TWISTING NEUTRON WAVES

"Controlling Neutron Orbital Angular Momentum," C. W. Clark, *et al.*, *Nature* **525**, 504 (2015)
"Holography with a neutron interferometer," D. Sarenac, , *et al.*, *Opt. Express* **24**, 22528 (2016)
"Spin-orbit states of neutron wave packets," J. Nsofini, , *et al.*, *Phys. Rev. A* **94**, 013605 (2016)

Dmitry Pushin

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NIST

UNIVERSITY OF WATERLOO | IQC Institute *for* Quantum Computing

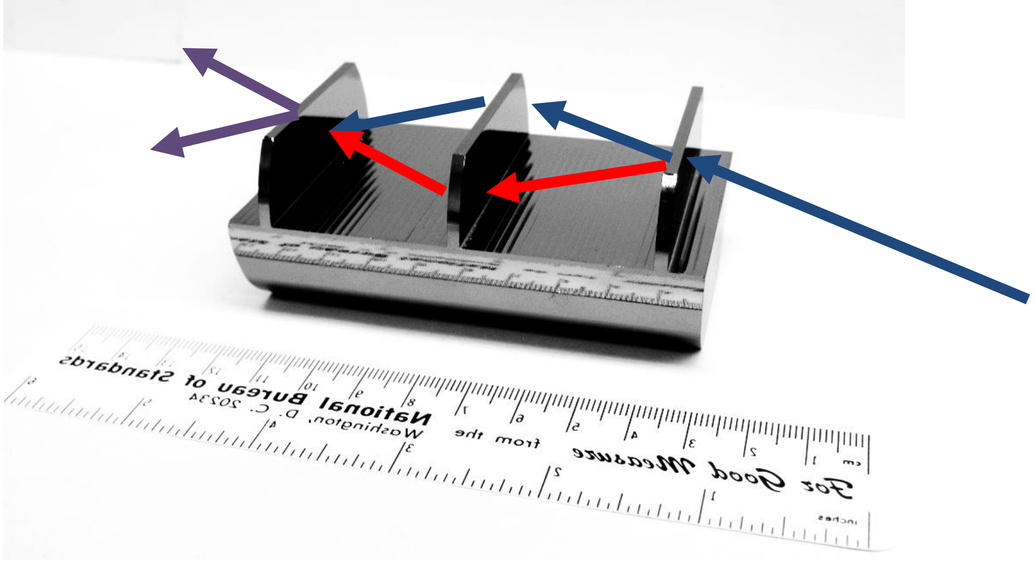
Outline

- Neutron Interferometry
- Controlling Neutron Orbital Angular Momentum
- Neutron Holography
- Spin-orbit states of neutron waves

Experiments performed at the NIST Center for Neutron Research
National Institute of Standards and Technology, Gaithersburg, Maryland


“The New Yorker”, 1940

Neutron Interferometer



NI history

a

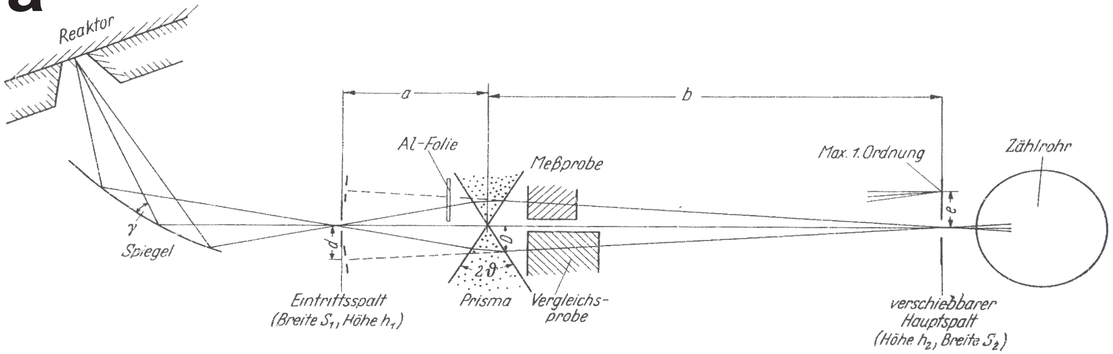
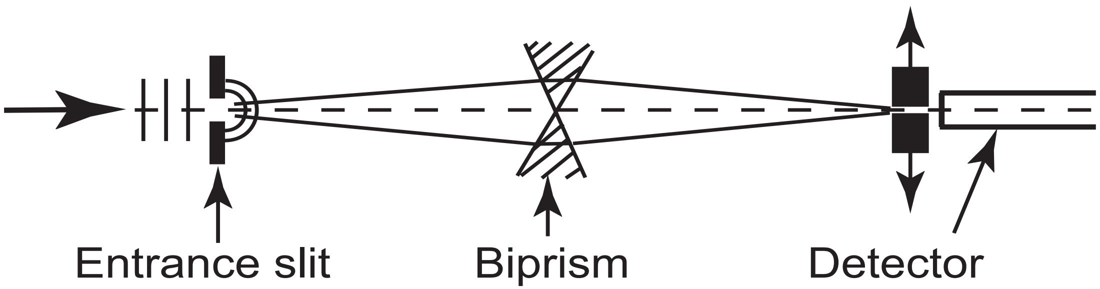


Fig. 1. Schema eines Neutroneninterferometers mit Fresnelschem Biprisma. Größenordnungsmäßig ist: Ablenkwinkel γ am Spiegel 0,1°, Abstand Eintritts-Austrittsspalt $a + b = 10$ m, größter Abstand der Strahlengänge $2D = 0{,}1$ mm. Die $\lambda/2$-Folie dient für das in Abschnitt 4 beschriebene Experiment

b



c

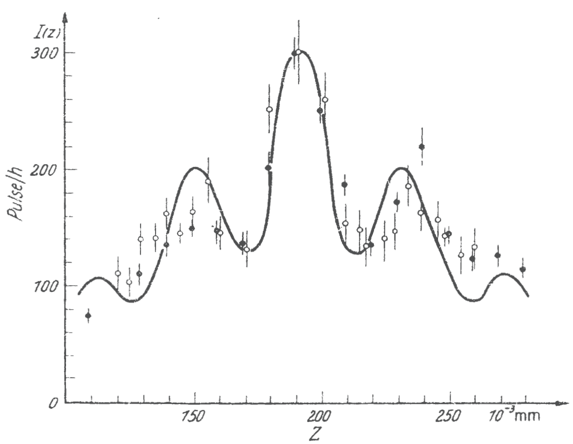
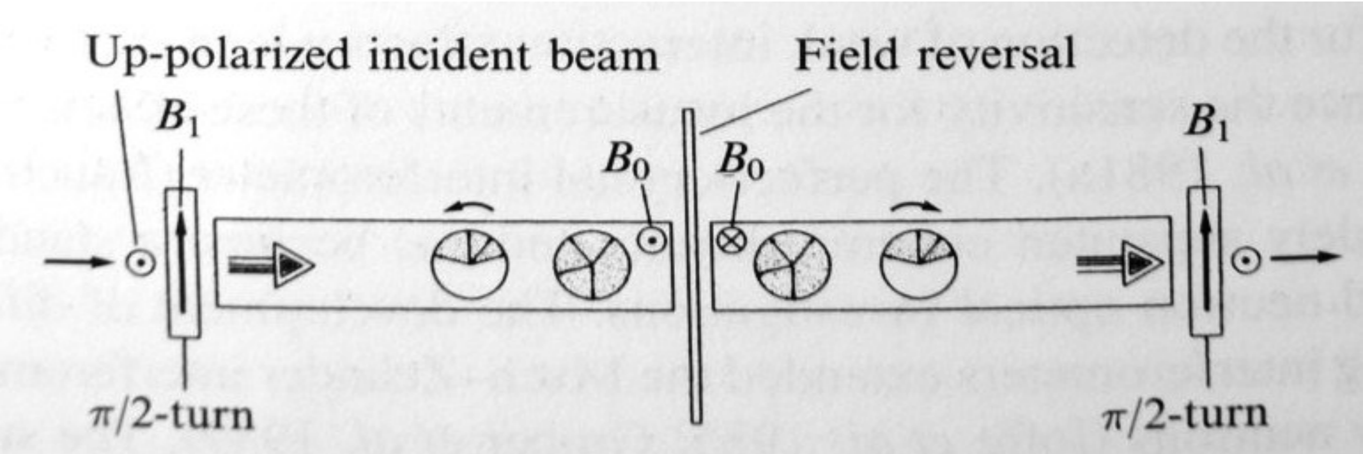


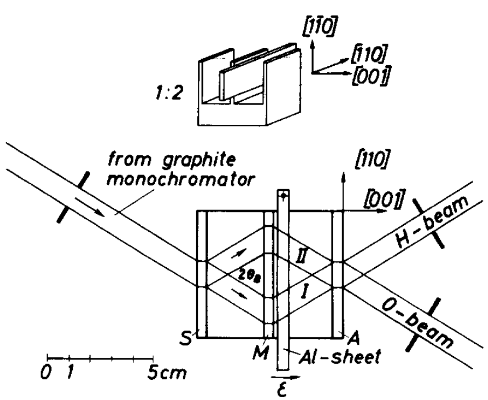
Fig. 9. Interferenzmuster. z Stellung des verschiebbaren Hauptspaltes. $I(z)$ Intensität (der Nulleffekt war bei diesen Messungen etwa 60 Pulse/Std). •, ∘ Voneinander unabhängige Meßreihen, erstere ist Mittel aus mehreren Durchgängen. Ausgezogene Kurve: Mit Cornu-Spirale berechnet unter der Annahme monochromatischer Neutronen mit 4,4 Å. Über Hauptspaltbreite gemittelt; endliche Breite des Eintrittsspaltes vernachlässigt. Theoretische Kurve und Meßpunkte der beiden Serien •, ∘ untereinander nur im Scheitel der Interferenzfigur aufeinander normiert

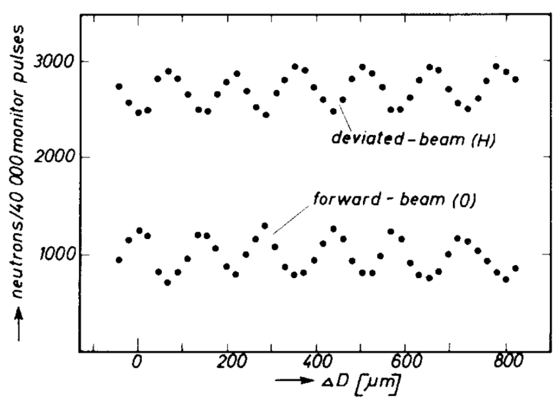
a) Biprism interferometer from Maier-Leibnitz and Springer paper *Z. Physik* 1962;
b) Sketch of the biprism interferometer setup. Wave front division interferometer based on single-slit diffraction. (Beam separation of the order of 60μm);
c) Intensity of the neutron on the detector due to vertical scan of the second slit.

NI history



Larmor and Ramsey type of interferometry, Mezei *Z. Physik* 1972





The perfect-crystal neutron interferometer was demonstrated by Rauch, Treimer, Bauspiess and Bonse in 1974 in Austria (*Phys. Lett. A*, 1974) and by Sam Werner in USA

Neutron Interferometry

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

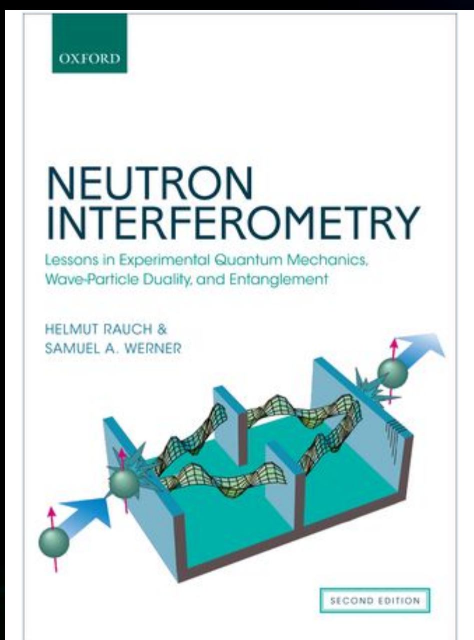
R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

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.

42st Anniversary
First measurement of the effect of gravity on a deBroglie matter wave.

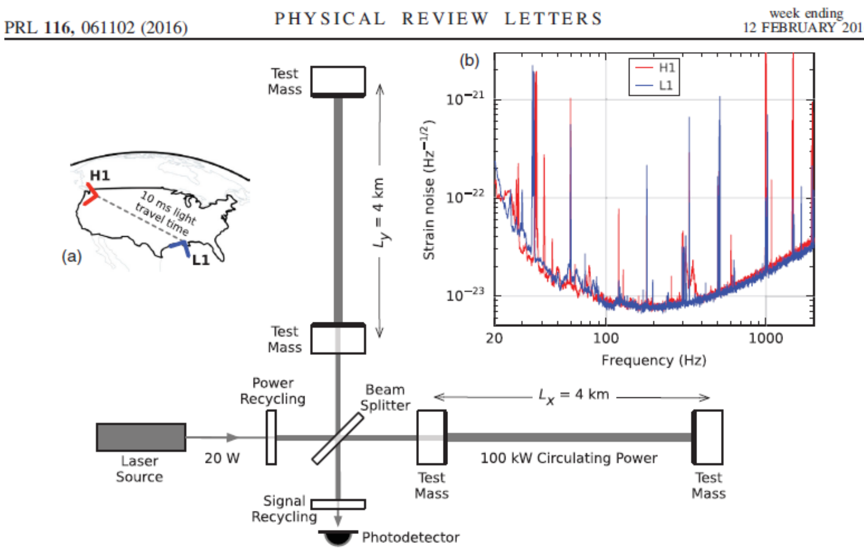


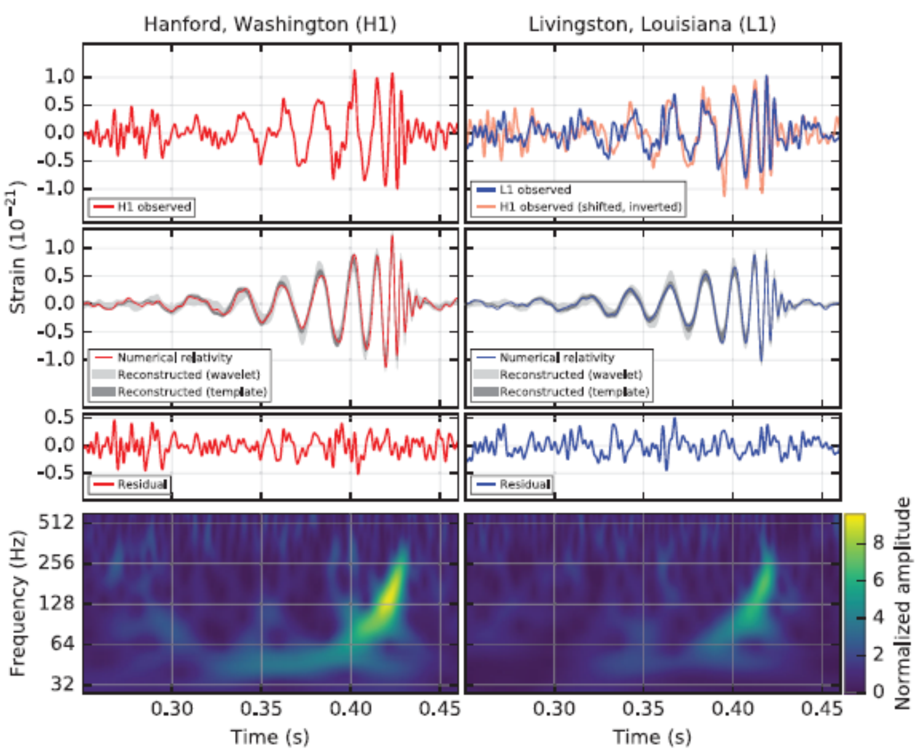
Second edition of monograph by Helmut Rauch and Sam Werner published by Oxford University Press, January 2015.

