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A Letters Journal Exploring the Frontiers of Physics

February 2025

EPL, **149** (2025) 36001
doi: 10.1209/0295-5075/adaf51

www.epljournal.org

Perspective

Attosecond microscopy —Advances and outlook

J. Vogelsang[1], A. Mikkelsen[2], C. Ropers[3,4], J. H. Gaida[3,4], M. Garg[5], K. Kern[5,6], J. Miao[7], M. Schultze[8] and M. Ossiander[8,9(a)]

[1] *Institute of Physics, University of Oldenburg - 26129 Oldenburg, Germany*
[2] *NanoLund and Department of Physics, Lund University - Lund 22100, Sweden*
[3] *Department of Ultrafast Dynamics, Max Planck Institute for Multidisciplinary Sciences - 37077 Göttingen, Germany*
[4] *4th Physical Institute–Solids and Nanostructures, University of Göttingen - 37077 Göttingen, Germany*
[5] *Max Planck Institute for Solid State Research - 70569 Stuttgart, Germany*
[6] *Institut de Physique, Ecole Polytechnique Fédérale de Lausanne - 1015 Lausanne, Switzerland*
[7] *Department of Physics & Astronomy and California NanoSystems Institute, University of California, Los Angeles Los Angeles, CA, USA*
[8] *Institute of Experimental Physics, Graz University of Technology - 8010 Graz, Austria*
[9] *John A. Paulson School of Engineering and Applied Sciences, Harvard University - Cambridge, MA, USA*

received 17 October 2024; accepted in final form 28 January 2025
published online 18 February 2025

Abstract – Attosecond microscopy aims to record electron movement on its natural length and time scale. It is a gateway to understanding the interaction of matter and light, the coupling between excitations in solids, and the resulting energy flow and decoherence behavior, but it demands simultaneous temporal and spatial resolution. Modern science has conquered these scales independently, with ultrafast light sources providing sub-femtosecond pulses and advanced microscopes achieving sub-nanometer resolving power. In this perspective, we inspect the challenges raised by combining extreme temporal and spatial resolution and then highlight how upcoming experimental techniques overcome them to realize laboratory-scale attosecond microscopes. Referencing proof-of-principle experiments, we delineate the techniques' strengths and their applicability to observing various ultrafast phenomena, materials, and sample geometries.

Attoseconds (1 as $= 10^{-18}$ s) are often visualized as the timescale of electron dynamics. Attosecond spectroscopy provides a time-domain perspective on the interaction of charge carriers with light in atoms, molecules, and solids. Due to its superior temporal resolution, it can resolve the build-up of light-induced excitation and distinguish between effects stemming from the electromagnetic fields making up a short light pulse and effects governed by the light pulse's intensity envelope [1]. By unraveling, and later manipulating, the very start of energy flow from light to charge carriers in a solid, and the subsequent transfer to other charge carriers, excitons, and phonons, attosecond science bears the potential to, *e.g.*, elevate communication and computation towards petahertz speeds or optimize the efficiency of light harvesting devices.

The energy of optoelectronically relevant charge carriers rarely exceeds that of photons in the ultraviolet region, *i.e.*, ~ 6 electron volts (eV). In a vacuum, an electron with such kinetic energy moves at a speed of $\sim 1.5\,\mathrm{nm/fs}$. In solids, a charge carrier's effective mass changes its (perceived) speed by up to 10-fold. This dictates that attosecond charge carrier dynamics occur on short length scales, limits the dimensions of devices that can manipulate them, and suggests that recording real-space-movies of attosecond electron dynamics requires high spatial resolution. Therefore, attosecond microscopy, *i.e.*, spatially resolving attosecond spectroscopy, is the key to enhancing its information content and increasing the variety of observable samples, and will play a crucial role in applying it to technologically relevant devices.

