Q-SORT

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Invited Speakers

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Design and potential applications of patterned electron mirrors

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Introduction

Following a recent suggestion [1] that interaction-free measurements [2] are possible with electrons, we have analyzed the possibilities to use this concept for imaging of biological specimen with reduced damage. We have also made preliminary designs for an atomic resolution interaction-free electron microscope, or "quantum electron microscope" [3]. In such a microscope we need two novel elements: a double mirror which enables an electron to pass multiple times through the same region, and a splitter/coupler which splits an electron wave front in two parts or combines two parts back into one. The latter should be equivalent to what a semitransparent mirror can do for light. We found that the mirror can be combined with the coupler in a grating mirror [4]. By having the electron wave front reflect on an equipotential surface with a line pattern, the reflected electron picks up a phase modulation which develops in the far field into a diffraction pattern. Of course, we are not restricted to a line pattern on the mirror, so, with a few notable restrictions, it is possible to imprint an arbitrary phase pattern onto an electron wave. This may be an alternative for a programmable phase plate in transmission mode [5].

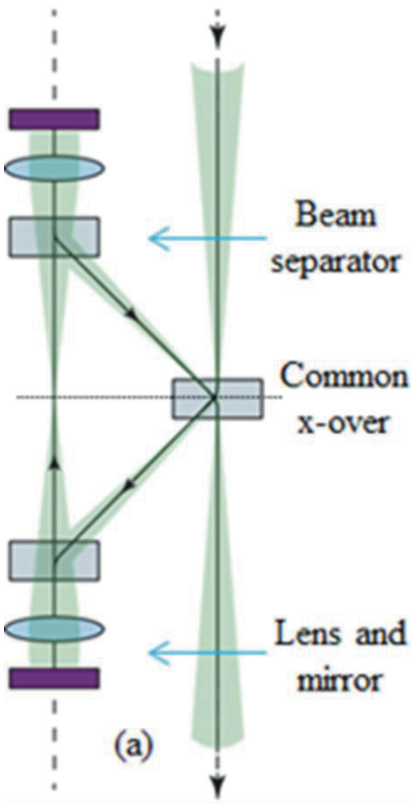

Figure 1: The electron beam trajectory through the test set-up for patterned mirror phase modulation.

Experimental Methods

We are now experimenting with patterned mirrors, for which we have built a set-up to fit in the specimen chamber of a scanning electron microscope. In order to avoid deflection dispersion and deflection aberrations, we deflect over small angles. This results in the technological challenge to design an electron optical system with two optical axis which are close to each other. We try to solve this challenge by using MEMS technology for the design of lenses, deflectors and mirrors. Thus far, we are able to detect the reflected beam from a single mirror, but we have not yet seen the effect of the pattern on the mirror.

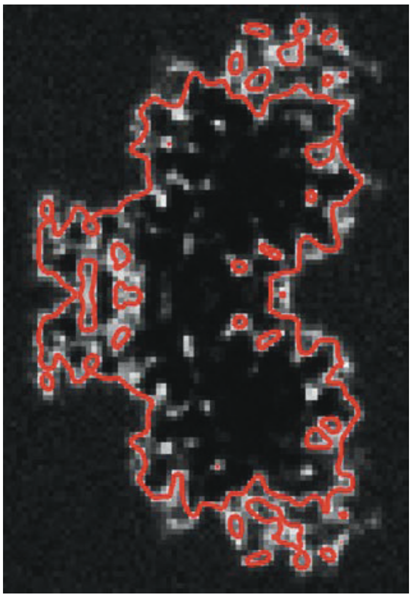

Figure 2: Simulation result shows a possible image of a HIV-1 Gag Protein from a Quantum Electron Microscope

Image simulations

In the meantime, we have developed a program to simulate images that we expect to obtain with a fully functional Quantum Electron Microscope [6]. Most theory on interaction-free measurements is limited to objects that are opaque. However, a biological sample in a TEM is semi-transparent and gives a phase shift to the electron wave. The contrast that can be expected for such samples is sensitive to the newly obtained free parameters in the microscope. We'll show that it is possible, in principle, to image only selected phase contours in the sample, without interacting with the rest of the sample.

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Quantum aspects of the interaction between beam electrons and optical near fields

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Electron beams are ideal tools to controllably excite and probe plasmons and other nanoscale optical excitations with an unparalleled combination of space and energy resolutions. Spectroscopy performed through the analysis of electron energy loss and cathodoluminescence are widely used to obtain snapshots of these excitations. Additionally, access to the ultrafast sample dynamics is possible by recording photoelectrons excited with femtosecond light pulses, while several experiments demonstrate optical pumping followed by electron-beam probing with similar temporal resolution. In this talk, we will review recent advances in these techniques and present a unified theoretical description, along with several potential directions for improving the space-time-energy resolution and accessing quantum aspects of the samples.

