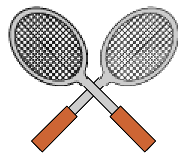
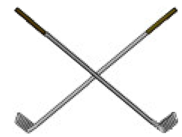
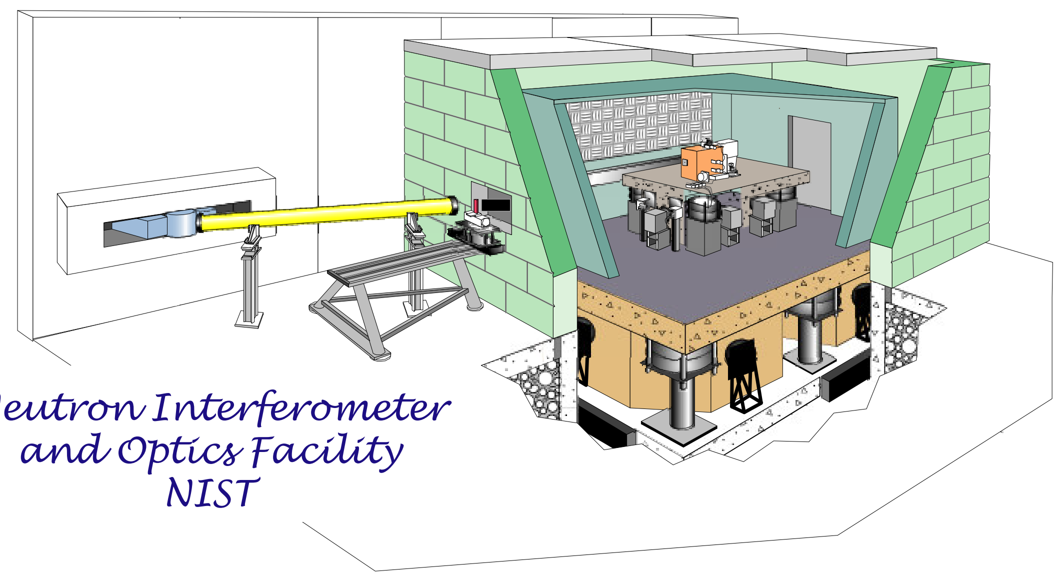
# Neutron Interferometry

## From Missouri to NIST



SAM WERNER
Retired






Symposium in honor of
Mike Rowe and Jack Rush
September 9, 2005
Gaithersburg, MD

# Introductory Comments

During the academic year 1983-1984 I was here on sabbatical leave from the University of Missouri. It was a wonderful year for me, both personally and scientifically. Every Friday afternoon, just after lunch, Sam Trevino, Hank Prask, Charlie Glinka and I would leave to play golf, and not come back to the lab for the rest of the day. I know that this grated on Jack Rush, for me to take 3 of his best scientists away for ½ day each week. But the gentleman that he is, he never said a word …at least to me. He may have docked these guys salaries. But, I don't know about that .

In the Fall of 1`983, the lab management decided that the NBS should have some big innovative projects, and they asked for proposals. Mike and Jack put in a proposal for the Cold Neutron Facility, I guess for something like $25M. I don't think that they really believed that the Department of Commerce would buy it, and that Congress would fund it. As always, in the government in matters like this, one has to ask for an independent expert review. Since I was the only unbiased, independent expert within 30 ft of Bob Carter's office, Mike asked me to be the Chairman of the Committee,. So we chose a committee, here it is (see next two slides)…and we held a 1-day review. The report was in the form of a 3 page letter that I wrote to Ernie Ambler, the NBS Director at that time. Here is the report (see the next two pages…one is missing). I have a copy here for Mike in case he runs out of reading material on the beach in Maui.

The rest is history. The project was funded, the cold source installed, and the guide hall built in the late 1980's. It has to be one of the most important successes in American science…Ever! All of us owe Jack Rush, Mike Rowe, Tawfik Raby, Bob Carter and everyone else involved in those days, and since, a debt of gratitude.

Thanks!

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March 13, 1984

Dr. Ernest Ambler
Director
National Bureau of Standards
Department of Commerce
Washington, DC 20234

Dear Dr. Ambler:

On February 21, 1984 our committee met at the Research Reactor Facility in Gaithersburg to review the proposed expansion plans for cold neutron research facilities at NBS. It was a pleasure for us to have the opportunity to review the plans for this exciting new facility and the expanded scientific opportunities that will become available to a wide spectrum of U.S. scientists in chemistry, biology, materials science, and physics. Although the time allowed for this meeting was limited, the sense of excitement that something really important was being proposed here grew during the day, both amongst the committee and the NBS staff. The discussions were divided into two roughly equal segments: new scientific opportunities and technical design features of the source, guide hall, and instruments. Since a number of the committee members are quite familiar with the ongoing scientific program at the reactor through previous scientific contacts and collaborations, little background and historical information was necessary. A series of questions (enclosed) were prepared (by the chairman) to guide the committee's thinking during the day. Although these are very difficult questions to answer conclusively as a result of a 1 day meeting, we believe that we have come part way in this task and would like to give you our impressions and conclusions.

As you are aware, the quality and sophistication of neutron scattering facilities in the U.S. has fallen seriously behind those in Western Europe during the past 5-10 years. This is particularly true with respect to cold neutron research. The opportunity that exists at the NBS reactor for expansion in this area of research is unique in the U. S., and it existed from the day the reactor went critical in 1969. The space allowed for the cold source directly adjacent to the reactor core, and the wide-angle access to it present especially flexible alternatives for large guide tube extraction systems of cold neutrons. Partly for historical reasons and partly for reasons associated with financial and scientific biases (perhaps one might say ignorance in retrospect), research utilizing cold neutrons in the U. S. has not developed, and is roughly speaking, nonexistent today in this country. It is now abundantly clear that the developments in this area of neutron research in Europe, particularly at the Institut Laue Langevin, and the risks assumed by their investments in this field have paid off handsomely in scientific productivity in many areas of rapidly developing fields, such as molecular biology, amorphous materials, polymer science, magnetism, and others. We are now left in a serious catch-up position. We

