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Perspective

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Free-electron quantum optics

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Recent theoretical and experimental breakthroughs have given rise to the emerging field of free-electron quantum optics, reshaping the understanding of free-electron physics. Traditionally rooted in classical electrodynamics, this field now reveals quantum-mechanical features that necessitate the frameworks of quantum electrodynamics and quantum optics. This shift compels a re-evaluation of well-established areas, bringing quantum-mechanical corrections to accelerator science and to electron-radiation phenomena. Simultaneously, the ability to shape single-electron wavefunctions opens new possibilities in microscopy and spectroscopy. These developments are primarily driven by innovations in electron microscopy and its intersection with laser science, where laser-driven electron modulation substantially influences quantum electron interactions with light and matter. In this Perspective, we review these developments, highlighting the current challenges and future opportunities. We explore the role of the free electron as a quantum resource, complementing conventional two-level systems and harmonic oscillators. In the coming years, free electrons may offer new modalities for reading and writing quantum information on ultrafast timescales, performing quantum-state tomography, and ultrafast quantum gates on the atomic scale.

Free-electron physics is a long-established field, already responsible for many applications ranging from X-ray tubes and microwave ovens to particle accelerators and free-electron lasers. Nevertheless, over the past 15 years, free-electron physics has started to move in a new direction, based on both new theoretical concepts and advances in experimental capabilities[1,2]. Innovative developments of experimental platforms such as ultrafast electron microscopy[3] facilitated effects such as photon-induced near-field electron microscopy (PINEM)[4–6] and ultrafast electron diffraction[7]. PINEM relies on the longitudinal quantum coherence of the free electron, the hallmark of which is the demonstration of discrete modulation of the free-electron-energy spectrum resulting from matter–wave interference. This phenomenon complements the established field of electron holography[8] that relies on the transverse quantum coherence of the electron wavefunction. Together, these effects demonstrate the important role of quantum coherence, both longitudinal and transverse, in free-electron physics.

More recent developments rely on the electron's quantum coherence in novel ways: electron coherence is instrumental for Talbot interferometry[9], Rabi oscillations[10], Ramsey interference[11], the dynamical Aharonov–Bohm effect[12], interaction-free measurements[13], electron quantum-state reconstruction[14] and classical–quantum correspondence in quantum walks[15]. The electron's coherence can also play a part in altering the coherence and spectral properties of its emitted radiation[16–19], and can even be used to tailor the radiation into desired quantum states of light[20–22]. The quantum-coherent interaction of PINEM can improve the sensitivity of near-field imaging by increasing the contrast[11,23]. Similarly, PINEM-type experiments in the terahertz domain enable the probing of charge dynamics and of ultrafast phenomena in condensed-matter physics[24,25]. While these terahertz-probing capabilities have so far relied on classical electron interactions, their extension to the quantum-coherent interaction regime could improve them in the future. Electron coherence has also been predicted to enable reading and writing of quantum states of matter via free-electron–bound-electron resonant interactions[26–29] and generalizations to different interactions of free electrons with dressed states of matter[30–32].

