Quantum Random Walks in Neutron Scattering

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Department of Physics and Astronomy & Institute for Quantum Computing,
University of Waterloo/National Institute of Standards and Technology

Outline

- Neutrons
- Bragg diffraction and Dynamical Diffraction
- Quantum Random Walk approach to neutron scattering
- Experiments and Applications

Waterloo, Ontario, Canada

Latitude:

London	N51.5072°
Monaco	N43.7389°
Waterloo	N43.7102°
Cannes	N43.5528°
Naples	N40.8358°

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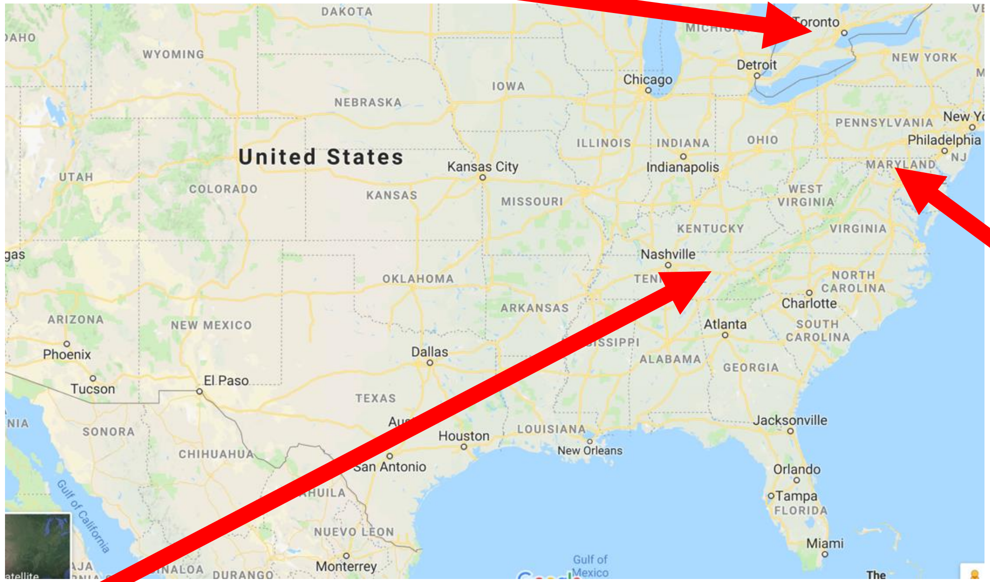
-Ivar Taminau
-Owen Lailey
-Joachim Nsofini
-Kam Ghofrani

-Dusan Sarenac
(University at Buffalo)
-Davis Last
-Olivier Nahman-Lévesque



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-Tom Gentile
-Wangchun Chen

-Lisa Debeer-Schmitt

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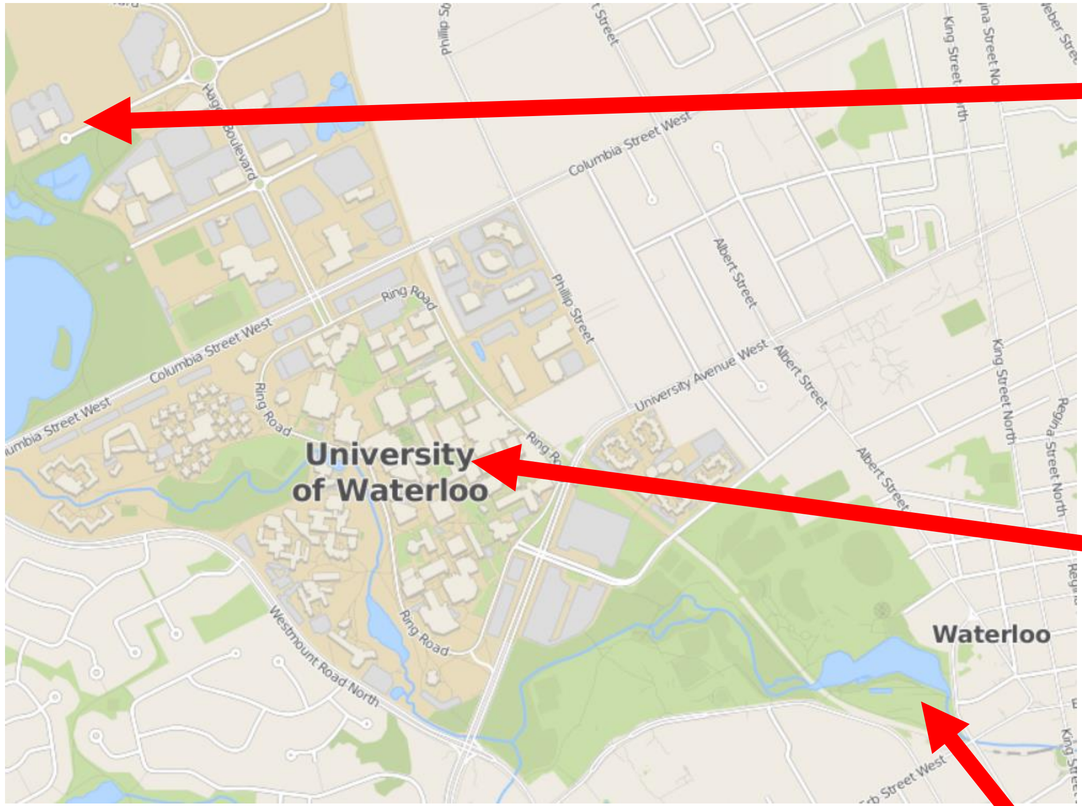

Mike Lazaridis

Our Lab

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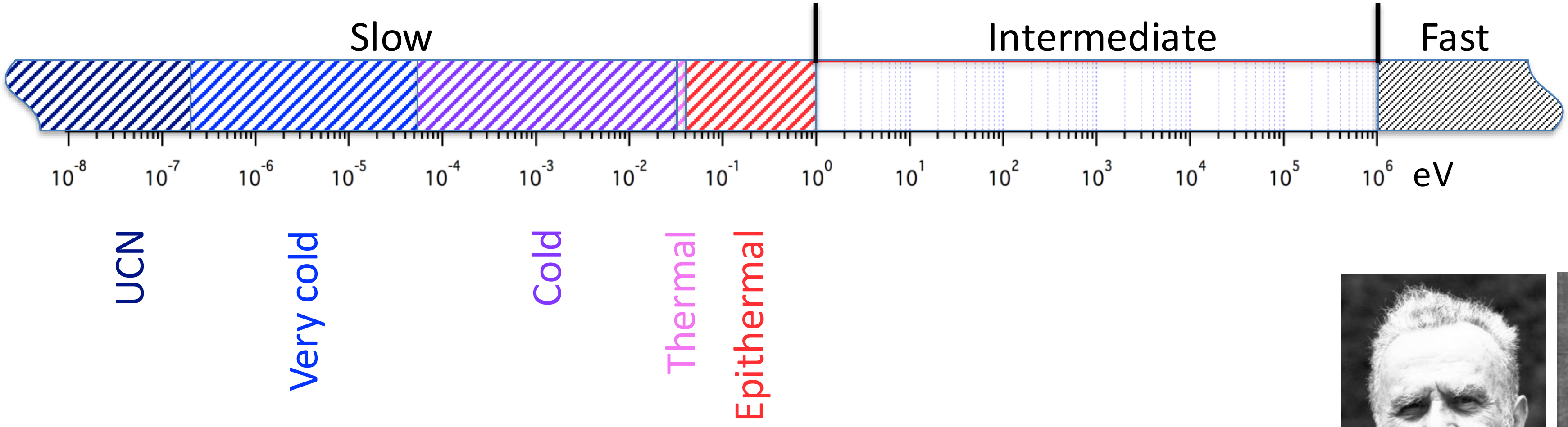
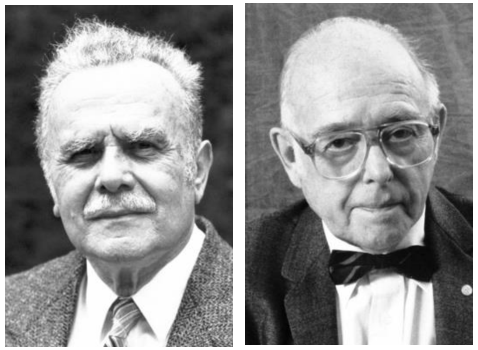
Perimeter Institute

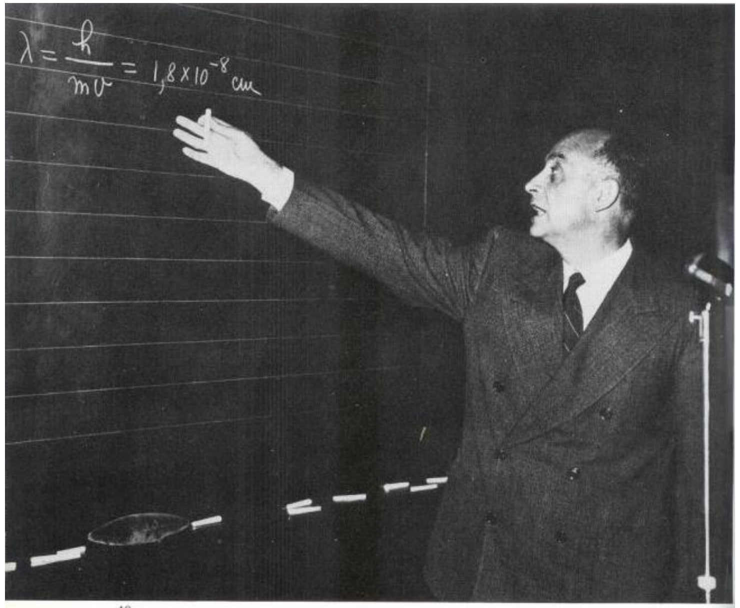
Neutron spectrum

1935, nobelprize.org





1994, nobelprize.org



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Enrico Fermi, 1946.

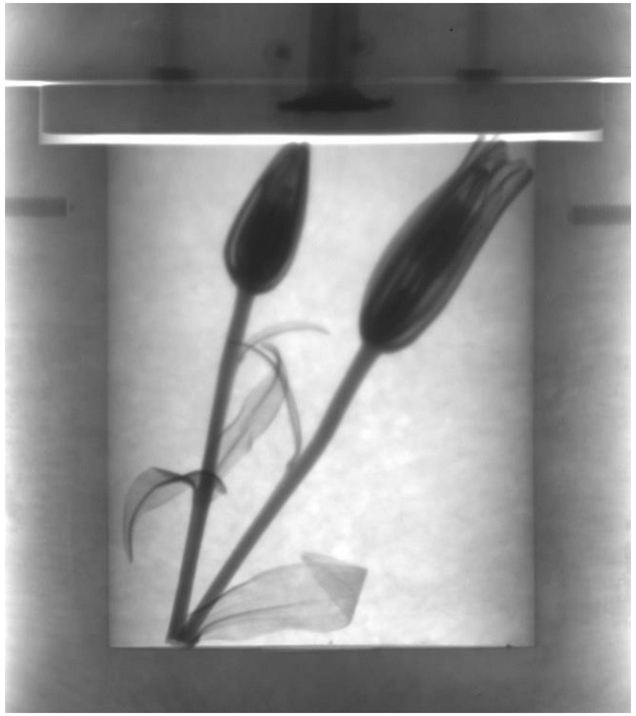
Rule of twos:

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

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

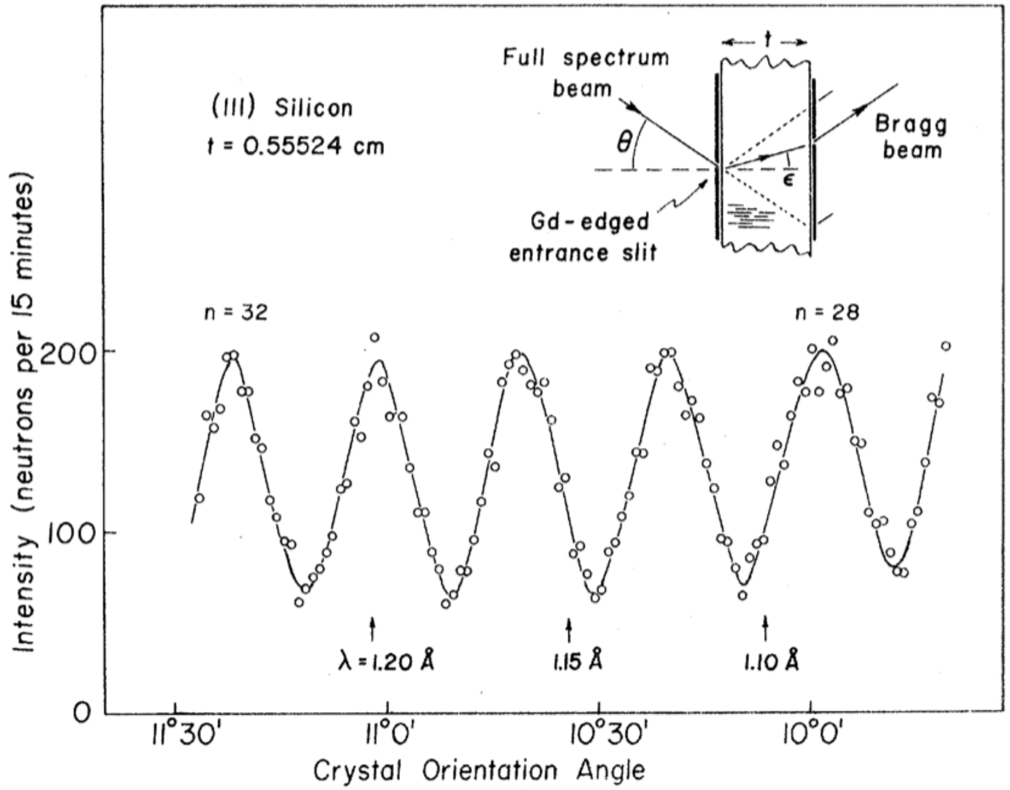
[Hussey, NIST]

Neutron Scattering – Perfect crystals

Volume 29, Number 13 PHYSICAL REVIEW LETTERS 25 September 1972

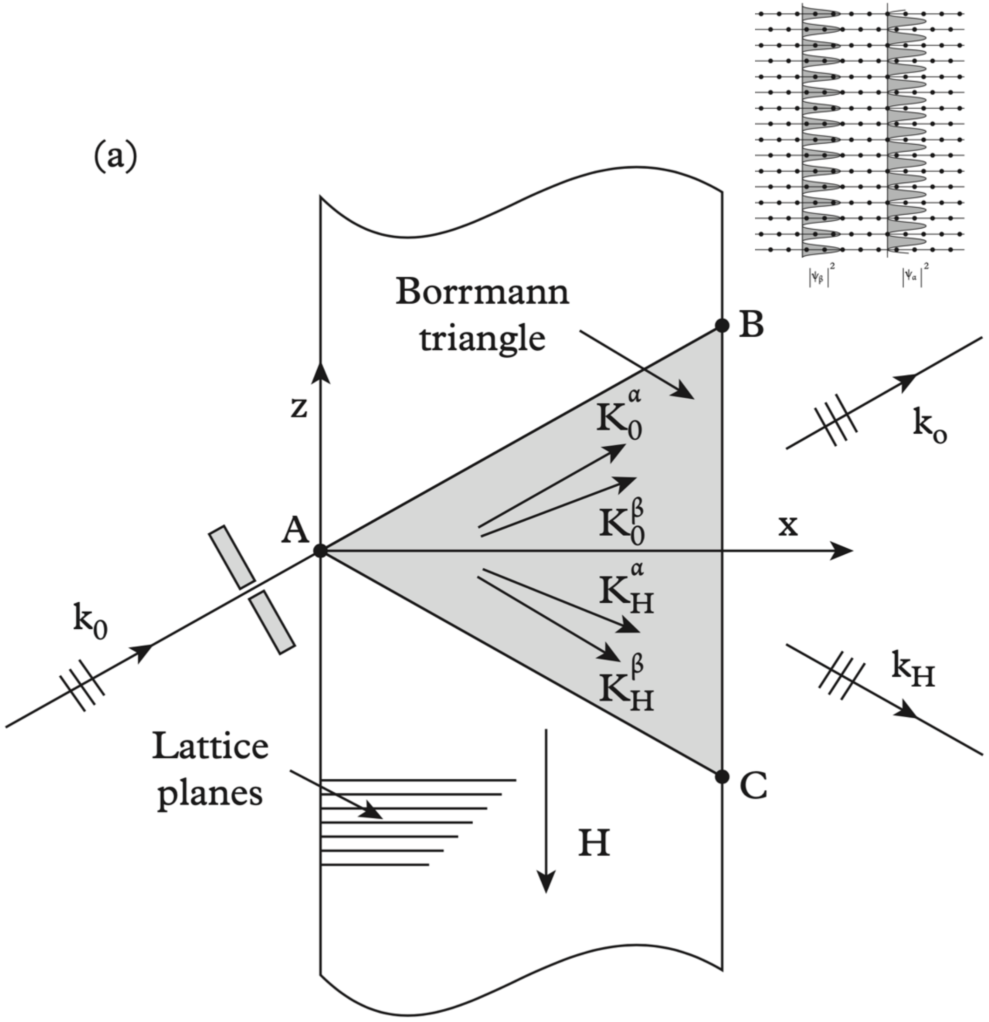
Spherical-Wave Neutron Propagation and Pendellösung Fringe Structure in Silicon*

C. G. Shull and J. A. Oberteuffer
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 11 August 1972)



Neutron Scattering – Perfect crystals

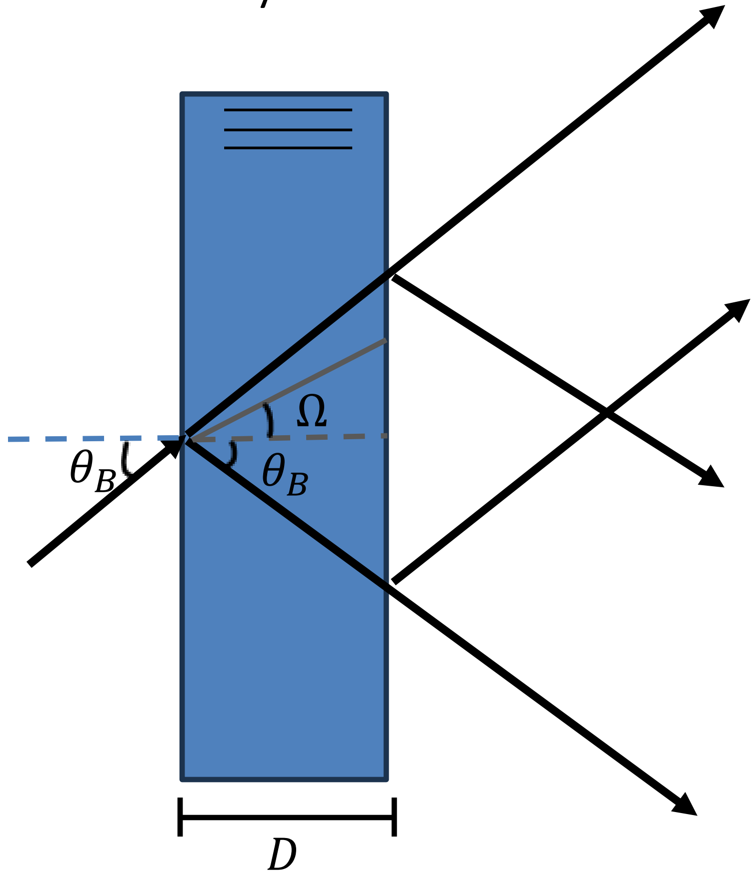
- Kinematic Diffraction: for single scattering events
- Dynamical Diffraction (DD): Incident plane wave to perfect Silicon crystal at Bragg condition
  - $\psi = \ e^{ik_0 \cdot r}$
  - $\lambda = 2d \sin \theta_B$
- Wave split according to interactions with atoms in periodic lattice
- Dynamic interchange of neutron intensity inside crystal
  - Pendellösung length (typically $\sim 50\ \mu m$)
    - $\Delta_H = \dfrac{\pi V_{cell} \cos \theta_B}{\lambda F_H}$

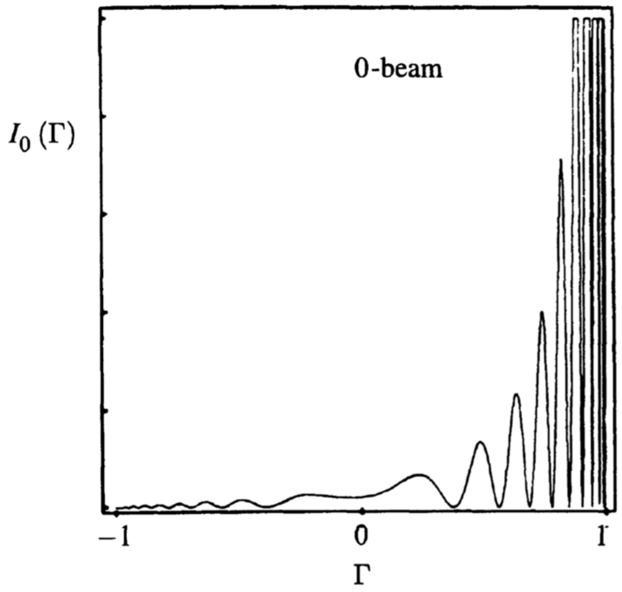


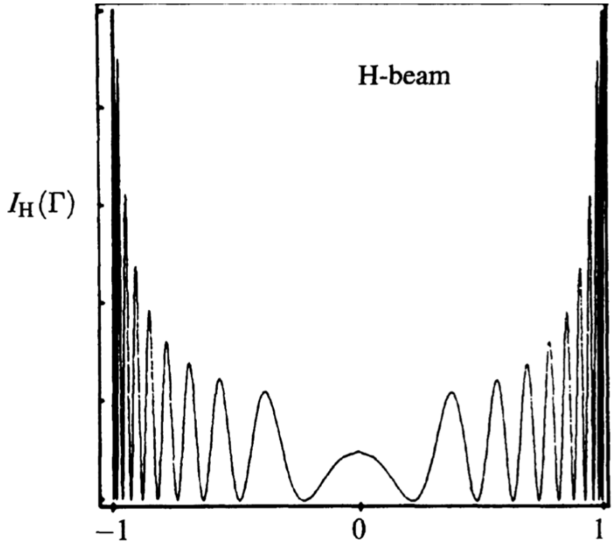
H. Rauch, S. A. Werner, Neutron Interferometry: Lessons in Experimental Quantum Mechanics, Wave-Particle Duality, and Entanglement, Vol. 12, Oxford University Press, New York, 2015.

Dynamical Diffraction

Laue Geometry:







Transmitted beam:

$$\boldsymbol{I_0(\Gamma) = \nu^2 |A_0|^2 \mathcal{J}_0^2\left(\frac{\pi D}{\Delta_H}\sqrt{1-\Gamma^2}\right)},$$

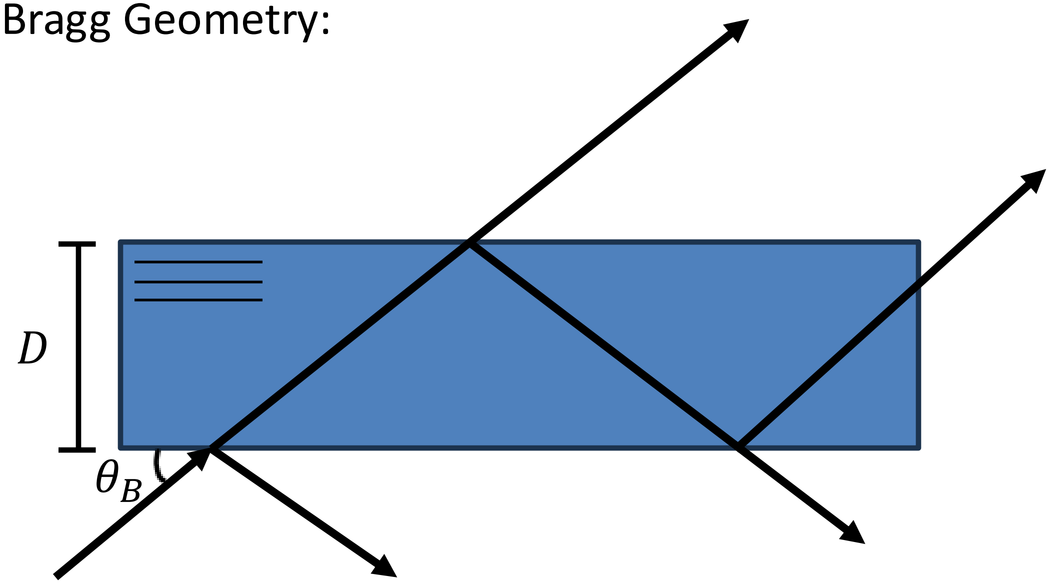
where $\nu^2 = \dfrac{\lambda^2 |F_H|^2}{V_{cell}^2}$ and $\Gamma = \dfrac{\tan\Omega}{\tan\theta_B}$.