Experiments attain temporal resolution by illuminating samples with a short photon or electron wave packet. The

(a) E-mail: marcus.ossiander@tugraz.at (corresponding author)

Fourier limit, $\tau_{\min}\Delta E > h/2$, dictates the minimal duration $\tau_{\min}$ of this wave packet and, thus, the best temporal resolution. It demands a broad spectral bandwidth ΔE, *e.g.*, at least $\Delta E = 2\,\text{eV}$ to obtain $\tau_{\min} < 1\,\text{fs}$. Additionally, a wave packet's group delay dispersion must be controlled to keep a wave packet short. In cases, the shortness of attosecond dynamics can be exploited to circumvent the Fourier limit: the electric field of a visible light pulse oscillates on the single-femtosecond scale, even if its envelope is temporally long. Therefore, dynamics finished within a single optical cycle or periodic with the light frequency can be observed with a temporal resolution defined by the optical cycle duration [2]. Experiments must simultaneously overcome the Abbe limit $d_{\min} > \lambda_0/(2\text{NA})$ which measures the best attainable spatial resolution $d_{\min}$. It demands a short vacuum wavelength λ_0 and a high numerical aperture (NA). The NA is limited to, at most, the refractive index of the medium surrounding a sample.

The key to an attosecond microscope is simultaneously achieving a large spectral bandwidth, dispersion control, a high NA, and (chromatic) aberration control. Concurrency requirements are simplified if short-pulse illumination before the sample provides temporal resolution and imaging after the sample provides spatial resolution, splitting dispersion control from high-NA imaging. Because the Fourier limit demands an absolute bandwidth ΔE for a given temporal resolution, increasing the illumination energy E decreases the relative bandwidth $\Delta E/E$ required for a short wave packet which relieves chromaticity and dispersion compensation. Still, uniting nanometer-scale spatial and sub-femtosecond temporal resolution stays challenging and instruments must be tailored to the sample and process of interest. Here, we introduce selected lab-scale strategies to realize an attosecond microscope.

Light-based attosecond microscopy approaches observe the transmission or reflection of samples and operate in the extreme ultraviolet (EUV) spectrum to achieve a sufficiently small wavelength ($\lambda_0 = 1239\,\text{nm eV}/E$ with the photon energy E) for sub-100 nm spatial resolution. They can leverage high-harmonic-generation (HHG) based sources that reliably provide light pulses with high photon energy, sub-femtosecond duration, and broad bandwidth [3]. Current pushes develop imaging techniques and optics that can combine a high NA, diffraction-limited imaging, and broadband operation.

Transient absorption spectroscopy. – Function in electronic, spintronic, or the envisioned orbitronic applications rests on the deterministic change of the state of matter and the use of the resulting final state as readable information carrier. For the canonical transistor, the possible final states are non-conductive (electrons in the immobile ground state) and conductive (electrons occupy conduction band states and contribute to electric conductance) and the external stimulus switching the semiconductor between the two states is an applied voltage. How fast the stimulus can toggle between states is an active

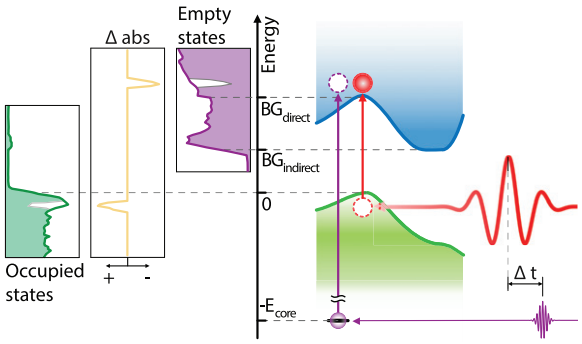

Fig. 1: Transient absorption spectroscopy: a laser pulse (red) changes a material's valence (green) and conduction (blue) band occupation. The ensuing occupation evolution modulates the absorption Δabs of an EUV pulse (purple) delayed by Δt and matched to the energy difference between a core-level and the investigated states.

field of research animated by findings that ultrafast laser pulses allow to alter a band-gap material's dielectric function at petahertz bandwidth, orders of magnitude faster than electronics. These observations raised questions regarding the electronic system's immediate response to the stimulating electric field and how charge excitation (*i.e.*, carriers gaining energy) and charge motion and currents (*i.e.*, carriers gaining momentum) evolve in time and space to dictate the electronic response.