1984

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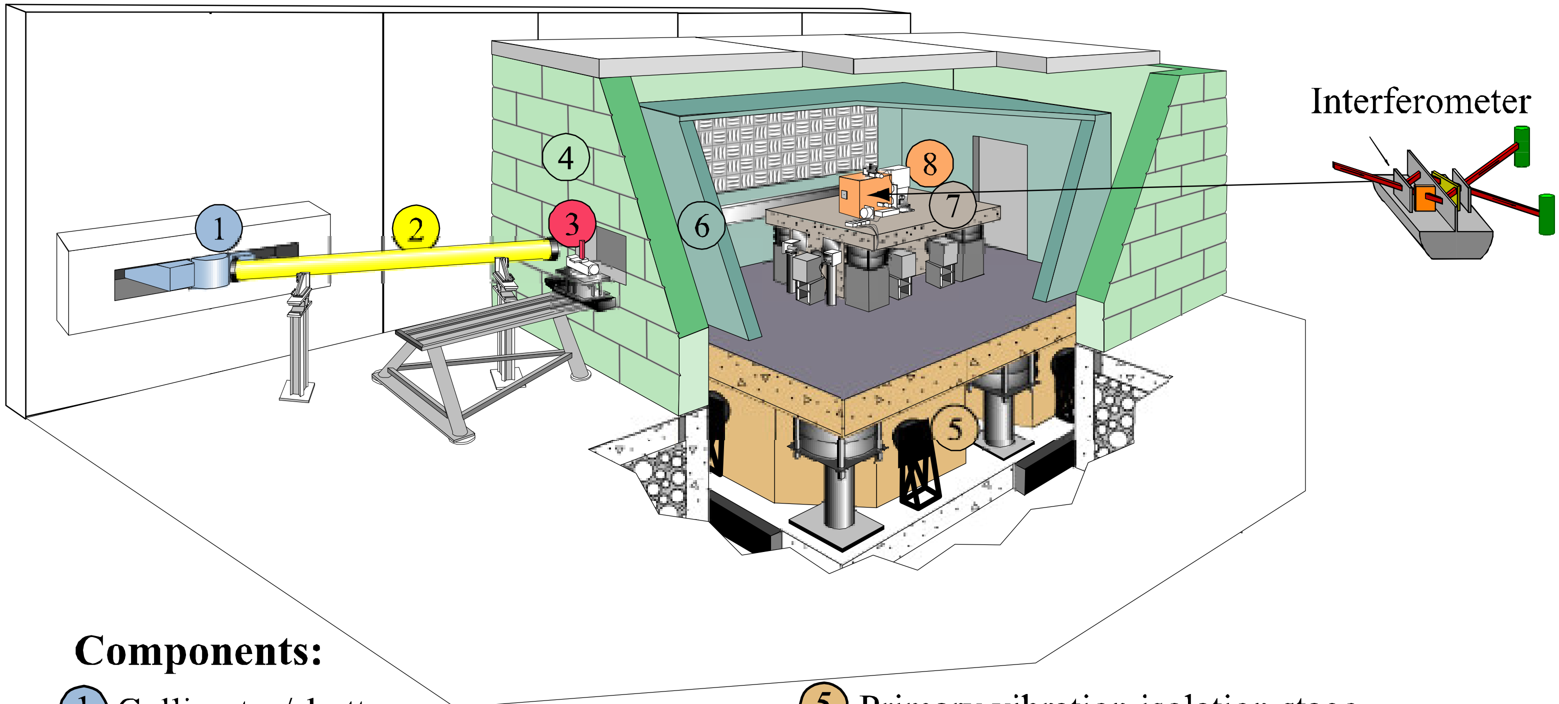
# Neutron Interferometry

- **1964** – Perfect crystal interferometer co-invented by Bonse and Hart for x-rays.
- **1974** – First demonstration of a working neutron interferometer Rauch, Treimer and Bonse.
- **1975** – Gravitationally induced quantum interferference by Collela, Overhauser and Werner.
- **1975-2005** – Many experiments at Missouri University Research Reactor, ILL Grenoble, France, MIT, Atominstitut Vienna, Austria, and Hahn Meitner Institute, Berlin, and 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

