Neutron Interferometry

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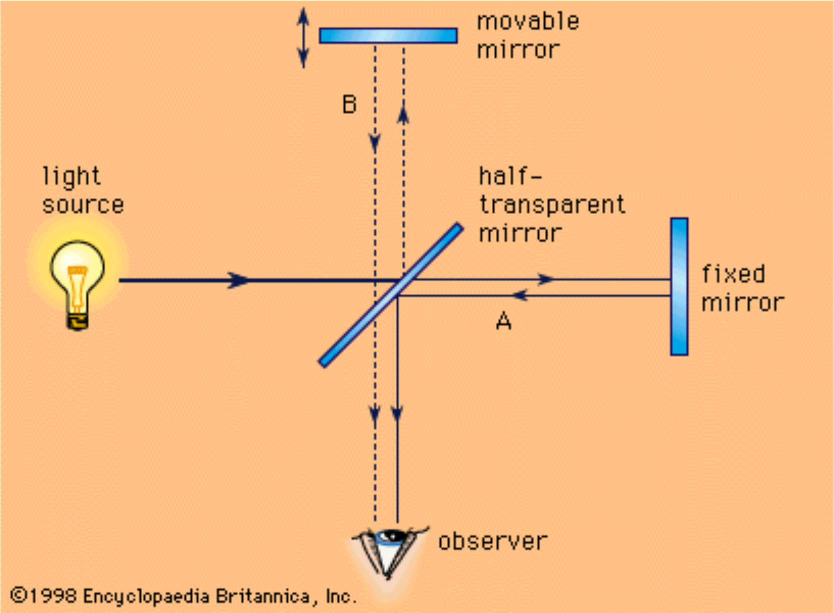
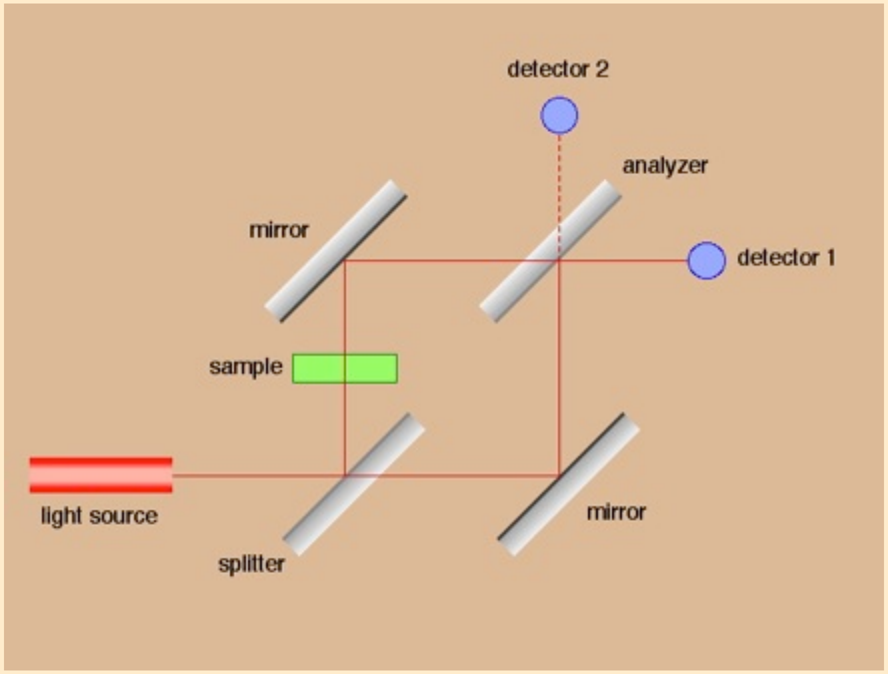
Tulane University

NIST
National Institute of Standards and Technology

Fundamental Neutron Physics Summer School 2015
June 19, 2015

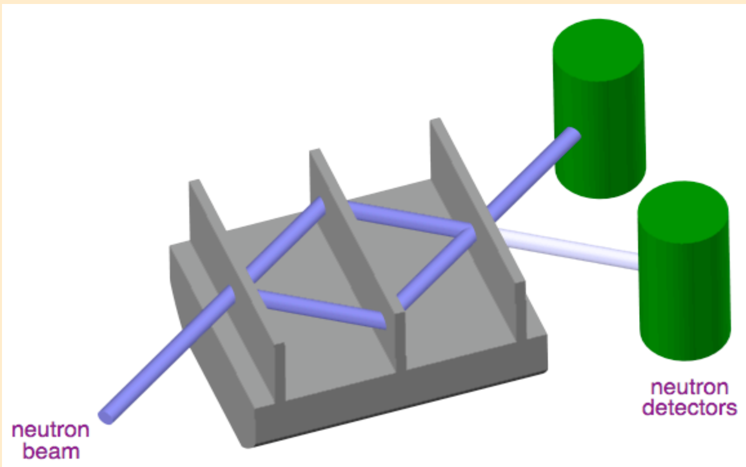
Michelson Interferometer

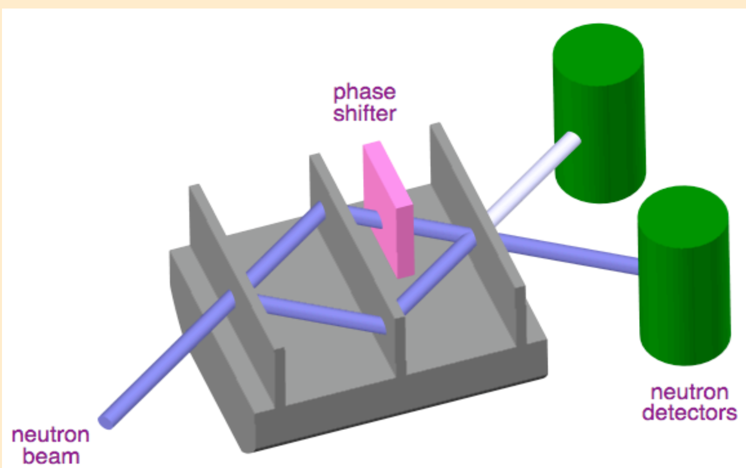


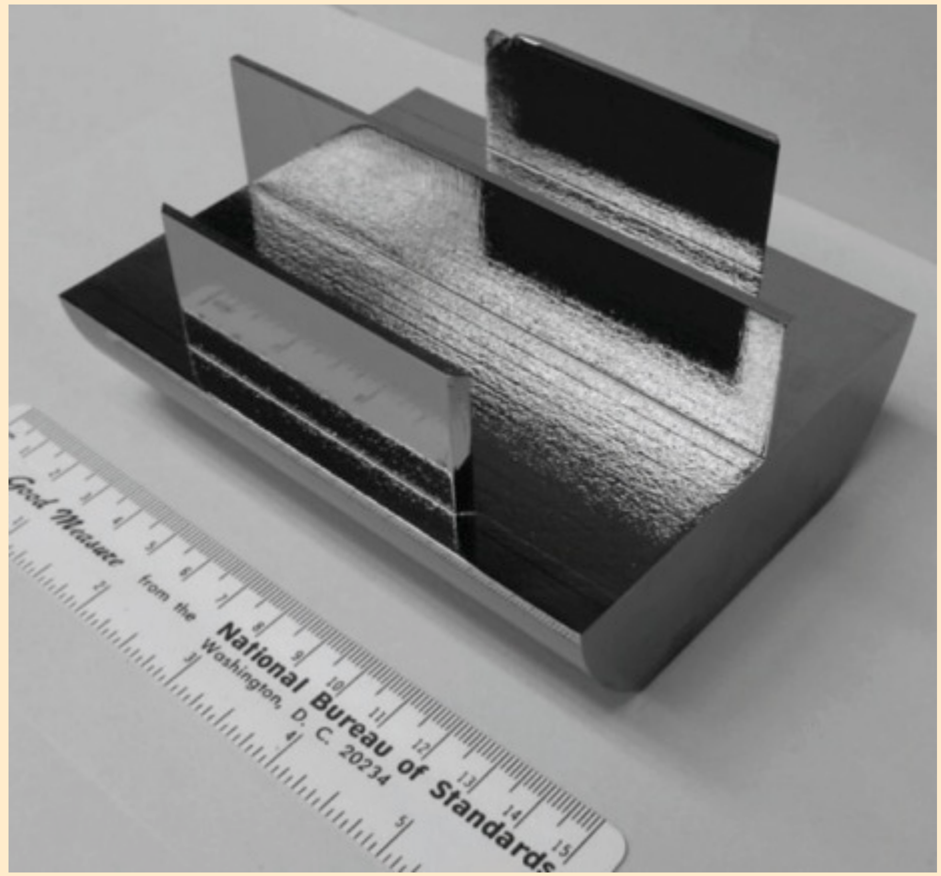


Mach-Zender Interferometer

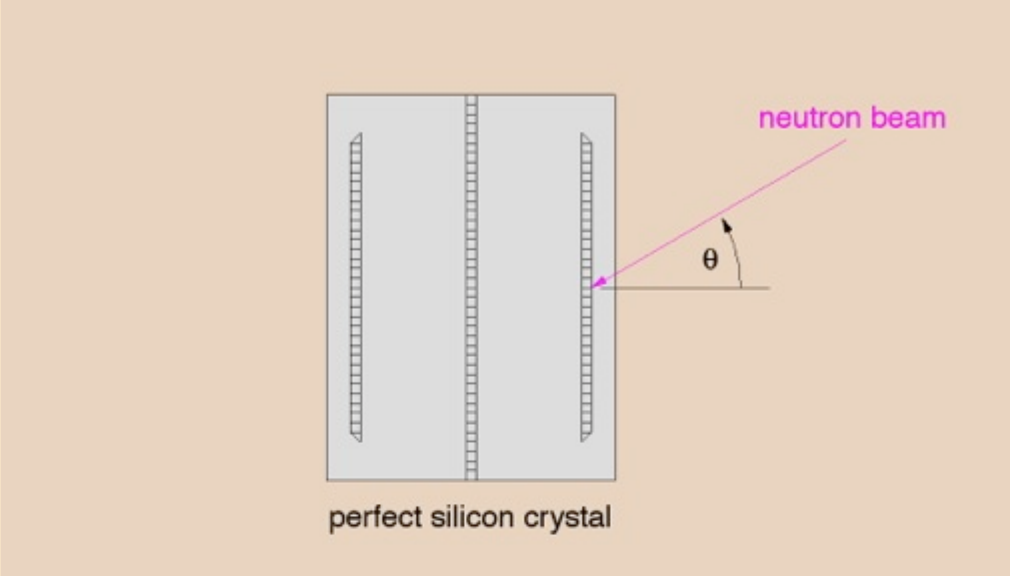
The Perfect Crystal Neutron Interferometer







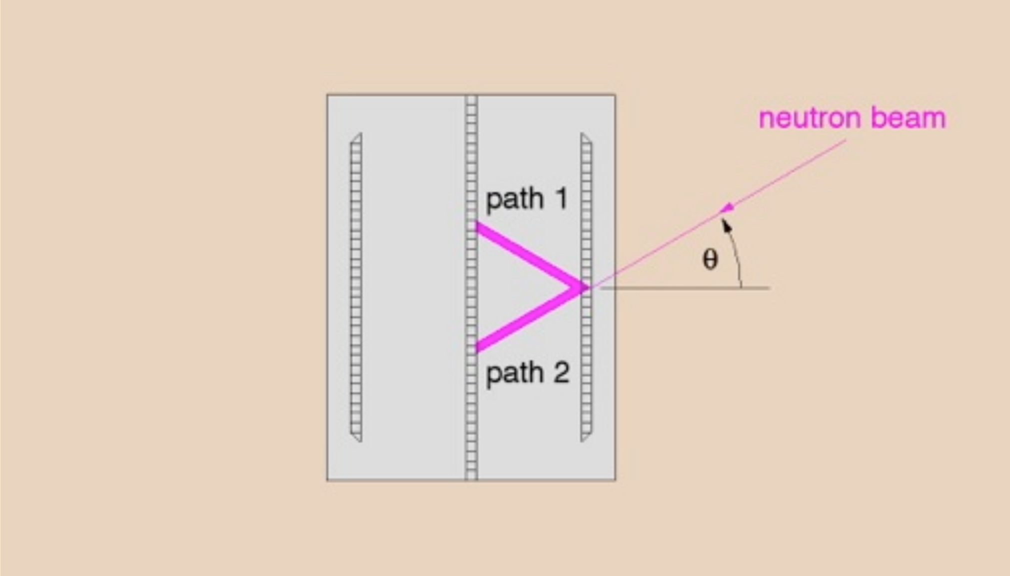
Perfect Crystal LLL Neutron Interferometer



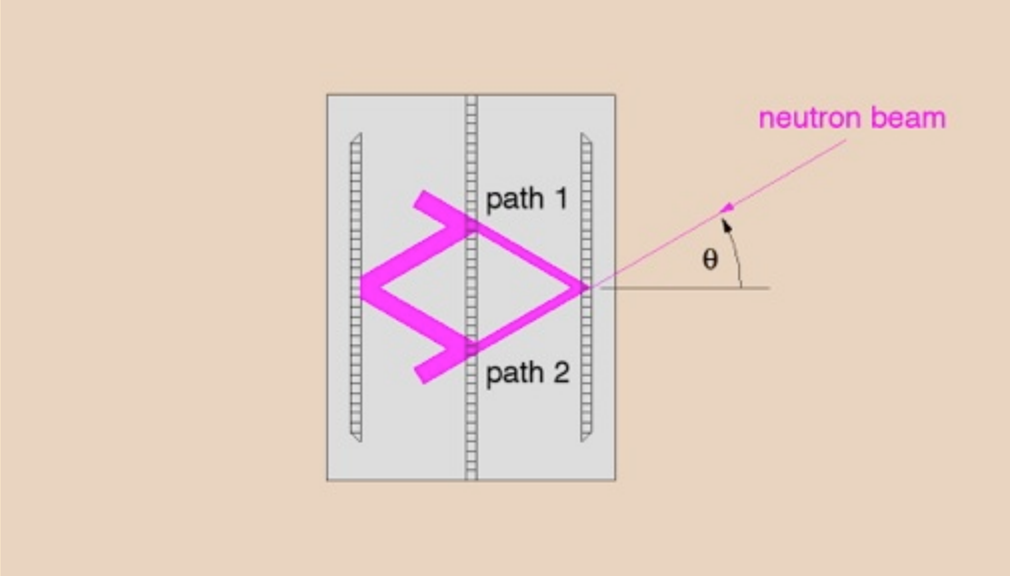
Bragg condition: $n\lambda = 2d\sin\theta$

d = lattice spacing

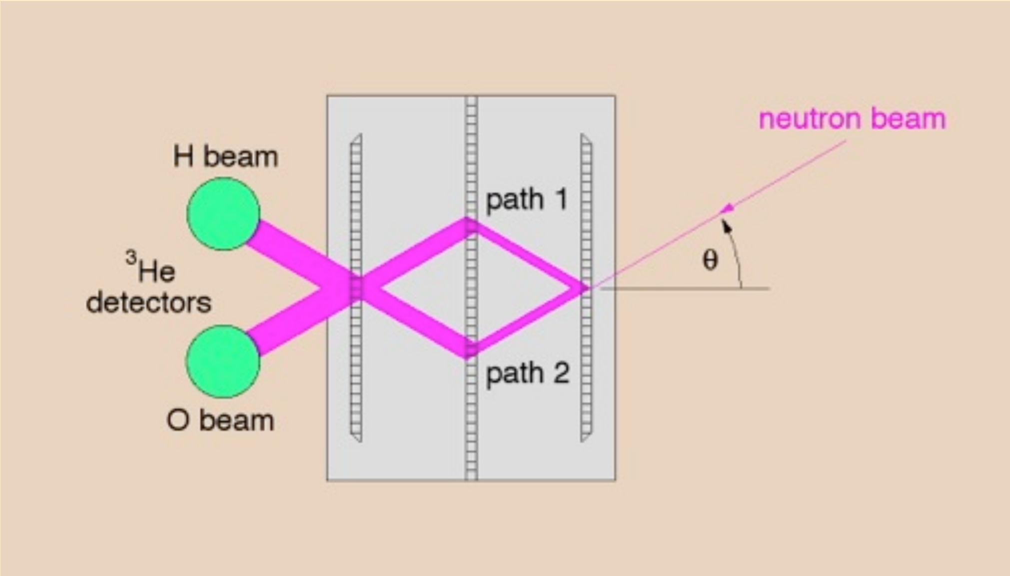
Perfect Crystal LLL Neutron Interferometer



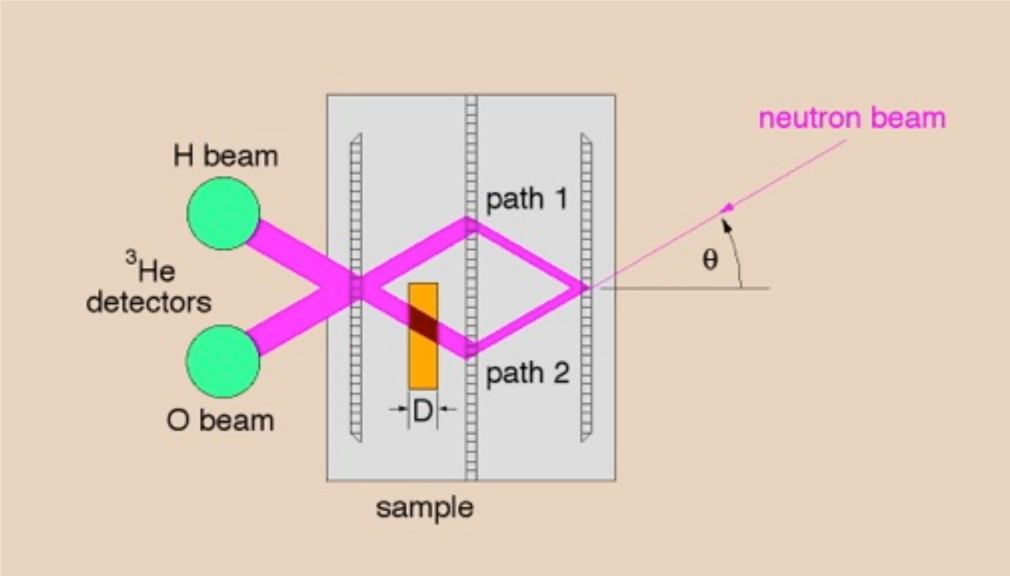
Perfect Crystal LLL Neutron Interferometer



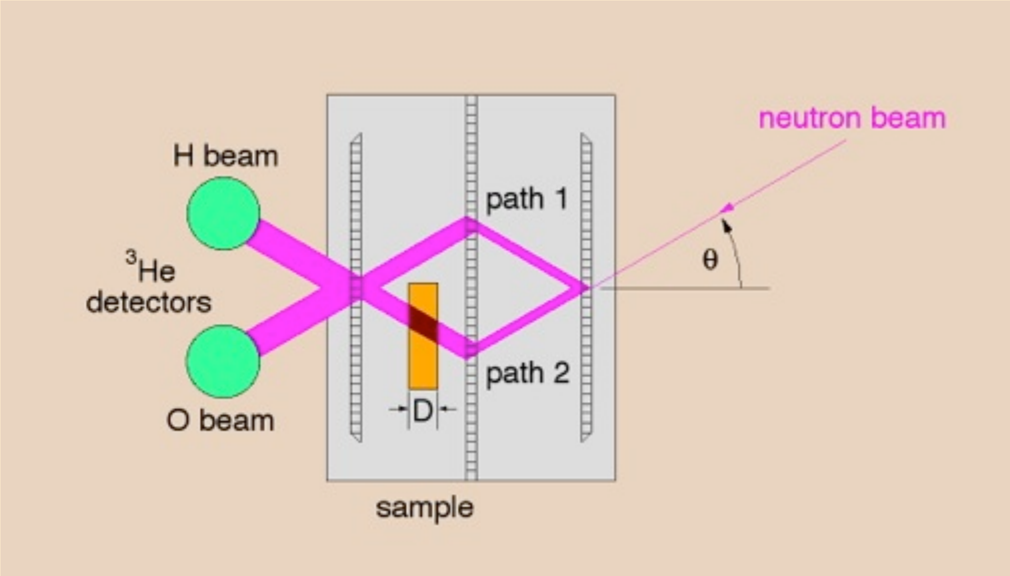
Perfect Crystal LLL Neutron Interferometer

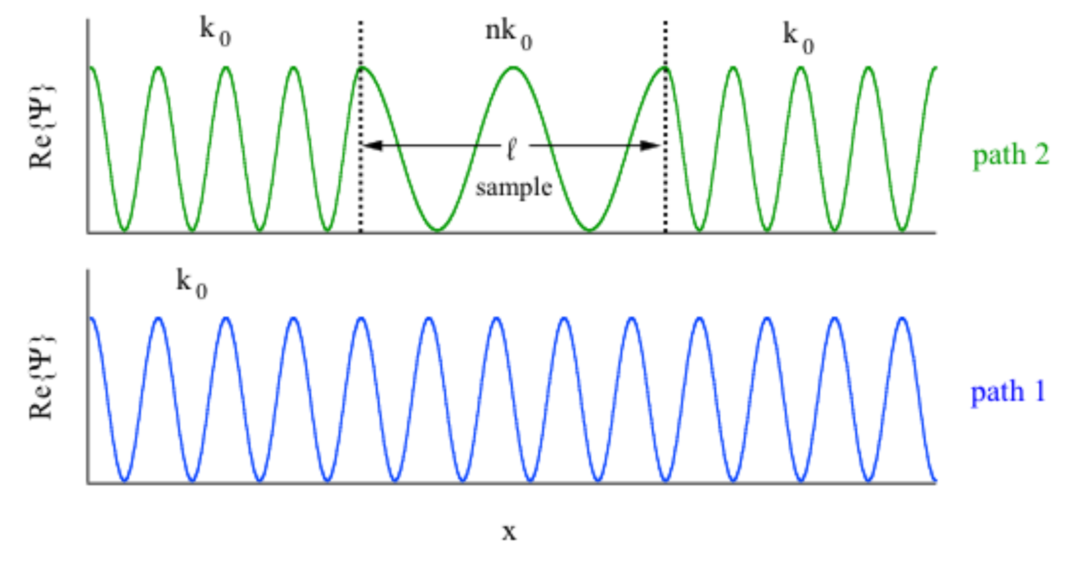


Nuclear Phase Shift



Nuclear Phase Shift





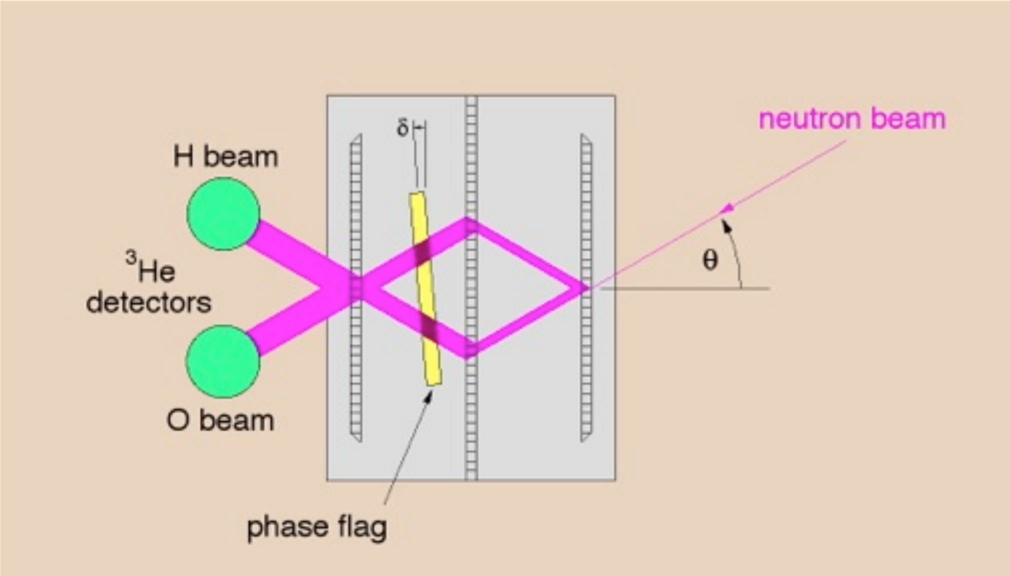
index of refraction: $n = 1 - \dfrac{Nb\lambda^2}{2\pi}$

relative phase shift:

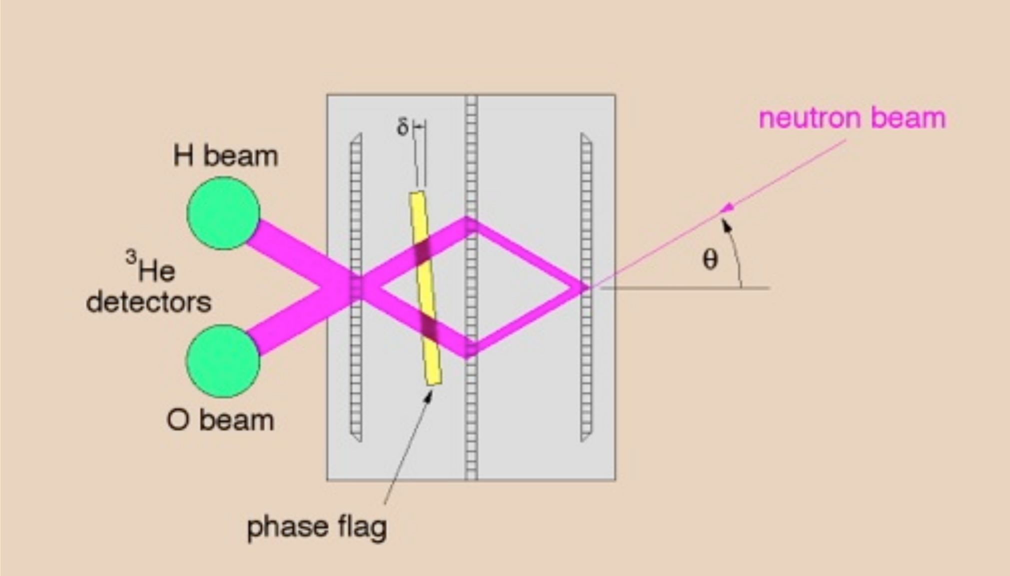
$$\Delta\chi = k_0\ell - nk_0\ell = Nb\lambda \frac{D}{\cos\theta}$$

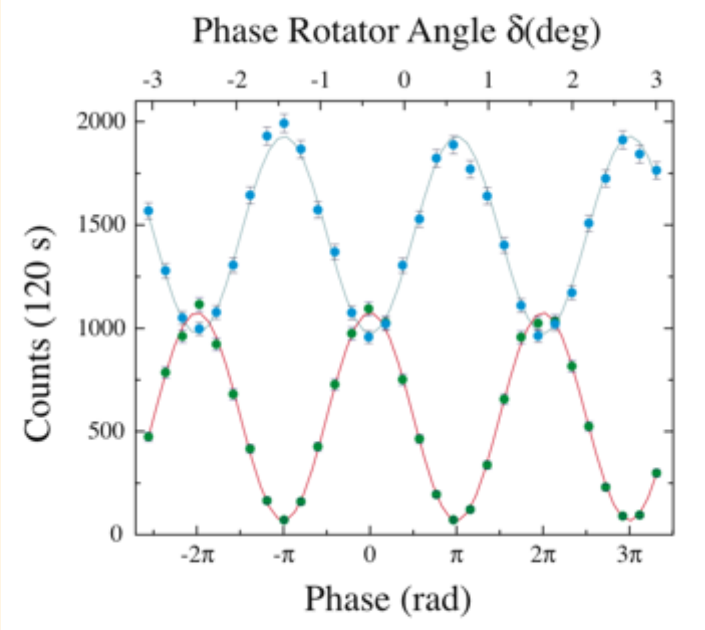
Question: Why, in transparent matter, is the index of refraction of light usually $n > 1$ and for neutrons usually $n < 1$?

Interferogram



Interferogram



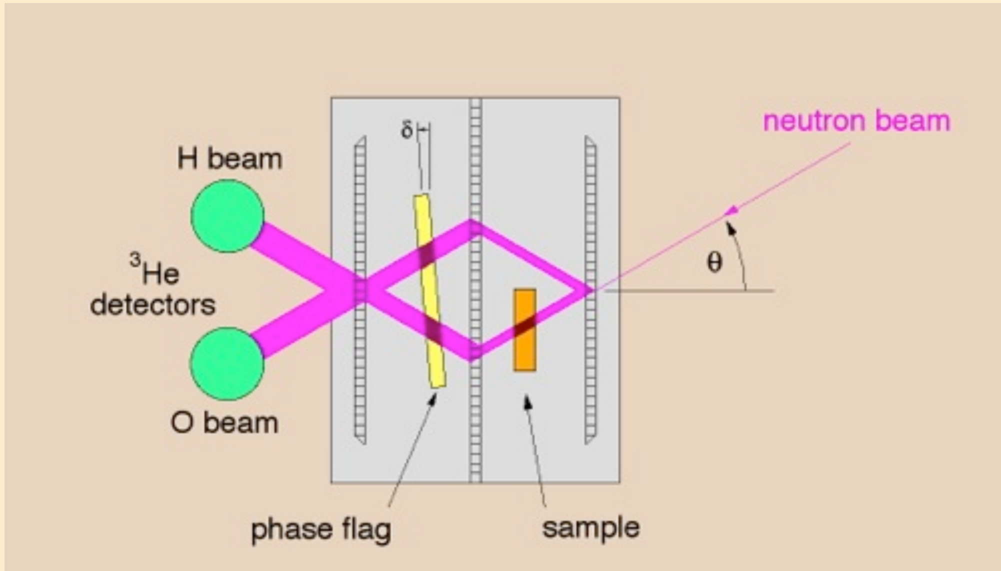


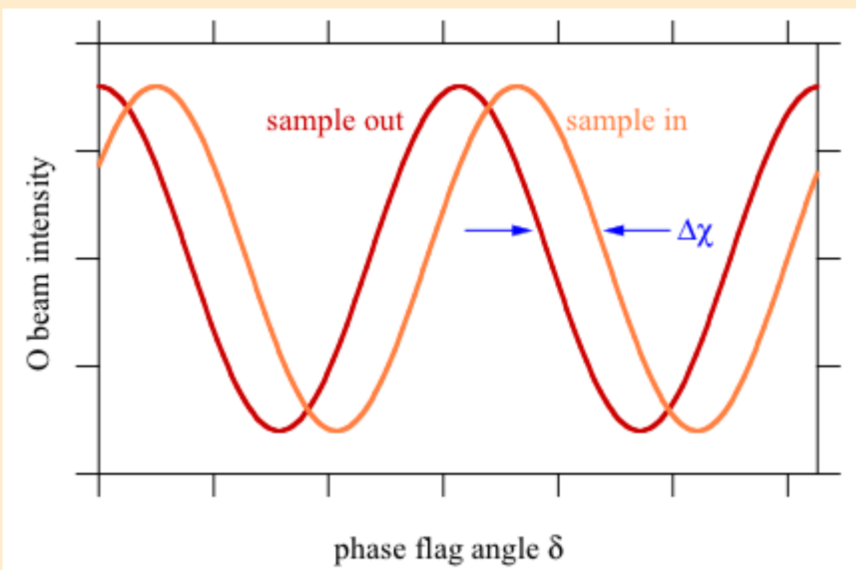
O beam: $I_O = A\left[1 + f\cos(\chi_2 - \chi_1)\right]$

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



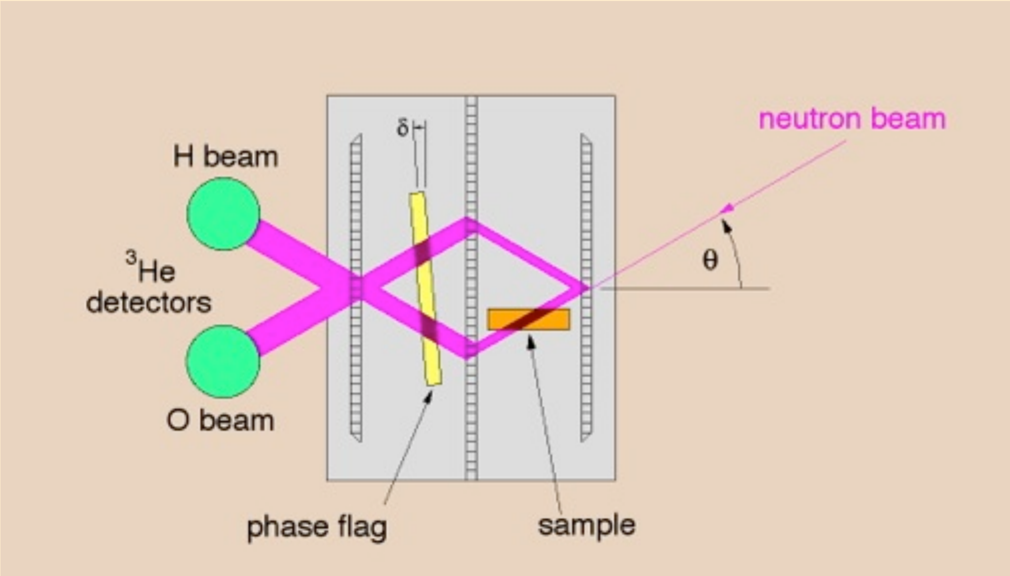


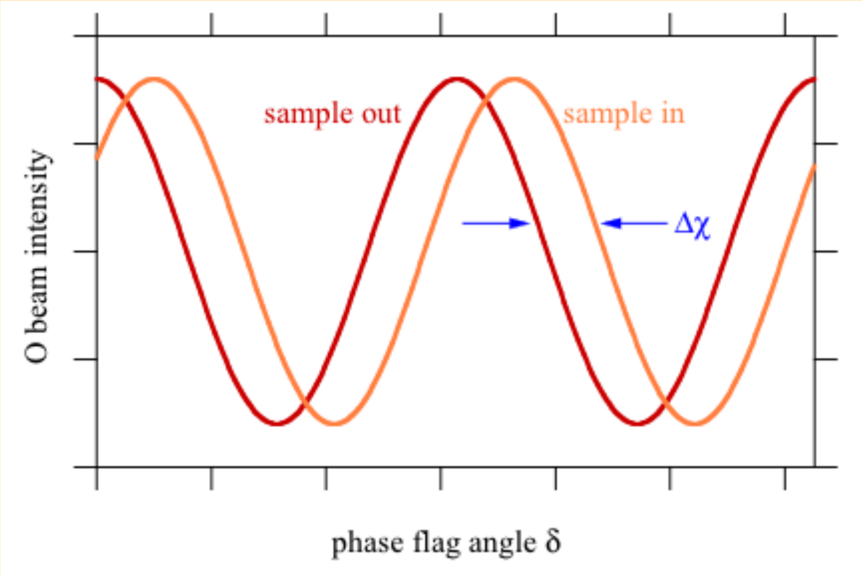
$$\Delta\chi = Nb\lambda\frac{D}{\cos\theta}$$

Example: aluminum sample,

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

Non-Dispersive Geometry





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

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

independent of λ

Question: Why, in transparent matter, is the index of refraction of light usually $n > 1$ and for neutrons usually $n < 1$?

Question: Why, in transparent matter, is the index of refraction of light usually n > 1 and for neutrons usually n < 1?

Answer: Special relativity

light

$$E = pc$$

$$v = \frac{d\omega}{dk} = \frac{dE}{dp} = \frac{E}{p} = \frac{\omega}{k}$$

$$v \propto \frac{1}{k}$$

neutron

$$E = \sqrt{p^2c^2 + m^2c^4}$$

$$v = \frac{d\omega}{dk} = \frac{dE}{dp} = \frac{pc^2}{E} \approx \frac{pc^2}{mc^2} = \frac{\hbar}{m}k$$

$$v \propto k$$

$$n \equiv \frac{k}{k_0}$$

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

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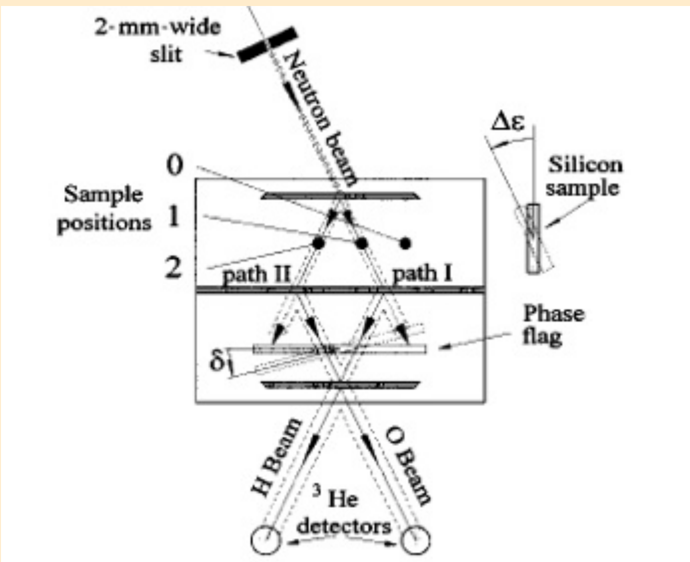
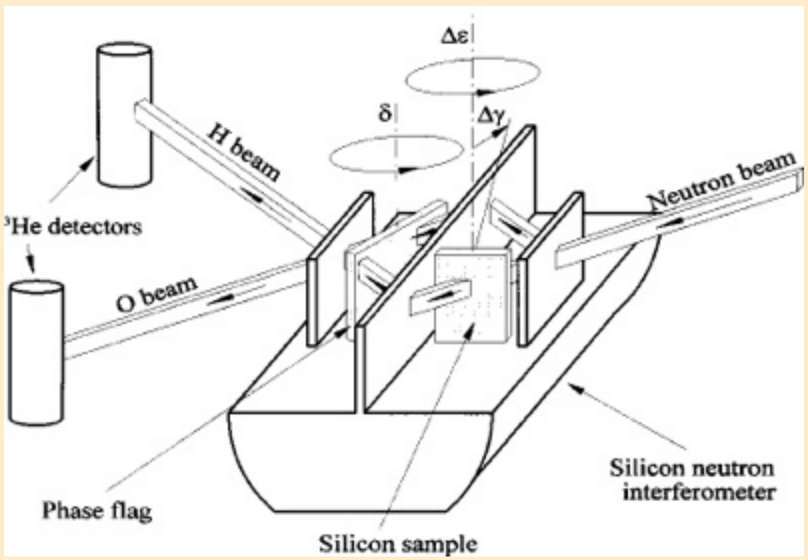
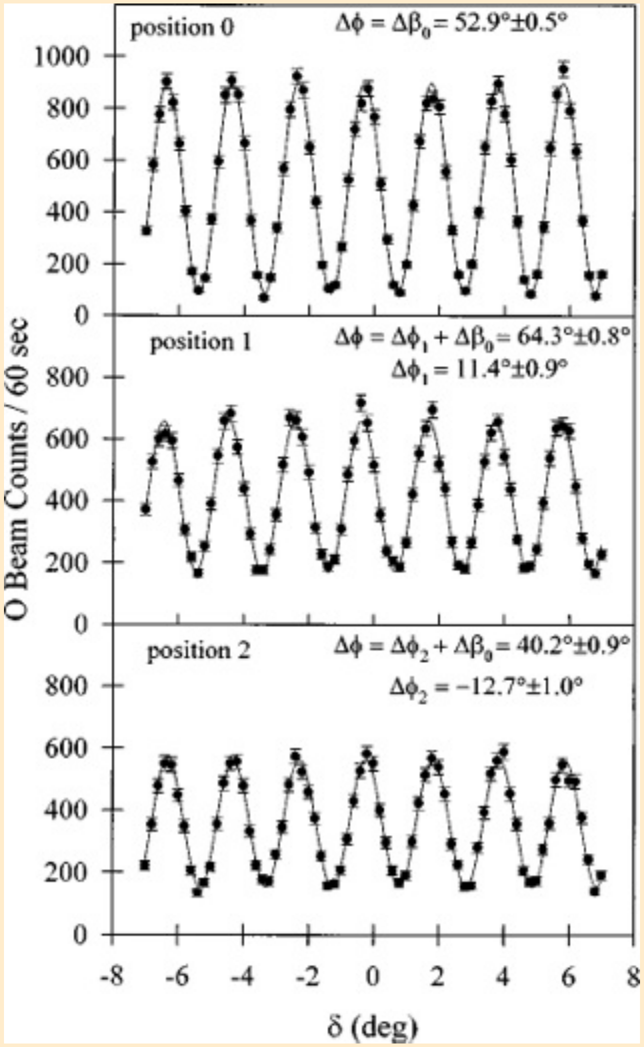
(Received 15 August 1997)

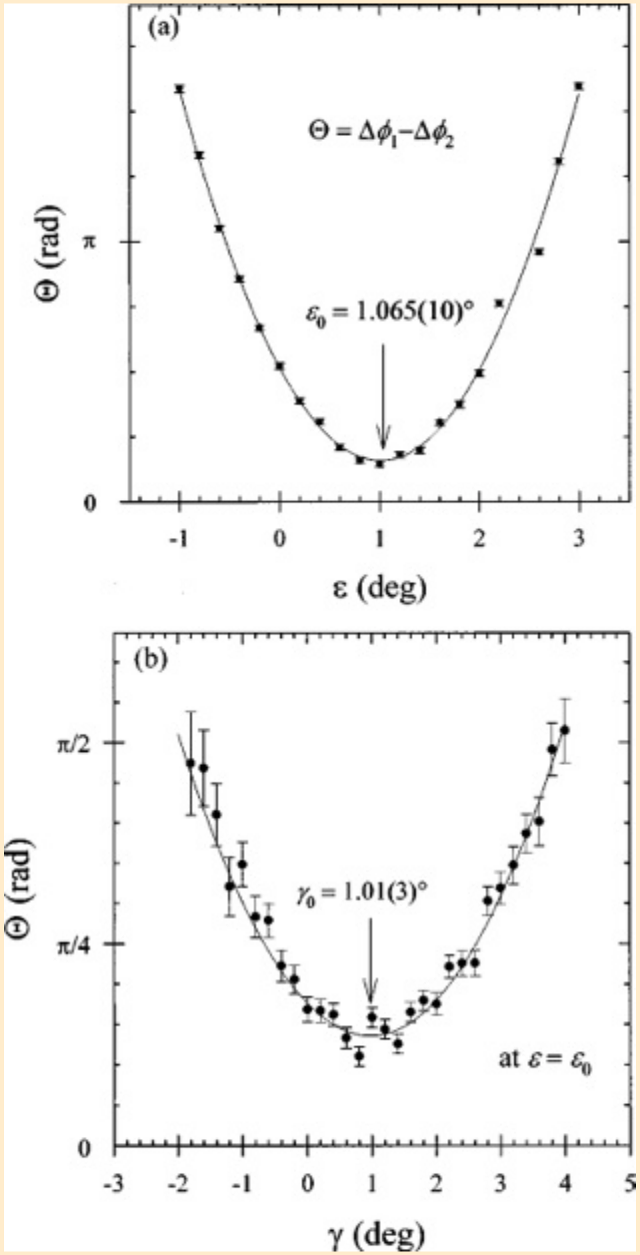
The neutron-interferometry (NI) technique provides a precise and direct way to measure the bound, coherent scattering lengths b of low-energy neutrons in solids, liquids, or gases. The potential accuracy of NI to measure b has not been fully realized in past experiments, due to systematic sources of 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