Transient absorption spectroscopy turned out to be powerful in sampling the energy-dependent states available to charge carriers and following the temporal evolution of their occupation [4–8]. The large photon energy of attosecond pulses generated by HHG can be tuned to resonance with a core transition of the sample such that the initial state of the transition is fixed in energy and the final state is in the valence and conduction band of the solid. As displayed in fig. 1, changes to the strength of these transitions Δabs then become a sensitive probe to changes of the occupancy caused by external stimuli via transition bleaching when previously empty conduction band states above the band-gap energy BG become occupied or via enhanced absorption into states in the valence band emptied by the stimulus. Scanning the arrival time difference Δt between the attosecond probe pulse and the stimulus (which is often an ultrashort optical waveform) then maps electronic excitations between valence and conduction band onto changes of the energy-resolved EUV absorbance. This allowed to time-track polarization response, population build-up, charge-lattice coupling, and early thermalization in several band-gap materials [4–9].

Though HHG-based transient absorption is not a microscopy technique providing direct spatial resolution (until EUV optics with high NA become available, see below), the element specificity of EUV transitions can be exploited to obtain atomic-scale resolved spatial information provided the crystal structure of the material is known *a priori*. With the attosecond pulse photon energy tuned to the

absorption edge of one of a material's constituents, the locality of charge transfer can be explored. That allowed time-tracking charge transfer and phase transitions in alloy materials including GaAs, TiS_2, VO_2 [10–12], charge and spin transfer across material interfaces in ferromagnetic and photocatalytic systems [13,14], and structural changes in molecules [15].

Broadband diffractive imaging. – One approach that can elegantly add spatial resolution to broadband attosecond spectroscopy without the need for novel optics is coherent diffractive imaging (CDI) [16–18], where a coherent wave illuminates a sample and the diffracted intensity is directly recorded. An iterative phase retrieval algorithm is then used to reconstruct both the phase and amplitude images of the sample and the illumination beam, with a resolution limited only by the wavelength and the NA of the setup. A powerful CDI method, called ptychography, achieves high-fidelity image reconstruction by acquiring diffraction patterns from many overlapping regions, with the large redundancy in the measured data ensuring convergence [19,20]. Although initial implementations of CDI assumed narrow spectral bandwidths to reduce the uncertainty in phase retrieval [16,21,22], recent developments have enabled significant increases in the highly spatially and temporally coherent bandwidth of HHG light [23–26] and new CDI methods are enabling accurate image reconstructions using broadband illumination [27–33].

One novel method, termed atto-CDI [32], used simulated attosecond pulses with a broad bandwidth HHG spectrum ranging from 4.1 to 12.4 nm to create a confined probe. The probe was scanned across a sample with large overlaps, producing a series of diffraction patterns. A flux of 10^7 photons per scan position was simulated, which can be achieved with HHG in this spectral region [23]. An advanced algorithm, called Spectrum, Probe, and Image REconstruction (SPIRE), was developed to simultaneously reconstruct the spectrum, 17 probe beams, and 17 spectral images of the sample [32]. Figures 2(a)–(f) show three representative probes and spectral images of a sample —a letter pattern with "atto" made of 200 nm thick aluminum and "CDI" of 200 nm thick boron. Boron was chosen because its K-absorption edge at 6.6 nm is within the simulated spectrum, providing a contrast difference to assess the reconstruction quality of the spectrum and spectral images (figs. 2(d)–(f)). The principle and feasibility of the method were further validated by conducting a ptychographic CDI experiment using a light-emitting diode with a broad spectrum ($\Delta E/E \approx 50\%$) [32].