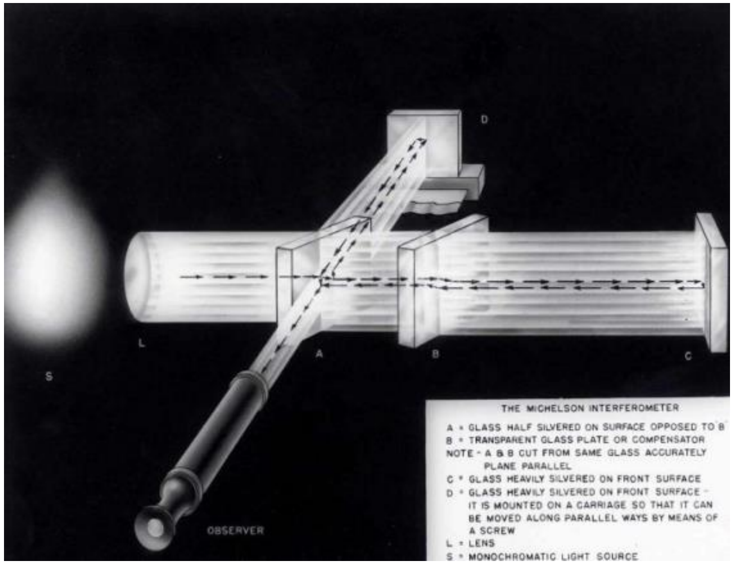
The superposition principle and conservation of momentum combine to make the most beautiful and most useful thing in all of the world:

Interference

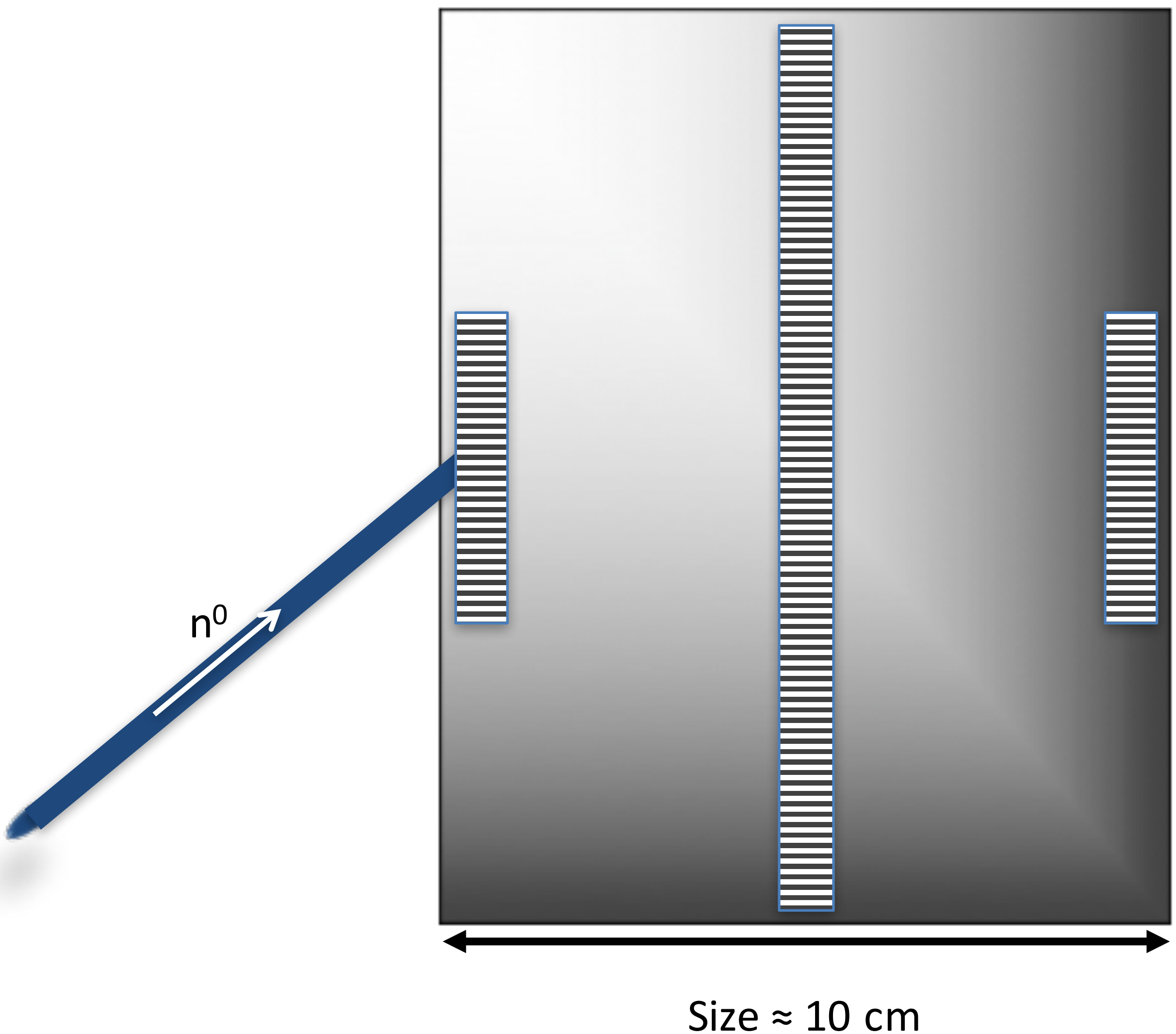
Discovery of gravitational waves (2016): Laser Interferometer Gravitational-Wave Observatory (LIGO) uses Michelson interferometer configuration. *Most sensitive measurement instrument ever made.*







Neutron Interferometry



Neutrons

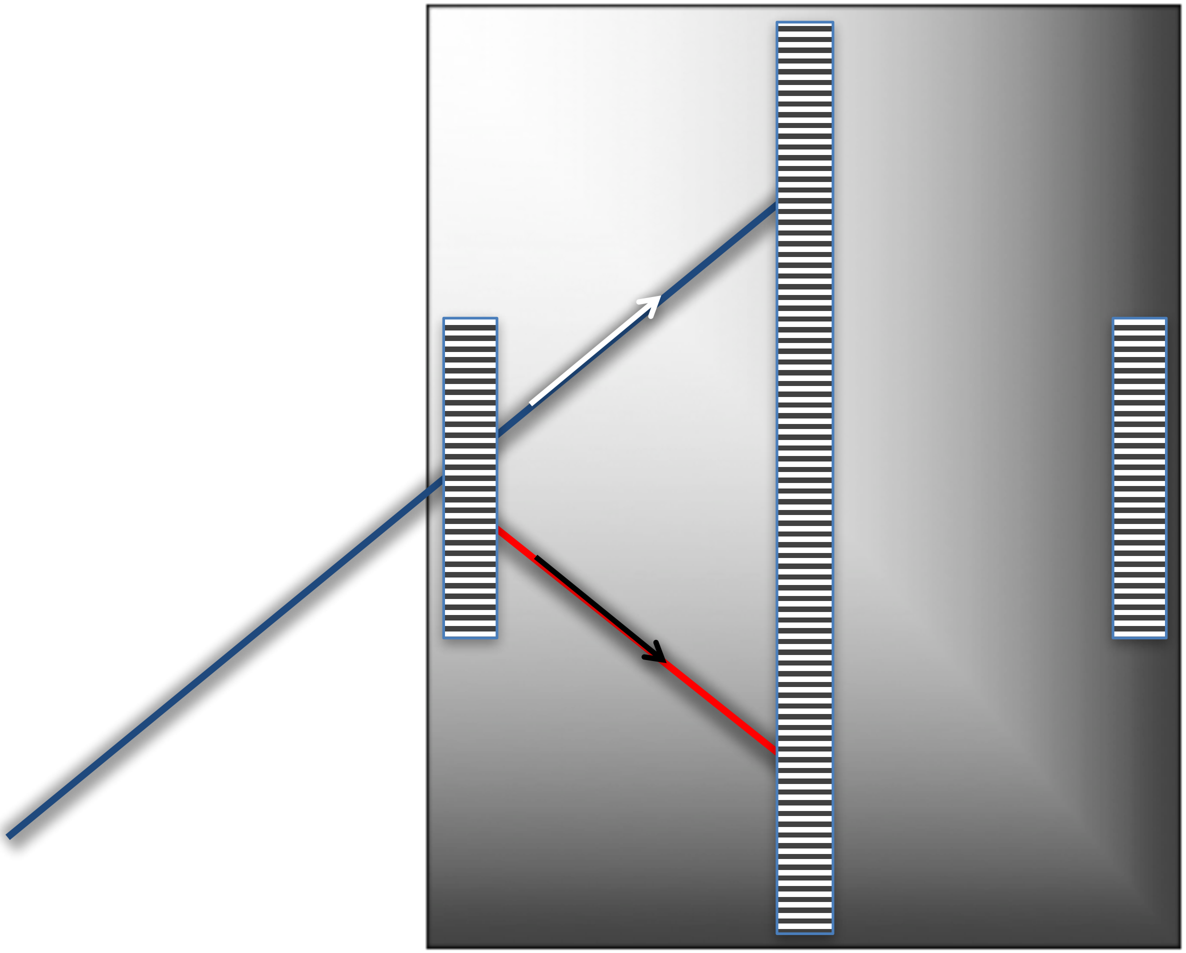
Wavelength: 2 Å

Velocity: 2000 m/s

Time: 50 μs / 10 cm

1 neutron every 1 ms

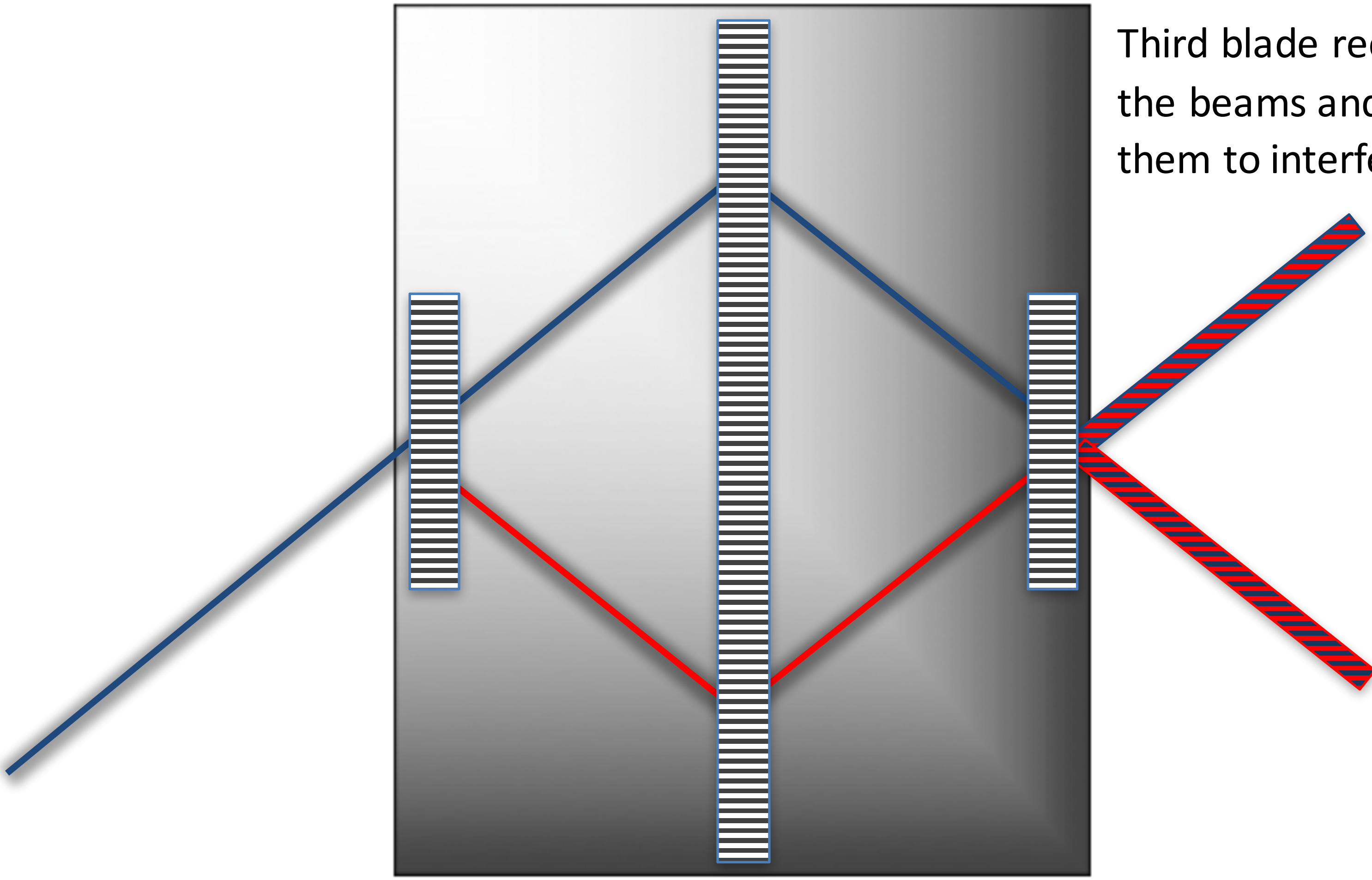
Neutron Interferometry



Bragg scattering
Each neutron is coherently spread over two paths

$$\psi = \frac{1}{\sqrt{2}}\left(\left|upper\right\rangle + \left|lower\right\rangle\right)$$

Neutron Interferometry

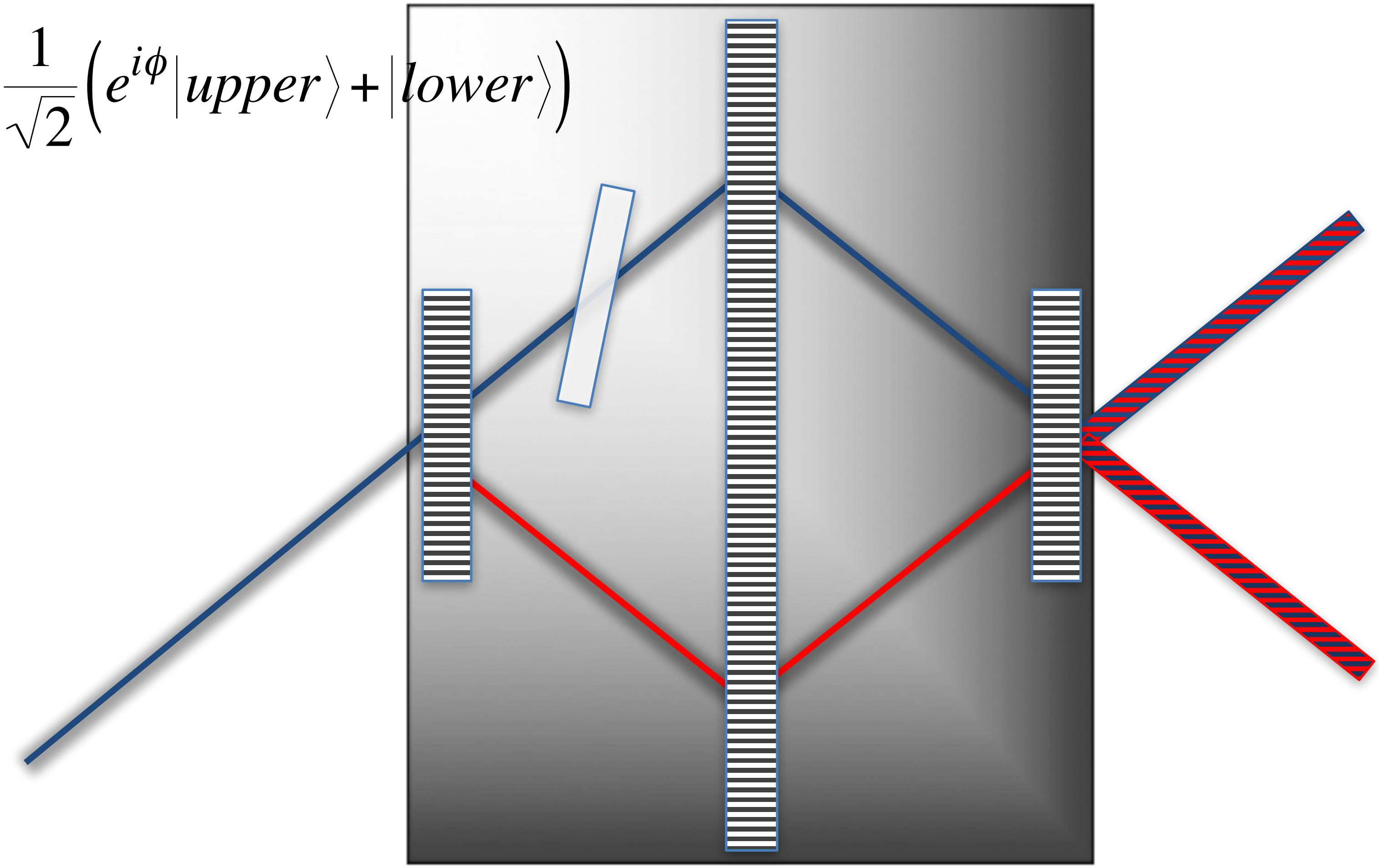


Third blade recombines the beams and allows them to interfere

$$\psi = \frac{1}{\sqrt{2}}\left(|upper\rangle + |lower\rangle\right)$$

Neutron Interferometry

$$\psi = \frac{1}{\sqrt{2}}\left(e^{i\phi}\left|upper\right\rangle + \left|lower\right\rangle\right)$$



