Structured Neutron Waves

Dmitry Pushin

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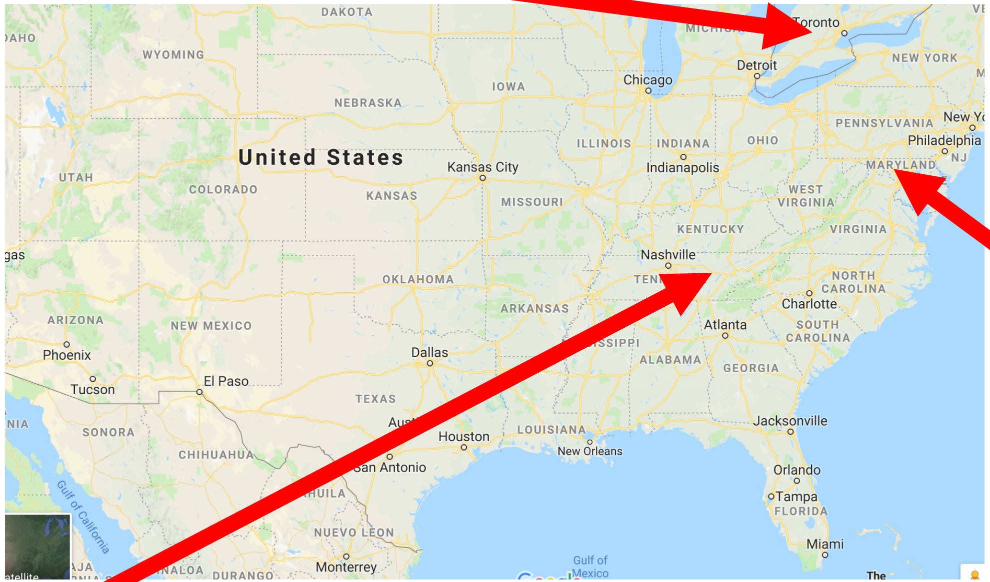
Waterloo, Ontario, Canada

Latitude:

London N51.5072°
Munich N48.1351°
Monaco N43.7389°
Waterloo N43.7102°
Cannes N43.5528°

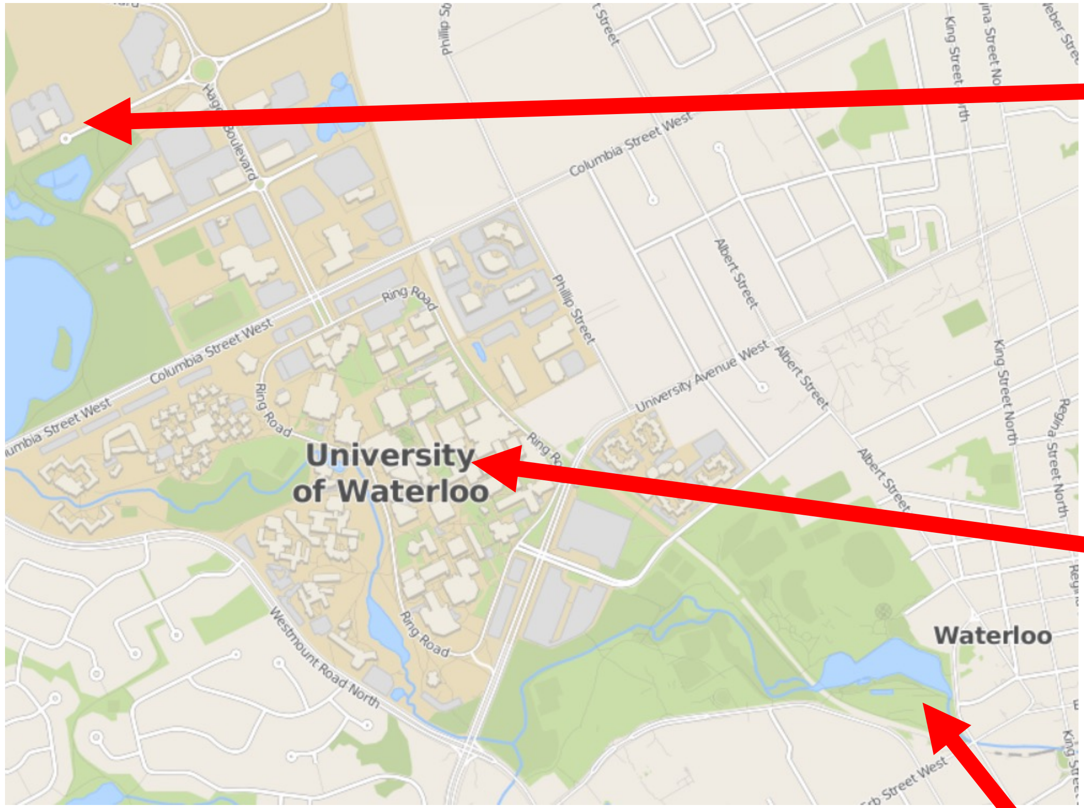
-David Cory
-Ivar Taminau
-Melissa Henderson
-Austin Woolverton
-Joachim Nsofini
-Dusan Sarenac
-Huseyin Ekinci
-Connor Kapahi
-Olivier Nahman-Lévesque



OAK RIDGE
National Laboratory
-Lisa Debeer-Schmitt

NIST
-Michael Huber
-Ben Heacock
-Shannon Hoogerheide
-Charles Clark
-Chandra Shahi
-Tom Gentile
-Wangchun Chen

University of Waterloo Campus



Our Lab

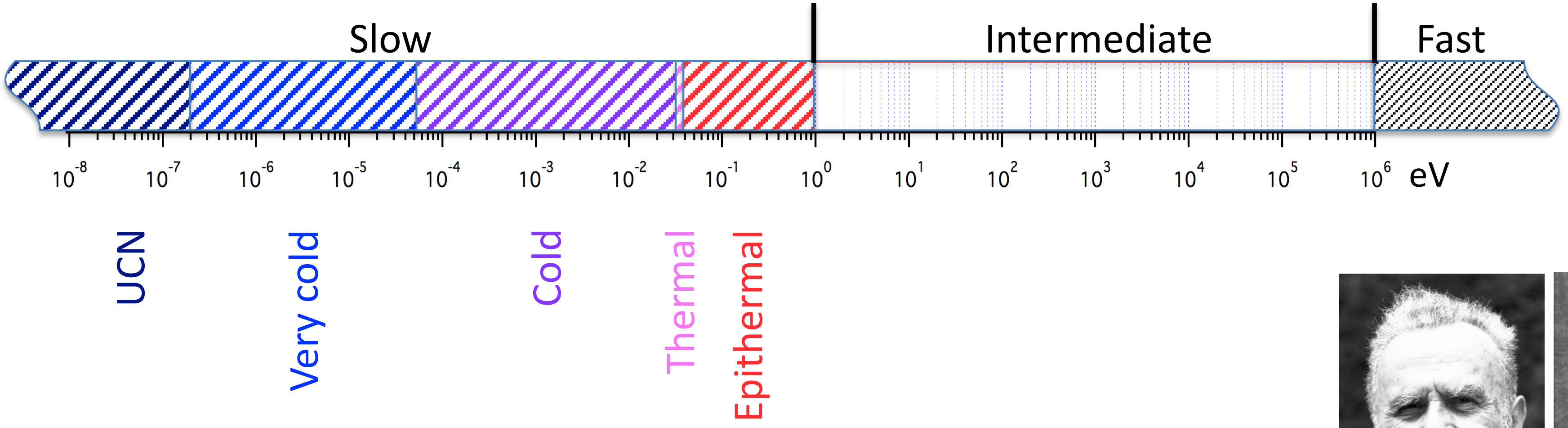
IQC QNC

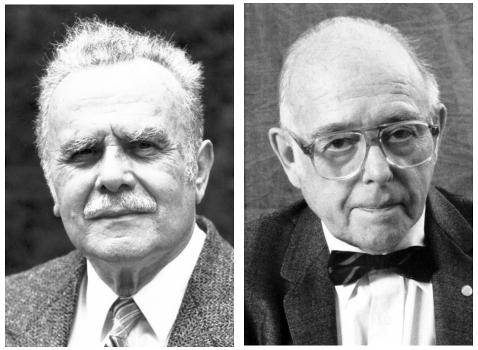
Mike Lazaridis

Perimeter Institute

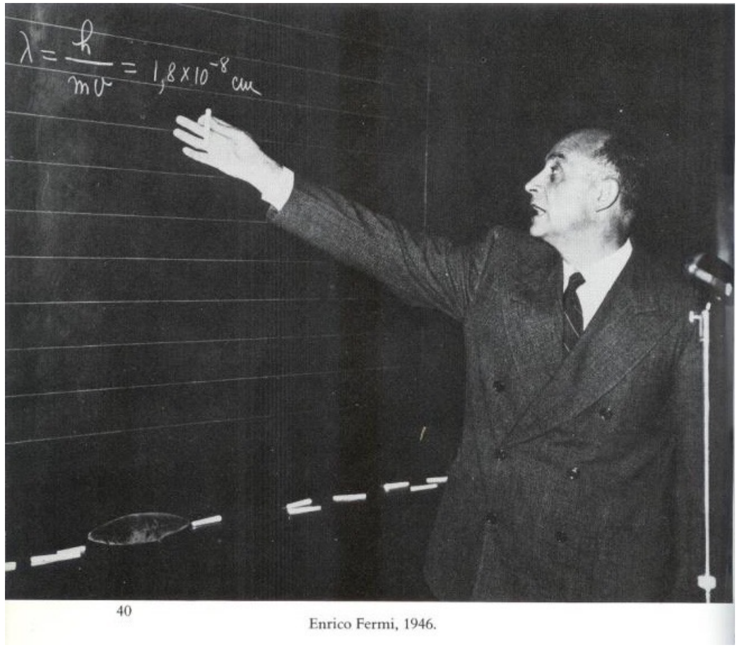
1935, nobelprize.org

Neutron spectrum



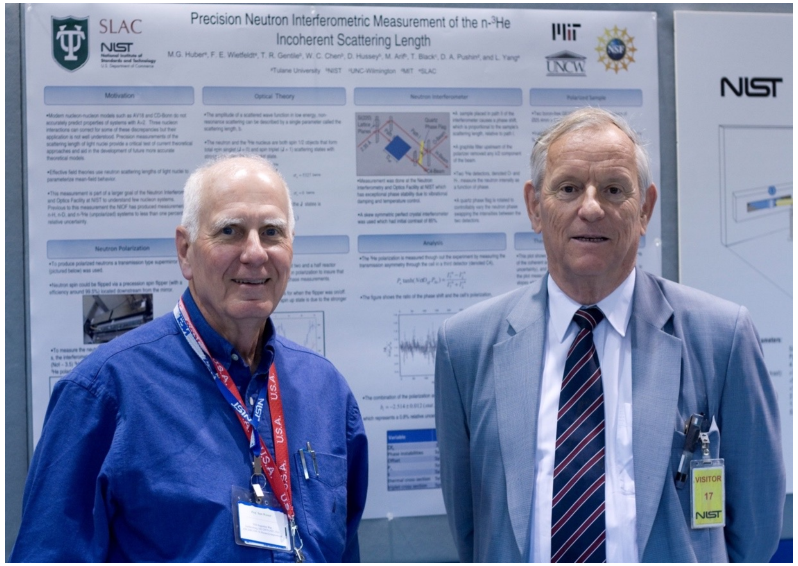


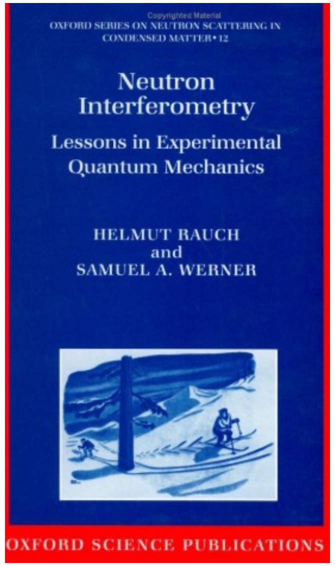
1994, nobelprize.org



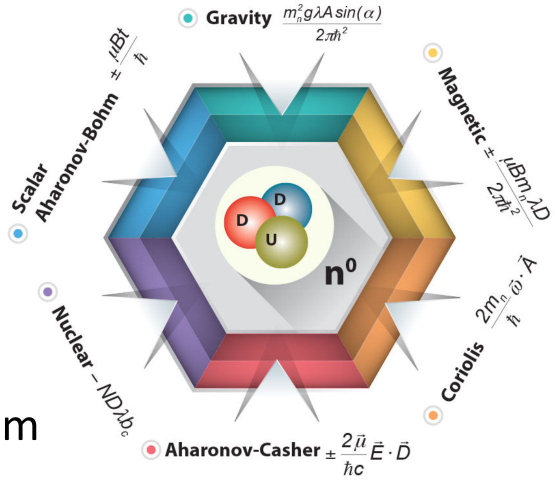
Rule of twos:

- Energy of 20 meV
- Wavelength of 2 Å
- Speed of 2000 m/s

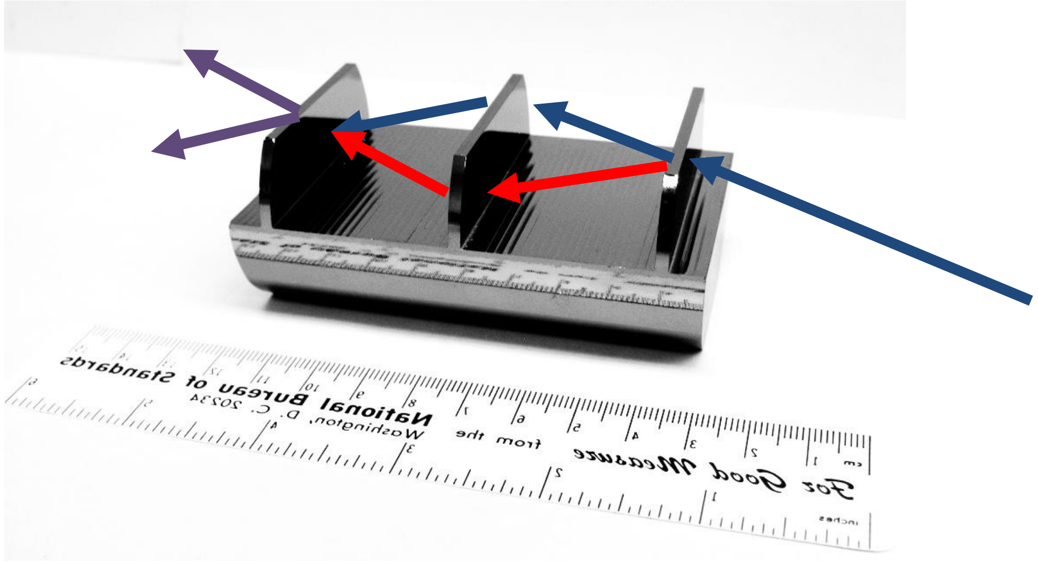


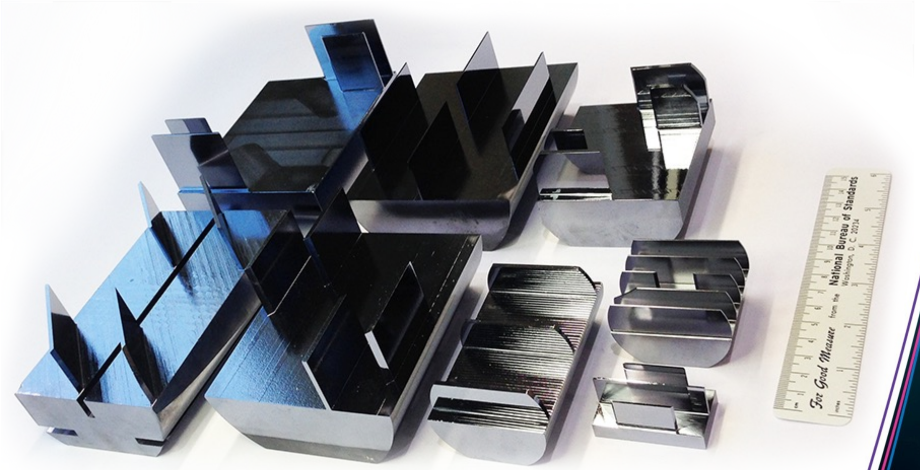


- Gravity
- Magnetic
- Coriolis
- Aharonov-Casher
- Nuclear
- Scalar Aharonov-Bohm