The continued development of atto-CDI could unify attosecond science and coherent diffractive imaging (CDI) to achieve high spatial and temporal resolution imaging (sub-10 nm, sub-fs) above and below characteristic absorption edges in materials. Such methods can leverage the broad spectrum of EUV attosecond pulse trains, and isolated attosecond soft x-ray pulses (fig. 2(g)), enhancing imaging efficiency and throughput. This new capability has

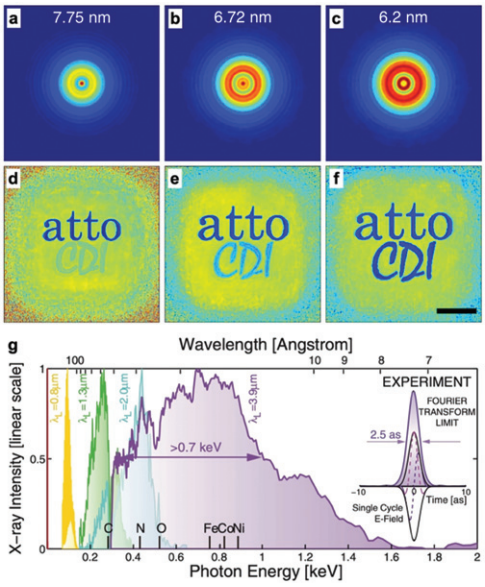

Fig. 2: Potential of attosecond CDI. Absorption images of a letter pattern at 7.75, 6.72, and 6.2 nm. Three representative probes (a)–(c) and spectral images (d)–(f) of, show how the image contrast of the "CDI" letters changes across the absorption edge of the material [32]. Scale bar: 2 mm. (g) Experimental HHG spectrum demonstrating that phase matching of HHG uniquely enables broadband laser-like beams from the EUV to the keV region [23] (Reprinted with permission from AAAS.), which is ideal for atto-CDI.

the potential to be transformational for functional imaging. Applications range from 3D imaging for nanoelectronics to supporting the development and integration of materials and interfaces for next-generation devices with optimized charge, spin, and phonon transport and energy efficiency [34]. Additionally, it can enhance understanding of spintronic [35] and quantum systems [36].

Optics and metaoptics for EUV light pulses. – In contrast to lensless techniques, direct light microscopy depends on large-magnification imaging systems and high-NA optics. But also transient absorption spectroscopy, diffractive imaging, photoelectron microscopy, and scanning-tunneling microscopy require (focusing) optics to route light to the sample and benefit from concentrating light on a small area of interest.

Reflective optics can efficiently guide EUV light beams incident grazingly over a broad spectral range. Impressive resolutions can be achieved in x-ray microscopes employing ellipsoidal, Kirkpatrick–Baez, or Wolter mirrors [37]. However, due to their aspherical shape and strict requirements for surface quality, implementing such setups with high NA and diffraction-limited performance is challenging and expensive. Toroidal mirrors, the current workhorse of EUV beamlines, only approximate ellipsoids and thus introduce coma when not used in a relay-imaging configuration, which presumes unity magnification [38,39]. Bragg-condition multilayer coatings can achieve high reflectivities at normal incidence for radiation

around a design wavelength [40]. Combined with spherical substrates, they can realize magnification. However, such mirrors introduce spherical aberrations and astigmatism due to an angle of incidence necessary to separate incoming and outgoing light. Using a Schwarzschild geometry circumvents astigmatism at the cost of reduced transmission.

Transmissive optics are desirable for realizing large (de)magnifications because they require no deflection from the optical axis. However, absorption prevents refractive optics (*e.g.*, lenses) in the EUV. Diffractive optics (*e.g.*, Fresnel zone plates) can focus EUV radiation [41] and introduce optical angular momentum [42,43].

Ten nm large nanostructures, smaller than the wavelength of EUV radiation, are now manufacturable. This opens the ability to create metasurfaces (two-dimensional metamaterials). Such surfaces consist of wavelength-scale nanostructures, called meta-atoms, whose optical properties are defined by their material and shape. *I.e.*, the transmission phase of each meta-atom can be determined during nanofabrication. An array of such meta-atoms imprints a spatially varying phase profile on a transmitted wavefront. Metasurfaces can use absorbing materials and still achieve viable transmission holograms because they are thin.