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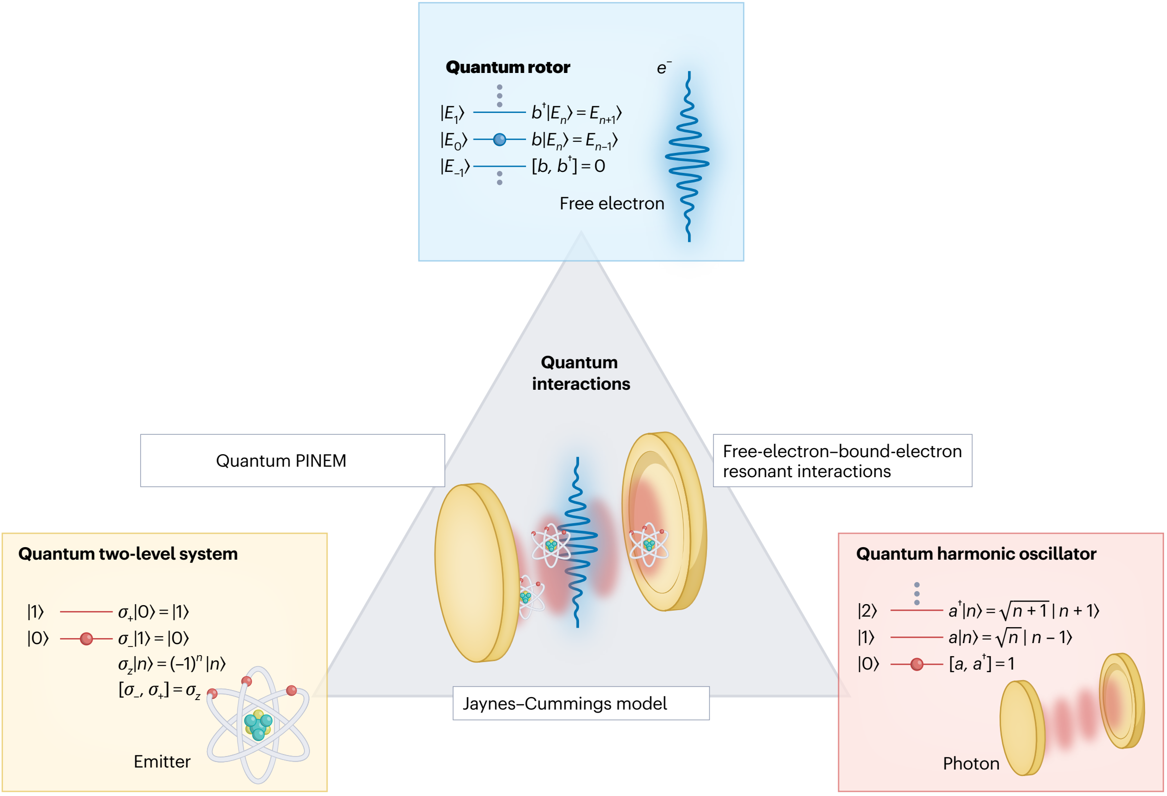

Fig. 1 | The triangle of interactions in free-electron quantum optics. The interactions of the free electron (blue) with the previous building blocks of quantum science—the photon (or generally, harmonic oscillator; red) and the emitter (or generally, two-level system; yellow). These interactions form a triangle, unifying the recent developments in free-electron physics under a single, extended framework of quantum optics. The photon vertex is described by the quantum harmonic oscillator, forming a semi-infinite energy ladder of states $|n\rangle$, where n is an integer. The emitter vertex is described by a quantum two-level system with the states $|0\rangle$ and $|1\rangle$. And finally, the electron vertex is described using a doubly infinite energy ladder known as a quantum rotor. Each edge in the triangle describes an interaction between two of these particles, providing a simple classification of the phenomena arising from their interactions. Box 1 summarizes the basic operators in the respective Hilbert spaces and the most general models describing the interactions between these physical objects.

This wide range of recent developments can now be understood using a unified framework—considering the free electron as a new type of quantum resource that carries quantum information and processes it through specific interactions with light and matter (Fig. 1 and Box 1). This way of thinking about free-electron quantum-coherent interactions provides the framework of free-electron quantum optics. The outlook gained by this framework could enable simpler designs of enhanced microscopy and spectroscopy schemes, utilizing the entanglement between a free electron and the sample it probes[33,34]. Aside from quantum coherence, free electrons can enable new capabilities when introduced to more established quantum-optical platforms such as cavity quantum electron dynamics (QED), integrated quantum photonics, quantum light sources, quantum information processing and quantum sensing. Free electrons enjoy unprecedented spectral tunability[1], ultrafast timescale operation[3] and strong interaction with light[34–37], with prospects for novel mechanisms of single-photon nonlinearities[38] and quantum gates based on free-electron–light interactions[39,40]. In particular, free electrons can be used to probe, drive and entangle quantum systems that are otherwise inaccessible with photonic probes[29,41], owing to either the diffraction limit, inhomogeneous broadenings or fast decoherence rates.

At the core of free-electron quantum optics are the coherent interactions between free electrons, photons and bound-electron emitters, constituting a triangle of quantum interactions, as illustrated in Fig. 1. The most fundamental light–matter interactions in conventional quantum optics usually rely on the quantum harmonic oscillator, describing the photon (right vertex in Fig. 1), and the two-level system, describing the emitter (left vertex in Fig. 1). Interaction between such systems can be universally described within the formalism of cavity QED (bottom edge in Fig. 1), for example, using the Jaynes–Cummings Hamiltonian[42], which applies to a wide range of platforms, from circuit QED to trapped ions and atoms. Free-electron quantum optics extends the language of quantum optics to include the free electron as a third type of quantum particle (top vertex in Fig. 1). As the electron is so energetic, it can emit and absorb many quanta of energy, making it effectively a doubly infinite ladder of energy states.