Reflected beam:

$$\boldsymbol{I_H(\Gamma) = \nu^2 |A_0|^2 \left(\frac{1-\Gamma}{1+\Gamma}\right) \mathcal{J}_1^2\left(\frac{\pi D}{\Delta_H}\sqrt{1-\Gamma^2}\right)}$$

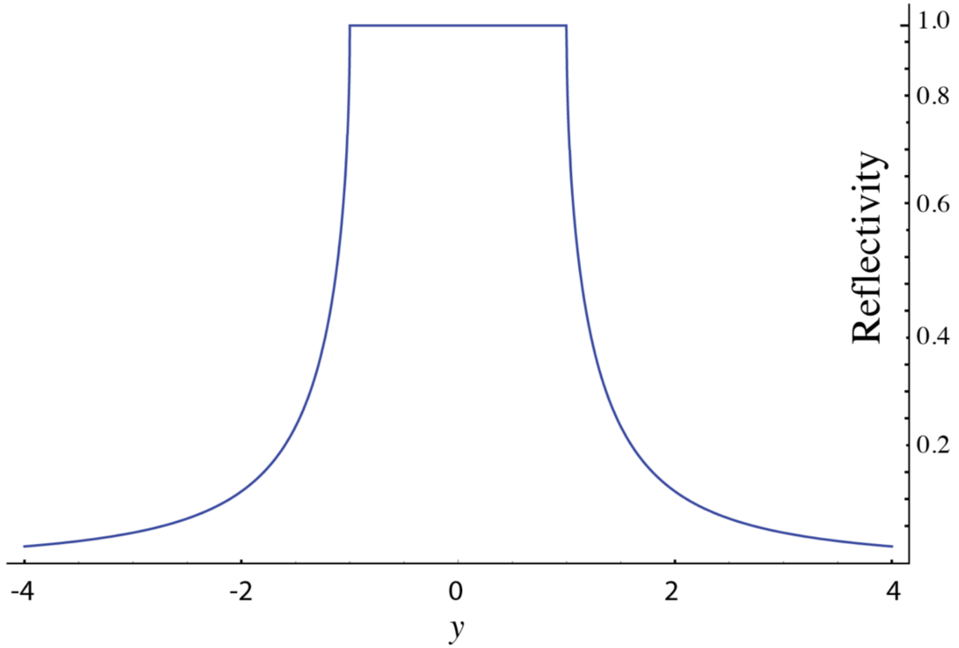
Dynamical Diffraction

Bragg Geometry:



- Complicated: multiple reflections from back face of the crystal
- Total reflection from surface near Bragg angle

Darwin plateau:

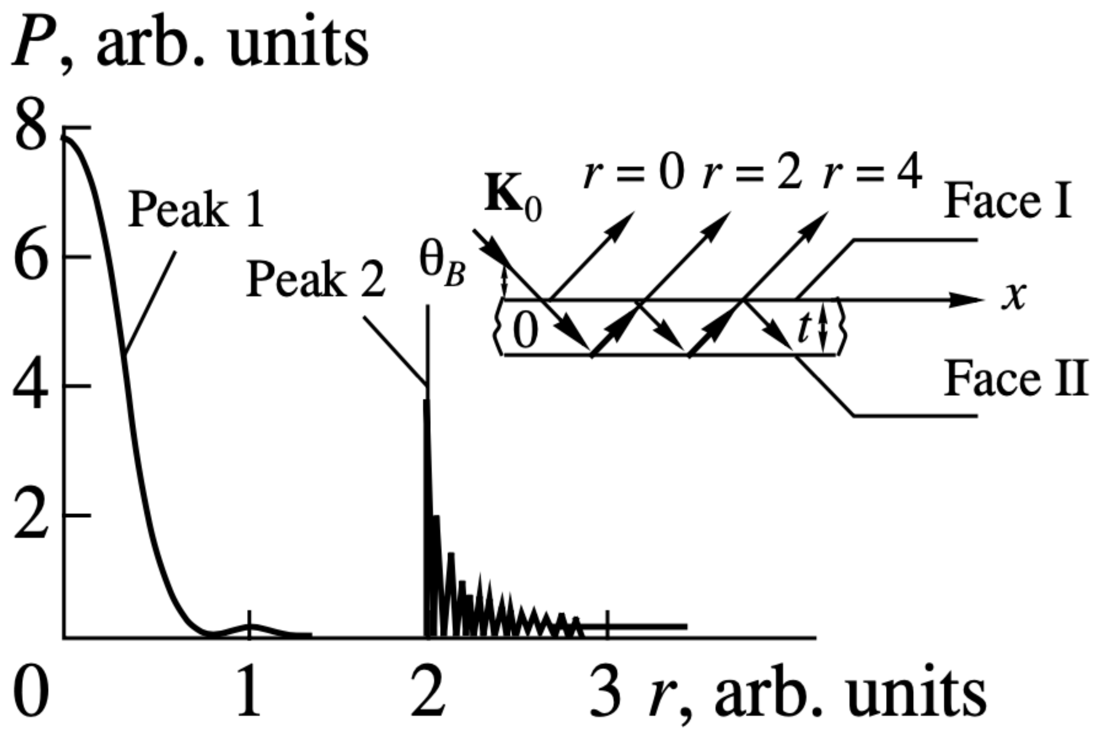


y: proportional to deviation from Bragg angle $\delta\theta_B$

neutroninterferometry.com

Limitations of Dynamical Diffraction

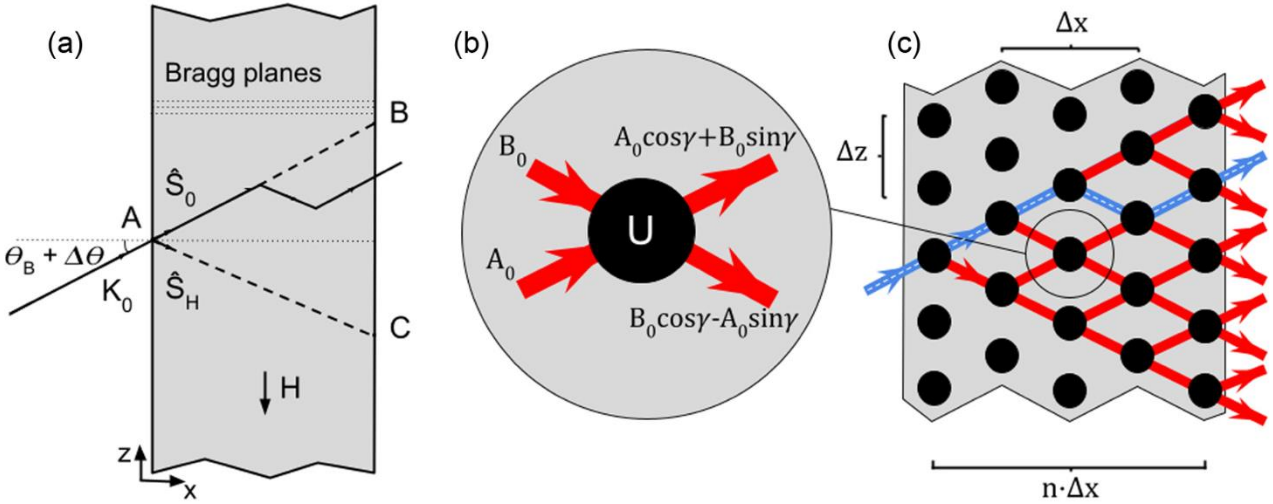
- Complex mathematical structure
- Even a single perfect Bragg crystal is considered to be infinitely thick to avoid back face reflection
- Impractical to deal with:
    - Imperfections
    - Deformations
    - Multiple crystal reflections/transmissions
    - Temperature gradients



Yu. G. Abov, N. O. Elyutin, and A. N. Tyulyusov, Dynamical neutron diffraction on perfect crystals, Phys. At. Nucl. 65, 1933 (2002).

Quantum Information (QI) Model for DD

- Quantum random walk
- Neutron input state to a node: $\begin{pmatrix}\alpha \\ \beta\end{pmatrix}$
- Unitary node operator:
  - $U = \begin{bmatrix} t_a & r_b \\ r_a & t_b \end{bmatrix} = \begin{bmatrix} e^{i\xi}\cos\gamma & e^{i\varsigma}\sin\gamma \\ -e^{-i\varsigma}\sin\gamma & e^{-i\xi}\cos\gamma \end{bmatrix}$
- Propagate through the layers:
  - $\psi_n = \prod_{i=0}^{n-1} C_{n-i}\psi_0$
- Equivalence relation:
  - $N\gamma = \frac{\pi D}{\Delta_H}$



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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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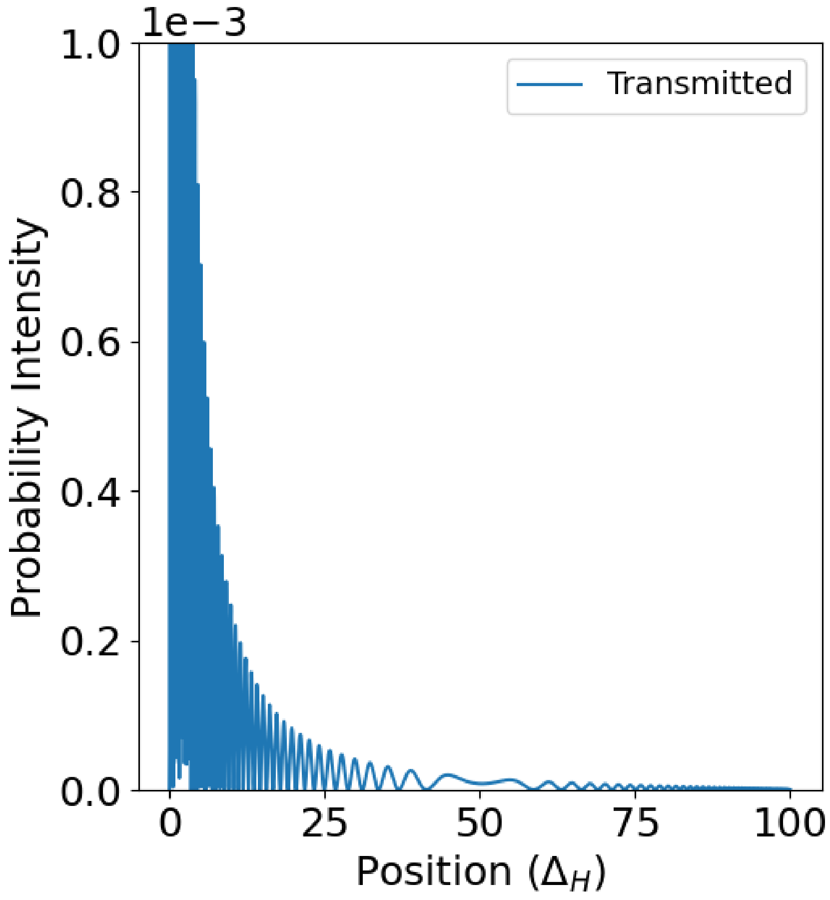
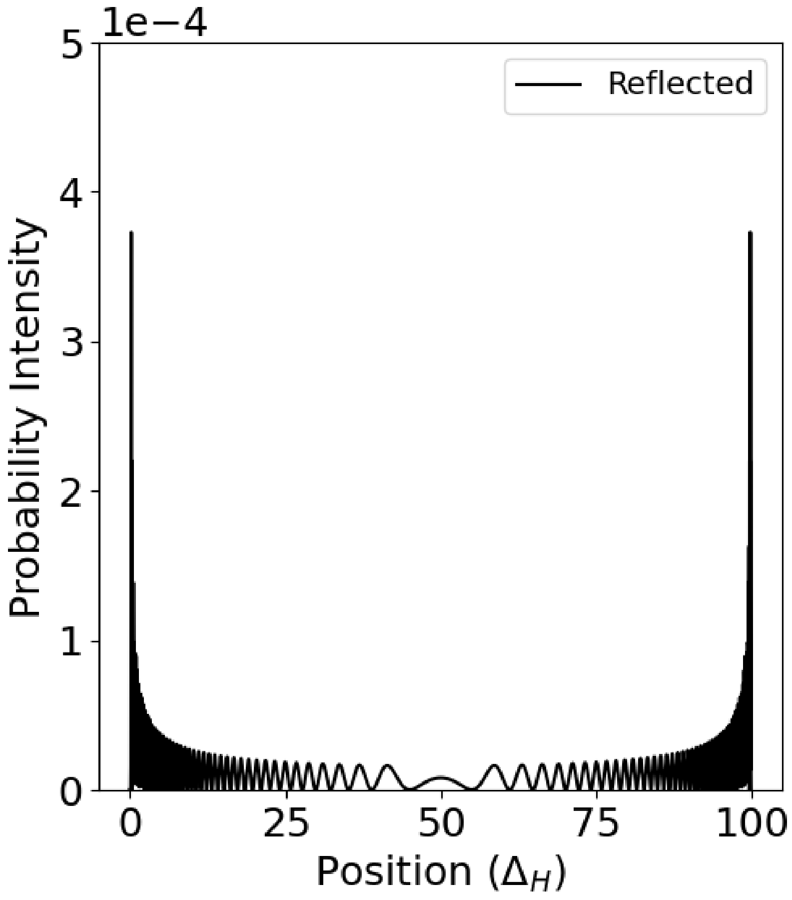
Quantum-information approach to dynamical diffraction theory