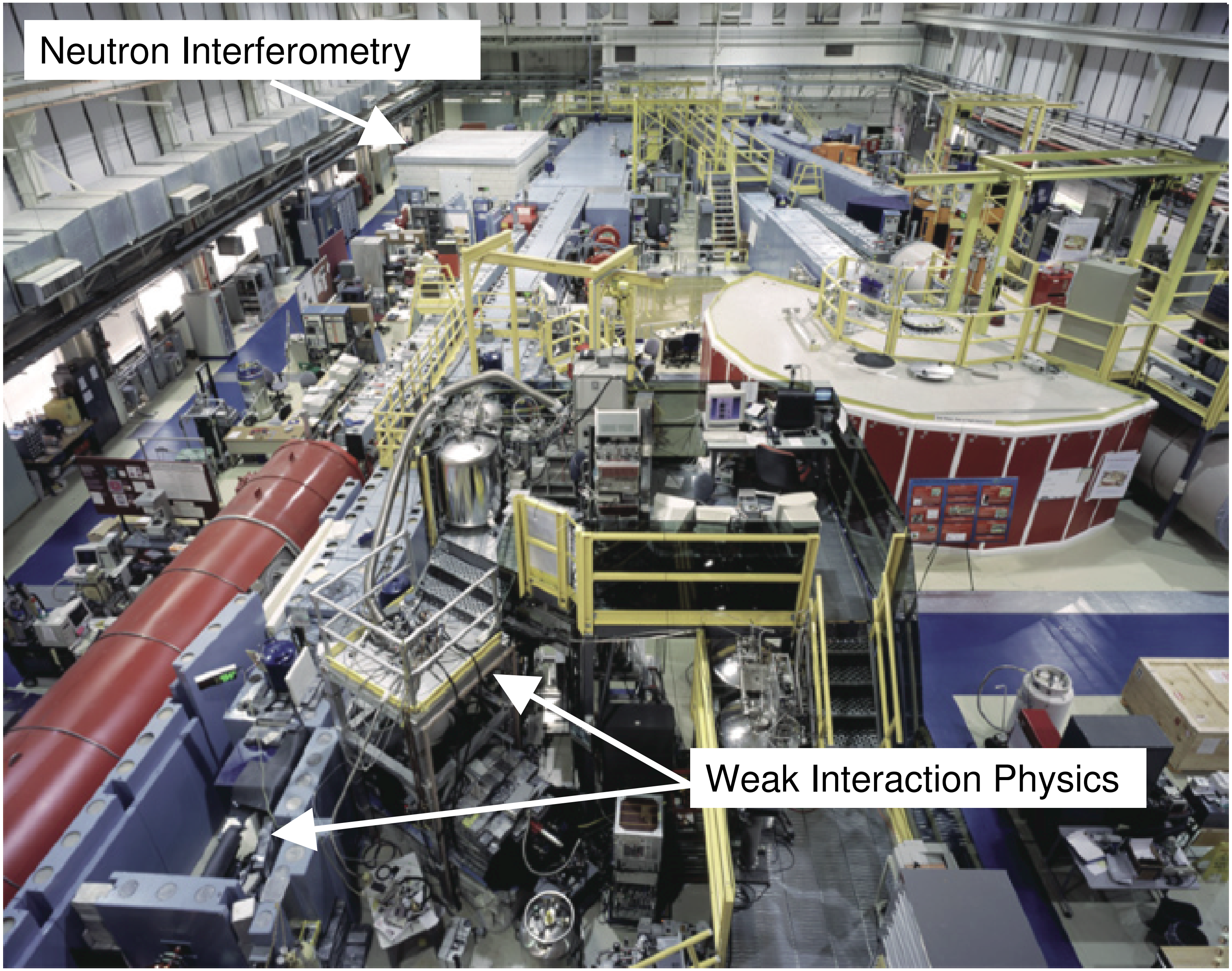
Vibration Isolation = $10^{-7}$g

Translation = Less than a μm

Rotation = Less than a mrad

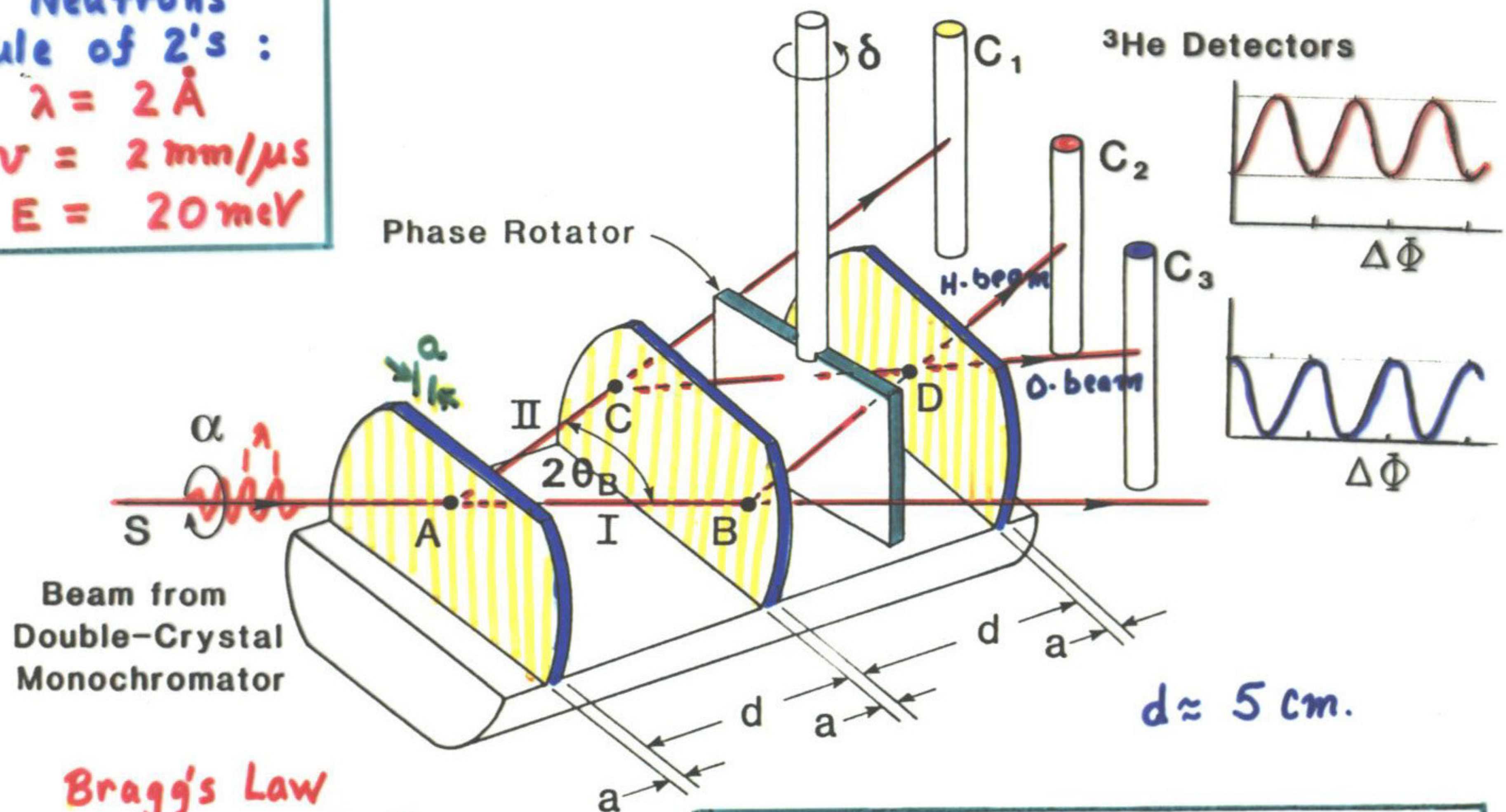
Temperature = 0.1 C

# Cold Neutron Guide Hall



# LLL SILICON CRYSTAL INTERFEROMETER

**Neutrons**
**Rule of 2's :**
$\lambda = 2$ Å
$v = 2$ mm/μs
$E = 20$ meV




$d \approx 5$ cm.

**Bragg's Law**
$\lambda = 2a \sin\theta_B$

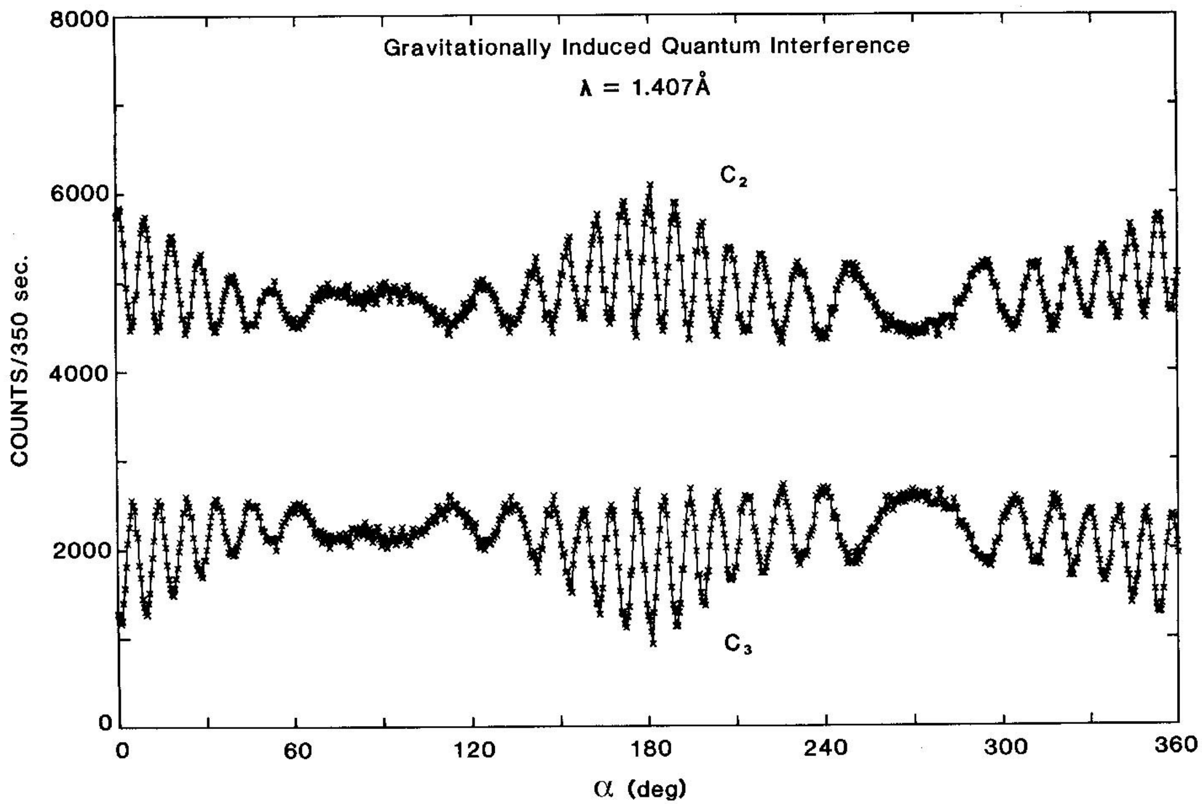
Phase Difference = $\Delta\Phi = \Phi_{II} - \Phi_I = \Delta\Phi(\delta,\alpha)$ $= \lambda N b D_{eff}$