The interaction between free electrons and photons (right edge in Fig. 1) has been thoroughly investigated as part of the science of cathodoluminescence, a well-established analytical tool for electron microscopy (Fig. 2), which relies on spontaneous emission directly from the electron, or indirectly via its excitation of materials. In contrast, stimulated electron interactions with intense laser fields are at the core of the PINEM effect[4]. This field has recently received increased interest in regimes in which the quantum photonic nature of light becomes important[15,43,44], accurately described by the quantum PINEM model. The effect of the quantum photon statistics of light on its stimulated interaction with electrons in quantum PINEM complements the earlier discoveries of how photon statistics is influenced by different regimes of spontaneous emission by free electrons, as was measured by photon coincidence in cathodoluminescence[45–47].

Free electrons can undergo a different quantum-coherent interaction with bound-electron systems (left edge in Fig. 1), such as atoms, molecules and quantum dots. This type of interaction was proposed theoretically only a few years ago[26,27], and experiments are still under

BOX 1

Modelling the quantum interactions of free electrons

Free-electron interaction with matter dipole transition

The Hamiltonian describing a paraxial electron propagating along z with velocity v and Lorentz factor γ, interacting with a two-level system with transition dipole $\mathbf{d}$ and frequency ω is:

$$H = -\mathrm{i}\hbar v \partial_z + \hbar\omega\sigma_z - \frac{e\gamma}{4\pi\varepsilon_0} \times \frac{z d_z \sigma_+ + r_\perp d_\perp \sigma_+}{\left(\gamma^2 z^2 + r_\perp^2\right)^{\frac{3}{2}}} + \text{c.c.} \quad (1)$$

σ_i are the Pauli operators, ε_0 is the vacuum permittivity, $\hbar$ is the reduced Planck constant, c.c. is the complex conjugate of the written interaction term and $r_\perp$ is the impact parameter (which is an electron position operator in the general case).

Using the Magnus expansion, this Hamiltonian can be analytically solved to first order in the coupling, resulting in the following S matrix:

$$S_\mathrm{M} = \mathrm{e}^{-\mathrm{i}g_\mathrm{M}\sigma_+ b + \mathrm{i}g_\mathrm{M}^* \sigma_- b^\dagger}. \quad (2)$$

$b = \mathrm{e}^{-\mathrm{i}\omega\frac{z}{v}}$ is the energy/momentum translation operator for the electron, decreasing its energy by $\hbar\omega$. The dimensionless coupling constant g_M is defined as:

$$g_\mathrm{M} = -\frac{e\omega}{2\pi\varepsilon_0 \hbar v^2} \times \left[\frac{\mathrm{i}d_z}{\gamma} K_0\left(\frac{\omega r_\perp}{v\gamma}\right) + d_\perp K_1\left(\frac{\omega r_\perp}{v\gamma}\right)\right] \quad (3)$$

where $K_i(x)$ are the modified Bessel functions of the second kind and $d_{z/\perp}$ are the components of the transition dipole. See ref. 28 for derivation and detailed notations.

Free-electron interaction with a photonic mode

Similarly, the Hamiltonian describing the interaction between a paraxial electron and a photonic mode with angular frequency ω is given by:

$$H = -\mathrm{i}\hbar v \partial_z + \hbar\omega a^\dagger a + \frac{ev}{\omega} E_z(\mathbf{r})\, a + \text{c.c.} \quad (4)$$

where $a, a^\dagger$ are the photonic ladder operators and $E_z(\mathbf{r})$ is the z component of the electric field of the photonic vacuum (expressed in terms of electron position operators).

Using the Magnus expansion, this Hamiltonian can be exactly solved, resulting in the following S matrix:

$$S_\mathrm{Q} = \mathrm{e}^{g_\mathrm{Q} a b^\dagger - g_\mathrm{Q}^* a b^\dagger}. \quad (5)$$

The dimensionless coupling constant g_Q is calculated for each transverse position $\mathbf{r}_\perp$ of the electron as:

$$g_\mathrm{Q} = -\frac{\mathrm{i}e}{\hbar\omega} \int_{-\infty}^{+\infty} E_z(\mathbf{r}_\perp, \xi)\, \mathrm{e}^{-\frac{\mathrm{i}\omega}{v}\xi} \mathrm{d}\xi. \quad (6)$$

Here, ξ is an integration parameter over the trajectory of the electron (taken to be the z-axis in our case). See ref. 43 for derivation and detailed notations.