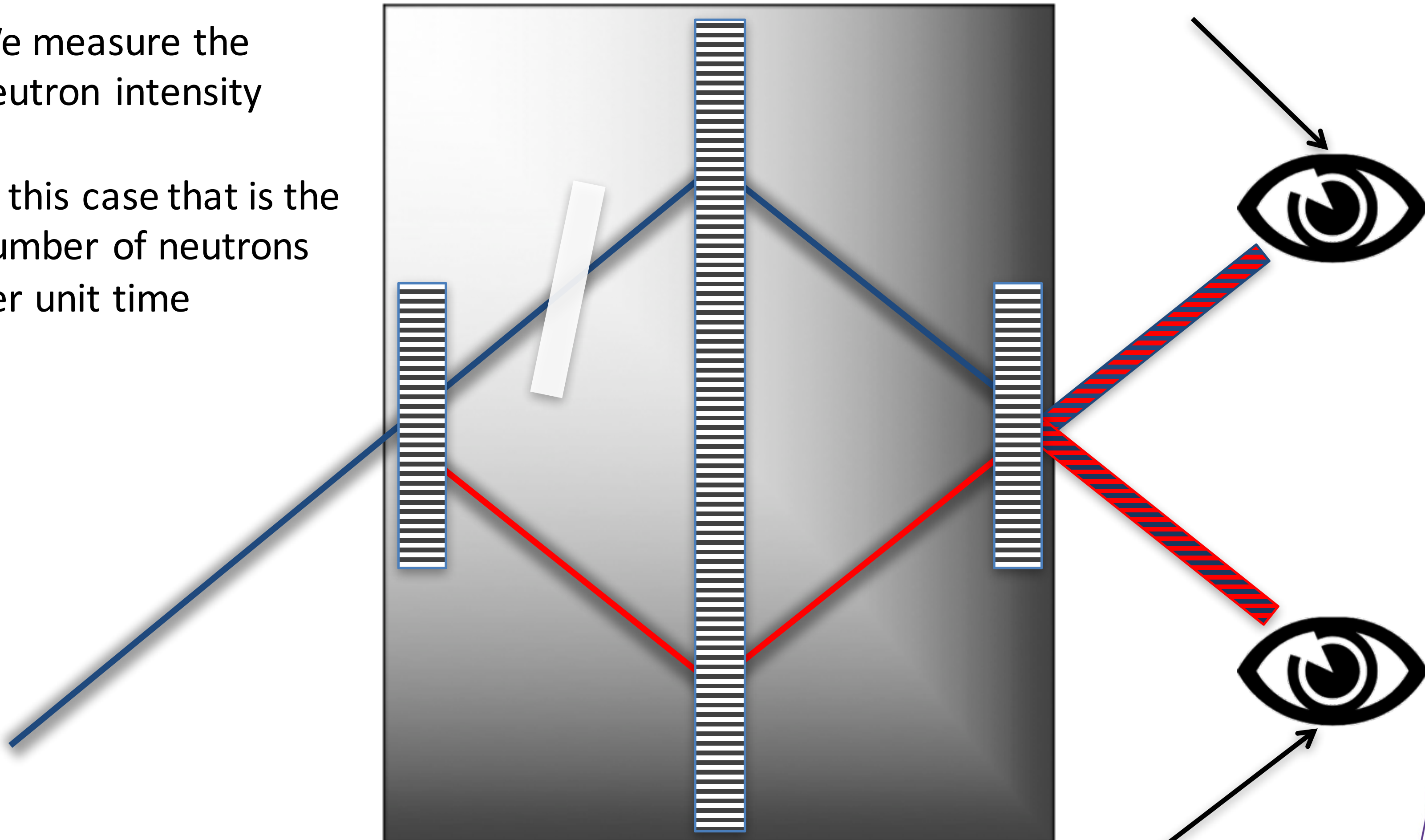
$$\psi = \frac{1}{\sqrt{2}}\left(\left|upper\right\rangle + \left|lower\right\rangle\right)$$

Neutron Interferometry

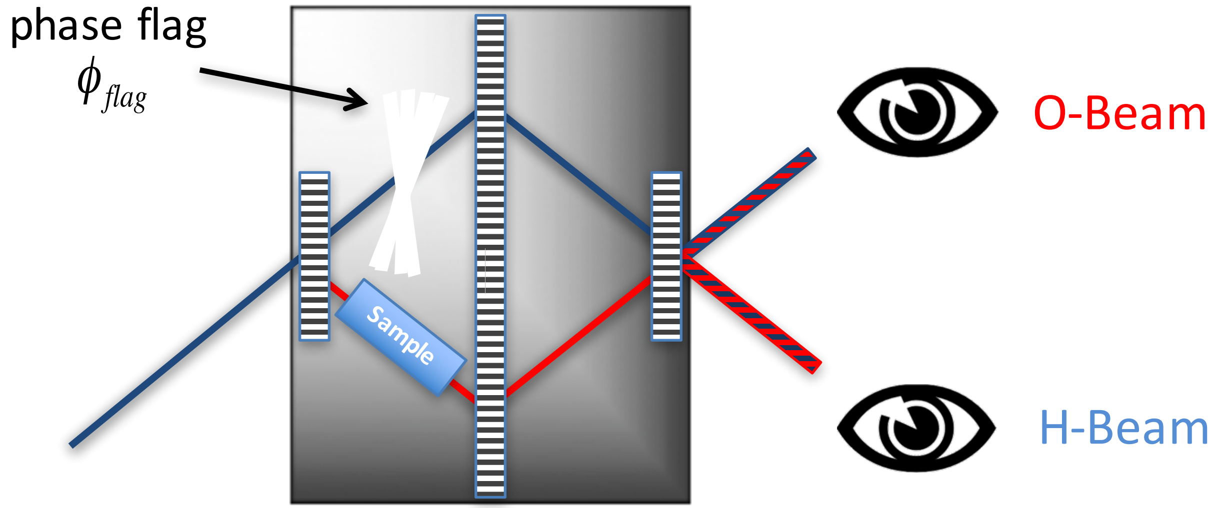
$$I_O = |\psi_O|^2 = |t|^2 |r|^4 [1 + \cos(\phi)]$$

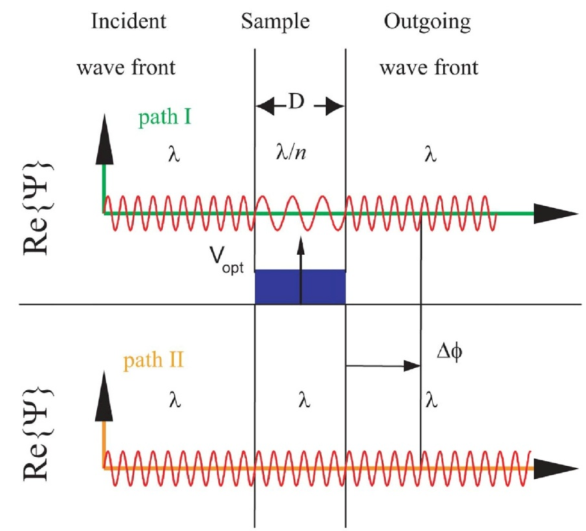
We measure the neutron intensity

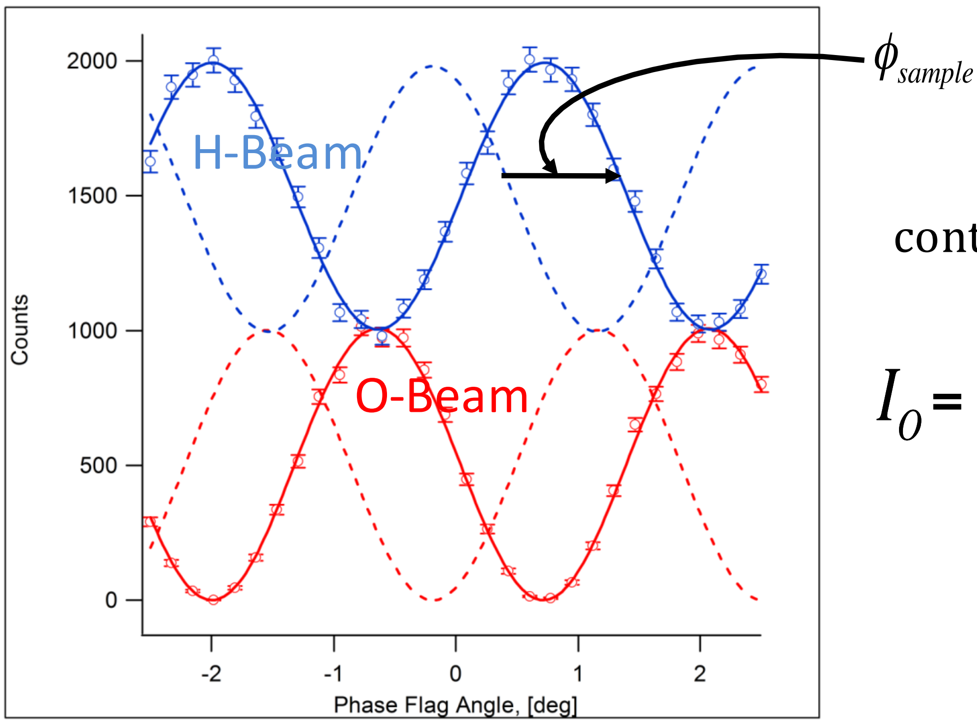
In this case that is the number of neutrons per unit time



$$I_H = |\psi_H|^2 = |r|^2 \left[\left(|t|^4 + |r|^4 \right) - |r|^2 |t|^2 \cos(\phi) \right]$$



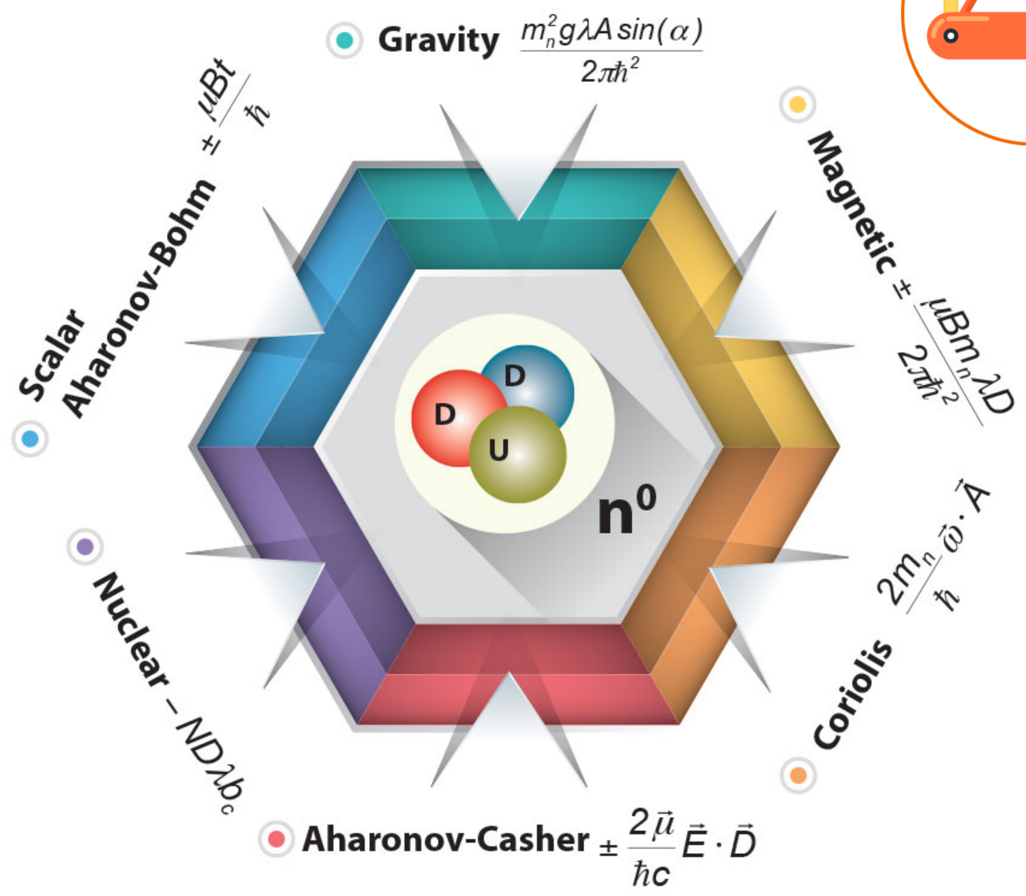




$$\text{contrast} = \frac{B}{A}$$

$$I_O = A + B\cos(\phi_{flag} + \phi_0 + \phi_{sample})$$

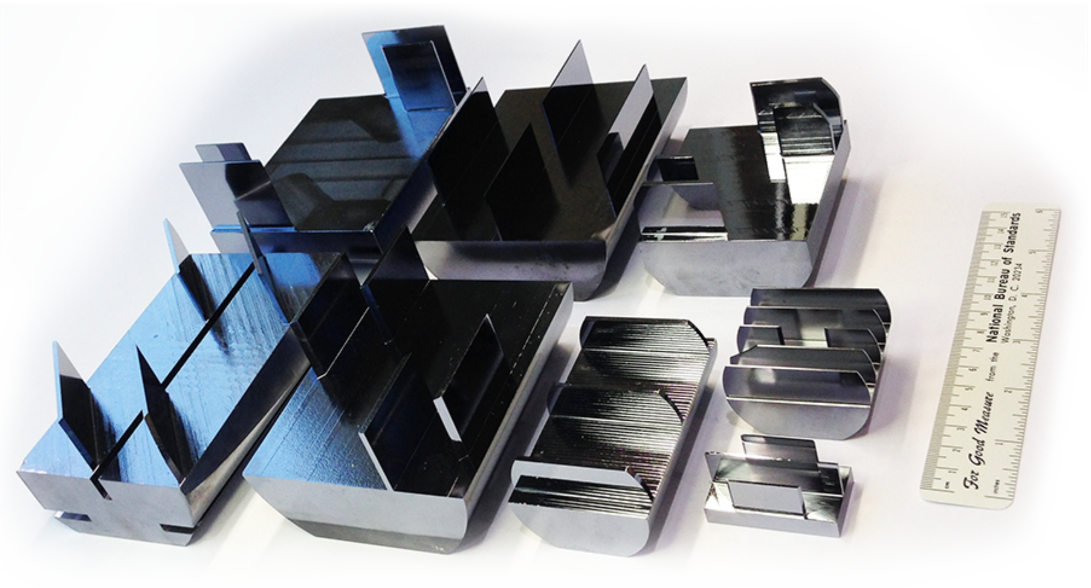
Multiple Interactions



Neutron interferometry is a diverse instrument

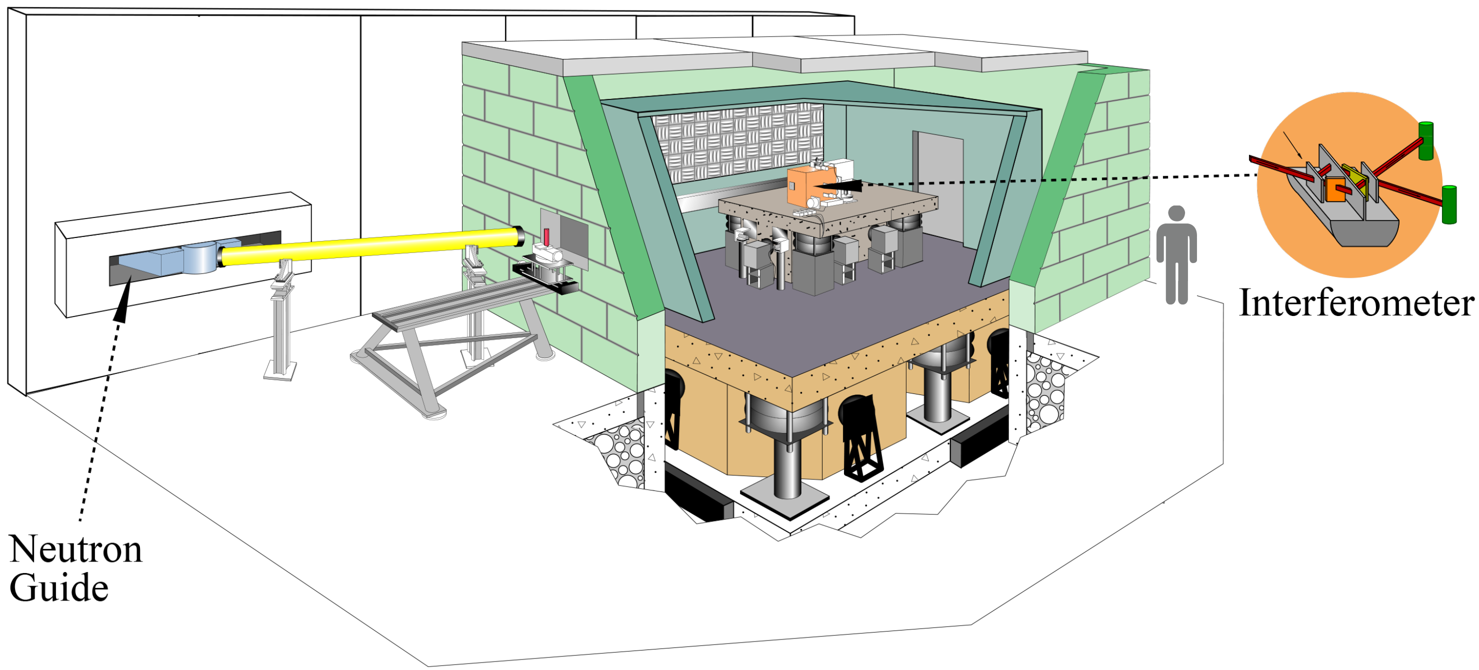
- Nuclear
- Gravity
- Magnetic
- Coriolis
- Aharonov-Cashir
- Scalar Aharonov-Bohm

Perfect Crystal Interferometer



- Cut from a single ingot of silicon
- Blades are machined and left attached to a common silicon base
- The crystals are cut such that the Si lattice planes are perpendicular to the surfaces of the blades
- Each crystal blade acts as a beam splitter

The Neutron Interferometer and Optics Facility



Isolated 40,000 Kg room is supported by six airsprings
Active Vibration Control eliminates vibrations less than 10Hz
Temperature Controlled to +/- 5 mK