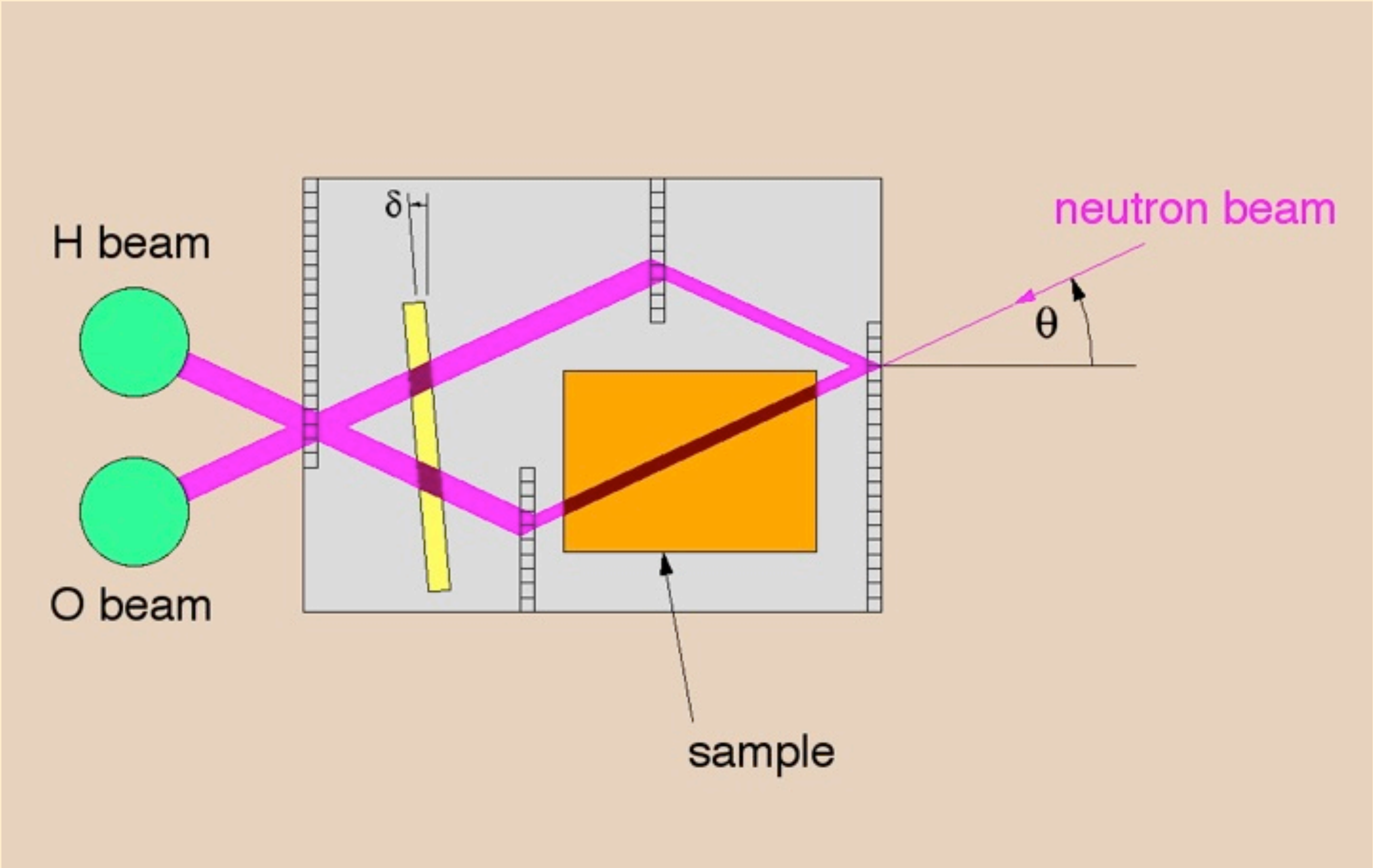




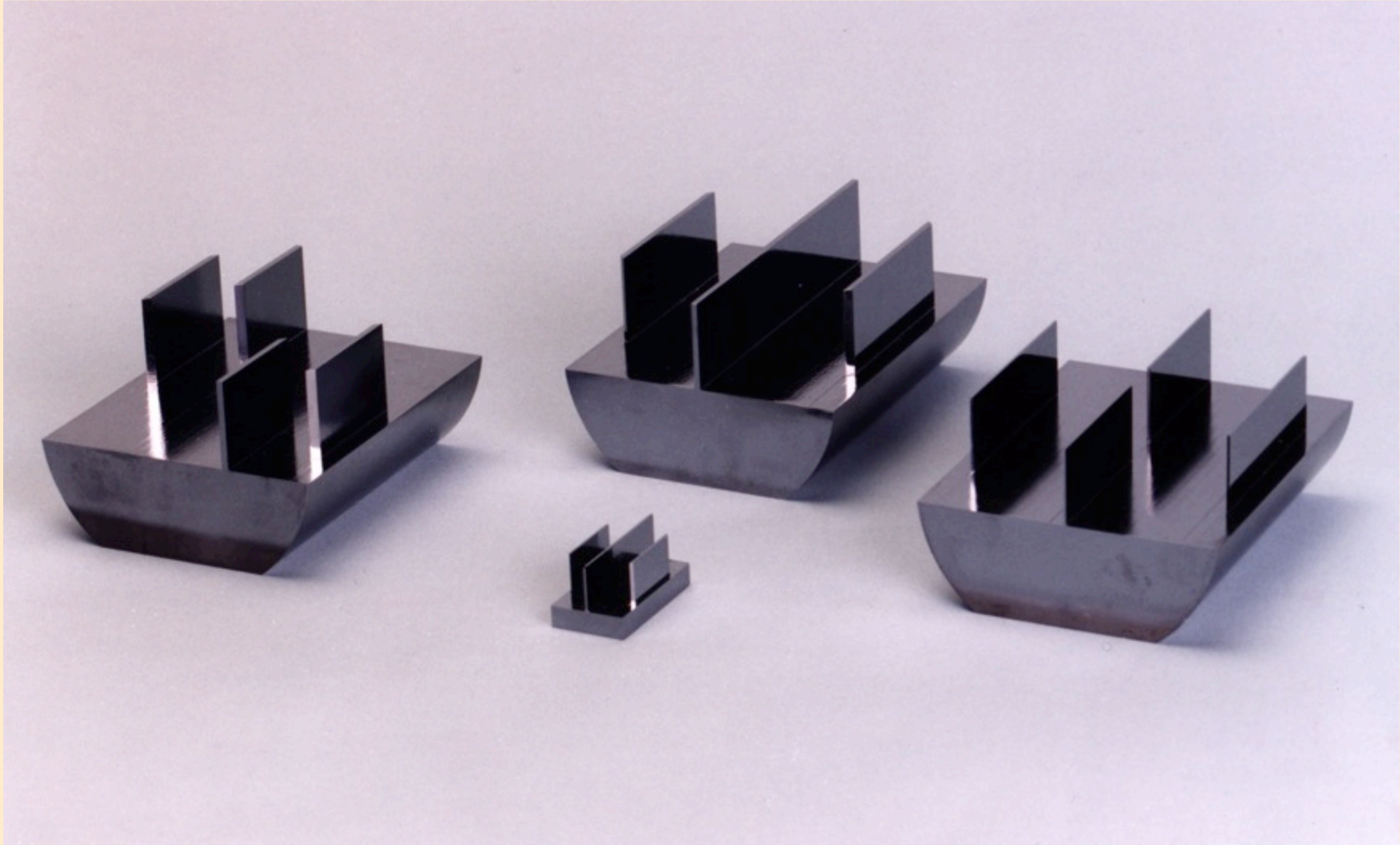
net phase shift: $\Theta(\varepsilon_0, \gamma_0) = 248\pi + 0.455(7)$ radians

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

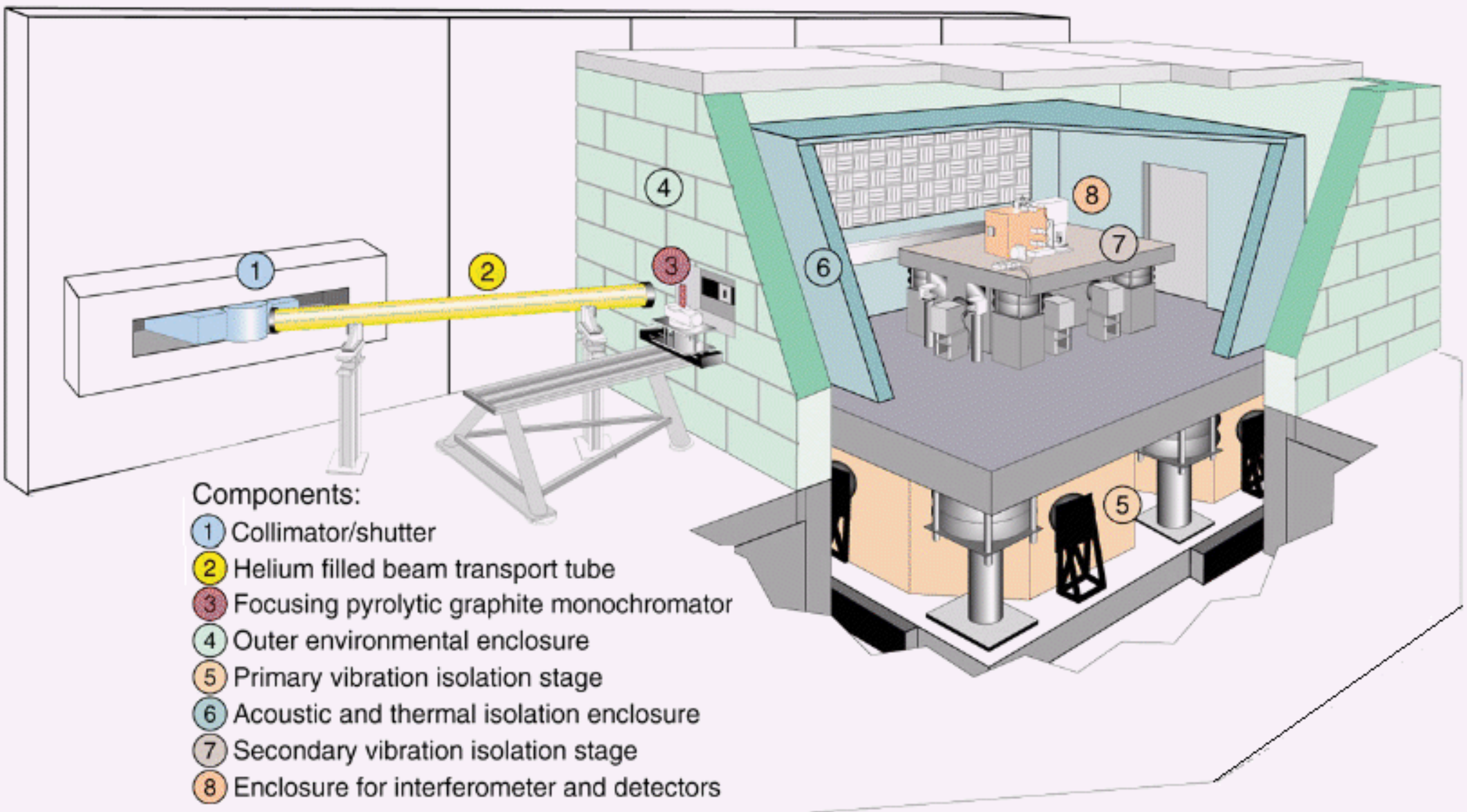
Skew-Symmetric Neutron Interferometer



NIST perfect crystal silicon interferometers



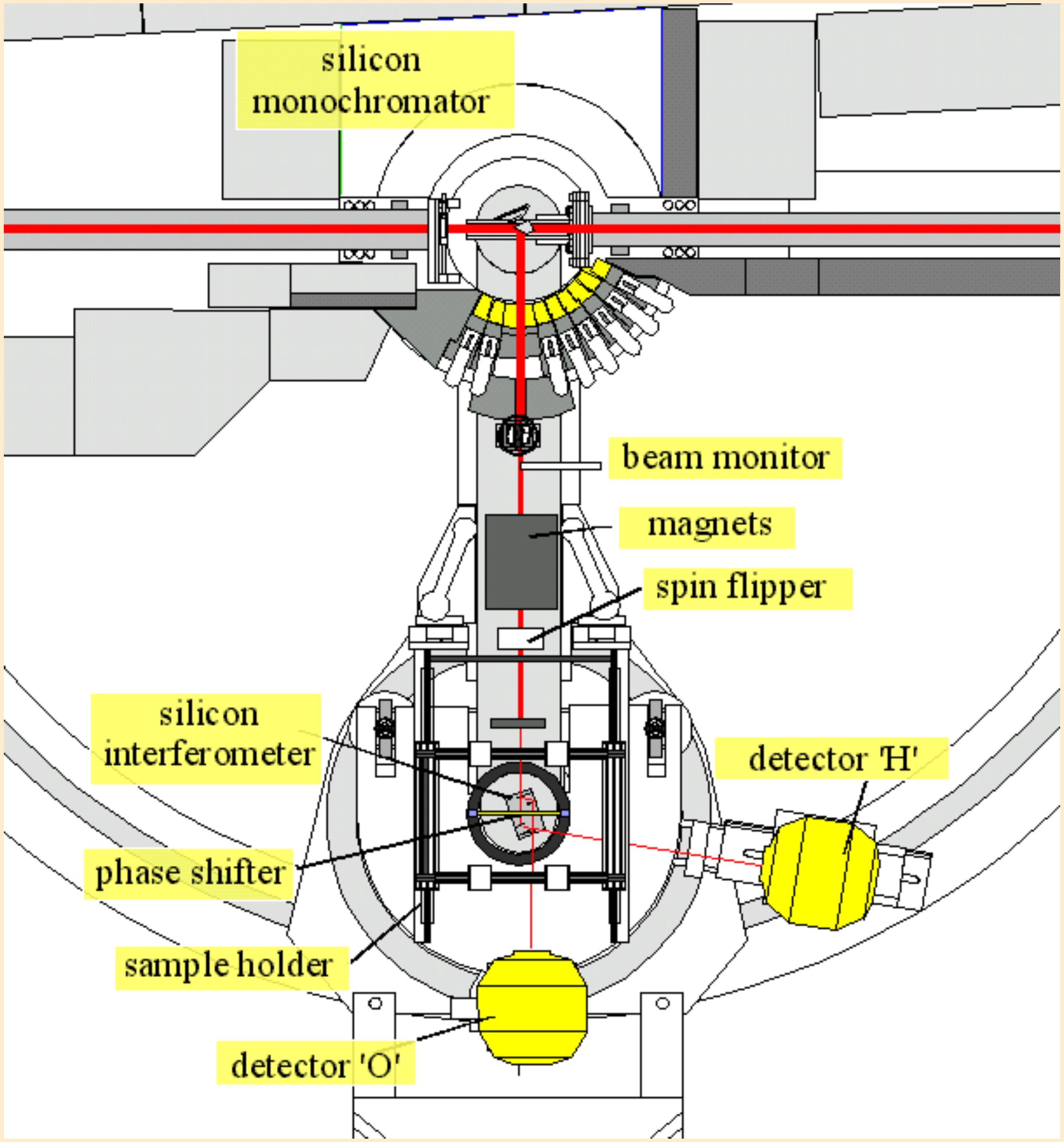
NIST Neutron Interferometer and Optics Facility



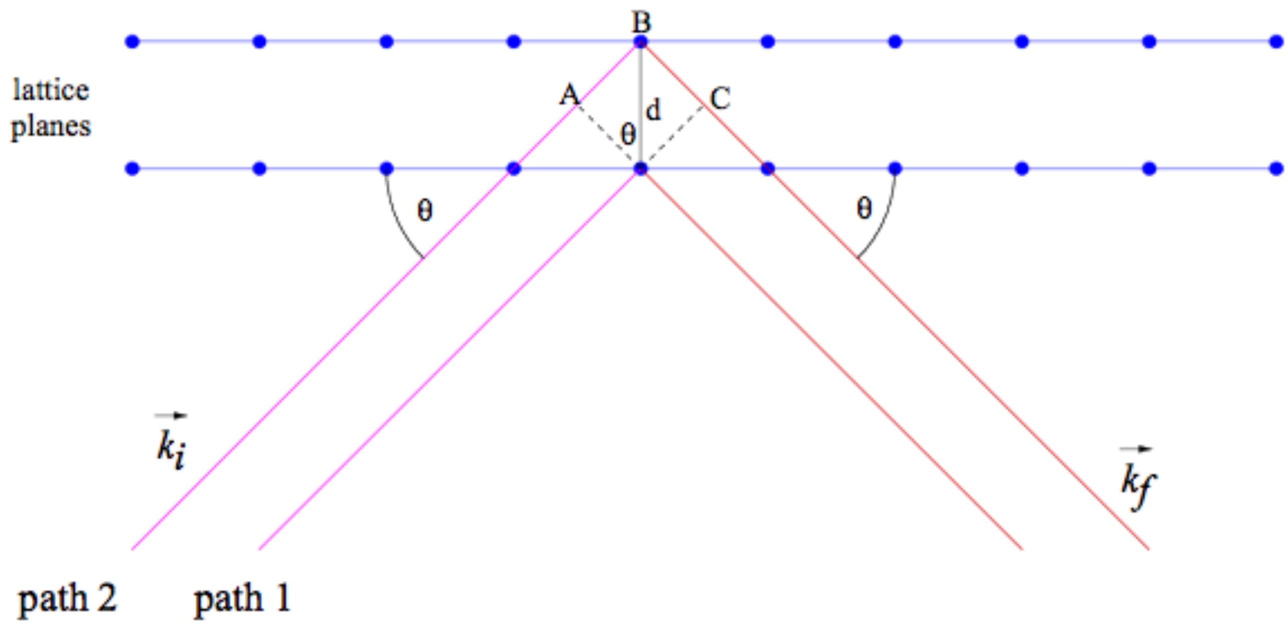
Components:

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

S18 Neutron Interferometer at the Institut Laue-Langevin



"Geometric" Bragg Reflection

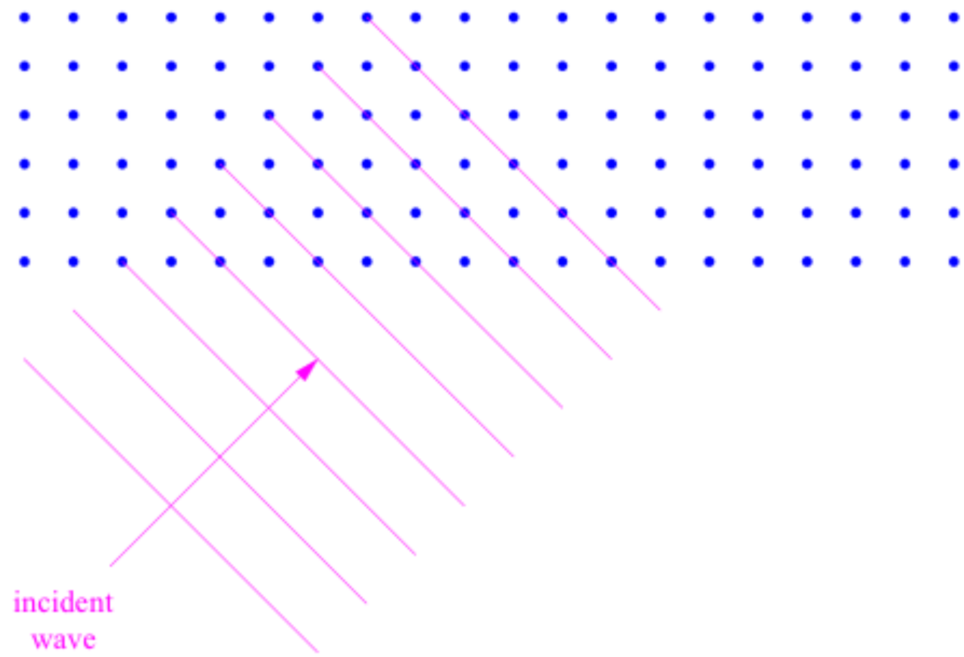


path 2 travels addition distance $\overline{AB} + \overline{BC} = 2d \sin\theta$

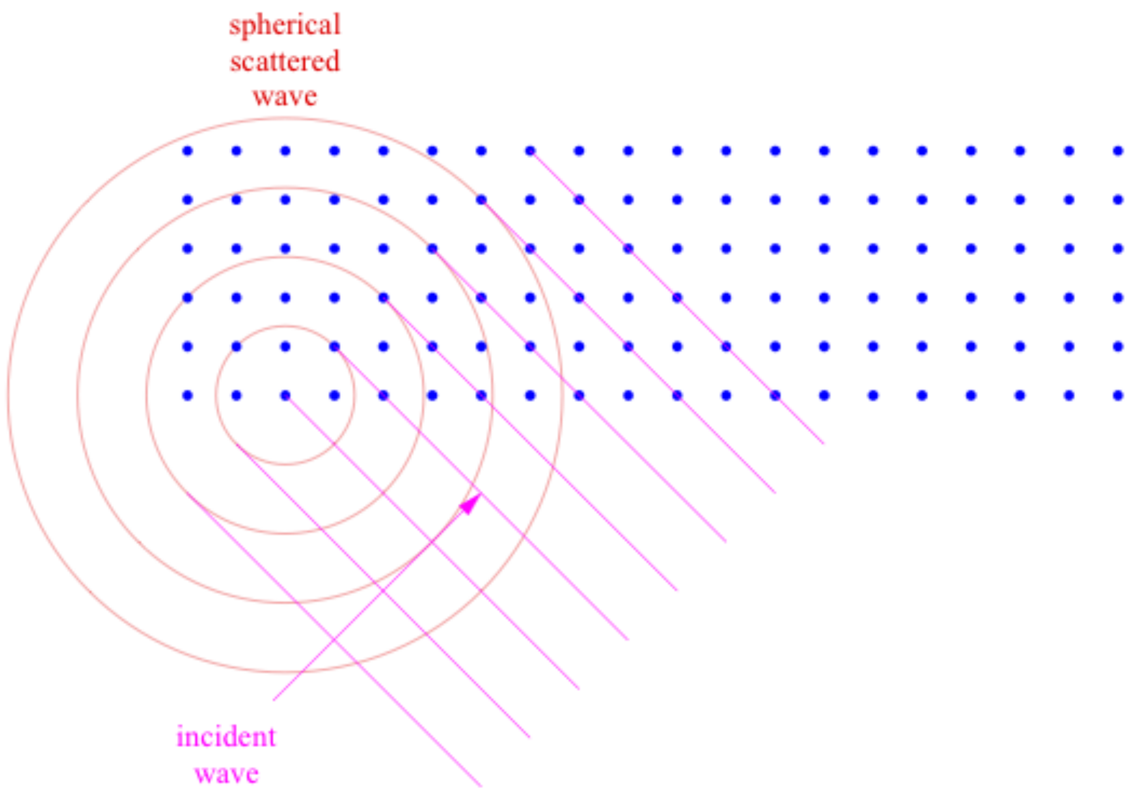
relative phase shift: $\Delta\phi = \dfrac{2d \sin\theta}{\lambda} \times 2\pi$

