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Single Electron Interferometry: A Step Toward Quantum Electron Microscopy

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Sub-angstrom resolved reconstructions of biological specimens could allow us to cure diseases, manufacture personalized pharmaceuticals, and understand biological mechanisms happening at the atomic level. Recently developed Transmission Electron Microscopy (TEM) techniques have enhanced our understanding of biomolecular materials through atomic resolution imaging. Unfortunately, these imaging methods are time-consuming, necessitate averaging images of potentially non-identical biomolecules and, most importantly, destroy the sample. Non-destructive imaging requires a significant decrease in the number of electrons hitting the sample: a dose limit approaching 1 $e^-/Å^2$ [1]. With current methods, if we decreased the dose such that we do not destroy the sample, we would not have enough signal-to-noise to recreate the faintest image of any specimen. Therefore, we need to develop a method to increase the information we get from each individual electron probing the sample. In quantum optics, a single photon interferometric technique exists in which information about the sample is gained even when the photon does not pass through the sample [2]. By using interaction-free photons, the dose decreases without sacrificing information. Theoretically, this quantum optics technique should be achievable with electrons [3]. Given this theory, single electron interferometry provides a low-dose, high-resolution TEM technique for imaging beam-sensitive materials.

In the original thought experiment done by Elitzur and Vaidman [4], shown in Fig. 1, a quanta traverses two paths within a Mach-Zehnder interferometer. One path passes through the sample region, while the other is preserved as a reference. If there is no sample (Fig. 1(a)), the particle propagates through the interferometer and constructively interferes with itself, causing a click at the bright port. If there is a sample (Fig. 1(b)), the particle either scatters and will not be detected or it will take the interaction-free path, which leads to a click at either port. Therefore, only a click at the dark port guarantees an interaction-free detection of the specimen.

In a TEM (Fig. 1(c)), two sinusoidal phase gratings (beam splitters) can be aligned on the optical axis, one above and one below the sample. An aperture blocks all beams except the zeroth and positive first order beams. The gratings are aligned such that electrons constructively interfere at the second grating, causing the positive first order probe at the camera to have zero intensity (the dark port, Fig. 2(a)). When a sample is inserted into one of the paths, the electron no longer interferes with itself. Thus, there is a non-zero probability for the electron to traverse to the dark port on the detector (Fig. 2(b)), which indicates an interaction-free detection of the phase specimen.

In both paths, the beams are focused at the sample plane and raster across the specimen. While scanning, both ports on the detector are monitored. When a click at the dark port is detected, an interaction-free measurement of an atom has been made and the sample position pixel is colored white. Dose limitations can be assessed by reconstructing images for different dose values.

Using previously developed theory of phase detection uncertainty [5], we calculate the number of electrons required to resolve a typical biological specimen. Assuming a perfect detector and perfect fringe

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visibility, an interference pattern formed by 200 electron counts would be the minimum required to quantitatively measure a 100 mrad phase shift, the approximate phase a 200 keV electron would acquire passing through a 2 nm thick biological specimen [6]. However, less than 50% of the electrons entering the interferometer actually pass through the sample. Thus, we predict the necessary dose level to be 100 electrons. Although this sensitivity does not achieve the desired 1 $e^-/Å^2$, this measurement can be performed at atomic spatial resolution with no defocus [7]. The phase sensitivity can be improved further in a multi-pass quantum TEM [8].

This work proposes a new interferometric electron microscopy technique at the quantum limit, which will advance the field of non-invasive quantum electron microscopy (QEM). If QEM is successful, researchers could reconstruct fragile organic materials never seen before at the atomic scale, which could be applicable in biology, energy, materials science and medicine.

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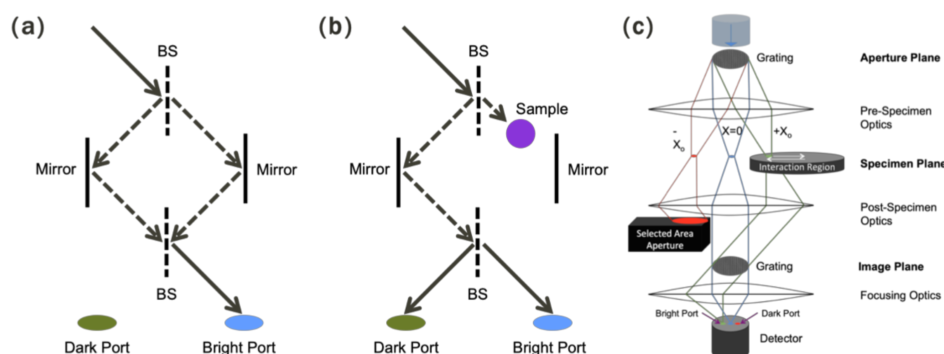

Figure 1. Interaction-free measurements with a Mach-Zehnder interferometer. (a) The beam splitters (BS) split are aligned such that all of the photons are collected at the Bright Port. (b) A sample is inserted into one of the paths such that 25% of the original photons are detected at the Dark Port. (c) Experimental set-up within TEM for interferometric STEM and electron Mach-Zehnder interferometer.

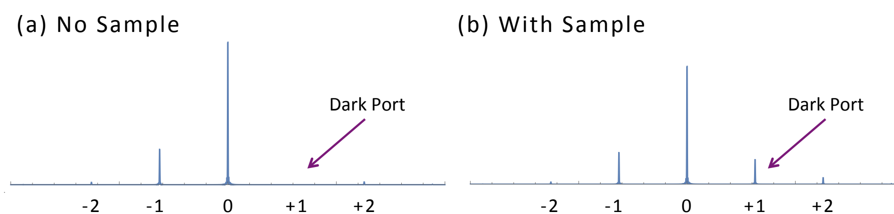

Figure 2. Simulated probe intensity distribution when the gratings are aligned and either (a) no sample is inserted or (b) a 10 nm thick biological sample is inserted into the interaction region.

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