Coherent interactions of energy-modulated electrons

To analyse the interactions of energy-modulated electrons, it is constructive to introduce a basis of Dirac-comb electrons, each being an equal superposition of the energy levels with a different phase ϕ:

$$|\psi_e\rangle \approx \frac{1}{N} \sum_{n=-\infty}^{\infty} \mathrm{e}^{\mathrm{i}\phi n} |E + n\hbar\omega\rangle \quad (7)$$

where n is an integer defining the electron's energy on the energy ladder (mathematically thought of being infinite), N is a normalization factor and ϕ is any real number. This state is an eigenstate of the operator b with eigenvalue $\mathrm{e}^{\mathrm{i}\phi}$. Such states can be approximately generated using laser pulses and PINEM interactions[70,71]. For such electrons, the S matrices presented above become a rotation ($R_x(\theta)$) and displacement operators ($D(\alpha)$), acting only on the two-level system and photonic mode, respectively:

$$S_\mathrm{M} \approx R_x(2|g_\mathrm{M}|), \qquad S_\mathrm{Q} \approx D(g_\mathrm{Q}\mathrm{e}^{\mathrm{i}\phi}). \quad (8)$$

The direction of rotation S_M is generally an axis on the x–y plane defined by ϕ and by the ground-state absolute phase. These cases exemplify how shaping free-electron wavepackets enable to coherently manipulate the state of both light and matter systems. The ideal Dirac-comb states cannot be generated: realistically, the sum must be over a finite bandwidth and the amplitudes are only approximately constant. This limitation reduces the fidelity of the above-mentioned gates as further described in ref. 22.

Quantum gates with free-electron qubits

On the basis of these interactions, free-electron ancilla qubits can be used to drive quantum gates. One possible qubit encoding can utilize parity of energy combs, where the logical states are defined as[70]:

$$|0_e\rangle \approx \frac{1}{N}\sum_n |E + 2n\hbar\omega\rangle, \qquad |1_e\rangle \approx \frac{1}{N}\sum_n |E + (2n+1)\hbar\omega\rangle. \quad (9)$$

In this case, the operator b becomes equivalent to the Pauli operator σ_x, acting on the electron–qubit subspace. The S matrices then constitute entangling gates between the electron and the light–matter systems. For the two-level system, the electron interaction constitutes a generalization of the Mølmer–Sørensen gate, or an x–x Ising coupling gate ($R_{xx}(\theta)$)[100] (using appropriate choices of the ground-state absolute phase), similar to trapped-ion systems. For the photonic mode, the electron interaction constitutes a conditional displacement ($C_i D(\alpha)$, where i=x, y, z note the control basis), which is universal for continuous-variable quantum information processing.

$$S_\mathrm{M} \approx R_{xx}(2|g_\mathrm{M}|), \qquad S_\mathrm{Q} \approx C_x D(g_\mathrm{Q}). \quad (10)$$

Other qubit encodings on electrons can use the intrinsic spin, two spatial paths or pairs of energy bins. For path-encoded electron qubits, the S matrix facilitates qubit rotations and entangling gates for both discrete- and continues-variable quantum systems. Utilizing photon blockade mechanisms or feed-forward operations after measurements, electron qubits can realize a deterministic universal set of gates[39,40].