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

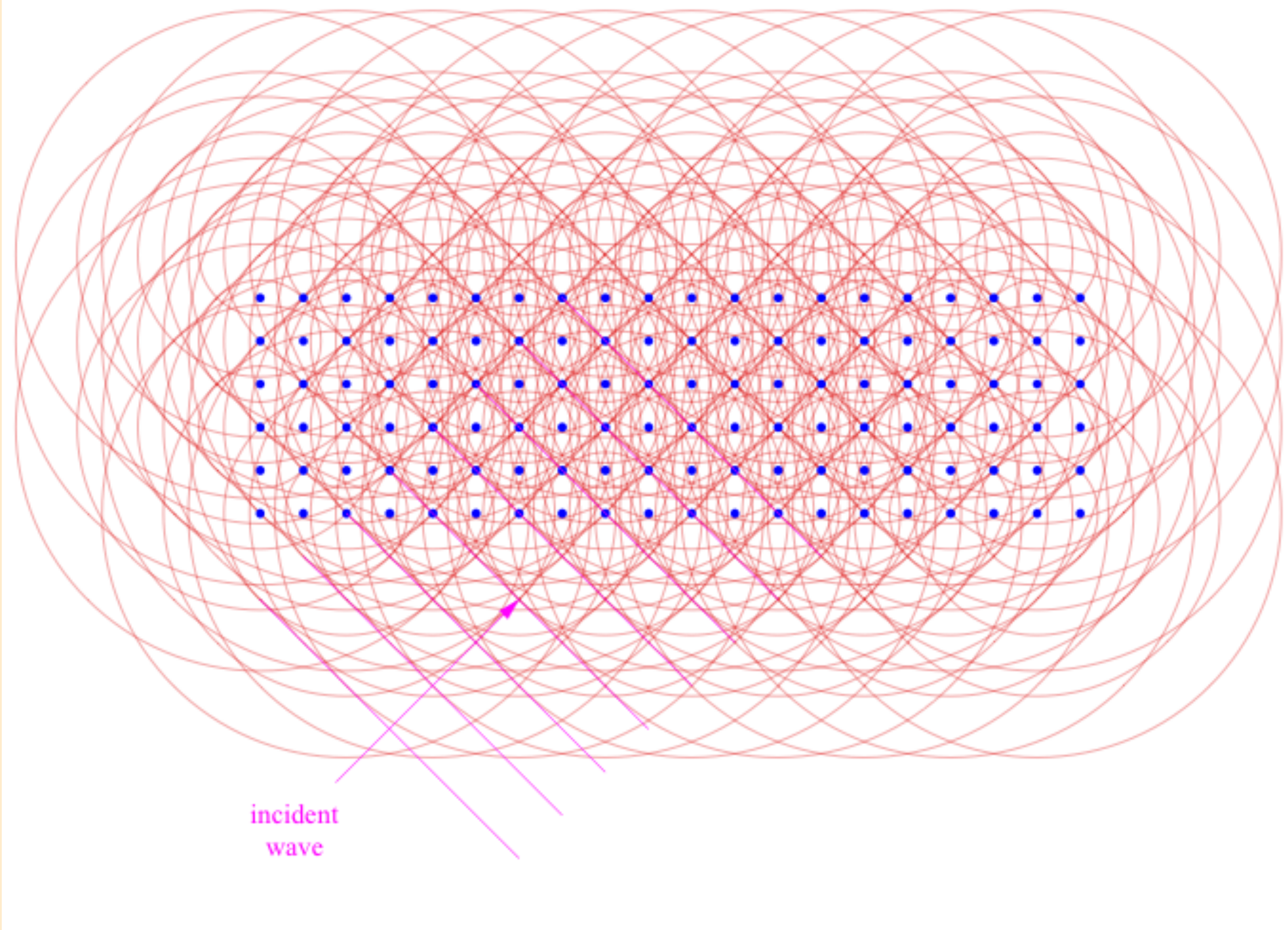
Kinematic Bragg Diffraction



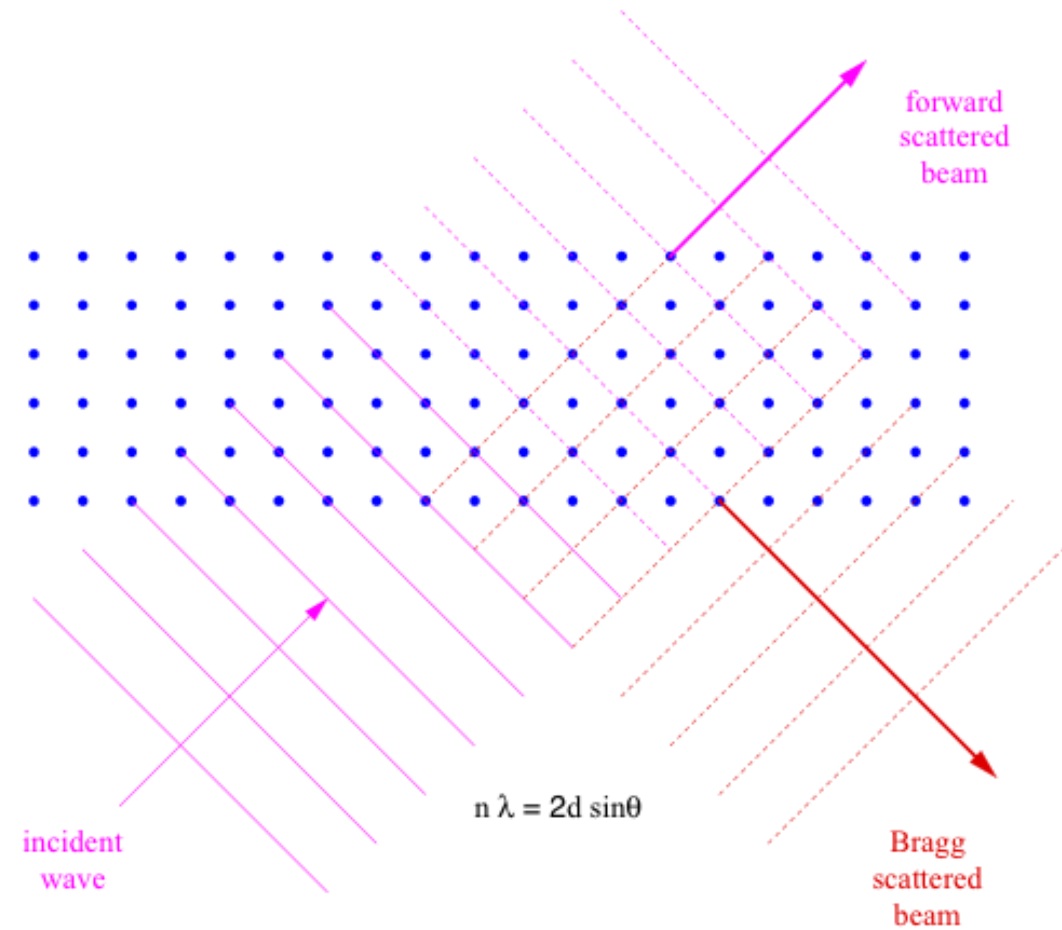
Kinematic Bragg Diffraction



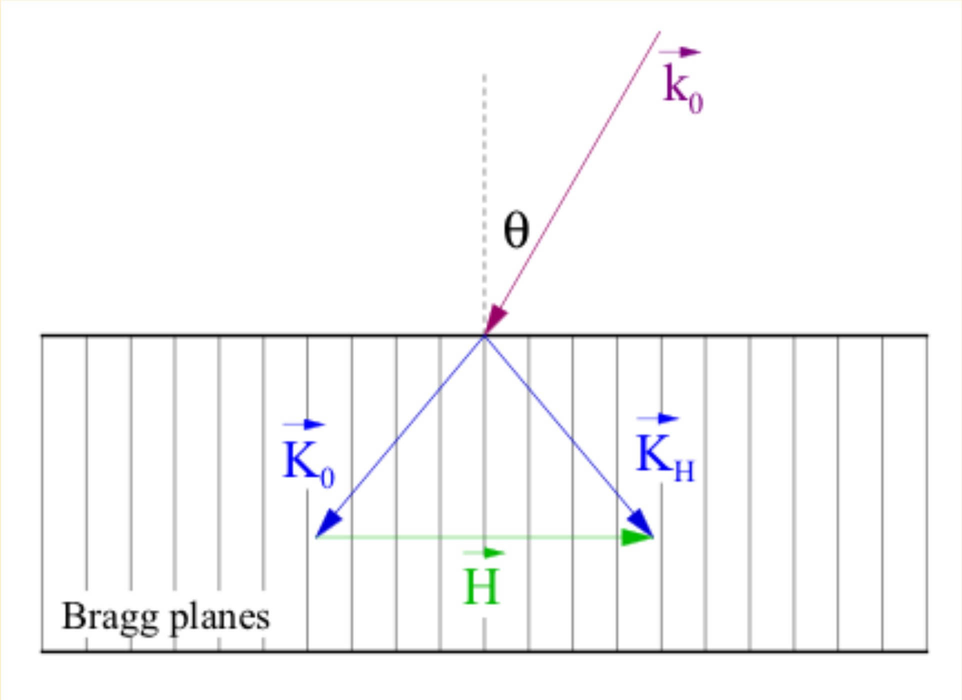
Kinematic Bragg Diffraction



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:

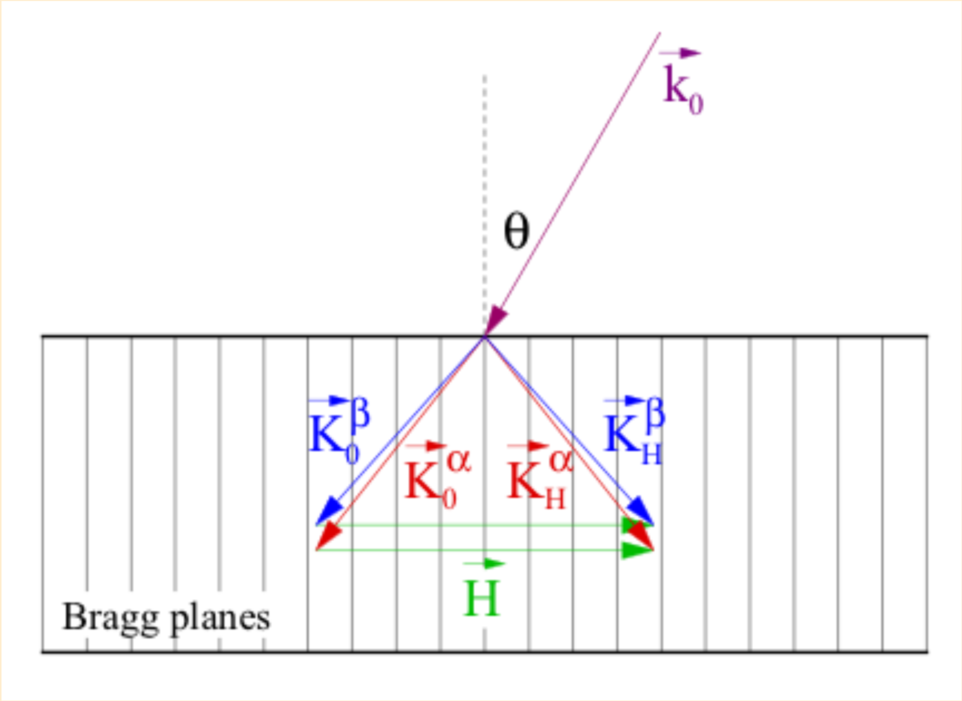
$$\vec{K}_H - \vec{K}_0 = \vec{H}$$

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

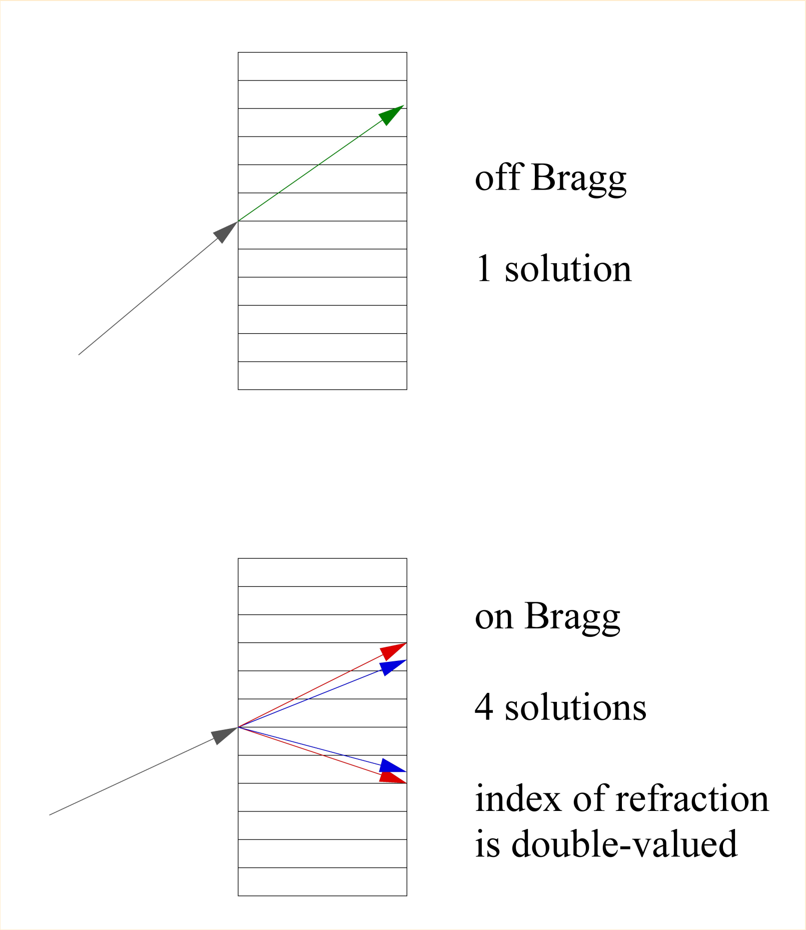


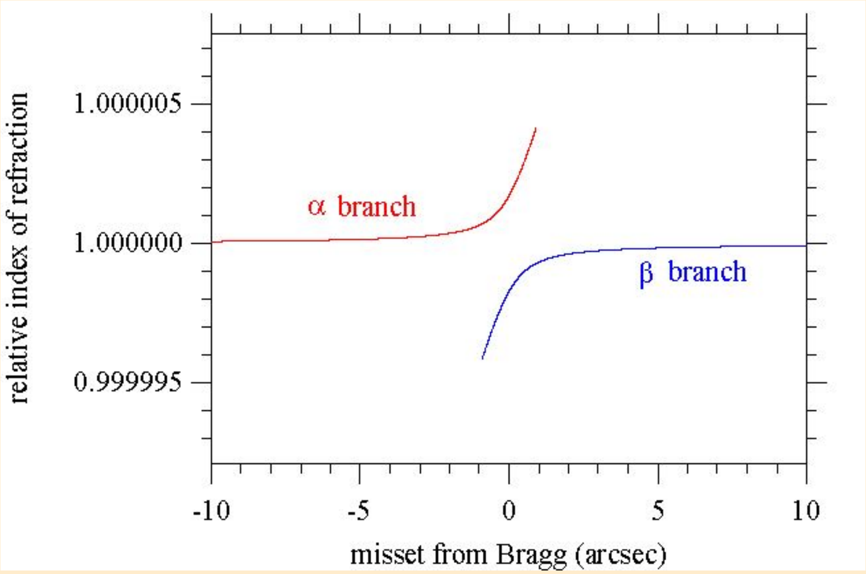
Dispersion Equation: $$\left(K^2 - K_0^2\right)\left(K^2 - K_H^2\right) = v_H^2$$

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

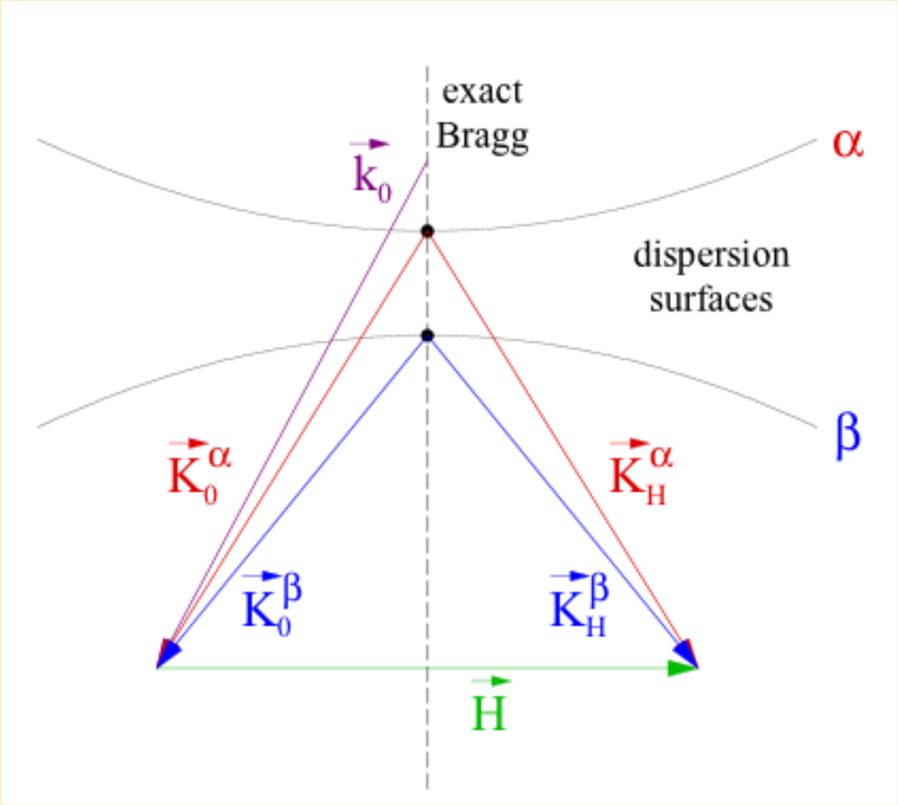
quadratic equation
2 solutions for K_0

Dynamical Diffraction Theory



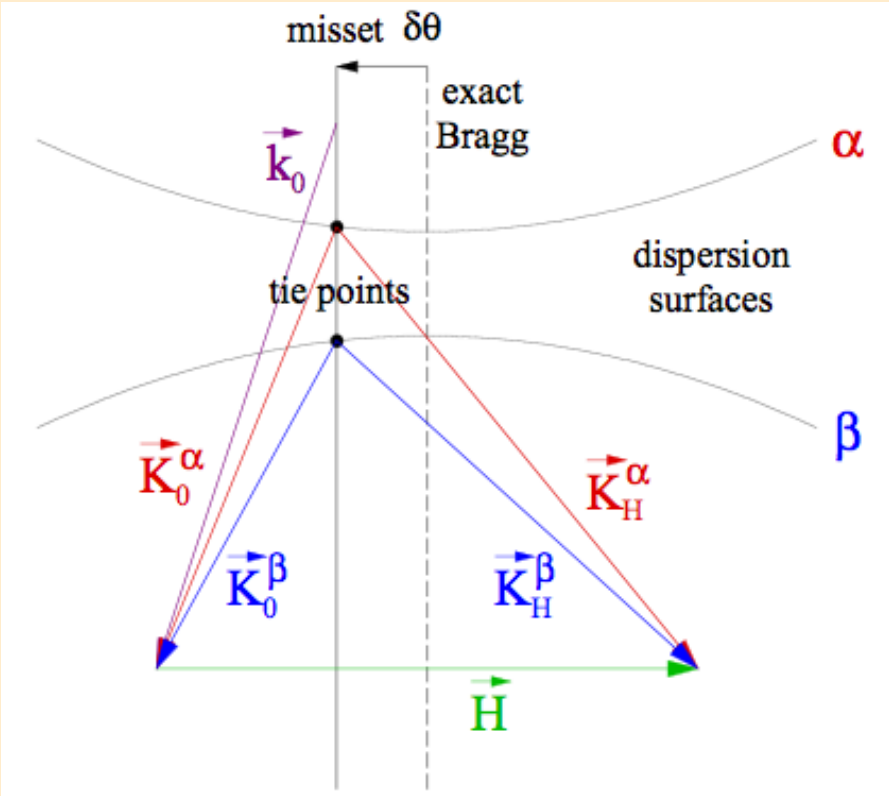


Dynamical Diffraction Theory



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

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

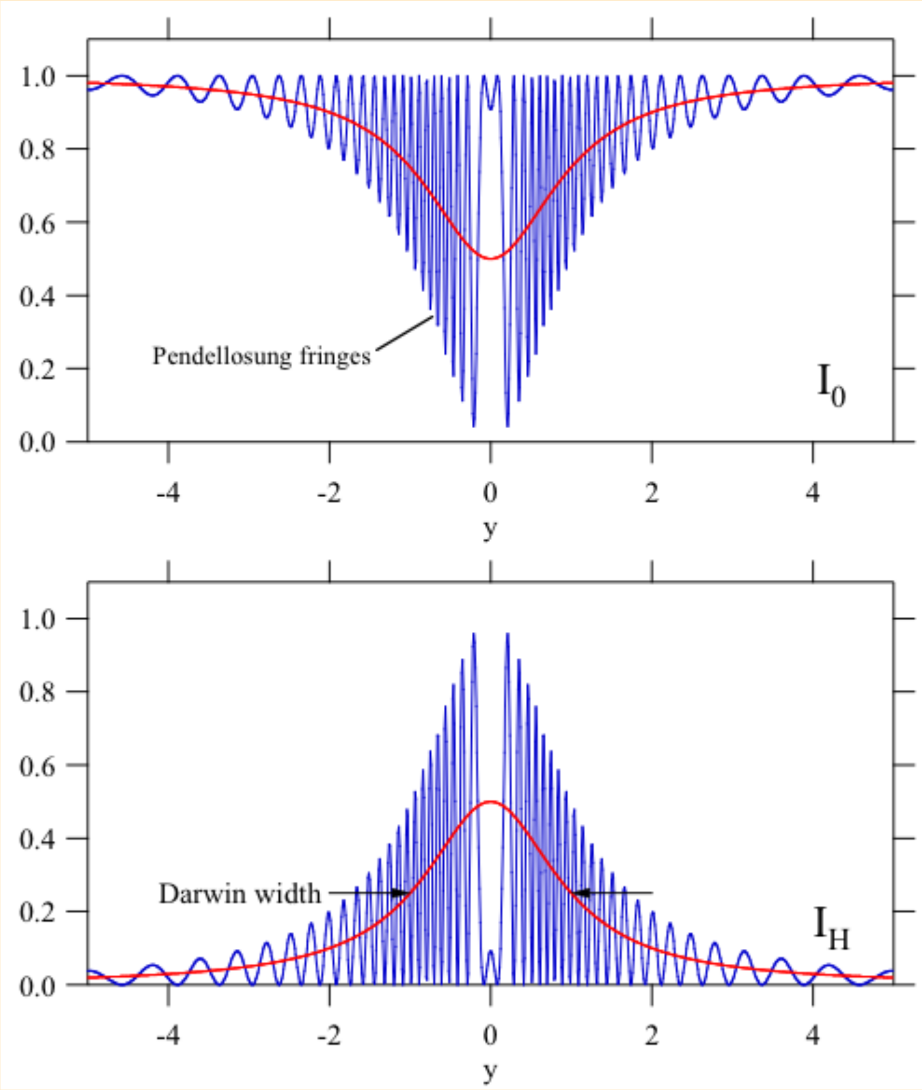
$$\Phi = \left(\nu_H \frac{1}{\sqrt{1+y^2}}\right)\frac{D}{\cos\theta_B}$$

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

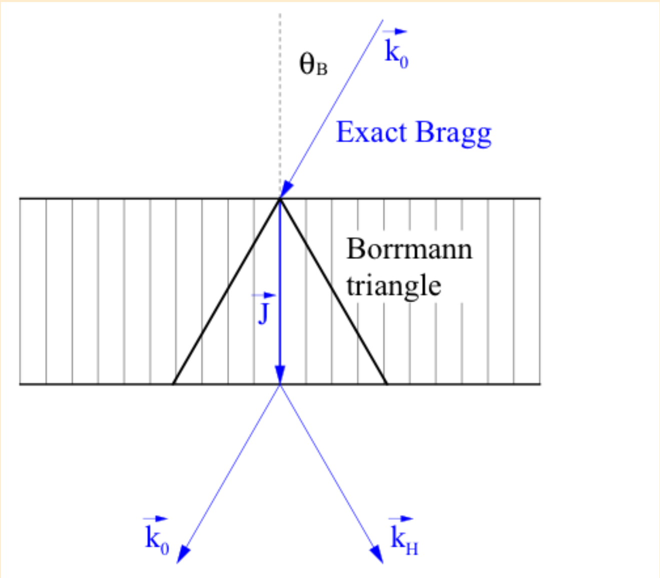
- Pendellösung interference

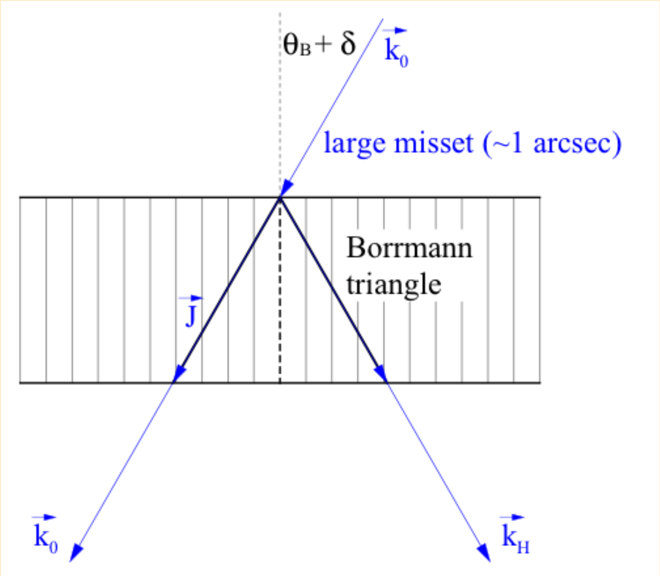
$$\Phi = \left(\nu_H \frac{1}{\sqrt{1+y^2}} \right) \frac{D}{\cos\theta_B}$$