A first demonstration of the efficacy of this concept in the EUV used circular holes with varying diameters, drilled through a free-standing, 220 nm thick silicon membrane, to focus 50 nm wavelength light [44]. Because the refractive index of silicon ($\tilde{n} = 0.77 + 0.02i$) is smaller than that of vacuum ($\tilde{n} = 1$), the perforations guide the EUV light, increasing the lens' transmission. The demonstrator lens with a 1 mm diameter and a 10 mm focal length focused incident light down to a 0.7 um wide waist which is 1.6 times the diffraction limit.

Exciting is the ability to create EUV phase holograms, and thus the possibility to introduce optical angular momentum, influence the polarization of light, and combine the function of multiple optics (*e.g.*, lenses, beamsplitters, axicons, Bragg gratings) in a single device.

Metalenses, as diffractive optics, are chromatic, and their focal length scales with the ratio of the design wavelength over the actual wavelength $f(\lambda_0) \sim f(\lambda_0^{\text{design}})\lambda_0^{\text{design}}/\lambda_0$. However, due to the small relative bandwidth necessary to achieve short EUV pulses, we are confident they provide a route to direct-imaging microscopy with sub-femtosecond resolution. Interestingly, phase-shifting structures are also successfully applied to enhance the performance of 13.5 nm wavelength optical lithography masks [45]. This indicates that metasurface technology can be pushed towards the short-wave EUV spectrum with improved nanofabrication which would further relieve relative bandwidth requirements.

The spatial resolution of microscopes observing electrons benefits from their (at typical kinetic energies E_{kin}) small wavelength ($\lambda_0 = 1.226\,\text{nm}\,\sqrt{\text{eV}}/\sqrt{E_{\text{kin}}}$) and mature electron optics. However, vacuum dispersion aggravates synthesizing short electron wave packets.

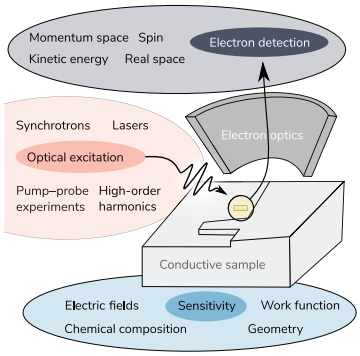

Fig. 3: Photoemission electron microscopy. Optical excitation followed by photoelectron spectromicroscopy of (conductive) samples is a flexible and sensitive technique as it allows independent optimization of the light source, electron microscope, and sample.

Photoemission electron microscopy. – PhotoEmission Electron Microscopy (PEEM) images photoelectrons emitted from a surface with a lateral resolution down to a few tens of nanometers (see fig. 3). It can retrieve chemical composition, electronic structure, and local field distributions [46,47] as used in combination with a range of advanced light sources including synchrotrons and lasers. PEEM microscopes have seen significant improvements in terms of spatial, energy, and momentum resolution in recent years [48]. Achieving simultaneous high space and time resolution is possible because the temporal (light) part of an experiment ends with photoemission where the spatial (electron) imaging part starts.

Many significant results on ultrafast local charge carrier and field dynamics have been achieved by imaging photoelectrons resulting from the simultaneous absorption of n photons. The PEEM image will then depend on the local light intensity on the surface raised to the power of n. This direct visualization of field dynamics with attosecond phase and nanometer space resolution has led to a deeper understanding of plasmon dynamics and the exploration of spectacular plasmon effects [49–51].