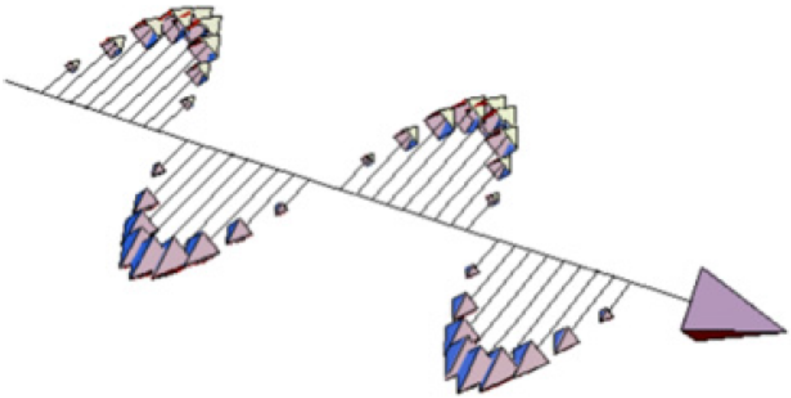
The Neutron Interferometer and Optics Facility

Isolated 40,000 Kg room is supported by six airsprings
Active Vibration Control eliminates vibrations less than 10Hz
Temperature Controlled to +/- 5 mK

Introducing

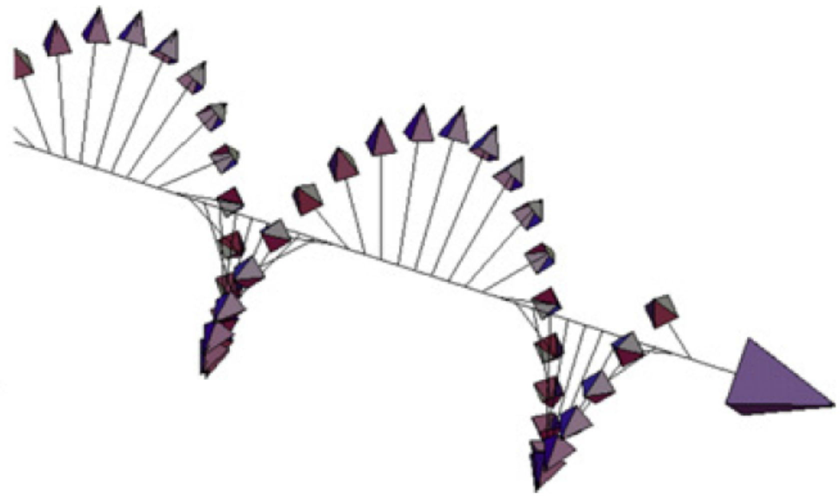
Control of neutron
ORBITAL ANGULAR MOMENTUM

Electromagnetic field



Linear polarized light

$$\hbar k_0$$



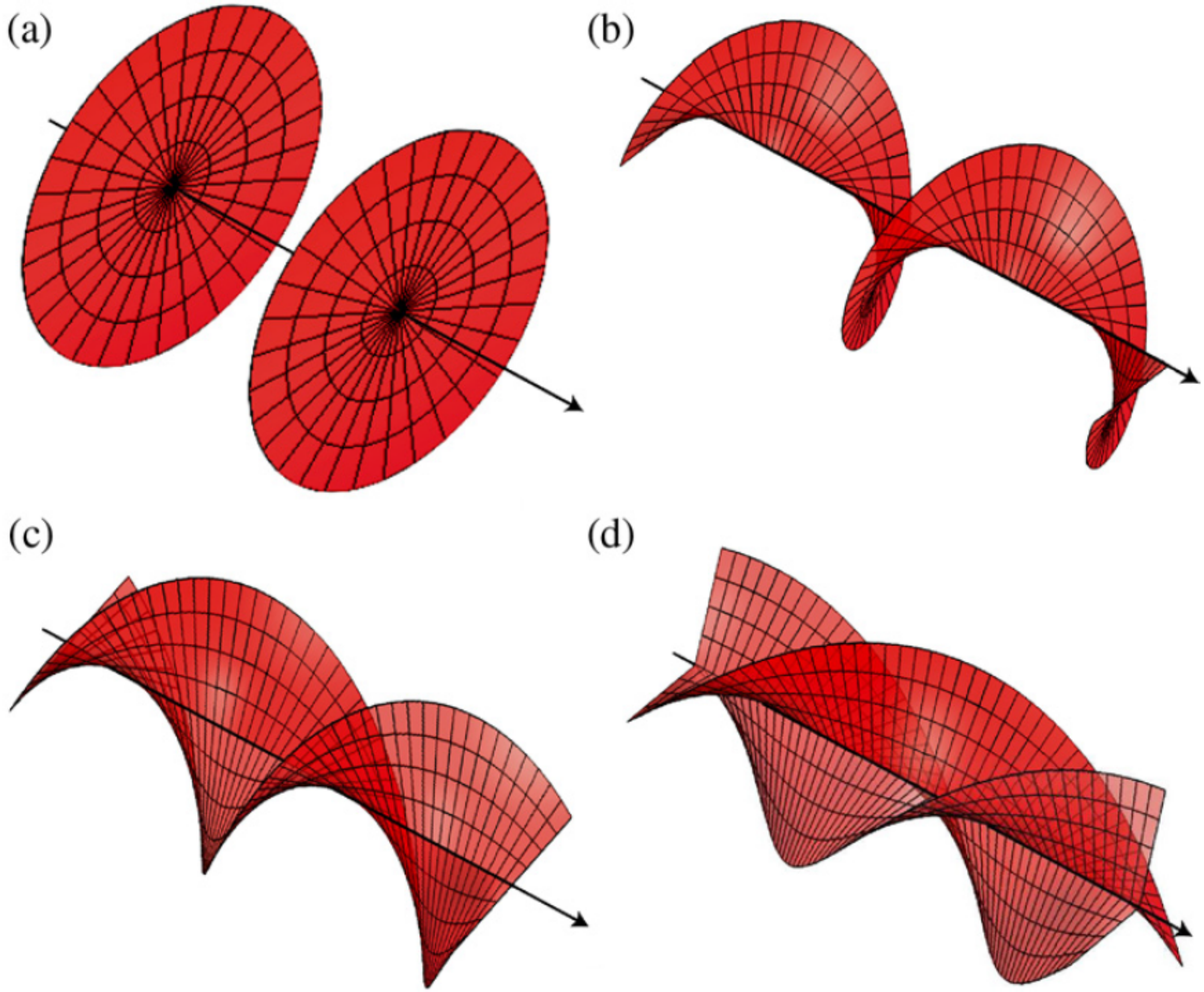
Circular polarized light

$$\pm\hbar$$

The spin angular momentum (SAM) of light is connected to the polarization of the electric field. Light with linear polarization (left) carries no SAM, whereas right or left circularly polarized light (right) carries a SAM of $\pm\hbar$ per photon.

Yao, A. M. & Padgett, M. J.
Adv. Opt. Photon. 3, 161–204 (2011).

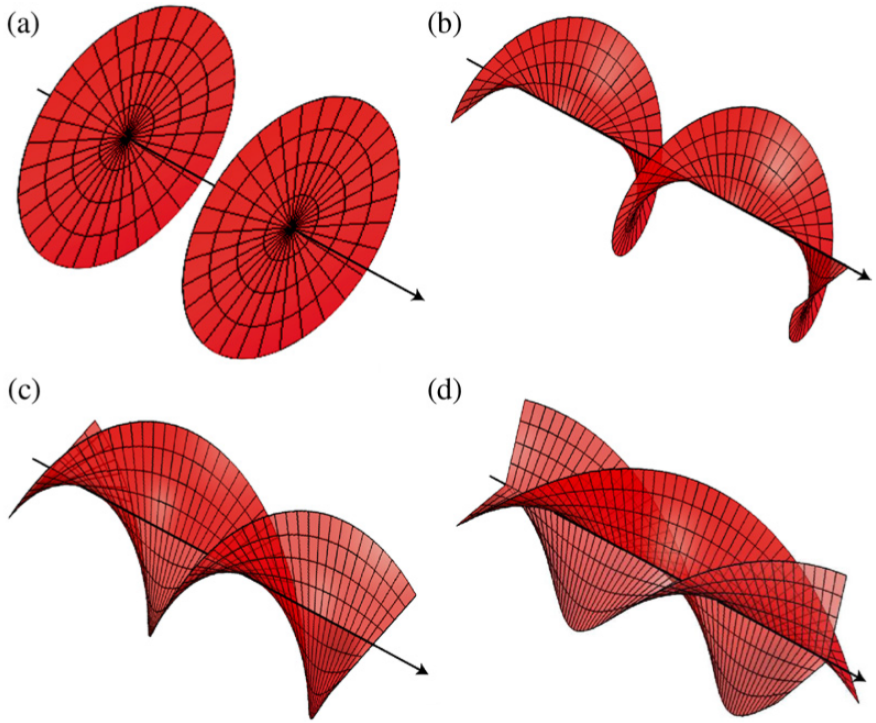
Yao, A. M. & Padgett, M. J.
Adv. Opt. Photon. 3, 161–204 (2011).



Helical phase fronts for (a) l=0, (b) l=1, (c) l=2, and (d) l=3.

- Waves 101: orbital angular momentum

$$\frac{\partial}{\partial t}\Psi(\mathbf{x},t) = i\nabla^2\Psi(\mathbf{x},t)$$



Orbital angular momentum (OAM) waves

$$\Psi_{k,q,l}(\mathbf{x}) = e^{ikx_3} J_l(q\rho) e^{il\phi}$$

Implemented in light (1990), ultracold atoms (2006), electrons (2010), neutrons (2015)

Field amplitude carries a spiral phase exp (*I* $l\ \phi$) . Helical phase fronts for (a) l=0, (b) l=1, (c) l=2, and (d) l=3.

A. M. Yao and M. J. Padgett, *Adv. Opt. Photon.* **3**, 161–204 (2011)

Письма в ЖЭТФ, том 52, вып. 8, стр. 1037 - 1039 25 октября 1990 г.

ЛАЗЕРНЫЕ ПУЧКИ С ВИНТОВЫМИ ДИСЛОКАЦИЯМИ ВОЛНОВОГО ФРОНТА

В.Ю.Баженов, М.В.Васнецов, М.С.Соскин

Экспериментально получены и исследованы когерентные световые поля с дислокациями волнового фронта различных порядков при прохождении лазерного пучка через многомодовый волновод и при дифракции на синтезированных голограммах.

Дислокации волнового фронта [1] или оптические вихри привлекают внимание как один из новых объектов, существующих в оптических полях сложной пространственной структуры или в лазерных резонаторах с большим числом Френеля [2]. При наличии винтовой дислокации волновой фронт представляет собой единую

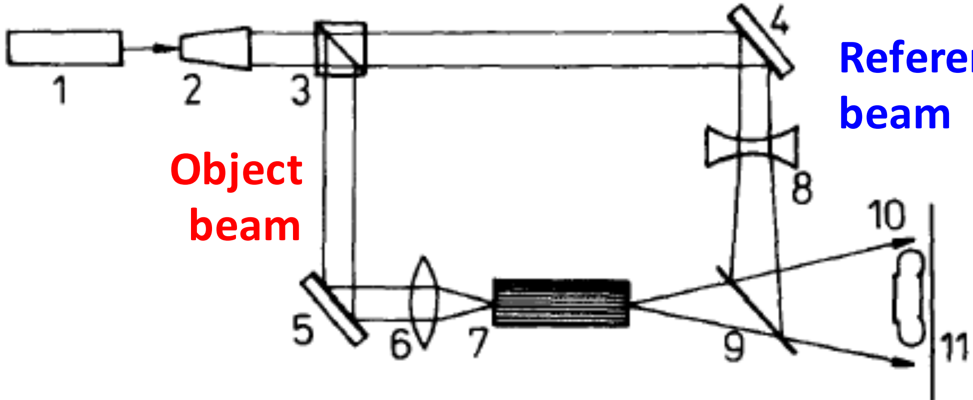
Laser beams with screw dislocations in their wavefronts

V. Yu. Bazhenov, M. V. Vasnetsov, and M. S. Soskin
Institute of Physics, Academy of Sciences of the Ukrainian SSR

(Submitted 28 August 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 8, 1037–1039 (25 October 1990)

Coherent optical fields with wavefront dislocations of various orders have been produced experimentally and studied during the passage of a laser beam through a multimode waveguide and during diffraction by some holograms which have been synthesized.

Wavefront dislocations[1] or optical vortices have attracted interest as some of the new entities which exist in optical fields with a complex spatial structure or in laser cavities with a large Fresnel number.[2] When there is a screw dislocation, the wavefront



The 1990 holograms of Bazhenov, Vasnetsov and Soskin

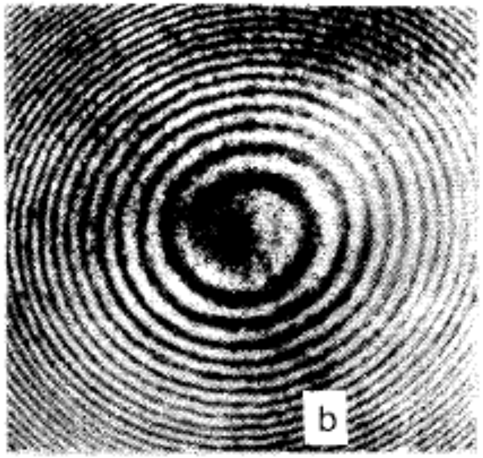
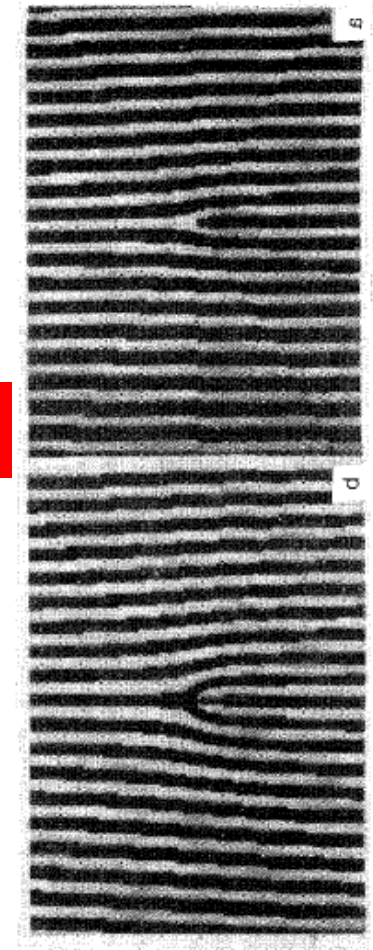


FIG. 1. a: Experimental setup. 1—He–Ne laser; 2—beam expander; 3—beam splitter; 4,5—mirrors; 6—objective; 7—braided optical fibers; 8—diverging lens; 9—half-silvered mirror; 10—camera; 11—screen for observing the interference of the beams. b: Interference pattern formed by the spherical reference wave and a wave with a screw wavefront dislocation.

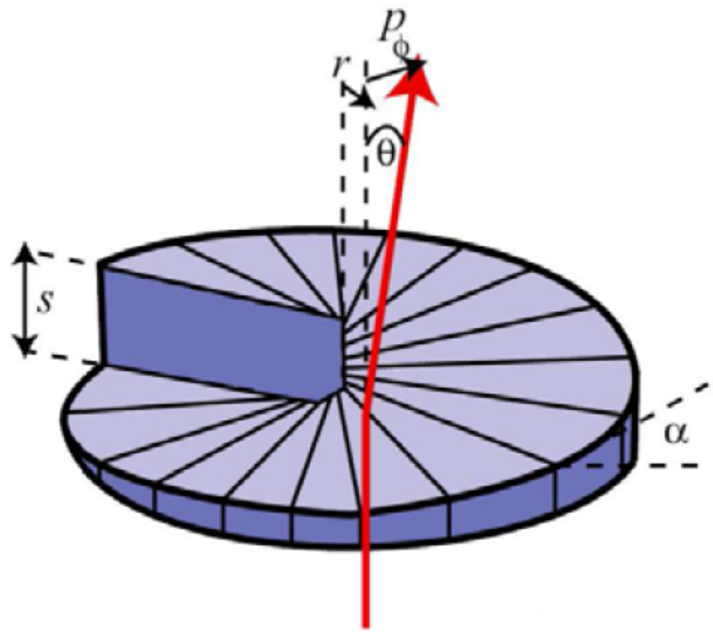
Above: Mach-Zehnder interferometer of Bazhenov *et al.* (1990)
Below: Hologram of optical vortex using *spherical-wave* reference beam