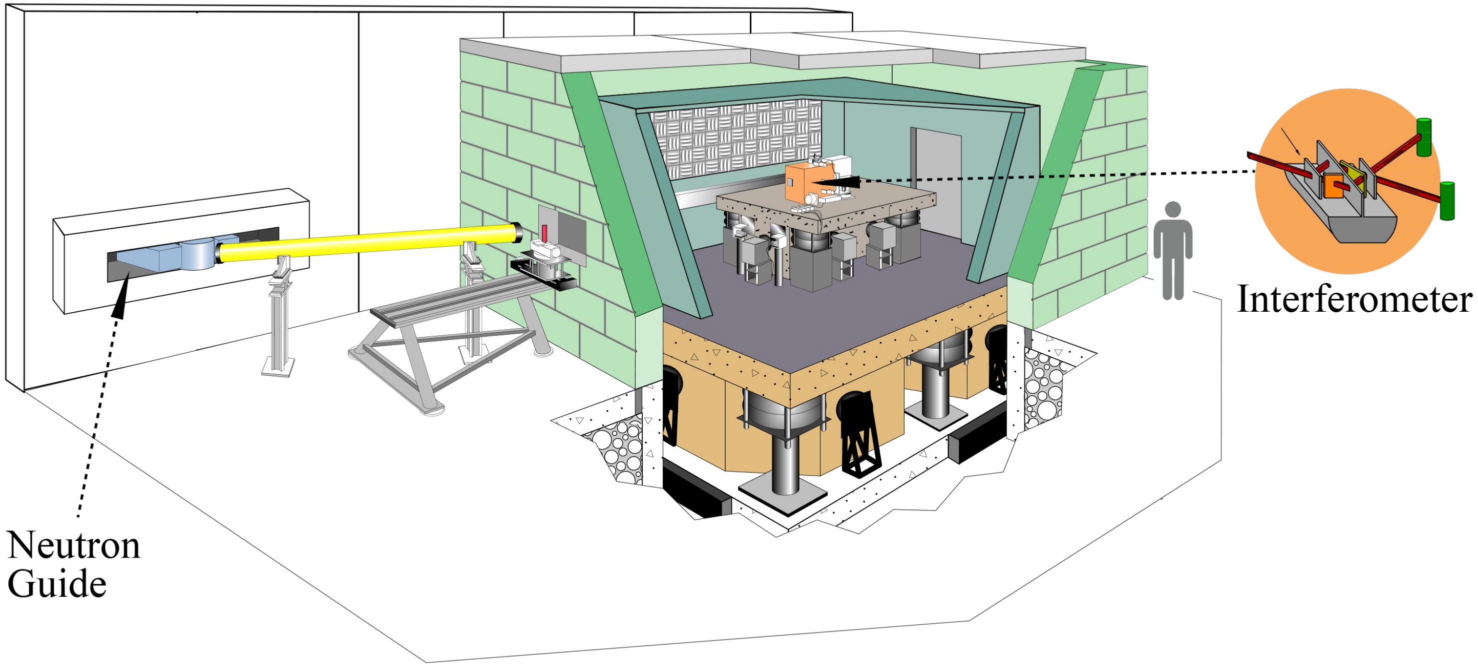


Neutron Interferometer





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

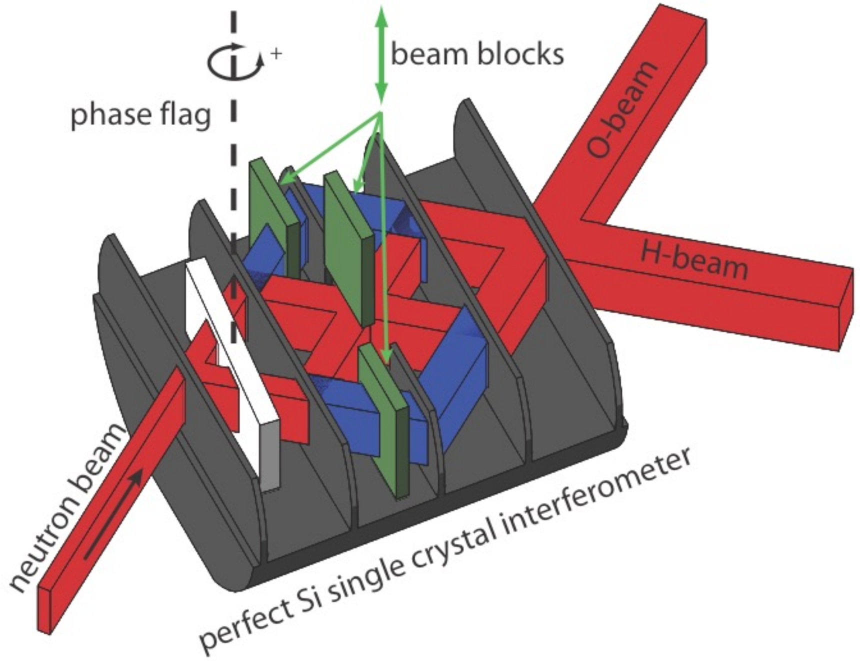
PRL 107, 150401 (2011) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2011

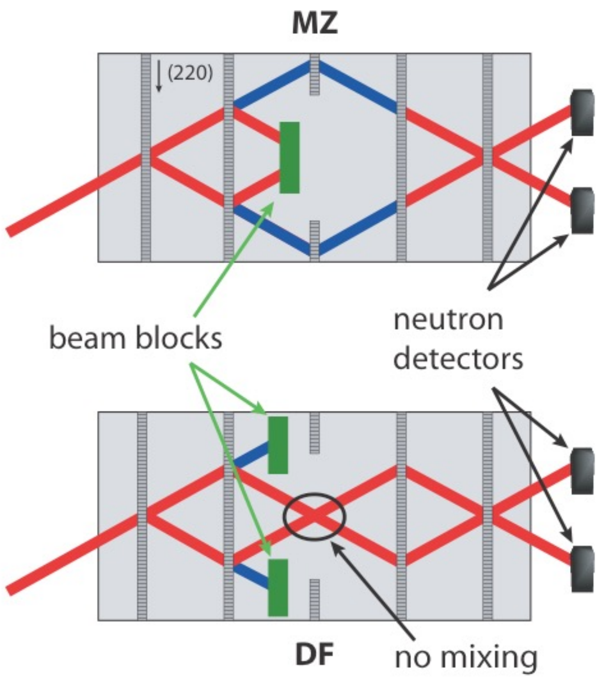
Experimental Realization of Decoherence-Free Subspace in Neutron Interferometry

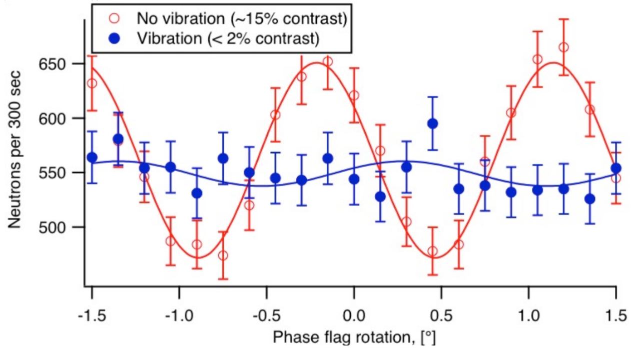
D. A. Pushin,[1,*] M. G. Huber,[2] M. Arif,[2] and D. G. Cory[1,3,4]

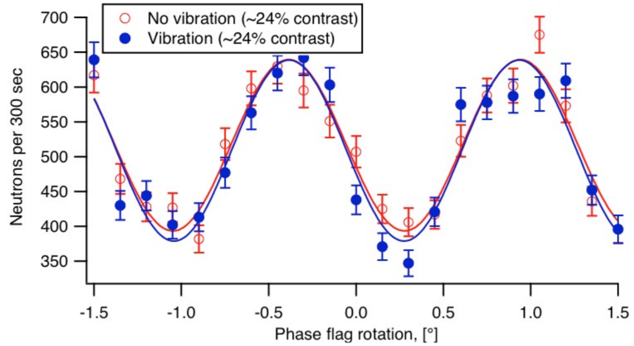
3+4=5?!

3 blade setup



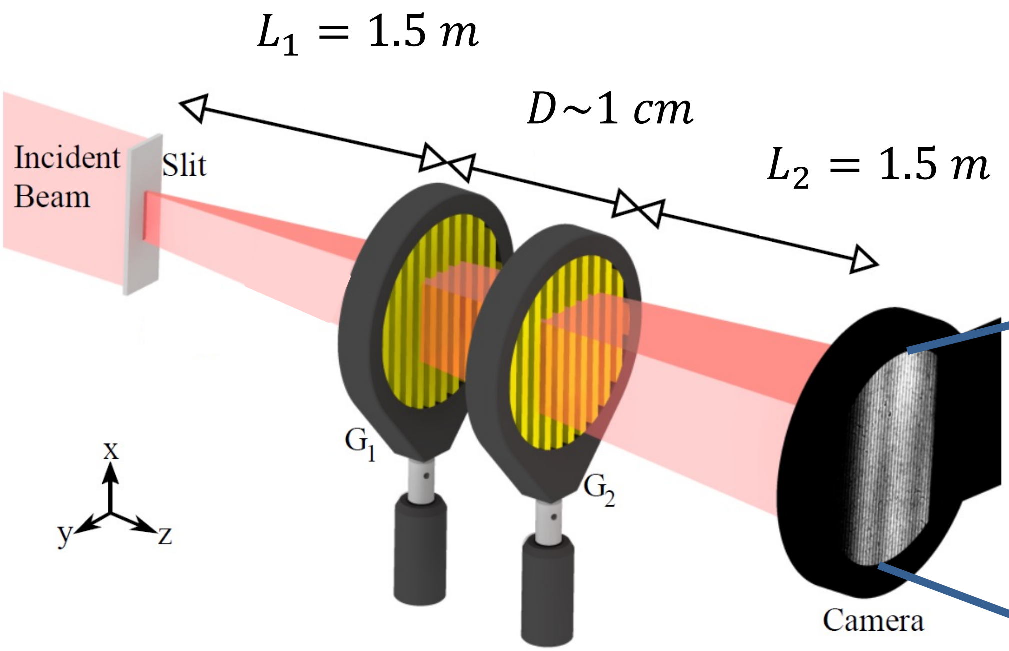




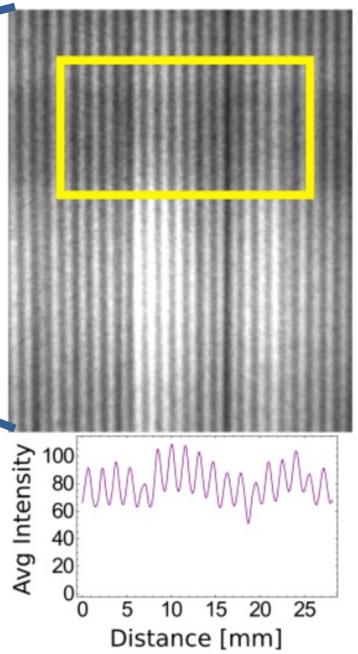


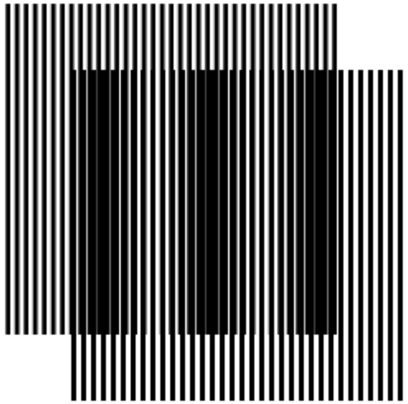
4 blade setup

Two phase-grating moiré NI



$$\lambda_d = \frac{L\lambda_G}{D}$$





By Emin Gabrielyan / Gabrielyan at en.wikipedia

Transverse coherence length at the grating: $\sigma = \frac{\lambda L_1}{s_w} \geqslant \lambda_G$

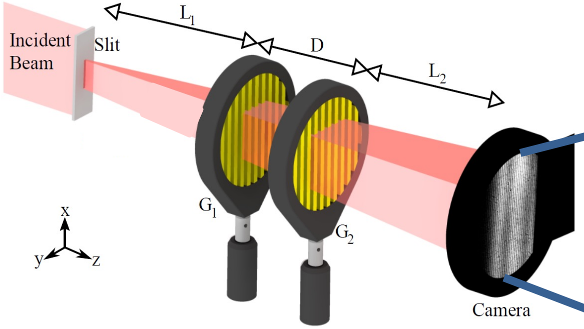
Both gratings: $\lambda_G = 2.4\ \mu m$ and $\varphi = \pi/2$

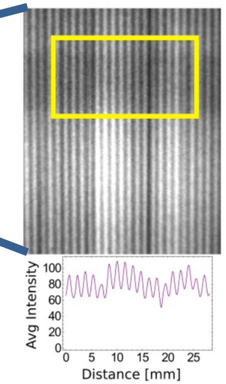
$$I = A + B\cos(2\pi f y + \varphi)$$

Pushin DA, Sarenac D, Hussey DS, Miao H, Arif M, Cory DG, Huber MG, Jacobson DL, LaManna JM, Parker JD, Shinohara T. Far-field interference of a neutron white beam and the applications to noninvasive phase-contrast imaging. Physical Review A. 2017 Apr 26;95(4):043637.

What we have so far

$$\lambda_d = \frac{L\lambda_G}{D}$$





PHYSICAL REVIEW A **95**, 043637 (2017)

Far-field interference of a neutron white beam and the applications to noninvasive phase-contrast imaging

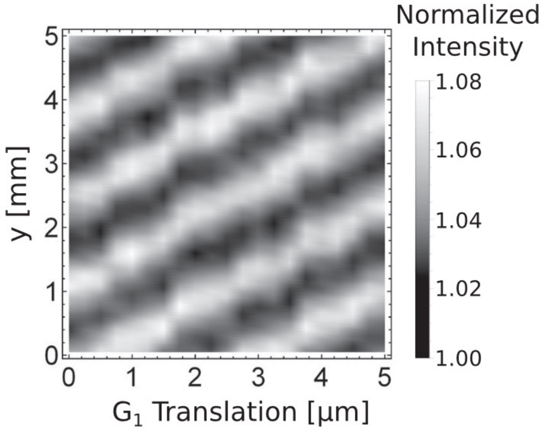
D. A. Pushin,[1,2,*] D. Sarenac,[1,2] D. S. Hussey,[3] H. Miao,[4] M. Arif,[3] D. G. Cory,[2,5,6,7] M. G. Huber,[3] D. L. Jacobson,[3] J. M. LaManna,[3] J. D. Parker,[8] T. Shinohara,[9] W. Ueno,[9] and H. Wen[4]

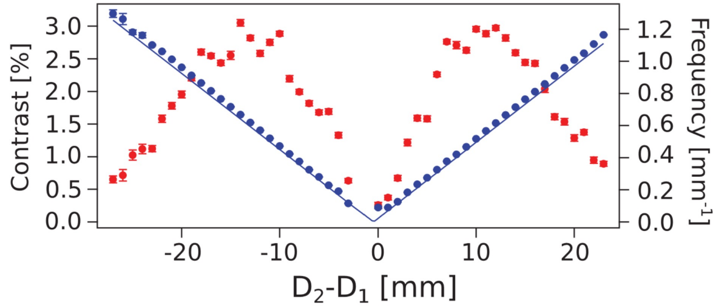
PHYSICAL REVIEW LETTERS **120,** 113201 (2018)

Editors' Suggestion | Featured in Physics

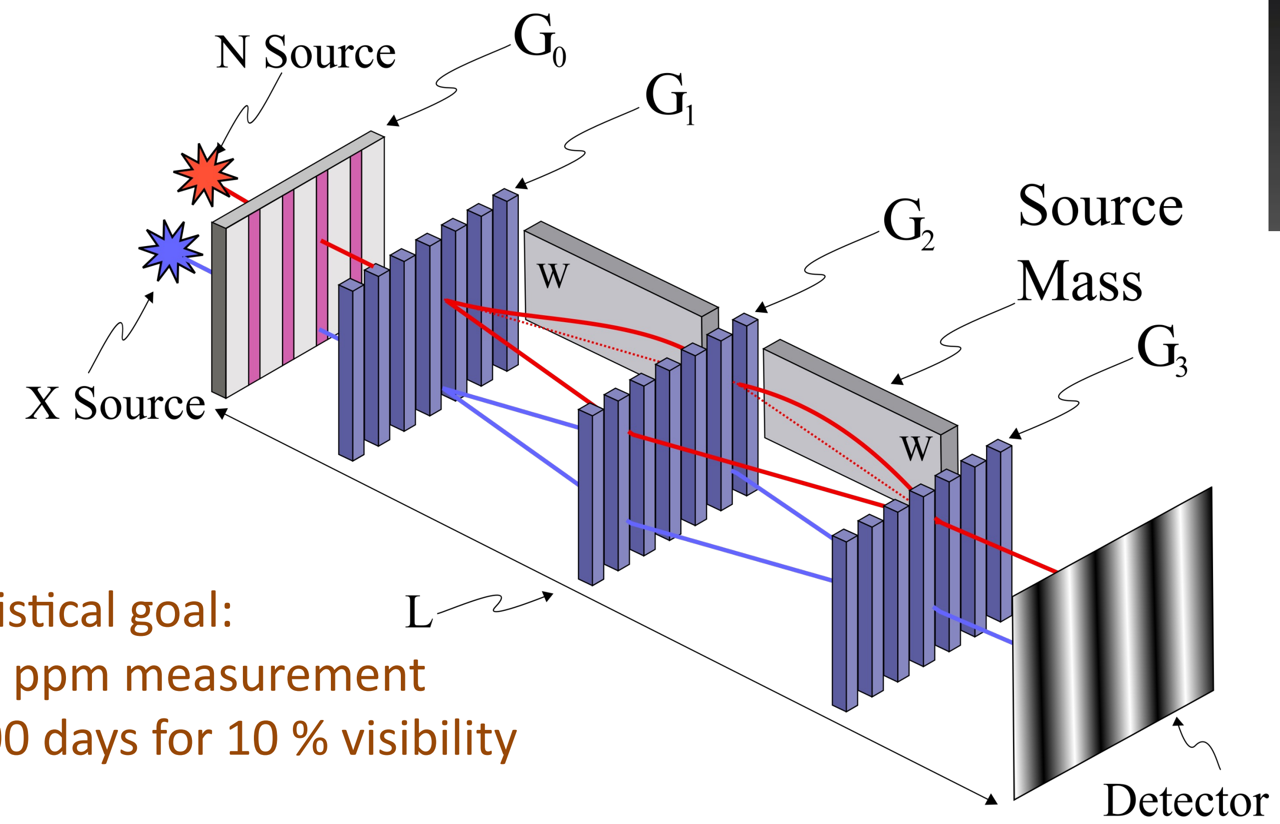
Three Phase-Grating Moiré Neutron Interferometer for Large Interferometer Area Applications

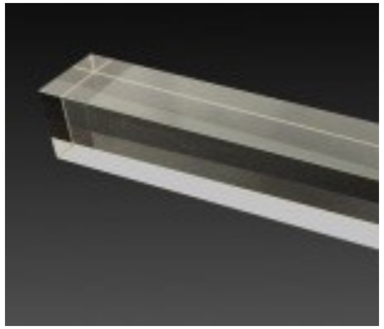
D. Sarenac,[1,2,*] D. A. Pushin,[1,2,†] M. G. Huber,[3] D. S. Hussey,[3] H. Miao,[4] M. Arif,[3] D. G. Cory,[2,5,6,7] A. D. Cronin,[8] B. Heacock,[9,10] D. L. Jacobson,[3] J. M. LaManna,[3] and H. Wen[4]





Measuring Small Forces with **Neutron Interferometric Microscopy**: *A wholly unique and novel paradigm for Big-G*