Using spectrally narrow ($\sim 100\,\text{meV}$) IR to EUV pulses, PEEM can follow the band structure dynamics of photoexcited electrons. Emitted photoelectrons are spectrally differentiated in PEEM which can, *e.g.*, be used to directly image hot carrier relaxation and transport in nanostructures [52]. HHG is currently used by many groups to create high-energy photons that have a narrow spectral distribution in the 20–30 eV range [53,54]. With a temporal duration from ~ 10 to ~ 100 fs, the electronic structure in a wide energy range around the Fermi level can be explored. By setting the PEEM to image the electron momentum, charge transfer processes in reciprocal space can be recorded, *e.g.*, in two-dimensional materials [53].

With higher photon energies, electronic structure dynamics can be imaged simultaneously with chemical

composition via nanoscale core-level spectroscopy. Using spectrally broader HHG pulses (width of $\sim$ 2 eV) with durations in the sub-femtosecond range, attosecond photoelectron dynamics can be studied. However, spectrally isolated features like (shallow) core levels must be targeted due to the reduced spectral resolution (see also transient absorption spectroscopy). Optical electric fields at the surface, synchronously excited with a second pulse, can accelerate the photoelectrons and thus imprint their current state with attosecond precision in the momentum of the photoelectrons [55,56]. Thus, experiments with elemental contrast and resolving the field dynamics around nanostructures are now within reach.

Scanning tunneling microscopy. – A way to image frontier orbitals of a single molecule with sub-Ångström scale spatial resolution is scanning tunneling microscopy (STM). Immediately after STMs became operational in laboratories around the world, attempts were made to integrate the high temporal resolution of ultrashort laser pulses with the high space-resolving capability of an STM. Nevertheless, thermal artifacts induced at the apex of an STM nanotip by the high-energy laser pulses plagued these efforts. Recently it was shown that very low-energy laser pulses in the visible to near-infrared (NIR) frequencies coming at high repetition rates can maintain stable conditions in an STM junction, and laser-driven tunneling currents from single molecules can be measured without the presence of thermal artifacts [57,58].

The unison of NIR laser pulses with an STM can drive laser-induced tunneling currents in the field-driven and the photon-driven tunneling regimes (fig. 4). In the field-driven tunneling regime, the potential barrier in the STM tunnel junction is distorted on ultrafast timescales, inevitably leading to an uncontrolled shaking of electronic and vibrational states of the molecules [57]. In the photon-driven tunneling regime, photons gently excite electrons from selective electronic states of the molecule, which can then tunnel to the other side of the STM junction [59]. This perturbative approach is ideally suited to investigate dynamics in single molecules.

Coherent control of electron tunneling current in the STM junction by tuning the carrier-envelope–phase (CEP) of two-cycle–long NIR laser pulses was demonstrated on timescales as short as two-hundred attoseconds [57]. Coherent oscillations of electronic motion between frontier orbitals of a complex molecule triggered by resonant laser pulses were directly imaged with ∼300 attosecond time and sub-Ångström spatial resolution [58]. Extreme confinement of laser pulses over a molecule in the picocavity formed between the nanotip of the STM, a molecule, and the underlying substrate enables very high spatial resolution in the imaging of molecular orbitals. A static bias in the STM junction enables selective excitation and tunneling of electrons from specific molecular orbitals [59].

Significant efforts during the last several years have also focused on combining long-wavelength terahertz (THz) pulses with an STM which can give picosecond time and Ångström-scale resolutions in imaging dynamics [60–63]. Nevertheless, the time resolution achievable by THz pulses is not sufficient to probe electron dynamics.

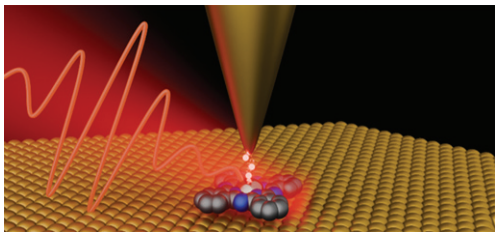

Fig. 4: Attosecond scanning tunneling microscopy. Schematic illustration of a single-cycle NIR laser pulse illuminating a picocavity formed between nanotip of an STM, a single molecule, and a metallic surface.