$C_2(\Delta\Phi) = A_2 - B_2 \cos(\Delta\Phi)$

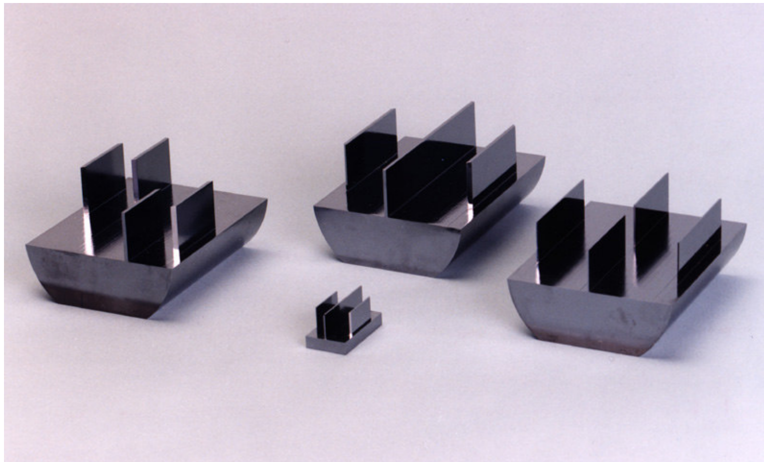
$B_2 = B_3$

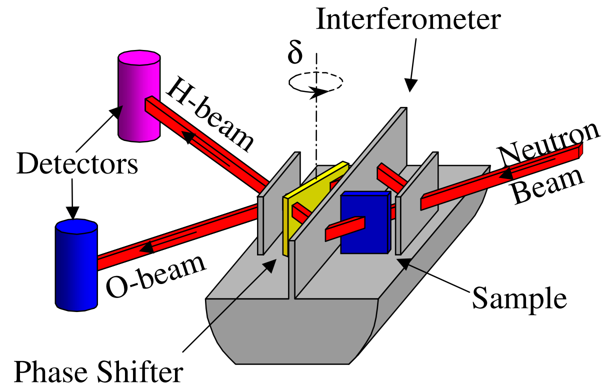
$C_3(\Delta\Phi) = A_3 + B_3 \cos(\Delta\Phi)$

# Gravitationally Induced Quantum Interference

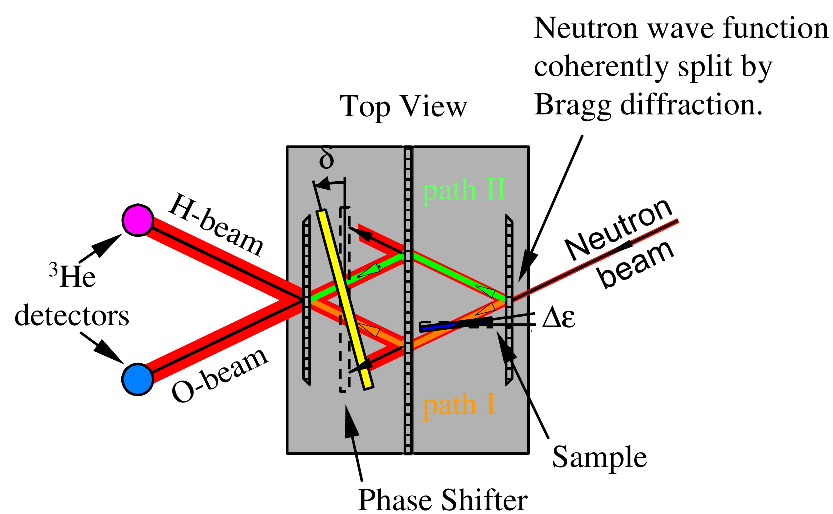


# Perfect Crystal Interferometer






- Cut from a single ingot of > 17 MΩ silicon.
- Three to four blades are machined and left attached to a common silicon base to maintain the perfect registry of all atoms in the crystal.
- The NIST crystals are cut such that the silicon (111) lattice planes are are perpendicular to the surfaces of the blades.
- Each crystal blade acts as a beam splitter in the transmission Laue-Bragg reflection geometry.



# Selected Neutron Interferometry and Optics Experiments

- Precision measuremet of Si-scattering length: $b_{Si}$=(4.1507±0.0002)fm
  - *(HMI, NIST, NPI of CAS, Missouri, LANL)*
- Double slit interference experiment
  - *(University of Vienna, NIST)*
- Phase Contrast Imaging –
  - *(University of Melbourne, NIST, Missouri)*
- Quantum entanglement in $H_2O/D_2O$ mixtures
  - *(Missouri, NIST, LANL, HMI-Berlin)*
- 4π rotation symmetry
  - *(HMI-Berlin, Missouri, NIST, LANL)*
- n-D, n-p, n-$^3$He scattering lengths
  - *(Missouri, NIST, N. Carolina-Wilmington, Indiana, LANL)*
- Reciprocal Space Imaging
  - *(MIT, NIST)*
- n-e scattering - neutron charge radius
  - *(Tulane ,Missouri, NIST, N. Carolina-Wilmington)*
- Neutron Fourier spectroscopy
  - *(NIST, Indiana, Vienna, MIT)*
- Spin-dependent neutron-$^3$He scattering amplitude
  - *(Tulane ,Indiana, NIST, N. Carolina-Wilmington)*
- Tests of decoherence for quantum information
  - *(MIT, NIST)*
- Gravity experiment with floating interferometer
  - *(Indiana, NIST, Tulane)*

VOLUME 90, NUMBER 19 PHYSICAL REVIEW LETTERS week ending 16 MAY 2003

# Precision Neutron Interferometric Measurement of the nd Coherent Neutron Scattering Length and Consequences for Models of Three-Nucleon Forces

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PHYSICAL REVIEW C 67, 044005 -2003!

# Precision neutron interferometric measurements and updated evaluations of the n-p and n-d coherent neutron scattering lengths

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-Received 10 December 2002; published 29 April 2003!

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# Precision neutron interferometric measurement of the n-$^3$He coherent neutron scattering length