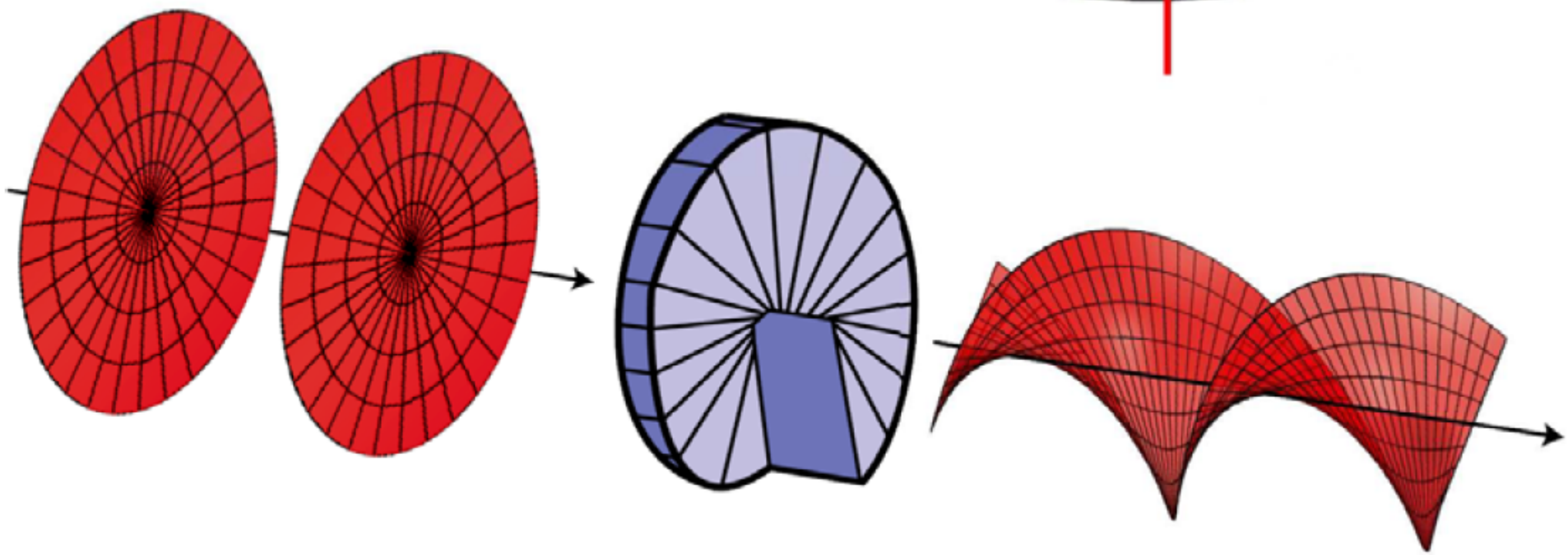


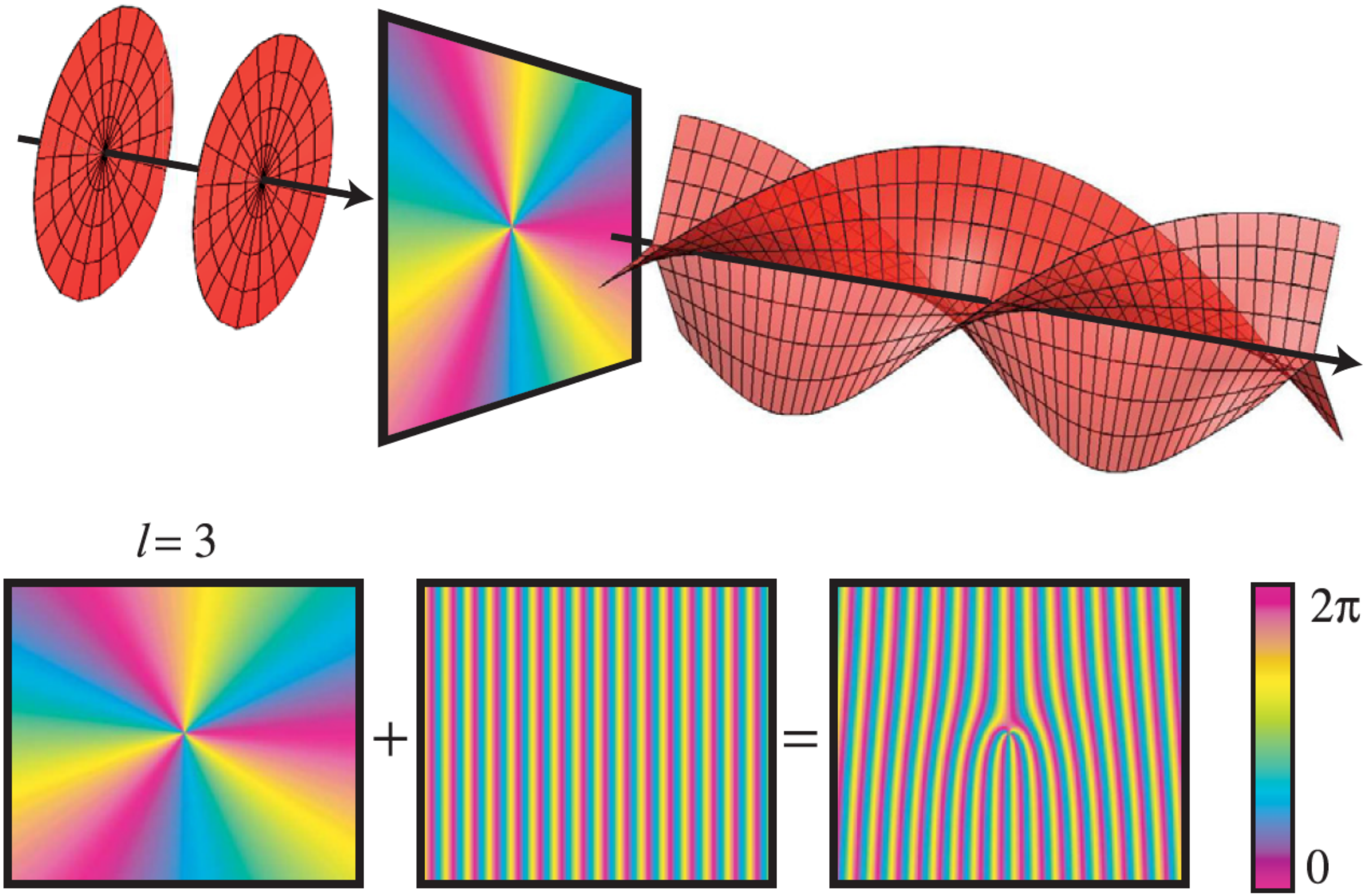
Synthetic holograms using plane-wave reference beam: *l* = 1 and *l* = 2

How to generate such modes?

Yao, A. M. & Padgett, M. J.
Adv. Opt. Photon. 3, 161–204 (2011).







l=3

Yao, A. M. & Padgett, M. J.
Adv. Opt. Photon. 3, 161–204 (2011).

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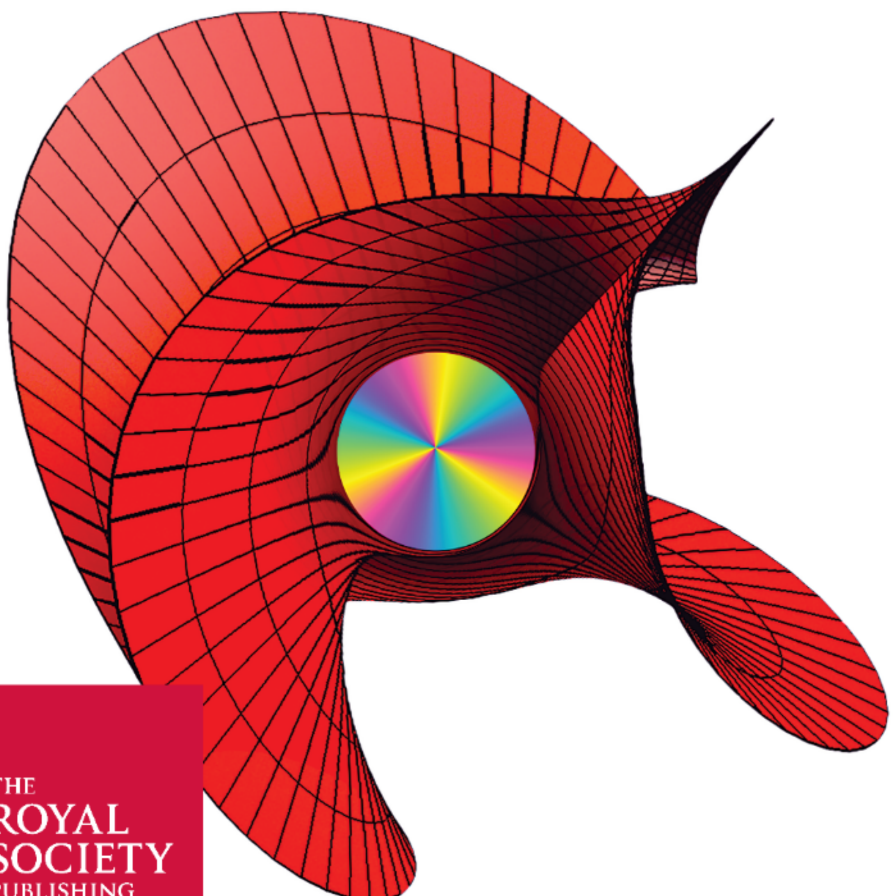
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Optical orbital angular momentum

Theme issue compiled and edited by Stephen M. Barnett, Mohamed Babiker and Miles J. Padgett



THE ROYAL SOCIETY PUBLISHING

J. Opt. **19** (2017) 013001 (51pp) doi:10.1088/2040-8978/19/1/013

Roadmap

Roadmap on structured light

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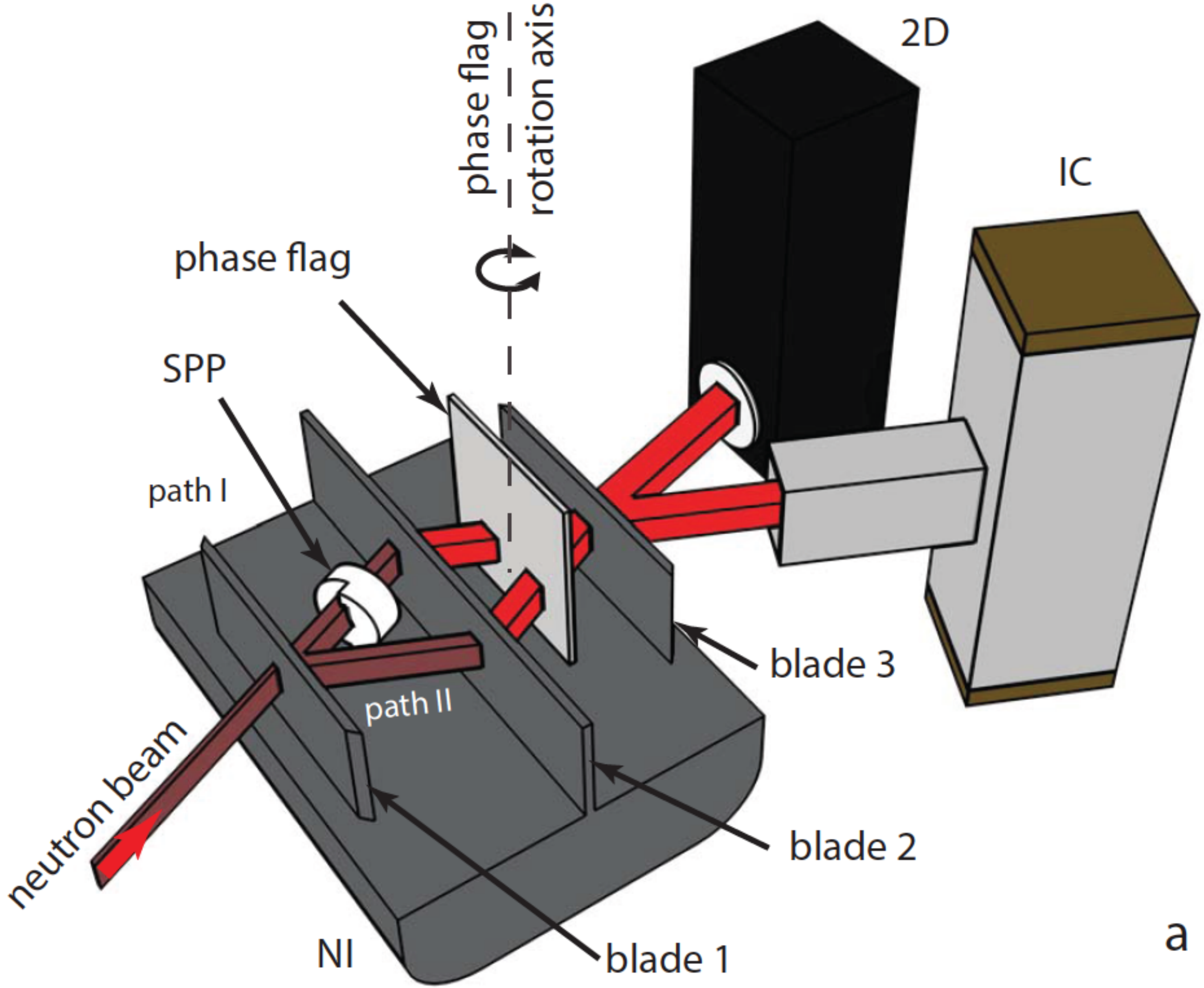
CrossMark

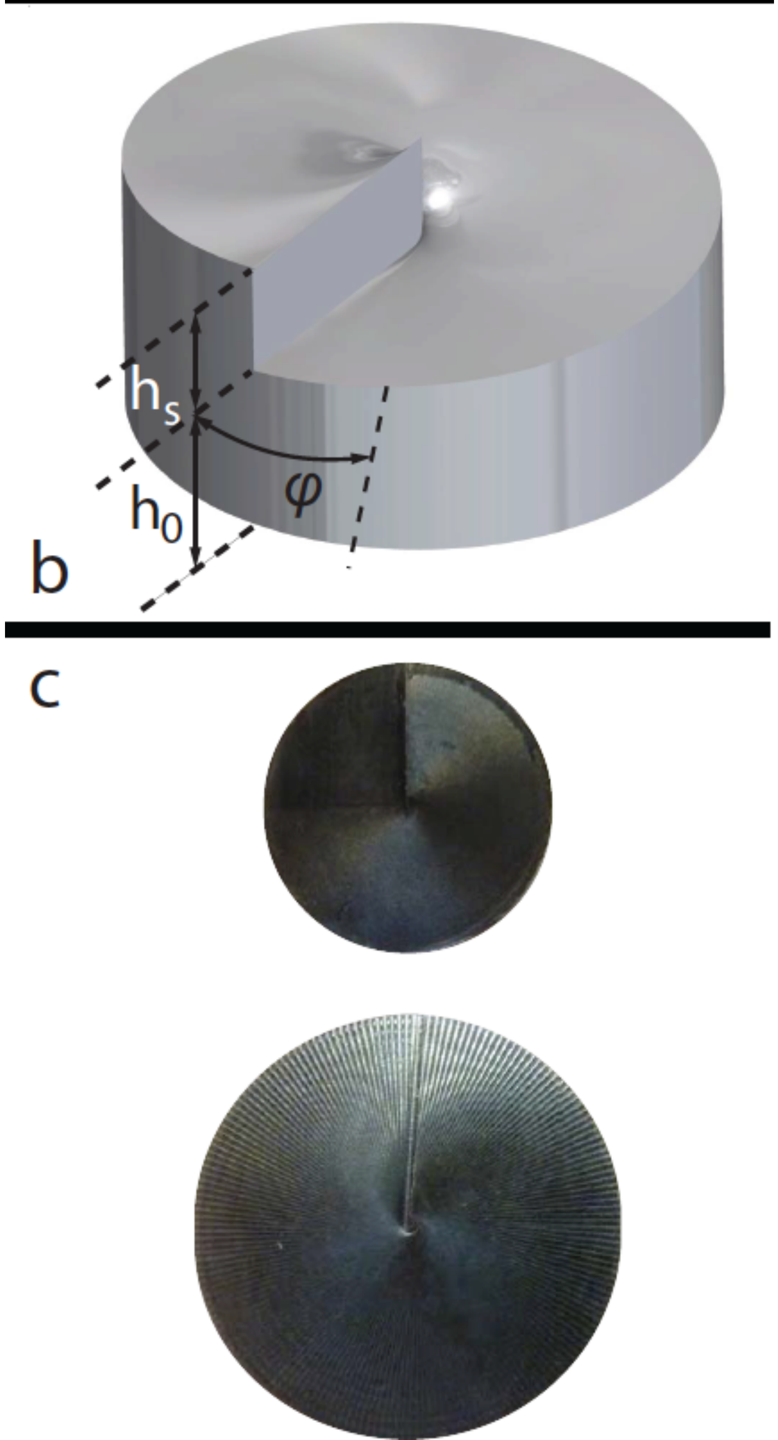
Abstract

Structured light refers to the generation and application of custom light fields. As the tools and technology to create and detect structured light have evolved, steadily the applications have begun to emerge. This roadmap touches on the key fields within structured light from the

[21] Guest editors of the roadmap.
[22] Authors to whom any correspondence should be addressed.

