Generation and Application of Structured Neutrons

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

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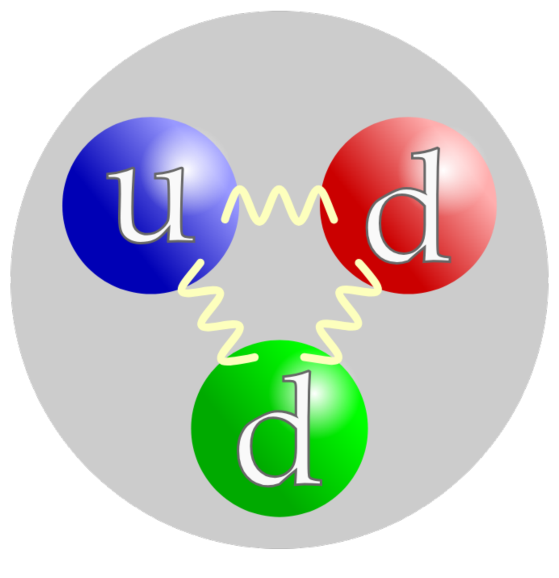
Neutrons

Neutrons are invaluable tools for non-destructive **material analysis** and the experimental verification of **fundamental physics** through their unique properties:

- Neutral charge
- Magnetic sensitivity
- Nanometer wavelengths
- High material penetrability
- Isotope sensitivity



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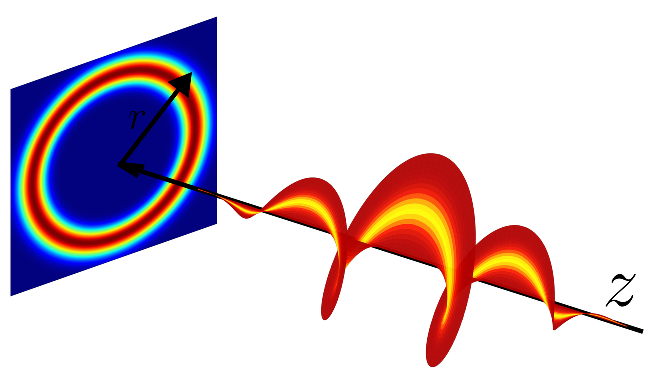
Structured Waves in Physics



$$\psi = J_\ell(k_r, r)e^{i\ell\phi}e^{ik_z z}$$

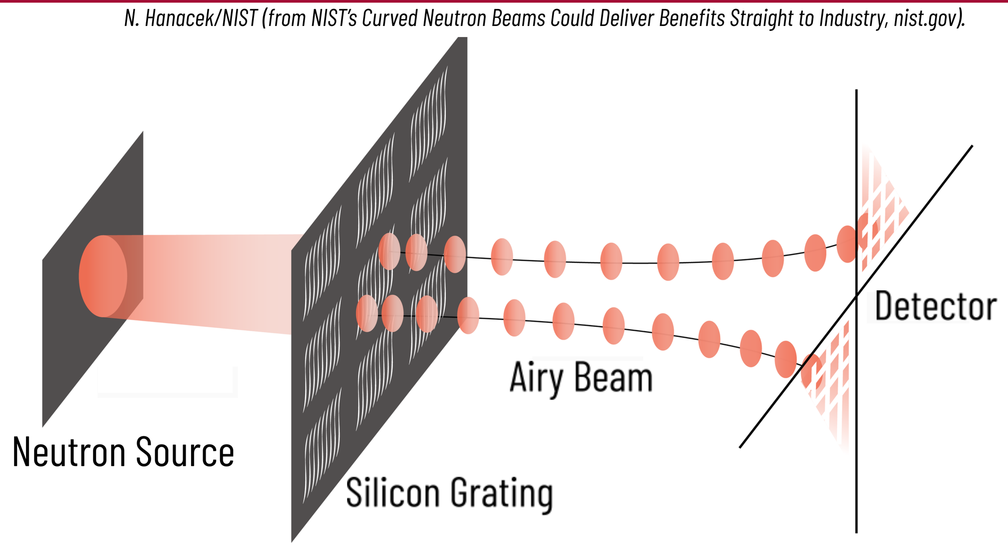
Structured waves are complex waves that cannot be approximated by a single plane wave. They possess **several unique properties** and are crucial for:

- Communication and imaging
- Quantum optics
- Optical and electron microscopy

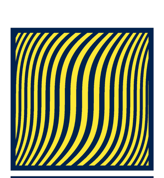
Holographic Generation of Structured Neutrons

An array of **silicon phase gratings** was fabricated using electron-beam lithography. These gratings **diffract** incident neutrons, imprinting the grating profile onto the wavefunction to **spatially structure** the beam **[1,2]**.

N. Hanacek/NIST (from NIST's Curved Neutron Beams Could Deliver Benefits Straight to Industry, nist.gov).

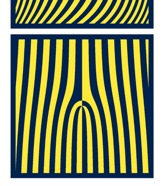


$$\frac{1}{2}\operatorname{sgn}\left(\sin\left[\frac{2\pi}{p}x + c_x x^3 - c_y y^3\right]\right) + \frac{1}{2} \longrightarrow$$



Airy Grating Profile

$$\frac{1}{2}\operatorname{sgn}\left(\sin\left[\frac{2\pi}{p}x + q\tan^{-1}(y/x)\right]\right) + \frac{1}{2} \longrightarrow$$

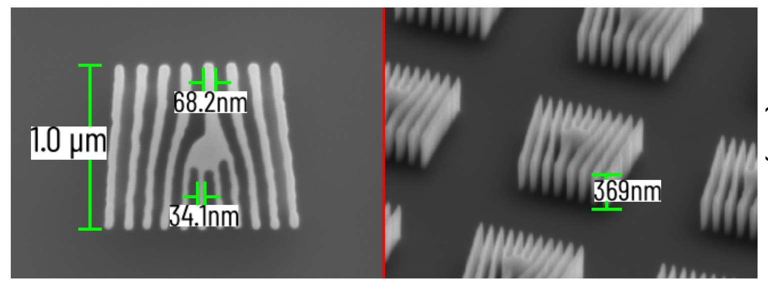


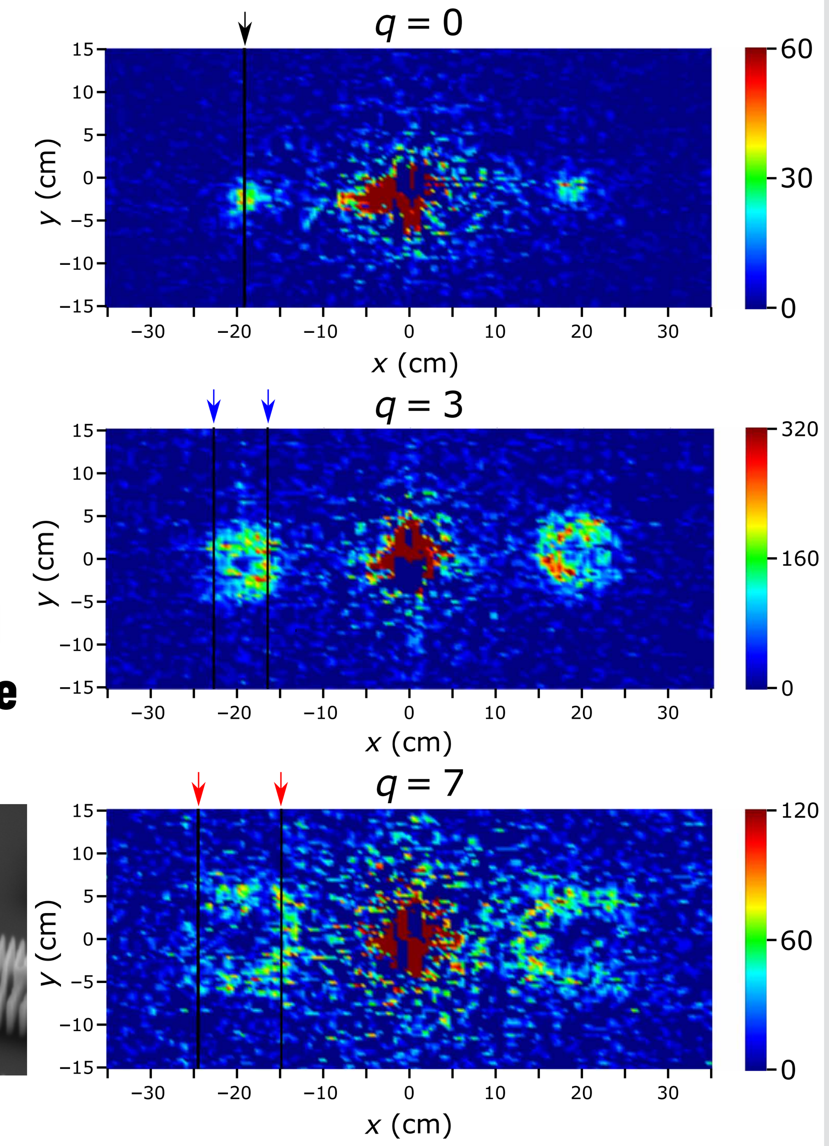
Fork Grating Profile

Neutrons with Orbital Angular Momentum (OAM)

Phase gratings with **q-fold fork dislocations** are a standard tool in optics that produce photons with an **OAM value of** $\ell = m\hbar q$ at the m[th] diffraction order.

- 6,250,000 **1×1 μm gratings.**
- period of 120 nm, height of 500 nm.
- The **angle of divergence** of the 1[st] diffraction order is $\theta \approx \lambda/p \approx 0.01$ rad this corresponds to a **spatial distance** of $x \approx 19$ cm on the camera **[1]**.