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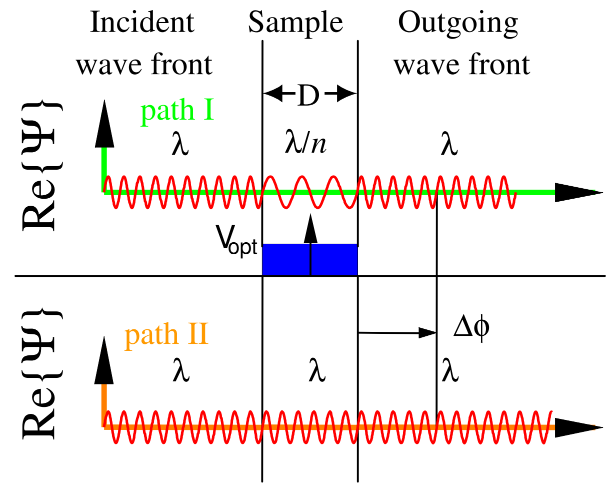
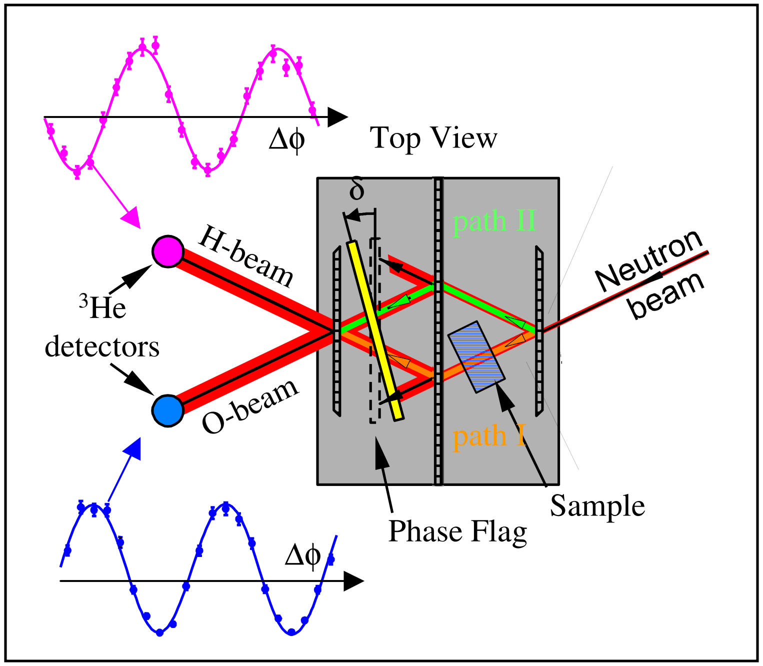
(Received 10 March 2004; published 15 July 2004)

# Phase Shift

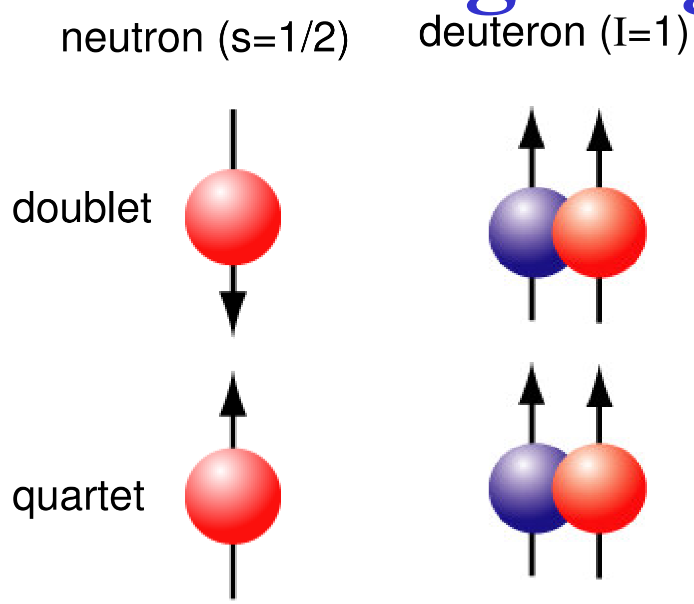
$$\Delta\phi = \frac{2\pi\,(1-n)}{\lambda}\,D = \lambda N b D$$




- Phase shifts are measured by rotating a quartz plate called a phase flag tracing out an interfereogram
  - $D \rightarrow D(\delta)$ so that $\Delta\phi \propto \delta$
- The data is fitted to a sinusoid allowing the phase shift due to the sample to be determined.
- This is done back to back within a 40 minute period to allow the systematic overall time dependent phase drift to be removed.



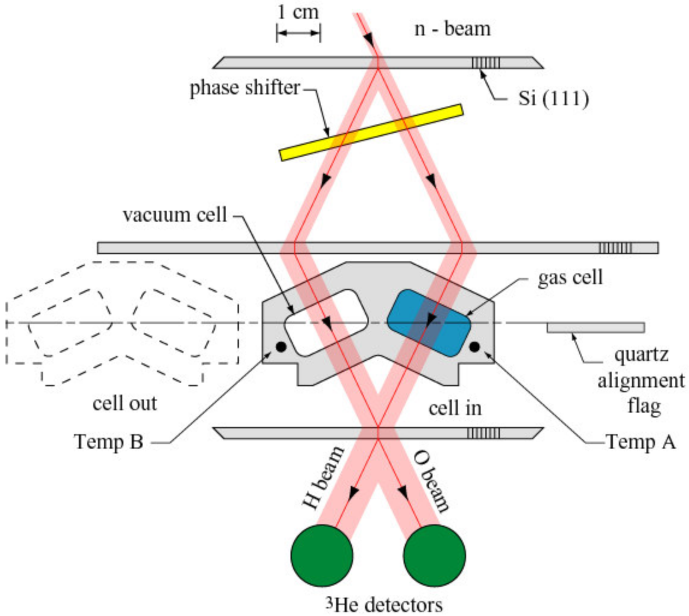
# *n-d* scattering length

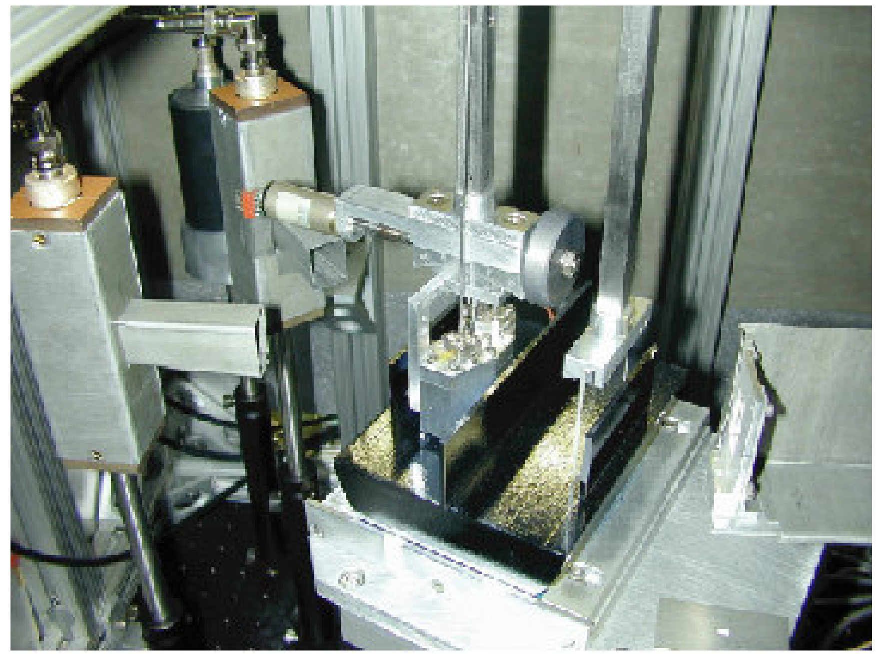


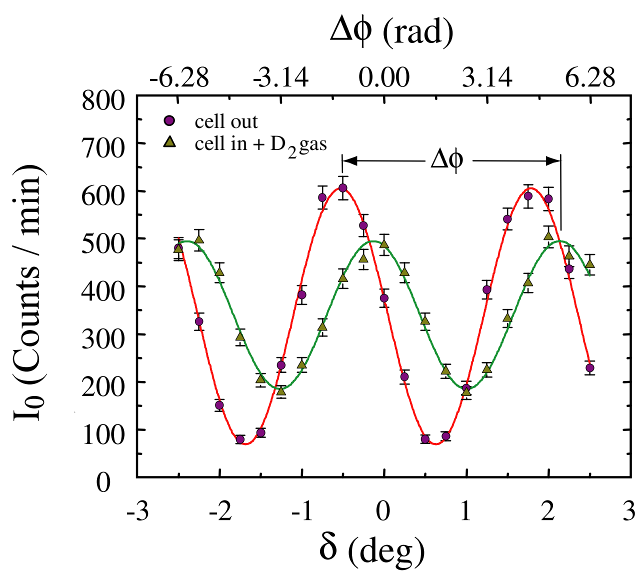

If both the sample and the neutron are unpolarized.

