^2}} \right) \frac{D}{\cos\theta_B}$$

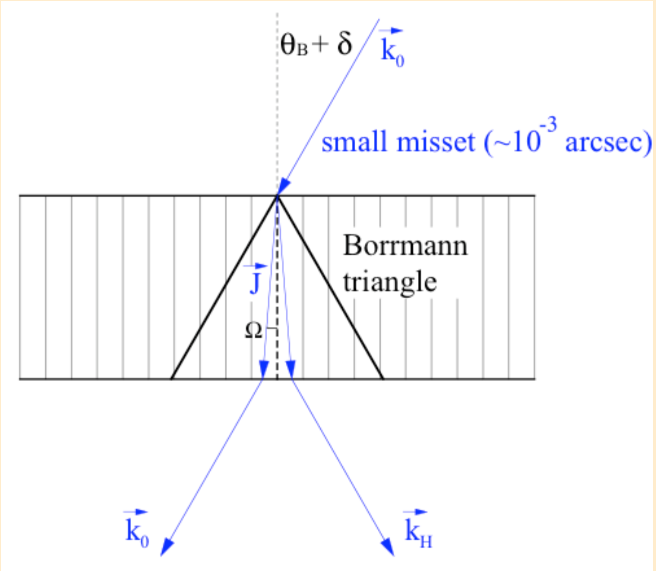
- Anomalous transmission

- Angle amplification

Angle Amplification

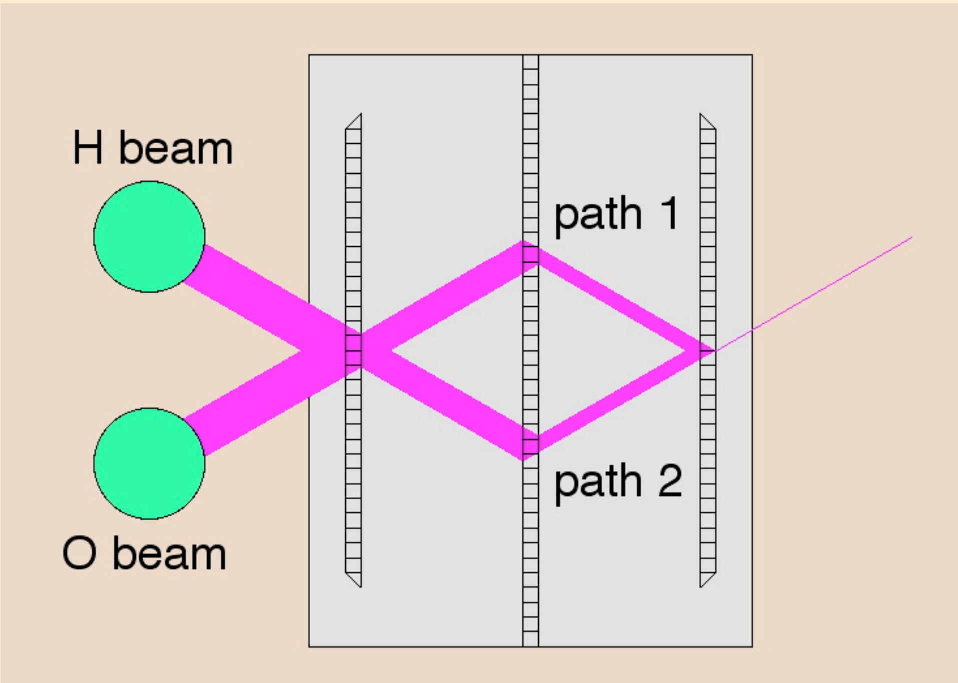


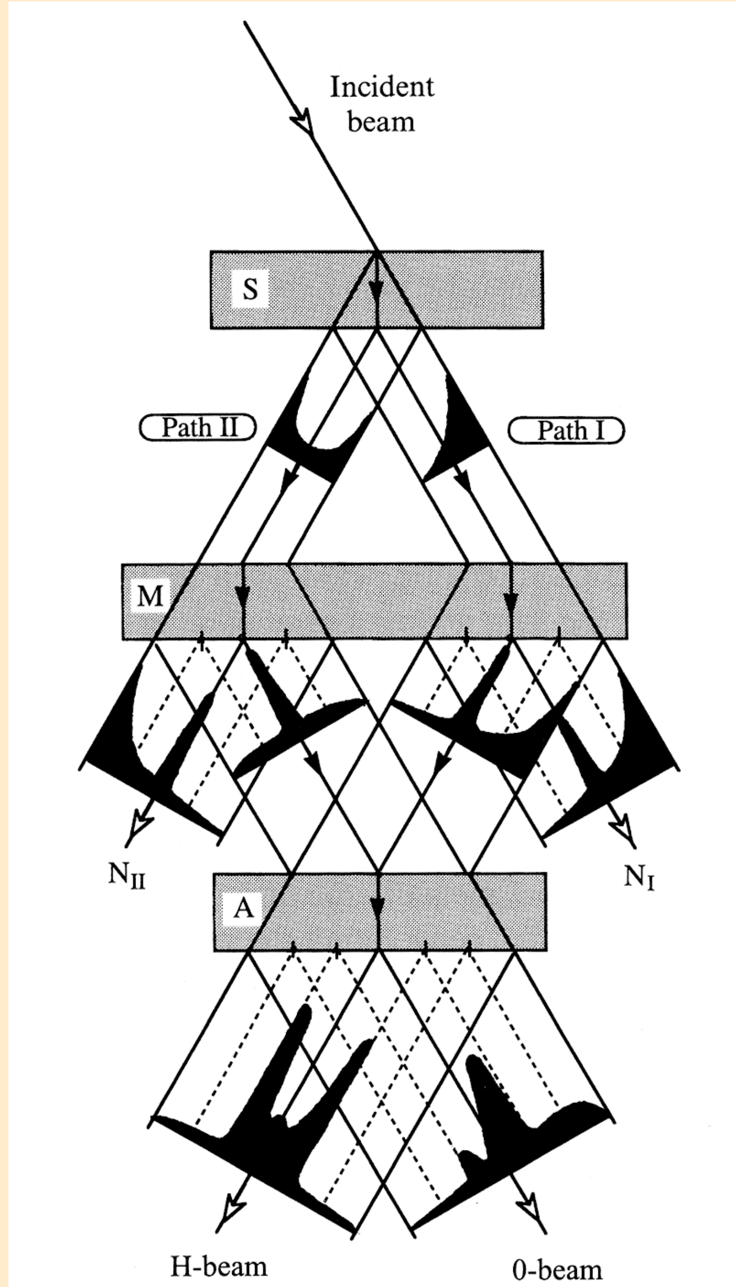




For small δ (~10^{-3} arcsec): $\dfrac{\Omega}{\delta} \approx 10^6$

Practical Neutron Interferometer





4π Rotational Symmetry of Spinors

Rotation operator: $R_{\hat{n}}(\alpha) = e^{-\frac{i}{\hbar}\alpha\hat{n}\cdot\vec{S}}$

Spin-1/2 particle: $\vec{S} = \frac{1}{2}\hbar\vec{\sigma}$ so $R_{\hat{n}}(\alpha) = e^{-i\frac{\alpha}{2}\hat{n}\cdot\vec{\sigma}}$

Rotations about z-axis: $R_z(\alpha) = \begin{pmatrix} e^{-i\alpha/2} & 0 \\ 0 & e^{i\alpha/2} \end{pmatrix}$

Symmetry:

$$R_z(2\pi)\chi = -\chi$$

$$R_z(4\pi)\chi = \chi$$

PHYSICAL REVIEW LETTERS

VOLUME 35 | 20 OCTOBER 1975 | NUMBER 16

Observation of the Phase Shift of a Neutron Due to Precession in a Magnetic Field*

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and

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and

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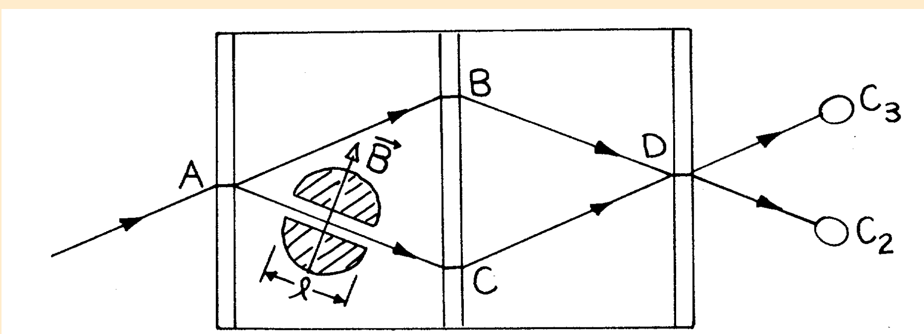
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 27 August 1975)

We have directly observed the sign reversal of the wave function of a fermion produced by its precession of 2π radians in a magnetic field using a neutron interferometer.



Larmor precession phase:

$$\Delta\phi = \pm 2\pi\mu_n m_n \lambda B\ell / \hbar^2$$

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Nuclear Instruments and Methods in Physics Research A 440 (2000) 575–578

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

4π-Periodicity of the spinor wave function under space rotation

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[c]*National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

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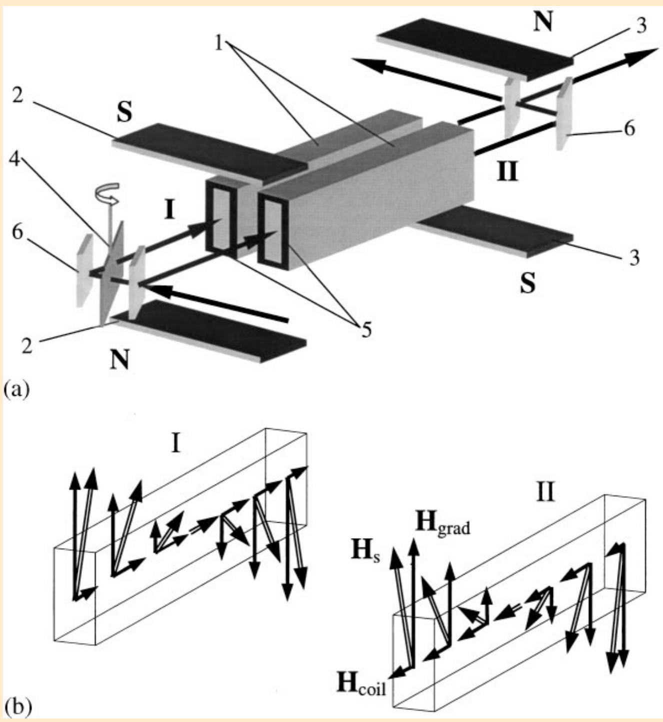
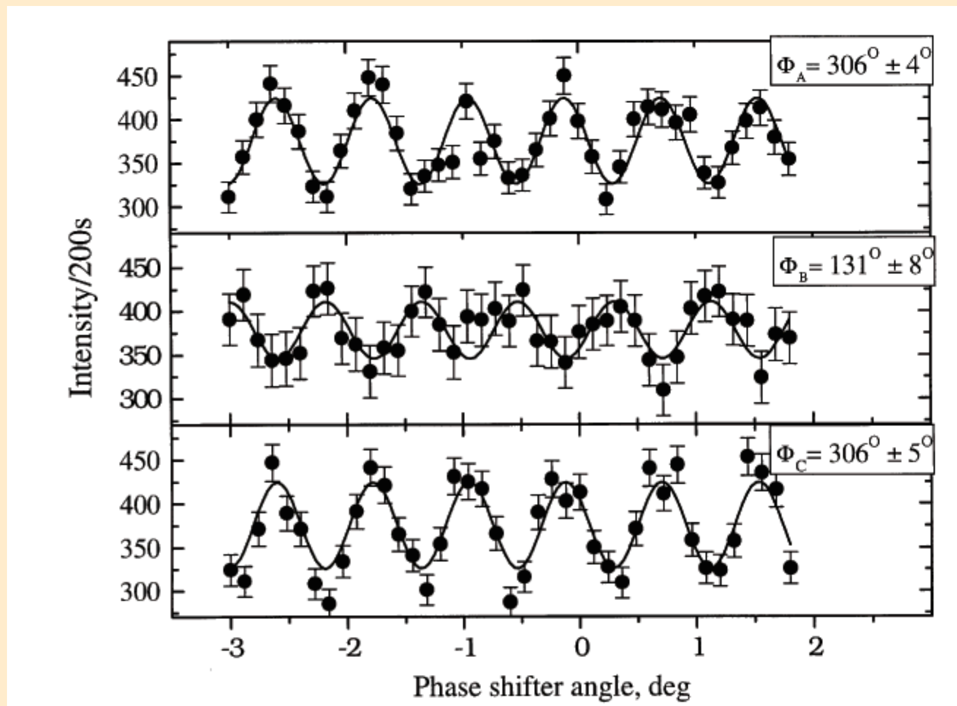
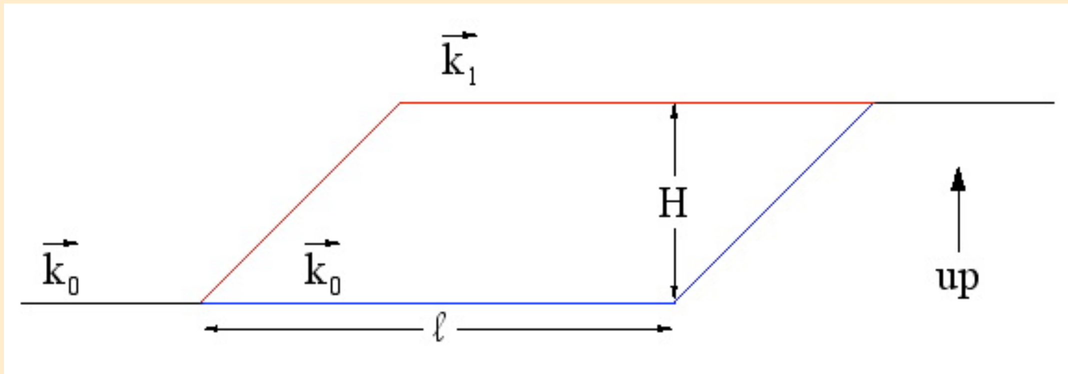




