46. EAS - Meeting "Extreme Atomic Systems"

1 – 6 February 2026, Riezlern/Kleinwalsertal

– list of abstracts –

Farouk Albalacy, Albert Ludwigs University, Freiburg

Single- and many-body interference in a generalized Mach- Zehnder interferometer

We study the interplay of single- and many-body interference effects by injecting one quantum object per port in a generalized Mach-Zehnder interferometer with three ports. Single-body interference is controlled by the phase shifts between the paths of the interferometer. The effect of bosonic many-body interference is singled out by tuning the individual constituents' mutual distinguishabilities through their internal states. We analyze the output counting statistics for three partially distinguishable bosons, as a function of their internal states and of the interferometer phases.

Mohanad Awad, Friedrich Schiller University, Jena

Compact solid-state high harmonic generation interferometry

We demonstrate high-harmonic generation interferometry using thin films of semiconductors. Zinc oxide (ZnO) thin films deposited on a dielectric sapphire substrate are driven by a mid-infrared laser pulse (3200 nm) to generate high-order harmonics. By coating both sides of the substrate, harmonics generated at the front and rear surfaces coherently interfere, enabling interferometric measurements. As a proof of concept, we use this scheme to characterize the linear and non-linear dispersion of the sapphire substrate. Subsequenty, we attempt to access the dipole phase of the harmonics.

Mikhail Bednov, University of Rostock

Plasmon-assisted photoelectron emission in a model cluster using time-dependent density-functional theory and the time-dependent surface-flux method

We investigate plasmon-assisted photoelectron emission using a one-dimensional time-dependent density-functional theory (TDDFT) model. Photoelectron spectra are computed with the time-dependent surface-flux (t-SURFF) method. In addition to the expected above-threshold ionization (ATI) comb, we observe peaks that arise from long-lived plasmon oscillations and the associated electron emission occurring after the laser pulse. We further analyze the positions of these peaks and their scaling behavior with the laser intensity.

Andreas Buchleitner, Albert Ludwigs University, Freiburg

Thermodynamics with minimal quantum ingredients

We'll discuss which minimal quantum ingredients suffice to cook up a consistent definition of thermodynamic state variables. Our results suggest that pressure, entropy and temperature are already reasonably well-defined for one or two (then, interacting) particles, if only their dynamics exhibit "molecular chaos" (Sommerfeld). Furthermore, the "eigenstate thermalization hypothesis" finds a very tangible illustration.

Matthias Bundy, Albert Ludwigs University, Freiburg

Entanglement shortcuts in the geometry of micromaser state preparation

Any desired state of a single, quantized cavity mode can be preparedby sequentially interacting with a string of two-level atoms. However, the fidelity of the preparation process much depends on the desired target state, the number of atoms, and the degree of their mutual entanglement. Here we investigate the state preparation process from a geometric perspective, by establishing an appropriate metric for the length of state preparation trajectories. We quantify how the entanglement of the atomic string shortens the path from the cavity mode's initial to target state, and discuss how these trajectories differ for classical and non-classical target states.

Stasis Chuchurka, Friedrich Schiller University, Jena

Theory of Superfluorescent Pervoskite Quantum Dots

S. Chuchurka[1], A. Gorlach[2], C. Mechel[2], S. Levy[2], S. Katznelson[2], R. Strassberg[2], Y. Bekenstein[2], I. Kaminer[2], and S. Gräfe[1] [1]Theoretical Chemistry, Friedrich Schiller University Jena, Germany; [2]Solid State Institute, Technion, Haifa 32000, Israel;

Perovskites exhibit intriguing optical and electronic properties together with broad tunability, making them promising for a wide range of technological applications [1]. Dozens of recent studies have reported collective light–matter phenomena in perovskite-based superlattices. Specifically, perovskite nanocrystal systems have renewed interest in superfluorescence (SF), with several demonstrations, for example, reported in [2]. Nevertheless, fundamental aspects of SF in these systems remain under debate, especially regarding the underlying mechanisms and scaling behavior. In this talk, I present a comprehensive quantum many-body theory of SF in perovskite nanocrystal superlattices in the low-fluence excitation regime. Our model incorporates the key competing processes—emitter interactions, inhomogeneity, dephasing, and nonradiative decay. Several central SF characteristics are shown to admit analytical descriptions. This comprehensive theory deepens the understanding of perovskite quantum materials and paves the way toward a theoretical description of the room-temperature and high-fluence regimes.

[1] Dey et al., ACS Nano (2021);
[2] Rainò et al., Nature (2018), Findik et al., Nat. Phot. (2021), Biliroglu et al., Nat. Phot. (2022), Levy et al., ACS Nano (2025), Biliroglu et al., Nature (2025), Luo et al., Nano Lett. (2025).

José R. Crespo López-Urritia , MPI for Nuclear Physics, Heidelberg

Ultrafast Kapitza-Dirac Diffraction of Strong-Field Photoelectrons at 100MHz Repetition Rate

Achieving the intensities required for strong-field phenomena such as multiphoton ionization (MPI) typically demands kilohertz-repetition-rate amplified laser systems. We demonstrate a femtosecond enhancement cavity seeded with a near-infrared frequency comb that delivers $10^{13}\,W\,cm^{-2}$ at a 100MHz repetition rate. The bow-tie cavity supports counter-propagating pulses that form a transient standing wave at the focus. When combined with a gas jet and velocity-map imaging (VMI) [1], this configuration allows for angle-resolved photoelectron spectroscopy, enabling comparisons between traveling-wave and standing-wave ionization [2].
With an additional interferometer, we can generate a second standing wave with a tunable time delay. While the first standing wave ionizes the target gas at the antinodes, the weaker second standing wave only diffracts the ionized electrons from its spatially periodic ponderomotive potential (ultrafast Kapitza-Dirac effect [3]). Because the momentum distributions of the direct and diffracted photoelectrons overlap, the electrons interfere, giving access to their femtosecond phase evolution at a megahertz repetition rate.

[1] J.-H. Oelmann et al., Rev. Sci. Instrum., 93(12), 123303 (2022).
[2] T. Heldt et al., Opt. Lett. 49, 6825-6828 (2024).
[3] K. Lin et al., Science 383, 1467-1470 (2024).