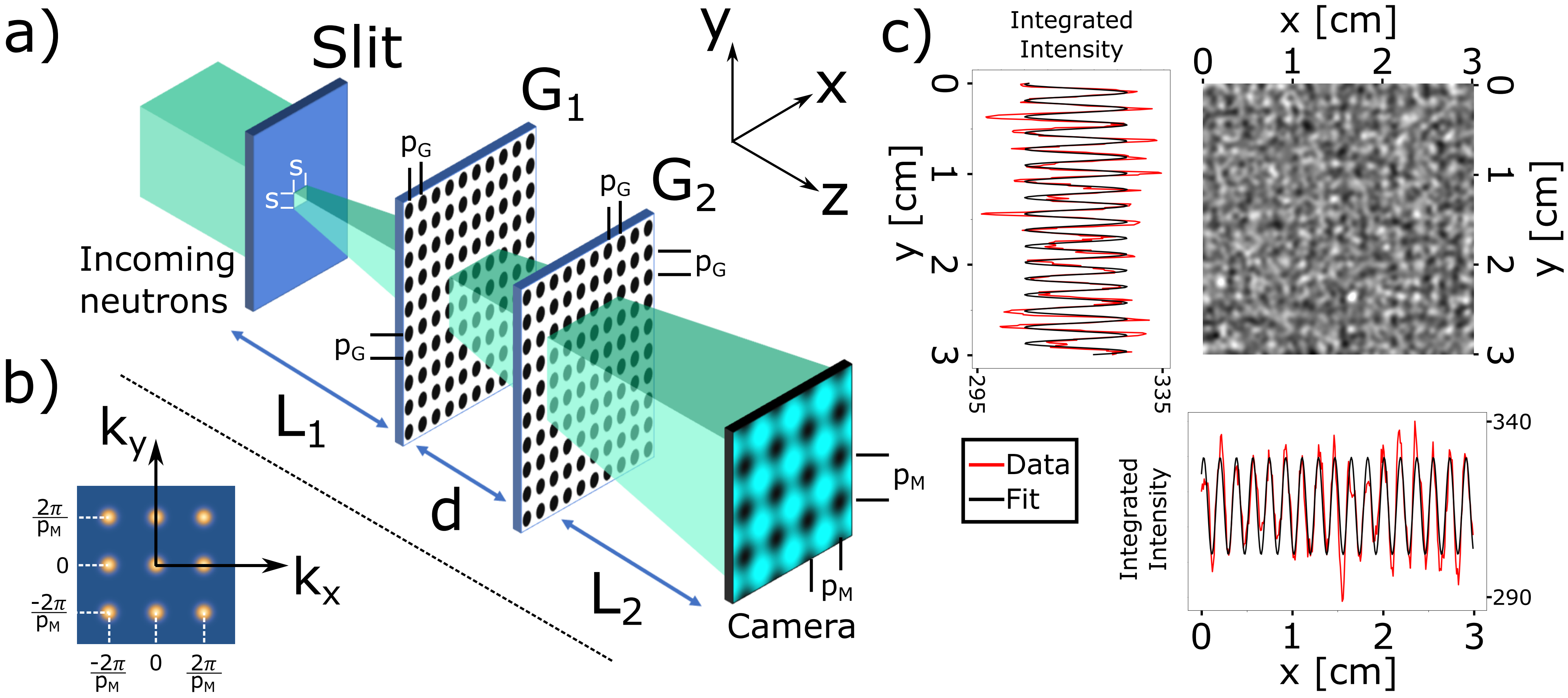




Lead Tungstate

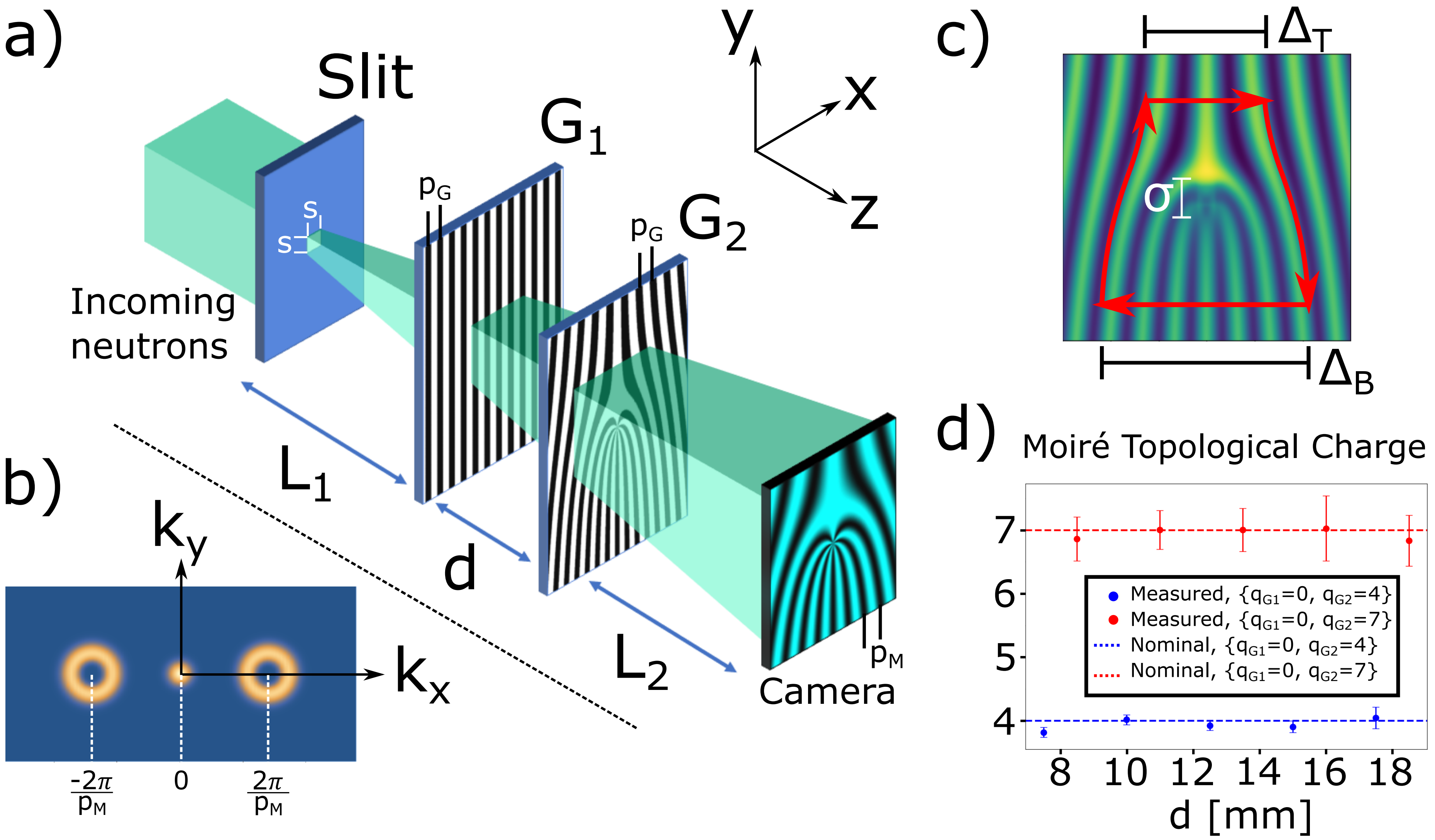
Statistical goal:
10 ppm measurement
~100 days for 10 % visibility

2d– grating interferometry



D. Sarenac, et. al. “Phase and contrast moiré signatures in two-dimensional cone beam interferometry”, arXiv:2311.02261

2d– grating interferometry



D. Sarenac, et. al. "Phase and contrast moiré signatures in two-dimensional cone beam interferometry", arXiv:2311.02261

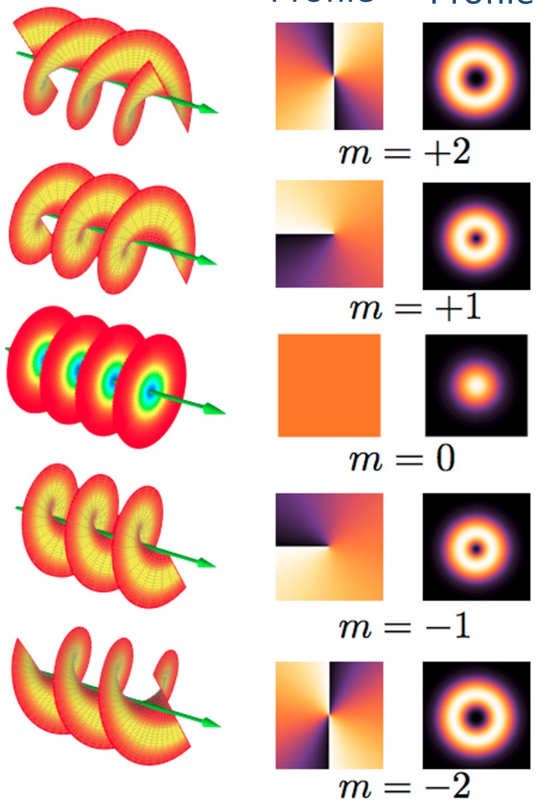
Structured Light and OAM

Phase Profile | Intensity Profile

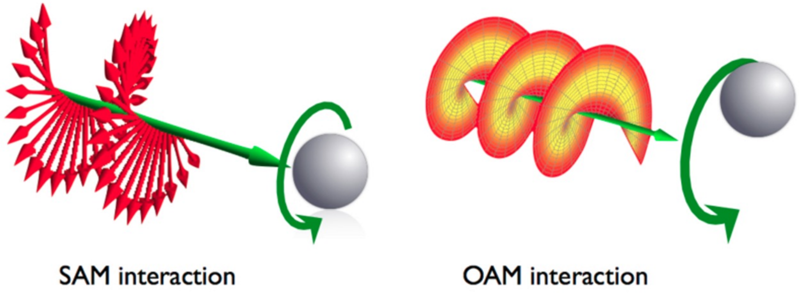
Helical Waves

Plane Wave

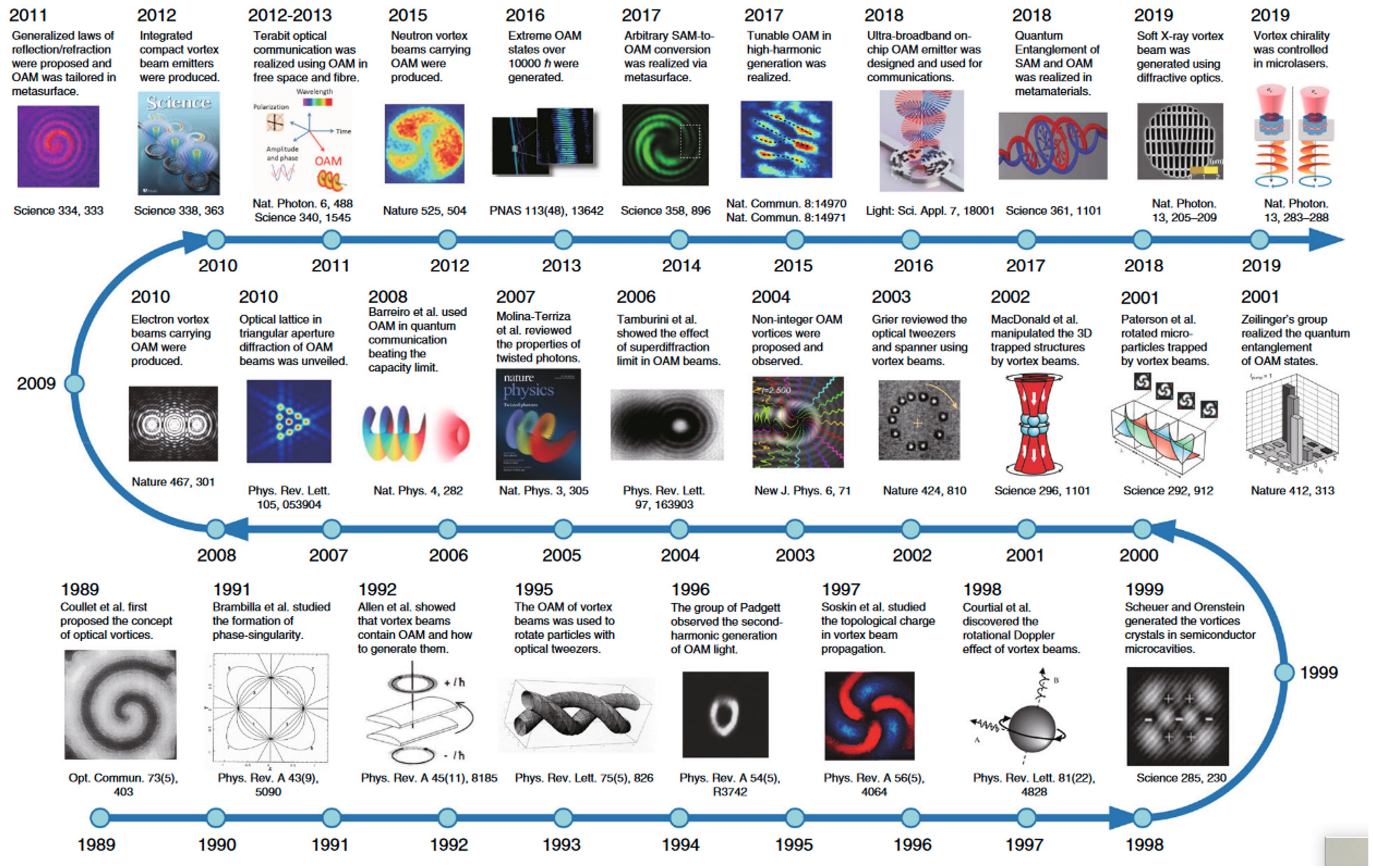
Helical Waves



OAM Transfer



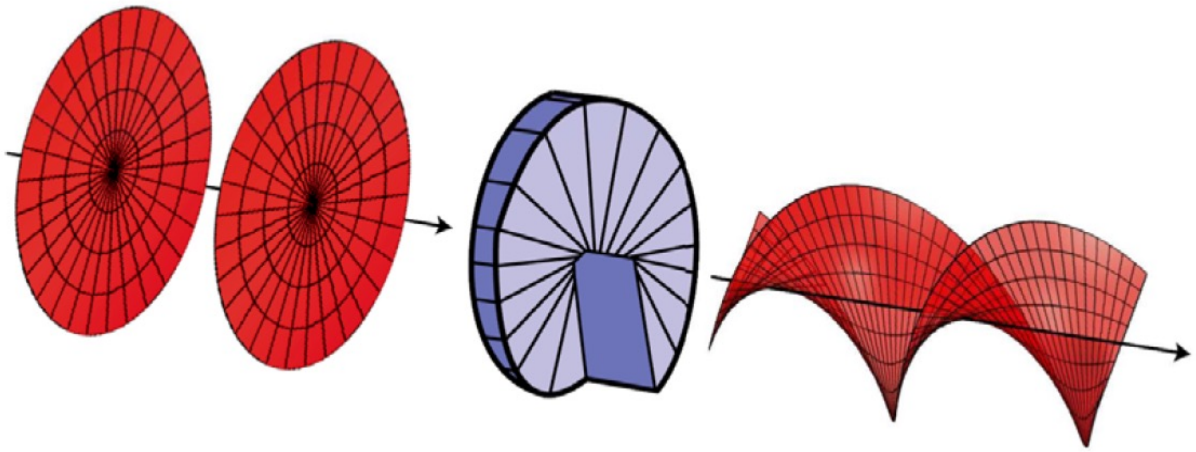
https://en.wikipedia.org/wiki/Orbital_angular_momentum_of_light



Shen et al. Light: Science & Applications (2019)8:90

How to generate such modes?

Plane Wave
$|\psi_{in}\rangle = e^{ikz}$



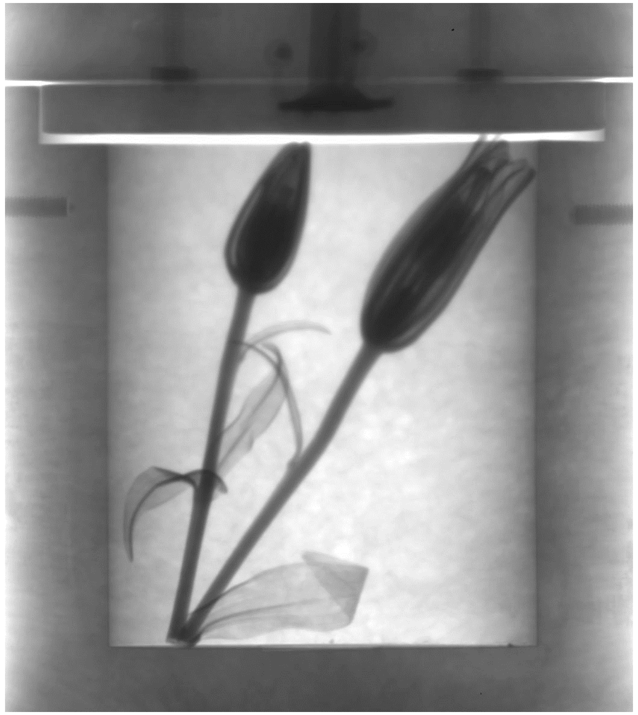
Helical Wave
$|\psi_{SPP}\rangle = e^{i\ell\varphi}e^{ik_z z}$

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

Imaging with Neutrons

The fine details of the water concentration in these lilies are clear to neutrons even in a lead cask