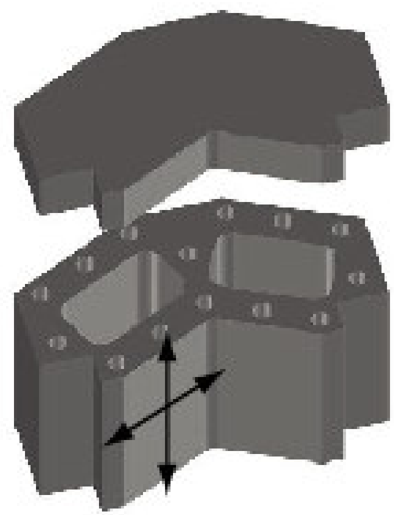
$$b_c = \frac{1}{3} b_{doublet} + \frac{2}{3} b_{quartet}$$

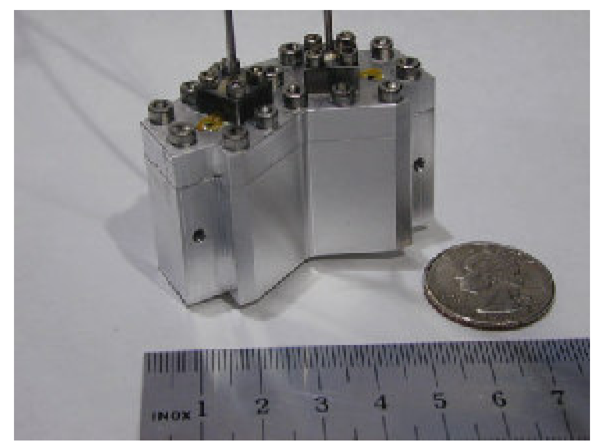
# Gas Phase Shift Cell

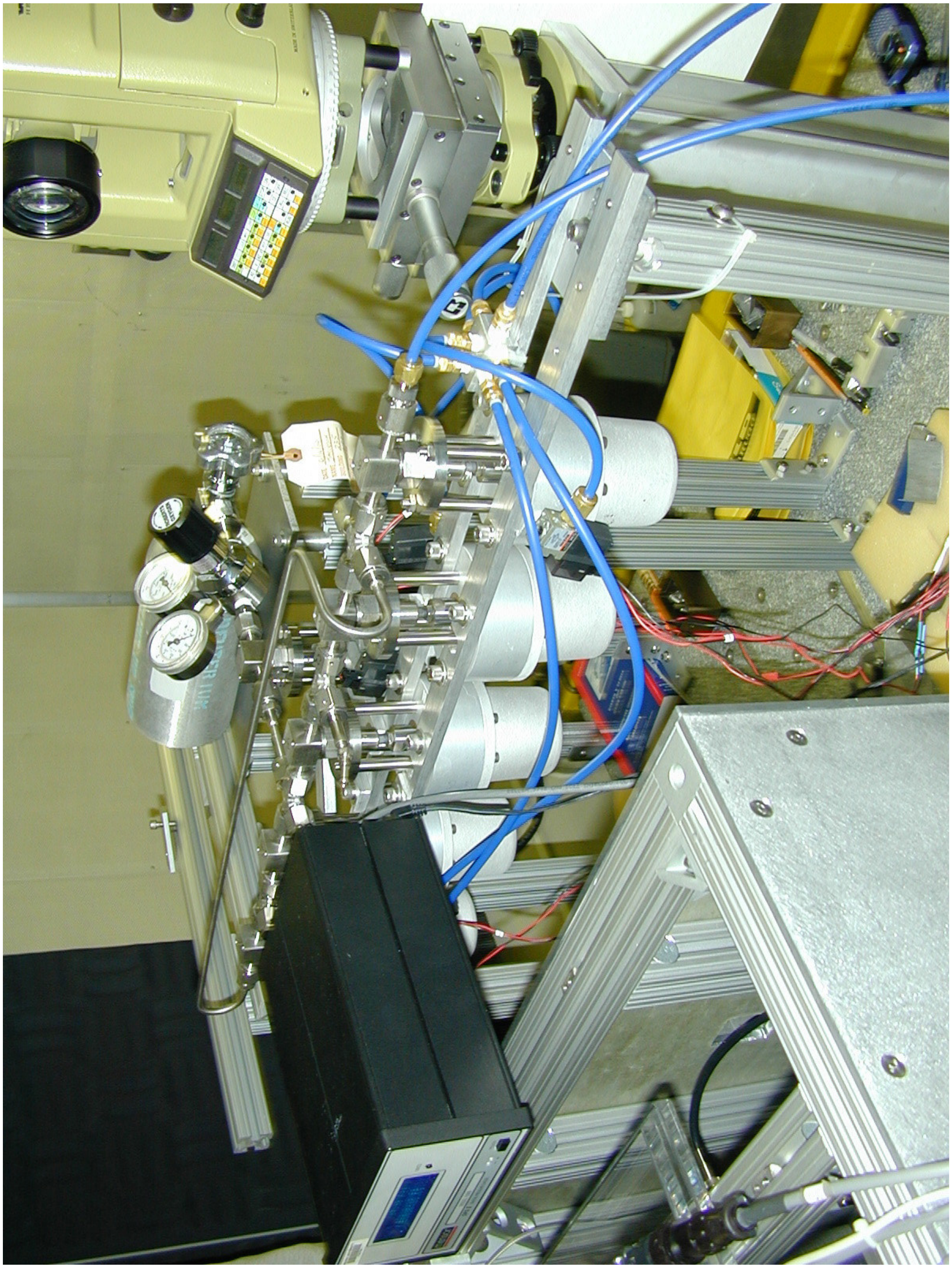


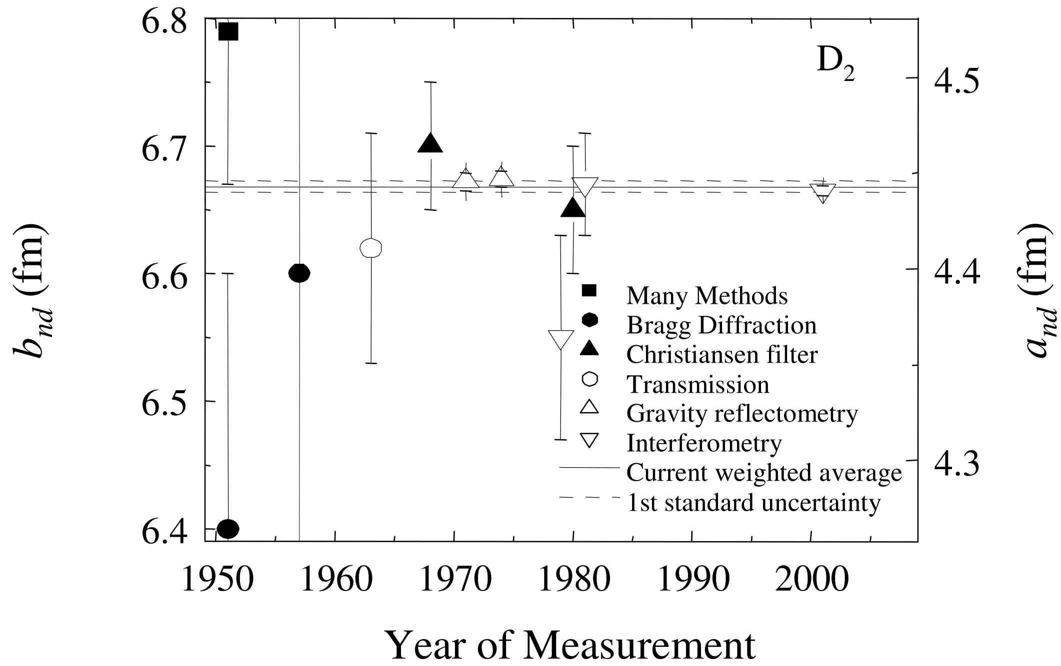






# Neutron Deuteron Scattering Length Measurements




Measured at NIST

$b_{\mathrm{nd}}$ = 6.6649+/- 0.0040 fm

$b_{\mathrm{doublet}} = (0.96 \pm 0.02)$ fm

New World Average

$b_{\mathrm{nd}}$ = 6.6683+/- 0.0030 fm

# Theory deuteron

| Potential Model | *b* (doublet) | *b* (quartet) | *b* (fm) |
|---|---|---|---|
| Yukawa | -3.15 | 9.585 | 5.34 |
| Exponential | -9.6 | 9.66 | 3.24 |
| MT I-II | 1.05 | 9.66 | 6.79 |
| RSC-5 | 2.64 | | |
| AV14 | 2.025 | 9.57 | 7.055 |