As a first challenge, we will discuss fundamental limits to the coupling between electrons and optical excitations based on suitably tailored beam-electron wave functions, thus opening new directions for further increase in time resolution and the exploration of nonlinear phenomena with nanometer resolution.

Additionally, we will discuss recent theoretical results on fundamental aspects of the interaction of fast electrons with localized optical modes that are made possible by the noted advances. Using a quantum-optics description of the optical field, we predict that the resulting electron spectra strongly depend on the statistics of the sample excitations (bosonic or fermionic) and their population (Fock, coherent, or thermal), whose autocorrelation functions are directly retrieved from the ratios of electron gain intensities. We further explore feasible experimental scenarios to probe the quantum characteristics of the sampled excitations and their populations.

Coherent Control of Single Electron Wave Packets with Light and Nanostructures

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Introduction

Electron-light interactions and the various mechanisms lying within this context have been discussed from the very early days of the rise of quantum mechanics. Transition from classical concepts such as Thomson scattering to more advanced quantum mechanical counterparts like Compton scattering, photoelectric effect, and more recently free-electron lasers, opened the way towards designing precise accelerating mechanisms [1, 2] and radiation sources [3, 4].

Here, we first discuss about electron-light interactions from the classical point of view. Mainly, we consider inelastic interaction of electron beams with optical near-field distributions in nanostructures. We further investigate the conservation of momentum and energy both from quantum mechanical first principles and classical electromagnetism, and show that near-field distributions can act as a mediator to transfer the energy between electron beams and light [4]. Moreover, this inelastic interaction can be employed to design coherent radiation sources, based on the contribution of the excited fields to the radiation continuum [5]. Moreover, thin film electron-driven photon sources can be employed inside electron microscopes, for the purpose of spectral interferometry [6].

In a second part of my talk, we will discuss electron-light interactions from semi-classical standpoint. First, we investigate the free-space interaction and consider the generalization of Kapitza-Dirac effect (KDE) to address quantum-coherent phenomena which occur as a result of interference between ponderomotive and absorptive/emissive parts of the minimal coupling Hamiltonian [7]. Then, we talk about the interaction of point-projection slow-electron wavepackets with light and nanostructures [8]. We will show that the coupling strength between electrons and near-field light is increased by decreasing the electron velocity; hence demonstrate the sensitivity of slow electrons to the electromagnetic interactions, covering both elastic and inelastic scattering. Our understandings particularly validate the suitability of point-projection electron microscopes for time-resolved spectroscopy and holography experimentations, at the benefit of employing less complication compared to the electron-optics in transmission microscopes.

Results

Spectral Interferometry – Swift electrons in an electron microscope can interact with collective electronic excitations in metals; such as volume and surface plasmon polaritons (SPP) [9]. Excited SPPs generally do not radiate, but propagate at a group velocity larger than the velocity of light in free space - additionally, their propagation is concomitant with large dissipation losses.

SPPs, however, can contribute to the radiation loss as well, when interacting with defects and incorporated gratings. When the electron traverses a metallic surface, transition radiation (TR) occurs as well, which has a typical dipolar-like radiation pattern for planar geometries. TR happens as a result of the sharp annihilation of a transient dipole, which is formed by the electron and its image charge in the metal. Nevertheless, TR radiation pattern can be effectively engineered, as well as the contribution of SPPs to the radiation, by means of curved geometries [6] or effectively engineering the positioning of defects [5] (see Fig. 1a and b), to form directional, broadband, and focused radiation. In order to mimic the behavior of curved spherical geometries, a hexagonal lattice of holes is projected from the spherical coordinate system to the cylindrical system [5]. By positioning a second sample at the focal point of the designed electron-driven photon source (EDPHS) and detecting the overall radiation at the far-field, the correlations between the collective excitations in the sample and the EDPHS is investigated. The time-energy correlation map can be also obtained by changing the distance between the EDPHS and the sample and is used to reveal the spectral phase [6].

Time–resolved holography with slow electrons – Interaction of slow electrons with light and nanostructures can be efficiently modeled using the minimal-coupling Hamiltonian. Both scalar and vector potentials should be used within this model; moreover, gauge theories are employed to relate the field quantities to the potentials. We will show that within the routinely employed Coulomb gauge, it is the scalar potential which describes efficiently the near-field mediated electron-light interactions, when particles with dimensions much smaller than the wavelength of light are introduced (Fig. 2). However, free-space electron-light interaction, and particularly KDE is described using the solenoidal vector potential. Furthermore, both the ponderomotive interaction and photon-absorption/emission are responsible for electron-light interactions, and can even cause various quantum-coherent paths, where their dynamics can be controlled via various laser and electron wavepacket parameters; namely, polarization, velocity, propagation direction, laser intensity, as well as interaction time.