Quantum Phase Shift Due To Gravity (COW Experiments)



$$\boxed{\Delta\phi = \frac{2\pi\lambda g A}{h^2} m_{\text{in}} m_{\text{grav}}}$$

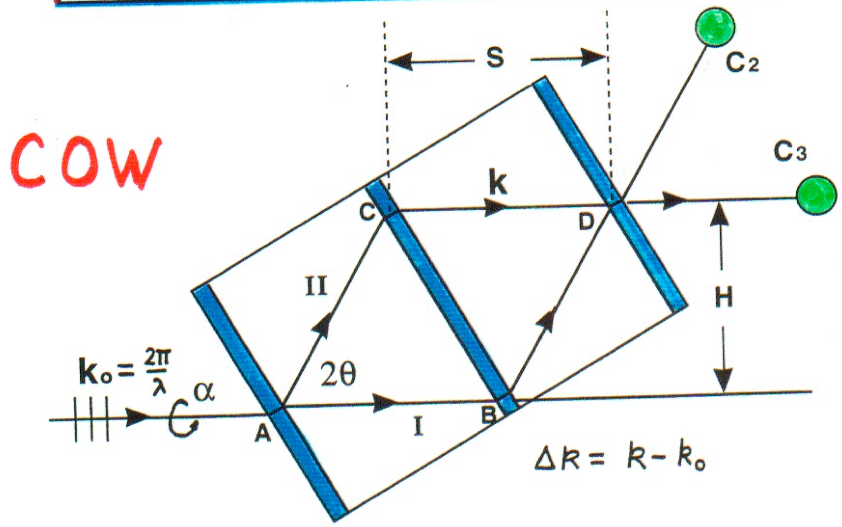
m_{in} = neutron inertial mass

m_{grav} = neutron gravitational mass

$A = H\ell =$ area of parallelogram

test of weak equivalence principle at the quantum limit

GRAVITATIONALLY INDUCED QUANTUM INTERFERENCE



phase difference $= \Delta\Phi = \Delta k \cdot S$

Energy Conservation: $\frac{\hbar^2 k_o^2}{2m} = \frac{\hbar^2 k^2}{2m} + mgH = \mathcal{E}_o$

$$\Delta k = -\frac{1}{2}\,\frac{mgH}{\mathcal{E}_o}\cdot k_o$$

$$H = H_o \sin(\alpha)$$

Thus,

$$\Delta\Phi = -\frac{1}{2}\,\frac{(k_o m g H_o S)\sin(\alpha)}{(\hbar^2 k_o^2/2m)}$$

Or,

$$\Delta\Phi = -2\pi\left(\frac{g}{h^2}\right)\lambda m^2 A \sin(\alpha)$$

$$= q \sin(\alpha)$$

$A = H_o S =$ Enclosed Area of Beam Paths.

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

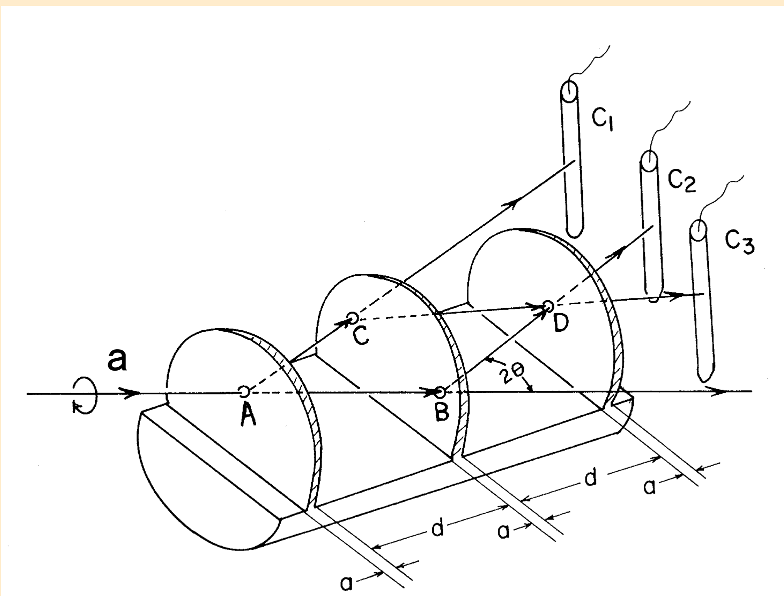
Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

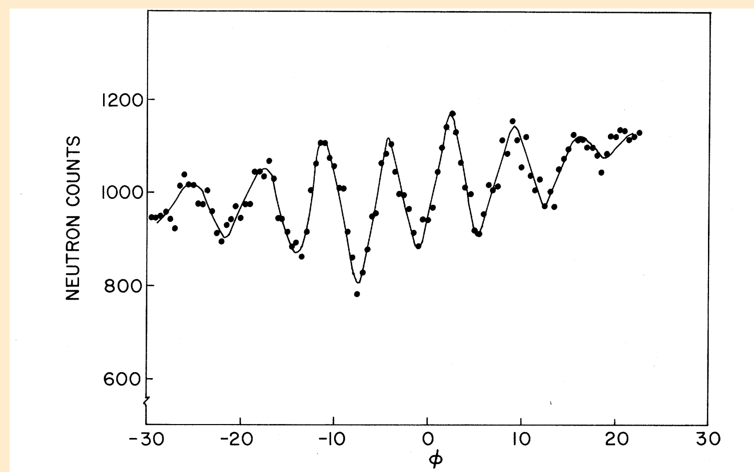
S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.



$$\Delta\phi_{\mathrm{grav}} = \frac{2\pi\lambda g A_0}{h^2} m_{\mathrm{in}} m_{\mathrm{grav}} \sin\alpha = q \sin\alpha$$

$A_0 =$ area of parallelogram at $\alpha = 0$



measured: q = 54.3
theory: q = 59.6

Systematic Effects in the COW Experiments

$$q_{\text{COW}} = \left[\left(q_{\text{grav}}(1+\varepsilon) + q_{\text{bend}} \right)^2 + q_{\text{Sagnac}}^2 \right]^{\frac{1}{2}}$$

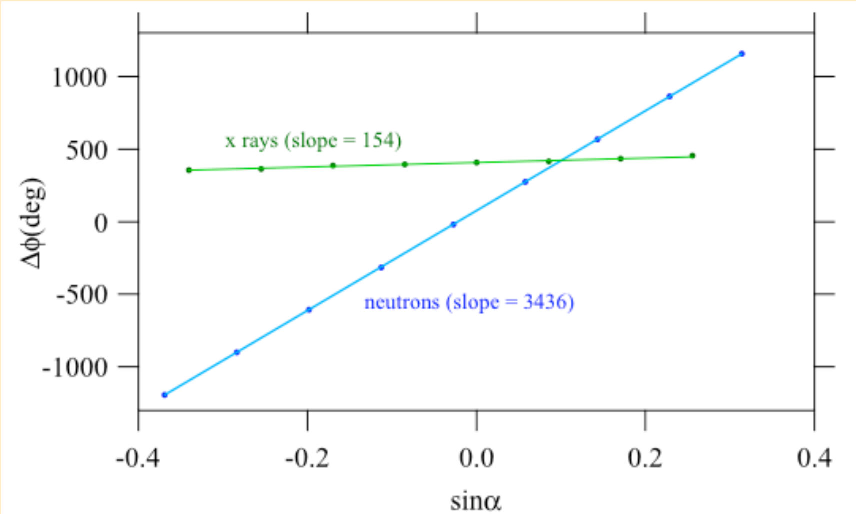
dynamical diffraction correction

bending of interferometer

Earth’s rotation

Sagnac effect: $\Delta\phi_{\text{Sagnac}} = \frac{2m_{\text{in}}}{\hbar}\vec{\Omega}\cdot\vec{A}$ due to Earth's rotating frame

bending effect: repeat experiment with x rays, different wavelengths



data from Werner, *et al.* (1988)

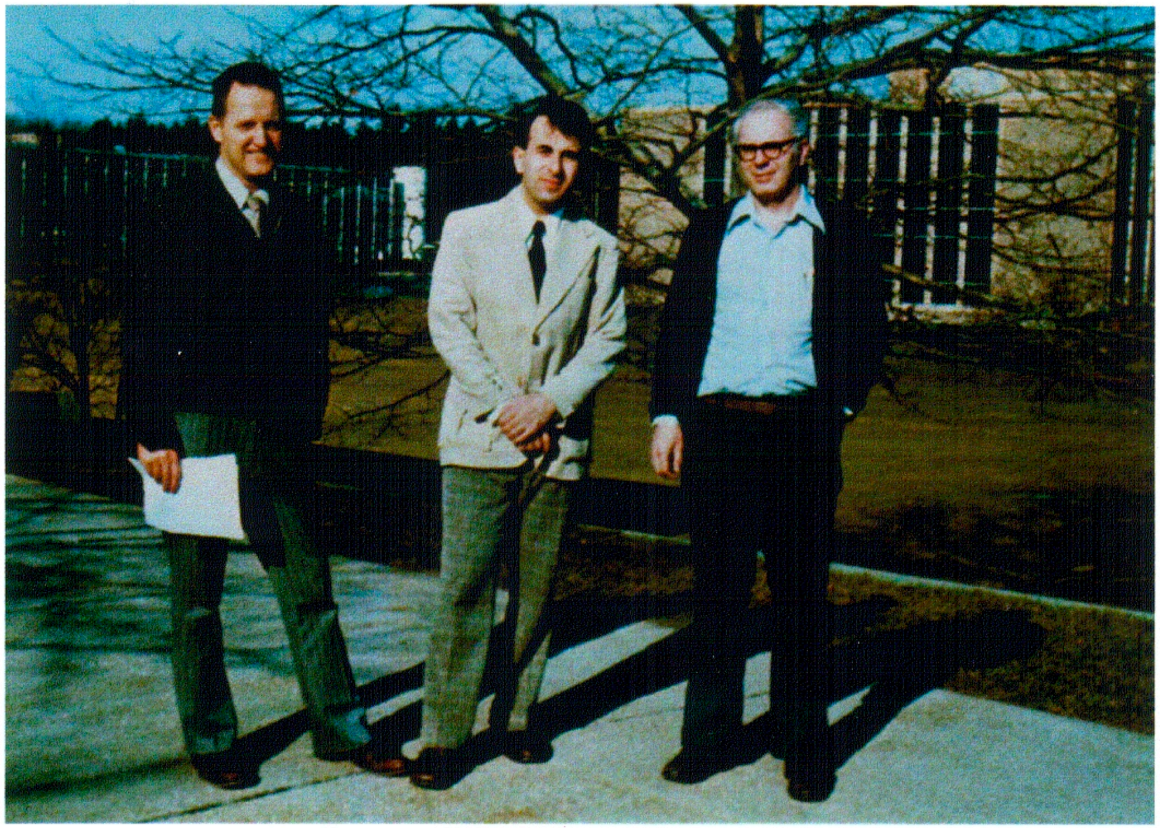
Littrell, *et al.* (1997) results:

experiment	q_{COW} theory [rad]	q_{COW} meas. [rad]	discrepancy (%)
SS, 440	50. 97(5)	50.18(5)	-1. 6
SS, 220	100. 57(10)	99. 02(10)	-1. 5
LLL, 440	113. 60(10)	112. 62(15)	-0. 9
LLL, 220	223. 80(10)	221. 85(30)	-0. 9

Layer and Greene (1991): x rays do not fill the Borrmann fan as completely as neutrons

Upcoming new effort (H. Kaiser, S. Werner, FEW, et al.):

Suspend interferometer inside chamber filled with $ZnBr_2$+D_2O (floating COW)



The COW Experiment

Observation of Gravitationally-Induced Quantum Interference by Neutron Interferometry

(left to right)
Al Overhauser, Roberto Colella, Sam Werner

Photo taken in front of the Phoenix Memorial Laboratory, The University of Michigan, Ann Arbor, 1974

Measuring the Neutron's Mean Square Charge Radius Using Neutron Interferometry

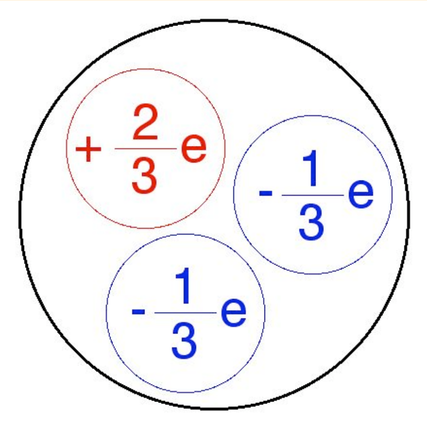
F. E. Wietfeldt, M. Huber
Tulane University, New Orleans, USA