Bikash Kumar Das, Friedrich Schiller University, Jena

High-order harmonic generation in ZnO driven by a Laguerre-Gauss vortex beam

The direct observation of electron motion in atoms, molecules, and condensed phases requires probes operating on attosecond timescales (1 as $= 10^{-}18s$). High-order harmonic generation (HHG) provides such probes by converting an intense, ultrashort laser pulse into coherent extreme-ultraviolet and soft X-ray radiation through a highly nonlinear, non-perturbative interaction. Because the harmonic emission inherits key characteristics of the driving laser — its polarization, spatial profile, and temporal structure — HHG allows the controlled synthesis of either isolated attosecond pulses or attosecond pulse trains. This sensitivity to the driving field has recently motivated a surge of interest in using spatially structured beams carrying orbital angular momentum (OAM) to generate short-wavelength radiation with high and tunable OAM. While HHG driven by OAM beams in atomic gases is well-established — leading to generalized selection rules, the demonstration of optical self-torque and twisted attosecond pulses, and insights beyond the dipole approximation — its solid-state counterpart remains largely unexplored.
We theoretically investigate the HHG process in a ZnO semiconductor crystal, driven by light beams OAM. Our studies focus on the transfer of OAM from the driving field to the harmonic field and the conservation of OAM in the strong-field regime. To this end, we combine the semiconductor Bloch equations with the thin slab model. This approach allow us to simulate the HHG process in semiconductor media and to compute the far-field properties of the generated harmonic fields. Our theoretical approach successfully reproduces key experimental features previously observed in ZnO when the driving field is a Laguerre-Gaussian beam.

Barbara Dietz-Pilatus, MPI for the Physics of Complex Systems, Dresden

Spectral Properties of Relativistic Quantum Billiards versus those of Haldane Graphene Billiards

In distinction to nonrelativistic quantum billiards (QBs), relativistic neutrino billiards (NBs), which consist of a spin-1/2 particle governed by the Weyl (Dirac) equation and confined to a bounded planar domain, do not have a well-defined classical limit. Yet, their spectral density is well approximated by a semiclassical trace formula, that is, in terms of a sum over periodic orbits of the classical dynamics associated with the QB. This led to the question to what extent the Berry-Tabor Bohigas-Giannoni-Schmit conjectures concerning the spectral properties of typical nonrelativistic quantum systems with an integrable and chaotic classical dynamics, respectively, apply to NBs. I will present some results and then come to graphene billiards (GBs), that is finite- size honeycomb lattices. It is well known that in the region of low-energy excitations around the Dirac points, where the dispersion relation is linear, the electronic properties of graphene are described by the same relativistic Dirac equation as NBs. Yet, GBs exhibit eigenstate properties of typical nonrelativistic QBs. I will demonstrate that, on the contrary, they comply with those of NBs for GBs subject to the Haldane-model on-site potential and next-nearest-neighbor tunneling at critical points.

Kartik Eswaran, Jagiellonian University, Krakow

Aspects of quantum geometry in photonic time crystals

We develop a geometric description of quantum light in photonic time crystals on the SU(1,1) coherent-state manifold. In a projective picture, the evolution of each mode appears as a Möbius isometry on the Poincaré disk, where topologies of trajectories distinguish stable, unstable, and critical regimes. The geometric phase is related to the hyperbolic area enclosed by cyclic paths in the complex projective Hilbert space. This framework offers an intuitive view of stability and phase space structure in quantum photonic time crystals.

Lars Funke, TU Dortmund

Measurement of neon photoemission delays and double-core-hole Auger-Meitner lifetime using Angular Streaking

The extreme brightness of X-ray free electron lasers allows probing non-linear processes in atoms and molecules in single-shot measurements. The addition of a temporal reference, e.g. through an Angular Streaking setup, enables the direct measurement of observables previously only accessible indirectly. Here, we report on a European-XFEL measurement that simultaneously yields relative emission delays for multiple transitions triggered by 990 eV photons in neon. Specifically, we are able to clock 1s, 2s and 2p photoelectrons, single- and double-core-hole Auger-Meitner electrons at the same time, owing to a multi-resolution time-of-flight detector setup covering a broad electron energy range.

Miriam Gerharz, MPI for Nuclear Physics, Heidelberg

XFEL anomalies in nuclear resonance scattering: From fundamental understanding to non-invasive precision probes

The defining feature of Mössbauer nuclei is their narrow linewidth, which forms the basis for all their applications. On the downside, the narrow linewidth so far restricts all applications to the low-excitation limit, with less than one signal photon per x-ray pulse on average. However, with the availability of X-ray free electron lasers (XFELs), which provide a large number of resonant photons per pulse, this situation has changed. The experimental progress opens up new possibilities, e.g. to study extremely narrow resonances [1] or photon-number resolved observables [2]. So far no deviation from the standard theory as applied for synchrotron experiments has been found [2,3]. In previous experiments in the forward scattering geometry we found deviations from the conventinal theory. A detailed study of this phenomena was conducted in our latest beam time. In this talk, I will present the experimental findings and show how Mössbauer nuclei can potentially be used to probe XFEL-induced dynamics.

[1] Y. Shvyd'ko et al., Resonant X-ray excitation of the nuclear clock isomer 45Sc, Nature 622, 471 (2023).
[2] A. I. Chumakov et al., Superradiance of an ensemble of nuclei excited by a free electron laser, Nature Physics 14, 261 (2018).
[3] M. Gerharz et al., Single-shot sorting of Mössbauer time-domain data at X-ray free electron lasers, arXiv:2509.15833

Andre Giraldi, MPI for Nuclear Physics, Heidelberg

Towards experimental studies of interatomic Coulombic electron capture (ICEC)

This work targets the experimental detection of an environment assisted atomic decay mechanism, referred to in literature as "excitation transfer ionization". The process constitutes the resonant excitation of a neon atom in a cluster by electron impact to a $2p^5$ 3s or $2p^5$ 3p state (excitation energy on the range of 16 – 19 eV), and subsequent deexcitation by ionizing a neighboring Ar atom (ionization potential of 15.8 eV). This reaction has been evidenced by laser-induced excitation of neon, but remains to be detected by means of an electron beam as the excitation mechanism. The confirmation of such process could provide insight into the role of the atomic environment on energy transfer and help gather information about ICD- and ICEC-like reactions. Presently we are adapting an electron and ion momentum spectrometer (reaction microscope) and are optimizing the formation of neon-argon dimers or bigger mixed clusters which requires the determination of the optimal conditions (nozzle temperature, gas pressure and mixing ratio). First results will be presented.

