Probing Dynamic Responses of Nano-Materials at the Boundary between Classical and Quantum Mechanics detecting Coherent-Inelastic Electron Self-interferences

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The Copenhagen convention of quantum mechanics describes a boundary between the quantum world, where wave functions are indefinite in space and time, and the classical world of particles that we perceive as definite. Heisenberg's Uncertainty Principle defines this boundary, but details about its relationship to electron-sample interactions remain incomplete. Specifically, it seems unfortunate that matters concerning wave-particle duality, time-dependent measurements, or the entanglement of wave functions and their collapse at a detector still require detailed investigations to enable progress. Certainly, this is no academic matter because such aspects become the bottleneck for the deployment of microscopes with high spatiotemporal resolution that already reaches towards ~ 1 Å spatial resolution with ~1 ps time resolution and enable investigations of dynamic processes in solids (1,2). With the development of aberration-correction, the characterization of static nano-materials by electron microscopy has made tremendous progress. The point is reached where single atoms can be chemically identified and detected in 3D that reveal beam-induced, dynamic behavior (3). Further, their operation in ultra-low dose conditions guaranties that only single electrons participate in scattering events (4), which allows maintaining the pristine structure of radiation sensitive matter. Here, we explore new principles by experimentally analyzing the relation between particle and wave descriptions of electron-matter interactions measuring the delocalization of an evanescent field in energy-filtered real-space images of sample/vacuum interfaces recorded. Its spatial extension coincides with the energy-dependent self-coherence length of propagating wave packets that obey the time-dependent Schrödinger equation and undergo a Goos-Hänchen shift. The wave packets are created by self-interferences during coherent-inelastic Coulomb interactions and exhibit a decoherence phase $\Delta\varphi = 0.5$ rad. Due to a reciprocal dependence on energy, they shrink below atomic dimensions for electron energy losses beyond 1000 eV when the wave packets appear particle-like. Consequently, atomic resolution observations inevitably include pulse-like wave propagations that stimulate structural dynamics at any electron energy loss.

References:
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