M. Arif, D. L. Jacobson, S. A. Werner
National Institute of Standards and Technology, Gaithersburg, USA

T. C. Black
University of North Carolina, Wilmington, USA

H. Kaiser
Indiana University, Bloomington, USA

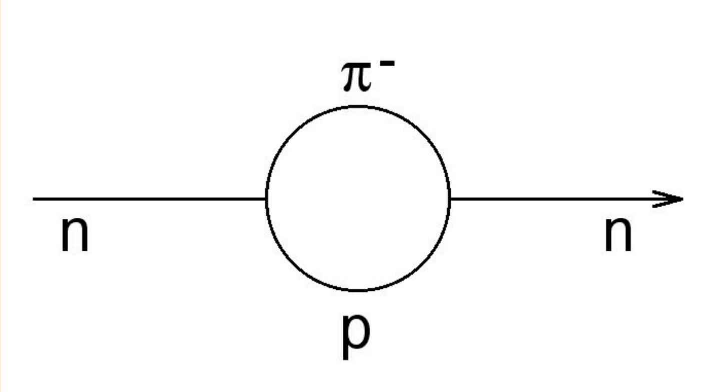
neutron: neutral but consists of charged quarks



neutron mean square charge radius:

$$\left\langle r_n^2 \right\rangle = \int \rho(r)\, r^2 d^3 r$$

expected to be negative (positive core, negative skin):



Fermi and Marshall, 1947

Neutron Electric Scattering Form Factor

$G_E^n(Q^2)$ = Fourier transform of neutron charge density (Breit frame)

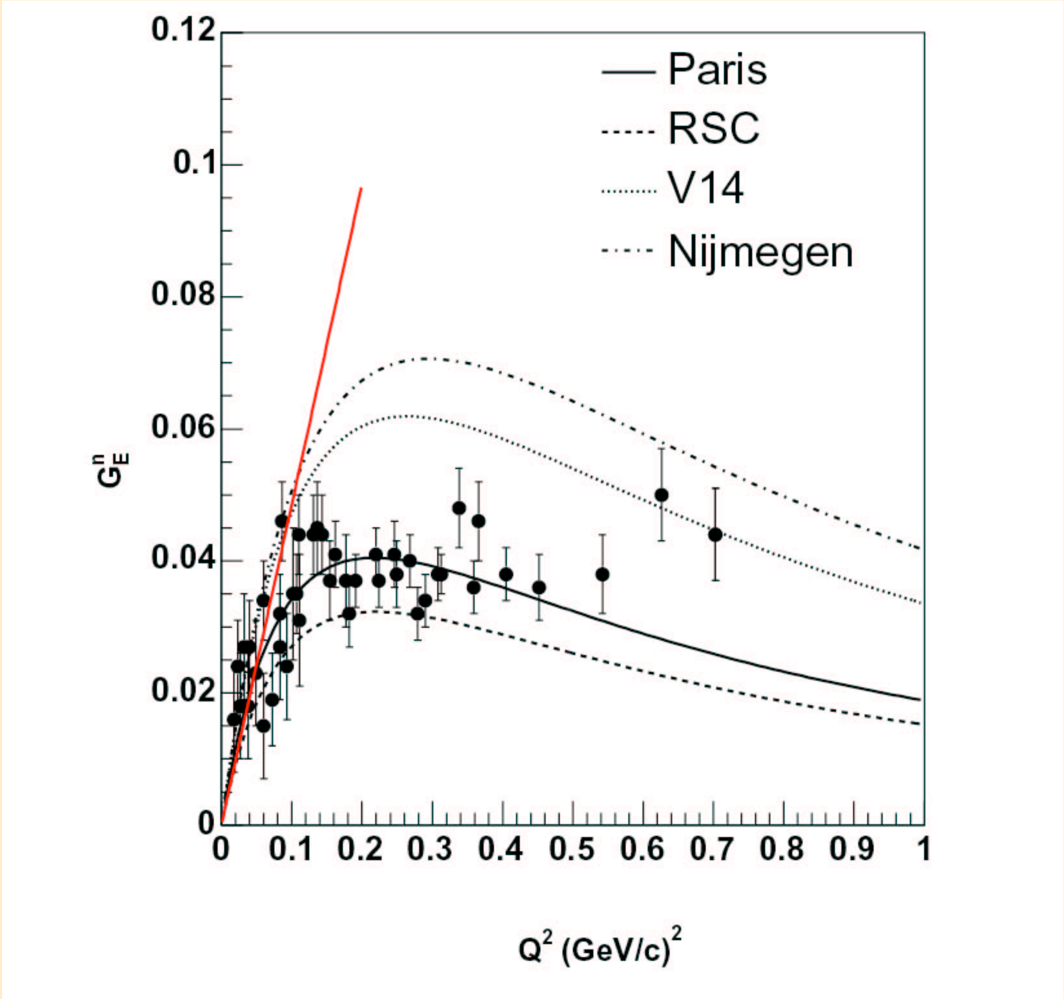
Expanding in momentum transfer Q^2 :

$$G_E^n(Q^2) = q_n - \frac{1}{6}\left\langle r_n^2 \right\rangle Q^2 + \ldots$$

In the low Q^2 limit:

$$\left\langle r_n^2 \right\rangle = -6 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2=0}$$

$\langle r_n^2 \rangle$ constrains the slope of $G_E(Q^2)$ in electron scattering experiments and theory (*e.g*. Bates, Jefferson Lab)



V. Ziskin Ph.D. thesis, 2005

Neutron-Atom Coherent Scattering Length

$$b_{\mathrm{coh}} = b_N + Z\left[1 - f(q)\right]b_{ne}$$

Fourier transform of charge density

$$f(q) = \frac{1}{\sqrt{2\pi}}\int e^{iq\cdot r}\rho_{\mathrm{atom}}(r)\,d^3r$$

b_{ne} = neutron-electron scattering length

In 1st Born approximation: $$\left\langle r_n^2 \right\rangle = 3a_0\left(\frac{m_e}{m_n}\right)b_{ne} = \left(86.34\ \mathrm{fm}\right)b_{ne}$$

Foldy Scattering Length

$$b_F = -\frac{\gamma e^2}{2m_e c^2} = -1.468 \times 10^{-3}\ \text{fm}$$ from neutron's magnetic moment

Incorrect interpretation: $b_{ne}(\text{meas.}) = b_{\text{intrinsic}} + b_F$

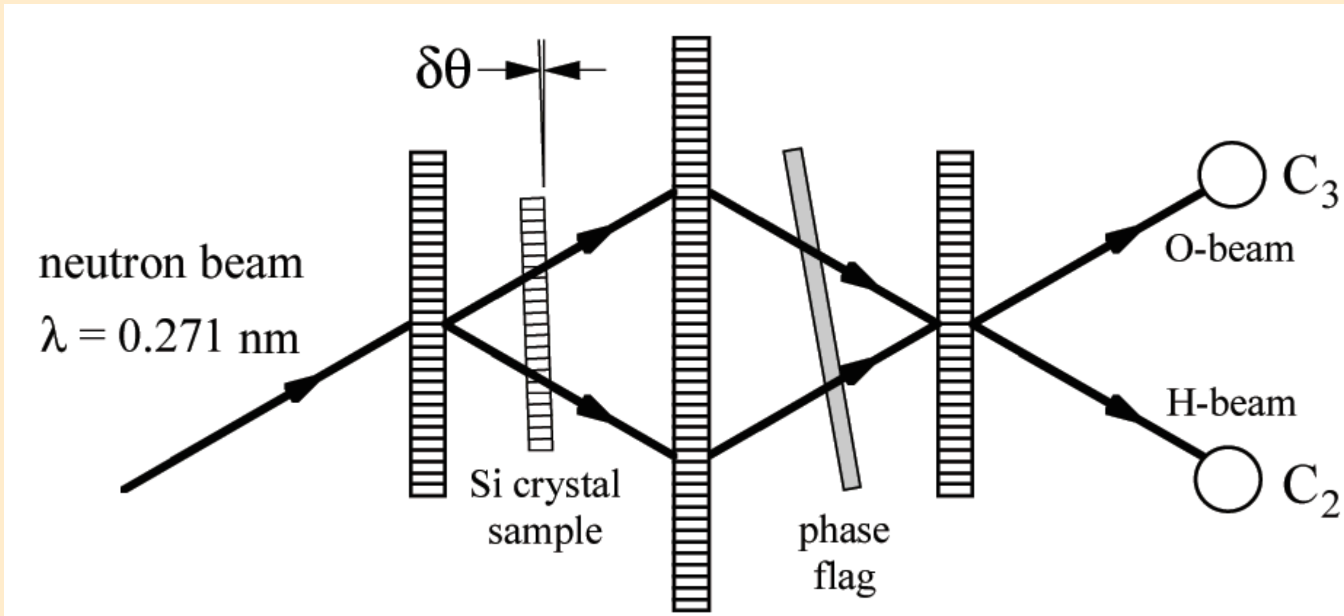
Correct interpretation: The experimentally measured value of b_{ne} is *entirely* due to the static charge distribution in the neutron.
[N. Isgur, Phys. Rev. Lett. **83**, 272 (1999)]

Previous Experiments

TABLE I. Experimental results of b_{ne} in units of 10^{-3} fm.

Experiment	Target	Result	Reference
Angular scattering	Ar	-0.1 ± 1.8	1947 [7] Fermi
Transmission	Bi	-1.9 ± 0.4	1951 [8] Havens
Angular scattering	Kr, Xe	-1.5 ± 0.4	1952 [9] Hamermesh
Mirror reflection	Bi/O	-1.39 ± 0.13	1953 [10] Hughes
Angular scattering	Kr, Xe	-1.4 ± 0.3	1956 [11] Crouch
Crystal spectrometer transmission	Bi	-1.56 ± 0.05	1959 [2] Melkonian
		-1.49 ± 0.05	1976 in Ref. [15]
		$-1.44\pm0.033\pm0.06$	1997 this work
Angular scattering	Ne, Ar, Kr, Xe	-1.34 ± 0.03	1966 [12] Krohn
Angular scattering	Ne, Ar, Kr, Xe	-1.30 ± 0.03	1973 [13] Krohn
Single crystal scattering	^{186}W	-1.60 ± 0.05	1975 [14] Alexandrov
Filter-transmission, mirror reflection	Pb	-1.364 ± 0.025	1976 [15] Koester
Filter-transmission, mirror reflection	Bi	-1.393 ± 0.025	1976 [15] Koester
n-TOF transmission, mirror reflection Ref. [17]	Bi	-1.55 ± 0.11	1986 [16] Alexandrov
Filter-transmission, mirror reflection	Pb, Bi	-1.32 ± 0.04	1986 [17] Koester
n-TOF transmission	thorogenic ^{208}Pb	$-1.31\pm0.03\pm0.04$	1995 [1] Kopecky
		$-1.33\pm0.027\pm0.03$	1997 this work
Filter-transmission, mirror reflection	Pb-isotopes, Bi	-1.32 ± 0.03	1995 [5] Koester
Garching-Argonne compilation	[12,13,15,17]	-1.31 ± 0.03	1986 [3] Sears
Dubna compilation	[14,16]	-1.59 ± 0.04	1989 [19] Alexandrov
Foldy approximation, b_F		-1.468	1952 [18] Foldy

Neutron Interferometer Experiment



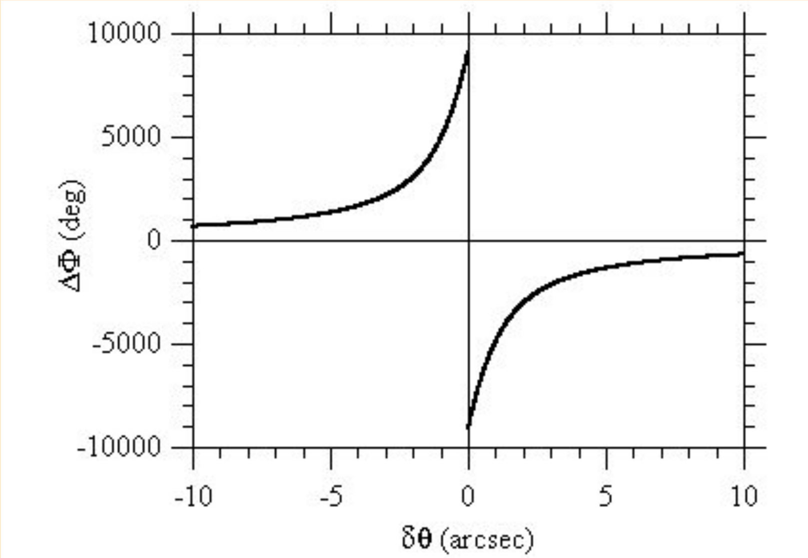
off Bragg: $b_{\text{coh}} = b_N + Z[1 - f(0)]b_{ne} = b_N$

near Bragg: $b_{\text{coh}} = b_N + Z[1 - f(\vec{H}_{111})]b_{ne}$

Dynamical Phase Shift Through Bragg

$$\boxed{\Delta\Phi_{\text{dyn}} = \frac{\nu_H}{\cos\theta_B}\left(y \pm \sqrt{1+y^2}\right)D}$$