Ordinary photography

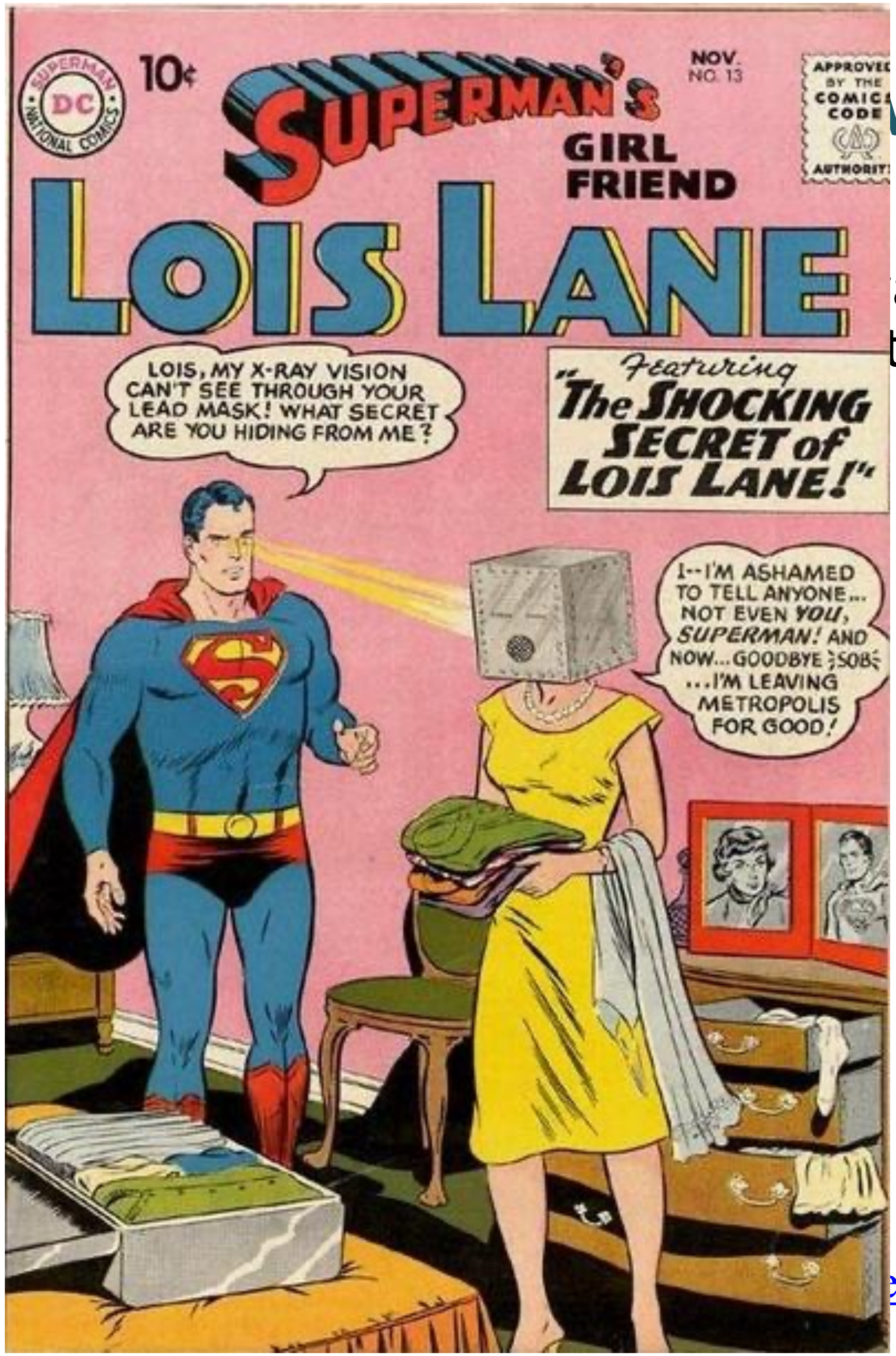


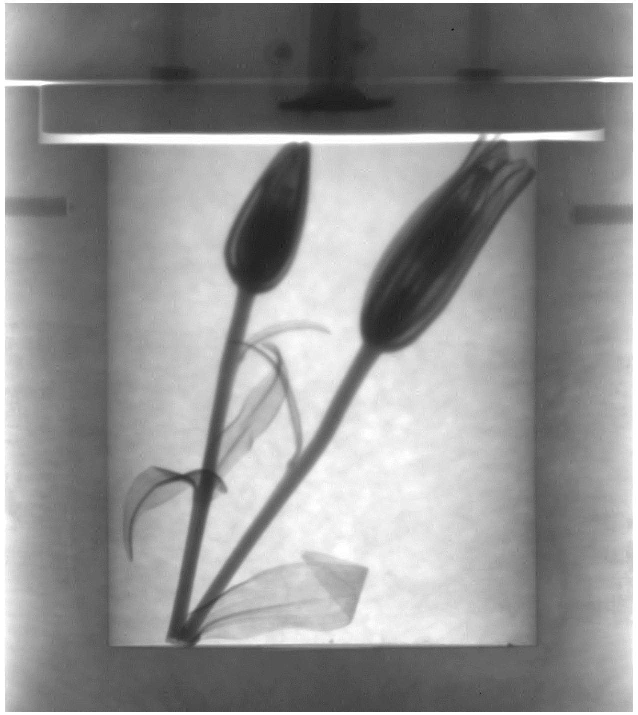
Neutron radiography

Hussey, NIST

with Neutrons

ater concentration in these lilies
trons even in a lead cask

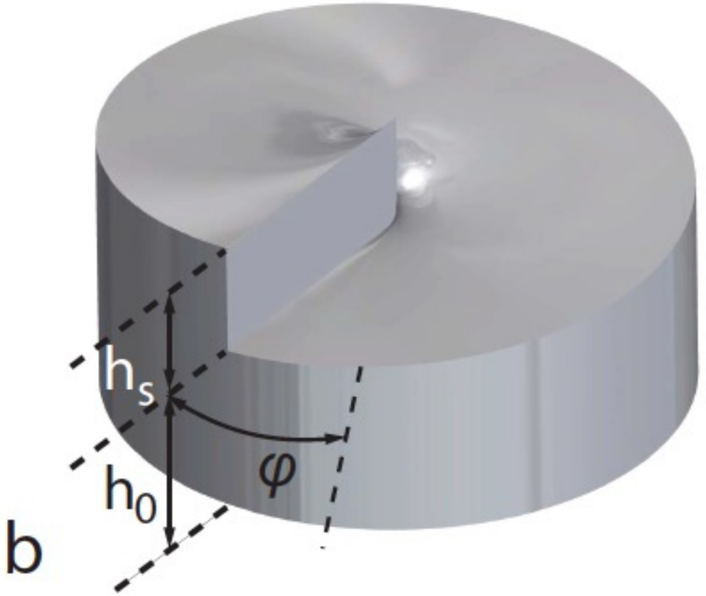




ey, NIST

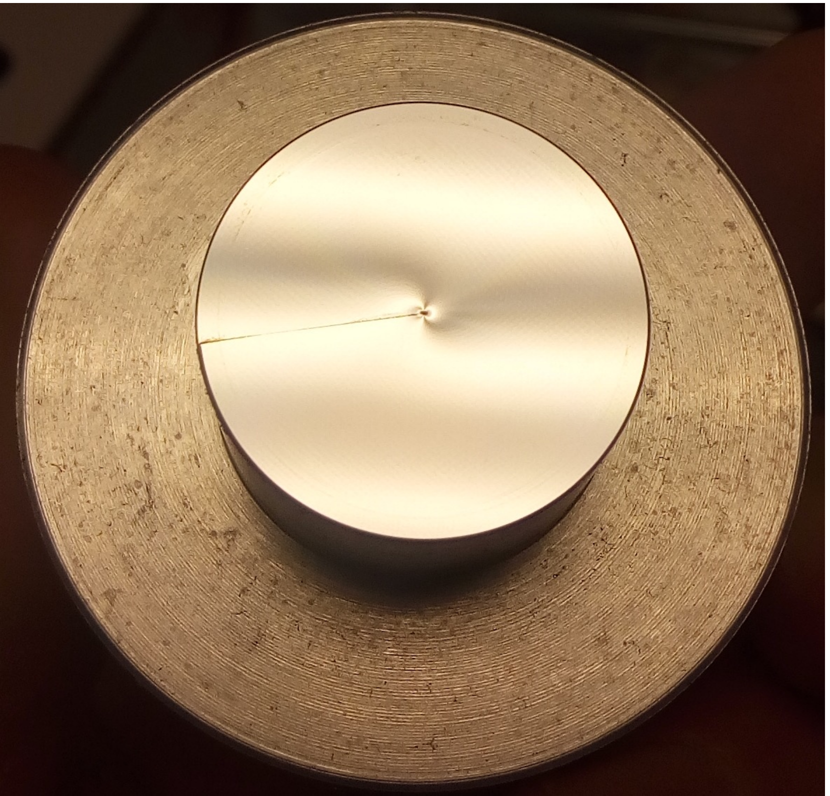
Neutron radiography

Aluminum spiral phase plates for neutrons



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

Phase of wavefunction increases linearly with azimuthal angle φ.



SPPs as seen from above, 25 mm diameter respectively.
Milled from Al 6061 dowel by diamond turning.

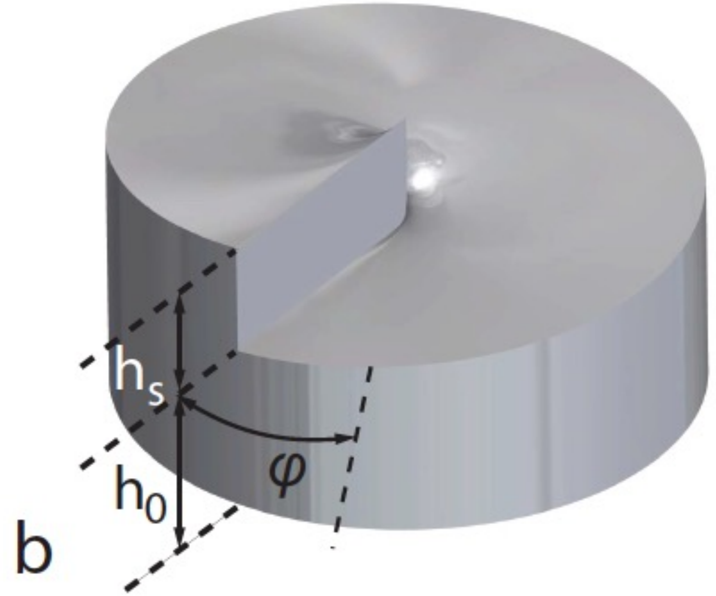
h_s = 112 μ per 2π phase step.

Index of refraction $n = 1 - 2.43 \times 10^{-6}$

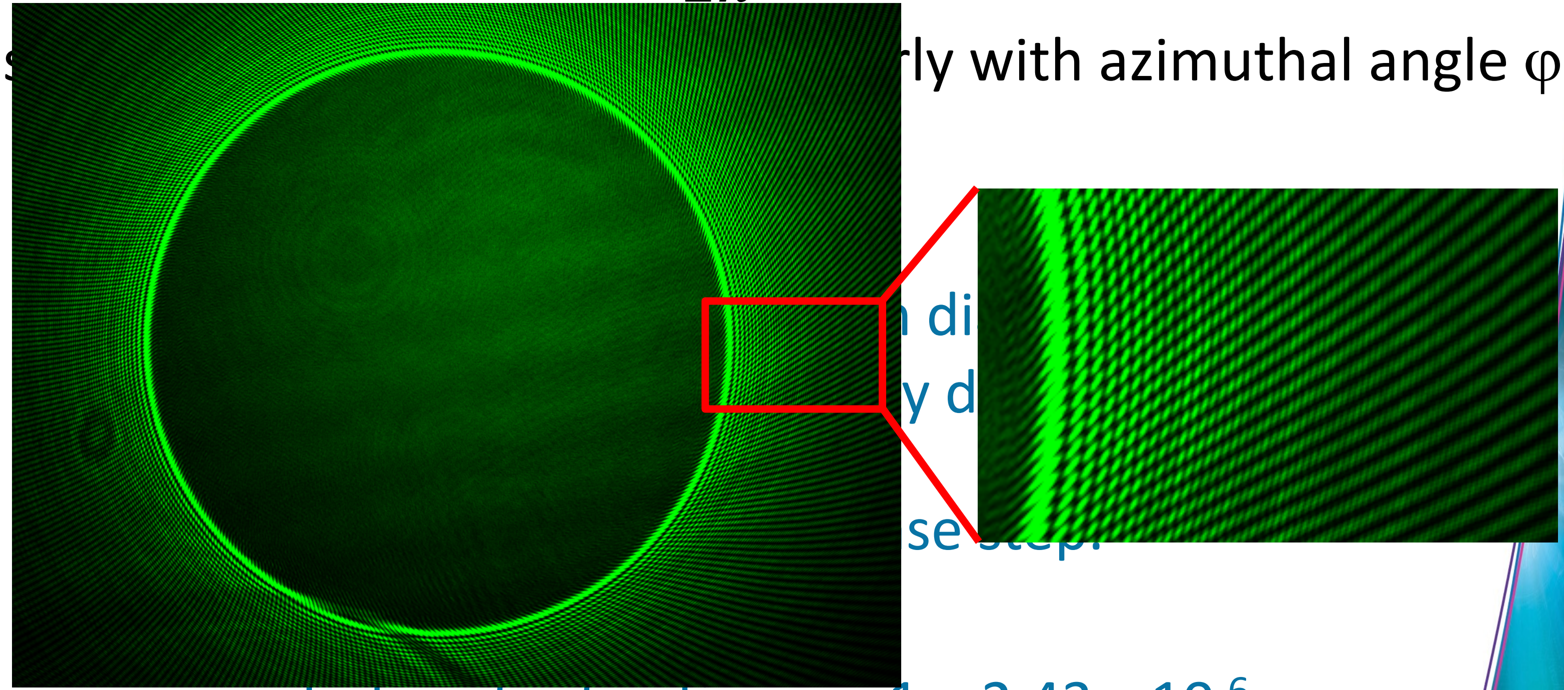
Control phase of λ =0.271 nm wave motion with 0.1 mm dimensional figure!

Aluminum spiral phase plates for neutrons

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

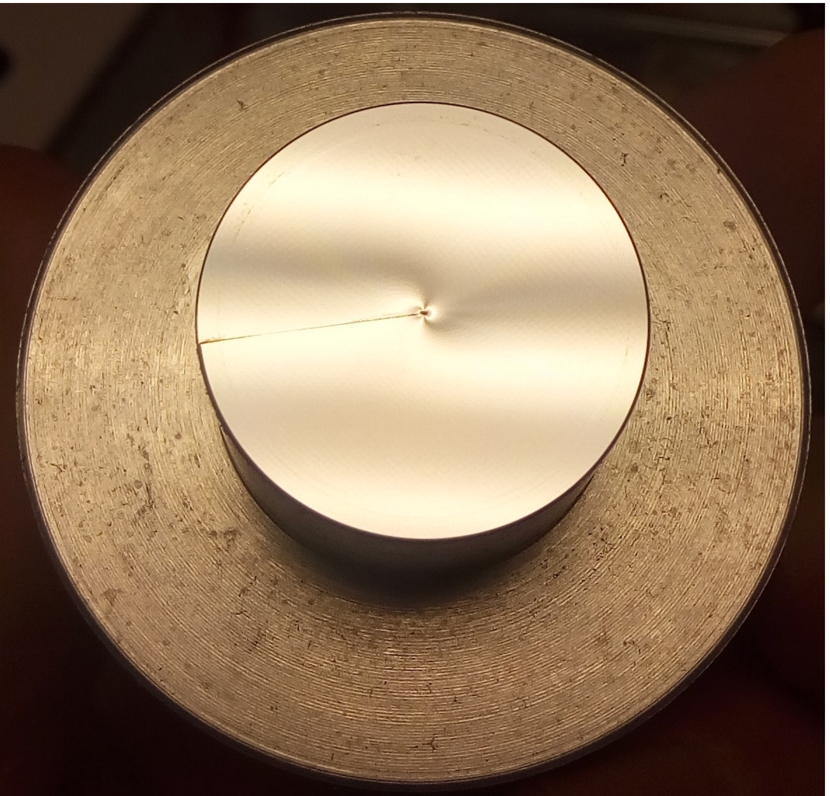


Phas... rly with azimuthal angle φ.



...di
...y d
...se step.

Index of refraction $n = 1 - 2.43 \times 10^{-6}$



Control phase of λ =0.271 nm wave motion with 0.1 mm dimensional figure!

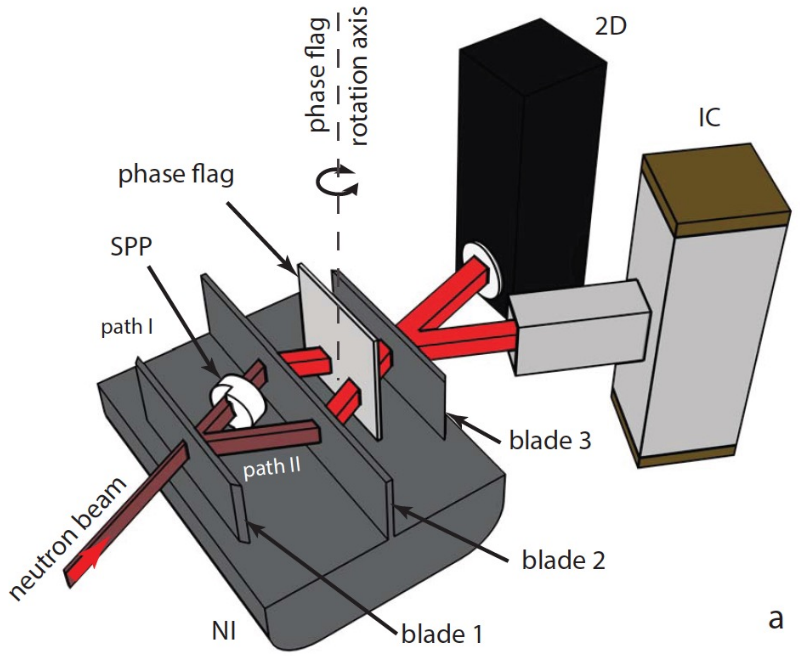
nature
International journal of science

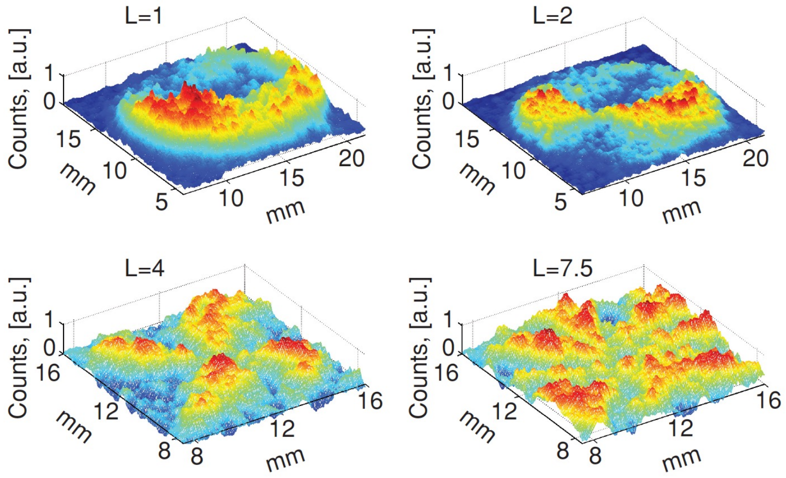
Letter | Published: 23 September 2015

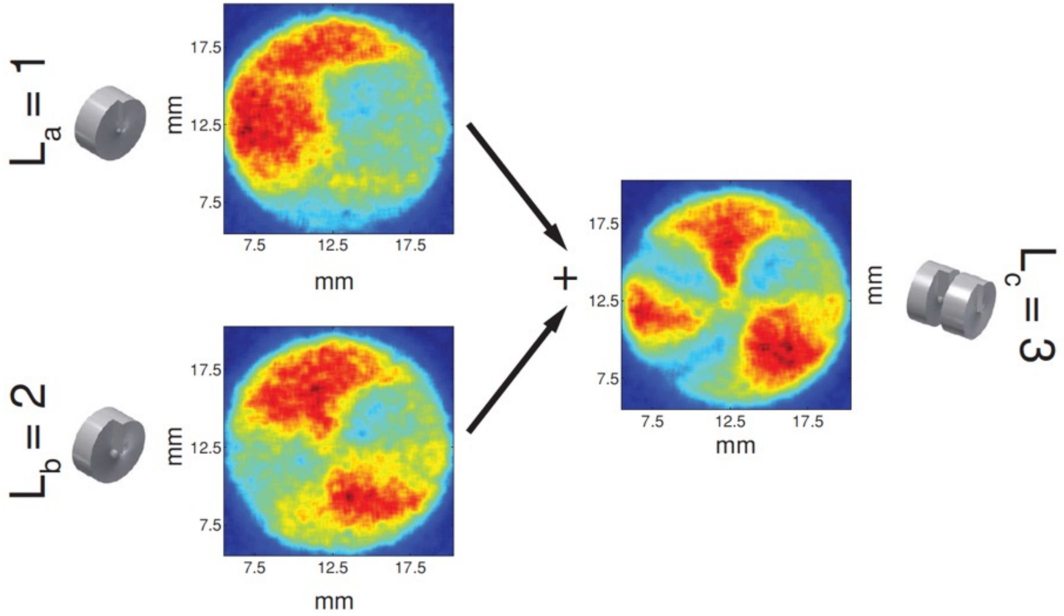
Controlling neutron orbital angular momentum