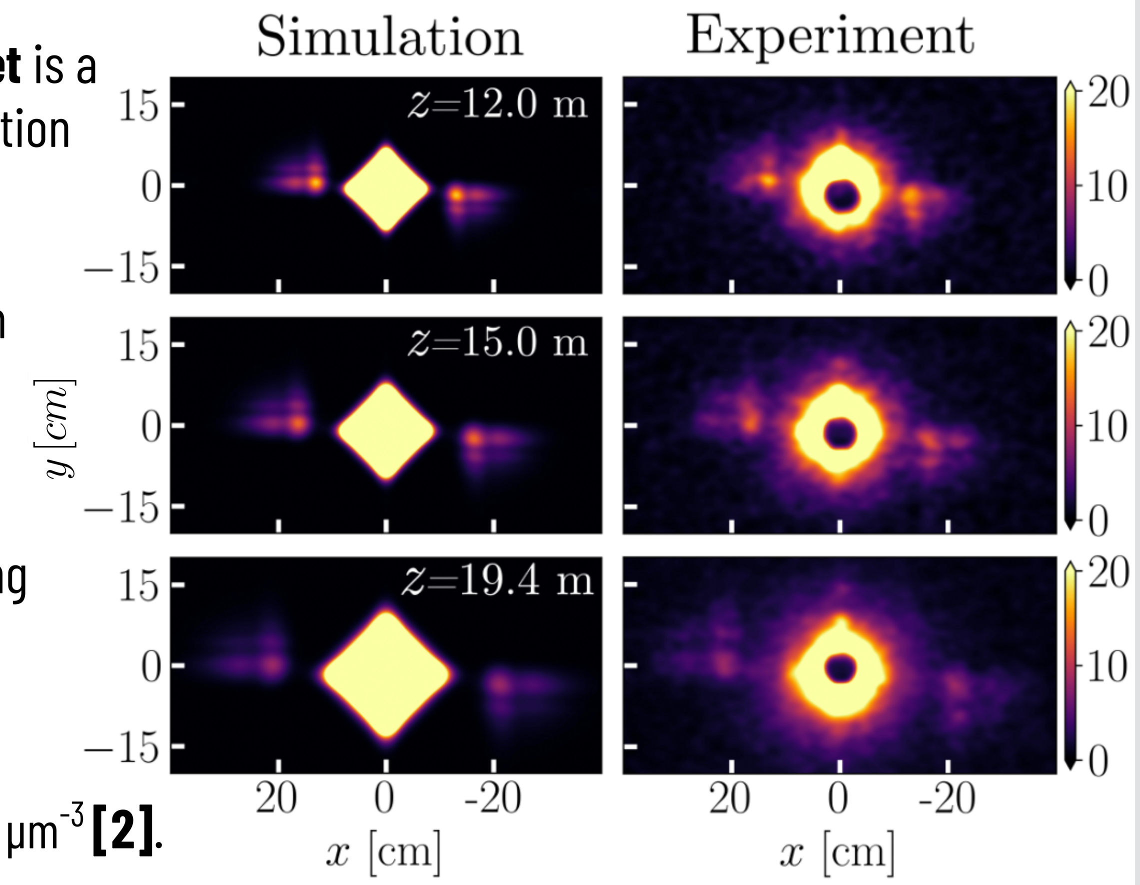


Neutron Airy Beams

The **Airy wave packet** is a **diffraction-free** solution to the potential-free Schrödinger equation that manifests a form of **self-acceleration** and **self-healing**.

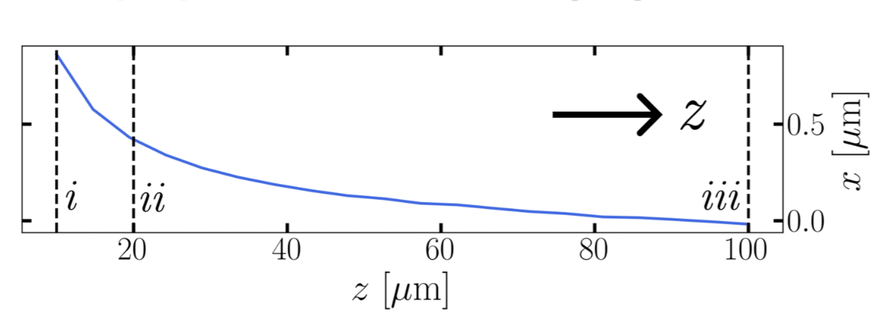