$D =$ crystal thickness



scaled misset angle $y = \dfrac{k\sin 2\theta_B}{2\nu_H}$

$$\nu_H = \frac{F_{111}\lambda}{V_{\text{cell}}} = \frac{\sqrt{32}\lambda}{V_{\text{cell}}} b_{\text{coh}}$$

near Bragg: $b_{\text{coh}} = b_N + Z[1 - f(\vec{H}_{111})]b_{ne}$

What we must measure:

1. Net dynamical phase shift through Bragg $\rightarrow$ v_H $\rightarrow$ $b_N + Z[1 - f(\vec{H}_{111})]b_{ne}$
   to $\sim 10^{-5}$

   The maximum slope is $\sim 88\pi/$arcsec so we need 0.01 arcsec angular precision to detect every 2π of phase shift

2. Forward phase shift off Bragg $\rightarrow$ b_N to $\sim 10^{-5}$ and subtract

3. Neutron wavelength to $\sim 10^{-3}$

4. Calculate $f(\vec{H}_{111})$ to $\sim 10^{-3}$

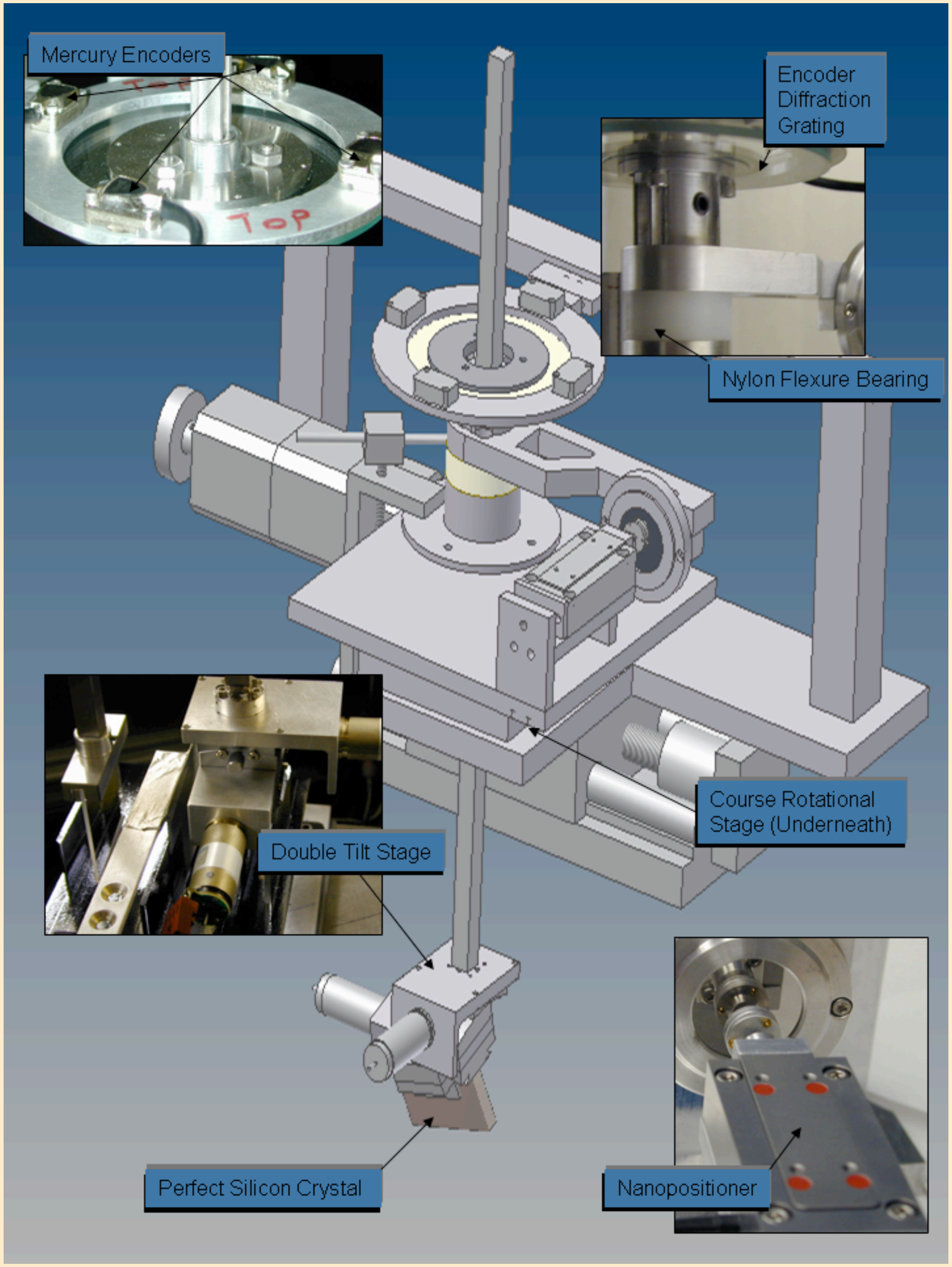
This will give b_{ne}, and hence $\langle r_n^2 \rangle$, to $< 1\%$

Tulane-NIST neutron charge radius experiment

10 cm lever with nylon flexure bearing

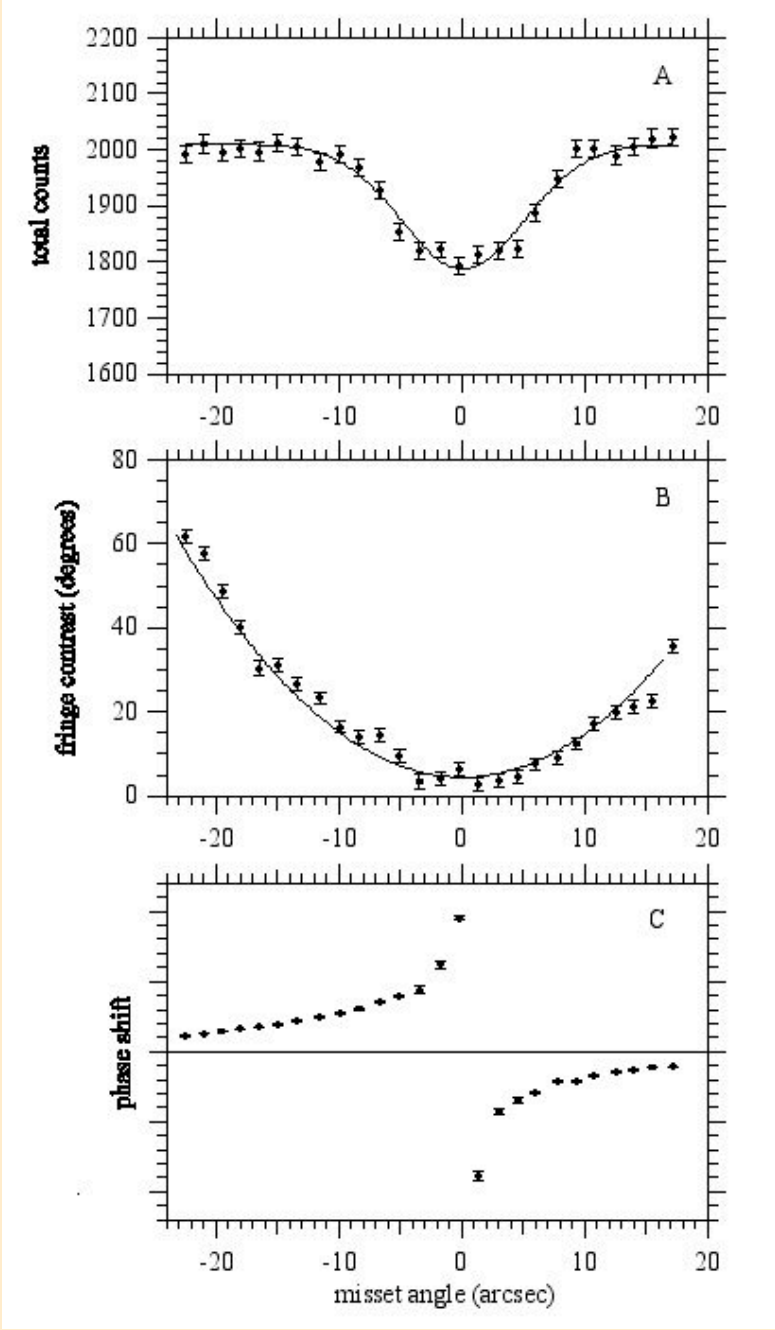
Physik Instrumente
P-753 PZT nanopositioner
25 mm range
1.0 nm precision (.002 arcsec)

Four Micro-E
mercury rotation encoders
.010 arcsec precision



Preliminary Data:

These data were taken at
NIST in September 2005



Precision Neutron Interferometric Measurements of Few-Body Neutron Scattering Lengths

F.E. Wietfeldt, M. Huber, P. Hao
Tulane University

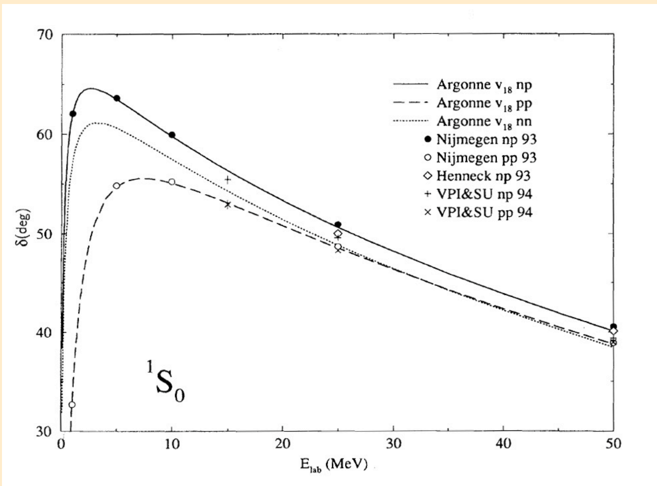
D.L. Jacobson, M. Arif, T. Gentile, W.C. Chen,
D. Pushin, P.R. Huffman, S.A. Werner
NIST

T. C. Black
University of North Carolnia, Wilmington

H. Kaiser, K. Schoen
University of Missouri-Columbia

W. M. Snow
Indiana University

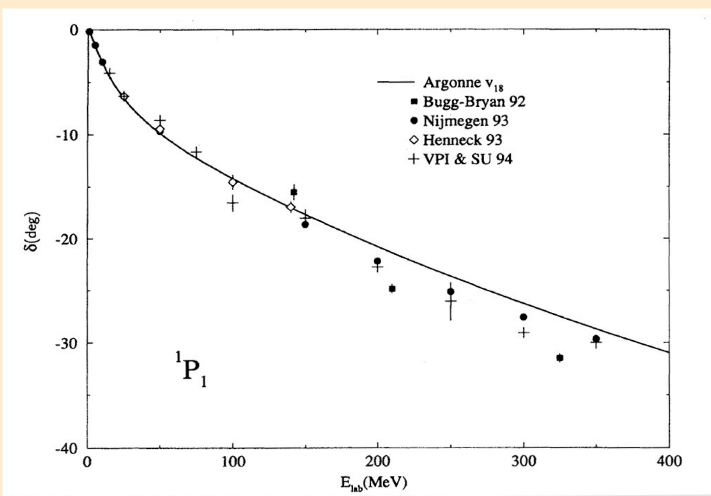
Semi-phenomological nucleon-nucleon potential model AV18