Charles W. Clark, Roman Barankov, Michael G. Huber, Muhammad Arif, David G. Cory & Dmitry A. Pushin

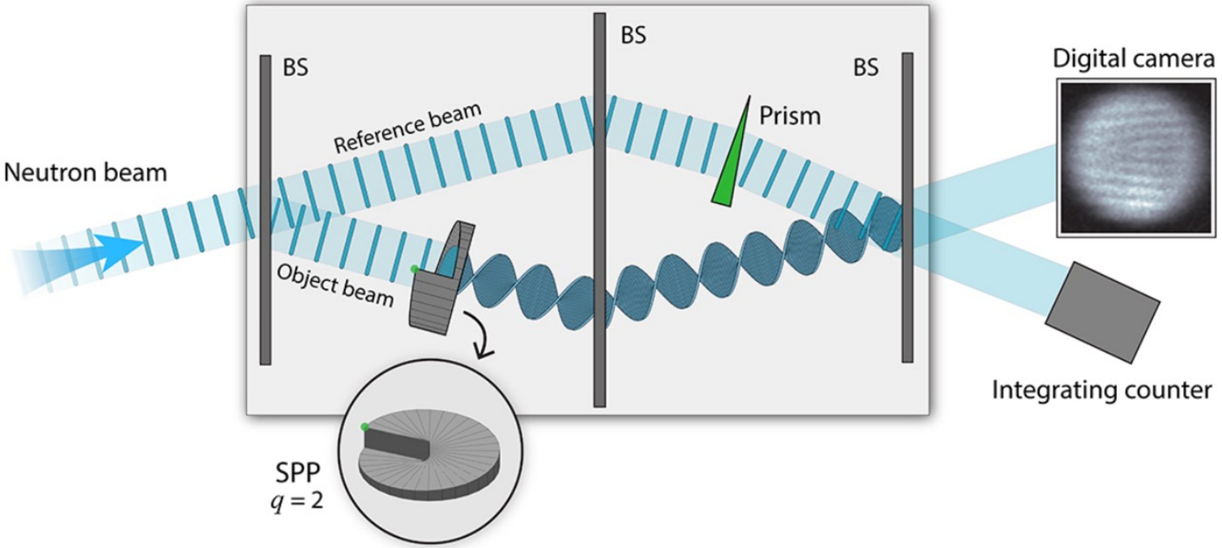
Nature **525**, 504–506 (24 September 2015) | Download Citation







Neutron Holography



Sarenac, Dusan, Michael G. Huber, Benjamin Heacock, Muhammad Arif, Charles W. Clark, David G. Cory, Chandra B. Shahi, and Dmitry A. Pushin. "Holography with a neutron interferometer." *Optics express* 24, no. 20 (2016): 22528-22535.

APS News Top Ten Physics Newsmakers of 2016

1. Ripples in Spacetime
2. Nobel Prizes
3. Rise and Fall of the 750 GeV Bump
4. Celebrity Elements
5. Neutron Holography
6. The Solar System's 9th Resident?
7. Kokabee Freed
8. CERN's First Female Director
9. Rosetta's Last Signal
10. In Memoriam

Neutron Holography

In 2016, researchers reported using neutrons to make holograms based on the same principles used in optical holography. A neutron enters an interferometer and is separated into two paths by a beam splitter, generating reference and object beams. The object beam was given a spatially varying phase after passing through a test object called a spiral-phase plate (a device that imparts helicity), while the reference beam, as in optical holography, is unaltered. The two beams were combined at another beam splitter, and the resulting beams sent to an imaging detector. The unique setup may offer a new way to study neutrons and use neutron imaging for characterizing properties of materials.

APS NEWS

Top Ten Physics Newsmakers of 2016

More

Each year, *APS News* selects the top ten physics stories that made it into newspapers and onto televisions in the U.S. and across the world. While the selections may be scientifically important, the main criterion is how much coverage they generated.

Ripples in Spacetime

It was the black hole merger heard around the world. In February 2016, researchers announced the first direct observation of gravitational waves. The Laser Interferometer Gravitational Observatory Scientific Collaboration (LIGO) and the Virgo Collaboration attributed the signal to a merger of two black holes, whose death spiral could be heard as a "chirp" when converted to an audio waveform. Then in June 2016, the research teams presented results from a second merger, this time of two black holes with smaller masses. The LIGO detectors were shut down for upgrades and restarted in November for a second observing run. Also in June, the European Space Agency had a successful test run of the Laser Interferometer Space Antenna Pathfinder mission, showing the feasibility of operating gravitational wave detectors in orbit.

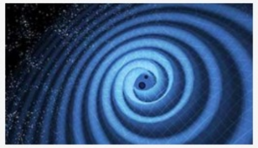
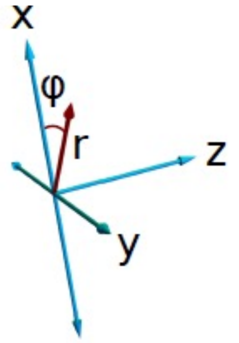
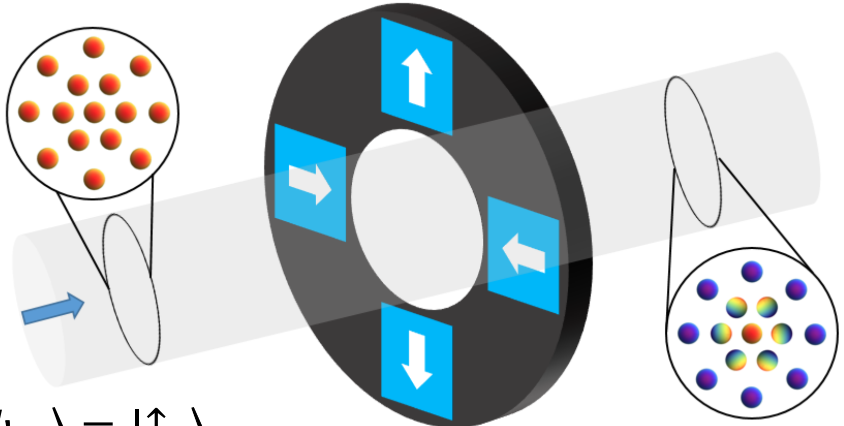


Image: LIGO

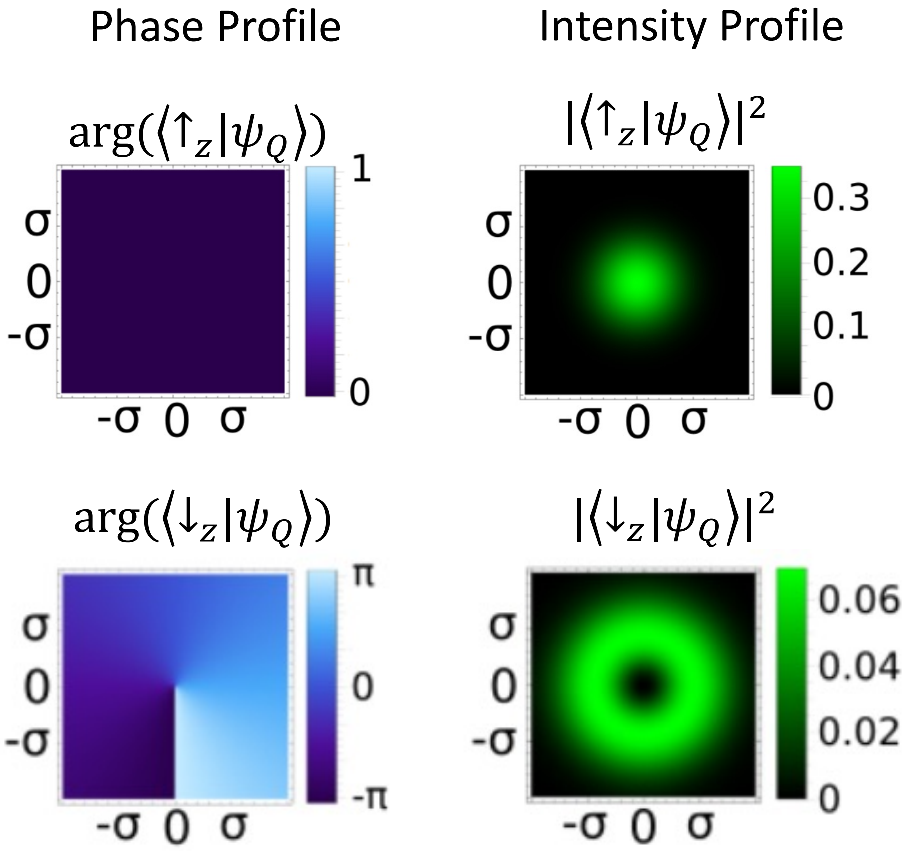
Making waves

On-Axis Spin-Orbit States





$|\psi_{in}\rangle = |\uparrow_z\rangle$

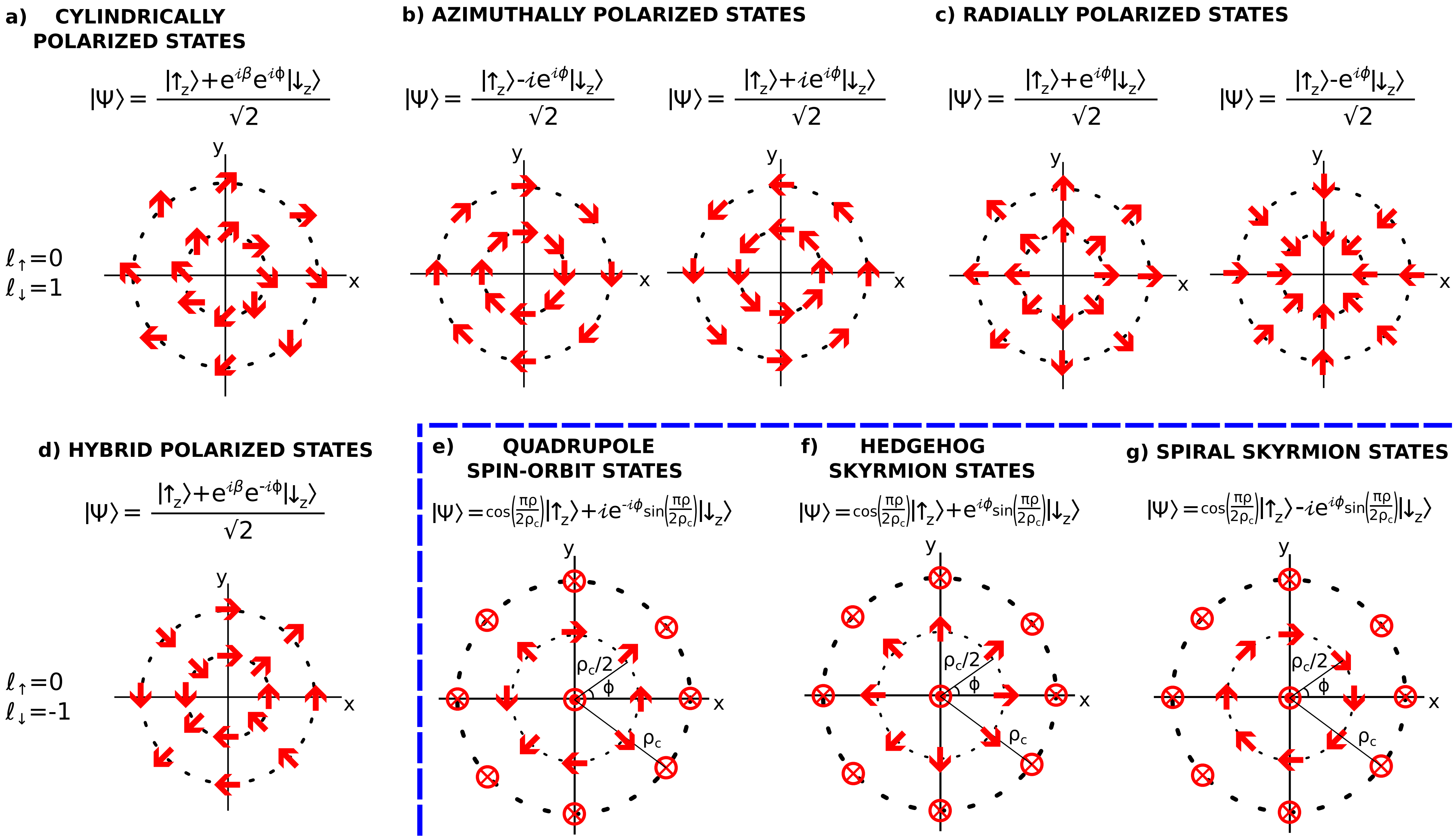


$$|\psi_Q\rangle = U_Q|\psi_{in}\rangle$$

$$= cos\left(\frac{\pi r}{2r_c}\right)|\uparrow_z\rangle + isin\left(\frac{\pi r}{2r_c}\right)e^{-i\varphi}|\downarrow_z\rangle$$

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*

Neutron Spin-Orbit States



Sarenac, D., Nsofini, J., Hincks, I., Arif, M., Clark, C.W., Cory, D.G., Huber, M.G. and Pushin, D.A., 2018. Methods of preparing and detecting neutron spin-orbit states. *New Journal of Physics 20 (10), 103012*

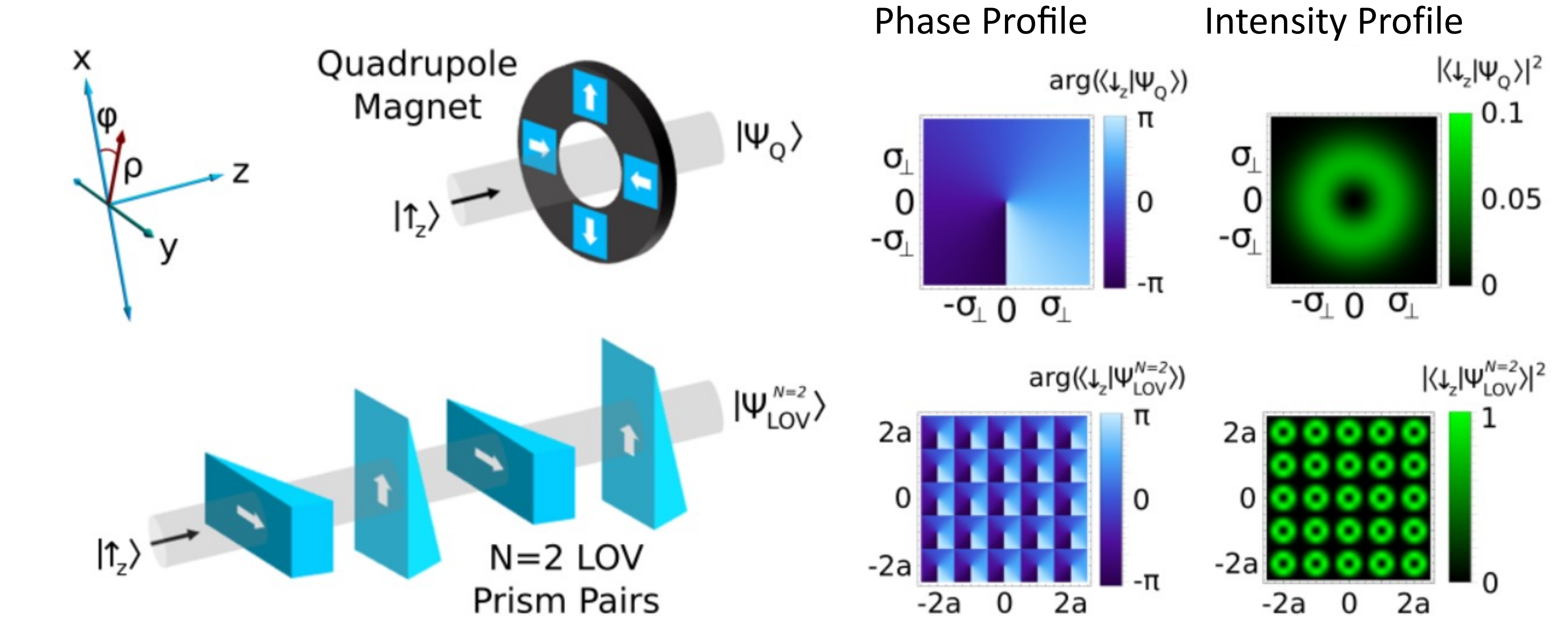
Neutron Spin-Orbit States

Quadrupole operator: $U_Q = e^{-i\frac{\pi r}{2r_c}(-\cos[\varphi]\sigma_x+\sin[\varphi]\sigma_y)} = \cos\left(\frac{\pi r}{2r_c}\right)\mathbb{1} + i\sin\left(\frac{\pi r}{2r_c}\right)(l_+\hat{\sigma}_+ + l_-\hat{\sigma}_-)$