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

QI Model – Laue Crystal

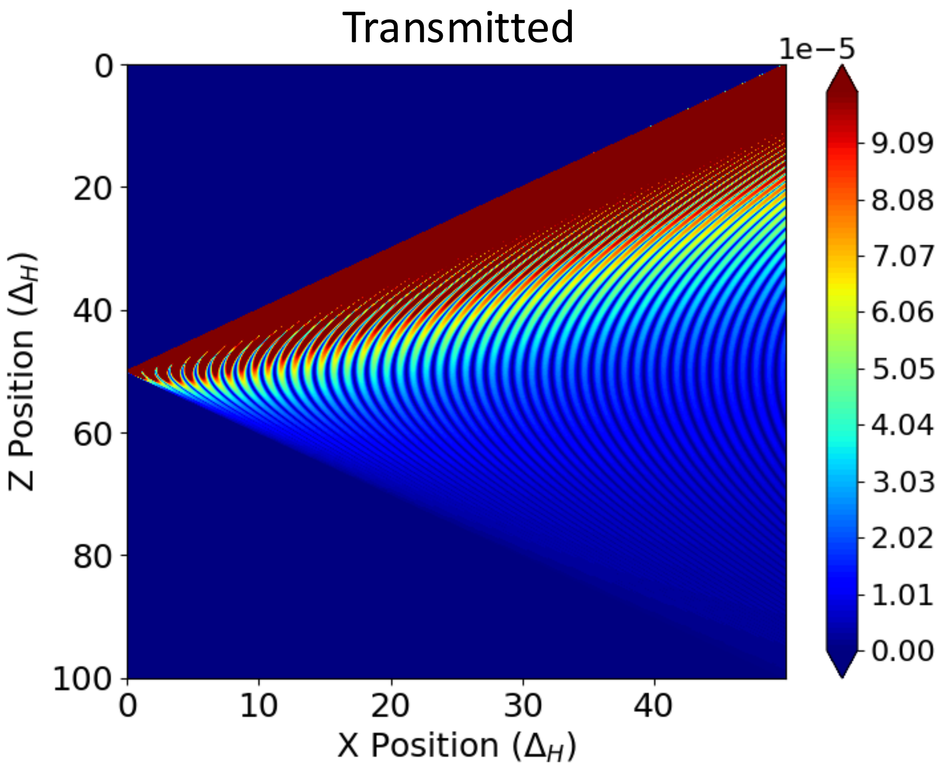


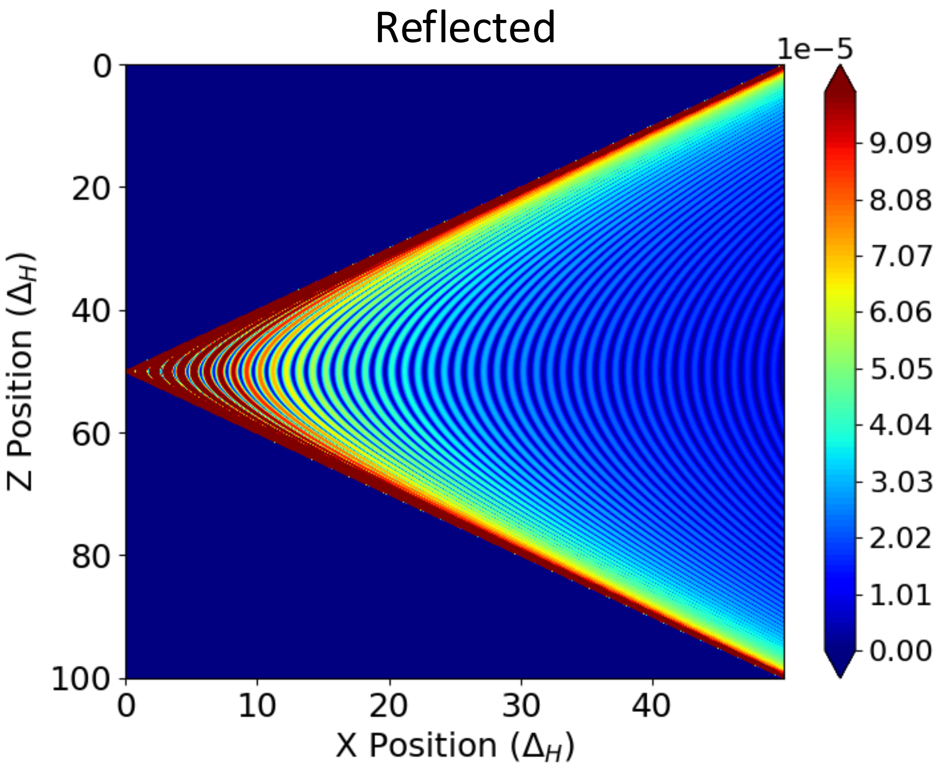


Parameters:
$D = 2.5\ mm$, assuming
$\Delta_H = 50\ \mu m$

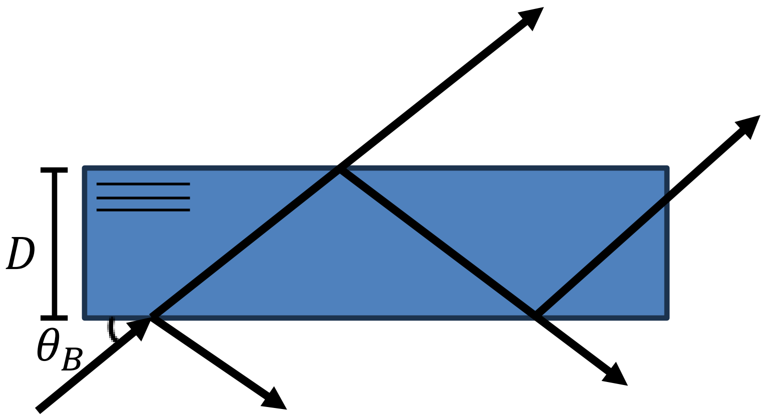
- Intensity profiles predicted by DD are reproduced with a QRW