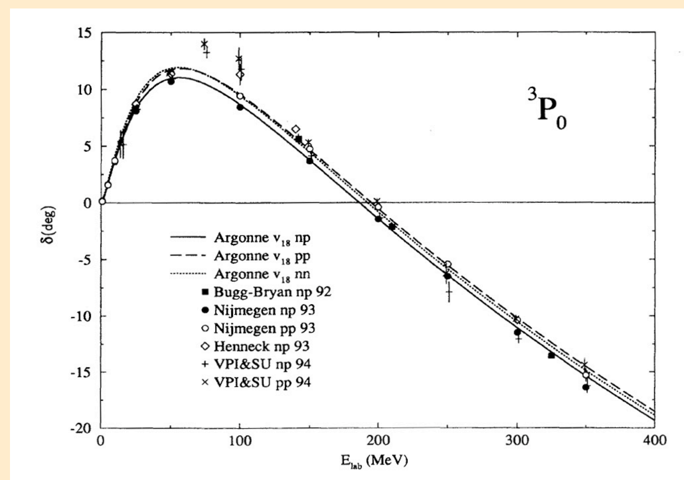


Great success with NN scattering lengths,

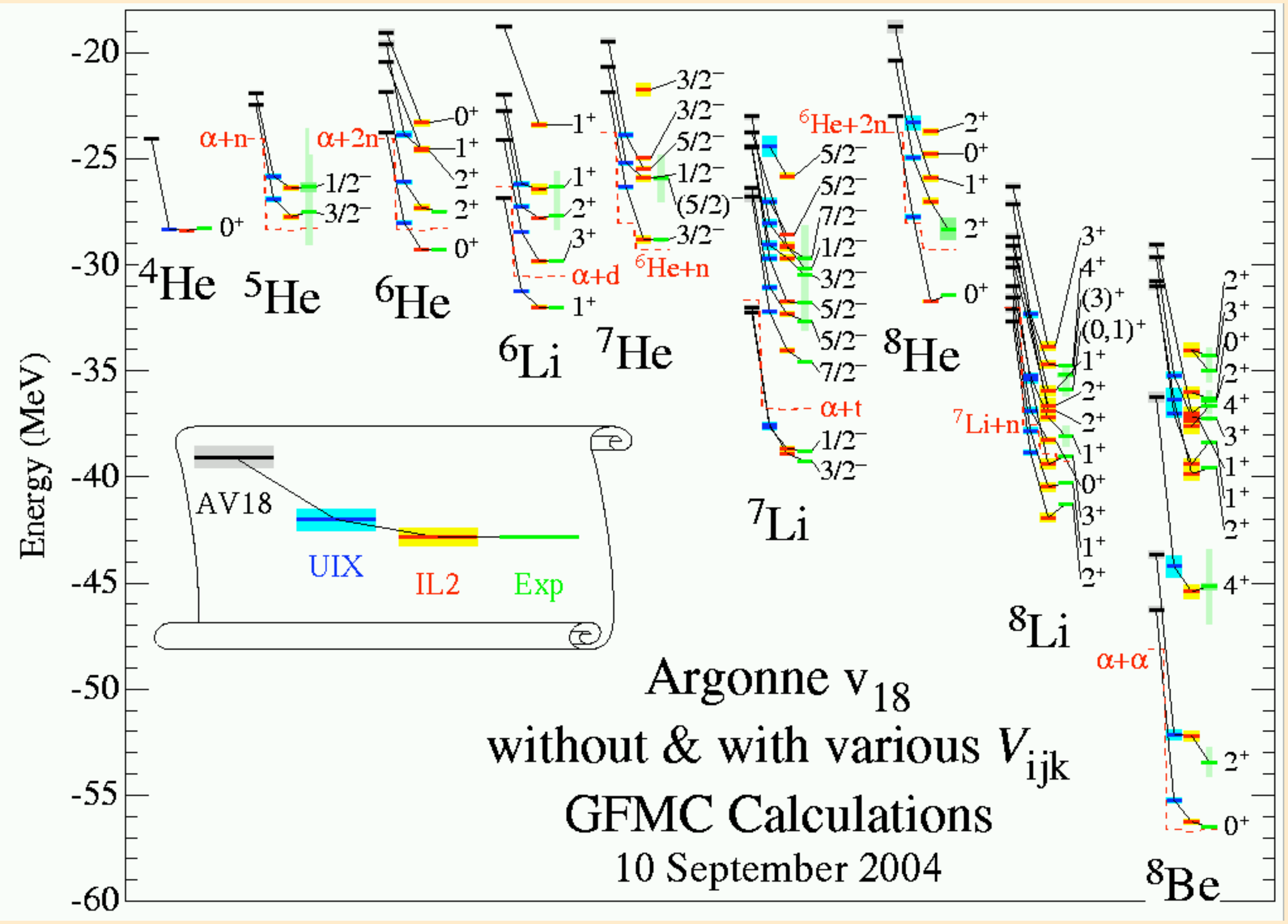
but unable to predict ^{3}He, T binding energies

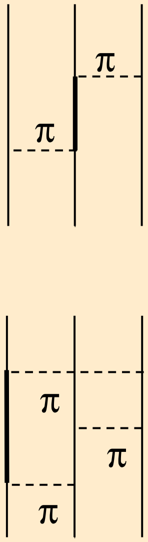
Data from Wiringa *et al.*, Phys. Rev. C 51, 38 (1995)





NN Potential Models



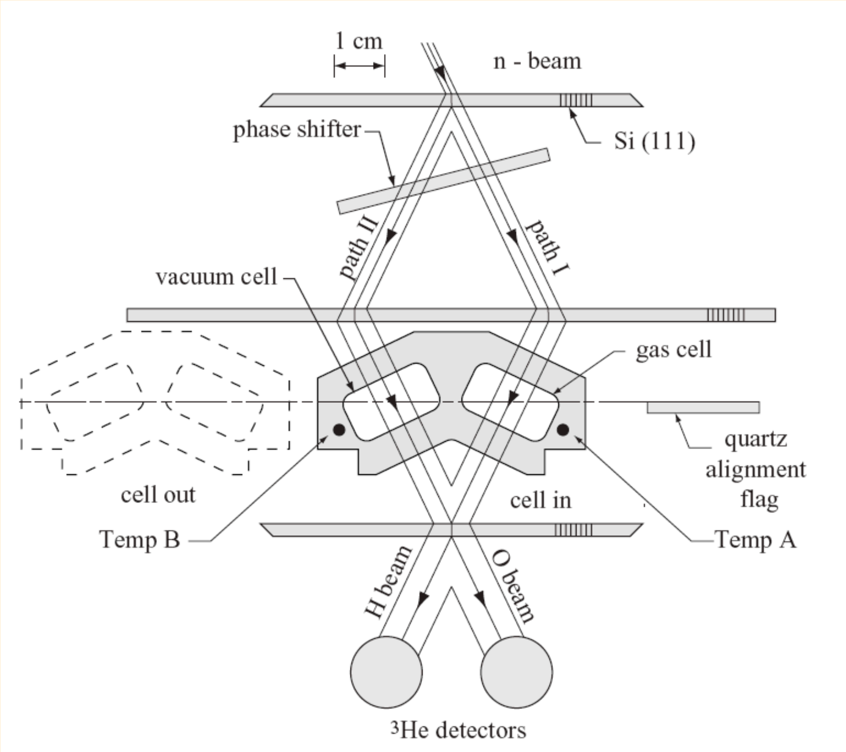


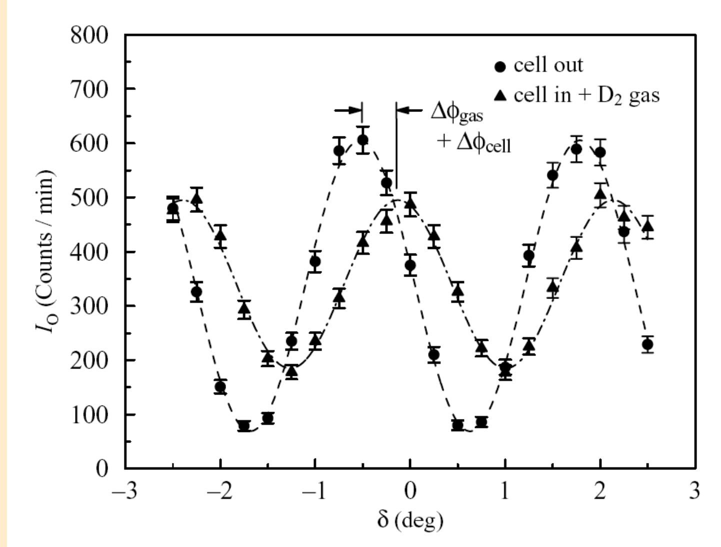
Motivation

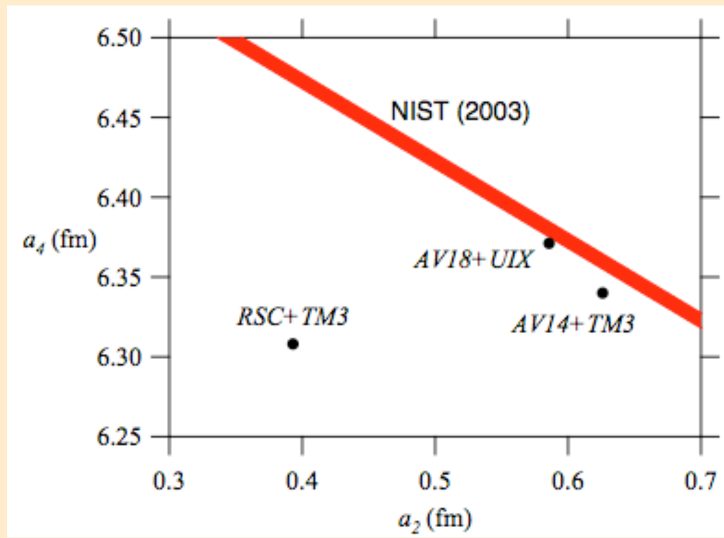
- Precision few-body neutron scattering lengths provide an additional challenge for nuclear potential models.

- Few body nuclear effective field theories (EFT) require precision experimental measurements to constrain short-range mean field potentials.

Precision neutron interferometric measurement of the n-D coherent scattering length at NIST (2003)



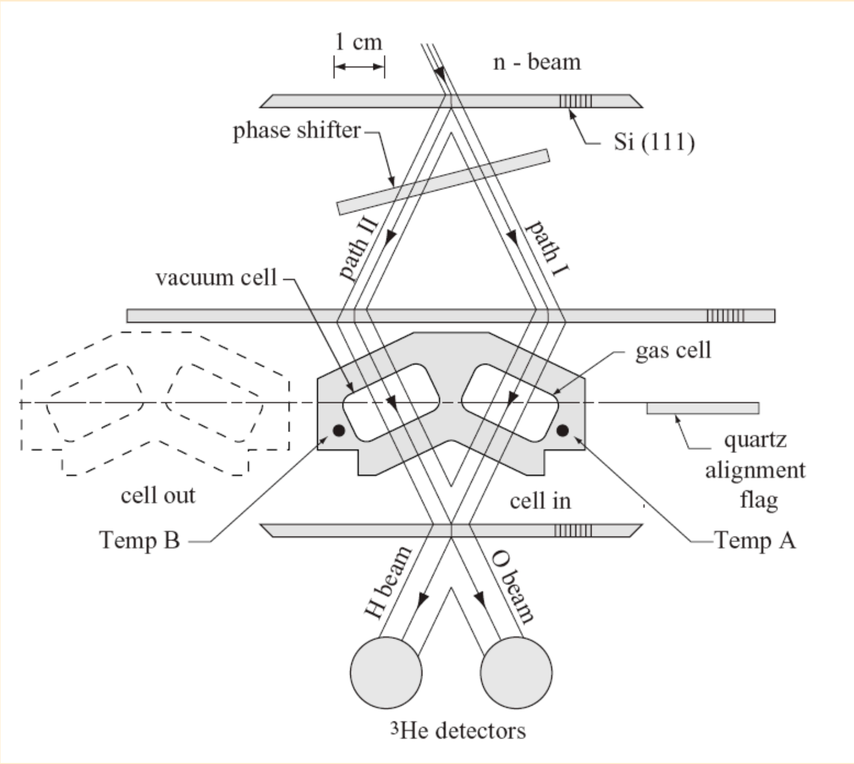


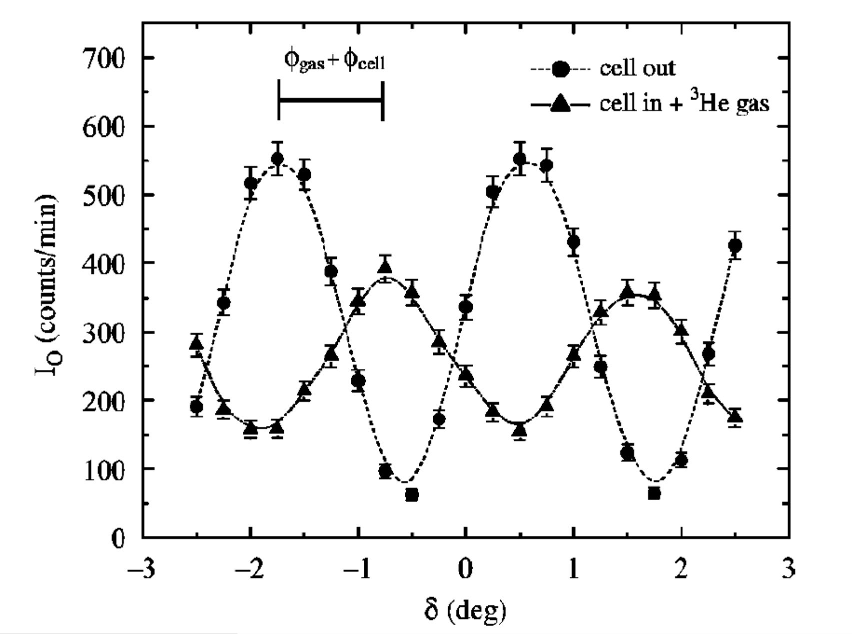


$b_c = 6.6727 \pm 0.0045$ fm

Schoen, *et al.*, Phys. Rev. C 67, 044005 (2003)

Precision neutron interferometric measurement of the n-^{3}He coherent scattering length at NIST (2004)