Jörg Götte, MPI for the Physics of Complex Systems, Dresden & University of Glasgow
Optical skyrmions

Optical skyrmions represent a fascinating class of topological structures in electromagnetic fields, characterized by spatially varying polarization configurations that exhibit particle-like properties. These three-dimensional topological textures carry well-defined optical helicity and angular momentum, offering new opportunities for structured light-matter interactions beyond conventional Gaussian or Laguerre-Gaussian beams. In this talk, I will present our recent work on the fundamental properties of optical skyrmions and give an outlook towards their interaction with atomic systems. Starting from the conservation laws governing optical helicity transfer, I will show how the topological nature of skyrmion fields leads to distinct selection rules and angular momentum exchange mechanisms. The interplay between spin and orbital angular momentum in these fields creates spatially inhomogeneous light-matter coupling that can be exploited for enhanced chiral discrimination and novel optical manipulation schemes. Looking forward, I will discuss the prospects for using optical skyrmions in ultracold atomic systems, including Bose-Einstein condensates and cold atomic vapours. The spatial structure of skyrmion fields naturally couples to collective excitations in BECs, potentially enabling topological imprinting and the creation of quantized vortex structures. Furthermore, the many-body dynamics of atoms in periodic arrays of skyrmions may reveal new phases of light-matter interaction, where topological protection and quantum correlations play complementary roles.

Moritz Grunwald-Delitz, European XFEL, Hamburg
Temporal evolution of x-ray fluorescence of highly charged xenon ions under FEL irradiation

We present the results of x-ray emission spectroscopy (XES) measurements on the interaction of intense x-ray free-electron laser pulses with xenon gas, aiming for a state-resolved exploration of non-linear multiphoton ionization and excitation processes. We utilize the 1D-imaging spectrometer [M. Agåker et al., J. Synchrotron Radiat., 31(5), 2024.] at the SQS instrument of European XFEL and its gas cell sample environment, which allows for studying Xe at a few mbar, a regime where, besides photon-driven processes, electron collisions start to contribute to the highly charged ion and excited state populations. Interestingly, this was not observed during prior studies on neon gas under similar conditions [S.-K. Son et al., Phys. Rev. A, 112(5), 2025, L051101.]. Our measurements monitor the evolution of these contributions over several nanoseconds after the XFEL pulse, revealing a distinct double-peak structure in the time-of-flight distribution.

Tobias Heldt, MPI for Nuclear Physics, Heidelberg
Ultrafast Kapitza-Dirac diffraction of strong-field photoelectrons at 100MHz repetition rate

Achieving the intensities required for strong-field phenomena such as multiphoton ionization (MPI) typically demands kilohertz-repetition-rate amplified laser systems. We demonstrate a femtosecond enhancement cavity seeded with a near-infrared frequency comb that delivers $10^{13}\,W\,cm^{-2}$ at a 100MHz repetition rate. The bow-tie cavity supports counter-propagating pulses that form a transient standing wave at the focus. When combined with a gas jet and velocity-map imaging (VMI) [1], this configuration allows for angle-resolved photoelectron spectroscopy, enabling comparisons between traveling-wave and standing-wave ionization [2].
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[1] J.-H. Oelmann et al., Rev. Sci. Instrum., 93(12), 123303 (2022).
[2] T. Heldt et al., Opt. Lett. 49, 6825-6828 (2024).
[3] K. Lin et al., Science 383, 1467-1470 (2024).

Sebastian Hell, Friedrich Schiller University, Jena
Multiphoton ionization quantum eraser

The quantum eraser experiment demonstrates that the visibility of double-slit interference fringes depends on the non-existence of which-way information. Here, we report a quantum eraser experiment with an entangled electron-ion pair, produced by strong-field dissociative ionization of the D_2 molecule. We demonstrate that entanglement between the photoelectron and the bound electron leads to the formation of a Bell-like state, manifested in the correlated emission directions of photoelectron and ion, and observed using a COLTRIMS reaction microscope. The holographic interference fringes contained in the photoelectron momentum distributions are recorded with high resolution. These fringes vanish if and when the ion emission direction is correlated with that of the electron, indicating the existence of which-way information. Finally, we show that the which-way information is erased, and the interference pattern is restored when a single ionic state is selected. The experimental observations and conclusions are fully supported by a quantum mechanical model based on numerical solutions of the time-dependent Schrödinger equation. Our work demonstrates that coincidence spectroscopy of ions and electrons is a powerful method for studying fundamental concepts of quantum information science within the context of ultrafast light-matter interactions.

Tanausú Hernández Yanes, Jagiellonian University, Krakow
Non-stabilizerness in quantum-enhanced metrological protocols

Non-stabilizerness (colloquially "magic") characterizes genuinely quantum (beyond-Clifford) operations necessary for preparation of quantum states, and can be measured by stabilizer Rényi entropy (SRE). For permutationally symmetric states, we show that the SRE depends, for sufficiently large systems, only on a constant number of expectation values of collective spin operators. This compact description is leveraged for analysis of spin-squeezing protocols, which inherently generate non-stabilizerness. Under one-axis twisting (OAT), the generation of optimal squeezing is accompanied by a logarithmic divergence of SRE with system system size. Continued time evolution under OAT produces metrologically useful "kitten" states-superpositions of rotated GHZ states-that feature many-body Bell correlations but exhibit a smaller, system-size-independent SRE that decreases with increasing Bell-correlation strength. Our results reveal connections between non-stabilizerness, multipartite correlations, and quantum metrology, and provide a practical route to quantify non-stabilizerness in experiments for precision sensing.