QI Model – Laue Crystal



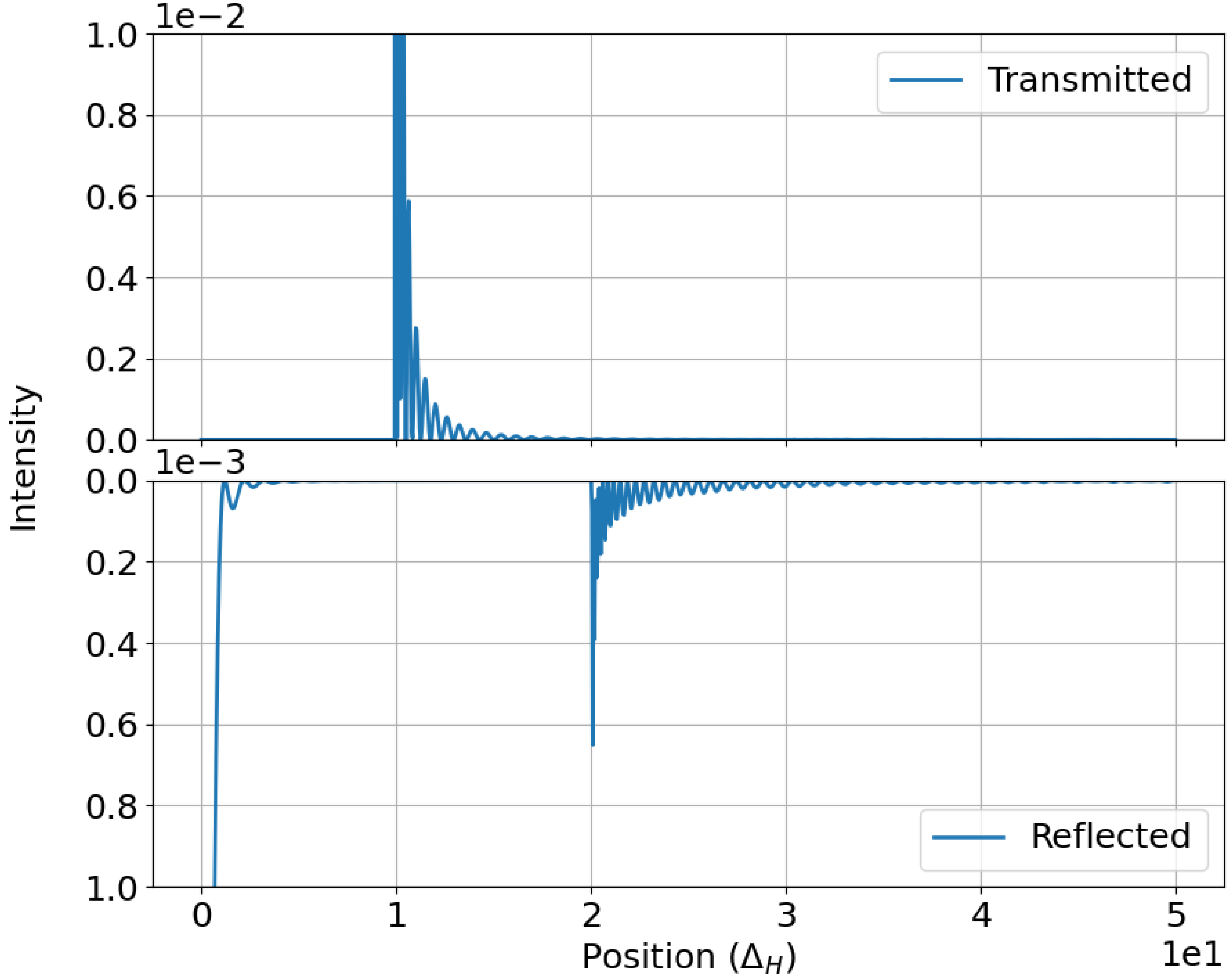


QI Model – Bragg Crystal

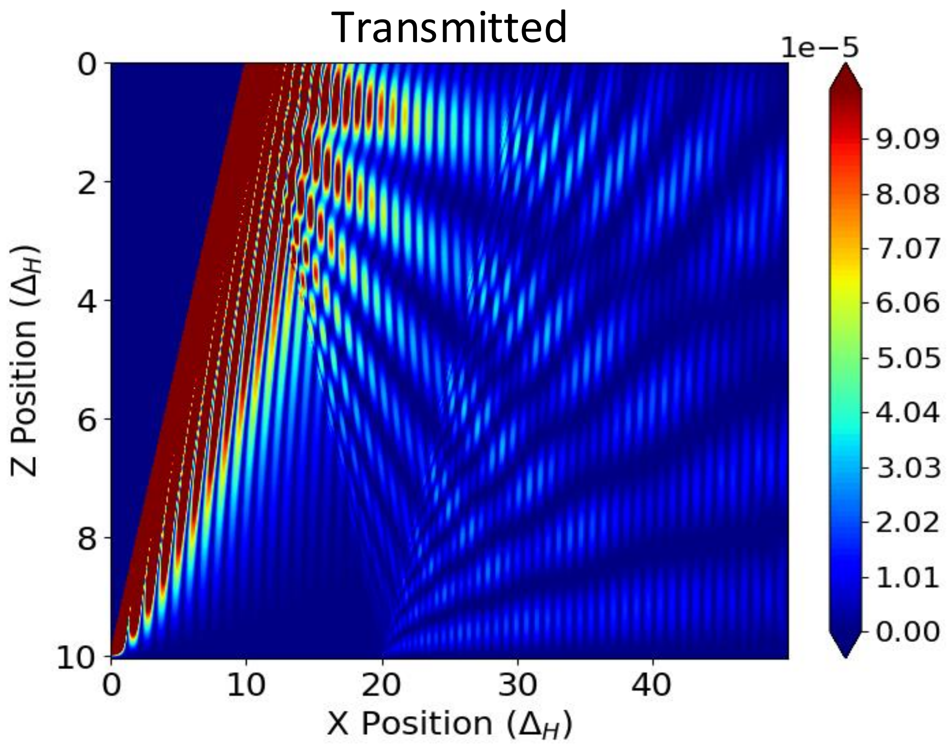


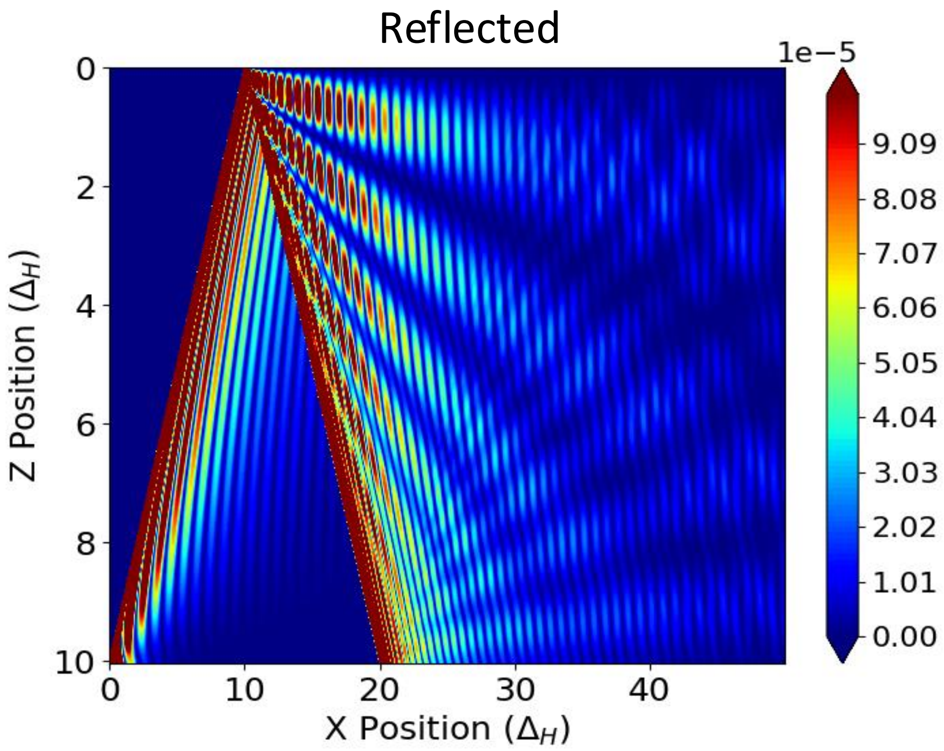
Parameters:
$D\ = 0.5\ mm$, assuming $\Delta_H\ = 50\ \mu m$

- Intensity profiles predicted by DD are reproduced with a QRW



QI Model – Bragg Crystal

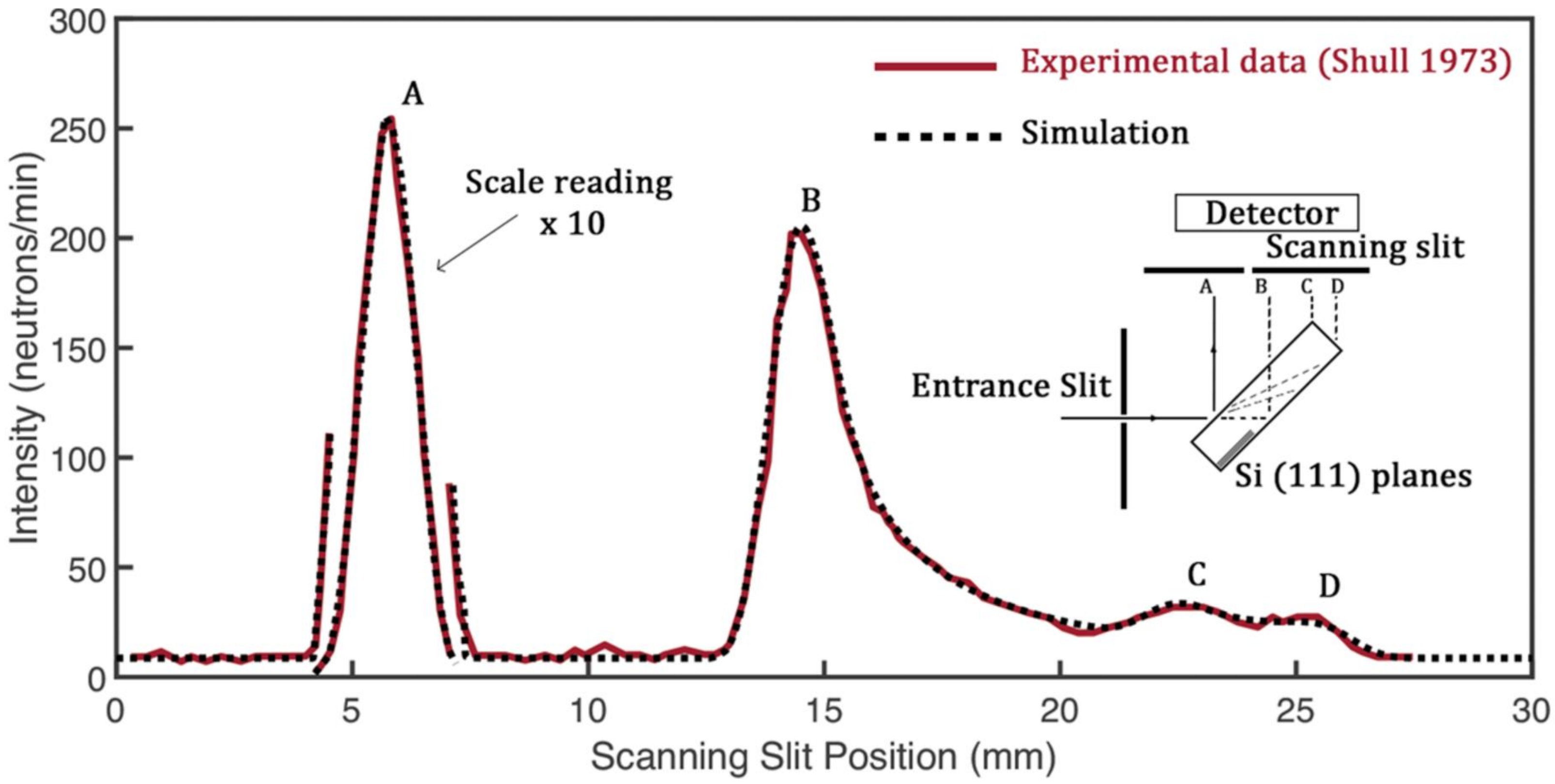




Comparison with Experiments

Experiment:
4.43 Å neutrons
$\theta_B = 45°$
111 reflection

- Account for incoming beam shape by convolving simulation with experimental profile



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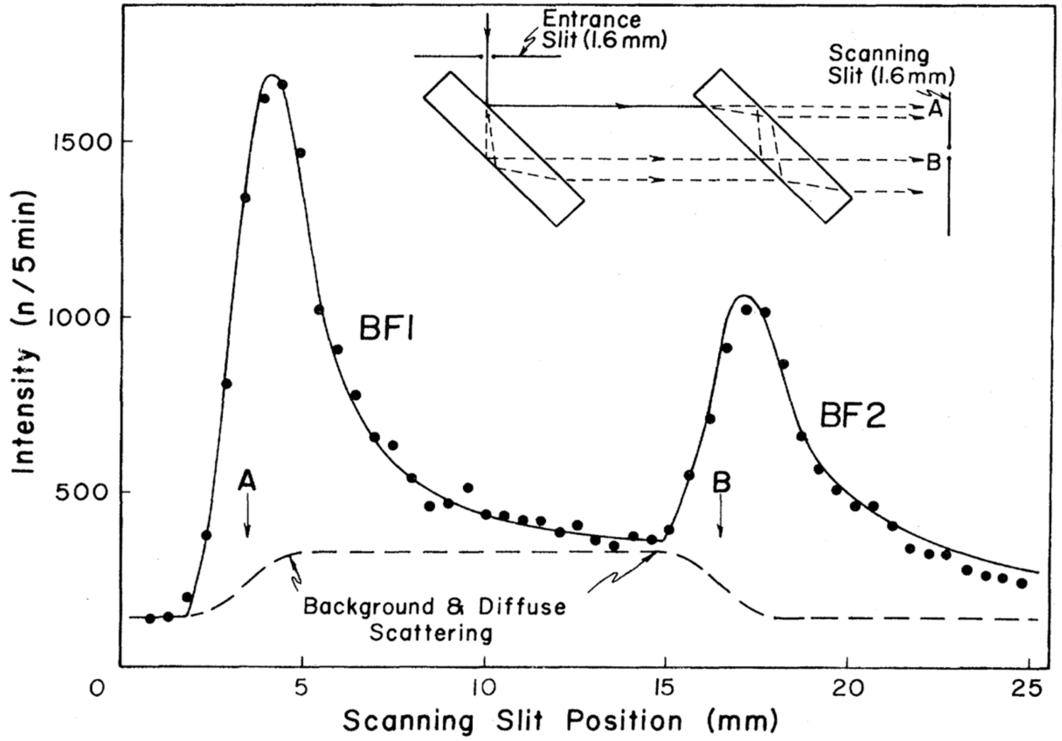
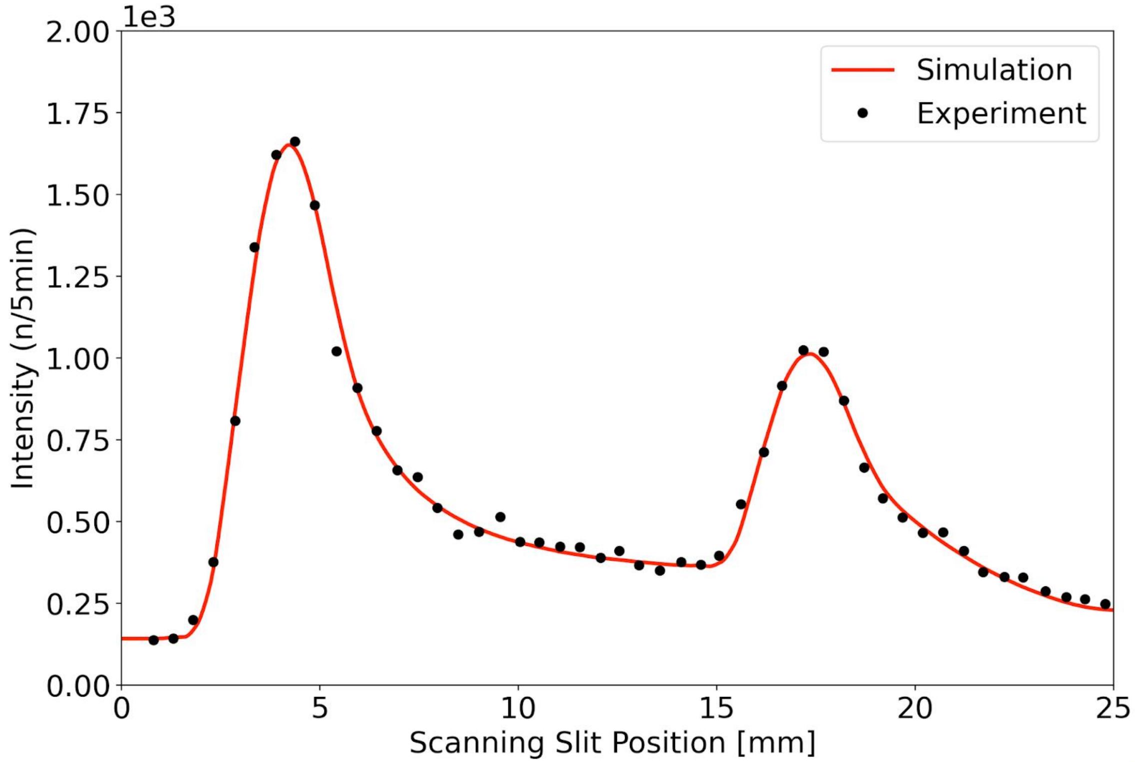
C. G. Shull, Perfect crystals and imperfect neutrons, J. Appl. Crystallogr. 6, 257 (1973)