Setup


phase flag
rotation axis
2D
IC
phase flag
SPP
path I
path II
blade 3
blade 2
blade 1
neutron beam
NI
a



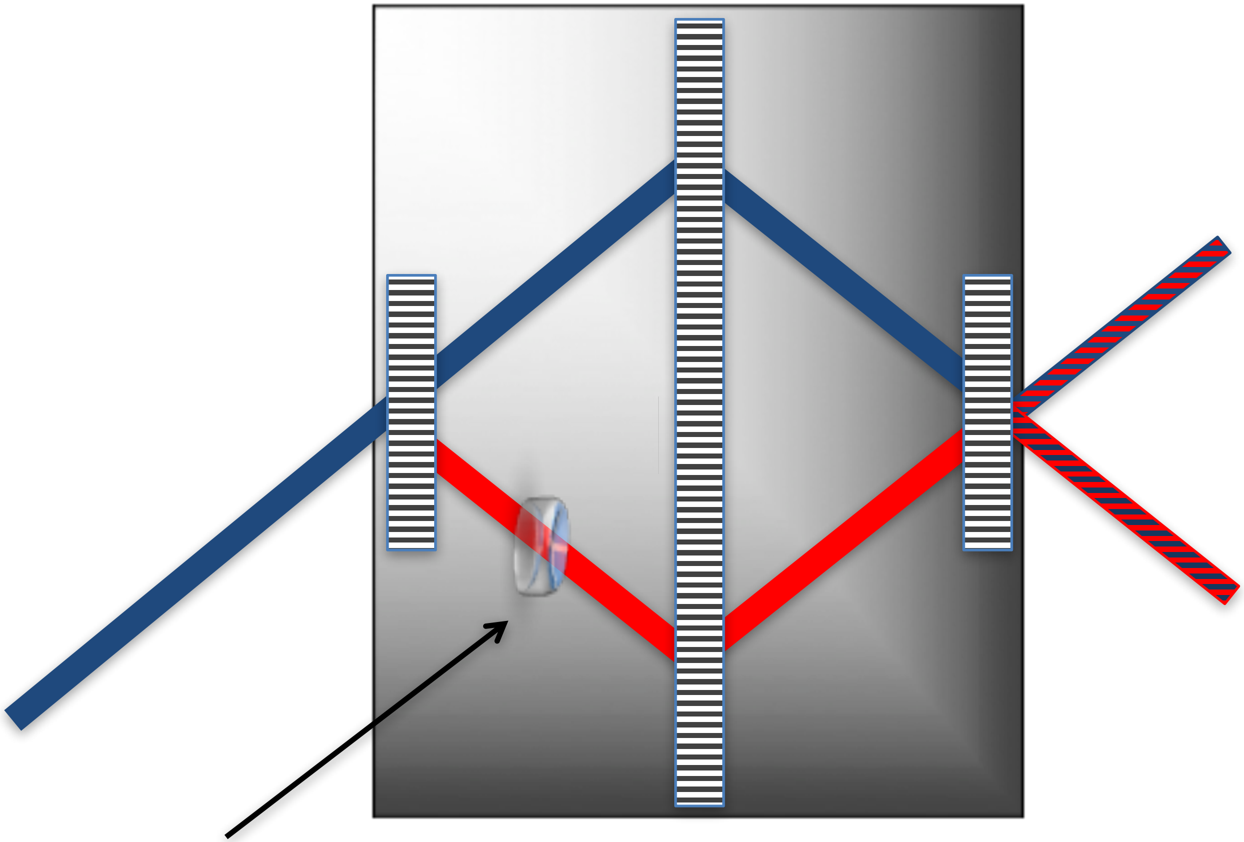
$$h = h_0 + \frac{h_s \varphi}{2\pi}$$

Spiral Phase Plate

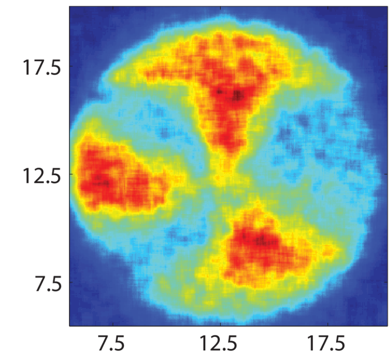
$$\Delta\theta = -N b_c \lambda h = -N b_c \lambda \left(h_0 + \frac{h_s \varphi}{2\pi} \right)$$

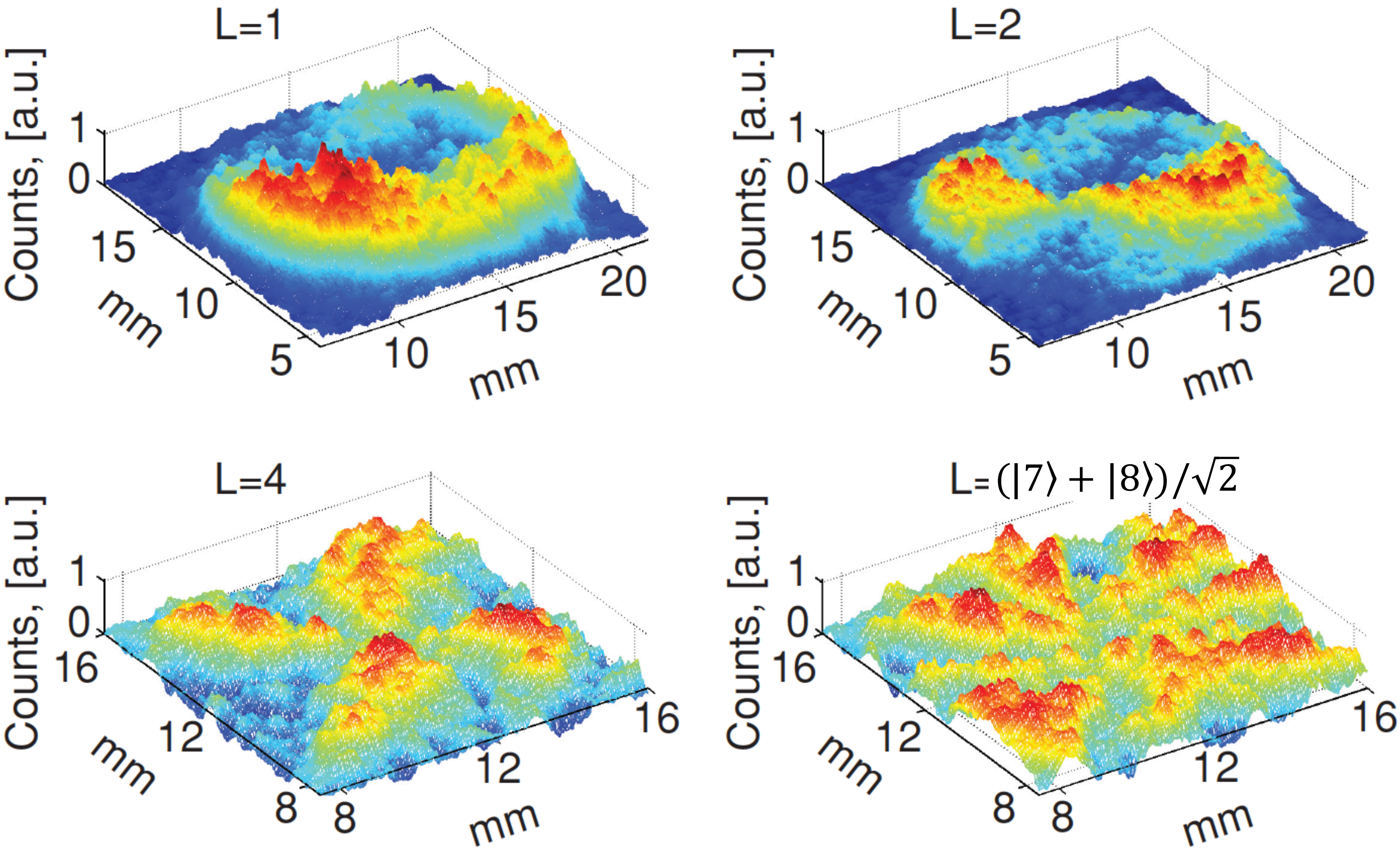
Contrast Over the Neutron Beam

$$I_0 \propto [1 + \cos(3 \cdot \alpha)]$$

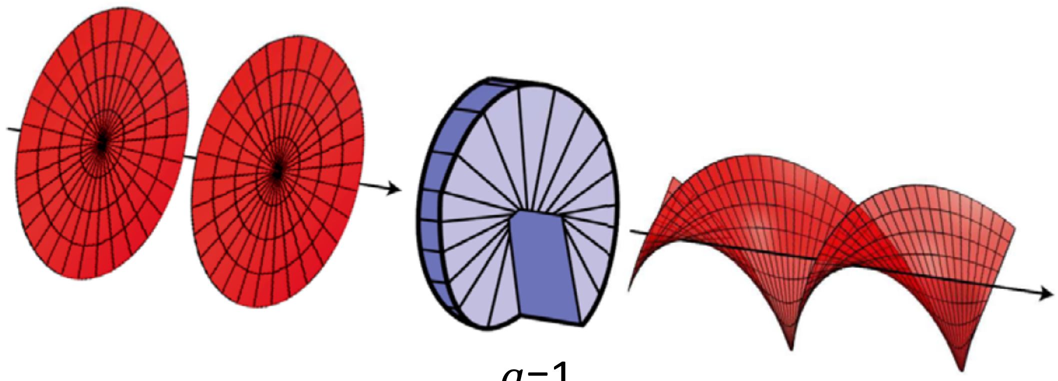


Spiral Phase Ramp





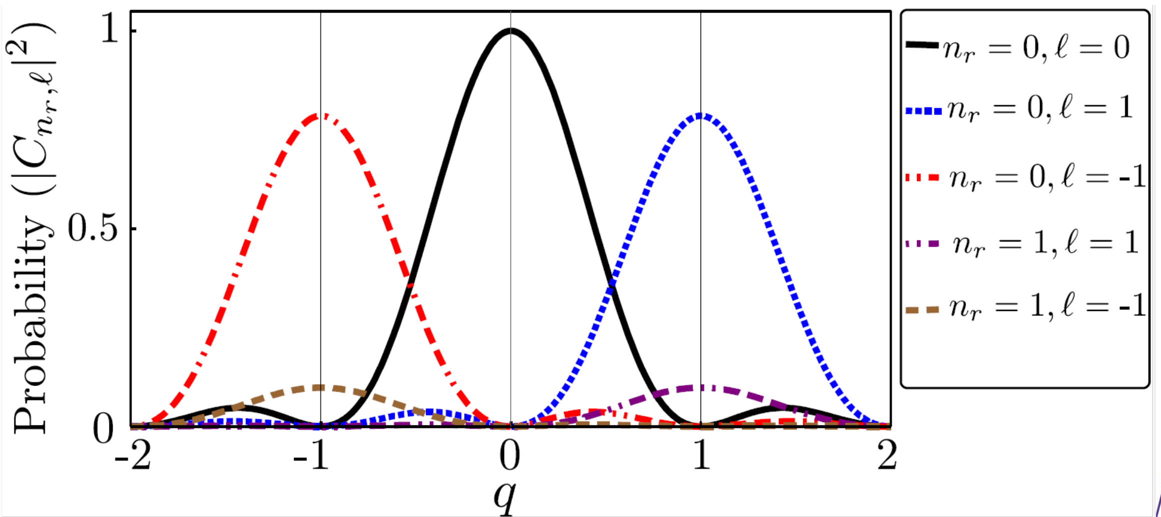
"Controlling Neutron Orbital Angular Momentum," C. W. Clark, *et al.*, *Nature* **525**, 504 (2015)

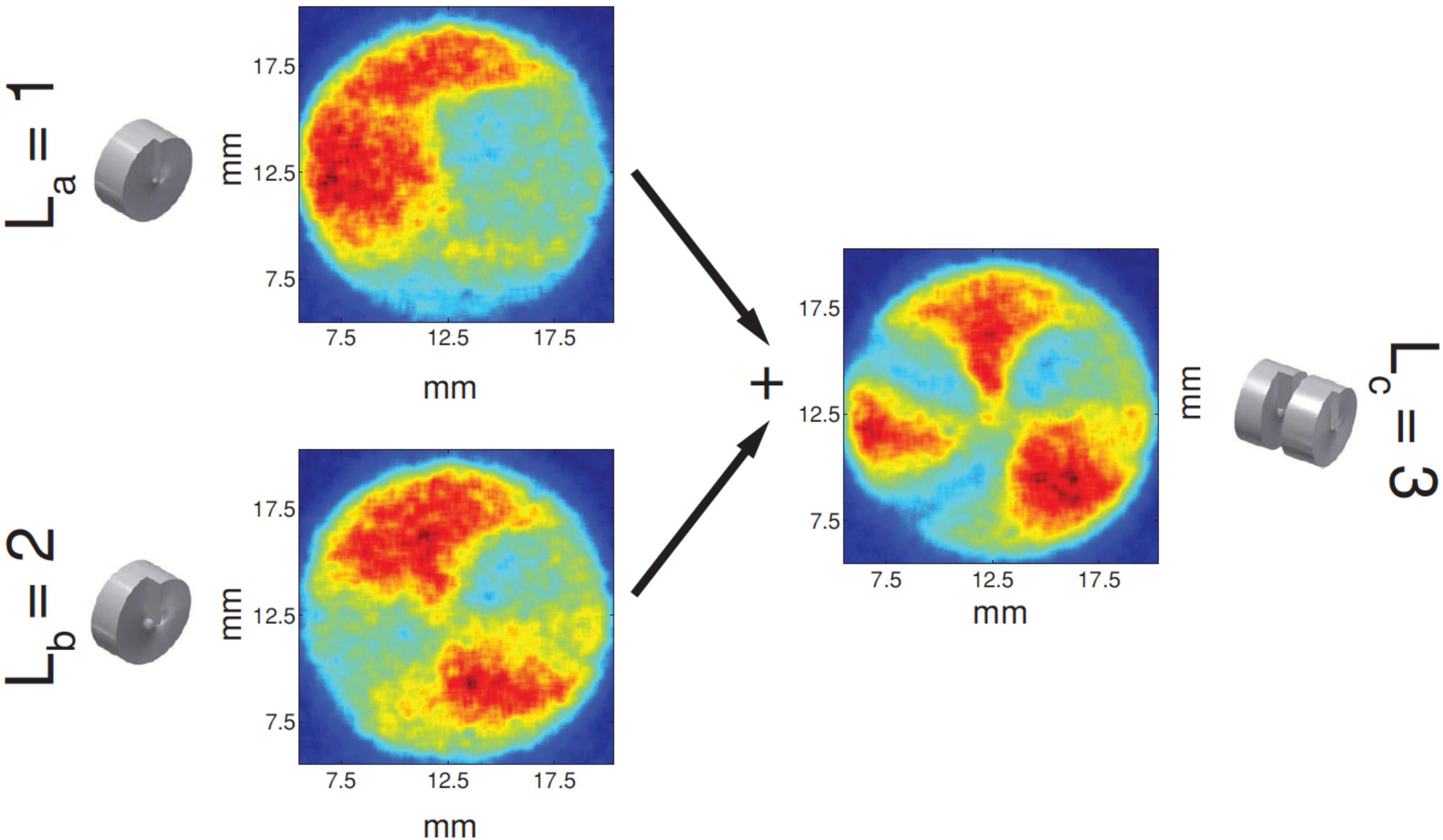


$$|\Psi_{SPP}\rangle = \sum_{n_r=0}^{\infty} C_{n_r}\, e^{i\ell\overline{\varphi}} e^{ik_z\bar{z}}$$

$$|n_r,\ell,k_z\rangle = \mathcal{N}\xi^{|\ell|} e^{-\frac{\xi^2}{2}} \mathcal{L}_{n_r}^{|\ell|}\left(\xi^2\right) e^{-i\ell\phi} Z(z)$$

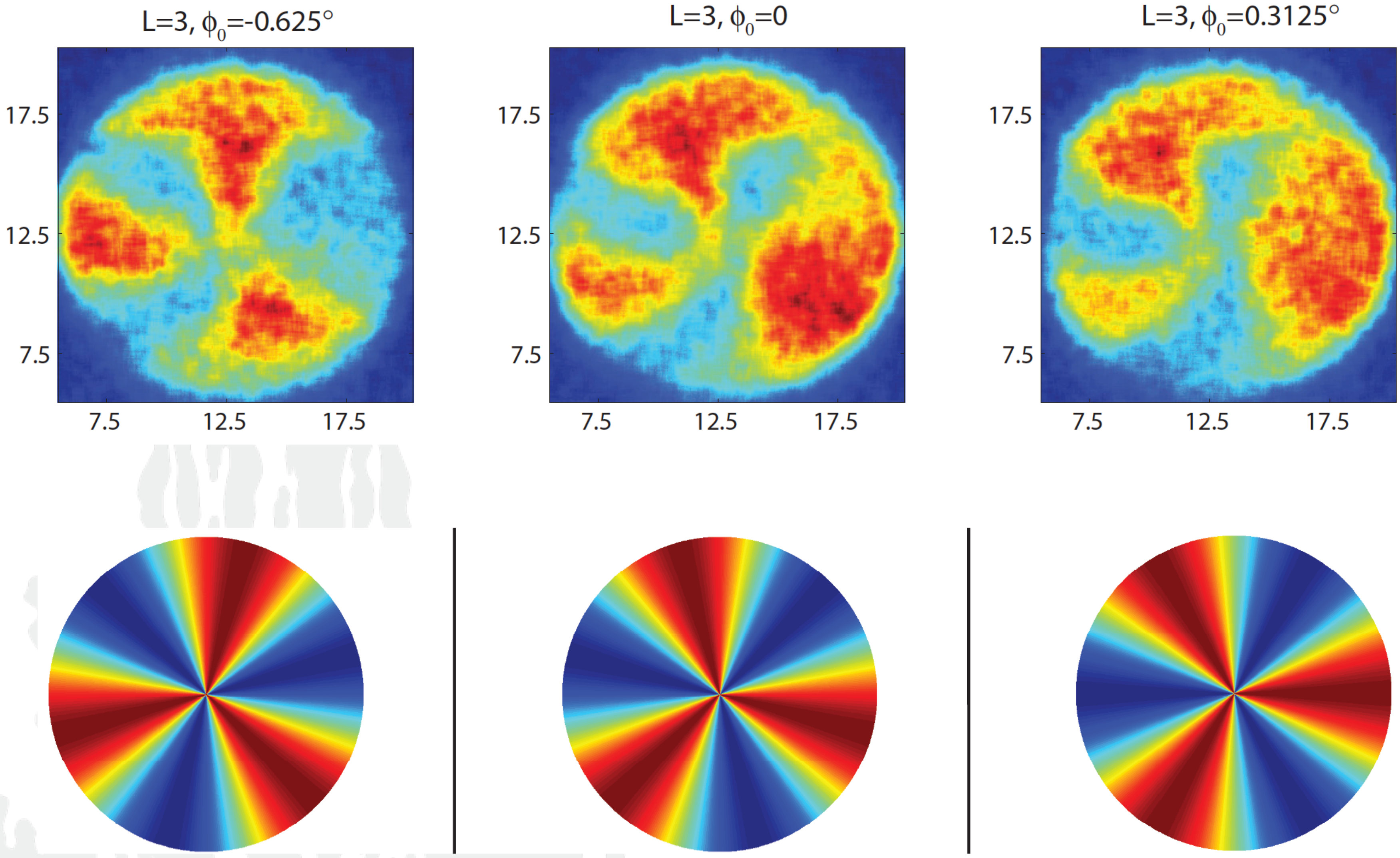
$$C_{n_r,\ell} = \int_0^{2\pi}\int_0^{\infty} \langle n_r,\ell\,|\Psi_{\mathrm{SPP}}\rangle\, r dr d\phi$$





“Controlling Neutron Orbital Angular Momentum,” C. W. Clark, *et al.*, *Nature* **525**, 504 (2015)

Transforms as angular momentum under rotation



“Controlling Neutron Orbital Angular Momentum,” C. W. Clark, *et al.*, *Nature* **525**, 504 (2015)

Holography

nobel.se public domain

Dennis Gabor
1900 - 1979
1971 Nobel Prize in Physics
"for his invention and development of the holographic method."