Each individual grating possessed:

- period of 120 nm
- height of 300 nm
- $c_x = 55\ \mu m^{-3}$, $c_y = 45\ \mu m^{-3}$ **[2]**.

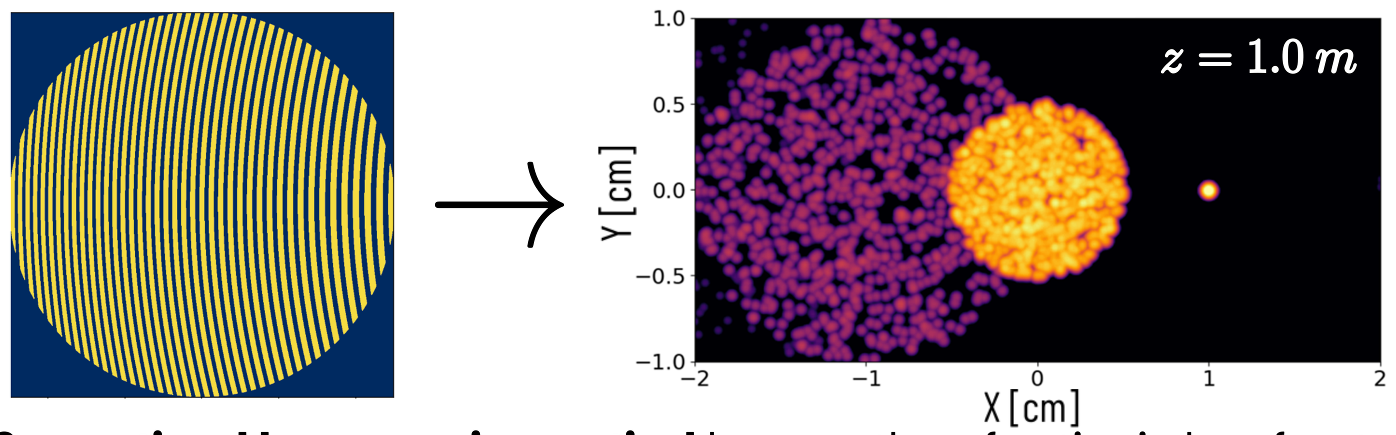


$$\mathrm{Ai}(s) = \frac{1}{\pi}\int_0^\infty \cos\left(\frac{1}{3}t^3 + st\right) dt$$