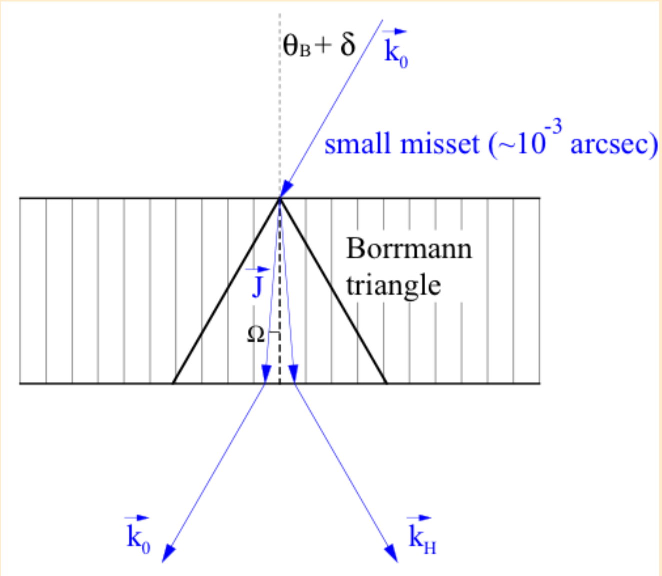
- Anomalous transmission

- Angle amplification

Angle Amplification

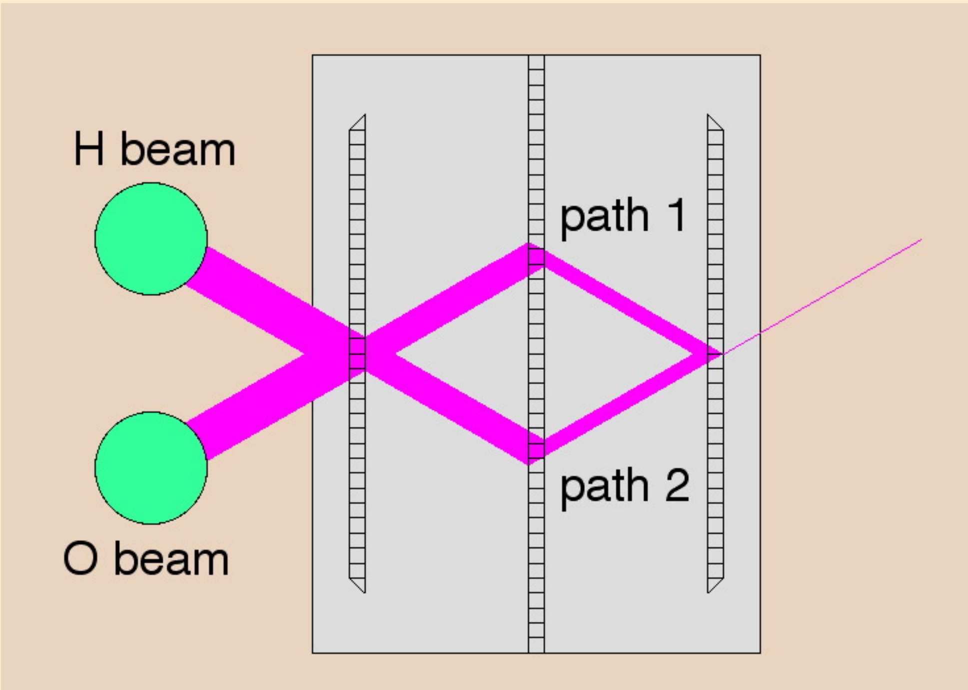


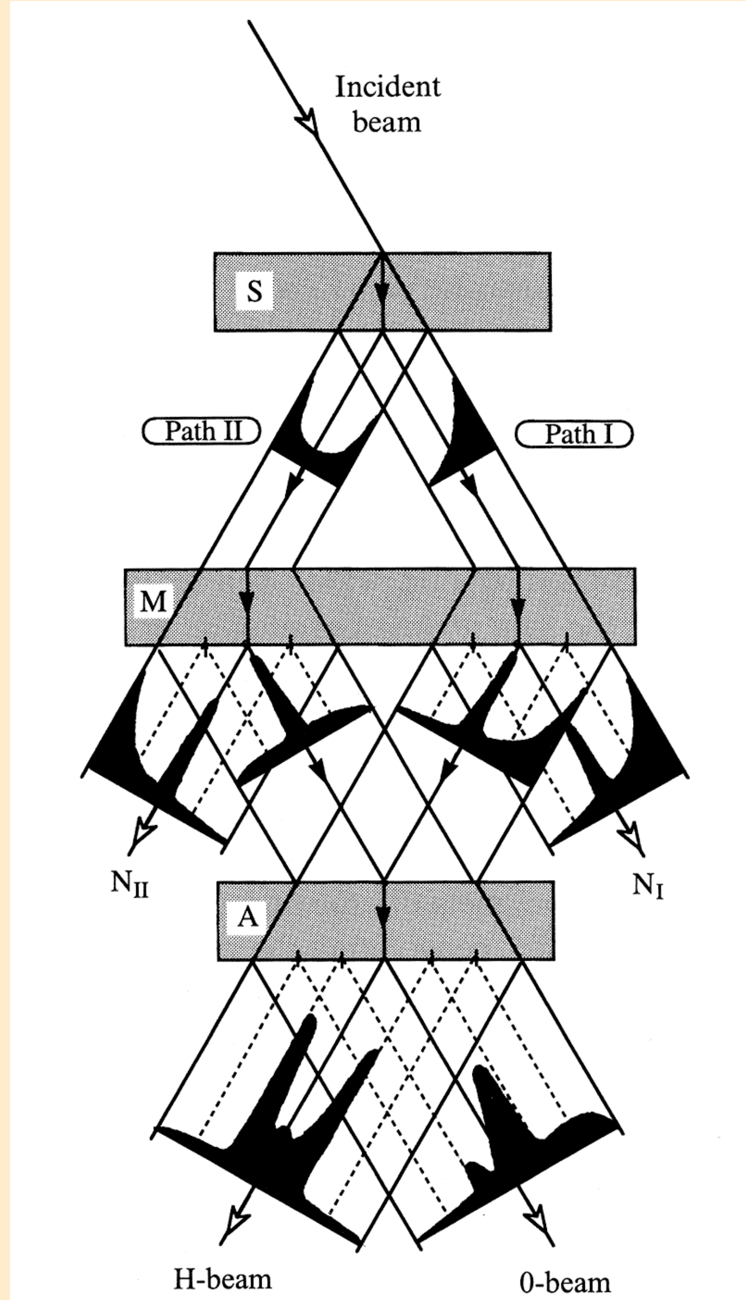




For small δ (~10^{-3} arcsec): $\dfrac{\Omega}{\delta} \approx 10^6$

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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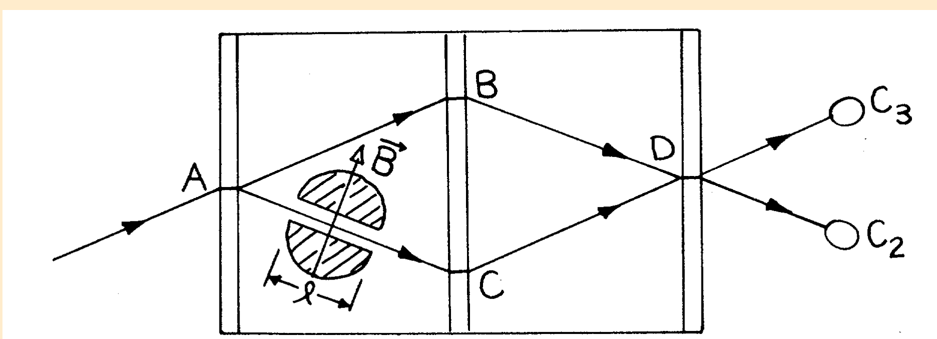
and

C. F. Eagen
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

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

P. Fischer[a], A. Ioffe[b,c,*], D.L. Jacobson[c], M. Arif[c], F. Mezei[a,d]

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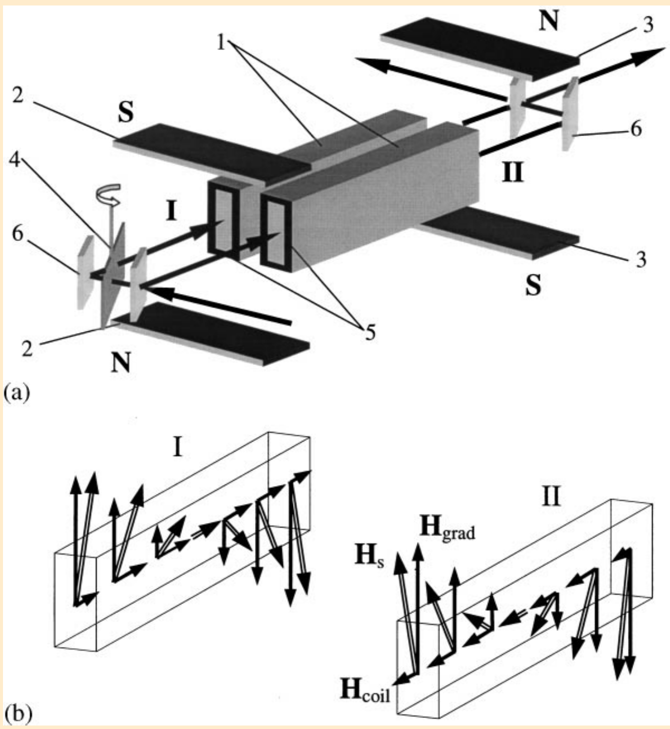
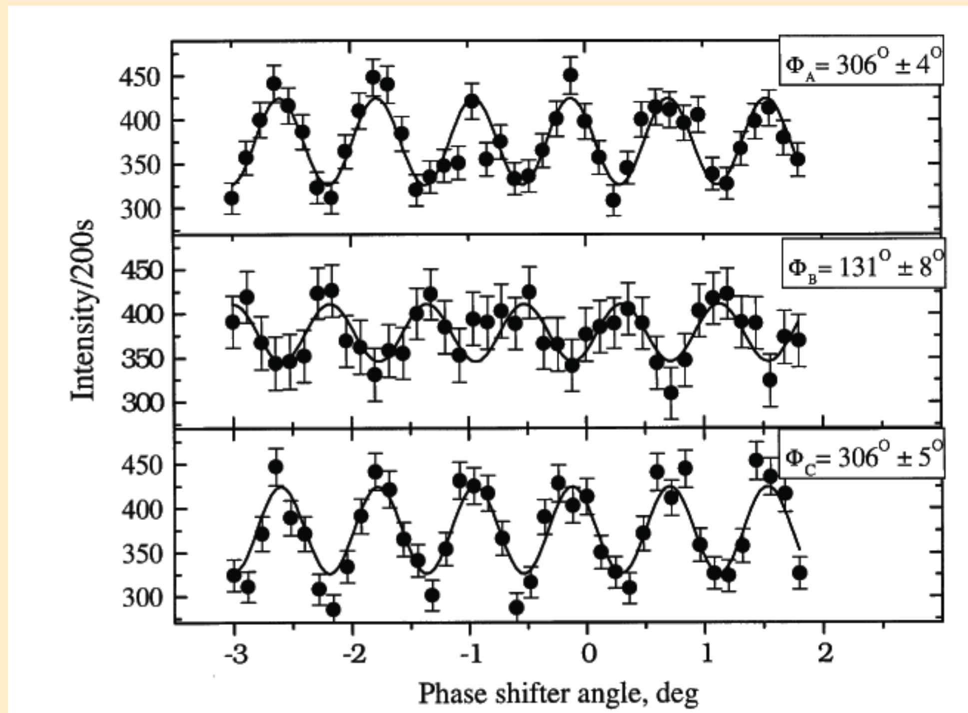
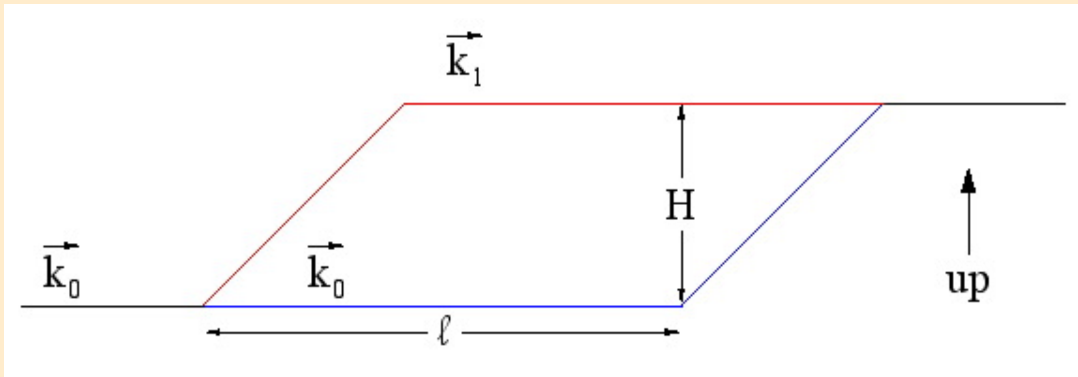
[d]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*





Quantum Phase Shift Due To Gravity (COW Experiments)



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

$A = H\ell =$ area of parallelogram

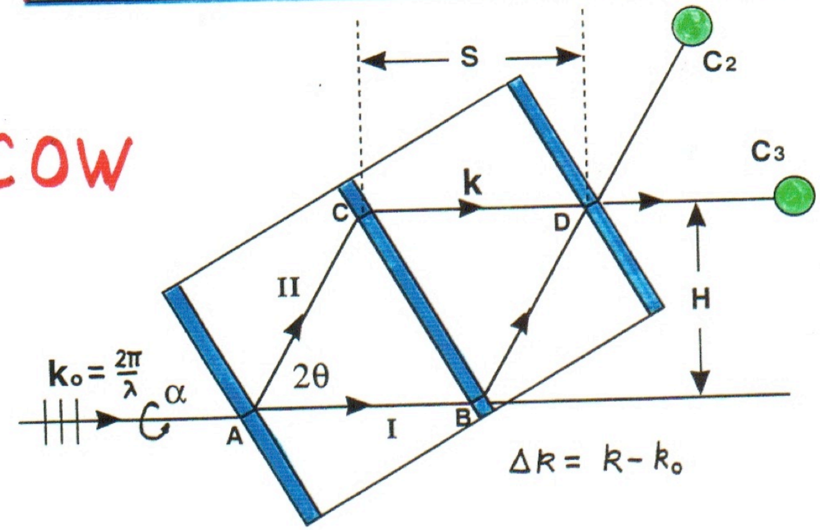
$m_{\text{in}} =$ neutron inertial mass

$m_{\text{grav}} =$ neutron gravitational mass

test of weak equivalence principle at the quantum limit

GRAVITATIONALLY INDUCED QUANTUM INTERFERENCE

COW



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

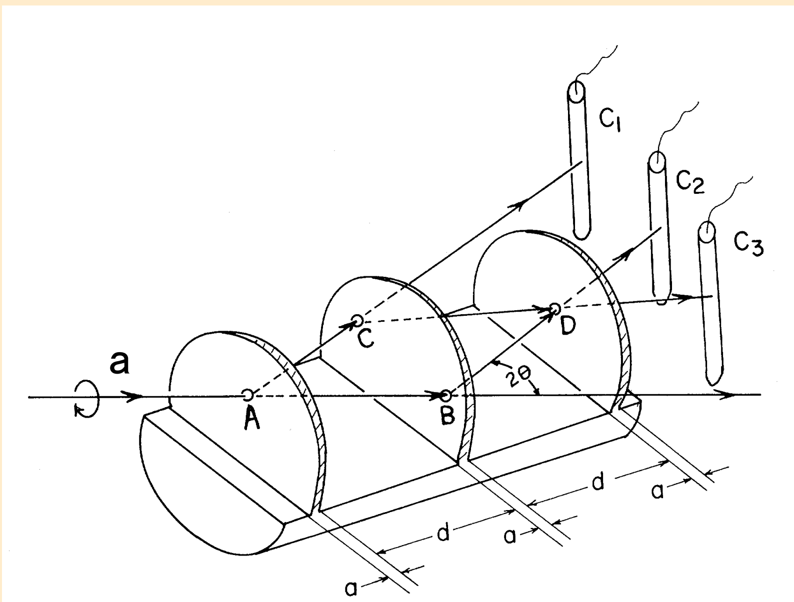
Observation of Gravitationally Induced Quantum Interference*

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

and

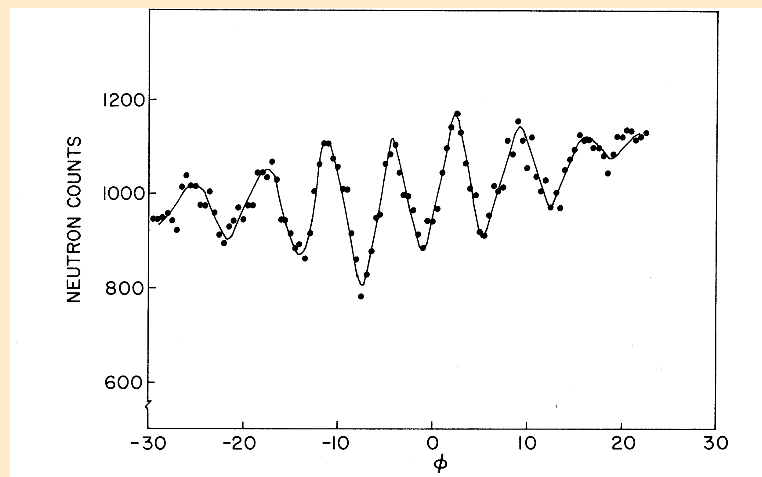
S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

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



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

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



measured: q = 54.3
theory: q = 59.6

Systematic Effects in the COW Experiments

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

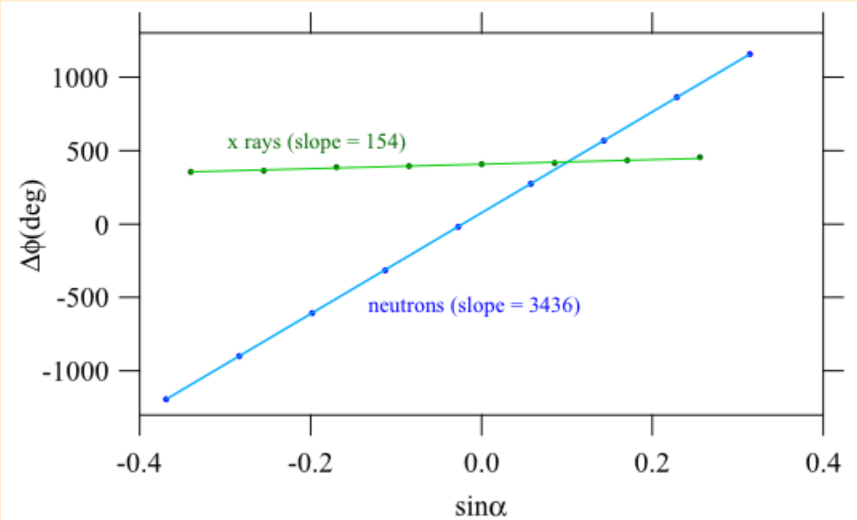
dynamical diffraction correction

bending of interferometer

Earth's rotation

Sagnac effect: $\Delta\phi_{\mathrm{Sagnac}} = \frac{2m_{\mathrm{in}}}{\hbar}\vec{\Omega}\cdot\vec{A}$ 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

Possible improvement (A. Zeilinger, S. Werner, FEW, et al.):

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

Precision Neutron Interferometric Measurements of Few-Body Neutron Scattering Lengths

R. Haun, C. Shahi, F.E. Wietfeldt
Tulane University

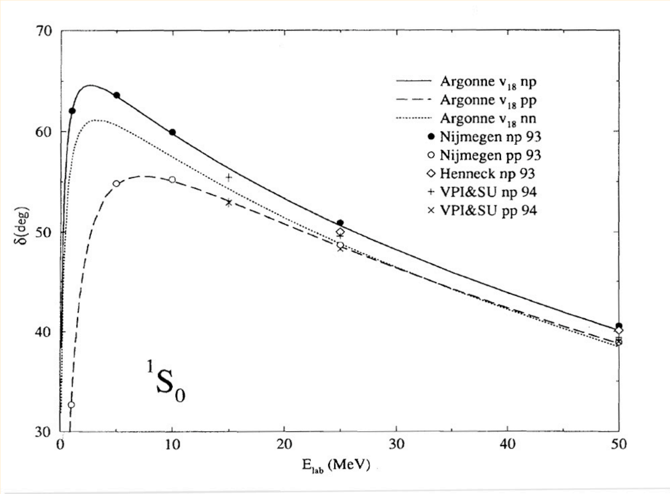
M. Arif, W.C. Chen, T. Gentile, M. Huber, D.L. Jacobson,
D. Pushin, S.A. Werner, L. Yang
NIST

T. C. Black
University of North Carolina, Wilmington

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

W. M. Snow
Indiana University

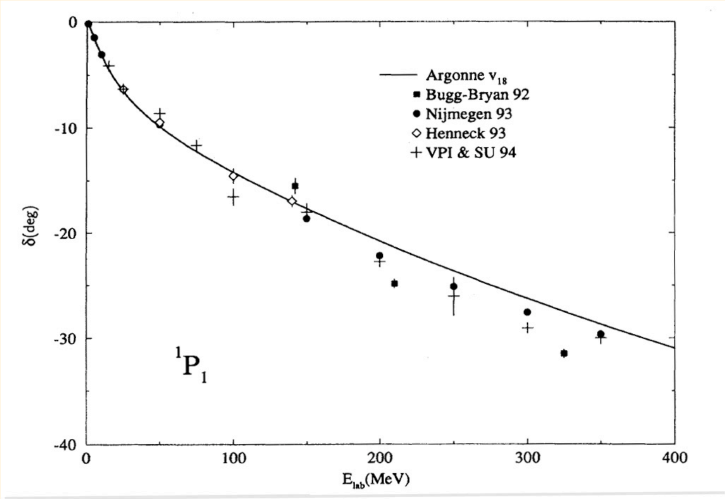
Semi-phenomological nucleon-nucleon potential model AV18

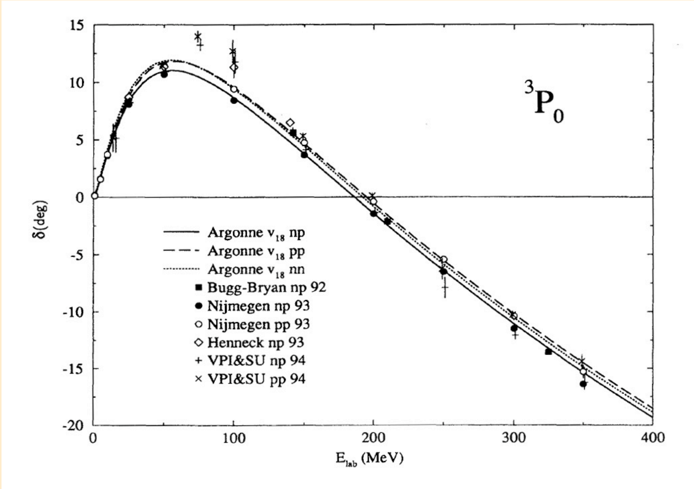


Great success with NN scattering lengths,

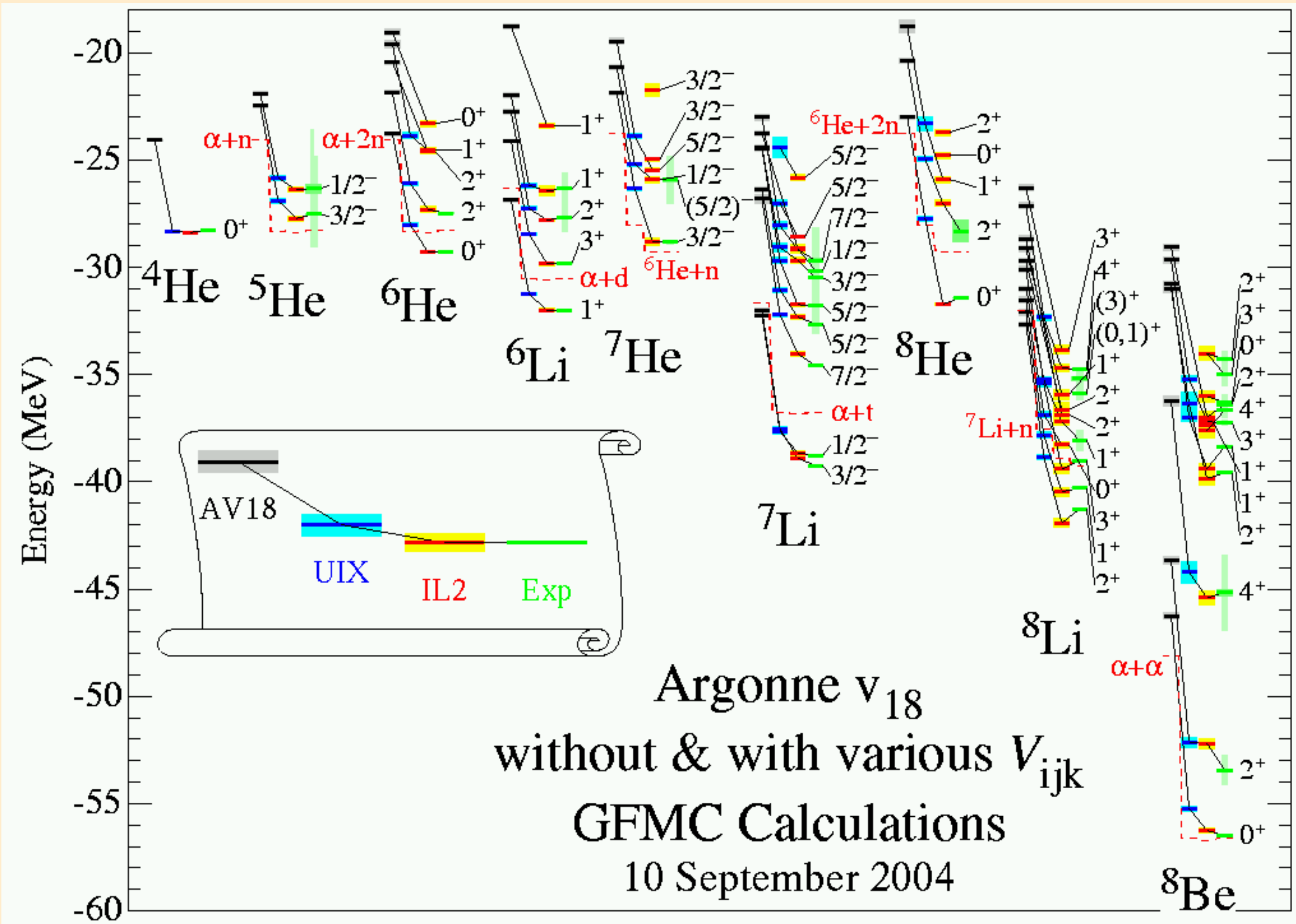
but unable to predict ^{3}He, T binding energies

