Quantum Electron Microscope (QEM) Development Program

A new microscopy tool based on quantum physics and electron microscopy will be investigated. The proposed quantum electron microscope (QEM) may enable imaging of biological samples with radiation doses so small that they are non-lethal. The instrument will rely on the interaction-free (IFM) non-destructive measurement principle, which has been proven with photons, but has yet to be demonstrated with electrons. The development program seeks to advance the state-of-knowledge in order to assess the realism of such an instrument. In recent years, new approaches have emerged which allow for unprecedented levels of control over the quantum motion of electrons in free space. We seek to exploit these methods to make proof-of-principle demonstrations of the IFM measurement principle. We anticipate that these foundation experiments will have technology impact beyond microscopy. For example, extensions of the IFM principle allow for controlled entanglement of electron wavefunctions, enabling, for example demonstration of free electron-based CNOT.

Overview

Recent advances in the quantum level control of electrons open the possibility of development electron microscopes based on non-destructive quantum measurement principles. Such instruments may enable real-time, non-destructive imaging of biological samples.

The concept of interaction-free measurements was proposed by Elitzur and Vaidman (Foundations of Physics 23, 987-97 (1993)). Kwiat and colleagues first experimentally demonstrated that non-destructive/interaction-free measurements (IFM) can be performed efficiently with photons [P. G. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)] [P. G. Kwiat, A. G. White, J. R. Mitchell, O. Nairz, G. Weihs, H. Weinfurter, A. Zeilinger, PRL, 83, 4725 (1999)]. In this class of measurement, experimentally realized in optical systems, quantum interference is exploited to non-invasively detect the presence or absence of an absorbing element. An example of a realization of this measurement class is an optical resonator (*e.g.* Fabry-Perot interferometer): if the frequency of the input beam of light is tuned on resonance with the cavity, the beam transmits through the cavity; on the other hand, if an absorber is in the cavity, the resonance required for transmission is spoiled, and the light reflects from the input mirror, with negligible light transmitted into the cavity. Thus the presence or absence of the absorber is determined with negligible interaction with the absorber. This measurement protocol is closely related to those exploited in cavity QED systems, where both dispersion and absorption are used to non-destructively detect atoms or ensembles of atoms in high-finesse optical cavities. Central to the realization of these non-destructive measurements is the existence of a resonator which allows for repeated coherent interrogation of a target object.

Yanik and co-workers have proposed making interaction-free measurements with electrons to perform non-destructive electron microscopy [W. P. Putnam and M. F. Yanik, Phys. Rev. A 80, 040902 (2009)]. In this case, realization of interaction free measurement requires development of structures manipulating electron wavepackets. A proof-of-concept microscope would follow from non-invasive detection of an absorber introduced into the electron resonator. More mature implementations would run at energies required for high contrast imaging of biological samples (above 100 keV) in an image scanning configuration, and with grey-scale resolution.

The research program builds on decades of work in electron holography and interferometry [see F. Hasselbach, Reports on Progress in Physics **73**, 016101 (2010); J. C. H. Spence, in Compendium of Quantum Physics, edited by D. Greenberger, K. Hentschel, and F. Weinert (Springer Berlin Heidelberg, Berlin, Heidelberg, 2009)]. Our development program extends this work with the idea that repeated coherent interrogations of a sample can significantly alter the radiation damage/imaging balance, to the extent that non-destructive imaging of biological samples may be feasible. The key electron optical elements requiring demonstration are low-loss beamsplitters and multi-pass electron resonators. The technological challenge is integration of these elements into realistic electron microscope configurations.

Ultimately, we wish to employ these techniques in microscope configurations appropriate to imaging of biological samples, where radiation damage [see, for example, R. F. Egerton, P. Li, and M. Malac, Micron 35, 399–409 (2004)], sample preparation [for example, M. William H., Micron 42, 141–151 (2011)] and contrast enhancement [*e.g.* D. J. Flannigan, B. Barwick, and A. H. Zewail, PNAS 107, 9933–9937 (2010)] are central issues. Our work seeks to validate the basic science underlying the possible future operation of a non-destructive/IFM microscope.

Some of the envisioned approaches will also serve as a technological foundation for advanced electronic devices based on free-electron quantum interference and ultra-fast laser triggered field-emission photocathodes. Envisioned devices include, for example, very high speed (terahertz and above), high-resolution A/D converters, ultra-fast magnetometers (based on the Aharanov-Bohm effect), and quantum gates/registers/processors (based on guided electron entanglement). For example, the non-destructive measurement protocols described above are well known to result in entangled states between the probe (in the case of optical implementation, the incident light beam) and the object in the cavity (in conventional cavity QED work, a single atom or ensemble of atoms). The electron resonators to be demonstrated in this work will possibly allow generation of entanglement between electrons (probe) with other electrons (which are coupled to the cavity). Such entanglement protocols can be used to realize CNOT gates, and perhaps universal quantum logic.

Investigators

Mark Kasevich-Stanford

Karl Berggren-MIT

Peter Hommelhoff-Max Planck

Peter Kruit-Delft U.

Fatih Yanik-MIT