Nadine Homburg, GSI, Darmstadt
Towards a quantum logic clock for precision spectroscopy of highly charged heavy ions

Quantum logic spectroscopy (QLS) has driven significant advances in optical frequency metrology by enabling optical clocks based on ions that lack direct laser cooling and state detection transitions. Heavy highly charged ions (HCIs) offer optical transitions with strongly suppressed systematic shifts and enhanced sensitivity to fundamental physics. Substantial progress on medium-mass HCIs has been demonstrated, but extending QLS to the heaviest HCIs remains an open challenge. In this contribution, we present our experimental setup for QLS on heavy HCIs, specifically targeting the optical hyperfine-structure transition in $^{207}Pb^{81+}$ at 1019.7 nm. The experiment, located at GSI in Darmstadt, will provide suitable cryogenic trapping conditions for such extreme charge states. A monolithic linear Paul trap is under development for reduced excess micromotion and trap-related systematic effects. Additionally, the setup includes laser systems for in-situ production of the logic ion Be^+, laser cooling to the motional ground state, and coherent manipulation of qubit and HCI clock transitions.

Kateryna Korshynska, PTB, Braunschweig
Collisional decoherence in a BEC double-well accelerometer

Modern quantum sensors provide a way to measure accelerations and gravitational fields to tremendous precision, surpassing their classical counterparts. A possible setup for such a quantum sensor is a Bose-Einstein condensate (BEC), trapped in a double-well potential. The BEC exhibits quantum tunneling between the wells, emerging as the oscillations of their particle occupations. Such oscillations rely on the coherence between the potential wells, which in the weakly-interacting gas can decrease due to the collisional decoherence. We describe this decoherence process analytically with the density matrix approach and show how the Josephson oscillations decay with time. When this system is subject to external acceleration, the interplay between the acceleration and collisions shifts the oscillation frequency. This shift, as a response of the system to acceleration, leads to the concept of a BEC double-well accelerometer.

Matthias Kübel, Friedrich-Schiller-University, Jena
A "complete" molecular movie of photodissociation of CH3I

One of the most interesting aspects of ultrafast molecular dynamics lies in the fact that there are two different types of particles involved: electrons and nuclei. When their dynamics are coupled, for example at conical intersections, the situation is particularly challenging for theory and for experiments alike. Using a reaction microscope, we can detect photoelectrons and nuclear fragments simultaneously and in coincidence. This gives us access to electron-nuclear correlations in energy and momentum and even investigate entanglement phenomena. By applying pump-probe schemes using ultrashort laser pulses, snapshots of the transient molecular structure can be observed. In my talk, I will briefly review how momentum-resolved measurements of ions and electrons can be used to image nuclear and electronic structures, respectively. Subsequently, a time-resolved coincidence experiment tracking electronic and nuclear dynamics following the excitation of iodomethane by a UV pump pulse will be presented. We will discuss the relationship between the measured molecular-frame photoelectron momentum distributions and the time-dependent charge density in the molecule.

Zhamila Kulchukova, PTB, Braunschweig
Stable Optical Vortex Rings in Linear and Nonlinear Media

Vortex rings are fundamental to both classical and quantum physical systems, from turbulent fluids to BECs. In optics, vortex rings are quantized ring-shaped vortices with vanishing intensity at the core, appearing as threads of darkness tied into a loop. Studying the nature of optical vortex rings and ways of manipulating them opens novel avenues for applications of structured light, i.e. optical tweezers, and helps to uncover the underlying mechanisms of physical phenomena not yet fully understood, such as quantum turbulence and spontaneous knotting. In this talk, we theoretically investigate an experimentally accessible system that exhibits stable vortex rings in vacuum and in nonlinear (focusing and defocusing) Kerr media. We demonstrate that the rings are not destroyed by symmetry-breaking and nonlinear effects, but instead undergo topological transformations of varying complexity. Despite its simplicity, our system provides a useful framework to study optical vortex rings and their dynamics. Moreover, it can open new ways to investigate the fine structure of the light and its applications in light-matter interactions.

Maja Maschke, PTB, Braunschweig
Hybrid van Hove approach to mixed quantum-classical gases

In cold matter physics, the search for effective approximation schemes is a constant one due to the difficulty of many-particle calculations at the fully quantum level. One set of such schemes are semi-classical approaches in which one sector of a quantum system is treated classically. Historically, such hybrid theories have often been proposed ad-hoc, rather than being derived from a set of first principles. Recently, an axiomatic approach to mixed quantum-classical systems based on a Hilbert space formulation of classical mechanics due to van Hove has been proposed [1]. To date, the consistency of this novel approach was demonstrated at the few-particle level only. In this talk, we extend this work to many-particle systems and discuss its applicability to cold bosonic gases. We will demonstrate how to derive a mean field theory of an interacting hybrid gas at finite temperature featuring a quantum ground state (BEC) and a classical thermal cloud. We present a quantitative analysis of the critical temperature and the condensate fraction and compare our self-consistent numerical approach to the well-established ZNG theory. Our results mark a successful consistency check for the hybrid van Hove-formalism and illustrate to which extent a purely classical description of the thermal cloud is sufficient.

[1] M. Reginatto et al 2025 J. Phys.: Conf. Ser. 3017 012037

Alejandro Mendoza Coto, MPI for the Physics of Complex Systems, Dresden & UFSC
Quantum Cluster Quasicrystals in Bose Gases: From Interaction Design to Emergent Phases

Quantum cluster quasicrystals represent a fascinating class of structures in which long-range orientational order emerges without translational symmetry. In this talk, I will present recent theoretical advances in identifying the key ingredients, particularly in terms of pair interactions, required to stabilize self-organized two-dimensional aperiodic structures with various rotational symmetries as the ground states of interacting bosonic gases. Using a spectral variational method alongside Gross–Pitaevskii simulations, we demonstrate that, in contrast to the classical case, the stabilization of quantum quasicrystals with different rotational symmetries requires a distinct number of unstable wave vectors in the pair interaction potential. Finally, I will comment on the nature of low-energy excitations in these structures and show how their properties can be analytically addressed from first principles.