All photoexcited dynamics, *e.g.*, chemical transformation, charge, and energy transfer in nature evolve by a conspicuous coupling of electronic and atomic motion in a molecule. Laser-induced tunneling currents in the STM junction dominantly provide information about electron dynamics and little insight into atomic dynamics. Realizing broadband four-wave-mixing spectroscopy (FWM), *e.g.*, coherent anti-Stokes Raman scattering (CARS) spectroscopy in an STM has enabled direct real space-time imaging of motion of atoms inside a single molecule [64,65]. Atomic motion in a single graphene nanoribbon evolving on timescales as short as $\sim$ 70 fs was probed with Ångström-scale spatial resolution. The realization of FWM in an STM opens the possibility to track electronic and atomic motions simultaneously with a time resolution as high as a few fs, faster than Raman variations of FWM (such as CARS).

These proof-of-concept demonstrations resolving electronic and atomic motion in a single molecule with atomic-scale resolution in space, time, and energy [64] open new possibilities to address fundamental questions in chemistry. Real space-time imaging of a chemical transformation in a single molecule is within reach and will hopefully resolve open questions related to conical intersection dynamics and transition state spectroscopy.

Transmission electron microscopy. – Instead of with light, transmission electron microscopy (TEM) illuminates samples with energetic electrons with de Broglie wavelengths of only a few picometers. It usually recovers the spatially varying Aharonov-Bohm phase imprinted on the electron wave function transmitted through a sample via phase-contrast imaging. TEMs routinely offer quantitative insights with atomic-scale spatial resolution into lattice structures, as well as electric and magnetic fields. Beyond the microscopy of static potentials, analyzing inelastic electron scattering reveals optical excitations and electronic (*e.g.*, core-level) transitions, in the form of cathodoluminescence or electron-energy loss spectroscopy [66].

Ultrafast TEMs are capable of tracing non-equilibrium phenomena, such as the evolution of structural phase transformations, the generation and propagation of strain waves, and laser- and current-induced magnetization dynamics by pulsing the probing electron beam. In particular, photoemission electron sources enable laser-pump/electron-probe TEM experiments on the femtosecond scale, primarily limited by electron pulse dispersion and Coulomb interactions. Reaching attosecond resolutions, *i.e.*, capturing dynamics within the cycle of visible light, requires advanced electron pulse structuring and readout techniques, which have recently been realized.

Specifically, temporal bunching of electrons to form an attosecond pulse train was accomplished by periodic phase modulation [67–69]. Using either stimulated inelastic electron light interaction (IELS) [70,71] or ponderomotive potentials [69], the periodic phase modulation of the electron beam and subsequent dispersive propagation produces a bunching of the electron density within each optical period, see fig. 5(a). A second, phase-locked action on this attosecond electron pulse train reveals its sub-cycle structure via measurements of the final electron energy [67,69] or transverse deflection [68]. In analogy to the method of spatially separated fields in atomic clocks, Ramsey-type oscillations in the final-state populations are found as a function of the relative phase of both interactions [72,73]. Energy filtering of electrons having gained (or lost) energy then yields phase-resolved representations of the optical response of materials and nanostructures, with a recent application in imaging near fields at a metallic taper [74] and polaritons on a boron nitride membrane [75]. Measuring the complete energy spectrum as a function of the relative phase of both interactions (fig. 5(b)), allows for a complete quantum state reconstruction of the electron density matrix [67]. In this way, harnessing analytical relations between the optical-field strength [76,77] and the inelastic scattering cross-section allows for a quantitative analysis of sub-cycle local fields.