$l_\pm = e^{\pm i\phi}$

$\hat{\sigma}_\pm = (\hat{\sigma}_x \pm i\hat{\sigma}_y)/2$

Suzuki-Trotter expansion: $U_Q = \lim_{N\to\infty}\left(e^{i\frac{\pi}{2Nr_c}x\sigma_x}e^{-i\frac{\pi}{2Nr_c}y\sigma_y}\right)^N$



Sarenac, D., Nsofini, J., Hincks, I., Arif, M., Clark, C.W., Cory, D.G., Huber, M.G. and Pushin, D.A., 2018. Methods of preparing and detecting neutron spin-orbit states. *New Journal of Physics 20 (10), 103012*

Generation and detection of spin-orbit coupled neutron beams

Dusan Sarenac[a,1], Connor Kapahi[a,b], Wangchun Chen[c,d], Charles W. Clark[e], David G. Cory[a,f,g,h], Michael G. Huber[i], Ivar Taminiau[a], Kirill Zhernenkov[a,j,k], and Dmitry A. Pushin[a,b]

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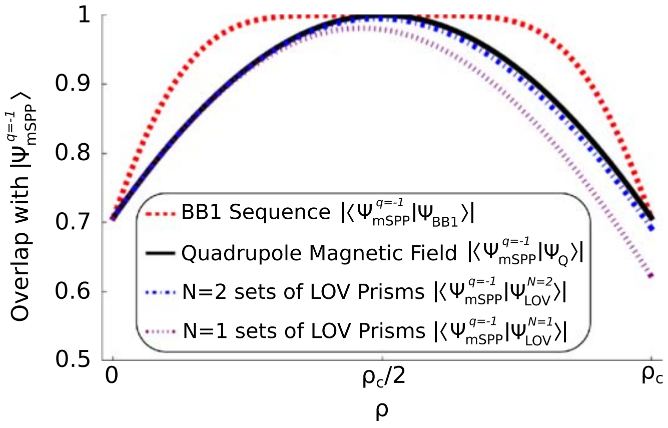
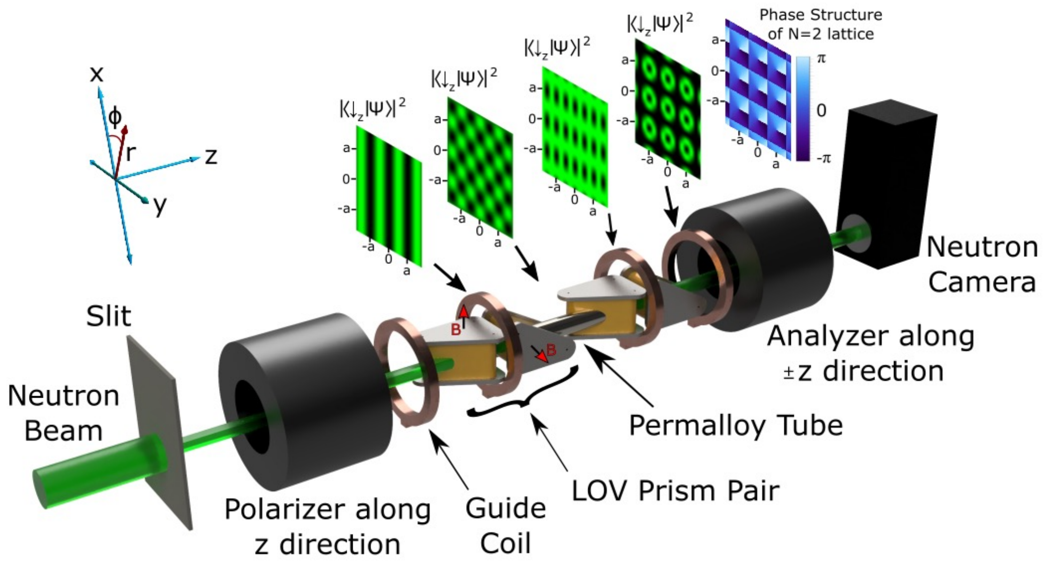
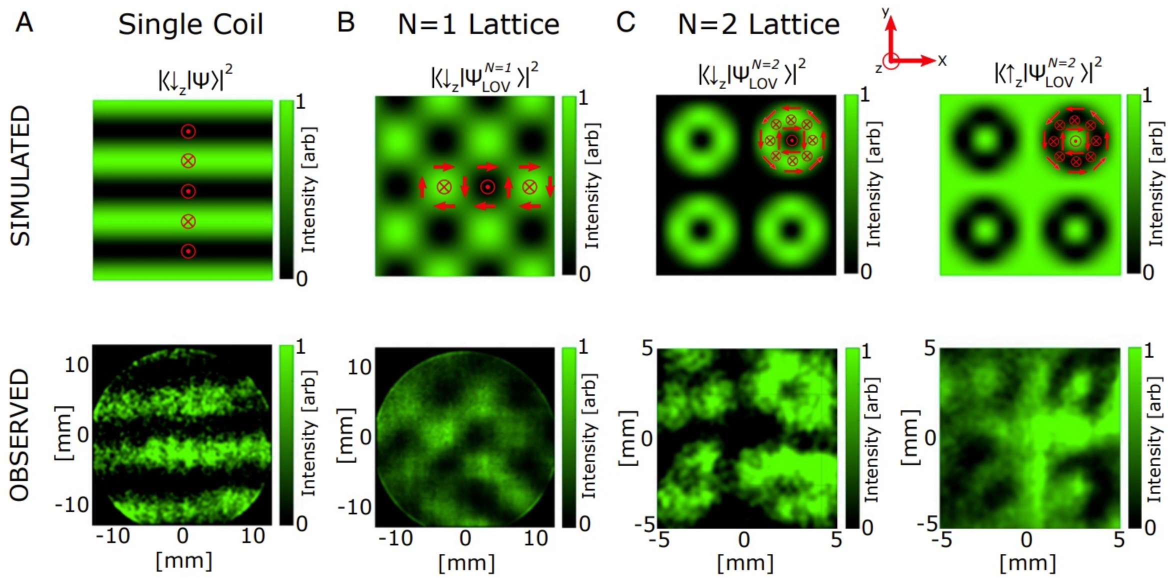
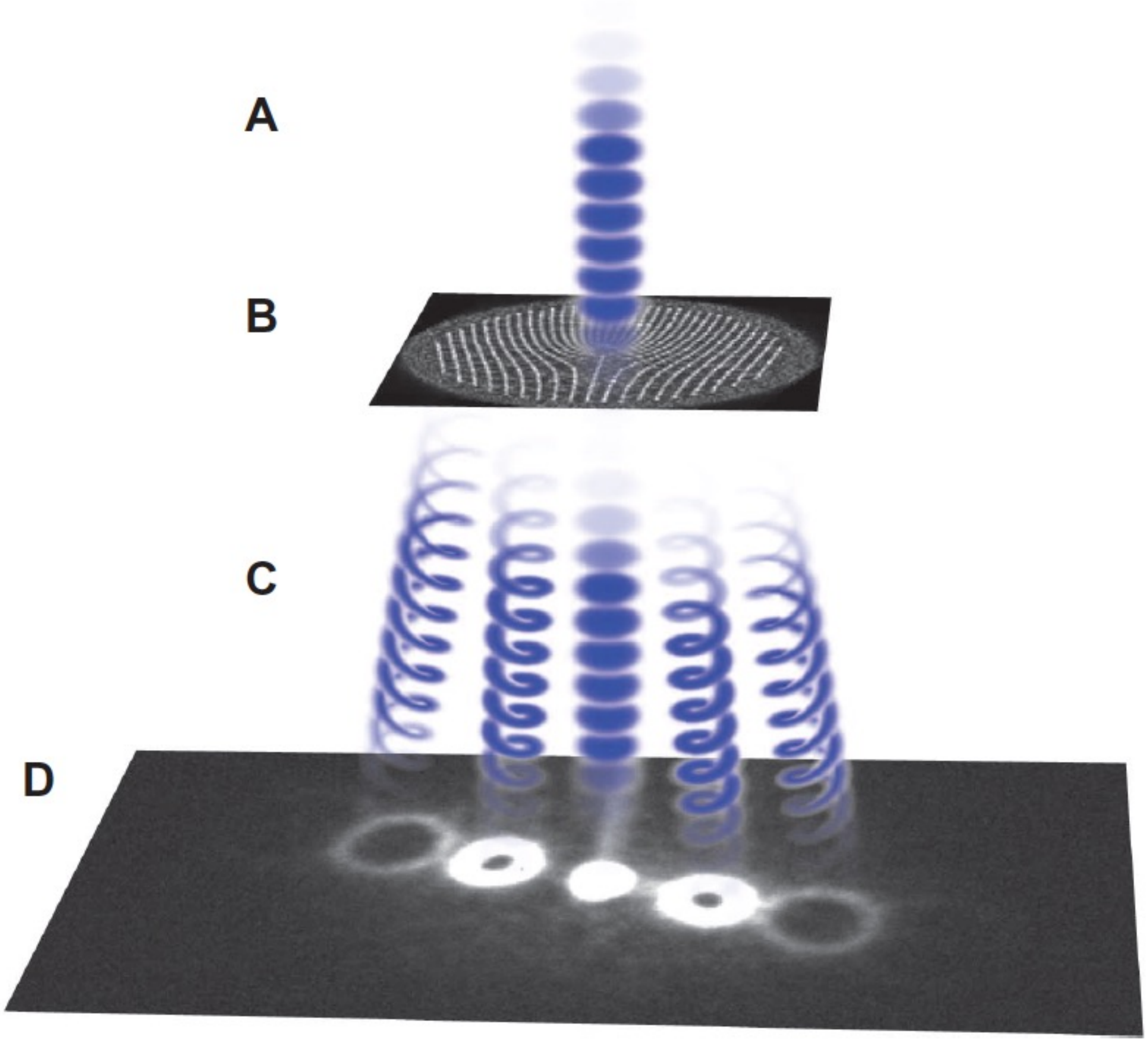


