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Ph.D. DISSERTATION DEFENSE

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Title:	Leveraging Spatial Modes of Light to Break Classical Information Bounds
Chairperson:	Dr. Yuping Huang, Department of Physics, School of Engineering & Sciences
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ABSTRACT

The information recoverable from a physical system depends on the measurement performed, not on the signal alone. A measurement can be blind to information that no subsequent processing of its outcomes can recover. In optics, direct intensity detection does not retain the full spatial coherence of a field. Quantum mode-projective measurements instead make detection sensitive to coherent combinations of its spatial components.

This dissertation implements programmable quantum mode-projective measurements through sum-frequency generation (SFG) in a nonlinear crystal. A shaped reference pump upconverts the overlapping components of an incoming signal, which are collected into a single spatial mode at the detector. Programming the pump's spatial profile changes the effective projection, allowing the measurement to be tailored to the problem.

The first project is motivated by Rayleigh's curse: the rapid loss of separation information in direct imaging of two closely spaced, mutually incoherent sources. We build on binary spatial-mode demultiplexing (SPADE), which accesses this information through spatial-mode projections before detection. An optimized Hermite–Gaussian pump superposition improves classification robustness to centroid misalignment and unequal source brightness relative to the standard first-order projection. At a separation one-fifth of the Gaussian point-spread-function width, paired classification success rates reach 89.5% under a centroid offset of half the separation. In a separate test with zero offset but 4:1 brightness mismatch, the paired classification success rate reaches 82.4%.

The second project probes the fundamental limits of extracting class information from a single detected photon and learns quantum mode-projective measurements tailored to this task. A non-linear optical neural network uses trained pump superpositions to classify phase-encoded digits 2, 4, and 7. On 450 test images, first-photon classification gives 56.2% accuracy, compared with 33.3% for object-plane intensity detection and 41.3% for a modeled Fourier-plane camera. Repeated single-shot trials give 53.9%.

Together, these studies demonstrate how spatially selective quantum measurements improve robustness and access phase-dependent information beyond specified intensity-based methods. Their performance depends on the chosen measurement, detection budget, and fidelity of the implemented mode projections.