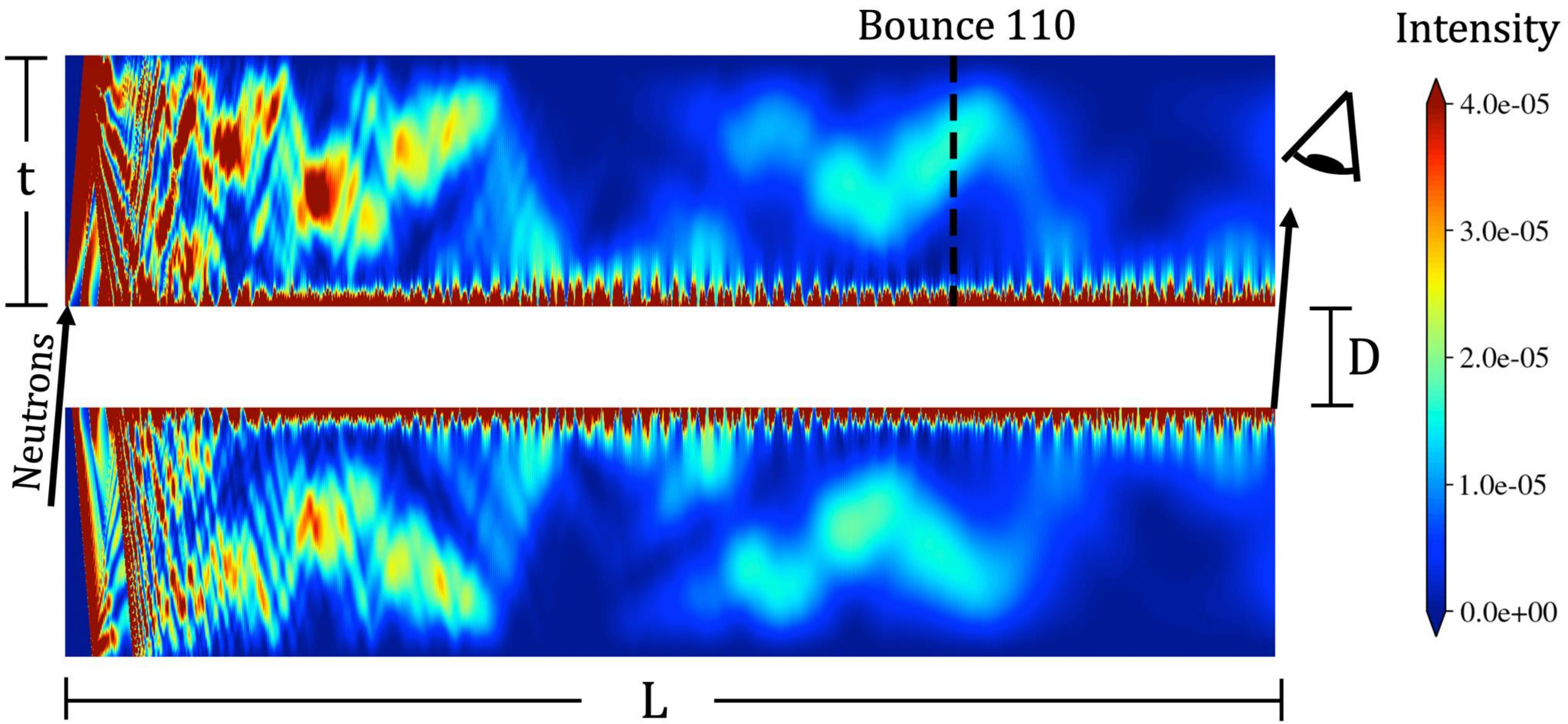
Comparison with Experiments



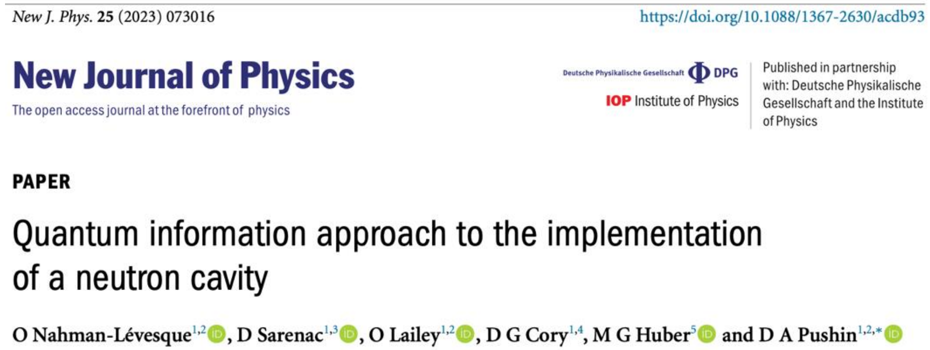


A. Zeilinger, C. G. Shull, J. Arthur, and M. A. Horne, Phys. Rev. A **28**, 487(R), 1983

Applications: Neutron Cavity



- Capable of long term neutrons storage
- Important device for neutron electric dipole moment measurements



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

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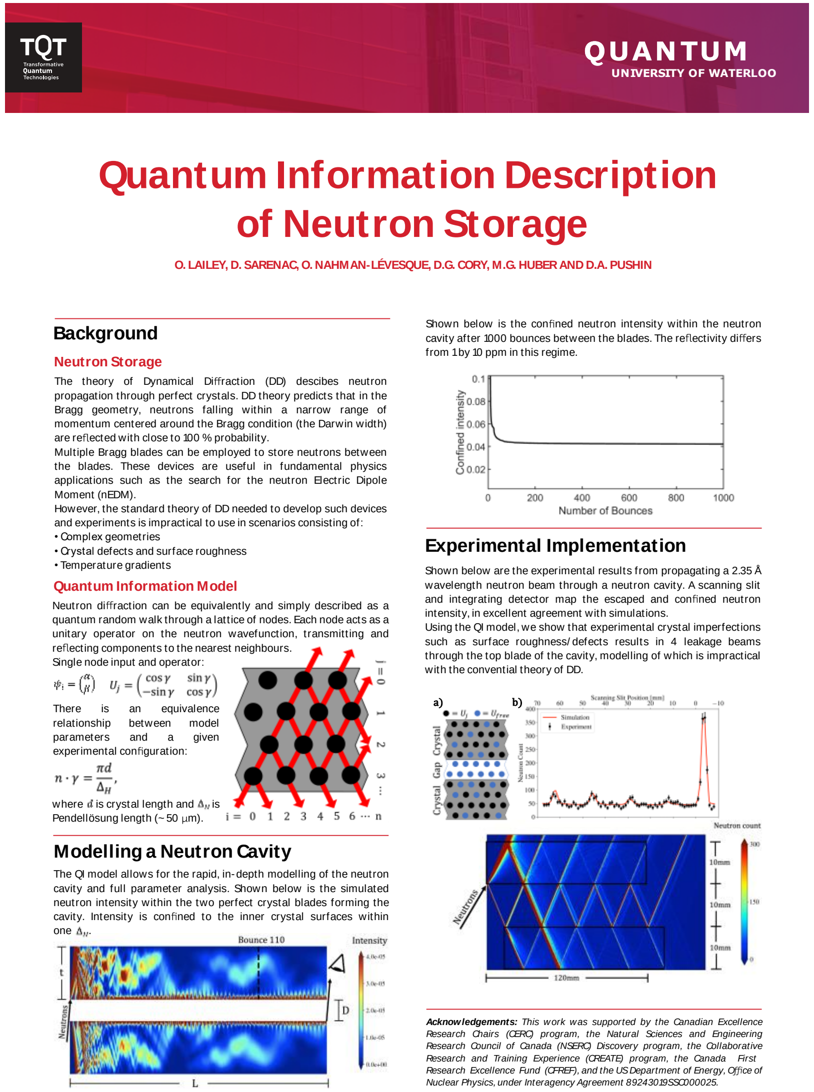
PAPER

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,*]

Applications: Neutron Cavity

- To learn more and see experimental results:
- Check out “Quantum Information Description of Neutron Storage” poster
- Wednesday January 15th 16:00 – 18:00
- Poster presenter: Owen Lailey, P013



