Unconditional violation of shot-noise limit with two-photon NOON states

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Interferometric phase measurement techniques are a vital toolset used to precisely determine quantities including distance, velocity, acceleration and materials properties. Without quantum enhancement, the precision limit in optical phase sensing (i.e. the minimum uncertainty) is the shot-noise limit (SNL): $\Delta\varphi = 1/\sqrt{N}$, where N is the number of resources (e.g. photons) used.

It has been known for several decades that probing with various optical quantum states can achieve phase super-sensitivity, that is, measurement of the phase with an uncertainty below the SNL [1]. The maximally phase-sensitive state is the NOON state [2], a path-entangled state of definite photon number N,

$$|\Psi_{NOON}\rangle = \frac{1}{\sqrt{2}}(|N\rangle|0\rangle + |0\rangle|N\rangle). \tag{1}$$

Despite theoretical proposals stretching back decades [3], no measurement using such photonic (i.e. definite photon number) states has unconditionally surpassed the shot noise limit. Previous demonstrations employed postselection to discount photon loss in the source, interferometer or detectors. Here, we use the state of art single photon generation and detection technology to respectively make and measure a two-photon NOON state and use it to perform unconditional phase sensing beyond the shot noise limit — that is, without artificially correcting for loss or any other source of imperfection [4].

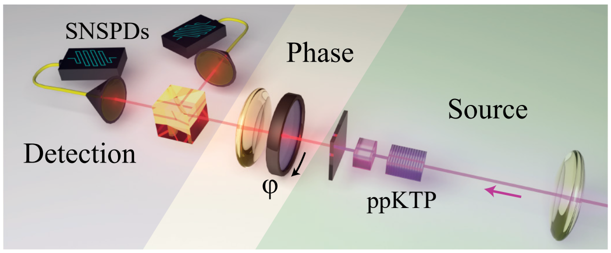

Figure 1: Photon pair source, based on periodically poled KTP (ppKTP) nonlinear crystal, was used to generate telecom wavelength photon pairs in a maximally-engangled polarisation NOON state. The photons were used to sample a birefringent phase shift φ in a polarisation interferometer and the output was detected with high efficiency superconducting nanowire single photon detectors (SNSPDs).

Our experimental setup (Fig. 1), uses photons generated from a high-heralding-efficiency, high purity source of telecom-wavelength photon pairs [5], and we employ high efficiency superconducting photon detectors [6] for photon counting at the output of the measurement setup. Unlike previous experiments, our apparatus does not require postselection to achieve phase uncertainty below that achievable in an ideal, lossless classical interferometer. We observed an interference fringe visibility of $(98.9 \pm 0.02)\%$ and symmetrical interferometer arm efficiencies around 80% (which include detectors efficiency), which was sufficient for beating the SNL with $N = 2$ NOON states [7, 8].

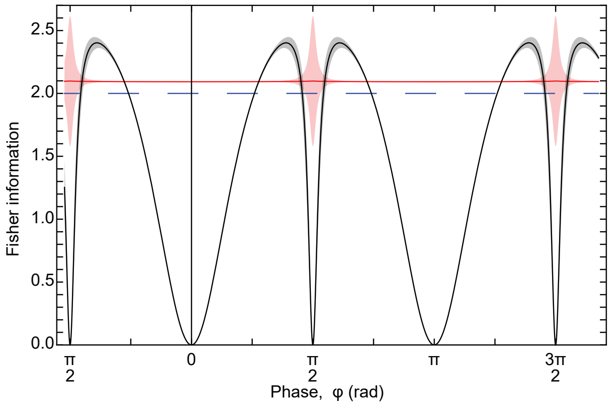

Figure 2: The black curve is the Fisher information determined from uncorrected experimental interferometric data. The dashed blue line is the naive SNL for this scheme, and the red curve is the SNL corrected for actual photon source and detector characteristics. Shading represents uncertainties. The experimentally-determined Fisher information surpasses the SNL over certain phase ranges.

Our results (Fig. 2) show a clear violation (for a range of phases) of the SNL bound, $F_{SNL} = 2.09635$, that takes into account the information in unrecorded trials arising from loss and higher order terms — making our demonstration unconditional. We also performed a direct phase sensing measurement and observed phase uncertainties more than 10 standard deviations below the SNL [4]. Our results enable quantum-enhanced phase measurements at low photon flux and open the door to the next generation of optical quantum metrology advances.

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