$$\psi_i(x_a, y_a, 0) = \mathcal{N} e^{-\frac{x_a^2+y_a^2}{2\sigma_i^2}} Ai\left(\frac{x_a}{x_0}\right) Ai\left(\frac{y_a}{y_0}\right)$$



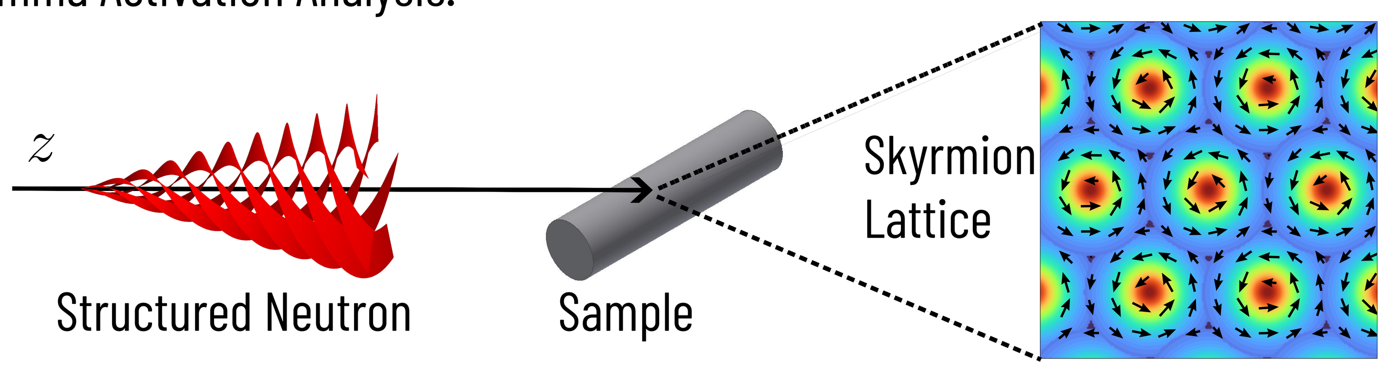
Focused Neutron Beams



- **Conventional lenses** are **impractical** because the refractive index of materials for neutrons is very close to unity (n ≈ 1).
- **Off-Axis Zone Plates** can serve as diffractive **neutron lenses** that separate the focal spot from the intense direct beam. This could significantly **enhance** the signal-to-noise ratio in **neutron imaging** and **scattering experiments [3]**.

Applications of Structured Neutrons

- ***Neutron OAM:*** Chiral skyrmion lattices, Quantum Information Processing (QIP), and OAM spectroscopy ***[1]***.
- ***Neutron Airy Beams:*** Airy-vortex beam generation, potential-free accelerating wave packets, and quantum gravitational states (Dark Sector searches) ***[2]***.
- ***Focused Neutrons:*** Airy beam enhancement, high-flux neutron imaging, and Gamma Activation Analysis.



Conclusions

- **Neutrons** play a vital role in **material analysis** and the experimental testing of **fundamental interactions**.
- **Neutrons carrying OAM** have an additional quantum degree of freedom.
- **Neutron Airy beams** can exhibit a form of self-acceleration and self-healing.
- **Zone Plates** can act as practical alternatives to conventional lenses.

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NSERC CRSNG | PSI | Oak Ridge National Laboratory | UKRI Science and Technology Facilities Council ISIS Neutron and Muon Source | TQT Transformative Quantum Technologies | NIST National Institute of Standards and Technology U.S. Department of Commerce

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