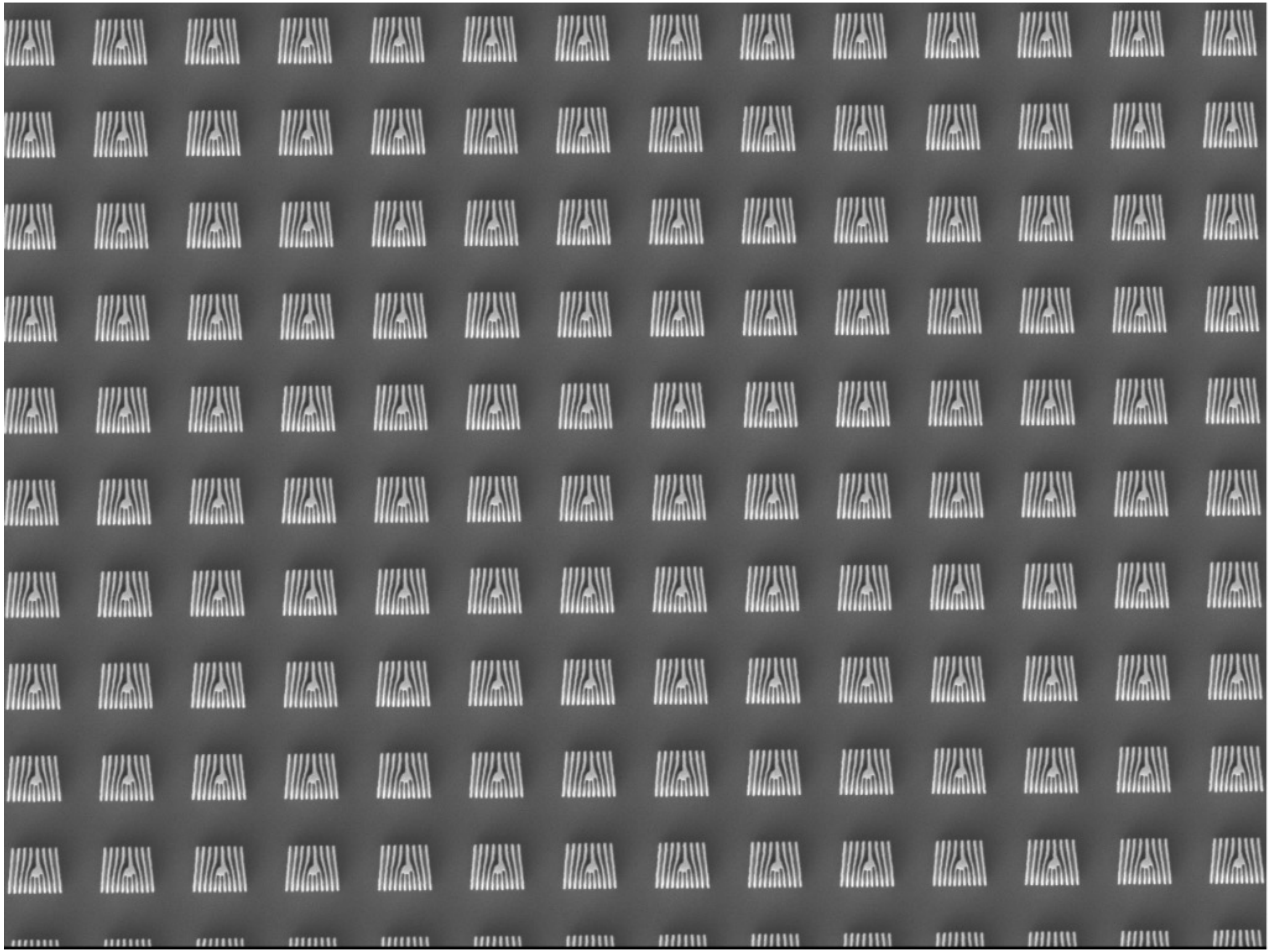




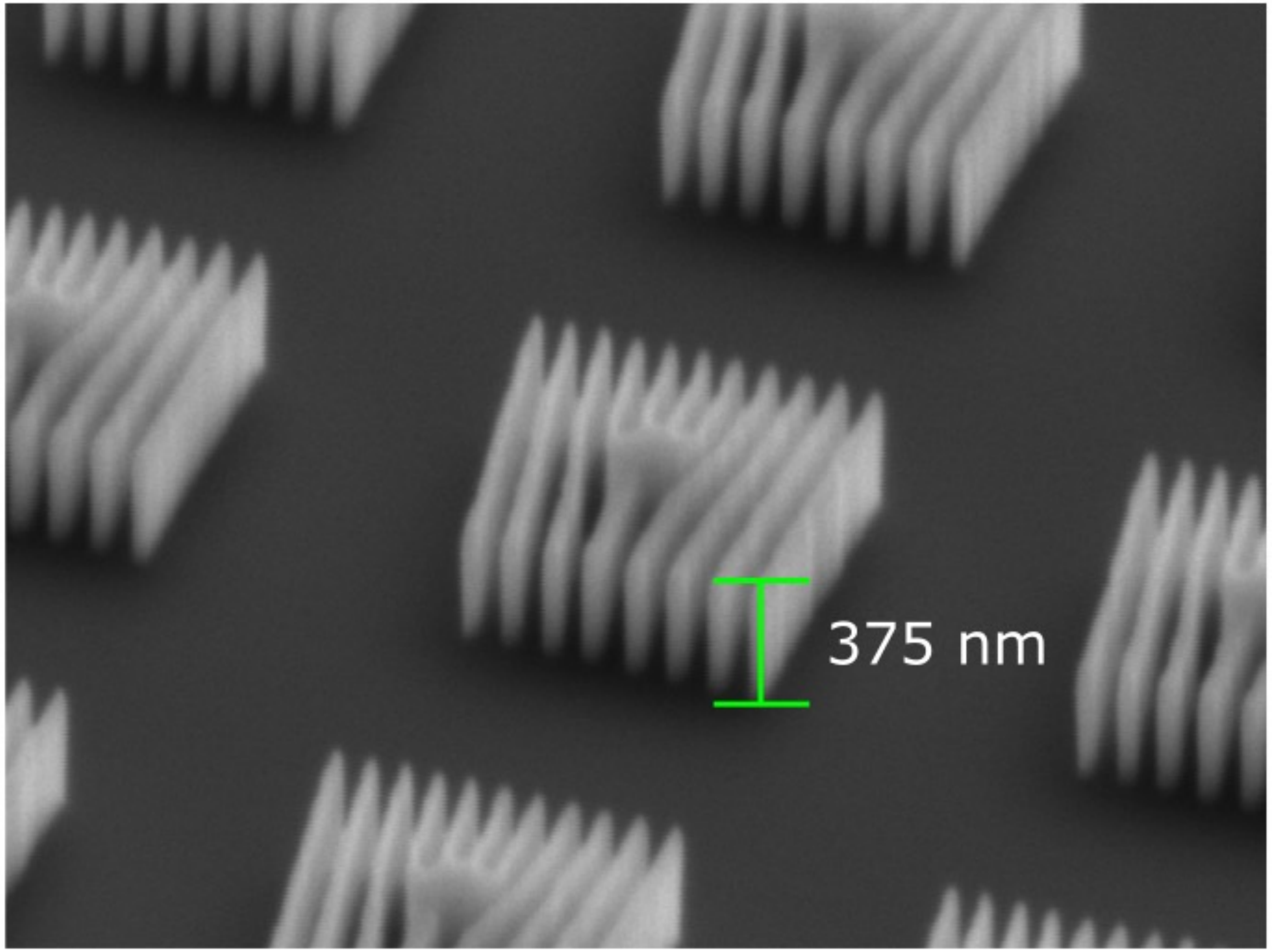


Electron OAM obtained using gratings
McMorran et al Science 2011

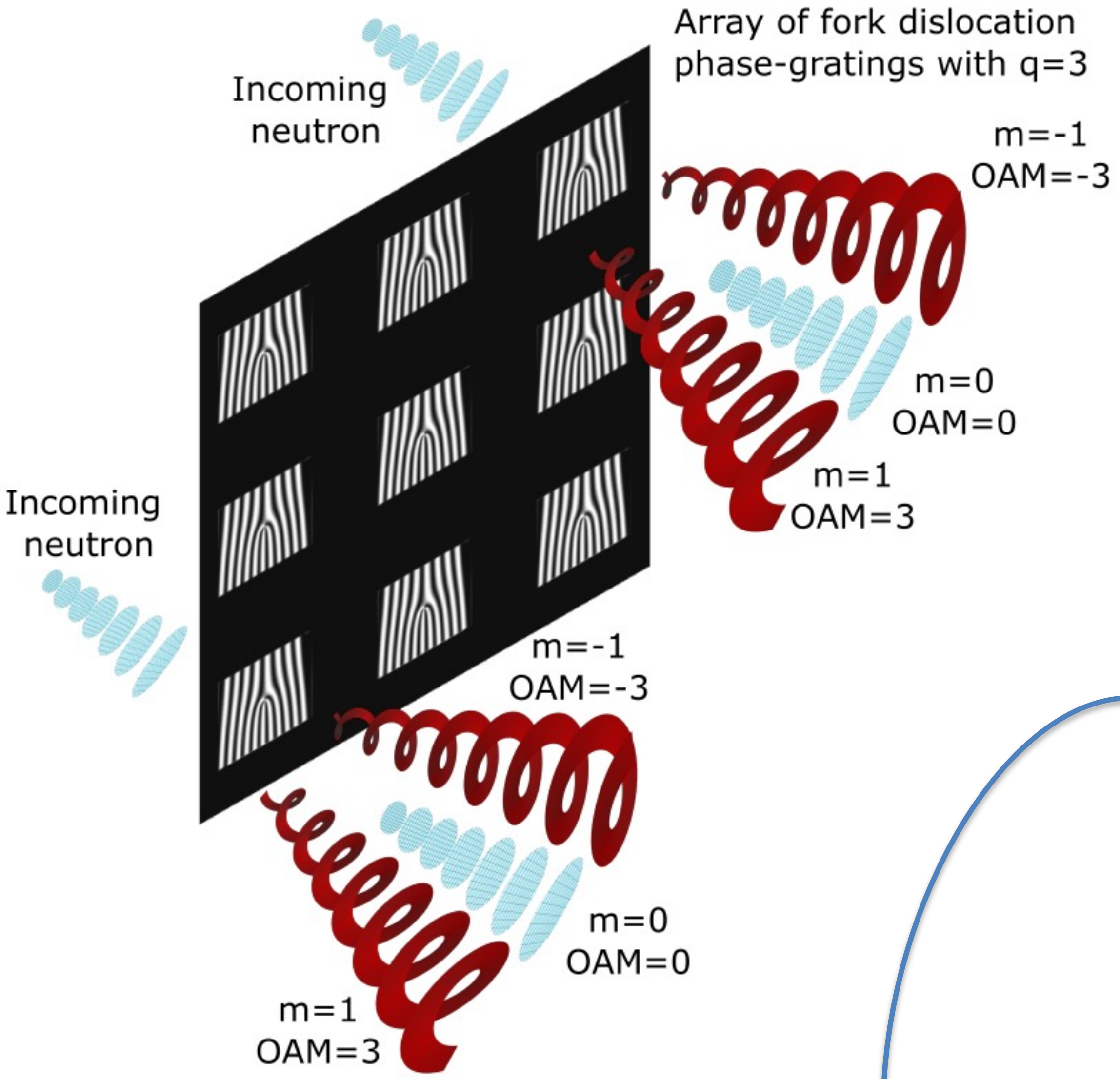
Back to neutrons



Side view of neutron diffraction gratings



2500 x 2500 =
6,250,000
gratings in square array



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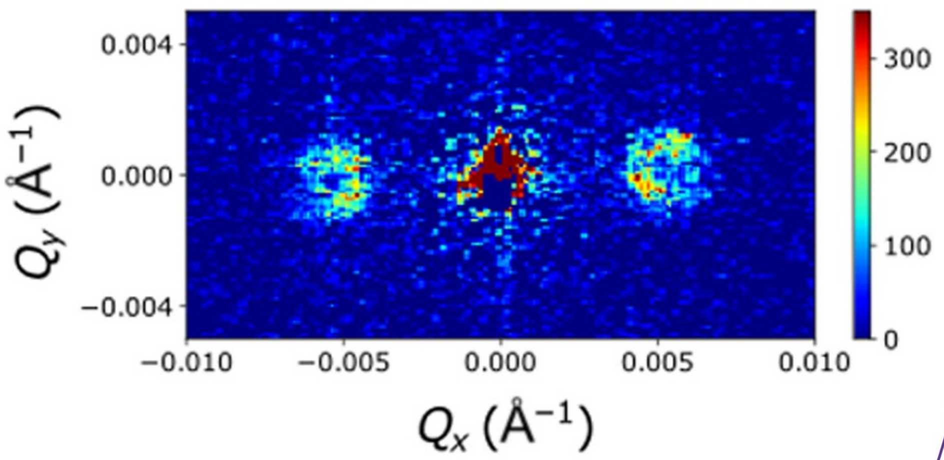
RESEARCH ARTICLE | PHYSICS

Experimental realization of neutron helical waves

DUSAN SARENAC, MELISSA E. HENDERSON, HUSEYIN EKINCI, CHARLES W. CLARK, DAVID G. CORY, LISA DEBEER-SCHMITT, MICHAEL G. HUBER, CONNOR KAPAHI, AND DMITRY A. PUSHIN Authors Info & Affiliations

SCIENCE ADVANCES • 18 Nov 2022 • Vol 8, Issue 46 • DOI: 10.1126/sciadv.add2002

Intensities from individual gratings combine in far field.

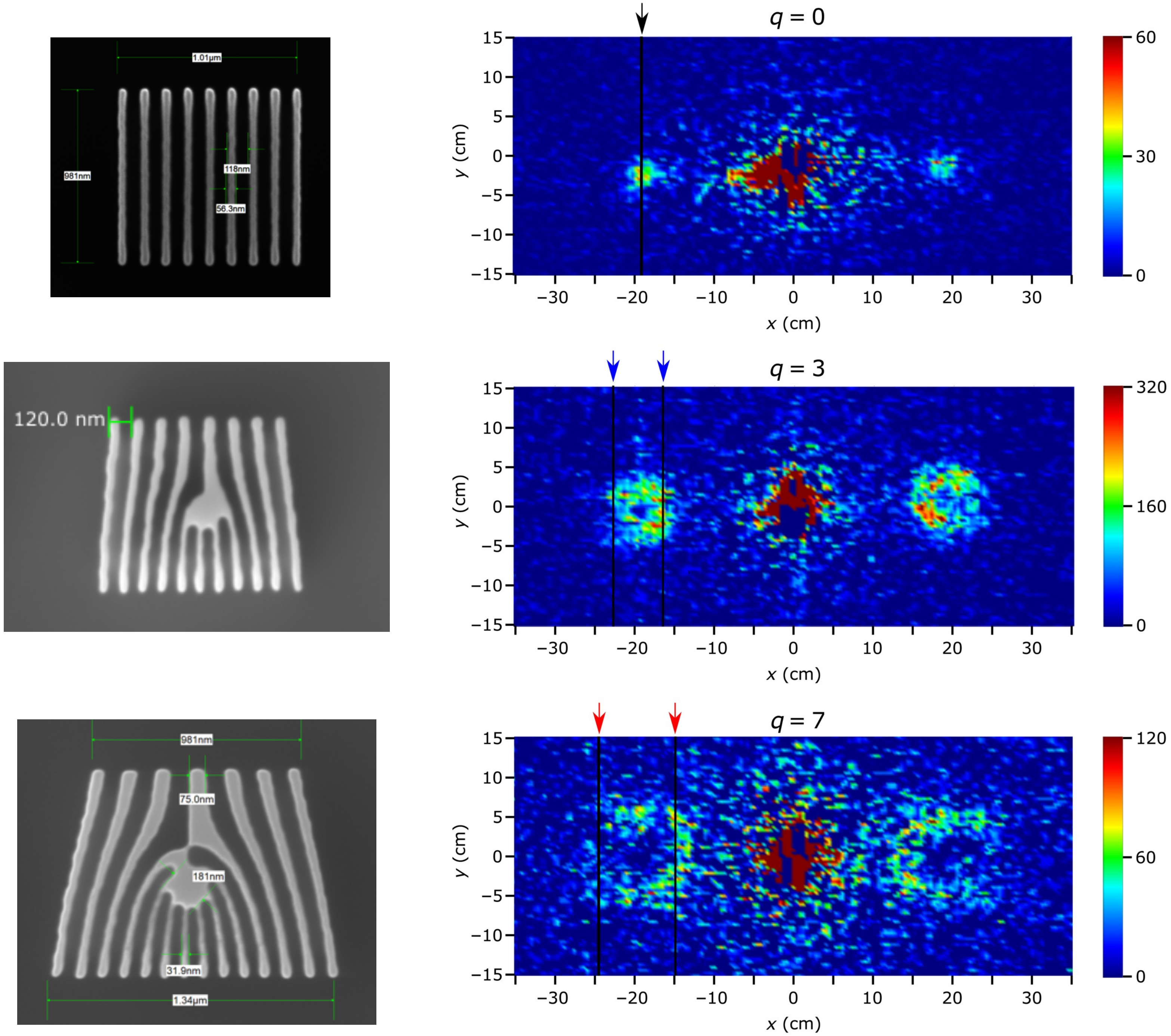


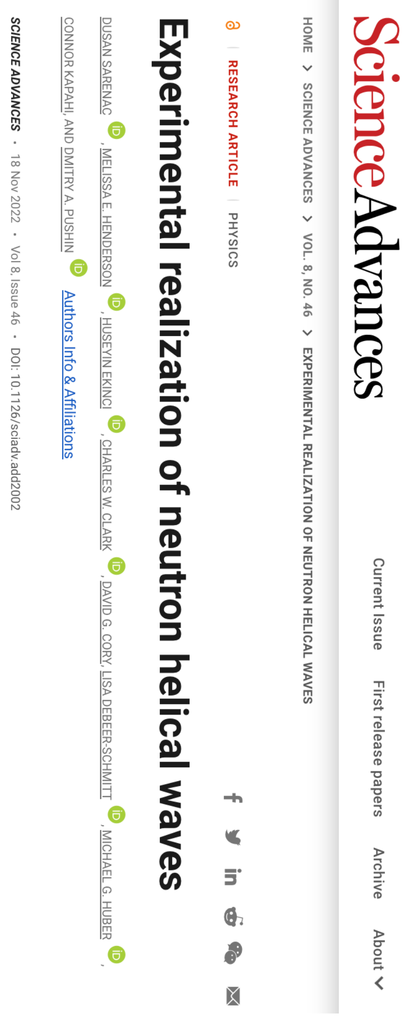
Each nanograting sees an $l = 0$ input, diffracts coherently.

q=0

q=3

q=7


1.01μm
981nm
118nm
56.3nm
120.0 nm
981nm
75.0nm
181nm
31.9nm
1.34μm
q = 0
q = 3
q = 7
y (cm)
x (cm)
15
10
5
0
−5
−10
−15
−30
−20
−10
0
10
20
30
60
30
0
320
160
0
120
60
0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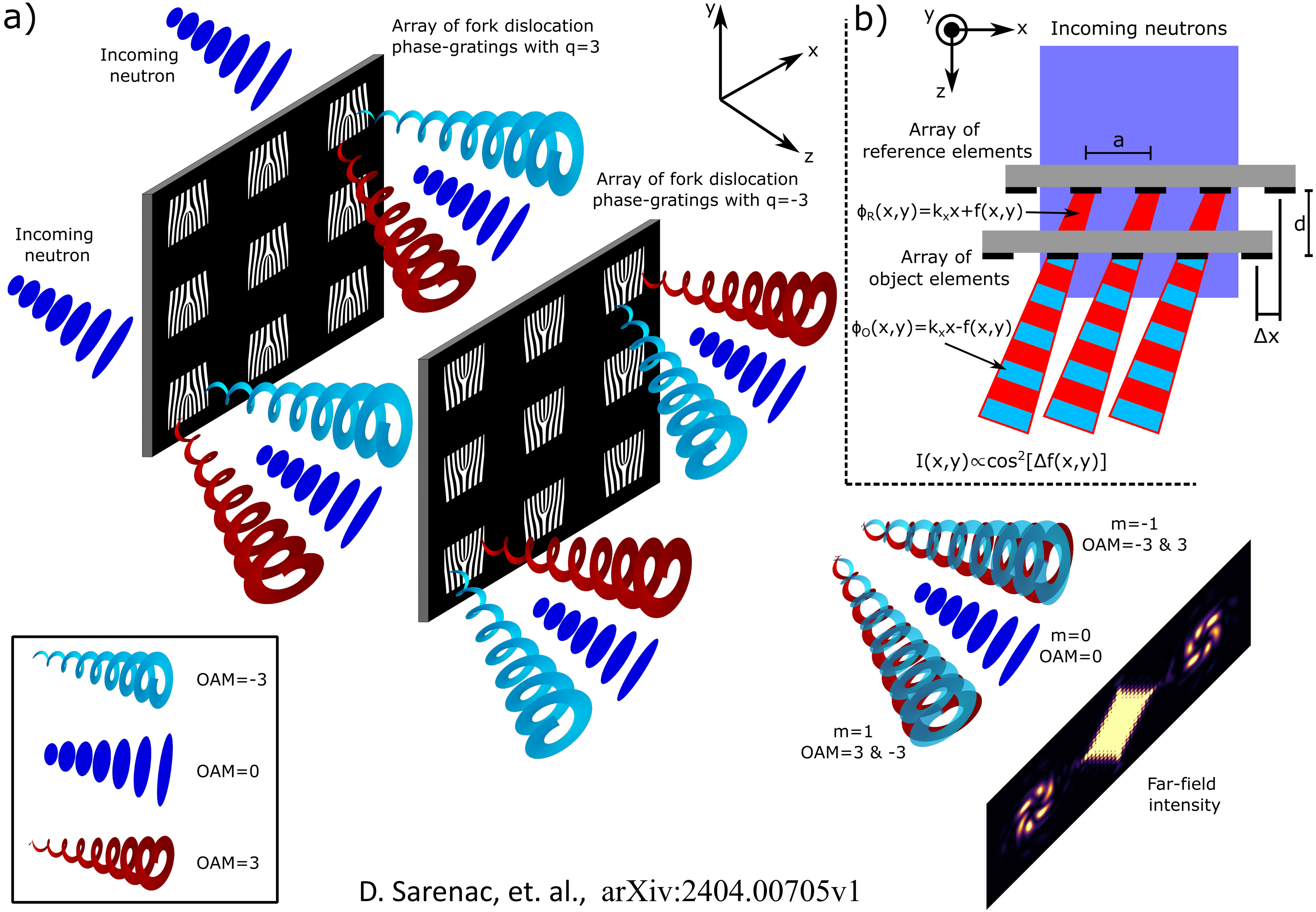
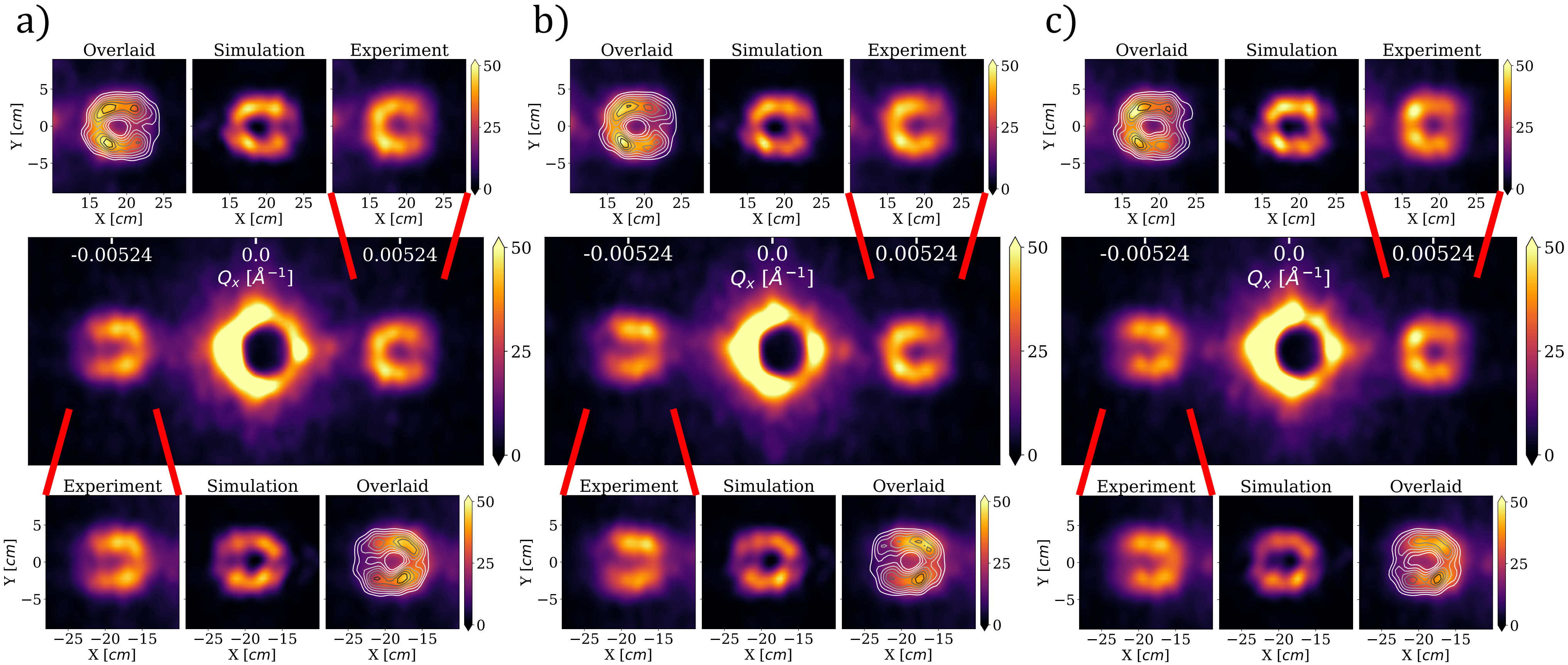
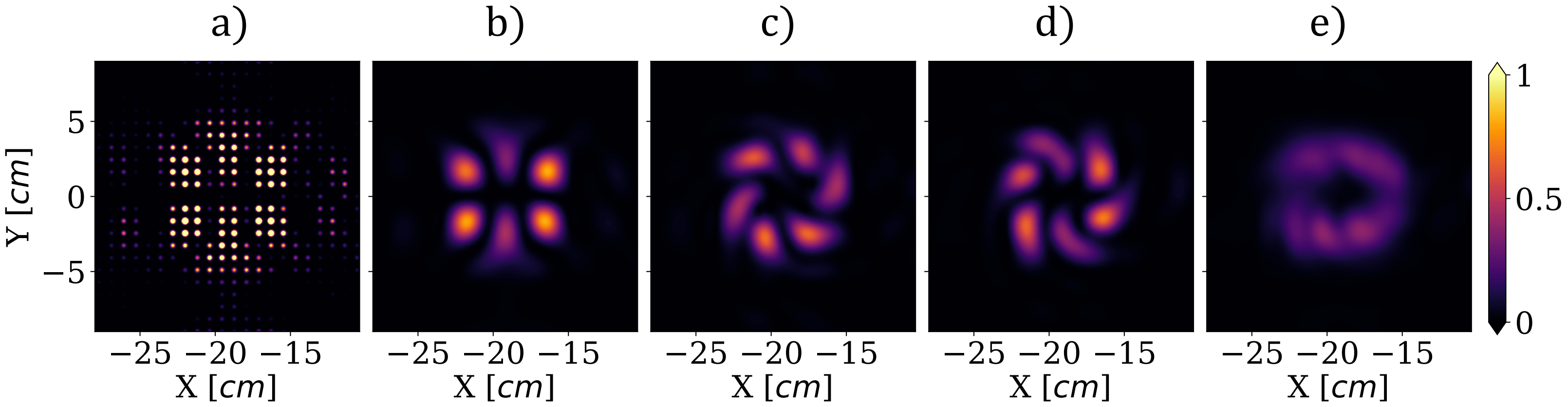


D. Sarenac, et. al., arXiv:2404.00705v1



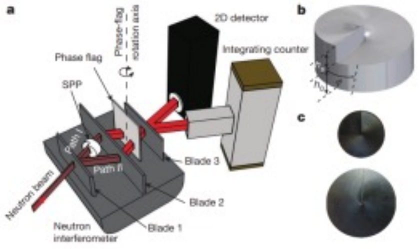


D. Sarenac, et. al.,
arXiv:2404.00705v1

Neutron OAM Timeline

2015

C. W. Clark, et al.
Nature 525, 504–506 (2015).



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Joachim Nsofini, et al. PRA 94, 013605 (2016).