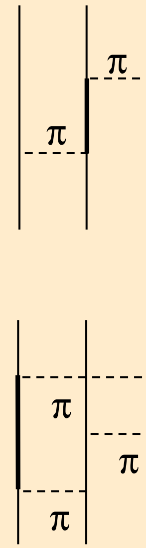
Data from Wiringa *et al.*, Phys. Rev. C 51, 38 (1995)





NN Potential Models



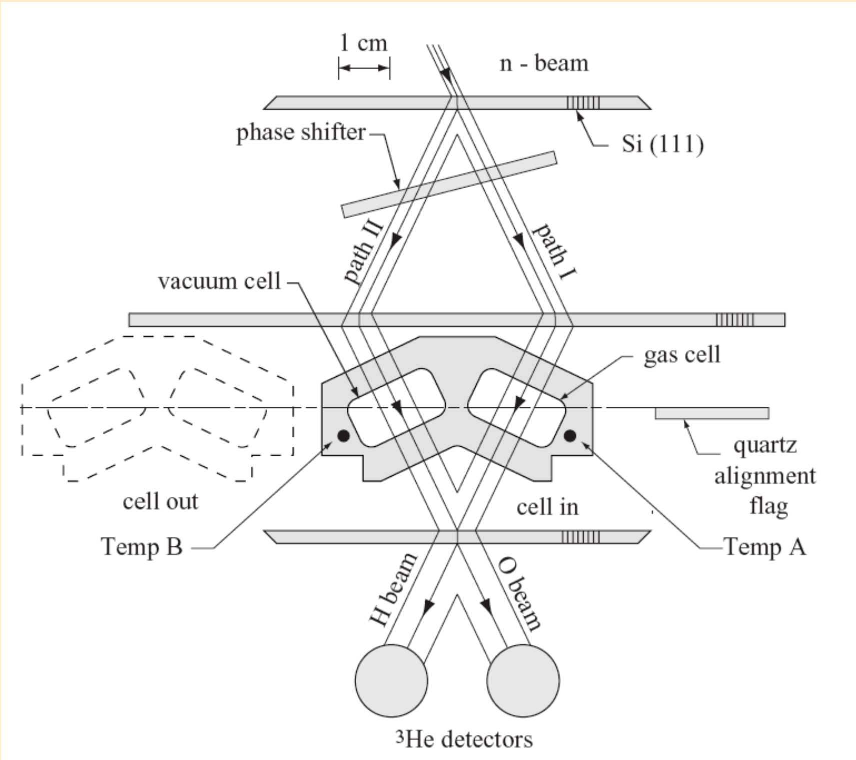


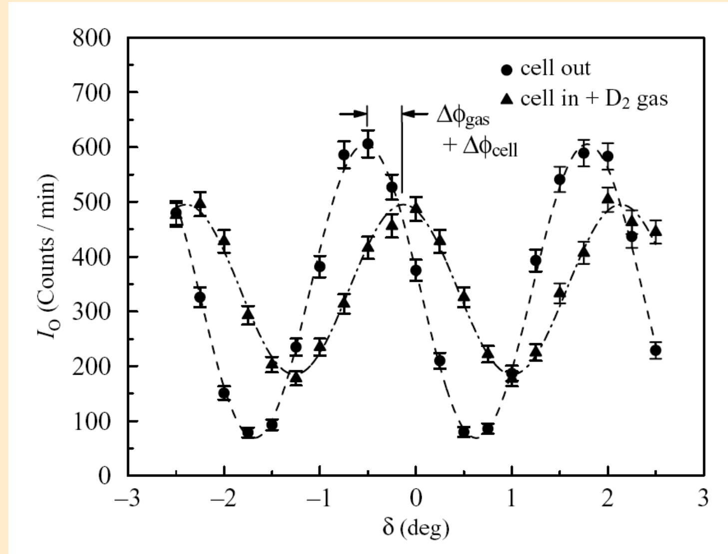
Motivation

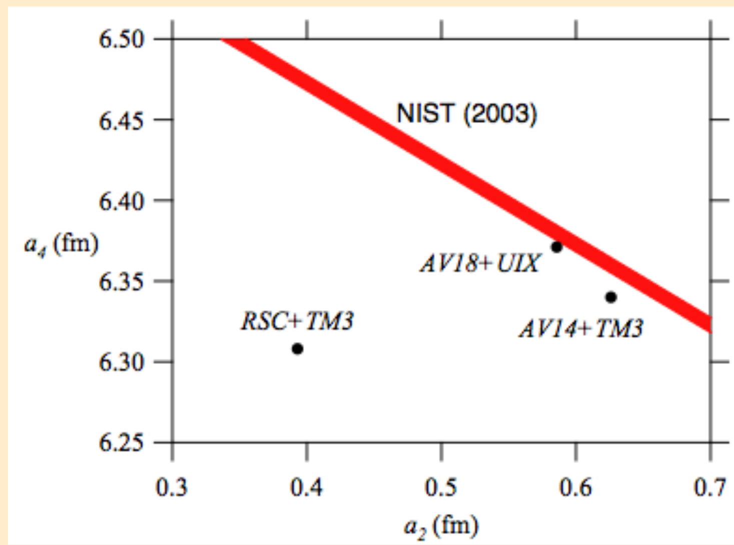
- Precision few-body neutron scattering lengths provide an additional challenge for nuclear potential models.

- 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)



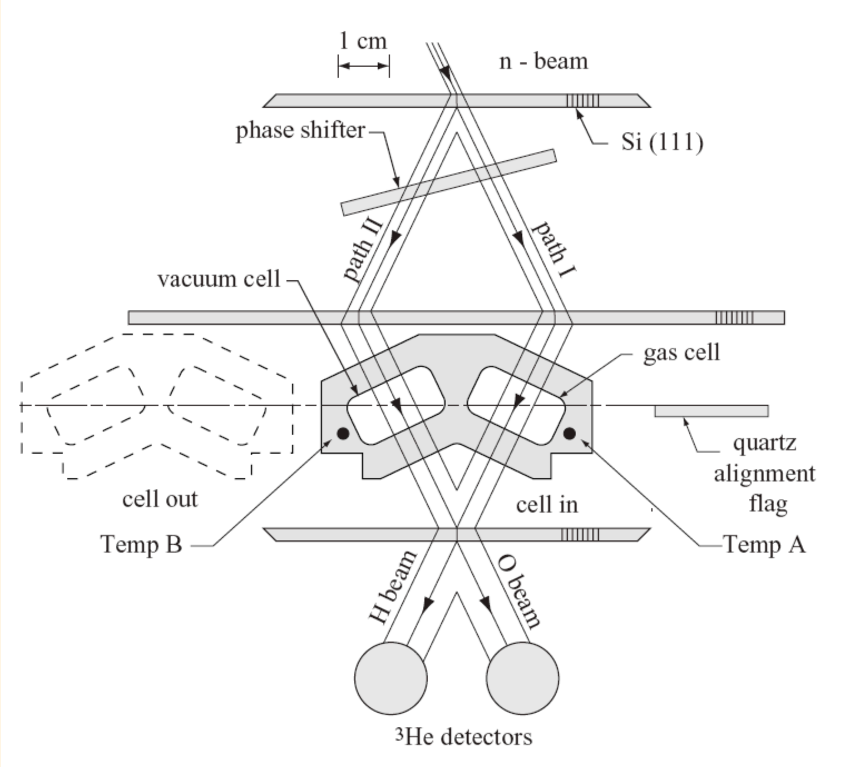


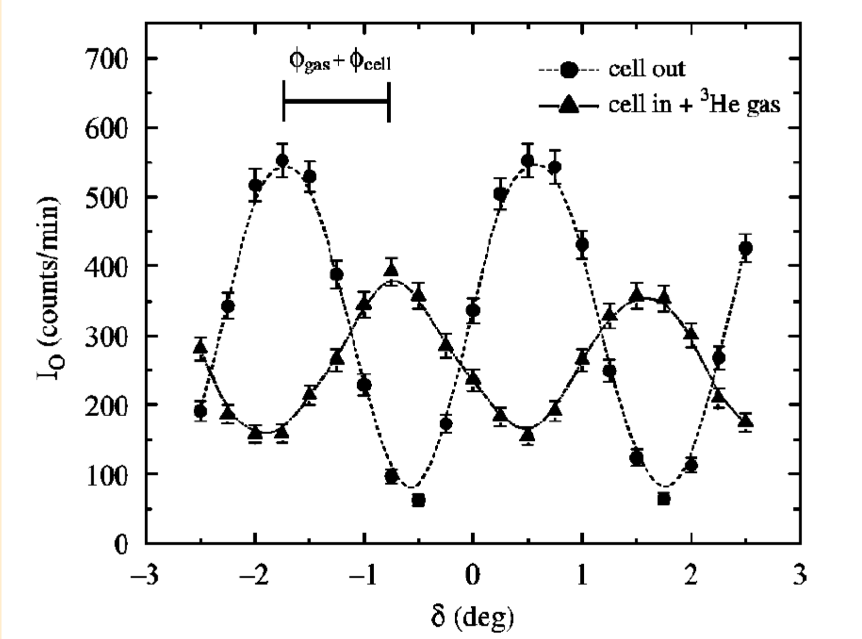


$b_c = 6.6727 \pm 0.0045$ fm

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

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

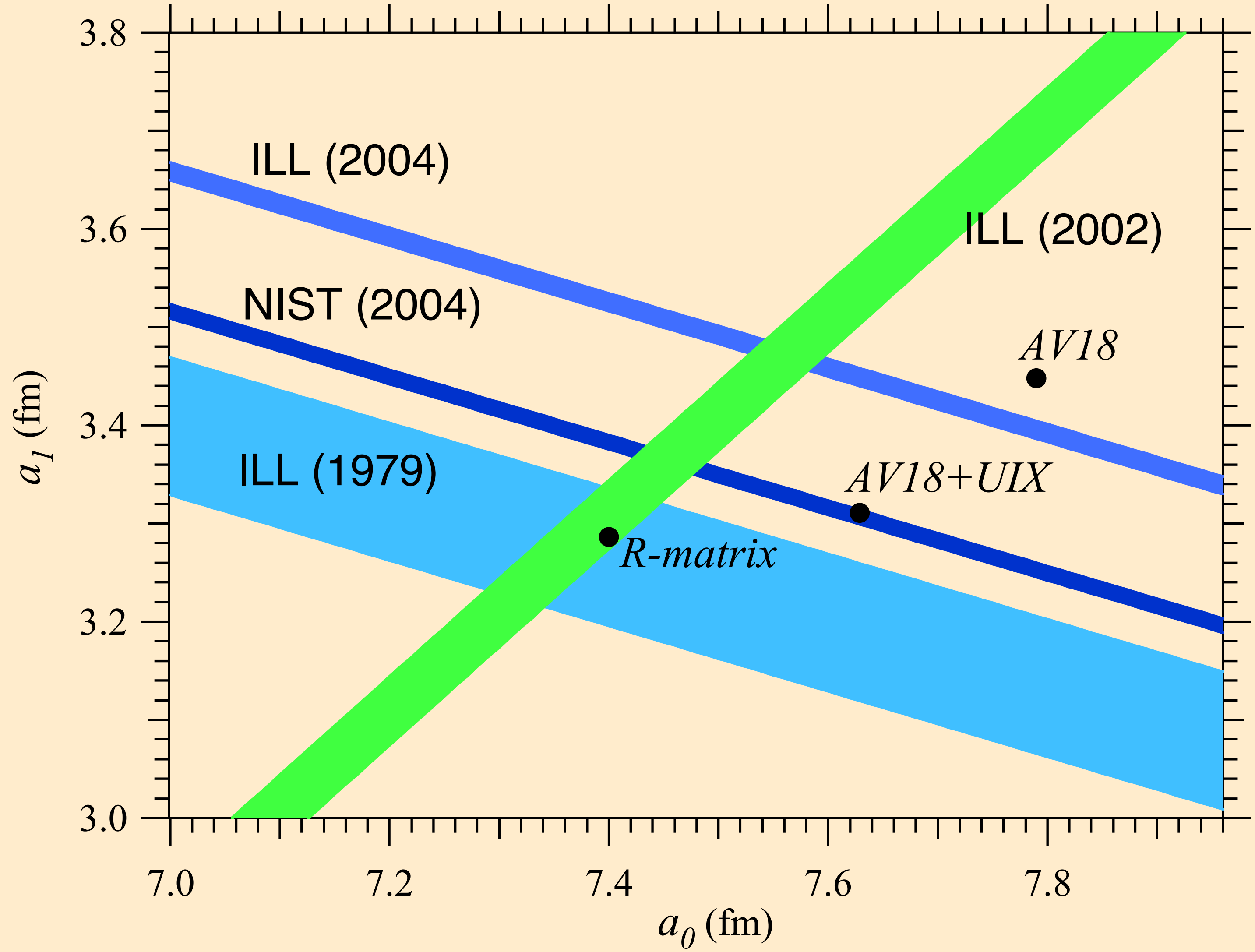




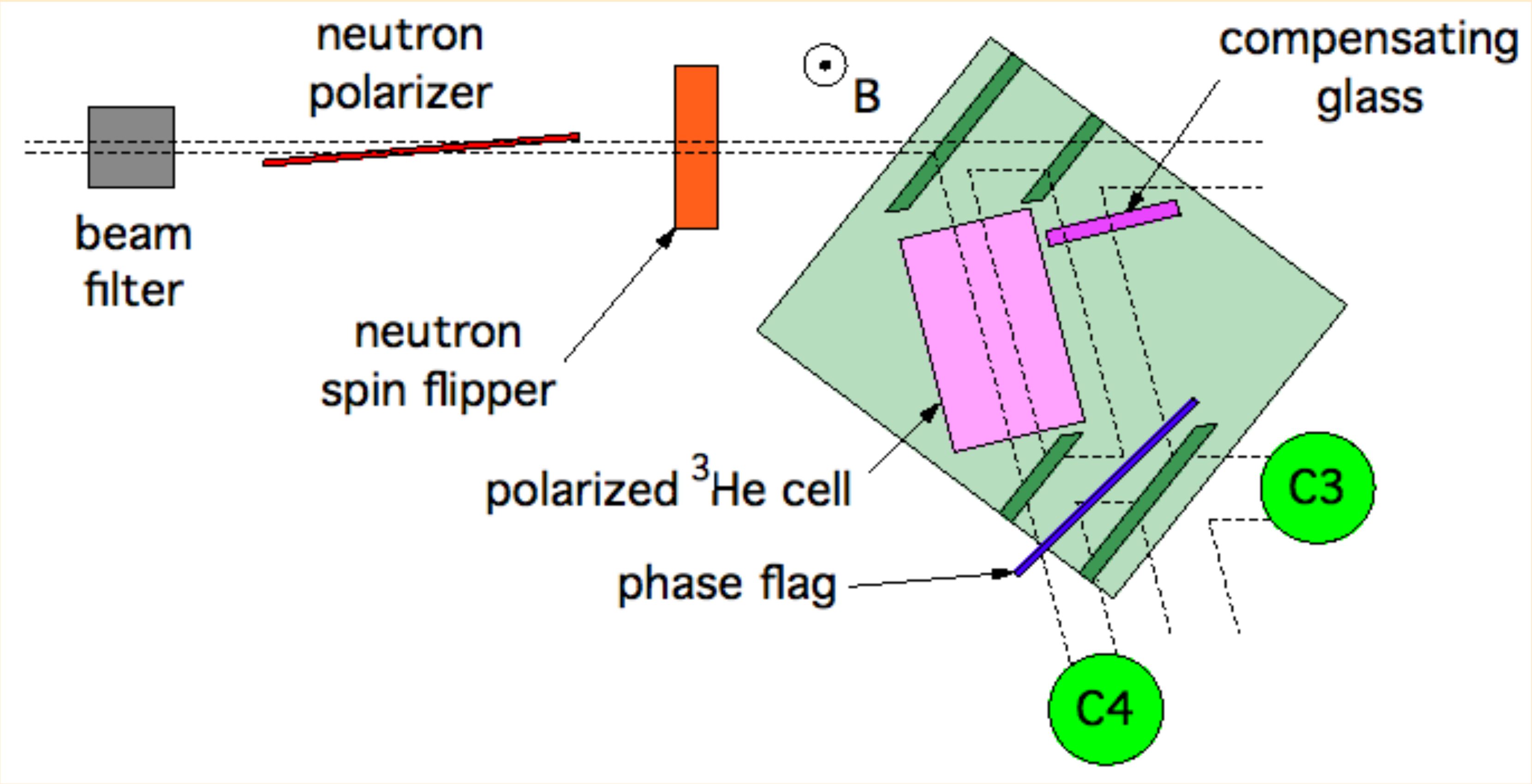
$b_c = 5.8572 \pm 0.0072$ fm

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

n-^{3}He Scattering Lengths



A measurement of the n-^{3}He spin-incoherent scattering length at NIST (2008-2014)



Spin-dependent neutron scattering

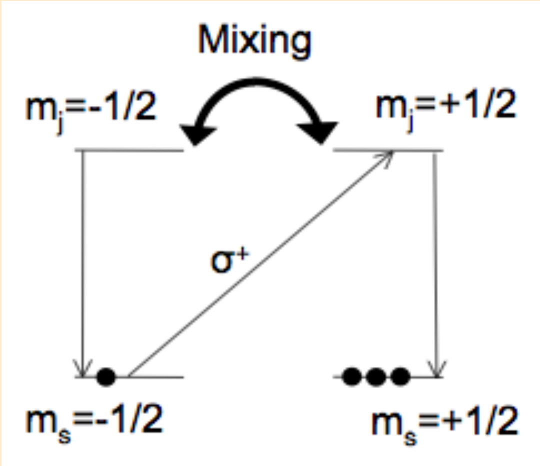
total scattering length: $$b = b_c + \frac{2b_i}{\sqrt{I(I+1)}} \vec{I} \cdot \vec{\sigma}_n$$

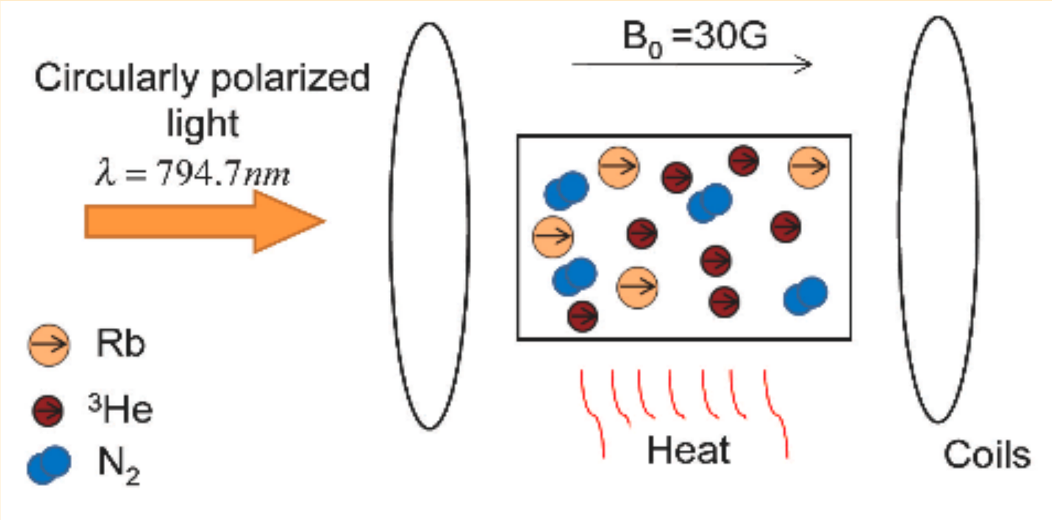
coherent: $$b_c = \frac{I+1}{2I+1} b_+ + \frac{I}{2I+1} b_-$$

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 ^{3}He Cells

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

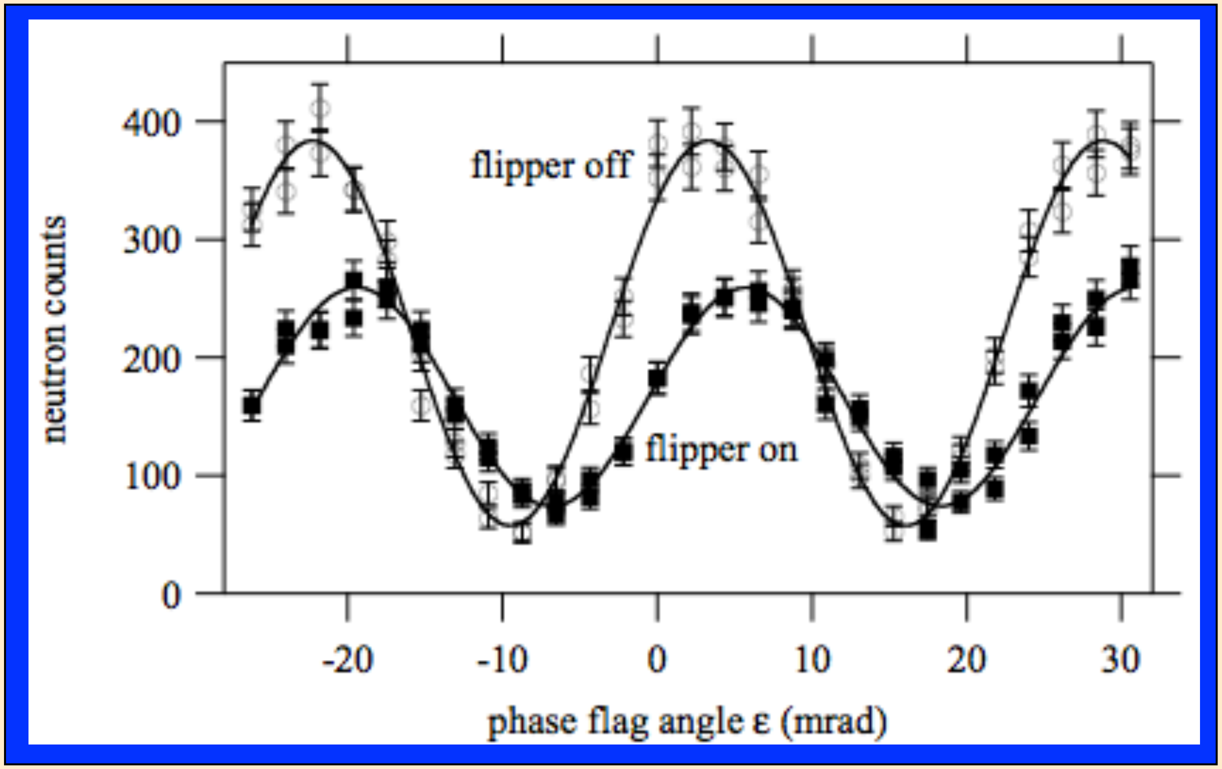
Two cells:
"Pistachio" (115 hours)
"Cashew" (35 hours)

