

## Neutron Interferometric methods and quantum sensing

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**Summary:** Advances in material science and engineering make it possible to access artificial materials or ‘metamaterial’ properties and structures on the length scale comparable to the wavelength of ultracold neutrons  $\sim 100$  nm. Strong neutron scattering effects such as Anderson localization, resonance scattering may be studied in the laboratory according to our recent theoretical studies. UCN interferometry and high-resolution spectroscopy (sub-pico-electronvolt resolution) in neutronic metamaterials are examples of new experimental possibilities that can probe quantum gravitational states of neutrons, and quantum sensing based on ultracold neutrons.

**Background:** Neutron interferometry is one of the most sensitive methods for quantum sensing [RW:2014], including sensing of the minute force of gravity and equivalent due to the unique electric charge neutrality of neutron. By using a thermal neutron beam, gravitationally induced quantum interference of neutron was first demonstrated in the seminal experiment of Colella, Overhauser and Werner (COW) in 1975. By using a very weak ultracold neutron flux, one-dimensional gravitationally bound quantum discrete states of ultracold neutron were reported in laboratory by V. V. Nesvizhevsky and collaborators in 2002. Gravitational quantum states of neutron couples both gravity and quantum physics on an energy scale of femto- eV ( $10^{-15}$  eV) or less on the spatial length scale of 10 micrometers [AJLS:2010], and

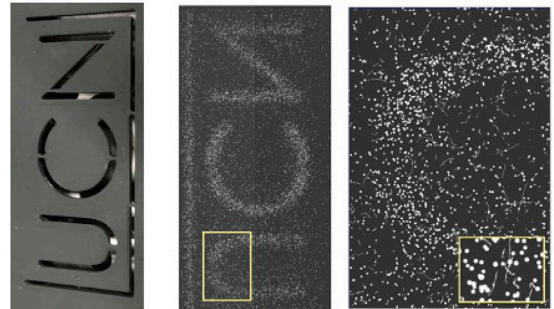


Figure 1. (Left) A 3D printed rectangular mask using thermoplastic material. This mask covered the full size of the detector (6 cm  $\times$  3 cm). The mask was positioned about 3 mm above the borated surface of the bCCD. (Center) A raw bCCD image showing the transmission flux of UCN through the mask. (Right) Zoom into the yellow box at the center panel, showing the hits from the different particles and different energies from the neutron capture reactions. Inset shows a zoom into an even smaller region of the image. More details in [KCC:2021].

therefore complement quantum gravitational states of cold atoms and laser gyroscopes. On the other hand, the current achievable ultracold neutron density is on the order of 100 /cc, which is much less than that of an ultracold atom cloud. In addition to testing the fundamental quantum physics and concepts using neutrons such as entanglement, contextuality, squeezing, post-selection, intensity interference, some of the open problems that can be probed by neutrons and especially gravitational quantum states of ultracold neutrons include non-Newtonian gravity, the fifth force, Casimir effects, the equivalence principles on sub-micron length scales, sub-keV dark matter search.

Ultracold neutron experiments are currently limited to a few facilities world-wide including LANSCE at Los Alamos. LANL and collaborator have also made significant advances in position-sensitive measurement of UCN. One recent publication reported a time-resolved UCN measurement with a few micro-meter resolution [KCC:2021]. Follow-on work has now demonstrated spatial resolution less than 1 micron, with a potential to approach the wavelength of a ultracold neutron or less. The new detector allows construction new types of neutron interferometers, for example, with small parallel neutron guides [WDMS:2020] as well as experimental studies of the equivalence principle led by the University of Tokyo.

**Timeline:** Initial experiment results can be demonstrated on the timeline of two to three years, paving the way towards a comprehensive experimental program in five to ten years.

**Resources required:** Support for 2.0 FTE senior scientist (Wang, Demartau, Kamiya, Liu, Makela, Morris, Shih, Young), one to two postdocs, two to three graduate students. Access to the UCN facility at Los Alamos.

**References:**

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[RW:2014] H. Rauch and S. A. Werner, *Neutron Interferometry*, 2nd ed. (Oxford University Press, 2014).

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