May 9, 2025

Faculté des sciences
Département de physique
Complexe STEM (336)

Faculty of Science
Department of Physics
STEM Complex (336)

613-562-5757
613-562-5190
phyinfo@uOttawa.ca
science.uOttawa.ca

150 Louis-Pasteur
Ottawa ON K1N 6N5
Canada

To: *The Scientific Council of the Discipline of Physical Sciences*

University of Warsaw

I have carefully reviewed the doctoral dissertation submitted by Ms Bohnishikha Ghosh, titled *"Observations of anomalous transverse local momenta in spatial wave functions,"* presented to the Faculty of Physics, University of Warsaw.

This dissertation investigates the phenomenon of *optical backflow*—a concept with foundational roots in quantum mechanics—through experimental realisations in classical and quantum optical setups. It further explores its manifestation in the single-photon regime and proposes a novel methodology for observing quantum backflow with electrons in a transmission electron microscope (TEM). The research is original, intellectually ambitious, and executed with commendable methodological rigour, contributing meaningfully to the expanding field of structured light and weak measurement analogues in optics.

A notable strength of the dissertation is its interdisciplinary scope, combining elements of wave optics, quantum measurement theory, and electron microscopy. At the conclusion of each chapter, the author has explicitly outlined the individual contributions, including her own, which adds transparency and clarity to the collaborative aspects of the work.

The key scientific achievements of the thesis—many of which have already been published in peer-reviewed journals—include:

- The experimental observation of optical backflow via interference of two beams using a Shack-Hartmann wavefront sensor.
- The first experimental realisation of azimuthal backflow employing Laguerre-Gaussian beams with helical phase structure.
- The backflow concept was extended into the single-photon regime using spontaneous parametric down-conversion (SPDC) and intensified sCMOS detection.
- A proposal and theoretical modelling for the observation of quantum backflow in a TEM, with indications that experimental efforts are underway in collaboration with other research teams.

The originality of this dissertation lies in making a concept previously considered theoretically elusive—quantum backflow—experimentally accessible. The author presents a coherent narrative that bridges foundational concepts with experimental implementation, with implications in:

- Super-resolution imaging via superoscillatory light fields;
- Quantum control of free electrons;
- Foundational studies in wave optics and quantum interference.

The dissertation is well-structured and clearly written. The introductory chapters provide a strong conceptual foundation, while each experimental section is carefully motivated with theoretical context. Figures are well-prepared and informative, and the bibliography is thorough and up-to-date. Of particular note are Chapter 2, which provides a detailed and pedagogical treatment of Shack-Hartmann wavefront sensing, and Chapter 5, which outlines robust methods for low-count single-photon detection. These sections stood out for their clarity and depth.

I have made minor annotations in the dissertation regarding consistency in notation, figure labelling, and citing other works overlooked by the author. These are offered as constructive suggestions to enhance the work's clarity and presentation, but do not affect its scientific content or integrity.

On a deeper level, I would like to offer the following suggestions:

- The author could strengthen the discussion on the quantitative significance of backflow, especially in the single-photon regime, by explicitly addressing the signal-to-noise challenges in those experiments, though it is already briefly discussed.
- Exploration of potential links with Bohmian mechanics or trajectory-based quantum interpretations could enrich the theoretical framework and offer broader insight into the phenomenon of backflow.

Despite these minor points, I am thoroughly impressed by the quality, originality, and execution of this doctoral work. Ms Ghosh has demonstrated a high level of scholarly independence and experimental skill, and her research clearly meets—and exceeds—the academic standards required for the degree of Doctor of Philosophy.

Final Recommendation:

I strongly recommend that this dissertation be accepted without revisions (except for minor editorial corrections) for the award of the doctoral degree.

Sincerely yours,

Prof. Ebrahim Karimi

Canada Research Chair in Structured Waves and Quantum Communication

PS: This letter has been proofread by an LLM.