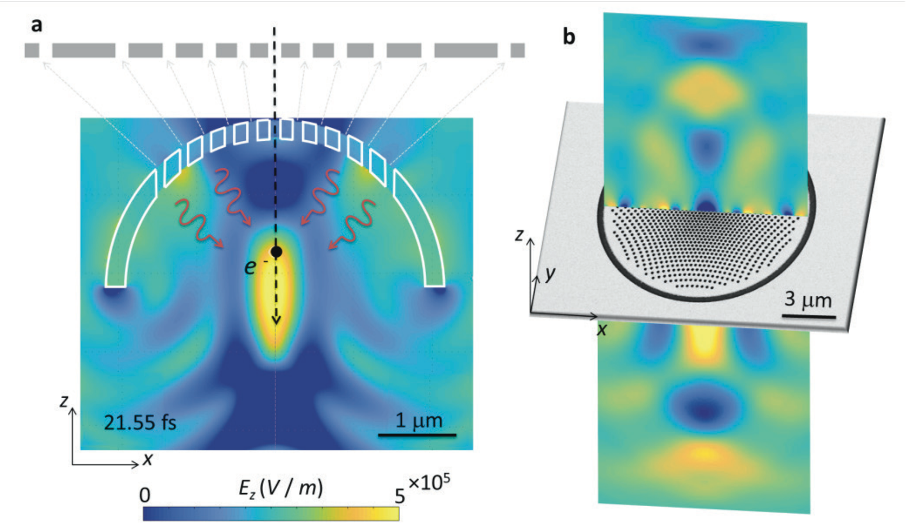

Fig. 1. Interaction of a swift electron at the kinetic energy of 30 keV with curved (a) and planar (b) gold thin films, resulting in a focused and directional ultra-broadband radiation. Depicted is the z-component of the electric field at a given time. Transmission electron microscope image: courtesy of Mario Hentschel (Stuttgart University) and Surong Guo (Max Planck Institute for Solid State Research).

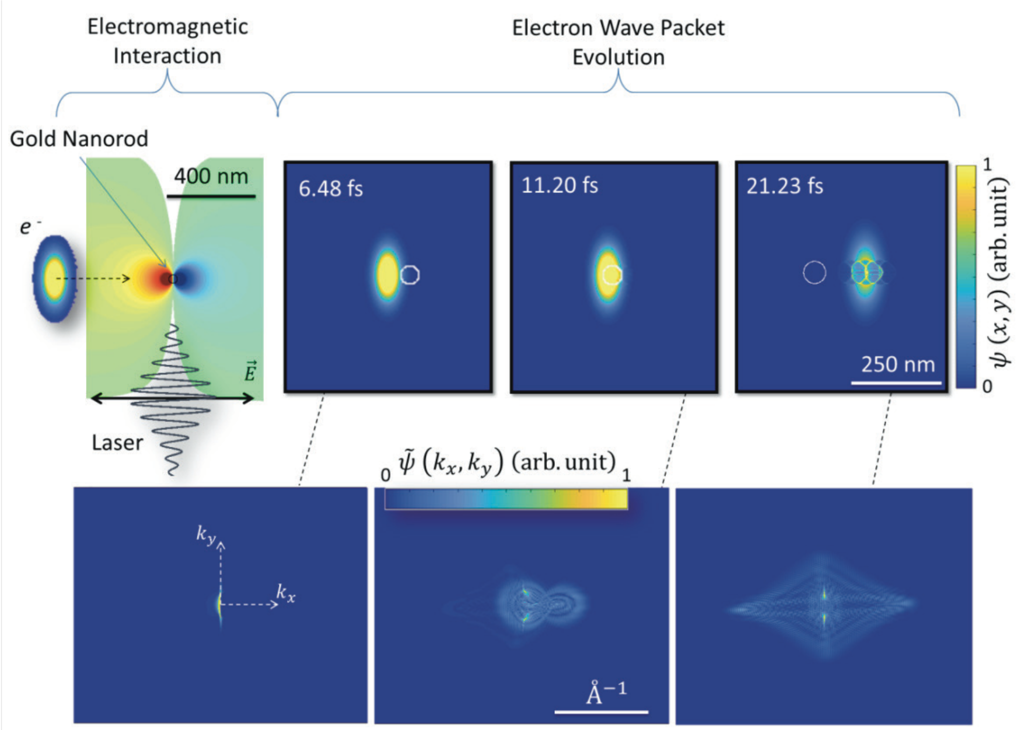

Fig. 3. Evolution of an electron wavepacket interacting with a gold nanorod with a radius of 25 nm. The gold nanorod is pumped by an ultrafast laser excitation at the carrier wavelength of 800 nm and duration of only 2 optical cycles, and causes a dipolar oscillation of the free electron gas inside the gold nanorod (a). The electron wavepacket has an initial energy of 400 eV and is propagating along the x-axis. Demonstrated is the evolution of the electron wavepacket at specific interaction times depicted on each frame, within the real space (b) and the reciprocal space (c). Simulations are in 2-dimensional space.