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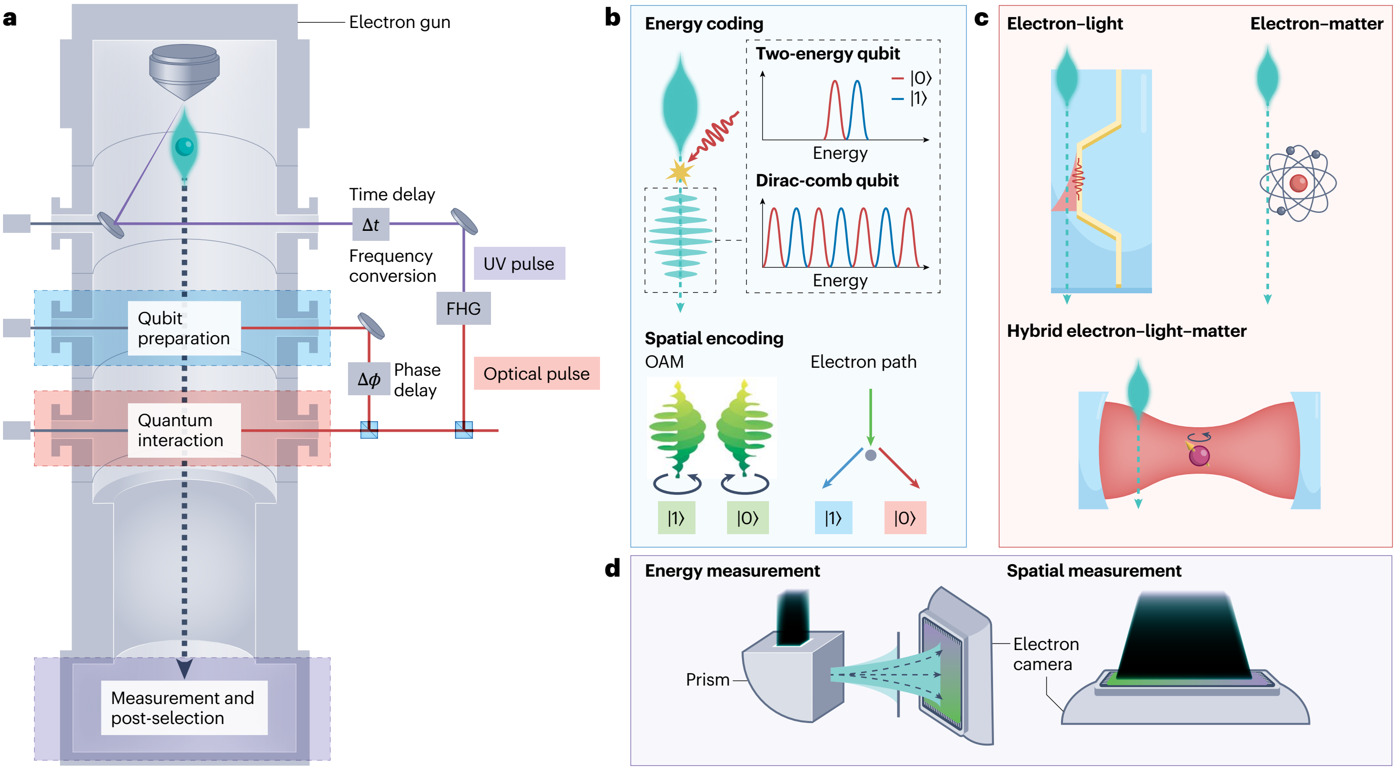

Fig. 2 | The electron microscope as a quantum-optical lab. a, Advanced electron microscopes, and especially the heavily modified ultrafast electron microscopes, contain the necessary ingredients to become quantum-optical labs. The illustrated microscope contains two interaction points with laser pulses, which have a relative phase delay $\Delta\phi$. It is photoemitted using a shorter-wavelength pulse (denoted UV) generated from the same laser pulse (for example, via fourth-harmonic generation, FHG). Temporal resolution is achieved using a controlled stage for relative time delay Δt. **b**, The free electron can encode quantum information on a few different degrees of freedom, including its energy levels, its path in space and its orbital angular momentum (OAM). **c**, The electron carrying the quantum information can later coherently interact with light, matter or hybrid light–matter excitations. **d**, The quantum information encoded on the electron is then measured by measuring either its energy or its spatial distribution, enabling post-selection and heralding.

way. In the first proposal of this interaction, dubbed free-electron–bound-electron resonant interaction[26], classically bunched free electrons coherently drive quantum two-level systems[27]. It was later realized that the fully quantum interaction between a free electron and a material qubit[28,29] or a hybrid light–matter system[31,32,48,49] gives access to features such as quantum coherence and entanglement. The coherent quantum interaction requires an excitation directly from the near field of the electron, rather than through a mediating particle such as a bulk plasmon or a phonon. This requirement makes the realization of free-electron–bound-electron resonant interaction-related effects particularly challenging as the dominant mechanism in the excitation of emitters is typically mediated trough bulk plasmons. What may help to mitigate this difficulty is an optical cavity with strong coupling to a bound-electron system and strong interaction of the free electron to that cavity[31,32,48].

Recent progress and promising directions

Encoding quantum information on free electrons

There are two common ways for the electron to encode quantum information: relying on the transverse or the longitudinal coherence of the electron. One can encode information on the electron transverse wavefront using phase masks[13,50,51], biprisms[8], structured light in the near field[52,53] or in free space[54,55]. Alternatively, quantum information can be encoded in the electron-energy spectrum by modulating the longitudinal electron wavepacket using laser interactions, for example, using PINEM[56,57] or free-space ponderomotive structured potentials[58,59].

The term 'modulated electron' refers to individual electrons that are coherently structured into a desired longitudinal shape along their direction of motion. Such structuring is possible because even a single electron is a quantum-coherent wavepacket whose shape can be varied. Although the energy spectrum of the electron is continuous, it can be treated as discrete when interacting with time periodic excitations of light or matter. Then, the free electron can lose or gain discrete quanta of energy and its Hilbert space is spanned by a doubly infinite discrete energy ladder, similar to a quantum rigid rotor[60]. As with the quantum rotor, there are multiple ways to encode a qubit—and more generally a higher-dimensional qudit—on the electron-energy spectrum[56,57]. The same electron can then also be used to read, write and transfer quantum information.