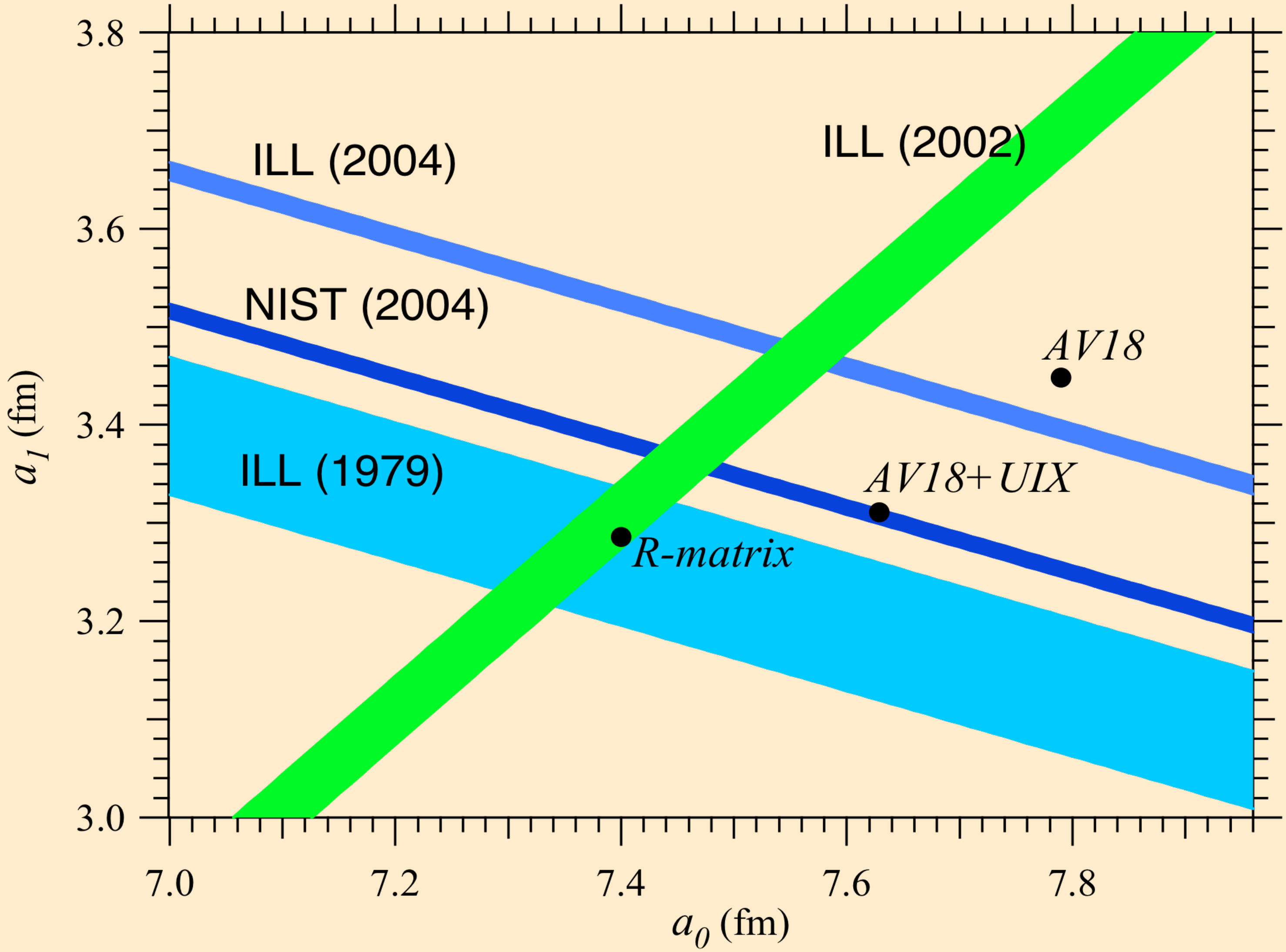




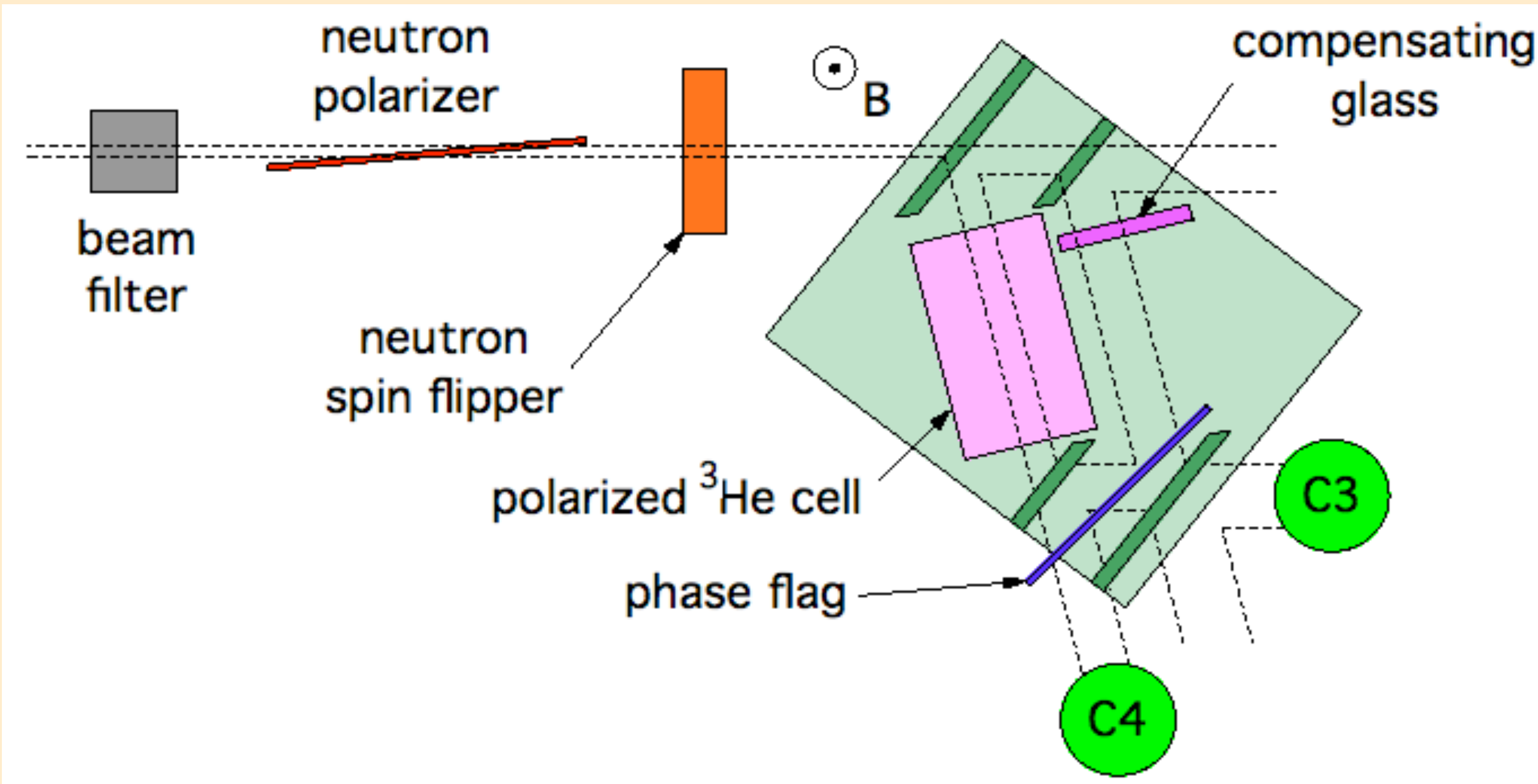
$b_c = 5.8572 \pm 0.0072$ fm

Huffman, *et al.*, Phys. Rev. C 70, 014004 (2004)

n-^{3}He Scattering Lengths



A new measurement of the n-^{3}He spin-incoherent scattering length at NIST (2008)



Spin-dependent neutron scattering

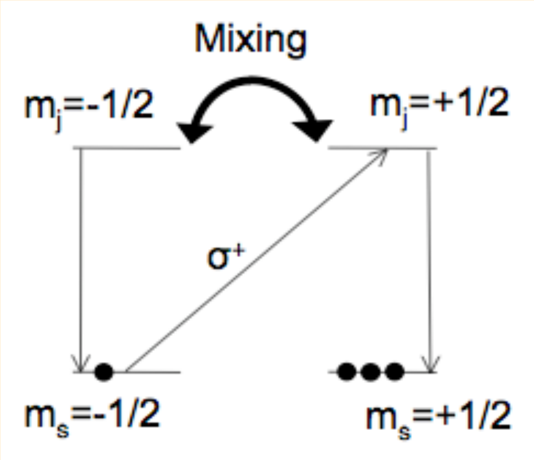
total scattering length: $$b = b_c + \frac{2b_i}{\sqrt{I(I+1)}}\vec{I} \cdot \vec{\sigma}_n$$

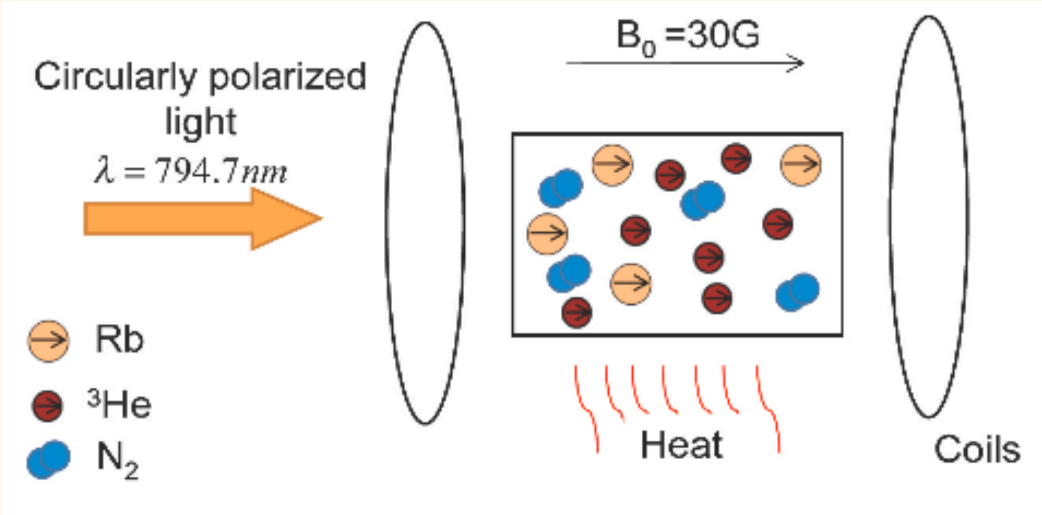
coherent: $$b_c = \frac{I+1}{2I+1}b_+ + \frac{I}{2I+1}b_-$$

incoherent: $$b_i = \frac{\sqrt{I(I+1)}}{2I+1}\left(b_+ - b_-\right)$$

Polarized ^{3}He gas target:
Spin Exchange Optical Pumping

Spin is transferred from optically polarized alkali atoms to ^{3}He nuclei via the hyperfine interaction in collisions.





The cell is polarized offline and then transferred to the neutron interferometer.

Polarized ^3He Cells

Target cells:

- Boron-free GE-180 glass
- 4 mm flat windows
- 40 mm long, 25 mm dia.
- 1.5 atm ^3He (with 4% N_2)

Two cells:

"Pistachio" (115 hours)

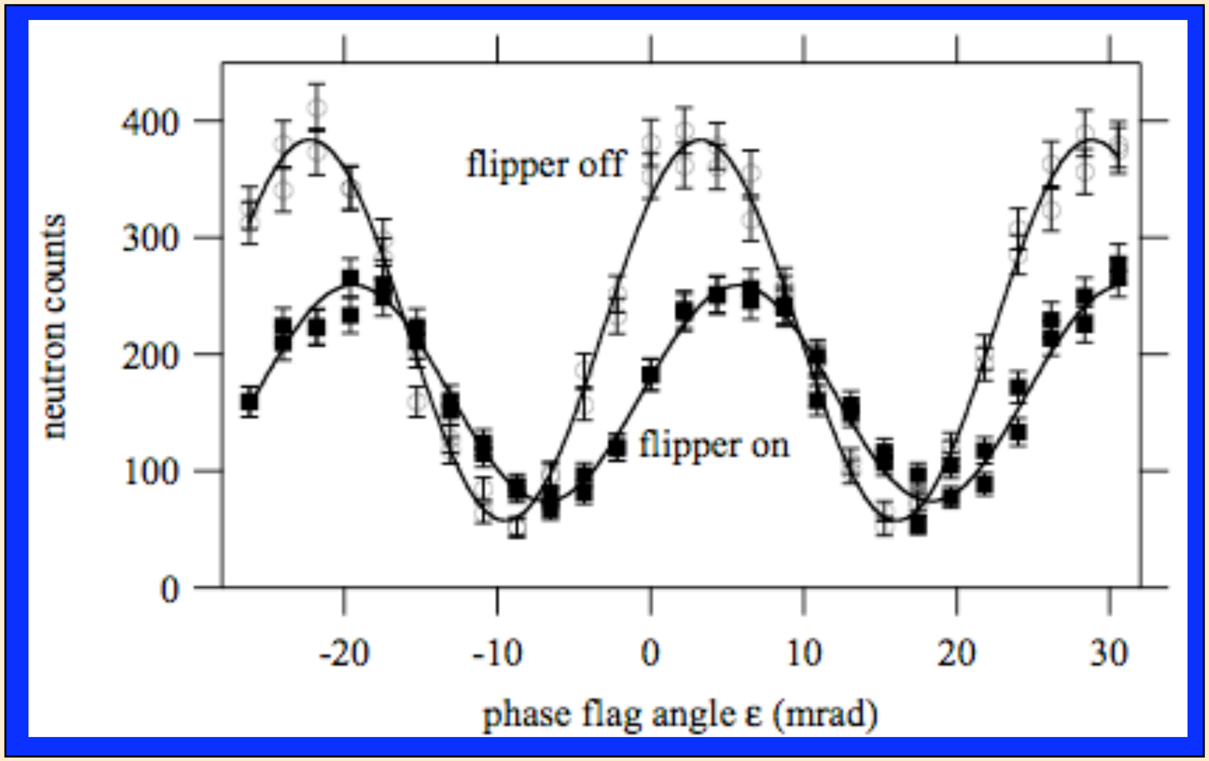
"Cashew" (35 hours)

