Coulomb-correlated multi-electron states in a transmission electron microscope beam

Rudolf Haindl[1,2], Dr. Armin Feist[1,2], Till Domröse[1,2], Dr. Marcel Möller[1,2], John H. Gaida[1,2], Dr. Sergey V. Yalunin[1,2], Prof. Dr. Claus Ropers[1,2]
[1]Department of Ultrafast Dynamics, Max Planck Institute for Multidisciplinary Sciences, Göttingen, Germany, [2]4th Physical Institute -- Solids and Nanostructures, Göttingen, Germany

Background incl. aims

In contrast to possibilities arising from electron correlations in condensed matter systems, stochastic Coulomb interactions in free electron beams are usually considered detrimental. In electron microscopy, electron repulsion leads to stochastic longitudinal and transverse emittance growth and limits the brightness of state-of-the-art electron sources. However, in a regime where few-body interactions dominate, Coulomb interactions can also have beneficial effects based on strong inter-electron repulsion, such as non-Poissonian electron beam statistics [1]. A powerful approach to induce such strong electron-electron interactions is femtosecond-triggered photoemission from nanotips [2, 3].
In this work [4], we characterize the strong Coulomb correlations of multi-electron states from a laser-triggered nanoscale field emitter, with applications in correlated probing applications, shot-noise reduction, and electron heralding schemes.

Methods

The experimental work is carried out in transmission electron microscopes that are modified for photoexcitation of the electron source [4, 5]. A laser pulse train with 2 MHz repetition rate and 160 fs pulse length generates ultrashort electron pulses by close-to-threshold laser-triggered Schottky emission [5]. The photoelectrons are analyzed with an event-based electron detector, which is mounted behind an imaging energy filter and characterizes the spectral and spatial properties of the electrons. The detected electrons are matched to the generating photoemission laser pulse, and the number of electrons n=1,2,3,4 is assigned to each pulse (see Fig. a).

Results

The single electron state spectrum exhibits a single peak at the beam energy of 200 keV (see Fig. b). Strikingly, the electron pulses with n>1 exhibit a distinctive spectral shape with the number of peaks identical to the number of electrons in the pulse (see Fig. c-e), indicating a strong interaction between the electrons in the pulse. The n=2,3,4 -states are plotted with respect to the state-averaged energy. For n=2, a projection of the energies of electrons A and B onto a two-dimensional energy pair histogram (Fig. f) shows a characteristic pair-correlation energy of about 2 eV. The strong inter-particle energy exchange is caused by acceleration-enhanced inter-particle Coulomb interaction, as confirmed by trajectory simulations. State-sorted beam caustics reveal a discrete increase in virtual source size, a longitudinal source shift, and a pronounced angular distribution of the few-electron states compared to single-electron pulses. As the correlation primarily emerges in the initial acceleration stages of the electron gun, controlling the electrostatic configuration enables control over the ratios of transverse and longitudinal Coulomb correlations. Using apertures along the optical axis, which limit the maximum transverse momentum of electrons transmitted into the column, we can decrease the current-current correlation function by lowering the extraction voltage applied to the nanotip cathode.

Conclusion

The high fidelity of few-electron pulses in conjunction with single-particle detection enables the preparation of distinctive electron states for correlated probing, as well as enhanced microscopy and lithography. Specifically, we propose schemes to generate an electron beam with sub- or super-Poissonian two-electron statistics. By means of spatial filtering with an annular aperture or spectral filtering with either a slit or a beam stop, the two-electron state is suppressed or enhanced, resulting in a shot-noise- (annular aperture, slit) or singlet-state-reduced (beam stop) electron beam, respectively. Applications of the two-electron state-enhanced electron beam include heralded single-electron sources and may foster new developments in free-electron quantum optics and quantum-enhanced electron microscopy.

Graphic:

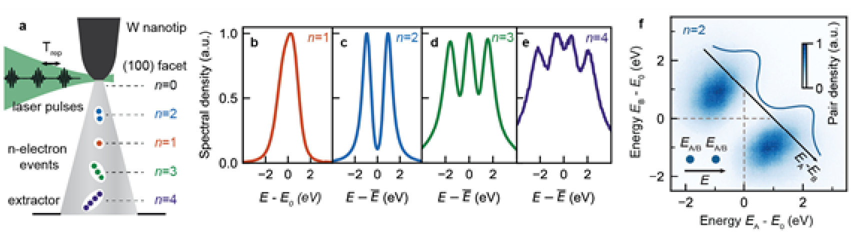

Figure 1 a) The photoexcitation laser generates multi-electron states via photoemission from a Schottky emitter. b-e) Event-resolved spectra with a distinctive spectral shape for n=1-4. f) The energy pair histogram of n=2-states with electrons A and B shows a spectral correlation of about 2 eV.

Keywords:

UTEM, Electron correlations, Electron sources https://doi.org/10.1051/bioconf/202412909010

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