The complementary method for encoding qudit information on a free electron is by shaping its transverse phase front[61]. Pioneering experiments in this direction encoded the qubit on a split electron path using biprisms and phase masks acting as electron beamsplitters[13,61,62], or encoded higher-dimensional quantum information in the electron orbital angular momentum[63].

In both encoding schemes, the free electron acts as a flying qubit (that is, qubits that propagate through space as opposed to trapped qubits). Unlike other forms of flying qubits, electrons promise excellent spatial and temporal resolution, together with relatively strong interaction. These characteristics are promising for interconnects with both light and matter systems on ultrafast timescales. The high kinetic energies of the electron (typically between 10 keV and 300 keV) also hold the potential for high detection fidelities.

Creation of correlated photonic states

Recent studies proposed the first concepts of free-electron-based sources of quantum light. In conventional free-electron radiation, electrons act as point-like particles generating classical light[1]. However, a full quantum-optical treatment shows that electron-emitted radiation does not necessarily take the form of classical light (that is, a Glauber coherent state) because electron–photon entanglement can become prominent. Such entanglement becomes apparent when the electron-energy uncertainty ΔE is smaller than the energy of individual emitted photons. Then, this entanglement influences both the quantum-optical coherence[17,18] and the state[19,21,22] of the generated light.

Correlations between electron energy and emitted photon number enable the non-deterministic preparation of photonic number states (Fock states) through coincident measurement of electron energy[22,35,64]. Detecting an electron-energy loss $\Delta E = n\hbar\omega$ heralds the creation of n photons with frequency ω, as recently shown experimentally[35]. Deterministic electron generation of Fock states was proposed using nonlinearities such as polariton blockade[39] or using quantum recoil-induced nonlinearities[38,65,66] that can become stronger in low electron energies[30,67,68].

Quantum light generation by free electrons can go beyond Fock states. Recent proposals involve modulating free-electron wavepackets into quantum combs[69–71] and post-selecting on electron-energy parity for generating and controlling cat states and Gottesman Kitaev Preskill (GKP) states[22]. Other suggested methods include using ponderomotive interactions to induce squeezing[21]. These capabilities highlight free electrons as a prospective resource for continuous-variable quantum information processing. The promise of such sources arise from their tunability in wavelength, subpicosecond timescales and room-temperature operation.

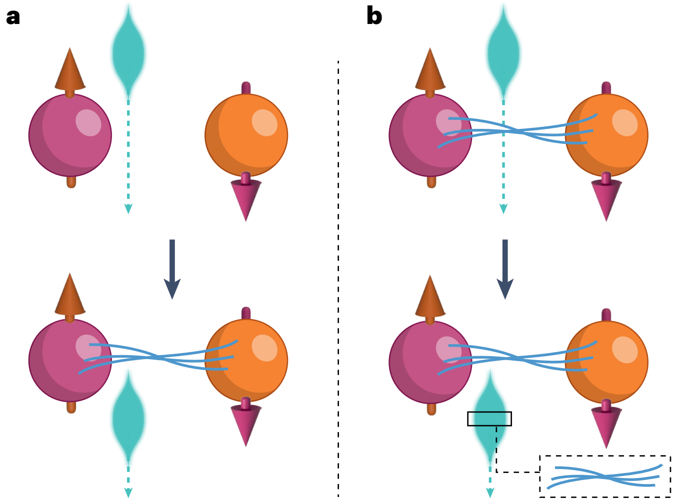

Fig. 3 | The free electron can create and measure quantum correlations. **a**,**b**, We envision how free electrons can be used to both generate (**a**) and probe (**b**) quantum correlations in light, matter and hybrid light–matter systems. Free electrons could enable unprecedented spatiotemporal resolution and apply to quantum systems across a wide range of energies. The blue wavy lines represent quantum correlations, which are either generated via the interaction with the electrons (**a**) or imprinted by the previously correlated matter on the electron wavefunction to be later measured and analysed.