Measuring the Scattering Length

$$b_{+} - b_{-} = -\frac{2\left(\phi^{\uparrow} - \phi^{\downarrow}\right)}{N_3 \lambda z P_3}$$

Measuring the Scattering Length

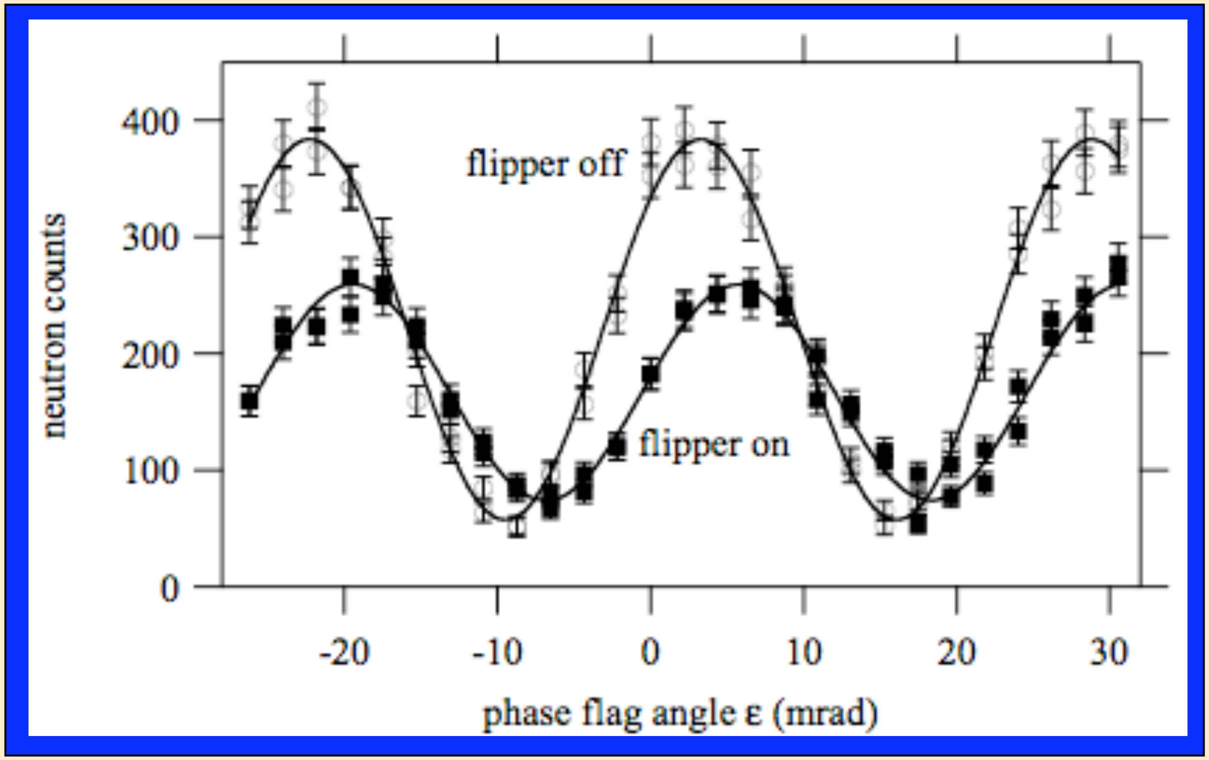
$$b_+ - b_- = -\frac{2\left(\phi^{\uparrow} - \phi^{\downarrow}\right)}{N_3 \lambda z P_3}$$



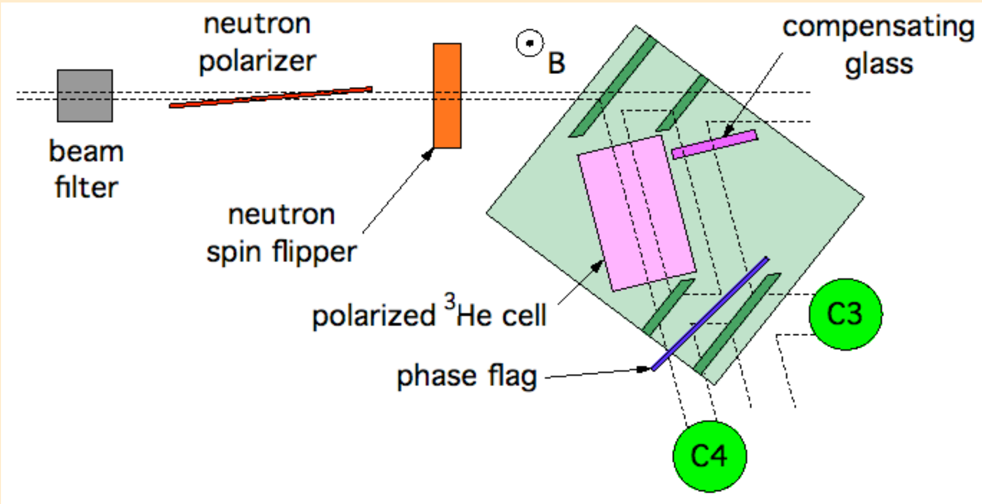
Measuring the Scattering Length

$$b_+ - b_- = -\frac{2\left(\phi^{\uparrow} - \phi^{\downarrow}\right)}{N_3 \lambda z P_3}$$

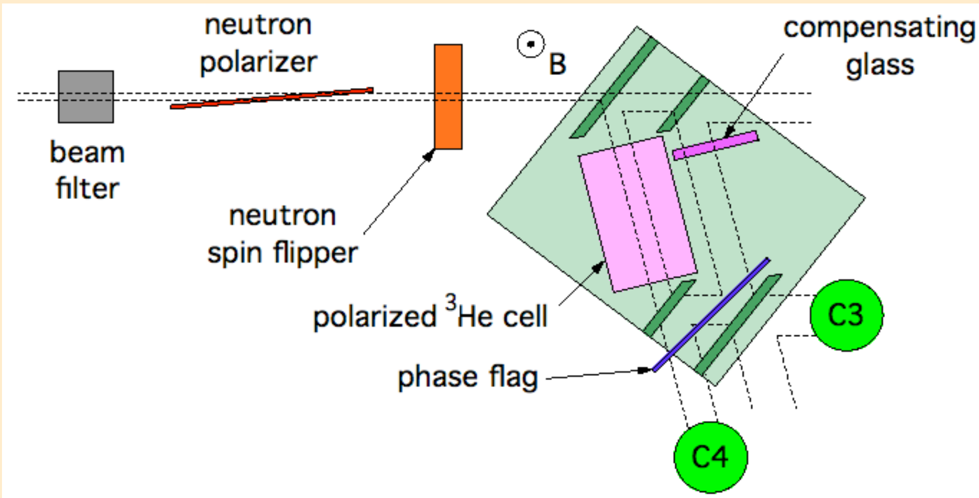
measured simultaneously from the asymmetry in counter C4



Measuring $N_3 \lambda z P_3$



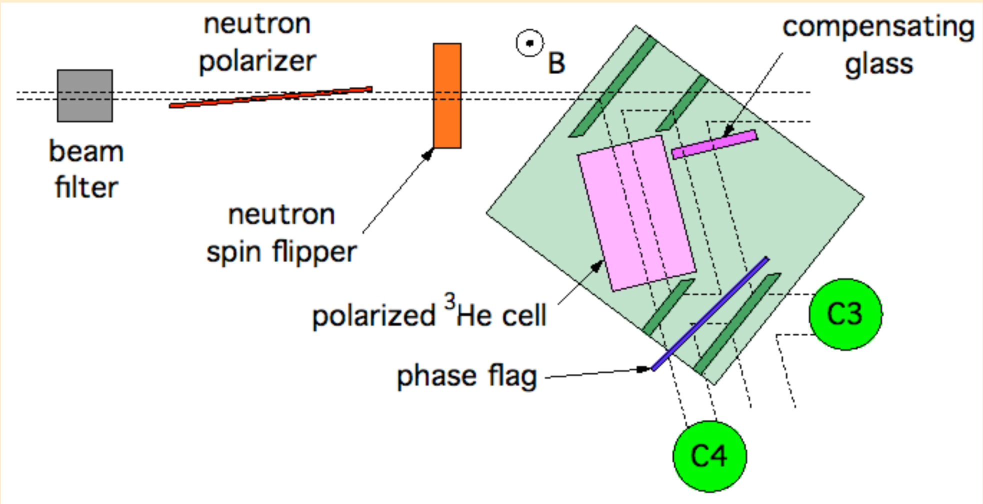
Measuring $N_3 \lambda z P_3$



$$\text{C4 asymmetry} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = \frac{\frac{1}{2}(1+s)P_n \tanh x}{1+\frac{1}{2}(1-s)P_n \tanh x}$$

$$x = \left(\frac{\sigma_0 - \sigma_1}{4\lambda_{\text{th}}}\right) N_3 \lambda z P_3$$

Measuring $N_3 \lambda z P_3$



$P_3 =$ ^{3}He polarization

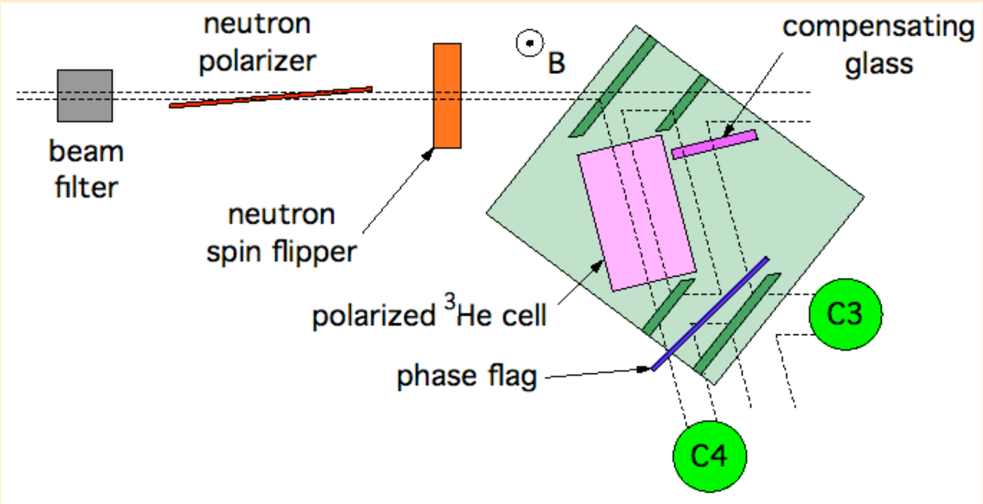
$P_n =$ neutron polarization (flipper off)

$$s = \frac{P_n \text{ (flipper on)}}{P_n \text{ (flipper off)}}$$

$$\text{C4 asymmetry} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} = \frac{\frac{1}{2}(1+s)P_n \tanh x}{1 + \frac{1}{2}(1-s)P_n \tanh x}$$

$$x = \left(\frac{\sigma_0 - \sigma_1}{4\lambda_{\text{th}}} \right) N_3 \lambda z P_3$$

Measuring $N_3 \lambda z P_3$



$P_3 =\ {}^3$He polarization

$P_n =$ neutron polarization (flipper off)

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$$x = \left(\frac{\sigma_0 - \sigma_1}{4\lambda_{\mathrm{th}}}\right) N_3 \lambda z P_3$$

^{3}He (n,p) cross section:

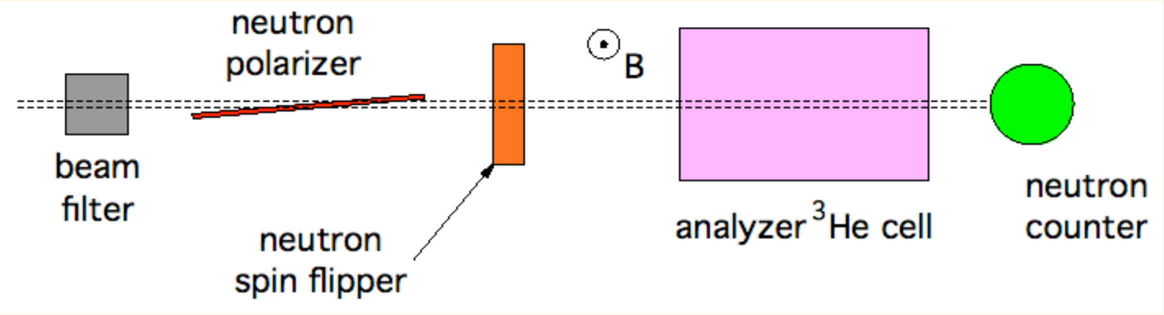
$$\sigma_{\mathrm{th}} = \frac{1}{4}\sigma_0 + \frac{3}{4}\sigma_1 = 5333(7) \text{ barns}$$

$$\frac{\sigma_1}{\sigma_0} \approx 0 - 2 \times 10^{-3}$$

(Hofmann and Hale, 2003)

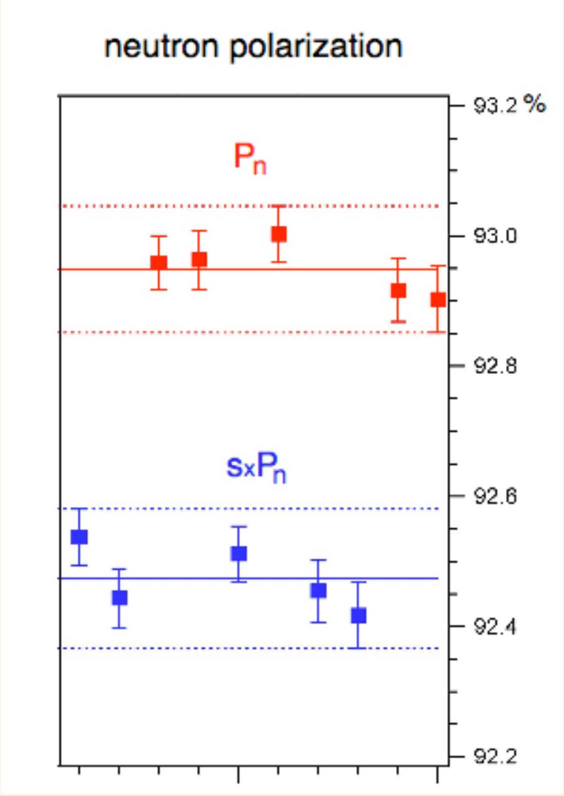
the dominant
systematic error
in this experiment

Neutron Polarimetry



Use optically thick (Nσz ~ 3) ^{3}He cell, with known polarization, in place of neutron interferometer.