Natalia S. Oreshkina, MPI for Nuclear Physics, Heidelberg
A story about three nuclear radii

Nuclear root-mean-square are fundamental benchmarks bridging various fields of physics. They serves as indispensable input parameters for nuclear-, atomic-, and molecular-physics calculations. Reliable rms radii are crucial for precision tests of quantum electrodynamics, for the determination of fundamental constants, and for many searches for physics beyond the Standard Model.
There are two main methods to determine absolute nuclear radii: electron scattering and muonic atom spectroscopy. The results of both, together with combined analyses, are tabulated for further use. In my talk, I will present the most recent advances in the determination of nuclear radii from muonic atom spectroscopy and will discuss the most typical underlying problems with the current values.

Tobias Over-Winter, Helmholtz Institute, Jena

A Novel Compton Telescope for Polarimetry in the MeV Range: Towards Delbrück Scattering

For photon energies from several tens of keV up to a few MeV, Compton polarimetry provides insight into subtle details of fundamental radiative processes in atomic physics. Within the SPARC collaboration [1] several segmented semiconductor detectors have been developed that are well suited for application as efficient Compton polarimeters. For scattering and photon emission processes in the hard x-ray regime this kind of detector enable revealing photon polarization effects in great detail [2]. Recently, a new polarimeter has been constructed within the SPARC collaboration based on an arrangement of two segmented semiconductor crystals in a telescope structure. This design allows us to employ the Compton polarimeter in a broad energy range of photon energies from 50 keV up to 1 MeV. In my contribution I will present this detector. Additionally, I will discuss first planned experiments utilizing this detector at high photon energies up to 1 MeV.

[1] Th. Stöhlker et al. Nucl. Instrum. Methods Phys. Res. B 365 (2015) 680.
[2] K.H. Blumenhagen et al. New J. Phys. 18 (2016) 119601.

Adisorn Panasawatwong, MPI for the Physics of Complex Systems, Dresden

Data-driven complexity

Understanding how complexity emerges at the interface between order and chaos remains a central question in dynamical systems research. We propose a specialized autoencoder that assigns minimal complexity to both regular and chaotic inputs while capturing structure in the intermediate regime. The design uses a linear encoder paired with two decoder variants (linear and non-linear), defining complexity as the difference in reconstruction loss—quantifying structure preserved under linear compression but recoverable only through non-linear decoding.
We validate this framework on synthetic datasets and dynamical systems including the logistic map, coupled logistic maps, and pendular systems, then extend it to neural networks during training and transformer-based language models. Our results establish that complexity is fundamentally relative, depending on temporal scale, encoding dimension, and measurement baseline. A central finding is that chaos and complexity are distinct: systems can be chaotic yet geometrically simple, or regular yet structurally complex, depending on how patterns organize in phase space.

Patil Parth, DESY, Hamburg

The fingerprint of chirality at the oxygen K-edge in model molecules

In living organisms, biomolecules such as amino acids and sugars exist exclusively as single enantiomers i.e. non-superimposable mirror images that exhibit nearly identical physical properties yet interact distinctly with other chiral entities. These differential interactions lead to dramatically different biological activities between enantiomers, making chirality detection crucial for understanding molecular function. Photoelectron circular dichroism (PECD) has emerged as a highly sensitive probe of molecular chirality, manifesting as a forward-backward asymmetry in photoelectron emission relative to the light propagation direction. This asymmetry reverses sign upon enantiomeric substitution, providing a direct spectroscopic signature of absolute configuration. While PECD has been extensively studied for valence electrons, the role of oxygen in chiral recognition remains underexplored despite it's enormous revalence in functional biomolecules and pharmaceuticals. We present a combined experimental and theoretical investigation of PECD in O 1s photoionization of gas-phase fenchone (CHO). Using circularly polarized synchrotron radiation, we measured the chiral asymmetry parameter across a photoelectron kinetic energy range of 3–15 eV for randomly oriented molecules.

Joanna Peszka, GSI, Darmstadt

Enhanced Antihydrogen Accumulation With Laser-Cooled Be+

The study of cold antihydrogen for CPT symmetry tests began in 2010 with the first successful demonstration of trapping individual antihydrogen atoms [1]. In the ALPHA experiment, antihydrogen is produced via a three-body recombination process involving one antiproton and two positrons [2]. Antihydrogen is formed by combining cold plasmas of positrons and antiprotons in a specialized Penning-Malmberg trap, which spatially overlaps with a magnetic minimum trap designed to confine antihydrogen atoms [3]. Due to the shallow depth of the magnetic potential - capable of trapping only atoms with kinetic energies corresponding to temperatures below 0.5 K - early experiments typically confined 20 antihydrogen atoms per production cycle. In 2017 the technique was advanced to allow continuous synthesis and accumulation of antihydrogen [4, 5], enabling key milestones such as the first high-precision measurement of the 1S–2S transition [6] and the first observation of gravity's influence on antimatter [7]. Antihydrogen production through the three-body recombination process depends on the thermal energy of the positrons; both the production and trapping rates increase as the positron temperature decreases. So far the temperature of positron plasma in ALPHA-2 trap was limited to around 20K, which was achieved via the cyclotron cooling mechanism in the high magnetic field. To reduce the temperature of the positron plasma even further, an active cooling mechanism is required. Inspired by pioneering work at NIST [8], a sympathetic cooling of positrons with laser-cooled beryllium ions (Be+) was proposed [9]. The Be+ ions are generated via laser ablation of a solid beryllium target [10], then confined within a Penning-Malmberg trap and Doppler cooled using a 313 nm laser. Upon merging with the positron plasma, the laser-cooled Be+ ions carry away thermal energy from the positrons through Coulomb interactions. Sympathetic cooling technique allowed to achieve 2.5 times lower temperatures of positron plasma than before [11]. Early development of Be+ laser-cooling technique suffered from irreproducibility of the number of ablated beryllium ions and inefficient laser-cooling scheme. Several laser system upgrades were performed, most importantly to allow for simultaneous laser-cooling and Be+ cloud compression using Rotating Wall technique [12]. This improved laser-cooling technique was successfully integrated into the standard antihydrogen synthesis cycle. An eight-fold enhancement in antihydrogen trapping efficiency per synthesis cycle has been demonstrated, enabling the accumulation of over 15,000 antihydrogen atoms in less than seven hours. The implementation of sympathetic cooling of positrons method into antihydrogen production cycle has not only accelerated the experimental timeline but also opened new opportunities for detailed investigations of fundamental symmetries. These include potential searches for sidereal variations and other precision tests of antimatter and its interactions, which were previously inaccessible due to limited sample sizes and extended accumulation times.