Moreover, such a coherent interferometric quantum state analysis alleviates the need for electron beam compression or dispersive propagation to retrieve attosecond optical responses in electron microscopy. Specifically, a general periodic optical response of a material will lead to an amplitude and/or phase modulation of the transmitted electron wave function at the fundamental driving frequency and its harmonics. Such modulations can be unambiguously discerned by quantum state reconstruction of the probing electron ensemble. Establishing free-electron homodyne detection (FREHD), in ref. [78], this principle was employed to image the sub-cycle evolution of optical resonances at a metallic nanotriangle (fig. 5(c)). These proof-of-principle studies illustrate the optically coherent readout of sub-cycle information imprinted onto free-electron states. In the future, such schemes can probe electronic and lattice dynamics and detect subtle changes in the structure factor induced by valence-electron motion. Moreover, quantum-state reconstruction is sensitive

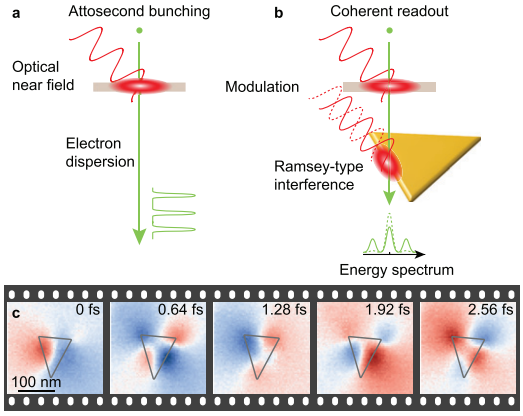

Fig. 5: Schematic and implementations of attosecond free-electron probing. Coherent inelastic electron-light scattering modulates the free-electron beam. (a) Group velocity dispersion of the electron beam after the modulation forms an attosecond electron pulse train, which can be used for imaging and spectroscopy. (b) The sequential interaction of a probe beam with a modulator and a sample, here a metallic nanotriangle, creates Ramsey interferences of the electron wave function and allows for a phase-resolved readout of the probed response by free-electron homodyne tomography (FREHD). (c) Temporal evolution of the electromagnetic light field on a triangular gold nanoprism measured by FREHD [78].

to decoherence phenomena and can be integrated with schemes that investigate spatio-temporal correlations of material excitations, potentially serving as future atomic-scale probes of quantum correlations and entanglement.

Outlook. – Other promising techniques are explored to gain insight into different sample properties, *e.g.*, optical coherence tomography provides depth-resolved imaging [79], HHG spectroscopy reveals the electronic structure of materials in high electromagnetic fields [80], and reconstruction of attosecond harmonic beating by interference of two-photon transitions (RABBITT) and attosecond streaking measure the phase evolution of electrons [81]. All techniques benefit from the maturing of femtosecond laser technology which increases robustness, possible integration times, and signal-to-noise ratios. Their simplified operation moves attosecond microscopy within the grasp of more laboratories and HHG sources driven by them can operate with higher repetition rate [82] and at higher photon energies [23], increasing the resolution and number of accessible materials. Furthermore, new synchrotrons and free electron lasers, which routinely reach deep core-level energies, start providing sub-femtosecond pulse durations [83,84]. Combining these with advanced optics and imaging techniques will develop attosecond microscopy into a powerful toolbox for time-resolving the fundamentals of condensed phase physics.

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JV acknowledges funding from the Niedersächsisches Ministerium für Wissenschaft und Kultur (DyNano) and

the Deutsche Forschungsgemeinschaft (462448709, Emmy Noether program). AM acknowledges funding from the Vetenskapsrådet (2020-04201), Wallenberg Initiative Materials Science for Sustainability (WISE) funded by the Knut and Alice Wallenberg Foundation (KAW). CR and JHG acknowledge great support by their collaborators, the Göttingen UTEM team, and funding by the Deutsche Forschungsgemeinschaft (German Research Foundation, Project-ID 432680300, SFB 1456, project C01). JM acknowledges support from the U.S. Air Force Office of Scientific Research (AFOSR) Multidisciplinary University Research Initiative (MURI) Program (Award No. FA9550-23-1-0281). MO acknowledges funding from the European Union (101076933 EUVORAM). Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the EU or the European Research Council Executive Agency. Neither the EU nor the granting authority can be held responsible for them.

Data availability statement: No new data were created or analysed in this study.

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