Measure neutron count rate with both flip states and both directions of P_3



$$P_n = 0.9291 \pm .0008$$

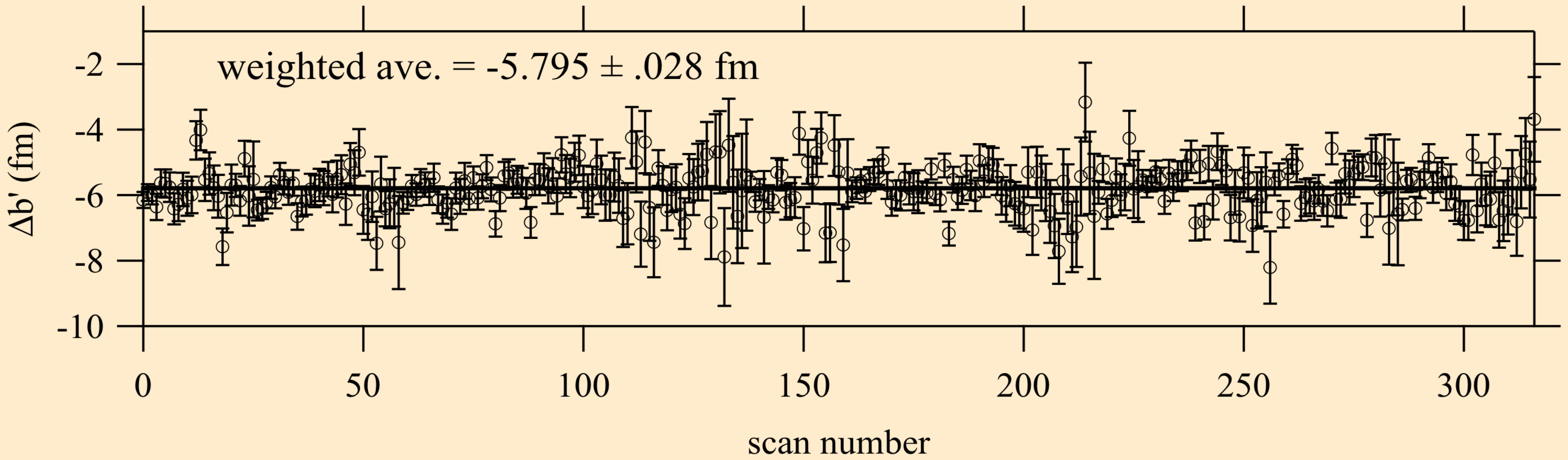
$$s = .9951 \pm .0003$$

Neutron Polarization Correction

$$\Delta\phi_{\text{meas.}} = \arctan\left(\frac{\sin\Delta\phi}{\eta^{\downarrow} + \cos\Delta\phi}\right) - \arctan\left(\frac{\eta^{\uparrow}\sin\Delta\phi}{1+\eta^{\uparrow}\cos\Delta\phi}\right)$$

$$\eta^{\uparrow} = \left(\frac{1-P_n}{1+P_n}\right)e^{-2\chi} \qquad \eta^{\downarrow} = \left(\frac{1-sP_n}{1+sP_n}\right)e^{+2\chi}$$

The Data



Fit to constant:

$$\chi^2 \,/\, \text{d.o.f.} = 371 \,/\, 316 \quad (p = 2\%)$$

The Result

$$b_+ - b_- = -5.802 \pm .028(\text{stat}) \pm .033(\text{sys})$$

$$b_i = -2.512 \pm .012(\text{stat}) \pm .014(\text{sys})$$

$$a_1 - a_0 = -4.346 \pm .021(\text{stat}) \pm .025(\text{sys})$$

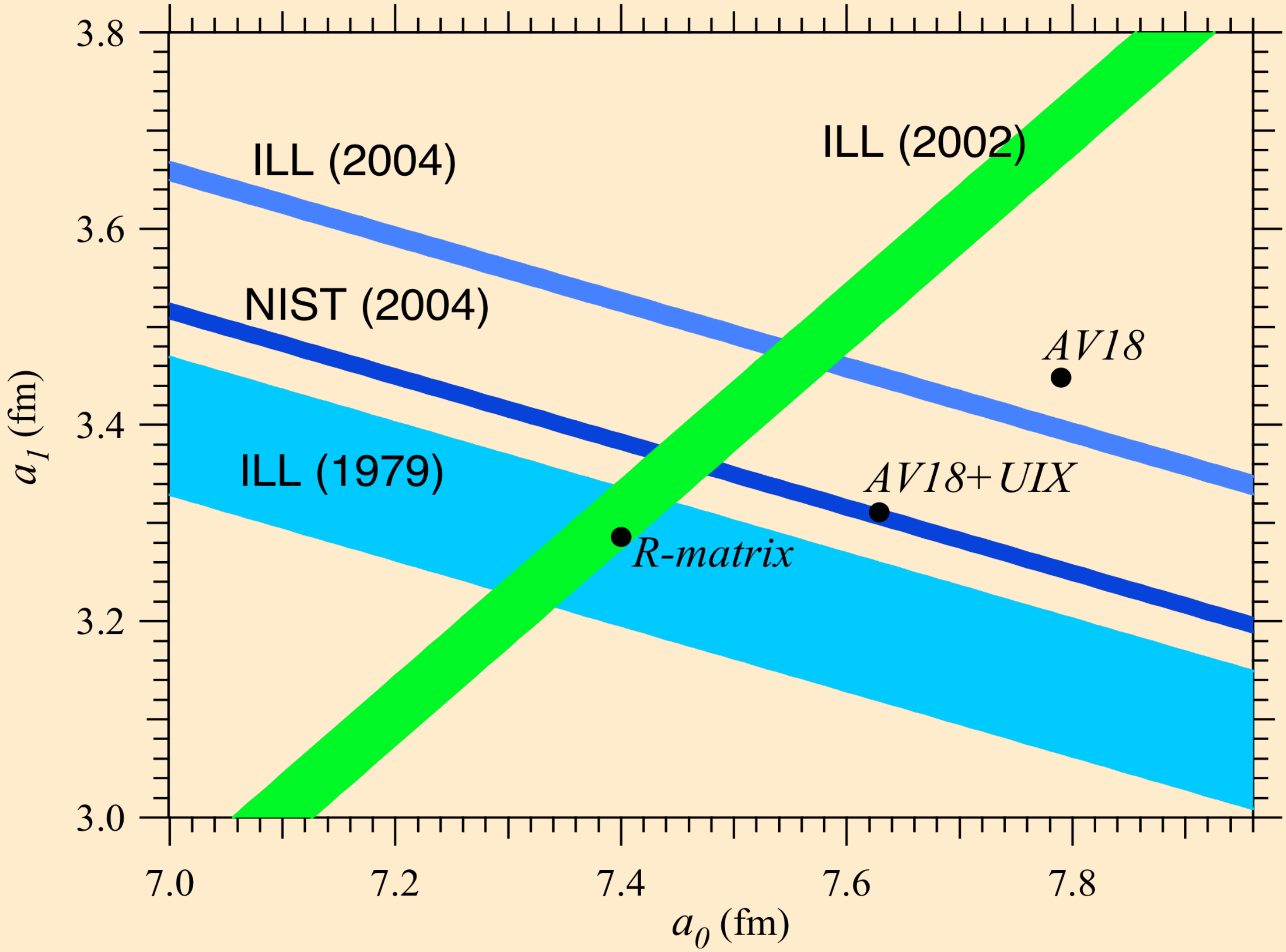
Error budget:

Source	Uncertainty (fm)
Phase instability	0.013
Neutron polarization P_n	0.006
Neutron spin flip factor s	0.002
Magnetic field gradient	0.009
n-^{3}He thermal abs. cross section σ_{th}	0.008
n-^{3}He triplet abs. cross section σ_1	0.027
Combined systematic uncertainty	0.033
Counting statistics	0.028

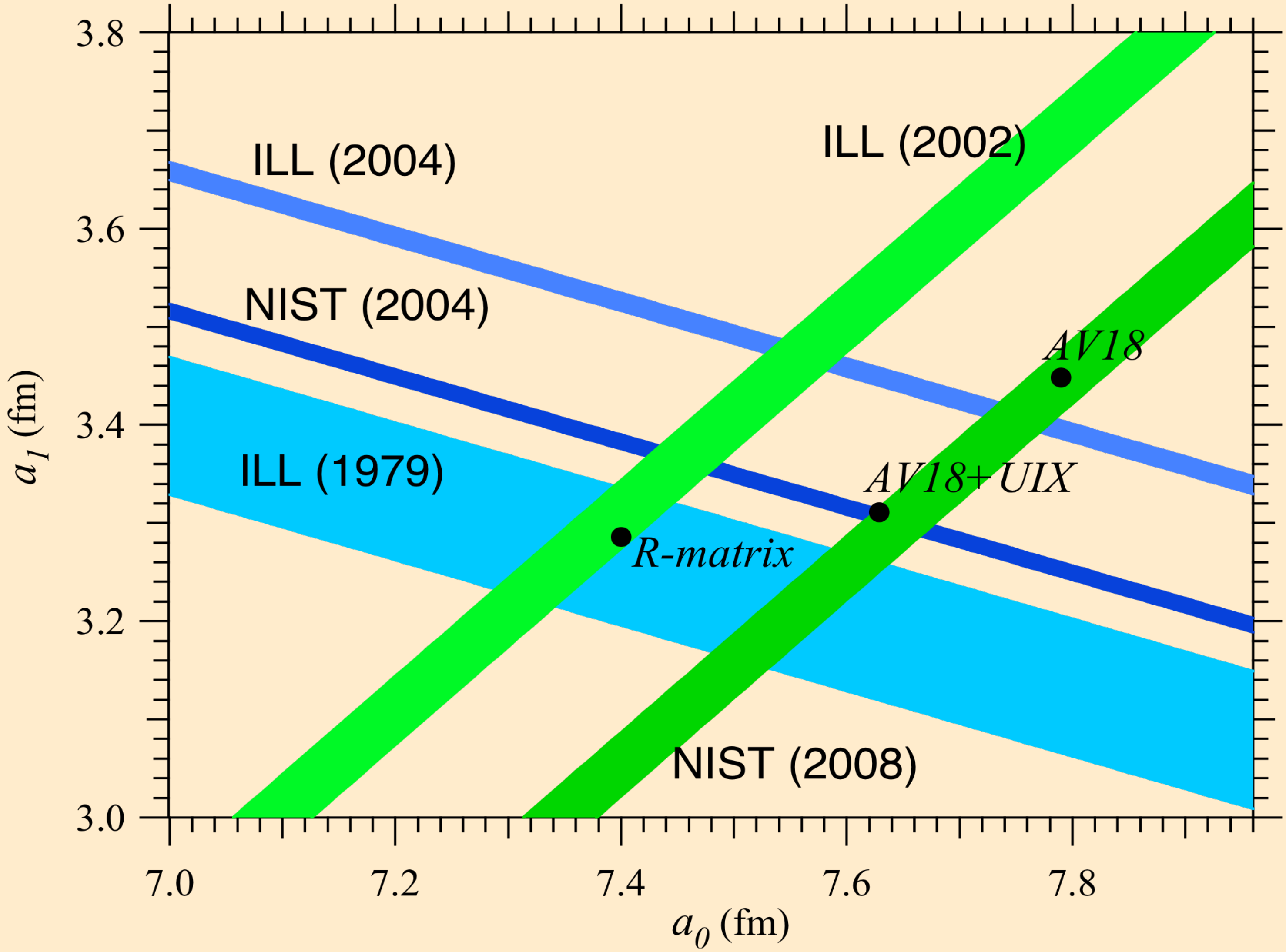
Michael Huber

Phys. Rev. Lett. 102, 200401

n-^{3}He Scattering Lengths



n-^{3}He Scattering Lengths



Light gas scattering lengths to measure precisely using neutron interferometry:

Completed:

- n-H
- n-D
- n-^{3}He
- n-^{3}He (spin incoherent) - new result

In Progress:

- n-^{4}He
- n-T

The Neutron

by Gina Berkeley

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 bombinate into the vacuum alone?
Its spin is 1/2, and its mass is quite large
-about 1 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 mute desolation
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 spining
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.