Creation of electron–photon correlations

Beyond their role as quantum light sources, free electrons may carry quantum information[56,61] and function as ancillas that distribute entanglement[39,40] between distant photonic systems. Encoded in energy[56] or path[61], free-electron qubits enable a universal set of gates between photonic qubits in both discrete- and continuous-variable quantum information processing. In discrete-variable scenarios, the predicted electron–photon blockade mechanism controls a polaritonic qubit[39], while in continuous-variable cases, the electron acts as a conditional displacement operator on cat and GKP states[40]. Complementary to photonic ancillas, free-electron qubits and qudits could offer high bandwidth and high spatial resolution for addressing multiple cavity systems at rates much faster than typical cavity lifetimes[39]. For example, the typical gate operation time is on the picosecond scale because that is the time it takes a free electron of 10 keV to 300 keV to pass through a cavity of a few hundred micrometres. This property could prove valuable for platforms such as cavity QED, whose operation rates are often limited by the timescale of gate operations.

Part of the electron-based gates require a strong electron interaction with the photonic mode, which translates to a quantitative requirement for the coupling constant g_Q to be on the order of unity ($|g_Q| \approx 1$). Such a strong interaction was recently demonstrated[36] for a free electron exciting a photonic quasiparticle in a hybrid metal–dielectric waveguide, in excellent agreement with the quantum PINEM theory[43,44]. Additional experiments in all-dielectric integrated photonic cavities[72] and slotted photonic crystal cavities[73] have reached values of $|g_Q| \approx 0.1$. However, owing to the continuum of guided modes along the waveguide (or multitude of cavity modes in a large microcavity), the electron couples to different modes, and the reported value of $|g_Q|$ is an incoherent sum over smaller coupling strengths to the different modes. A strong interaction with a single mode has not yet been demonstrated, owing to a trade-off between interaction strength and ideality (the ratio between $|g_Q|^2$ to the desired mode and the sum of all $|g_Q|^2$ to all modes). The achievable $|g_Q|$ is ultimately constrained by electron-beam diffraction[37]. Limitations owing to ideality and diffraction could be lifted using ponderomotive electron guiding for longer interactions as studied in hollow-core nanofibres[62,74], or using electron cavities for multi-pass interaction with the same photonic cavity structure[75,76].

Recent experiments showcased free-electron–photon pairs by coincidence measurements on electron interactions with integrated photonic devices[35] and with point-defect excited states[77]. Using spectrometers with event-based electron detectors, these experiments revealed correlations in arrival time and in electron energy. Anticipated improvements in outcoupling efficiency, together with higher $|g_Q|$ in dielectrics, will enable heralded, high-number Fock-state generation.

Creation of electron–matter and electron–light–matter correlations

Free electrons can resonantly drive bound-electron systems[26,27], inducing entanglement[28,29] among quantum states of free and bound electrons. However, experiments of such phenomena have not been achieved yet because of the inherently weak interaction strengths. Free electrons interacting coherently with light and matter can also become entangled with their hybrid light–matter excitations[31,32,48]. This entanglement is valuable for detecting strong coupling in light–matter systems and for revealing quantum coherence in polaritonic systems[31,32,34]. Such findings offer exciting prospects for generating many-body entanglement (Fig. 3a), leading to collective phenomena such as superradiance[78].

Creation of electron–electron correlations

Quantum correlations between electrons can involve different degrees of freedom, including the electrons' path, energy and momentum. Recent experiments have demonstrated energy-correlated multi-electron states via Coulomb repulsion in nanotip photoemission[79,80]. These electron states facilitate tunable sub- and super-Poissonian electron statistics through temporal delay or energy filtering. Quantum electron correlations have also been predicted to arise from their interactions with a quantum ancilla, which can be implemented as a photonic cavity[43,81] or a bound-electron system[82]. Electron correlated states can affect light emission patterns[83,84] and hold promise for quantum-enhanced imaging[82,85]. These advancements are pivotal for applications such as low-dose and low-shot-noise imaging in quantum electron microscopy[75,85].

Free electrons as quantum sensors of classical phenomena

The free electron is a versatile probe for phenomena happening on femtosecond timescales and nanometre length scales, relevant to a wide range of applications in nanophotonics and condensed-matter physics. Specifically, PINEM enables imaging optical cavity modes in nanophotonic structures[86,87], recording optical wavepacket propagation in two-dimensional materials[23,88], and mapping subcycle plasmonic field dynamics using attosecond electron pulse trains[89] or phase modulated electrons[90].

Both the transverse and the longitudinal quantum coherence of the free electron allow to coherently probe electromagnetic fields. The transverse coherence is traditionally shaped using passive[50] or programmable[51] phase plates. Biprisms[8] and phase masks[13] can implement various interferometry schemes, including Mach–Zehnder[13] configurations. Various holographic techniques can be used to image coherence lengths[91], magnetic circular dichroism[92] and symmetries of localized plasmonic modes[93]. Other versions of holography have implemented interaction-free measurements[13] and recently optical Lorentz microscopy[94]. Future advancements in shaping free-electron wavefunctions using light[53–55] will keep pushing the frontier of phase-contrast electron microscopy and holography.