- Invented by Dennis Gabor in 1947
- Invention of laser made it practical in the early 1960s

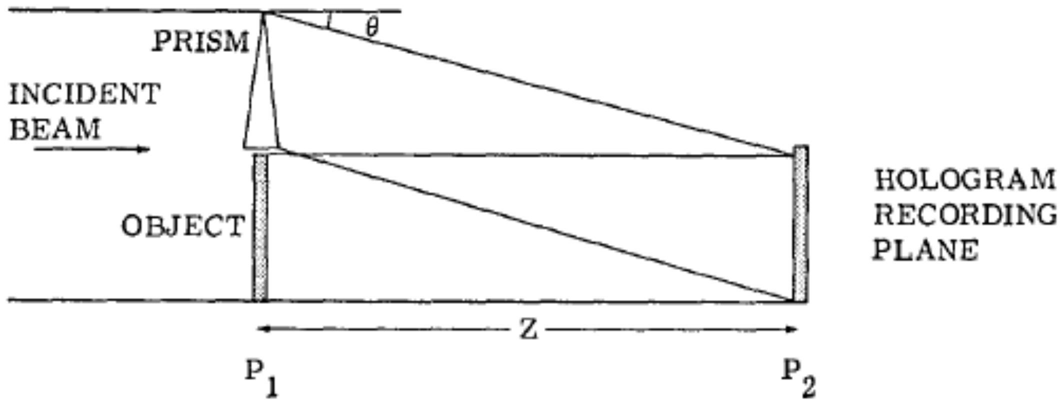


FIG. 1. Wedge technique for producing a two-beam hologram. The object is placed in the lower part of plane P_1; the hologram is recorded at plane P_2.

Emmet N. Leith and Juris Upatnieks, "Wavefront Reconstruction with Continuous-Tone Objects," *J. Opt. Soc. Am.* **53**, 1377 (1963)

Holography

nobel.se public domain

Dennis Gabor
1900 - 1979
1971 Nobel Prize in Physics
"for his invention and development of the holographic method."

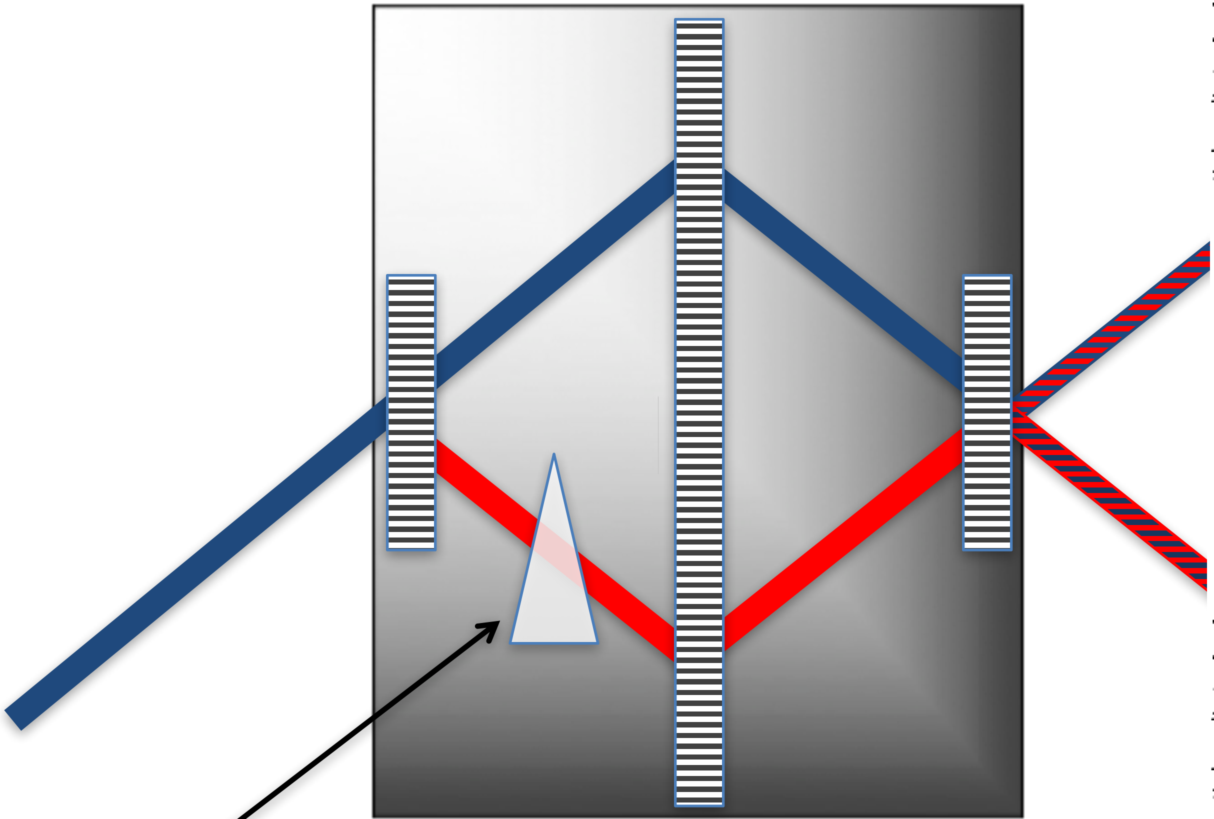
The object

The hologram

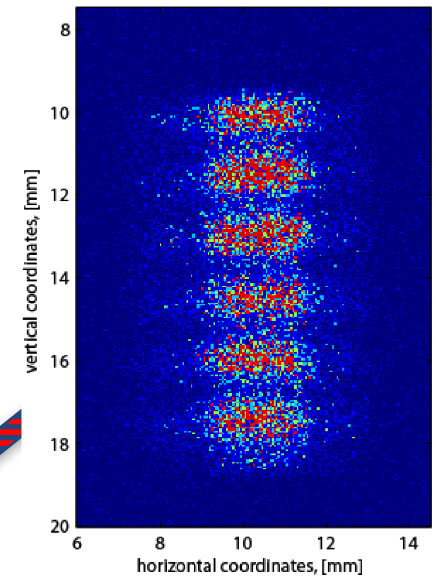
Emmet N. Leith and Juris Upatnieks, “Wavefront Reconstruction with Continuous-Tone Objects,” *J. Opt. Soc. Am.* **53**, 1377 (1963)

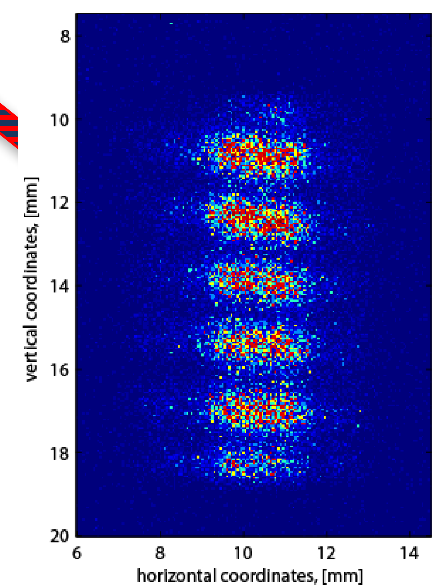
Contrast Over the Neutron Beam

$$I_O \propto \left[1+\cos(kz)\right]$$



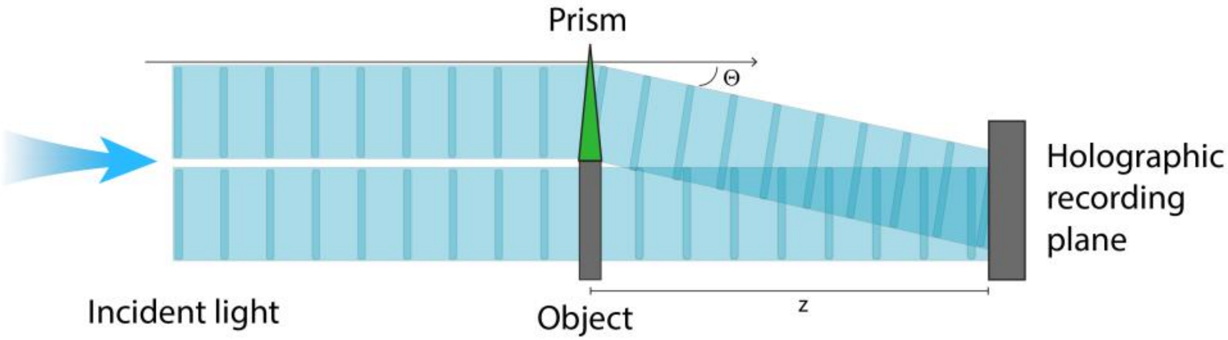
Wedge —
Linear Phase Ramp

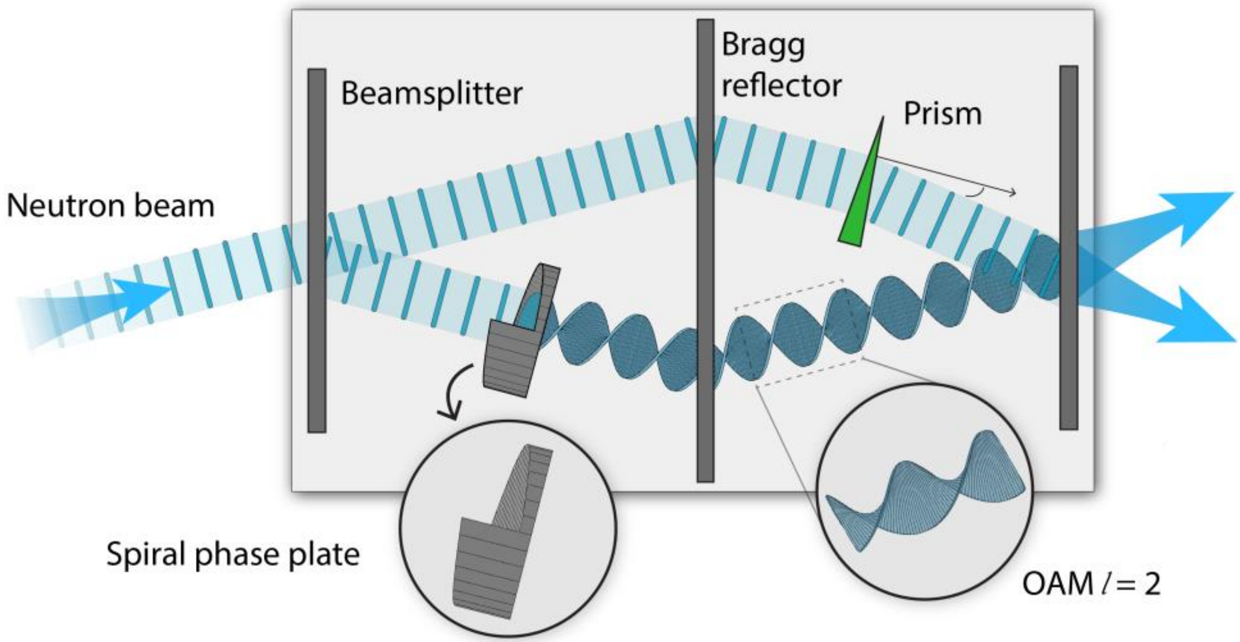




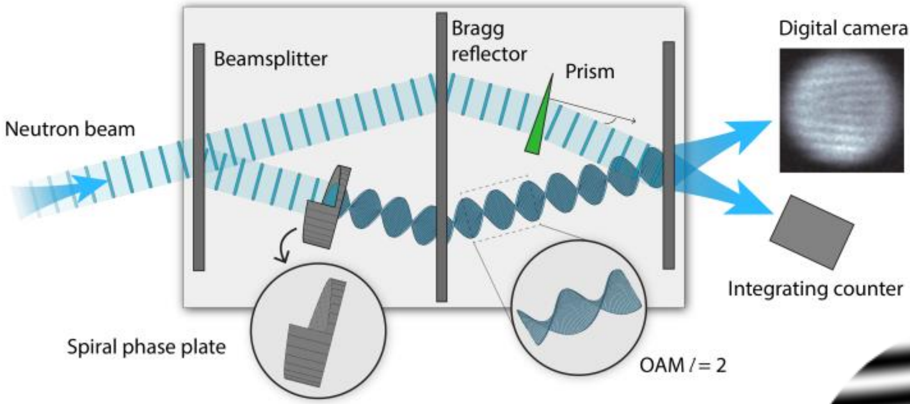
First forays in neutron holography

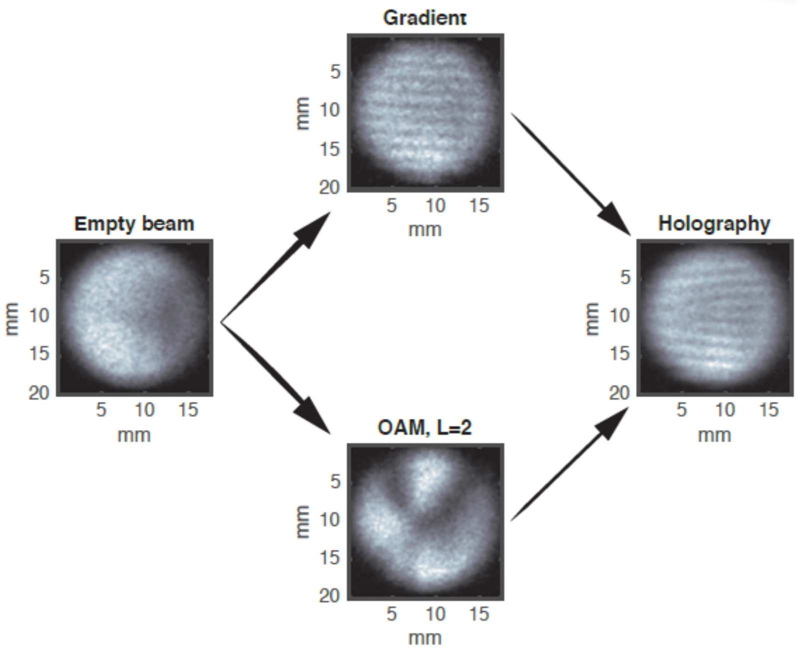
Leith and Upatnieks approach in a neutron interferometer





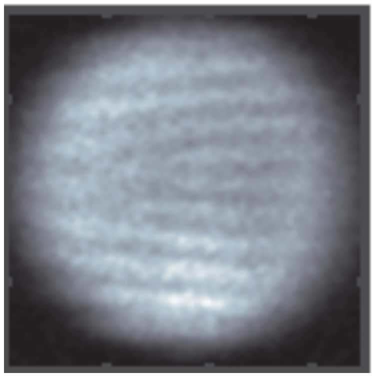
First forays in neutron holography



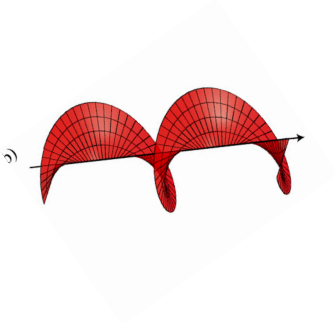


Ideal

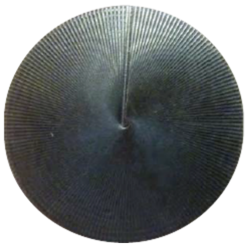
As observed



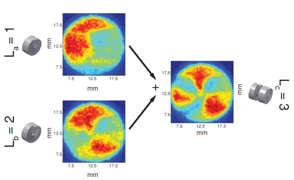
D. Sarenac, M. Arif, C. W. Clark, D. G. Cory, B. Heacock, M G. Huber, C. Shahi and D. A. Pushin, *Optics Express* (2016 in press)