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The Reality of the Quantum Electron Wavefunction in Interactions with Light and Matter

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"Does the wavepacket dimension of a free-electron quantum wavefunction have physical significance? Can it be measured?" "What is the role of wave-particle duality in quantum interactions between light and matter?" These questions lay in the foundations of Quantum Mechanics since its early conception[1].

In this presentation we respond to these challenges by presenting a universal formulation for interactions of single free electrons with light in general interaction schemes, such as Free Electron Lasers (FEL)[2], laser accelerators[3,4], and Photon-induced Near-field Electron Microscopy (PINEM)[5]. The formulation is based on modeling the electron as a quantum wavepacket of minimal Heisenberg uncertainty in Energy-Time phase-space. The topology of the wavepacket distribution in phase-space at the entrance to the interaction region determines entirely the nature of its post-interaction (Wigner) distribution and corresponding energy spectrum. Only three kinds of interaction regimes are universally possible (see figure):
A. a quantum regime of multi-photon emission/absorption and electron quantum recoils with PINEM-kind energy spectrum of discrete sidebands.
B. a classical regime of near point-particle acceleration energy spectrum.
C. a newly reported intermediate regime of quantum interference (Anomalous PINEM) that has not been observed so far.

This new formulation resolves the particle-wave duality question, delineates the transition from quantum to classical electrodynamics. It establishes the measurability of the history-dependent quantum electron wavefunction size and shape. It opens up deeper understanding of the fundamentals of light-matter quantum interactions[6-9], and can lead to development of new applications in electron microscopy and spectroscopy.

Under the assumption of the reality of the density and fields associated with the periodic modulation of the electron wavefunction envelope, new concepts in electron microscopy are proposed: "Free-Electron Bound-Electron Resonant Interaction FEBERI)" and "Resonant Cathodoluminescence (RCL)".

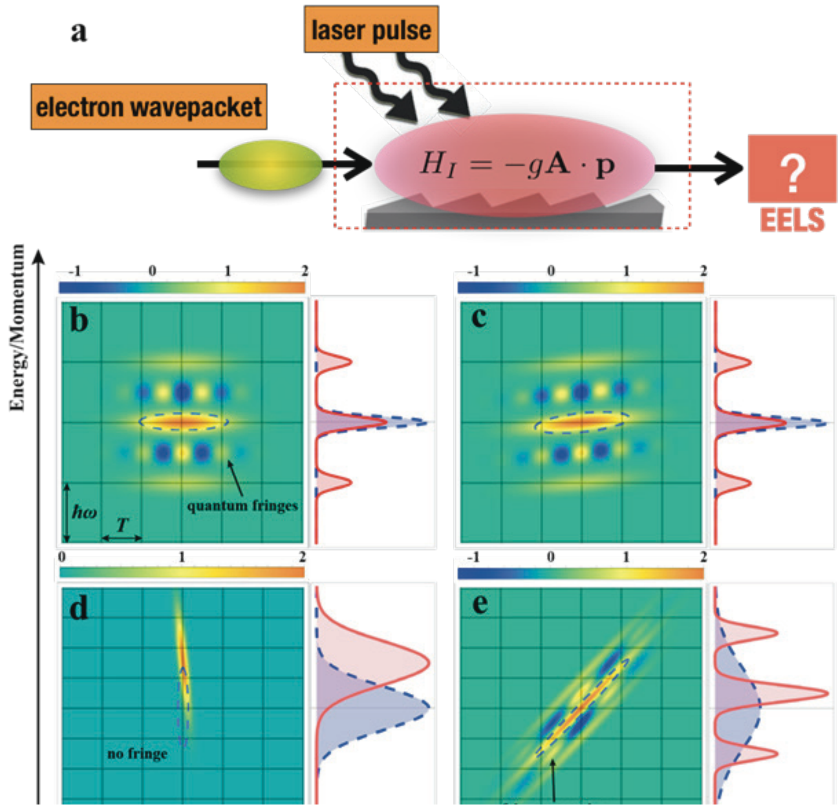

FIG. 1. *(a) A universal light-electron interaction scheme. (b-e) Illustration in energy-time (momentum-space) phase-space and energy (momentum) spectrum of the three possible interaction schemes of a single Quantum Electron Wavepacket (QEW): quantum multiphoton emission/absorption (PINEM) (b,c); point-particle-like acceleration (d); and sidebands quantum interference (anomalous PINEM) (e). Broken line: pre-interaction distribution, color: post-interaction.*

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