D. Sarenac, et al.
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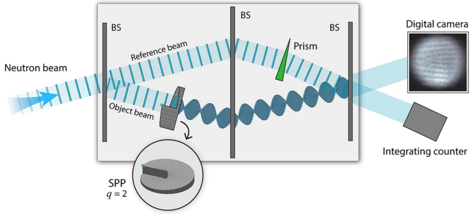

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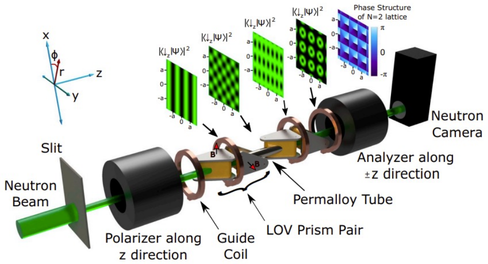

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N. Geerits et al. PRA 103, 6022205 (2021)

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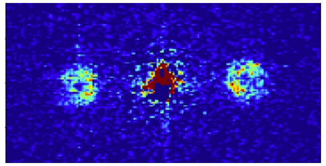
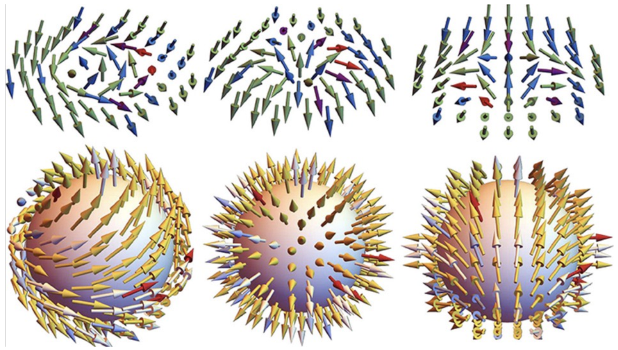


Something else

Topological Protection and Skyrmions

- Skyrmions represent topologically protected magnetic objects in which the spins wrap the entire unit sphere.

- The uniform stacking of these spin structures in 3D produces skyrmion strings which may be interrupted along their propagation length by defects at non-zero temperature.



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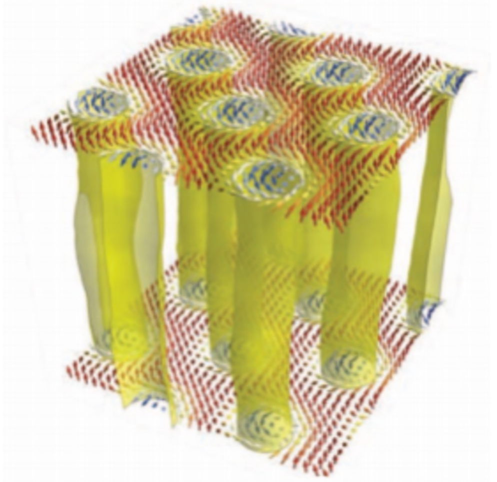

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nature physics

Article

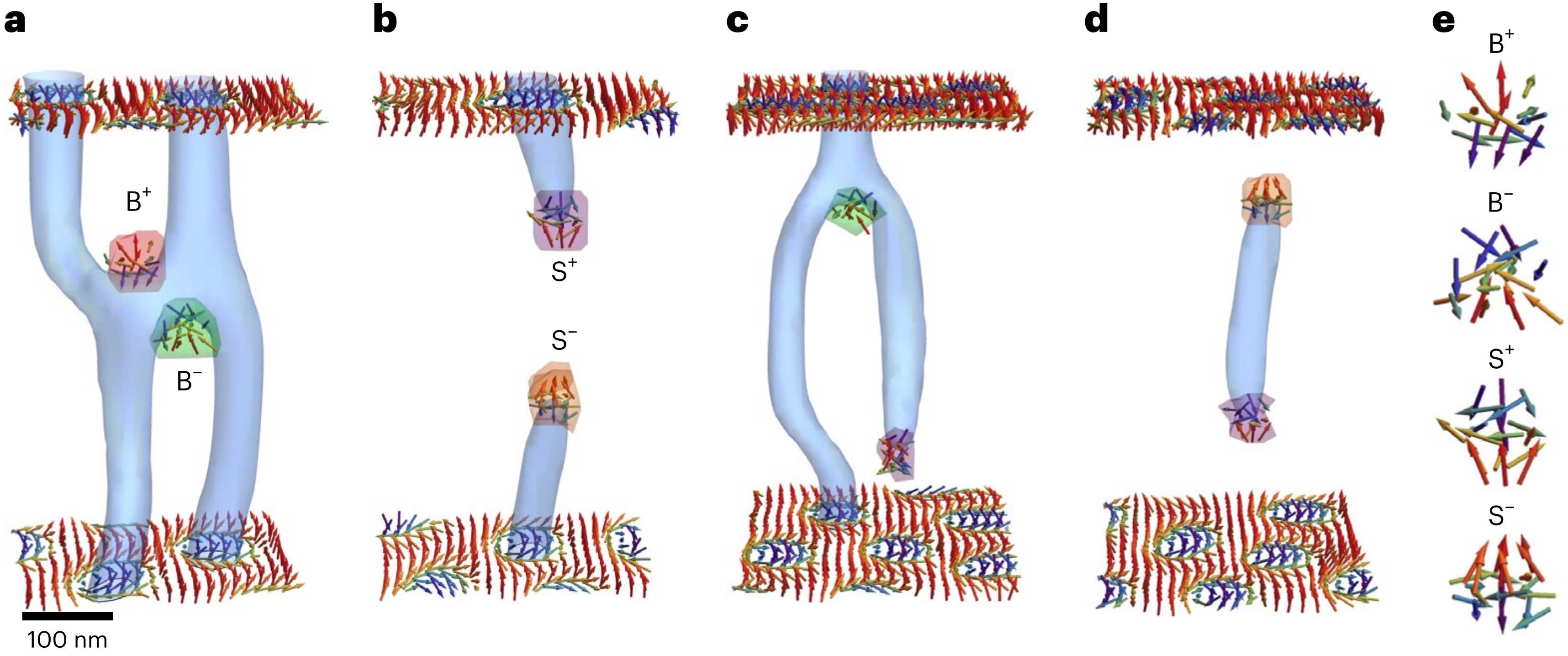
https://doi.org/10.1038/s41567-023-02175-4

Three-dimensional neutron far-field tomography of a bulk skyrmion lattice

Received: 30 August 2022

Accepted: 13 July 2023

M. E. Henderson[1,2,9], B. Heacock[3,9], M. Bleuel[3], D. G. Cory[1,4], C. Heikes[3], M. G. Huber[3], J. Krzywon[3], O. Nahman-Levesqué[1,2], G. M. Luke[5,6], M. Pula[5], D. Sarenac[1,7], K. Zhernenkov[1,8] & D. A. Pushin[1,2]



Quantum random walk for neutrons and other particles.

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Quantum-information approach to dynamical diffraction theory

J. Nsofini, K. Ghofrani, D. Sarenac, D. G. Cory, and D. A. Pushin
Phys. Rev. A **94**, 062311 – Published 8 December 2016

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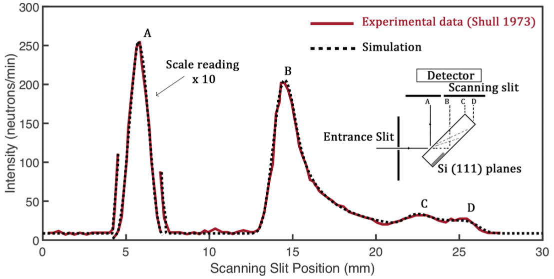
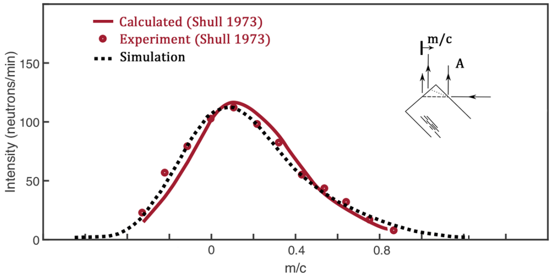
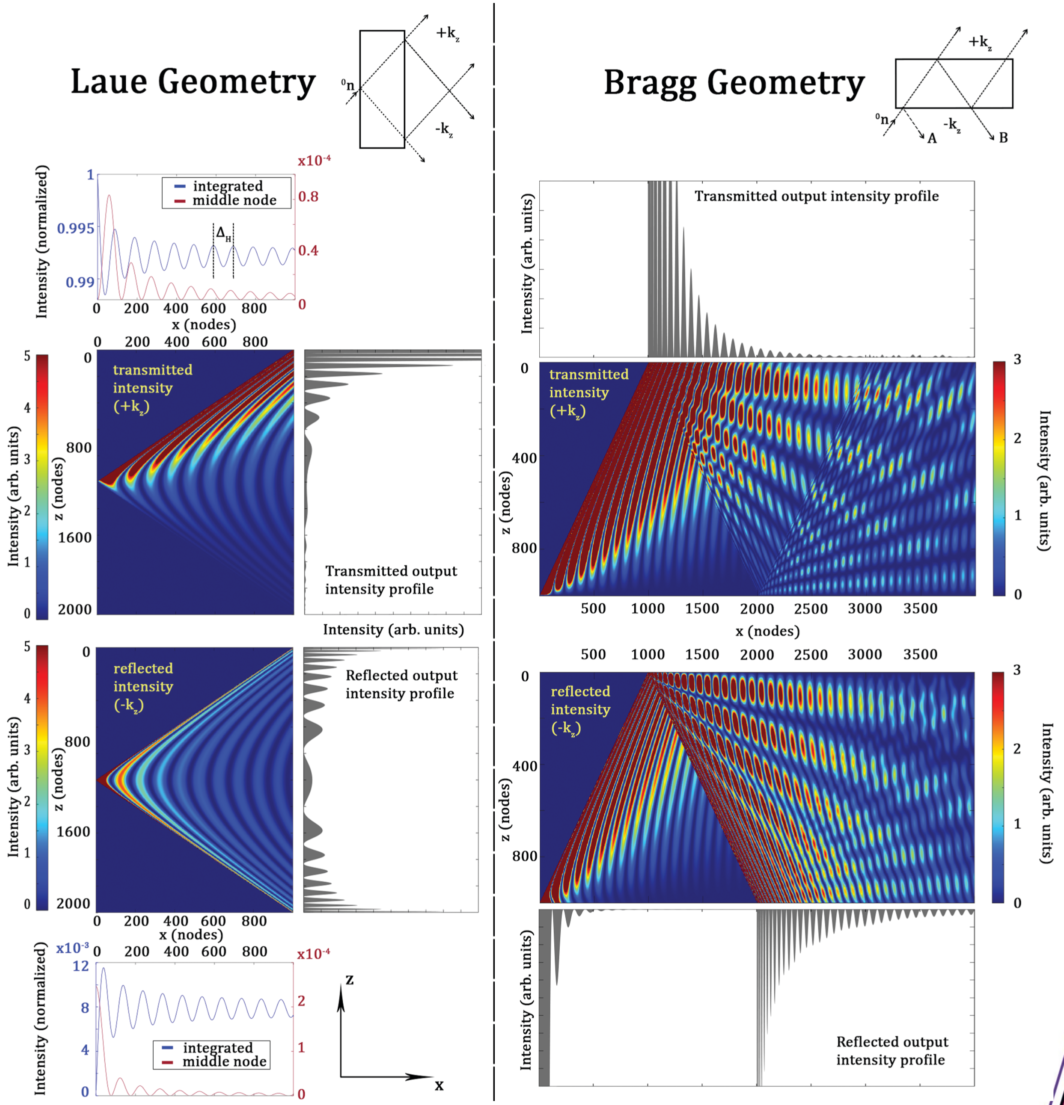
Generalizing the quantum information model for dynamic diffraction

O. Nahman-Lévesque, D. Sarenac, D. G. Cory, B. Heacock, M. G. Huber, and D. A. Pushin
Phys. Rev. A **105**, 022403 – Published 7 February 2022







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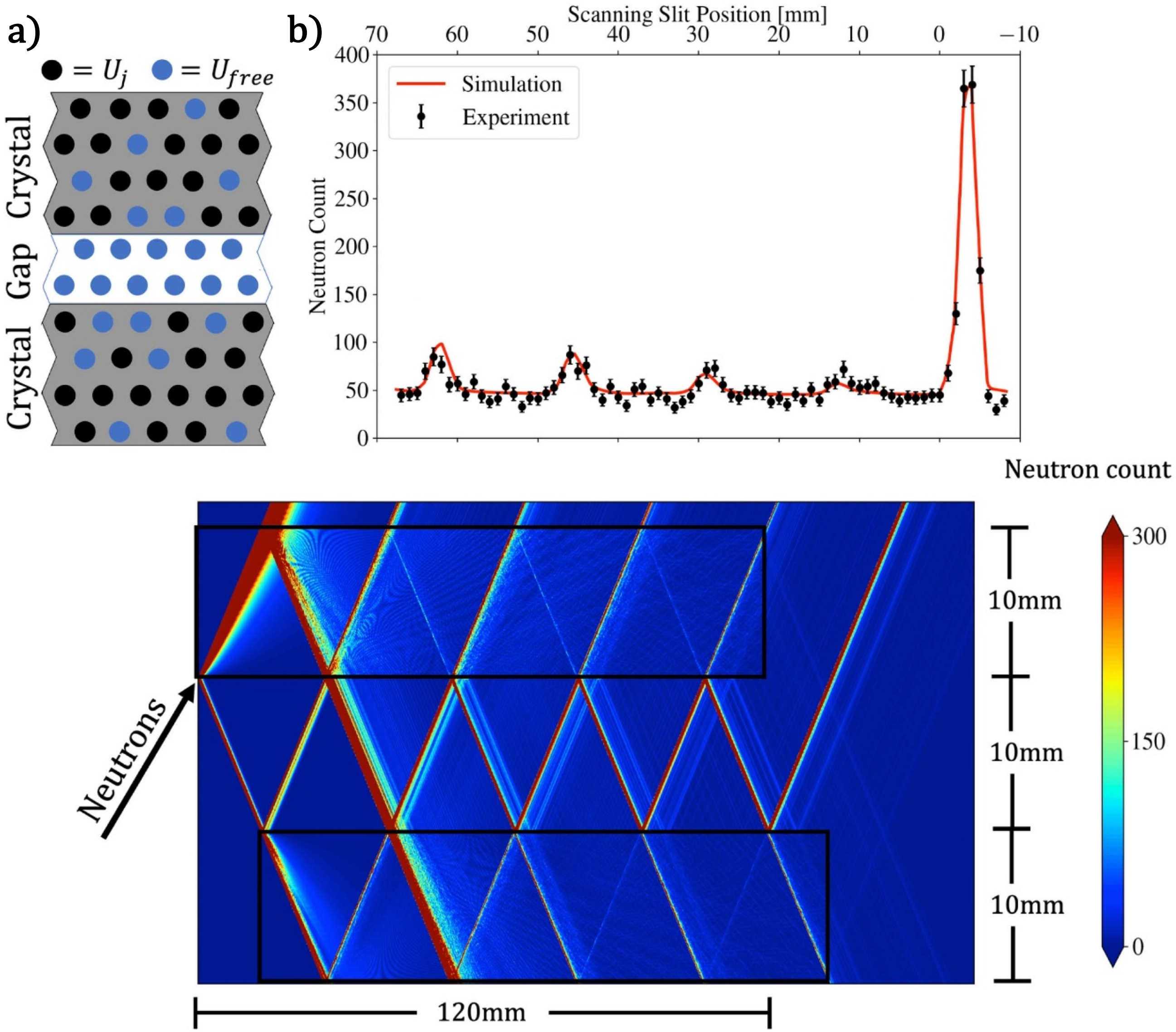

New J. Phys. **25** (2023) 073016 https://doi.org/10.1088/1367-2630/acdb93

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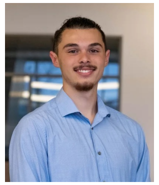
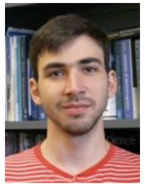
PAPER

Quantum information approach to the implementation of a neutron cavity

O Nahman-Lévesque[1,2], D Sarenac[1,3], O Lailey[1,2], D G Cory[1,4], M G Huber[5] and D A Pushin[1,2,*]



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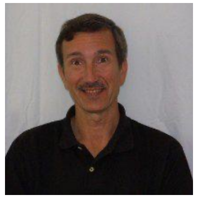

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