First demonstration of OAM control of neutron beams



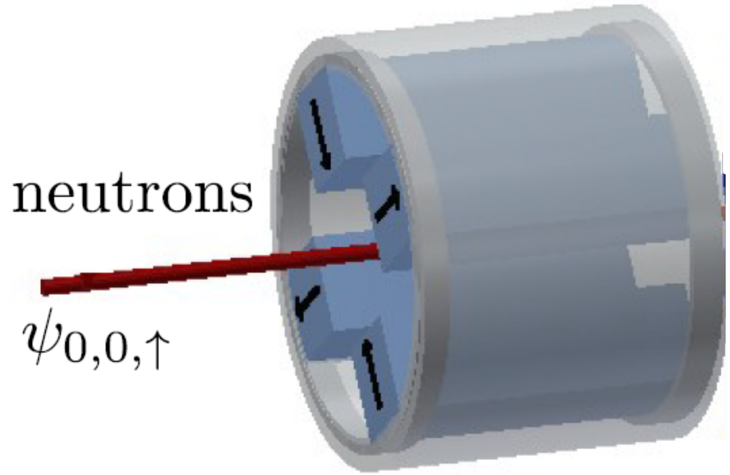
Simple macroscopic spiral phase plates possible



Demonstration of angular momentum addition and conservation of topological charge

New quantized degree of freedom for neutron-based QIP and general spatial filter for neutron beams

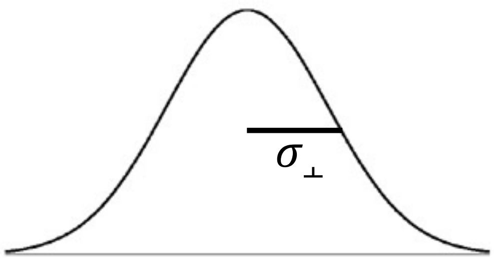
Spin Orbit States



Nsofini, J., Sarenac, D., Wood, C.J., Cory, D.G., Arif, M., Clark, C.W., Huber, M.G. and Pushin, D.A., 2016. Spin-Orbit States of Neutron Wavepackets. *Phys. Rev. A 94, 013605 – Published 13 July 2016*

Spin Orbit States of Neutron Wavepackets

Polarized Neutron Wave Packet

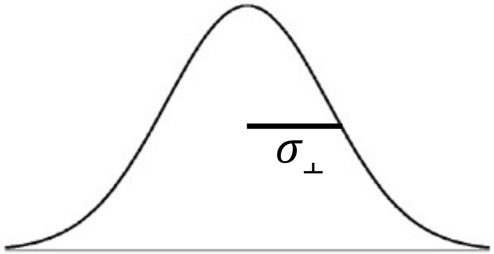


$$\Psi = R \otimes |\uparrow_z\rangle$$

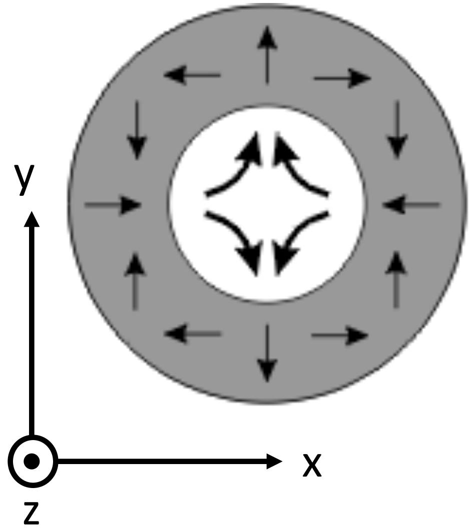
$$R = (2\pi\sigma_{\perp}^2)^{-1/2} e^{-r^2/(4\sigma_{\perp}^2)}$$

Spin Orbit States of Neutron Wavepackets

Polarized Neutron Wave Packet



Quadrupole Magnet



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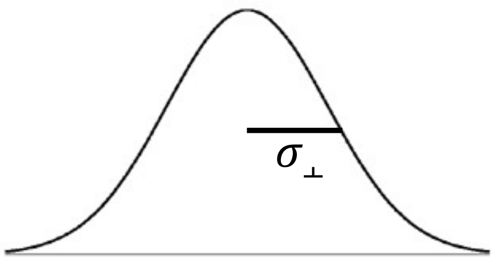
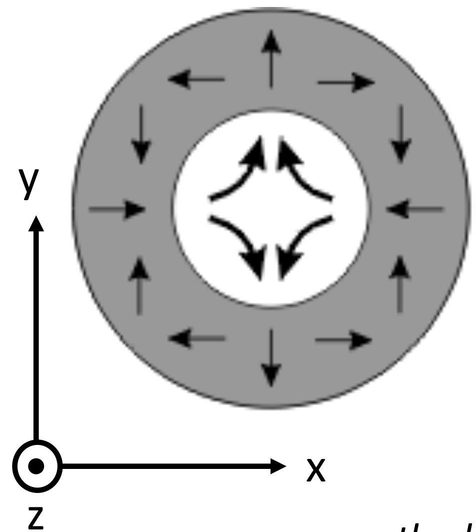
$$R = (2\pi\sigma_\perp^2)^{-1/2} e^{-r^2/(4\sigma_\perp^2)}$$

Spin Orbit States of Neutron Wavepackets

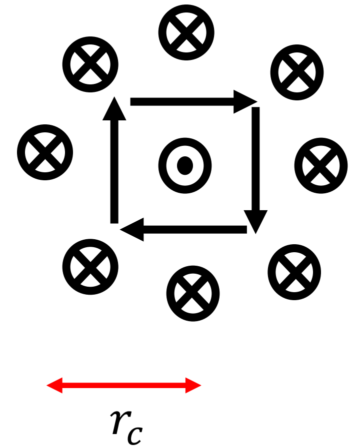
Polarized Neutron Wave Packet



Quadrupole Magnet



Spin Orbit State



the length at which there is a spin flip

$$\Psi = R \otimes |\uparrow_z\rangle$$

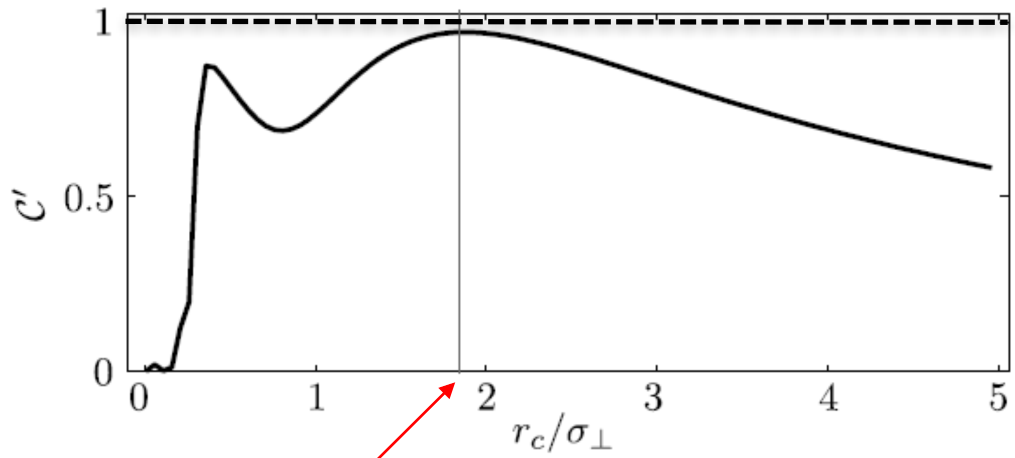
$$R = (2\pi\sigma_\perp^2)^{-1/2} e^{-r^2/(4\sigma_\perp^2)}$$

$$\Psi = R \otimes (a|\uparrow_z\rangle + ibe^{i\varphi}|\downarrow_z\rangle)$$

$$a = cos\left(\frac{\pi r}{2r_c}\right)$$

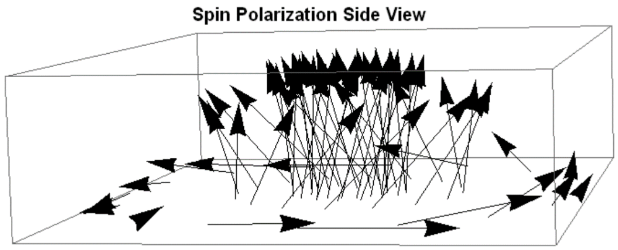
$$b = sin\left(\frac{\pi r}{2r_c}\right)$$

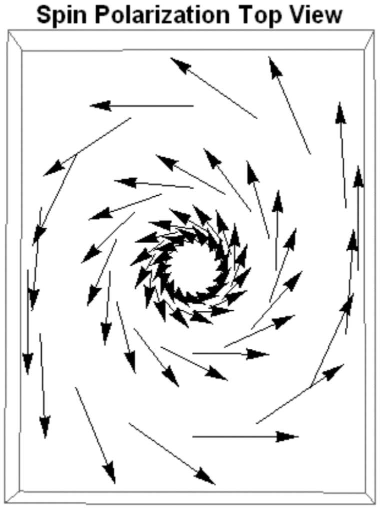
Concurrence



Entanglement maximized at $r_c/\sigma_\perp$=1.82

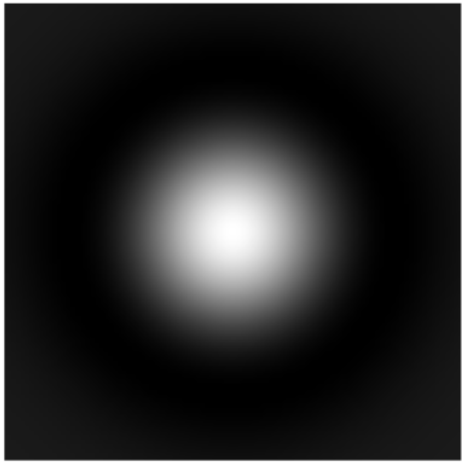
Polarization relatable to helical structures such as skyrmions



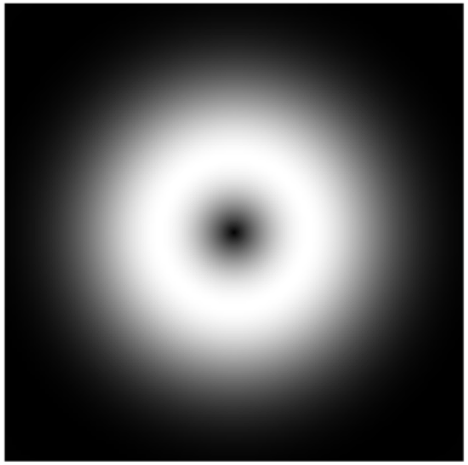


Intensity Profiles

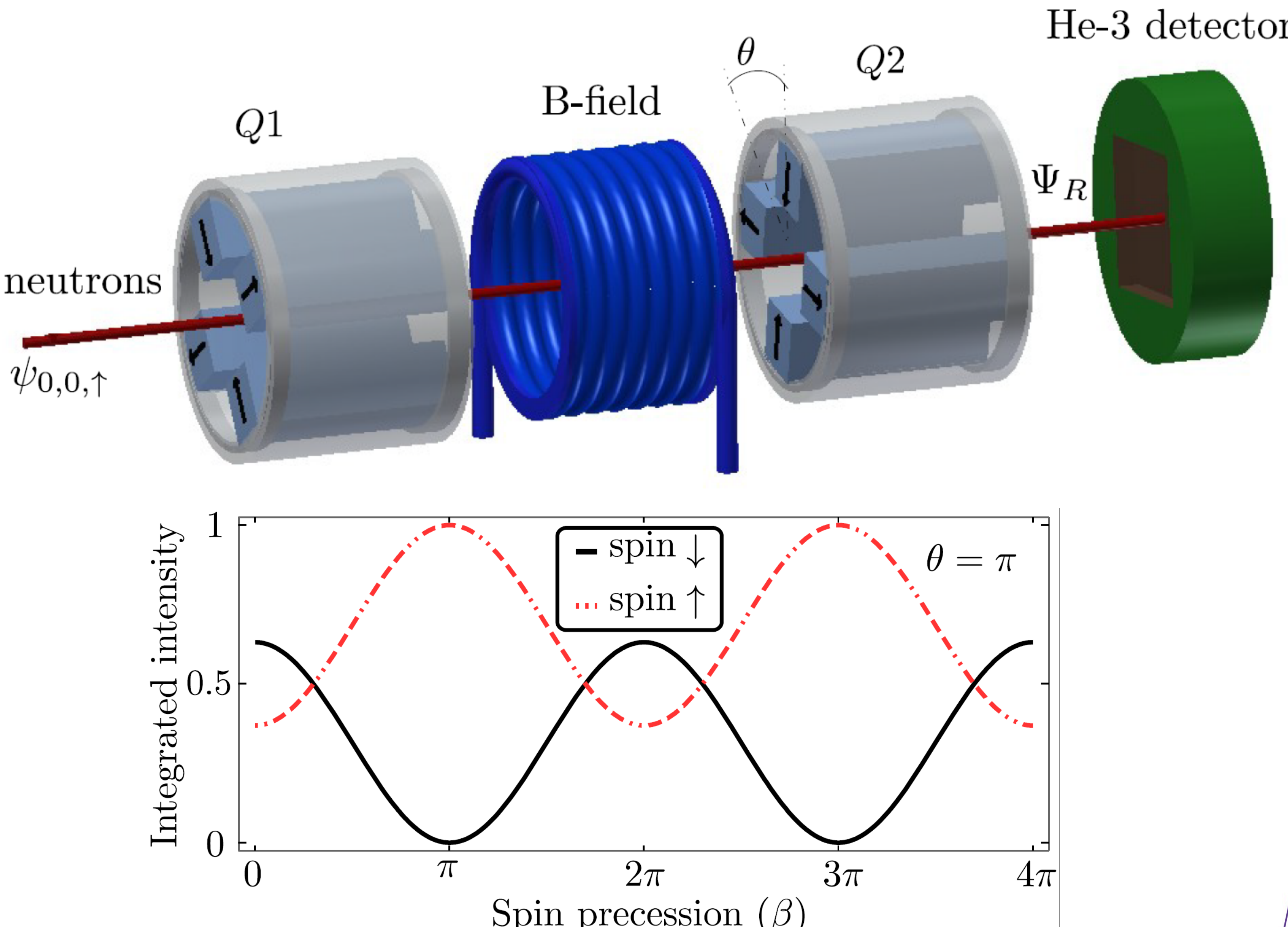
$|\uparrow_z\rangle$



$|\downarrow_z\rangle$



Coherent control over the SO state



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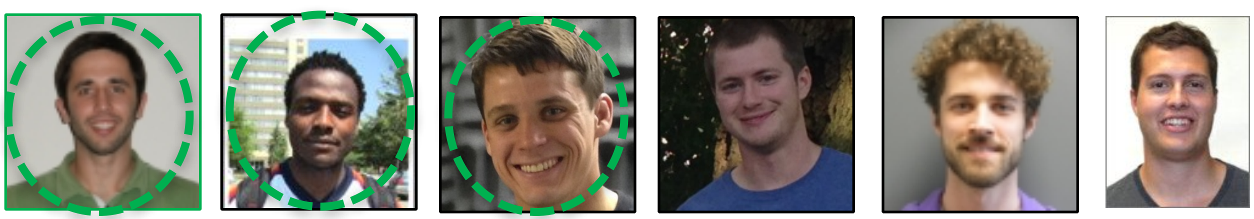
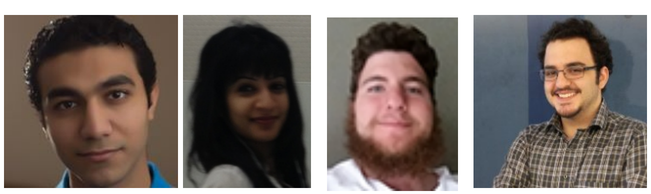

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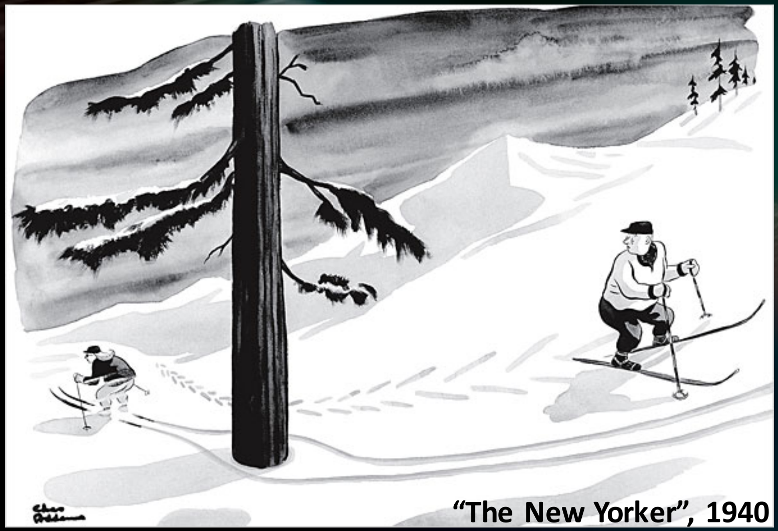
Thank you

Check your system before…



Quantum

Classical


"Tractricious"
Robert R. Wilson
A "spiral" defined
by straight rays
Fermi National
Accelerator Laboratory
Image: Fermilab


"Tractricious"
Seen from within,
Looking up
Richard C. Drew
RickDrew.com