Measuring the Scattering Length

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

Measuring the Scattering Length

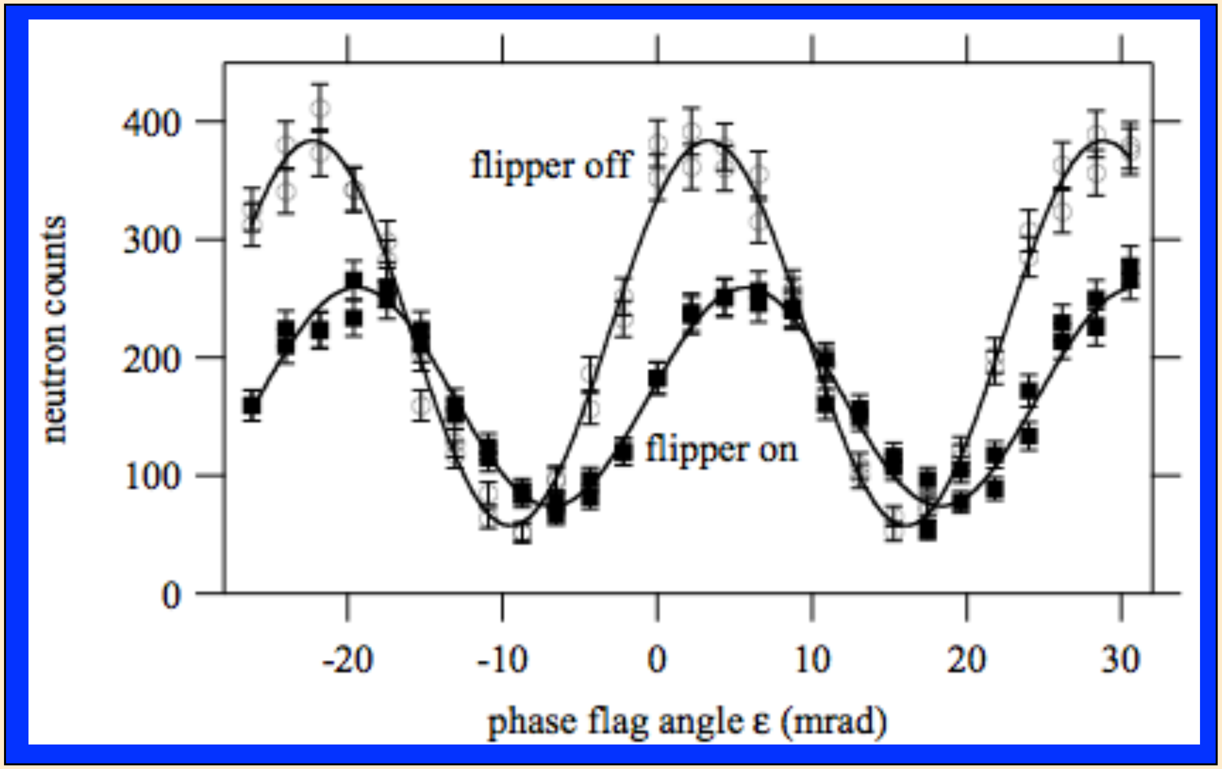
$$b_+ - b_- = -\frac{2\left(\phi^{\uparrow} - \phi^{\downarrow}\right)}{N_3 \lambda z P_3}$$



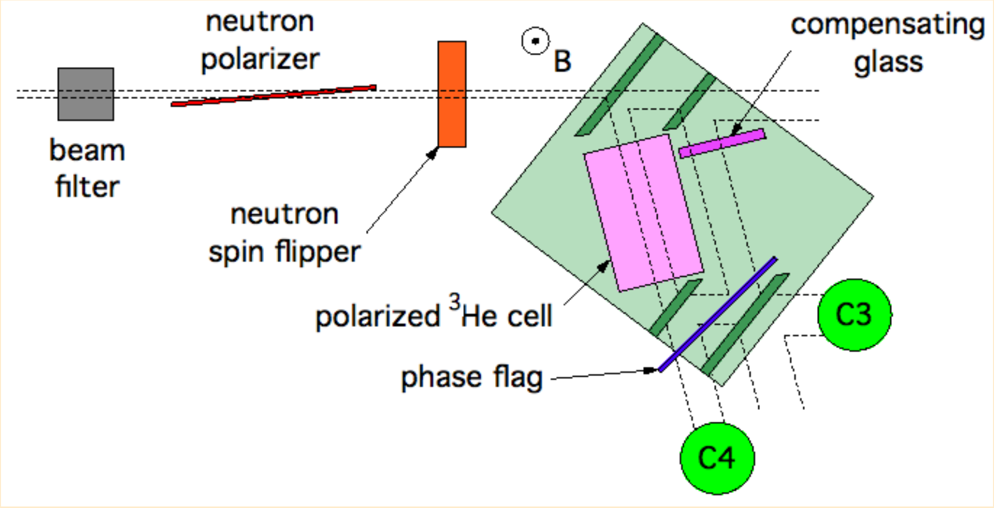
Measuring the Scattering Length

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

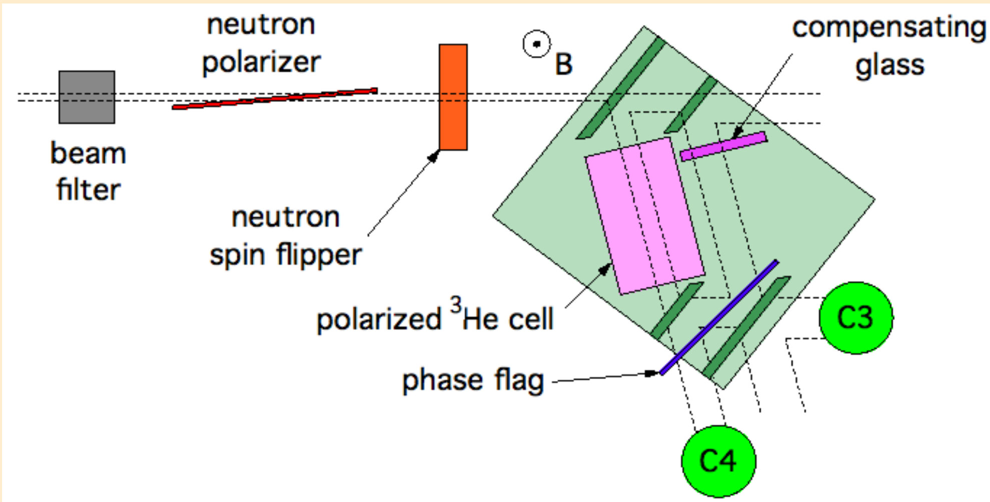
measured simultaneously from the asymmetry in counter C4



Measuring $N_3 \lambda z P_3$



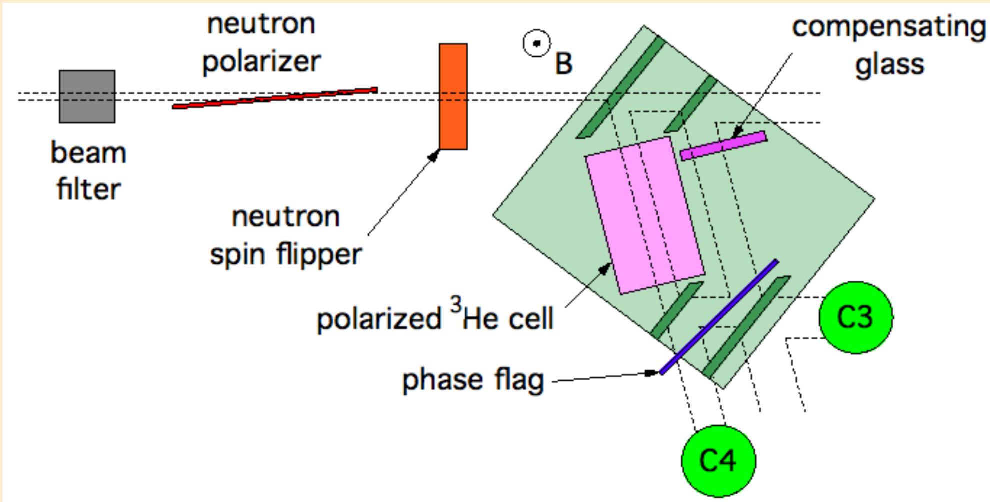
Measuring $N_3 \lambda z P_3$



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

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

Measuring $N_3 \lambda z P_3$



$P_3 =$ ³He polarization

$P_n =$ neutron polarization (flipper off)

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

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

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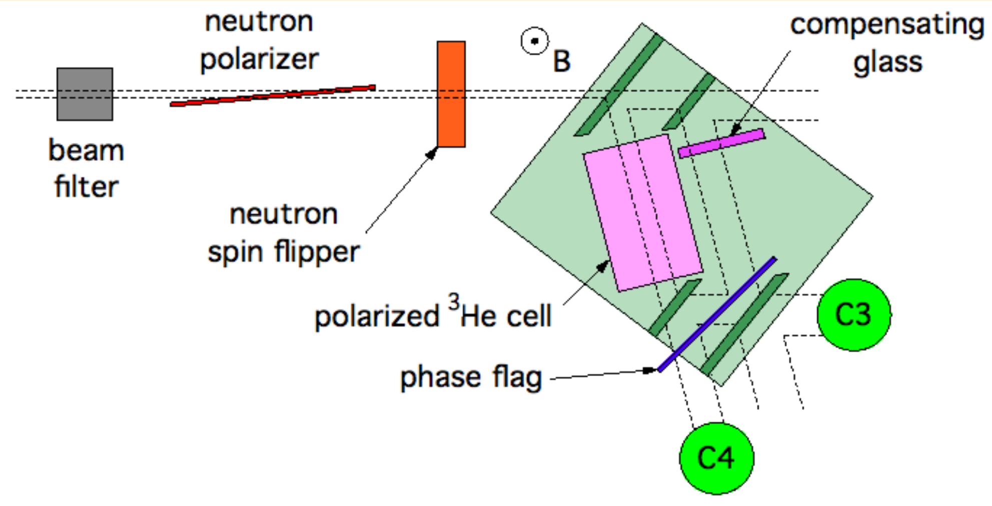
Measuring $N_3 \lambda z P_3$



$P_3 =$ ^{3}He polarization

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

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

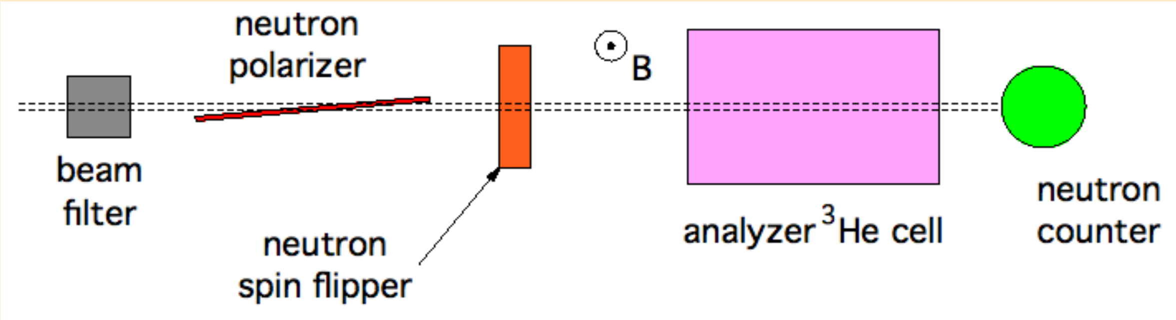
$$\sigma_{\text{th}} = \frac{1}{4}\sigma_0 + \frac{3}{4}\sigma_1 = 5333(7) \text{ barns}$$

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

(Hofmann and Hale, 2003)

the dominant systematic error in this experiment

Neutron Polarimetry

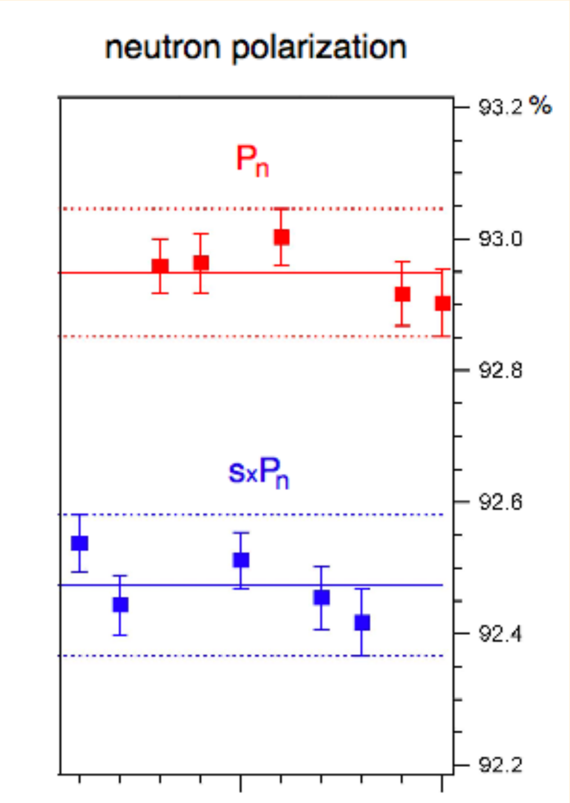


Use optically thick ($N\sigma z \sim 3$) ^{3}He cell, with known polarization, in place of neutron interferometer.

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

$$P_n = 0.9291 \pm .0008$$

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

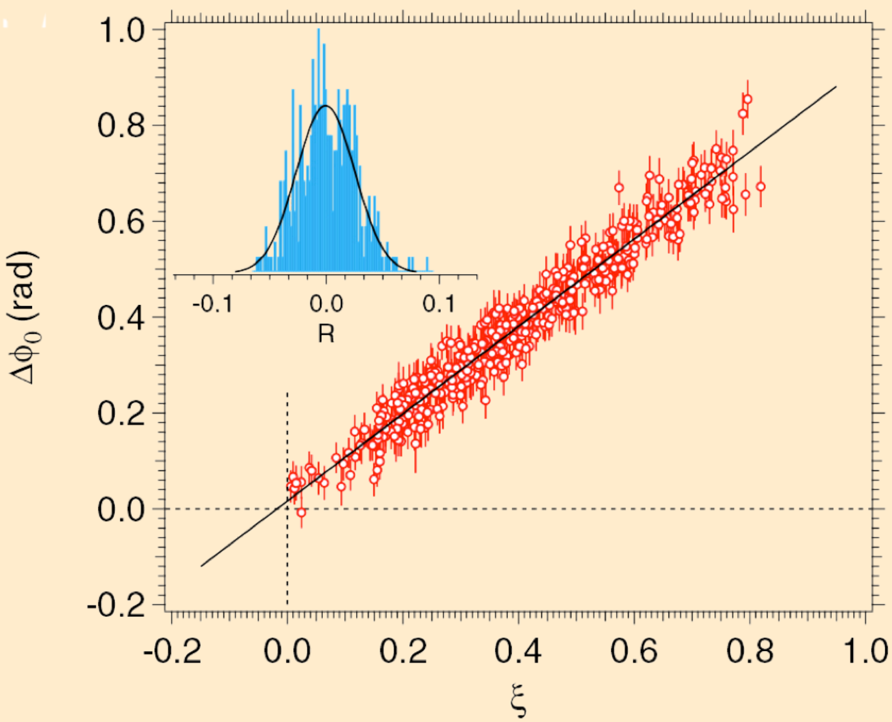


Neutron Polarization Correction

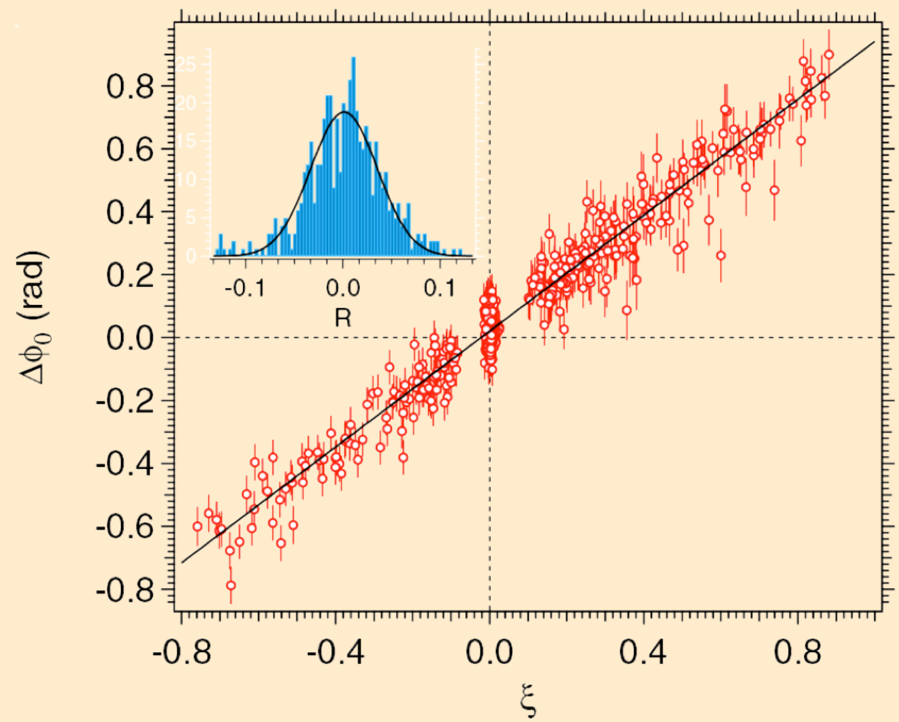
$$\Delta\phi_{\text{meas.}} = \arctan\left(\frac{\sin\Delta\phi}{\eta^{\downarrow} + \cos\Delta\phi}\right) - \arctan\left(\frac{\eta^{\uparrow}\sin\Delta\phi}{1 + \eta^{\uparrow}\cos\Delta\phi}\right)$$

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

The Data



2008



2014

The Result

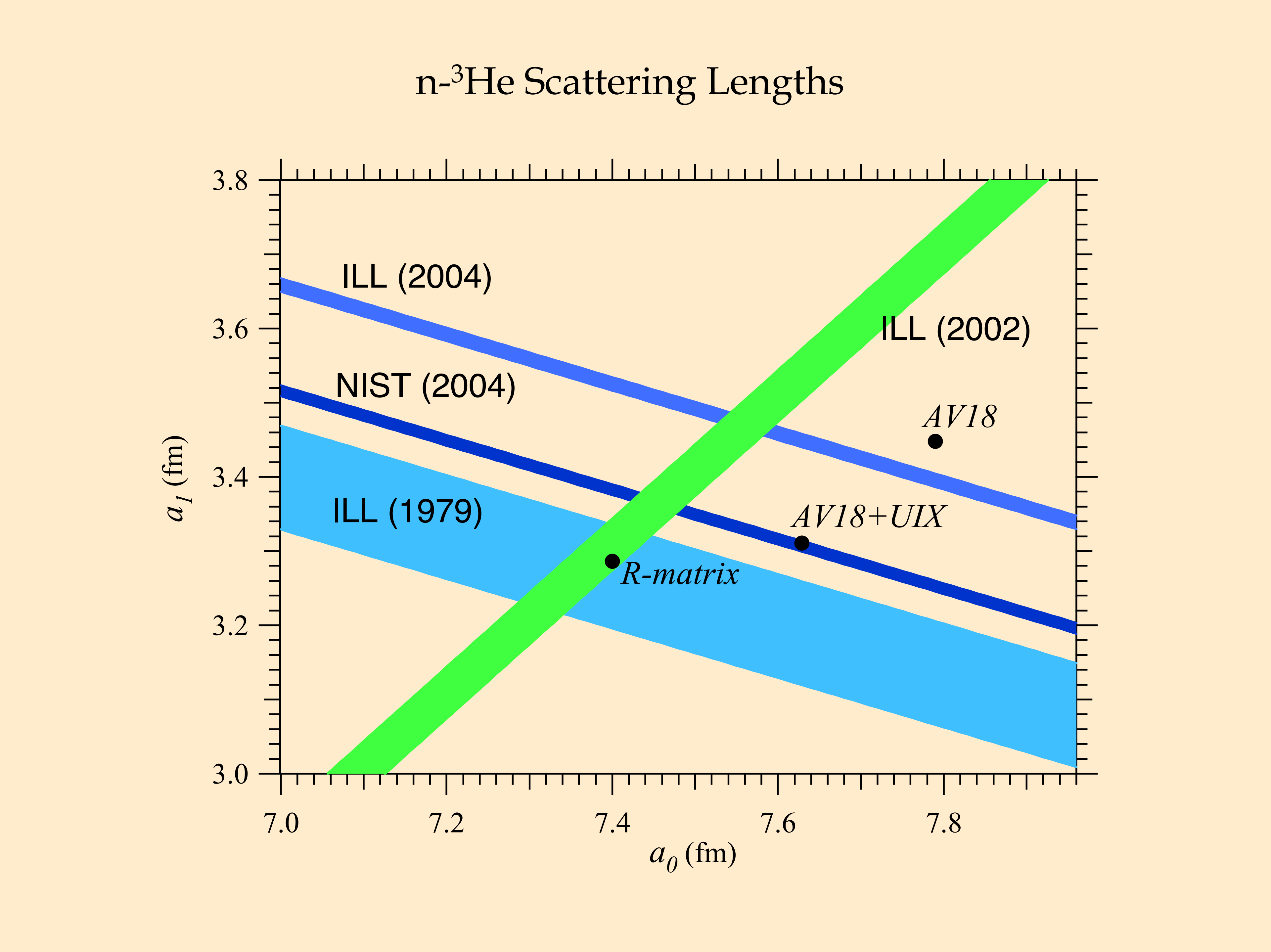
$\Delta b' = b_+' - b_-' = -5.411 \pm 0.031(\text{stat}) \pm 0.039(\text{sys})$ fm

$\Delta a' = a_1' - a_0' = -4.053 \pm 0.023(\text{stat}) \pm 0.029(\text{sys})$ fm

Error budget:

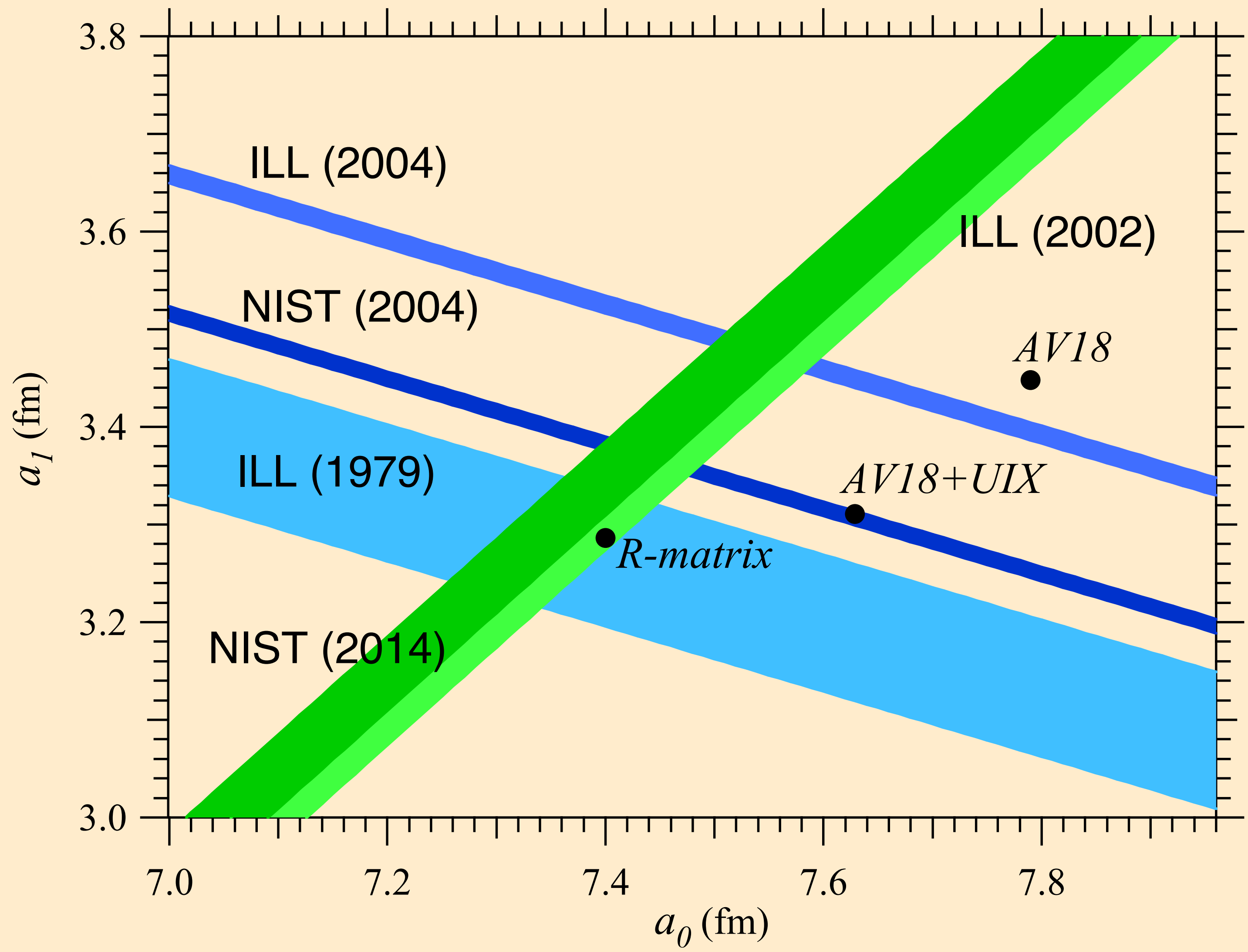
2008 σ (fm)	Parameter	2013 σ (fm)
0.053	$\Delta\phi_0/\xi$ Fit (Statistical)	0.038
0.028	Triplet absorption cross section σ_1	0.028
0.007	Total absorption cross section σ_{un}	0.007
0.029	Total systematic from cross sections	0.029
0.025	Phase instabilities	0.040
0.005	Neutron polarization P_n	0.004
0.002	Spin-flipper efficiency s	0.004
0.026	Total non-cross-section systematic	0.040
0.053	Total statistical	0.038
0.039	Total systematic	0.049

Huber, et al.
PRL 102, 200401 (2009)
PRL 103, 179903 (2009)
PRC 90, 064004 (2014)



n-³He Scattering Lengths
ILL (2004)
ILL (2002)
NIST (2004)
ILL (1979)
AV18
AV18+UIX
R-matrix
3.8
3.6
3.4
3.2
3.0
7.0
7.2
7.4
7.6
7.8
a1 (fm)
a0 (fm)

n-^{3}He Scattering Lengths



Light gas scattering lengths to measure precisely using neutron interferometry:

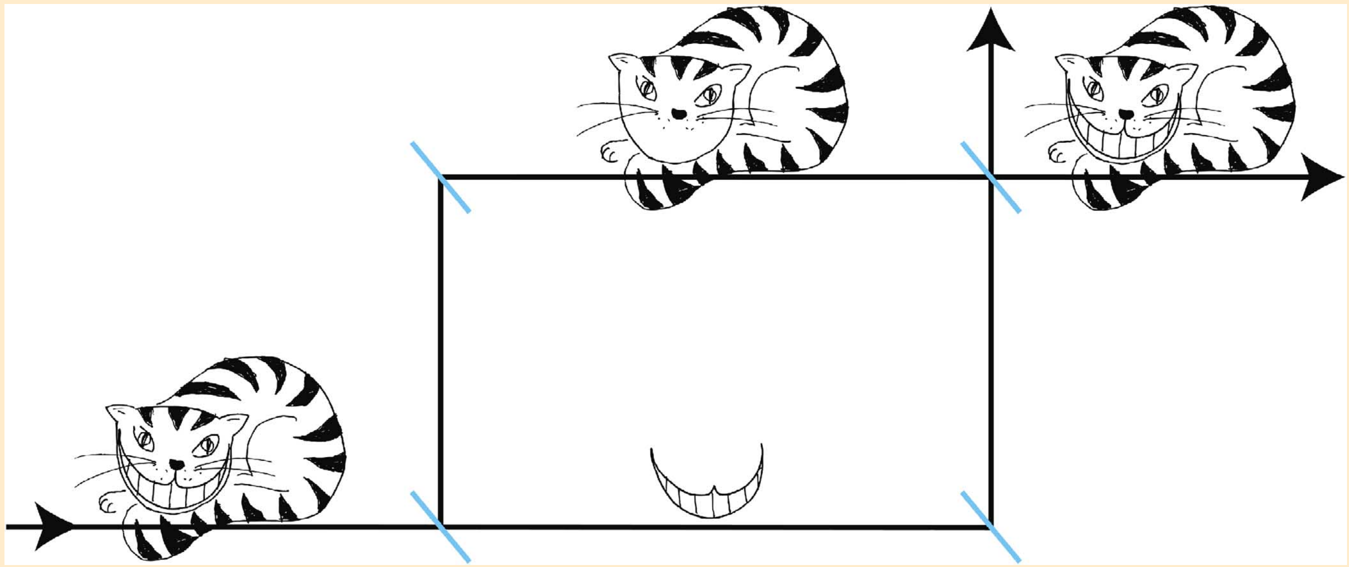
Completed:

- n-H
- n-D
- n-^{3}He
- n-^{3}He (spin incoherent) - new result (2014)

In Progress:

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

Quantum Cheshire Cat



"Well! I've often seen a cat without a grin," thought Alice, "but a grin without a cat! It's the most curious thing I ever saw in all my life!

Lewis Carroll,
Alice's Adventures in Wonderland

Weak Measurement

$$\left\langle \hat{A} \right\rangle_w = \frac{\left\langle \psi_f \middle| \hat{A} \middle| \psi_i \right\rangle}{\left\langle \psi_f \middle| \psi_i \right\rangle}$$

Aharanov, Albert, and Vaidman (1988)

Use quantum interference to measure the expectation value of a weakly coupled operator without measuring the state vector.

Real information is obtained, while leaving the QM state undisturbed.

Requires "post-selection" = interpretational questions

nature COMMUNICATIONS

ARTICLE

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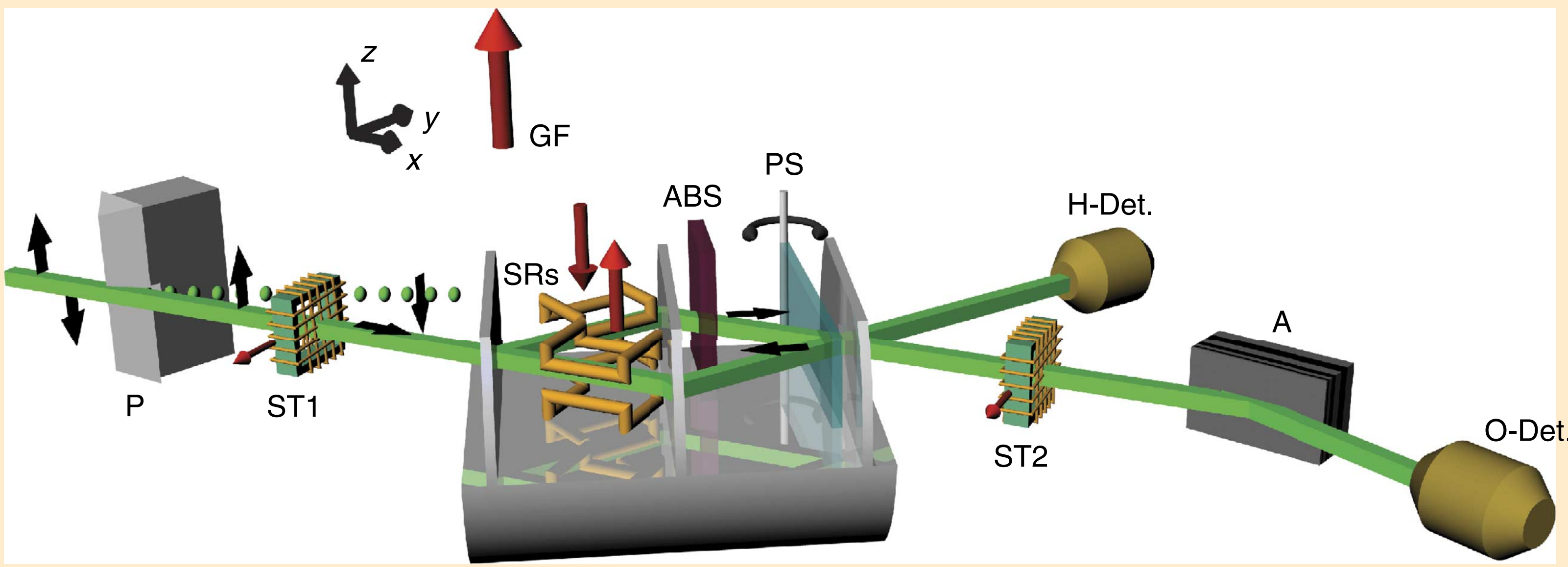
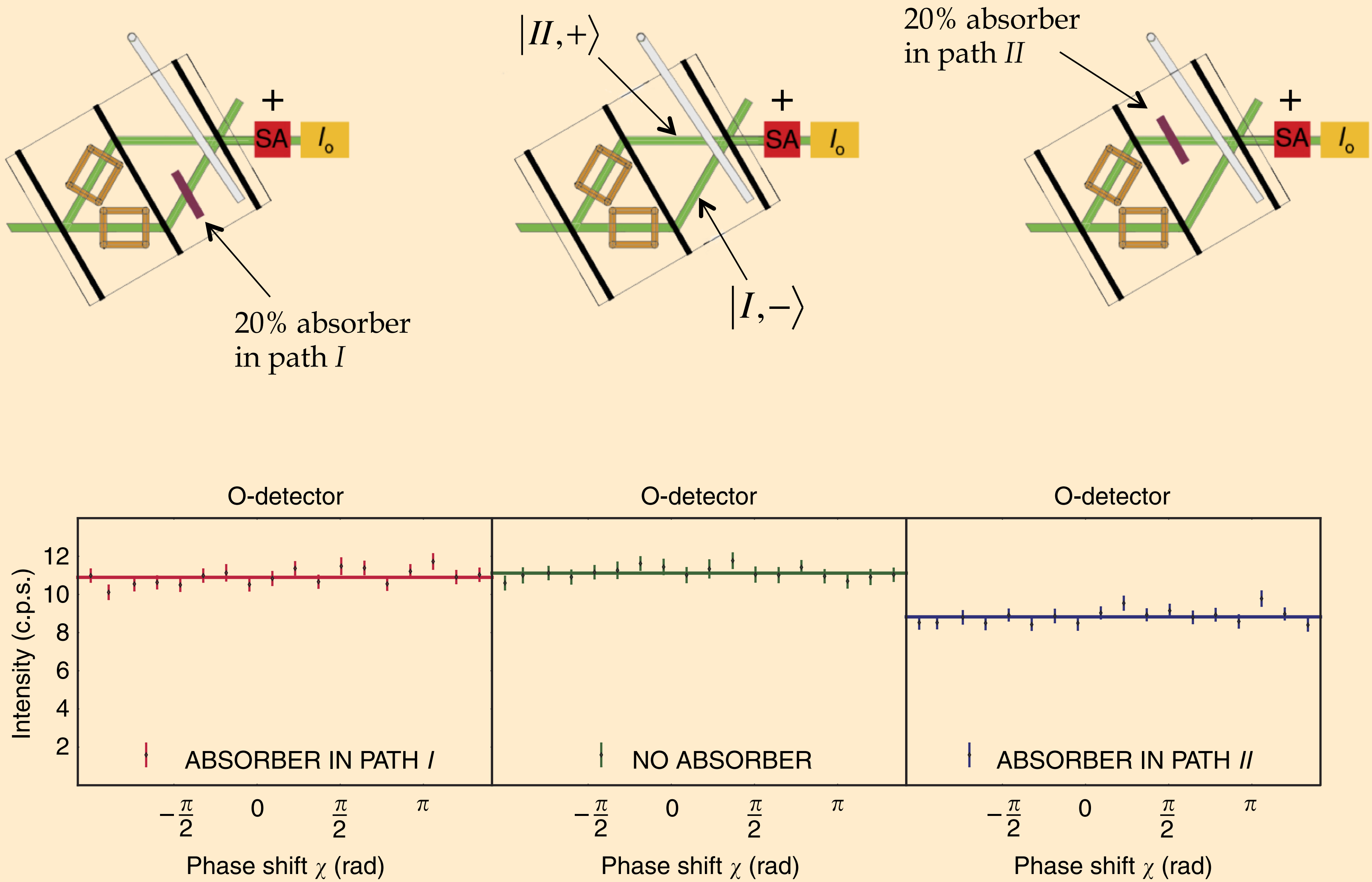
DOI: 10.1038/ncomms5492

OPEN

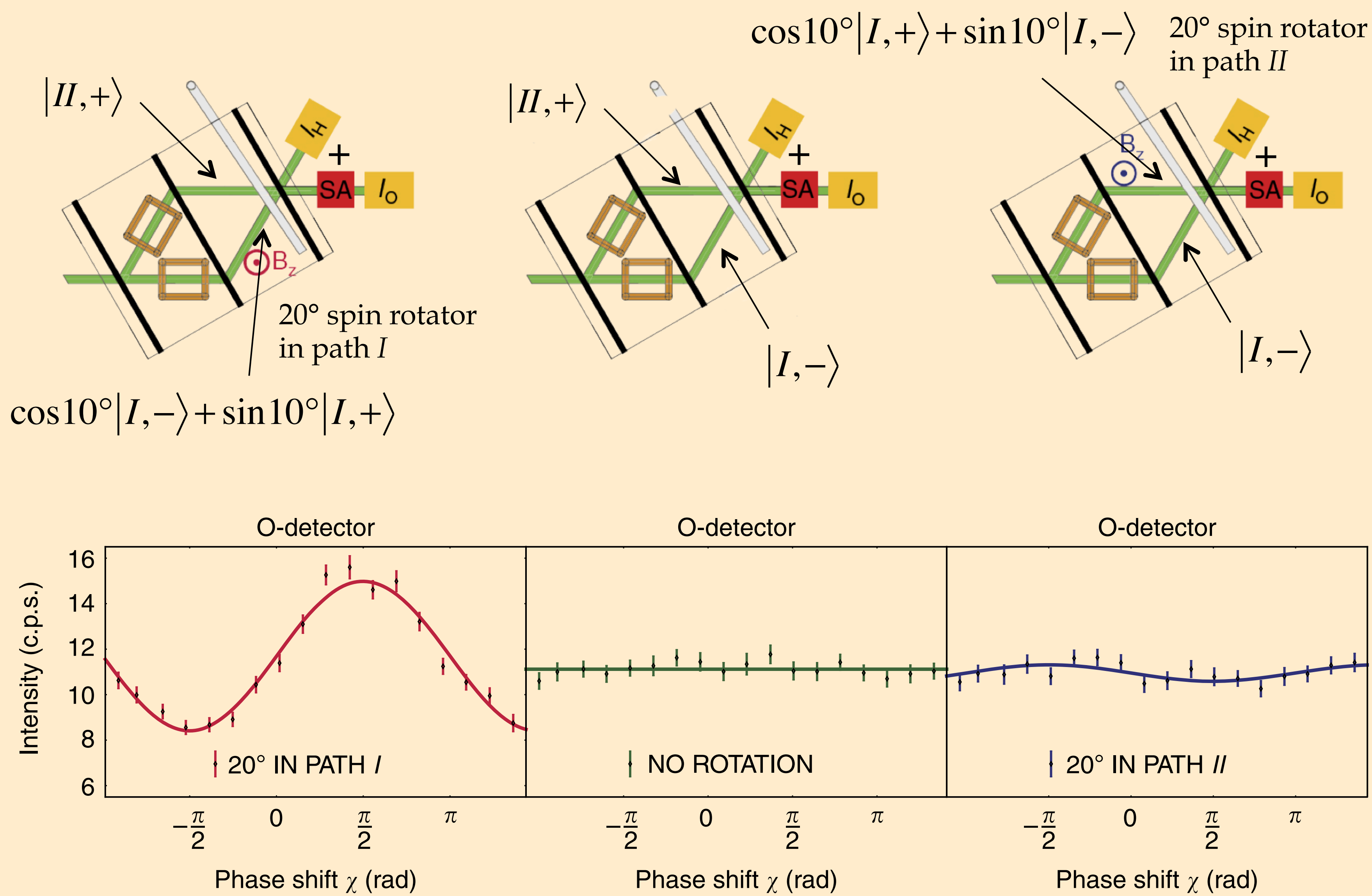
Observation of a quantum Cheshire Cat in a matter-wave interferometer experiment

Tobias Denkmayr[1], Hermann Geppert[1], Stephan Sponar[1], Hartmut Lemmel[1,2], Alexandre Matzkin[3], Jeff Tollaksen[4] & Yuji Hasegawa[1]



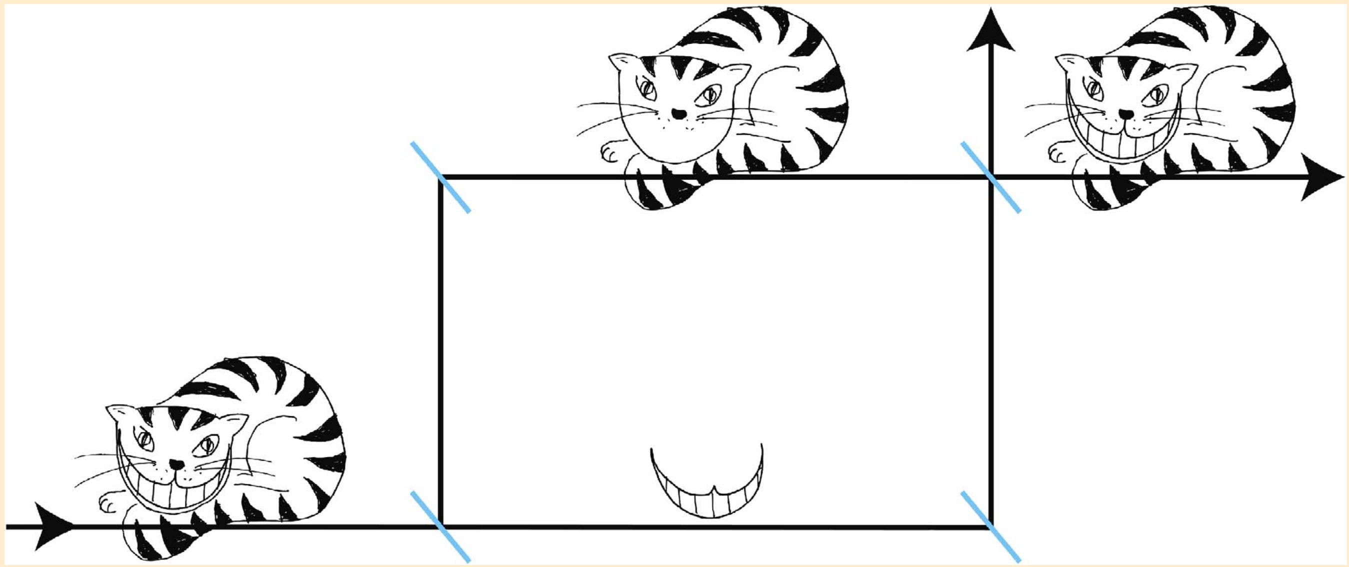


20% absorber
in path I
$|II,+\rangle$
$|I,-\rangle$
20% absorber
in path II
+
SA
I_o
O-detector
Intensity (c.p.s.)
ABSORBER IN PATH I
NO ABSORBER
ABSORBER IN PATH II
Phase shift χ (rad)



$|II,+\rangle$
$\cos 10°|I,-\rangle + \sin 10°|I,+\rangle$
20° spin rotator in path I
B_z
I_H
+
SA
I_O
$|II,+\rangle$
$|I,-\rangle$
$\cos 10°|I,+\rangle + \sin 10°|I,-\rangle$
20° spin rotator in path II
$|I,-\rangle$
O-detector
O-detector
O-detector
Intensity (c.p.s.)
16
14
12
10
8
6
20° IN PATH I
NO ROTATION
20° IN PATH II
$-\frac{\pi}{2}$
0
$\frac{\pi}{2}$
π
Phase shift χ (rad)
Phase shift χ (rad)
Phase shift χ (rad)

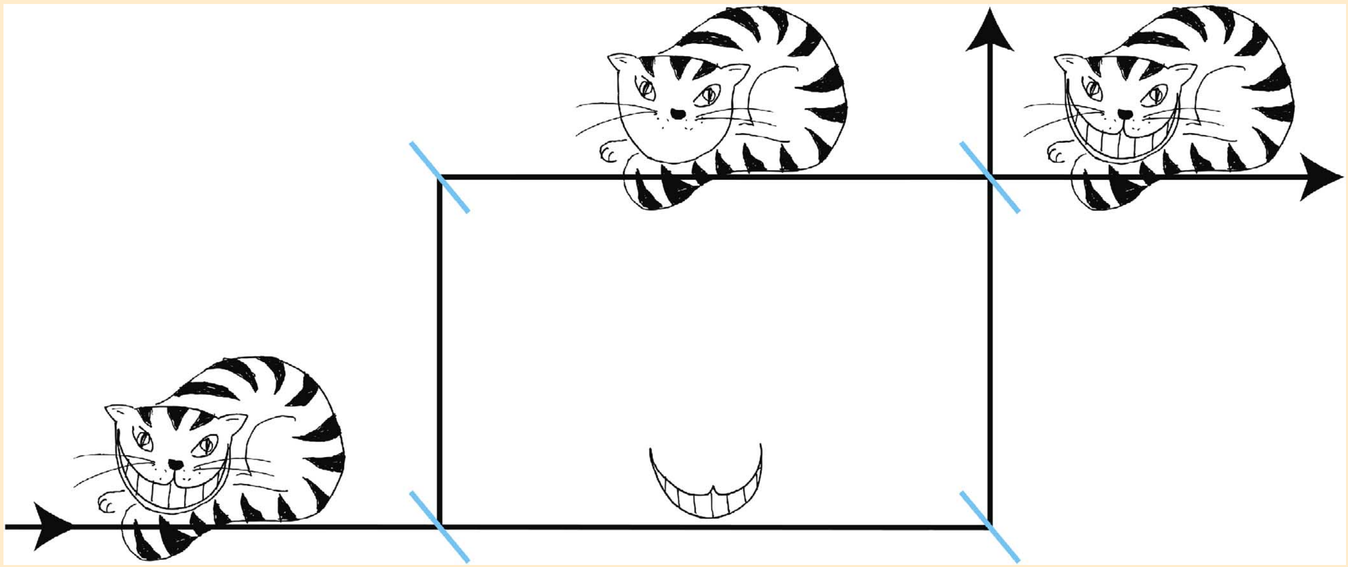
Quantum Cheshire Cat



So considering only post-selected events: $\left|\vec{k}_O,+\right\rangle$

Each neutron took path *II* but its spin (magnetic moment) took path *I*

Quantum Cheshire Cat



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Each neutron took path *II* but its spin (magnetic moment) took path *I*

A valid interpretation of reality?

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.