[1] ALPHA Collaboration, Nature 468, 673-676 (2010).
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[10] Sameed, M., Maxwell, D. Madsen, N., New J. Phys. 22, 013009 (2020).
[11] ALPHA Collaboration, Nat. Commun. 12, 6139 (2021).
[12] Danielson J. R. and Surko C.M., Phys. Rev. Lett. 94, 035001 (2005).

Thomas Pfeifer, MPI for Nuclear Physics, Heidelberg

Statistical light fields enhance temporal and spectral resolution for the exploration of atomic and molecular quantum dynamics

To resolve ultrafast events, we need controlled probes that are shorter than the delay between the events. Likewise, to resolve closely-spaced spectral lines, we need to achieve spectrometer resolutions better than their spacing. These statements appear correct, at first. Here, we shed light on this common knowledge, statistically structured light to be more precise. The stochastic nature of free-electron laser (FEL) pulses, obtained from self-amplified spontaneous emission (SASE) was often considered a nuisance, with every shot being a different pulse, i.e. a uniquely shaped time-dependent electric field, making comparisons to theory difficult. This poses a challenge, in particular in the absence of diagnostic measurement tools that record the temporal and spectral structure of each individual FEL pulse. Early experiments at the extreme-ultraviolet (XUV) FEL FLASH at DESY taught us that correlations in statistically structured SASE FEL pulses can increase temporal resolution. Time-dependent motion, structural dynamics, shorter than the FEL pulse duration are resolved, as demonstrated for the example of vibrational wavepackets in the D2 molecular ion, observed by ion coincidence spectroscopy with a reaction microscope (ReMi) in an XUV-pump–XUV-probe experiment [1]. Regarding enhanced spectral resolution, we learn from a recent "single-pulse" transmission spectroscopy experiment at EuXFEL. Here, correlations (this time not within the SASE pulses, but) within the physical interaction process itself (X-ray simulated Raman) can be harnessed (in a manner akin to super-resolution microscopy) to resolve spectral structures (a fine-structure splitting in Ne on the 100-meV level) that would otherwise appear only as a broadening in the (0.2 eV) resolution of an x-ray spectrometer [2]. Finally, we turn to our recent attosecond-pump–attosecond-probe experiment conducted at EuXFEL, with the aim to observe, understand, and control electron charge migration in the chemically important carboxyl group of organic acids. Making use of a recently established attosecond double-pulse operating regime at EuXFEL, in particular at closely spaced (mutually overlapping) spectra for pump and probe pulses, we measure spectral interference structures, encoding the time delay of the stochastically varying SASE pulses. Using post sorting based on shot-to-shot spectral diagnostics, we uncover transient changes of characteristic x-ray absorption below the oxygen K edge, encoding the motion of electrons in the vicinity of the two chemically distinct oxygen atoms in the COOH carboxy group [3].

[1] Yuhei Jiang et al. PRA 81, 051402(R) (2010), Kristina Meyer et al. PRL 108, 098302 (2012)
[2] Kai Li et al. Nature 643, 662–668 (2025)
[3] in preparation

Jan-Michael Rost , MPI for the Physics of Complex Systems, Dresden

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Ulf Saalmann, MPI for the Physics of Complex Systems, Dresden
Energiearme atomare Stöße

Time delays: Insights from scattering in 1D

Krzysztof Sacha, Jagiellonian University, Krakow
Time-tronics: from temporal printed circuit board to quantum computer

Time crystalline structures can be created in periodically driven systems. They are temporal lattices which can reveal different condensed matter behaviours ranging from Anderson localization in time to temporal analogues of many-body localization or topological insulators. However, the potential practical applications of time crystalline structures have yet to be explored. Here, we pave the way for time-tronics where temporal lattices are like printed circuit boards for realization of a broad range of quantum devices. The elements of these devices can correspond to structures of dimensions higher than three and can be arbitrarily connected and reconfigured at any moment. Moreover, our approach allows for the construction of a quantum computer, enabling quantum gate operations for all possible pairs of qubits. Our findings indicate that the limitations faced in building devices using conventional spatial crystals can be overcome by adopting crystalline structures in time.

Daniel Aaron Schnauß-Müller, Helmholtz Institute Jena
Precision X-Ray spectroscopy of Kα transitions in He-like uranium using metallic magnetic calorimeter detectors

He-like ions, as the simplest atomic multibody system, provide a unique testing ground for the interplay of the effects of electron-electron correlations and quantum electrodynamics (QED). Of particular interest are heavy highly charged systems, where inner shell electrons are exposed to extremely high field strengths. For L to K-transitions, experiments with ions at nuclear charge states Z ¿ 54 where not available until now. Two X-ray spectroscopy studies of He-like uranium ions have been performed at the electron cooler of the storage ring CRYRING@ESR at GSI Darmstadt, using novel detectors of the maXs series, developed within the SPARC collaboration. Those detectors are able to measure photons from a few keV up to over 100 keV allowing the simultaneous investigation of Balmer-like and K transitions. The achieved spectral resolution of better than 90 eV at X-ray energies close to 100 keV reveals the substructure of the Kα1 and Kα2 lines for the first time. The result of this experiment and the first insights of a rerun this year are presented in the talk.

Samuel Schöpa, University of Rostock
High-harmonic generation from organic molecules and their crystals

High-harmonic generation (HHG) offers a route to extract information on electronic structure and light-driven dynamics in molecular and crystalline systems. Recently, we used thin organic molecular crystals (OMCs) with perfectly aligned molecules as a target for high-harmonic spectroscopy to probe the crystal structure and the intermolecular coupling [1].
In this work, we combine simplified model descriptions with ab-initio simulations applied to both isolated molecules and their weakly coupled, ordered OMCs. Few-level approaches are used to analyze how below-threshold harmonics encode phase and polarization signatures arising from multiple excitation channels, while complementary crystal-level calculations show how intermolecular coupling and crystal structure shape the harmonic response in ordered OMCs.