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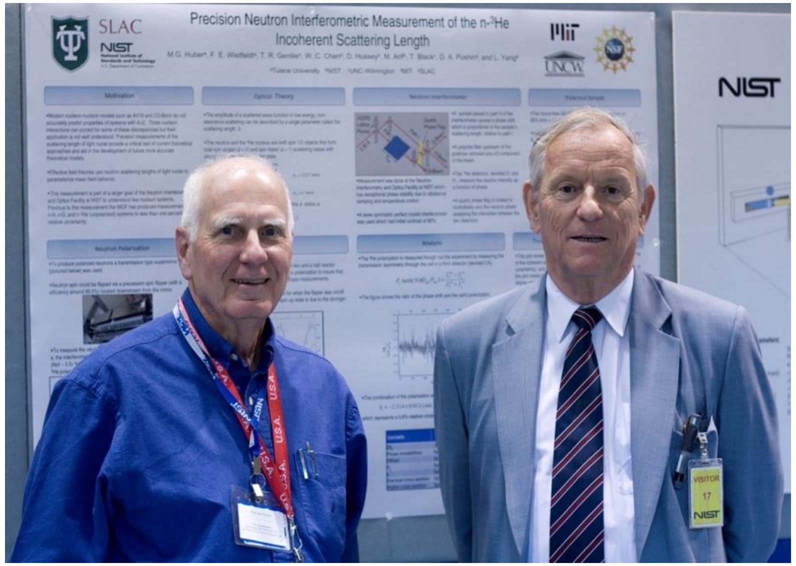
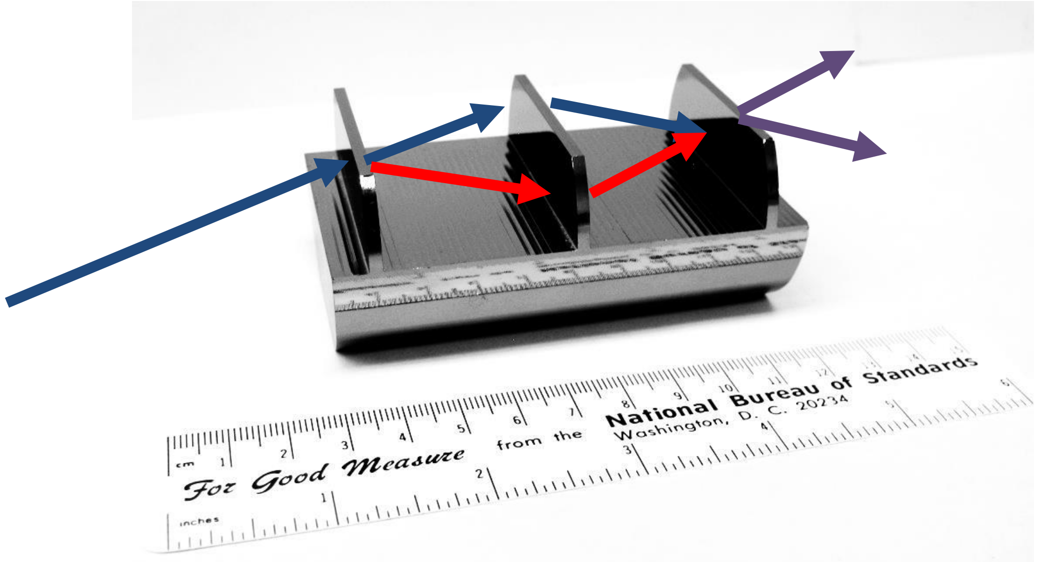
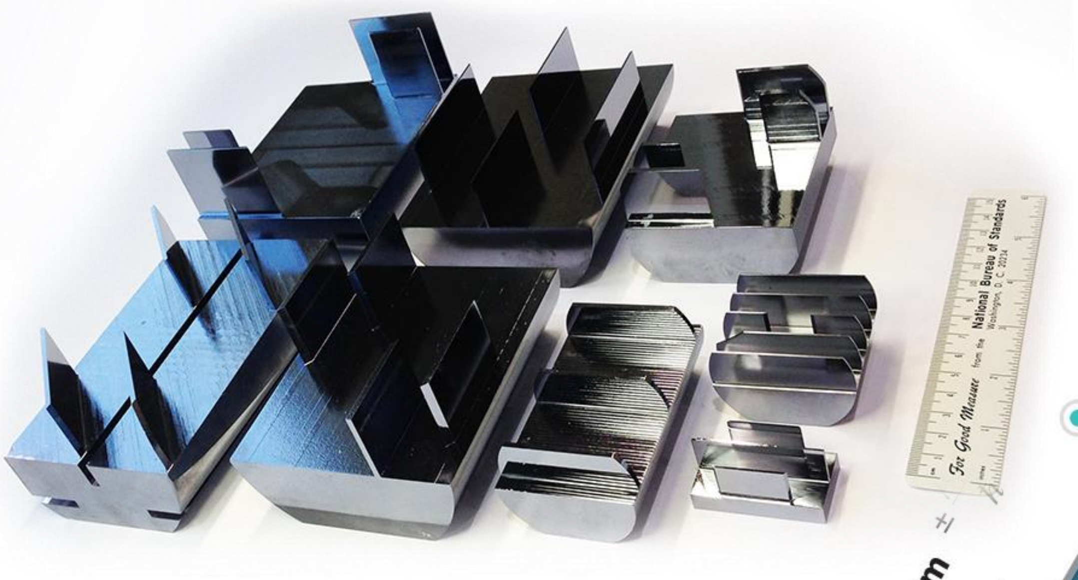
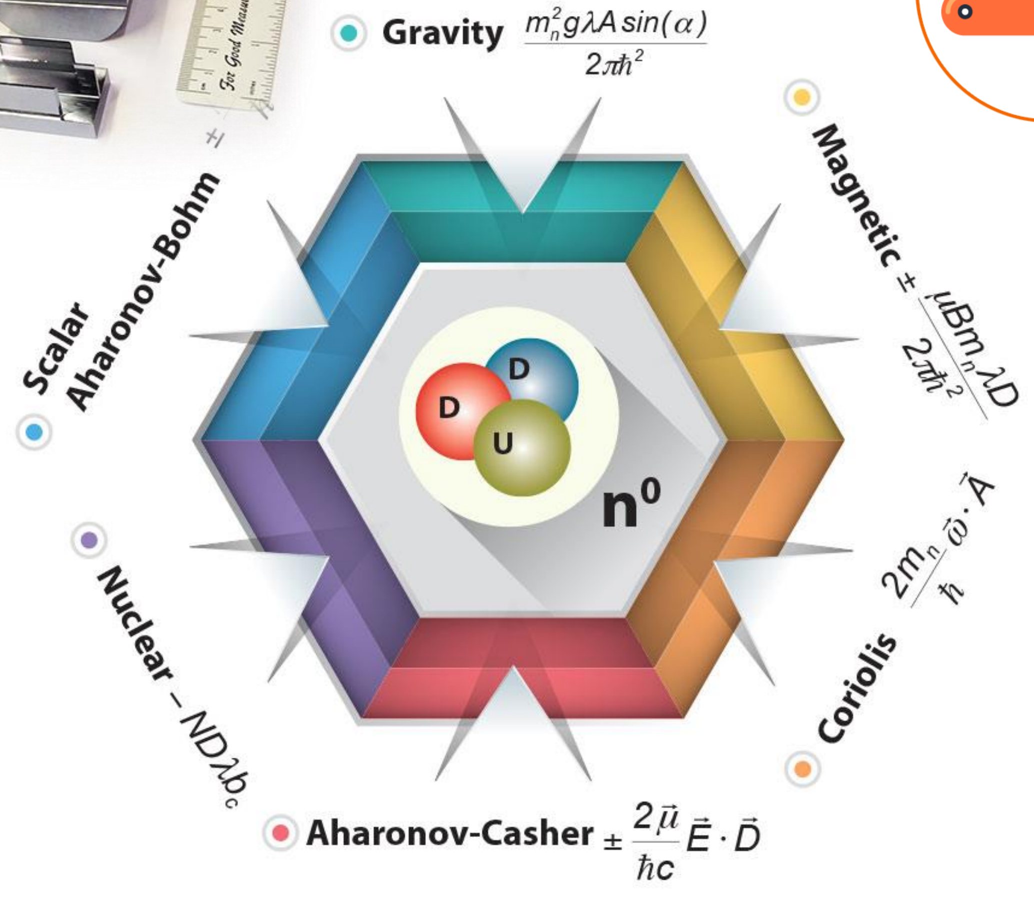


Neutron Interferometer





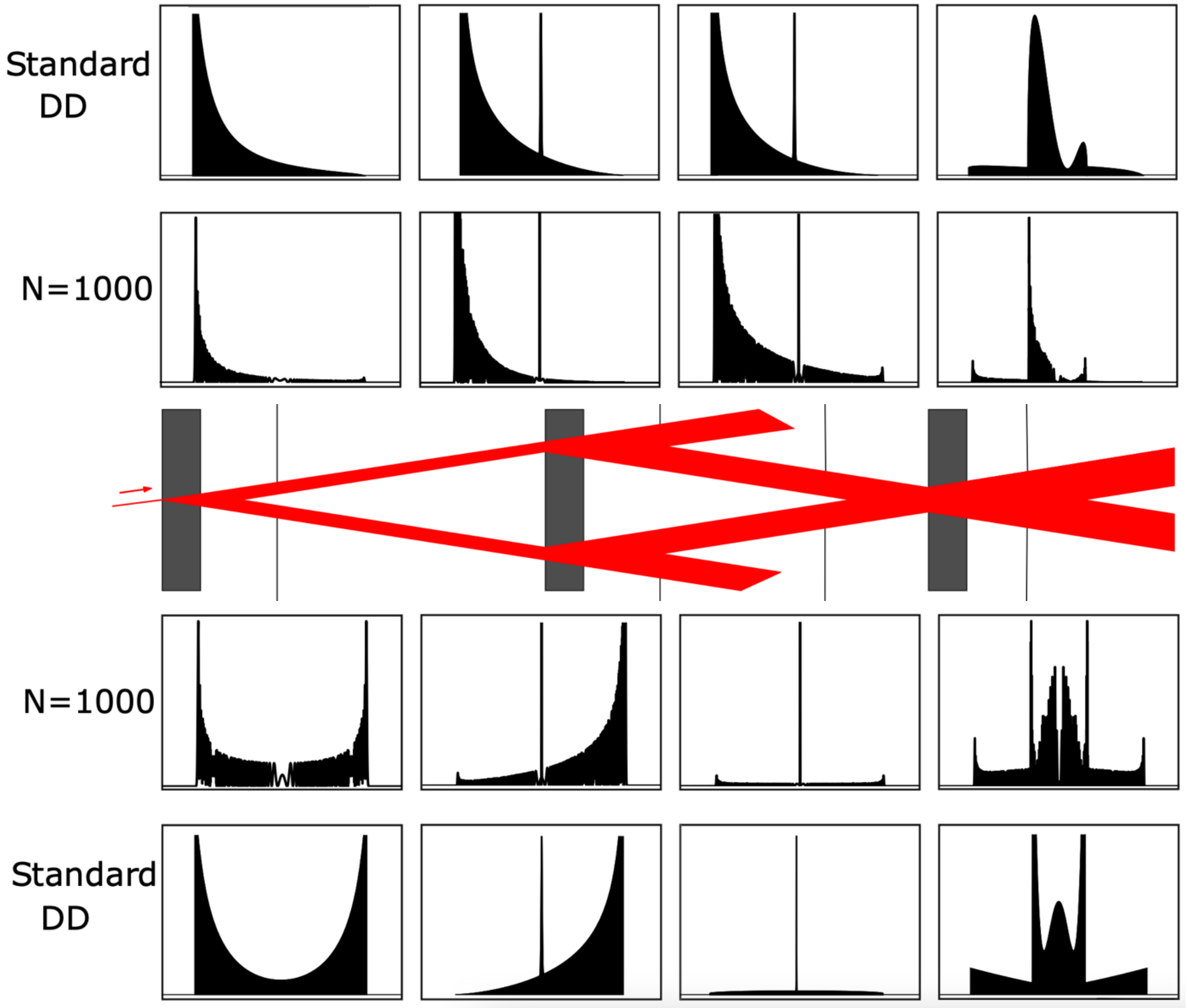
Multiple Interactions

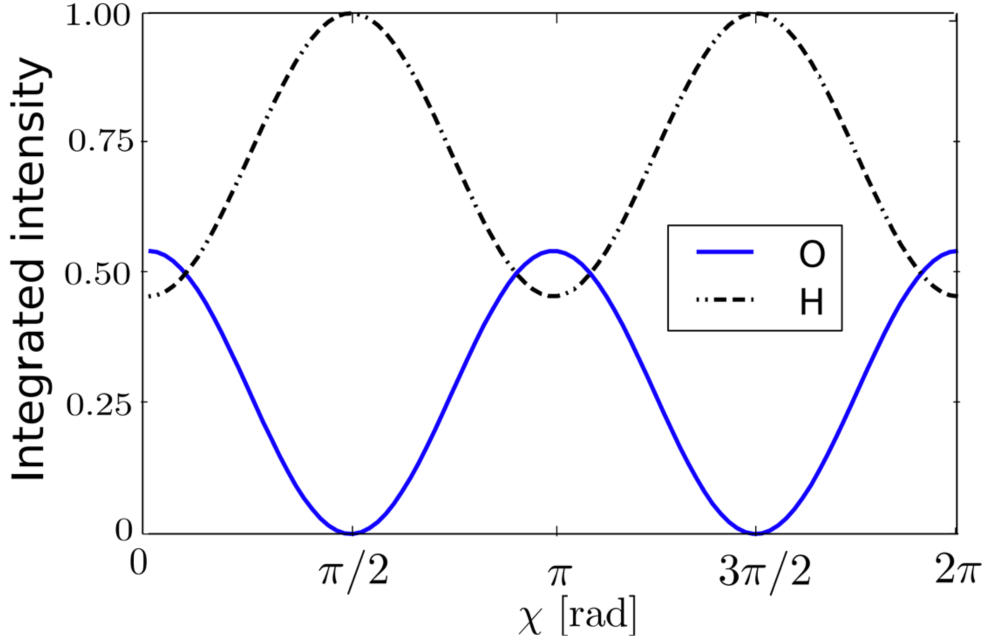


Neutron interferometry is a diverse instrument

- Nuclear
- Gravity
- Magnetic
- Coriolis
- Aharonov-Cashir
- Scalar Aharonov-Bohm
- Search for Dark Energy

Applications: Neutron Interferometer





Nsofini, J., Ghofrani, K., Sarenac, D., Cory, D. G., & Pushin, D. A. (2016). Quantum-information approach to dynamical diffraction theory. *Physical review A*, *94*(6), 062311.

