



The interaction of low-energy electrons with light reveals quantum effects

ICFO researchers lead a theoretical study on the interaction between low-energy electrons and light, showing for the first time the emergence of quantum and recoil effects as a consequence. The results could enhance ultrafast electron microscopy, among other potential applications.

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Free electrons and light (or, more precisely, optical fields), when coupled together, play a fundamental role in state-of-the-art electron microscopy. Their synergetic relation enhances spatiotemporal and energy resolution of electron microscopes down to the picometer-attosecond-microelectronvolt range (that is, to scales of one trillionth of a meter, one quintillion of a second and one millionth of an electronvolt). This way, one can study dynamical processes and quantum phenomena in matter with a resolution reaching the atomic level and ultrafast time scales.

In general, the electron beams employed in this kind of devices have kinetic energies significantly higher than those of the optical fields. Then, the probability of a single electron interacting with a single [photon](#) becomes much smaller than unity, which in turn implies a weak electron-light coupling. In spite of the many advances that have been achieved in this regime, where the electron beam is described by a classical point-charge following a straight-line trajectory, this feature entails some fundamental limitations. In particular, the energy-momentum mismatch hinders the capabilities of these techniques for imaging atomic excitations and accessing the plethora of quantum nonlinear effects in nanostructures. Therefore, to access such phenomena one needs to close the energy gap by lowering the electron energies until they are comparable to the photon ones. This approach has now been tackled by ICFO researchers **Adamantios P. Synanidis** and **Dr. P. Andre D. Goncalves**, led by **ICREA Prof. Javier Garcia de Abajo**, together with Prof. Dr. Claus Ropers from the Max Planck Institute for Multidisciplinary Sciences and the University of Gottingen. In a Science Advances article, they **theoretically show exotic quantum effects emerging from low-energy electron-light interactions** that do not manifest in the conventional high-energy regime, such as strong electron-photon coupling at crystal surfaces, classically forbidden electron backscattering from otherwise electron-transparent surfaces, and selective strong photon absorption and emission.

Adamantios P. Synanidis, first author of the article, clarifies: *By lowering the electron energy and using an appropriate scattering surface, the electron-light coupling can be drastically increased (even diverging to infinity in special configurations), since the kinematical mismatch between the two is minimized or completely bridged?*

The researchers showed that when low-energy free electrons encounter an evanescent optical field (for example, of a surface polariton) in an electron-transparent film, the electrons can backscatter. This effect, which is forbidden in the classical regime where the electron energy is much higher than that of the light, showcases the importance of recoil effects and the quantum character of the interaction. The team also showed the consequence of low-energy electrons diffracted by an illuminated atomic lattice, where the electron-light coupling can be selectively enhanced by correctly tuning the electron energy.

New future directions for electron microscopy, metrology and quantum coherent control

Besides the fundamental interest that intrinsically comes with exploring electron-light-matter interactions, this study finds potential applications in ultrafast electron microscopy or metrology.

Due to the excellent spatiotemporal control offered by electron beams, we expect several new and exciting applications to arise in the fields of ultrafast electron spectromicroscopy and quantum coherent control, further explains Synanidis. *One possible new development would be using electron beams not only as probes of physical processes in matter but also as a tool to transfer coherence to the sample by entangling with ma*

erial excitations, thus introducing novel techniques with entangled bea
si $\frac{1}{2}$. In the long-term picture, these results also contribute to the future goal of build
ng more compact electron microscopes, since low-energy electrons can greatly simpl
fy some aspects of the current electron-microscope columns. Additionally, the use of lo
-energy electrons increases electron-light coupling without the need for strong light field
, which enables electron-based spectroscopy of sensitive samples, such as biological ones.