Recently, interferometry involving the longitudinal electron coherence was applied as part of a microscopy technique, demonstrating subcycle field microscopy[23,89,90], by relying on the interference between reference and sample fields, imprinted on the free-electron spectrum. Such interferometry integrated into microscopy can implement coherent amplification in electron microscopy[11,23], reducing the necessary pump intensity while maintaining the image contrast[23]. This amplification is of particular importance for samples with low optical damage thresholds.

Free electrons as quantum sensors of quantum phenomena

Free electrons hold promise for both creating and measuring quantum correlations. Through the quantum PINEM theory[43,44], electrons have been predicted to be sensitive to the photon statistics[15,44]. This capability was experimentally demonstrated by comparing light with Poissonian and super-Poissonian statistics[15]. Additional interactions of each electron with a reference local oscillator before or after its interaction with a quantum photonic state can enable quantum-state tomography, reconstructing the photonic Wigner function[95]. This form of quantum-state tomography inherits the electron's nanometre spatial resolution and subpicosecond temporal resolution.

When such tomographic electron interactions are applied for bound-electron systems, they have the potential to reconstruct the state of bound-electron qubits[28,29] and of polaritonic qubits found in strongly coupled systems[31,48]. These capabilities could allow the imaging of vacuum Rabi oscillations[31], the extraction of decoherence times[28] of individual quantum emitters in large ensembles, and the study of complex collective phenomena and many-body dynamics that are otherwise inaccessible. Intriguing many-body physics becomes accessible because each free electron can simultaneously interact with the collective state of many emitters. For example, in grazing-angle geometries, each electron can interact with multiple quantum emitters and thus perform measurements of high-order correlations between the emitters. The emitters can be excited such that the transmitted electron observes an effectively larger superradiant dipole. This phenomenon can be observed in superradiant electron-energy-loss spectroscopy[78], which could reveal phenomena beyond conventional superradiance that emerge from the extended geometry and from dipole–dipole interactions—regimes of many-body quantum optics that cannot be captured analytically nor fully simulated on classical computers.

Another emerging approach is driving photon sources with the electron before its interaction with the sample[96], which can generate phase-locked photon–electron interactions that can be controlled via the delay between the photon source and the sample[97].

Final remarks

The theoretical investigation of free-electron quantum optics has produced many intriguing concepts that have not yet been realized in experiments. We expect this gap to gradually shrink over the coming years, by innovative experiments becoming feasible at the frontier electron microscopes that now support quantum-optical experiments in free electrons. The first demonstration of free-electron–bound-electron interactions, electron-heralded photonic cat states and cavity-mediated electron–electron entanglement are particularly anticipated goals.

To achieve these milestones, several instrumental challenges must be addressed. First, enhancing the coupling strength and coupling ideality of free electrons to photons in all-dielectric (or more generally, lossless) systems is a pre-requisite for many applications[98]. Development of a platform for coupling slow electrons and light will help accommodate the growing number of ideas in this domain[67,68]. Primarily, slow non-relativistic electrons are predicted to allow greater enhancement of the coupling to matter excitations, as well as generation of entanglement and single-photon nonlinearity via quantum recoil[38,66]. Development of spectrometers for scanning electron microscopes[99] will make free-electron quantum optics accessible to a broader community, using lower electron energies. For more energetic electrons, modular and customizable transmission electron microscopes will enable schemes relying on multiple points of electron–light interaction, such as generation of electron combs and interferometric experiments[13,71]. Technologies employing transverse coherence will benefit from further development of efficient two-port beamsplitters[62] and electron cavities[76], advancing ideas related to spatial entanglement and quantum electron microscopy. Finally, finding a suitable bound-electron system or hybrid light–matter system supporting strong free-electron interactions will open the way to a line of anticipated experiments on electron–matter entanglement[28,29,78].

We anticipate that upcoming developments will strengthen the connection of free-electron physics and fields such as photonics, condensed-matter physics, and quantum science and technology. Coherently modulated free-electron wavepackets, for instance, could serve as powerful probes of quantum correlations, especially in for many-body quantum systems on ultrafast timescales and within confined dimensions. Addressing these challenges will inspire the development of next-generation quantum microscopy and spectroscopy techniques, and of new paradigms in quantum light–matter interactions.

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Competing interests

The authors declare no competing interests.

Additional information

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