| SSCC | 1.98 | 9.615 | 7.07 |
| RSC-5 | 0.9 | | |
| RSC | 2.28 | 9.453 | 7.062 |
| RSC+TM3NF | 0.5895 | 9.462 | 6.505 |
| AV14 | 1.8 | 9.558 | 6.972 |
| AF14+BR3NF | 0.0015 | 9.567 | 6.379 |
| RSC+TM3NF | 0.99 | 9.45 | 6.63 |
| AV14+BR3NF | 0.855 | 9.57 | 6.67 |
| Yamaguchi | 0.984 | 9.405 | 6.60 |
| MTI-III | 1.065 | 9.645 | 6.79 |
| MTI-III | 1.053 | 9.663 | 6.793 |
| AV14 | 1.794 | 9.57 | 6.978 |
| AV14 | 1.7835 | 9.569 | 6.974 |
| AV14+TM3NF | 0.879 | 9.557 | 6.664 |
| AV14+BR3NF | 0.863 | | |
| AV18+UR3BF | 0.939 | | |

$b = (1/3)\, b_{doublet} + (2/3) b_{quartet}$

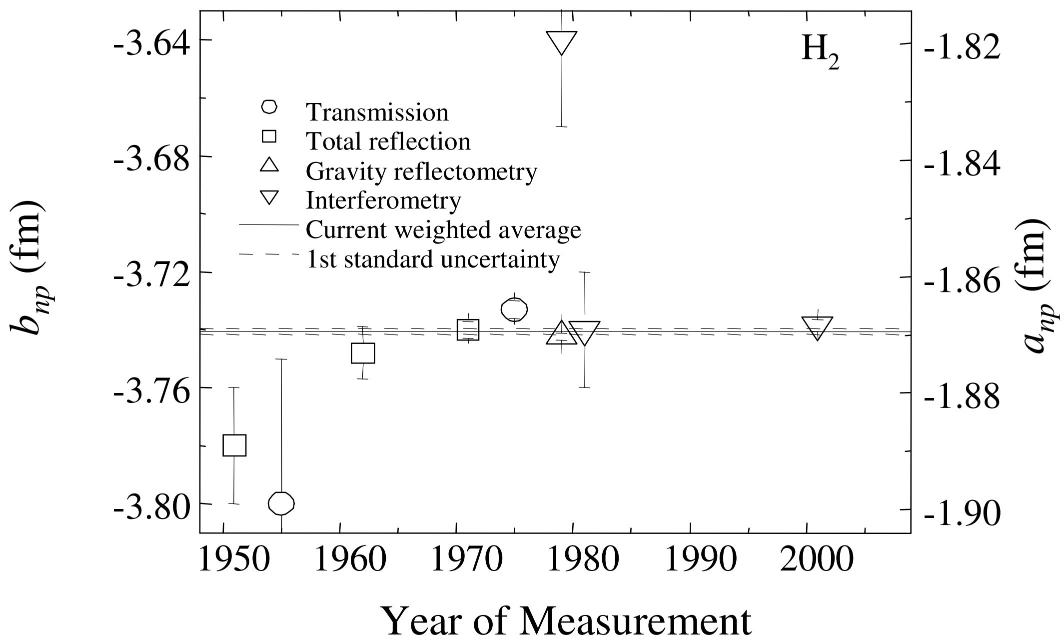
$b(exp) = (6.665 \pm 0.004)$ fm

$\bar{b}_{quartet}(theory) = (9.52 \pm 0.01)$ fm

Combining theory with experiment gives:

$b_{doublet} = (0.96 \pm 0.02)$ fm

# Neutron Proton Scattering Length Measurement



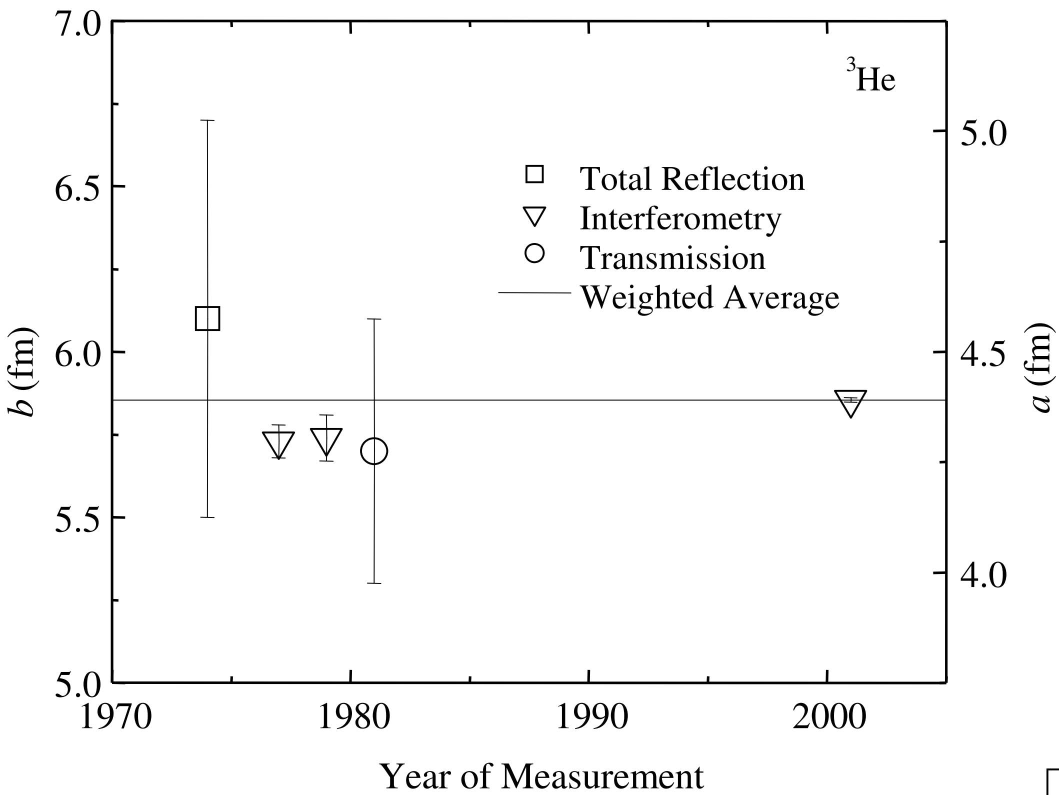

Measured at NIST

$b_{np}$ = -3.7384+/-0.0020 fm

New World Average

$b_{np}$ = -3.7405+/-0.0009 fm

# Neutron Helium-3 Scattering Length Measurements




Prior to Measurement at NIST

$b$ = 5.74 +/- 0.04 fm

Measured at NIST

$b$ = 5.8572+/- 0.0072 fm

New World Average

$b$ = 5.8530+/- 0.0070 fm

Lowered uncertainty by a factor of 6

**It is interesting to combine this result with the recent measurement by Zimmer, et al* of the bound incoherent scattering length:**

$$b_i = (-2.365 \pm 0.020)\ \text{fm}$$

$$b_{coh} = (5.854 \pm 0.007)\ \text{fm}$$

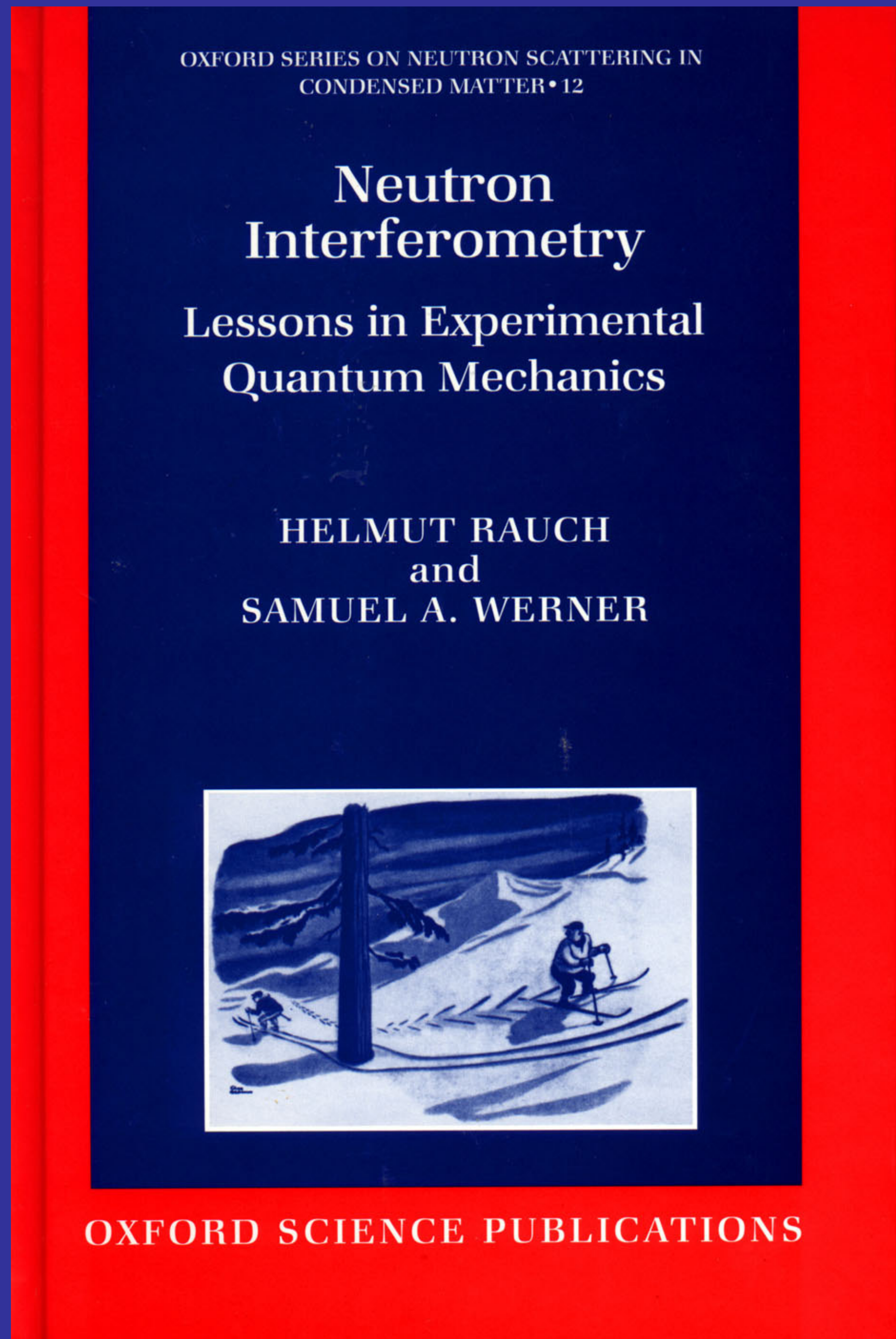
**to extract the singlet and triplet values of the bound scattering lengths**

$$b_0 = (9.949 \pm 0.027)\ \text{fm}$$
$$b_1 = (4.488 \pm 0.017)\ \text{fm}$$

**corresponding to free nuclear scattering lengths of**

$$a_0 = (7.456 \pm 0.020)\ \text{fm}$$
$$a_1 = (3.363 \pm 0.013)\ \text{fm}$$

*O. Zimmer, G. Ehlers, B. Farago, H. Humboldt, W. Ketter, and R. Scherm, **EPJdirect A1**, 1 (2002).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# Summary

*There is an active and growing program in fundamental neutron physics based at NIST. It is possible through strong national and international collaborations.*

## Thanks to ...

| Neutron Interaction and Dosimetry Scientific Staff | Postdocs | Graduate Students |
|---|---|---|
| Muhammad Arif (group leader) | Wangchun Chen (Indiana) | Chris Bass (Indiana) |
| Scott Dewey | Brian Fisher (Tulane) | Rob Cooper (Michigan)Mike |
| Tom Gentile | Dan Hussey (NIST/NRC) | Huber (Tulane) |
| David Gilliam | H. Pieter Mumm (NIST/NRC) | Da Luo (Indiana) |
| Craig Heimbach | | Dmitri Pushin (MIT) |
| David Jacobson | | Carroll Trull (Tulane) |
| Jeff Nico | | Liang Yang (Harvard) |
| Alan Thompson | | |

- 13 former thesis students; 7 current thesis students
- More than 30 students from undergraduate institutions and local high schools
- The work is supported by NIST Physics Lab, NCNR, and DOE. Experiments funded by NSF, DOE, and NIST.