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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: ï¿½By lowering the electr
n energy and using an appropriate scattering surface, the electron-light coupling can
e drastically increased (even diverging to infinity in special configurations), since t
e kinematical mismatch between the two is minimized or completely bridgedï?
½. The researchers showed that when low-energy free electrons encounter an evanes
ent optical field (for example, of a surface polariton) in an electron-transparent film, the elect
ons can backscatter. This effect, which is forbidden in the classical regime where the elec
ron 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-l
ght coupling can be selectively enhanced by correctly tuning the electron ene

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.

ï¿½Due to the excellent spatiotemporal control offered by electron beams, we expect sever
l new and exciting applications to arise in the fields of ultrafast electron spectromicrosco
y and quantum coherent controlï¿½, further explains Synanidis. ï¿½One possib
e new development would be using electron beams not only as probes of physical proces
es 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
sï¿½. 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.