[1] F.-E. Wiechmann et al., High-order harmonic generation in an organic molecular crystal, Nat. Commun. 16, 9890 (2025).

Michael Schulz, MPI for Nuclear Physics, Heidelberg

ReMi experiments at the Heidelberg Cryogenice Storage Ring

We have measured momentum-analyzed recoil-ions and ejected electrons in triple coincidence with projectiles neutralized in collisions of D- ions with He and Ar at projectile energies between 20 and 120 keV. From the data we extracted multiple-differential momentum distributions of electrons ejected in detachment accompanied by single target ionization. For the Ar target the results confirm a strong role played by a first-order correlated channel proceeding by a mutual interaction between the active projectile- and target- electrons which we observed earlier for Si- projectiles [1]. Surprisingly, this is the case even well below the threshold energy for this mechanism pointing to the significance of the interaction between the two active electrons in this fundamental scattering process. The first-order process is important for the He target as well, however, there signatures of higher-order channels are more pronounced than for Ar. The data are qualitatively well reproduced by our higher-order calculations.

Peter Schürger, MPI for the Physics of Complex Systems, Dresden

Challenges of exact factorization-based mixed quantum-classical methods for simulating ultrafast molecular dynamics

Photoexcitation of molecules generates non-stationary nuclear wave packets on excited electronic states, often leading to non-radiative relaxation via internal conversion. A fully quantum mechanical description of these ultrafast processes in medium-to-large molecular systems remains computationally prohibitive, motivating the development of approximate mixed quantum-classical approaches. In these methods, the nuclear degrees of freedom are treated classically, while the electronic subsystem is propagated quantum mechanically. In this talk, I discuss current challenges and recent advances in mixed quantum-classical dynamics, with particular emphasis on approaches derived from the exact factorization of the electro-nuclear wave function [Phys. Rev. Lett. 105, 123002 (2010)]. Within this framework, the nuclear trajectories evolves under time-dependent potentials that explicitly incorporate electronic back-reaction, and trajectory coupling systematically improves accuracy beyond standard surface-hopping- or mean field-type schemes. I illustrate these methods through applications to the photodynamics of 4-(dimethylamino)benzonitrile (DMABN) and fulvene [Chem. Phys. 162, 104117 (2025)].

Julian Späthe, Friedrich Schiller University, Jena

Coincidence spectroscopy with High Harmonics: Non-linear photoionization and pump-probe experiments in argon

We present coincidence spectroscopy experiments on argon atoms using a high-flux, quasi-monochromatic extreme-ultraviolet (XUV) source at 26.5 eV based on high-harmonic generation driven by a 515 nm, 100 kHz repetition rate laser system. By detecting Ar^{2+} ions and photoelectrons in coincidence, we investigate two-photon double ionization (TPDI) and identify three ionization pathways: direct TPDI, sequential TPDI, and auto-ionization due to a window resonance involving electron-electron dynamics. In addition, we perform TPDI measurements while scanning the XUV wavelength across the resonance. This enables a systematic comparison of the relative contributions of different ionization mechanisms on and off resonance, providing insight into the underlying resonance-enhanced ionization dynamics. Finally, we extend our study to XUV–VIS pump–probe experiments, focusing on laser-assisted (double) ionization. We discuss initial simulation results in comparison with experimental observations, demonstrating the power of combining coincidence spectroscopy with XUV–VIS techniques for capturing and understanding correlated electron motion in atoms and molecules.

Sebastian Ulbricht, PTB, Braunschweig
On classically mediated quantum entanglement

The question of whether quantum states can become entangled when they interact via a classical mediator is still a matter of ongoing discussion. This lively debate is deeply interwoven with the question of whether entanglement studies can prove the quantum - or classical - nature of gravity. In recent years, there have been numerous statements and no-go theorems, supporting one or the other position. However, while appearing to be universal, no-go theorems 'forbidding' classically mediated quantum entanglement do depend on the used quantum-classical hybrid theory. In this talk, we show that in Hybrid van Hove theory [1] two initially uncorrelated spins can become entangled even if they are only coupled via a classical harmonic oscillator. We further demonstrate that the spin-spin correlations and the entanglement of the spins closely resemble the fully quantum case. Our investigation shows that existing no-go theorems are not universal. It further implies that consistent quantum theories featuring classical gravity cannot be categorically ruled out by quantum entanglement studies.

[1] M. Reginatto, A.D. Bermúdez Manjarres, and S. Ulbricht, J. Phys.: Conf. Ser. 3017 012037 (2025)

Anna Viatkina, PTB, Braunschweig
Atomic parity violation in highly charged 40,48Ca and 208Pb ions

We calculate parity-violation-induced E1 amplitudes for the $1s \to 2s$ and $1s^2 2s \to 1s^2 3s$ transitions in H- and Li-like ions of ^{40}Ca, ^{48}Ca, and ^{208}Pb; neutron skin effects and nuclear uncertainties are included for each nucleus. We consider spin-independent weak-interaction contribution of the Z^0 boson described by standard model, as well as the effects of a hypothetical new Z' boson of varying mass. We conclude that the neutron-skin corrections in the ^{40,48}Ca isotope pair can be mostly neglected when considering Z' boson effects, which is an advantage for the search for new parity-violating physics. On the other hand, both the neutron skin effect and the sensitivity to hypothetical Z' interactions in ^{208}Pb is shown to be significant.

Robert Weiß, University of Heidelberg
Collisional spin entanglement beyond the Born-Markov approximation

It was shown experimentally that colliding cold atoms produce entanglement between their spin states [1]. A thorough theoretical foundation and prediction was restricted in modelling the internal and external atomic degrees of freedom due to computational constraints. We demonstrate why established analytical techniques restricting to the spins only and relying on the Born-Markov approximation fail to reproduce the experimental results. The Markov approximation is not applicable because the correlations in the motional degree of freedom do not decay on a short enough time scale. The Born approximation is questionable as the interatomic interaction is too strong. Numerical models are presented which capture the observed dynamics well including non-Markovian effects and the relative motion.