Pendellosung Interference

Q; Reciprocal lattice vector
b_N; Nuclear scattering length
Z; Atomic Number
f_e; Atomic form factor

The coherent scattering length has informations about

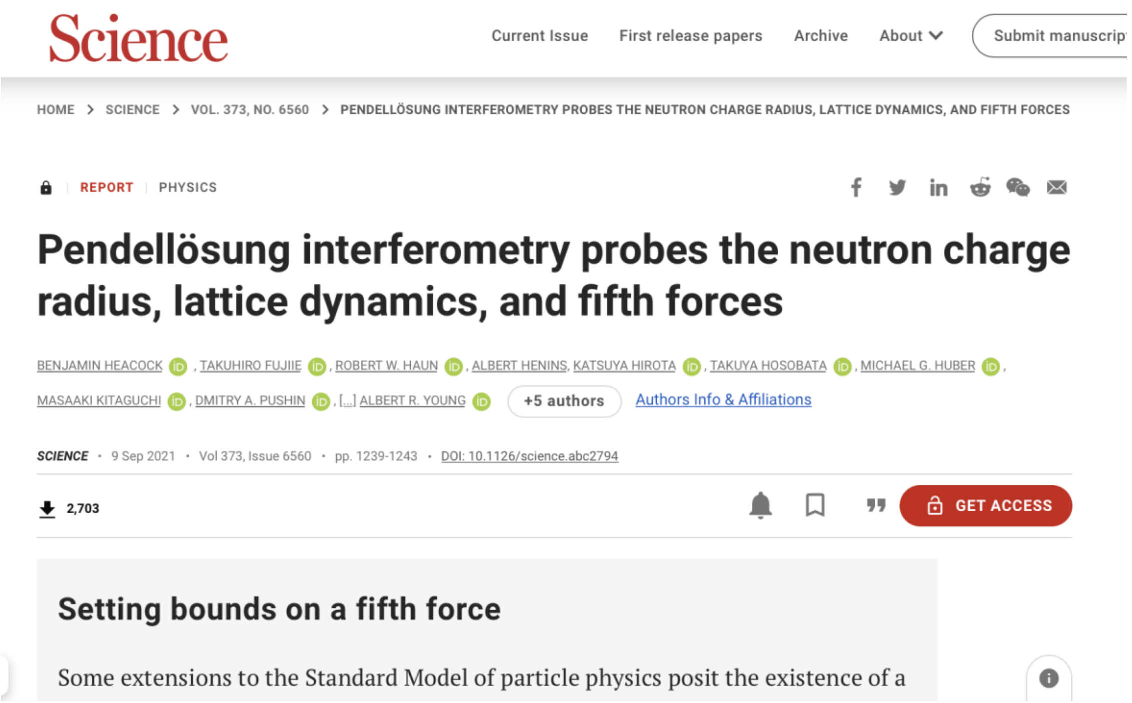
$$b(Q) = e^{-W(Q)}\{b_N + Z[1 - f_e(Q)] + b_5(Q)\}$$

Debye-Waller factor

neutron-electron scattering length

Fifth Force term

Results; (DWF) $B_{\mathrm{Si}} = 0.4761(17)\ \text{Å}^2$, $b_{ne} = -1.28(10) \times 10^{-3}$ fm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REPORT | PHYSICS

Pendellösung interferometry probes the neutron charge radius, lattice dynamics, and fifth forces

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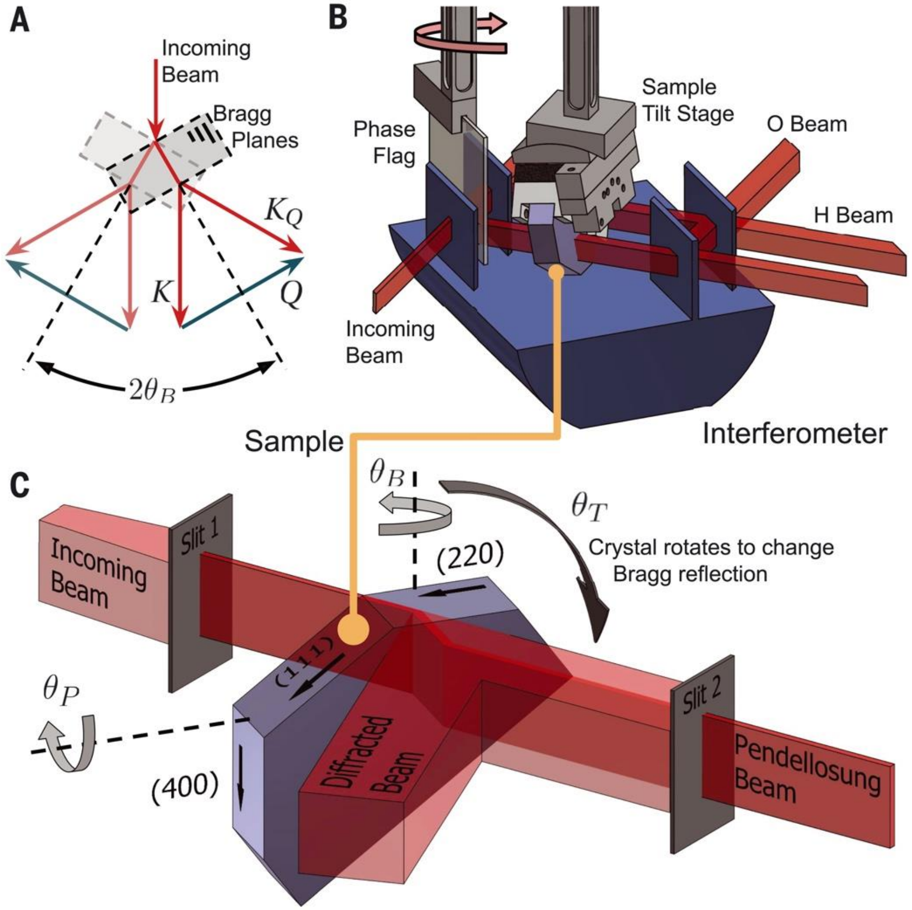
Setting bounds on a fifth force

Some extensions to the Standard Model of particle physics posit the existence of a



Pendellosung Interference

The coherent scattering length has informations about

$$b(Q) = e^{-W(Q)}\{b_N + Z[1 - f_e(Q)] + b_5(Q)\}$$

Q; Reciprocal lattice vector
b_N; Nuclear scattering length
Z; Atomic Number
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Debye-Waller factor | neutron-electron scattering length | **Fifth Force term**

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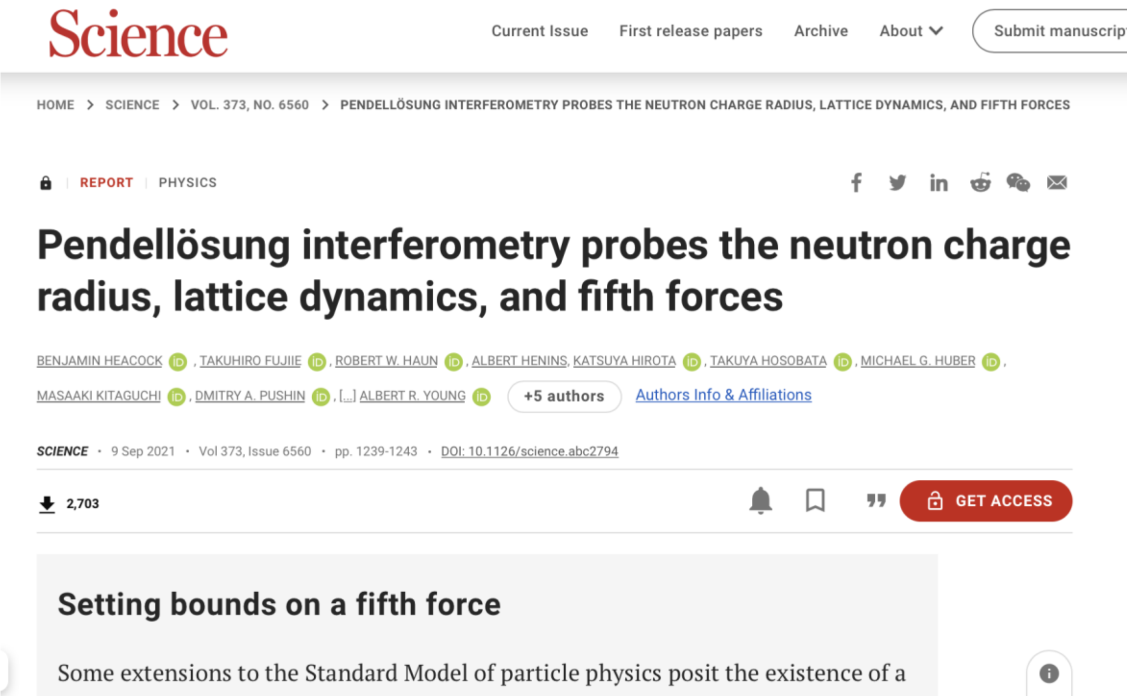
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Setting bounds on a fifth force

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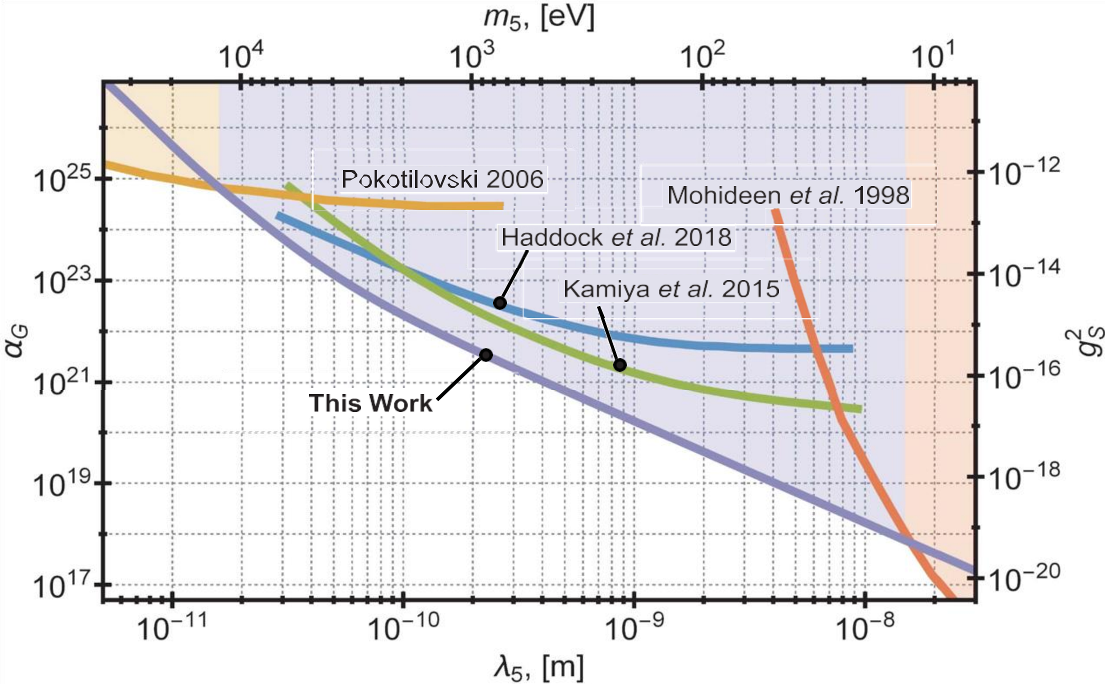

Heacock et al., Science (2021)





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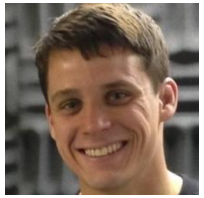



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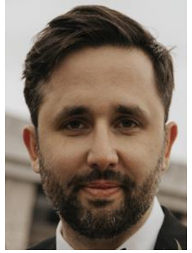

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