[1] P. Sompet et. al., Nat. Comm. 10, 1889 (2019)

Julius Willrich, Friedrich Schiller University, Jena
Slater-Koster-approach for optical properties of 2D-materials

For the calculation of optical properties of solids it is important that dipole matrix elements in the respective basis reproduce the symmetry of the system of interest. The Slater-Koster-rules provide an efficient way to start from a localized basis that shows good transferability for different geometries, while preserving all symmetries of the dipole operator. In this contribution, I will present and discuss an implementation of the Slater-Koster approach that uses numerical atomic orbitals up to l=3. The parametrization is tested by calculating absorption and high-order harmonic spectra of selected 2D-materials.

Matthias Wollenhaupt, Carl von Ossietzky University, Oldenburg
Multiphoton ionization with three-dimensional light fields

We report the first observation of free-electron angular momentum wave packets generated by atomic multiphoton ionization with bichromatic three-dimensional (3D) polarization-tailored ultrashort laser fields. These fields, created by the non-collinear superposition of two polarization-shaped pulses of different colors from a supercontinuum polarization pulse shaper, provide electric-field components along all spatial directions. The resulting photoelectron momentum distributions, recorded via velocity map imaging, demonstrate full 3D coherent control of electronic superposition states extending beyond the constraints of planar polarization fields by unlocking all dipole selection rules m=0,±1. As an application, 3D pump-probe fields are used to image previously unobserved photoelectron wave packets mapping spin-orbit dynamics of the potassium 3d fine structure doublet. Our shaper-based approach establishes a route to fully controllable 3D light fields for chiral-sensitive light-matter interactions and ultrafast spectroscopy.

Martin Wünsche, Friedrich Schiller University & Helmholtz Institute Jena
HHG-Driven 3D cross-sectional imaging at the nanoscale

We present an EUV broadband reflectometry method, which we call XUV coherence tomography (XCT), a non-destructive, rotation-free nanoscale 3D imaging technique extending OCT by three orders of magnitude in depth resolution, achieving down to 3 nm resolution. Using broadband HHG radiation and an interferometric setup with phase retrieval, XCT enables artifact-free cross-sectional imaging of different samples, while providing material contrast from spectral analysis.

Damian Włodzyński, Jagiellonian University, Krakow
Engineering interactions shape in resonantly driven bosonic gas

In systems with fast periodic driving, there are special subsets of (resonant) states, which behavior can be described with effective, time-independent Hamiltonian in a rotating reference frame. Here, we show that experimentally feasible system of ultracold bosonic atoms on a ring with rapidly oscillating scattering length can be used to simulate time-independent two-component atomic mixture with exotic, long-range interactions.

Paramjit Yadav, Friedrich Schiller University, Jena
Nonlinear polarization holography: Ultrafast dynamics in nanoscale metal and semiconductor

Understanding the third-order nonlinear optical response of nanoscale metal and semiconductor films is critical for nonlinear photonics and ultrafast science, yet conventional measurement techniques yield inconsistent results spanning four orders of magnitude. We present nonlinear polarization holography, a time-domain technique that isolates the nonlinear response of thin films from substrate contributions using holographic retrieval of transient absorption and transient dispersion. By employing local pump-probe geometry with tight pump focusing and distributed probe detection, combined with machine learning-based noise suppression, we achieve unprecedented sensitivity for measuring femtosecond dynamics in films thinner than 15 nanometers. We characterize gold and silicon films across multiple thicknesses and intensities, revealing counterintuitive thickness-dependent effects including giant Kerr response in ultra-thin gold films and intensity-dependent transitions between focusing and defocusing nonlinearities.
Spectral-temporal analysis further resolves intraband and interband relaxation mechanisms, providing fundamental insights into electron-phonon coupling and carrier dynamics in nanoscale systems. Our results demonstrate that nonlinear polarization holography offers quantitative, artifact-free characterization of third-order nonlinearities in films previously inaccessible to direct measurement.

Vladimir Yerokhin, MPI for Nuclear Physics, Heidelberg

Absolute nuclear charge radii determinations from ab initio QED calculations of Li-like ions

Recent advances in QED calculations for few-electron atoms have opened a way to determining absolute nuclear charge radii from spectra of highly charged electronic ions. These determinations are complementary to the traditional way of determining nuclear radii from muonic-atom spectroscopy. Compared with the muonic-atom approach, electronic atoms offer significant advantages, as uncertainties associated with the shape of the nuclear charge distribution can be made negligible and sensitivity to nuclear-polarization effects is strongly suppressed. The price to pay is that the finite-nuclear-size contributions to electronic transition energies are relatively small, requiring exceptionally accurate QED theory and highly precise experimental measurements.
We combine our recent advanced QED calculations of the $2p$-$2s$ transition energies of Li-like ions [1] with available experimental data [2-4] to determine the nuclear charge radii of the ^{208}Pb and ^{209}Bi isotopes [5]. By incorporating constraints derived from electron-scattering data, we obtain radii that are independent of the assumed model of the nuclear charge distribution. The accuracy of our radii is limited by the current experimental precision, which contrasts with the muonic-atom determinations limited by the nuclear theory.

[1] V. A. Yerokhin, Z. Harman, and C. H. Keitel, Phys. Rev. A 112, 042801 (2025).
[2] C. Brandau et al., Phys. Rev. Lett. 91, 073202 (2003).
[3] X. Zhang et al., Phys. Rev. A 78, 032504 (2008).
[4] P. Beiersdorfer et al., Phys. Rev. Lett. 80, 3022 (1998).
[5] V. A. Yerokhin and B. Ohayon, Phys. Rev. A, in press.

Sili Yi, Max Born Institute, Berlin

Two-color control of quantum harmonic generation in classically driven solids

Recent observation of Schrödinger cat states in strong-field regime has built a bridge between quantum optics and intense laser physics and opened up an exciting possibility of using intense light-matter interactions to generate bright quantum states of light. First, we demonstrate a novel route to generating harmonics in non-classical quantum states carrying massive number of photons. Starting with a strong laser pulse in a coherent state at a fundamental frequency, , and a quantum matter in an uncorrelated ground state (e.g., atomic system), the excitation of the matter by the generated harmonic light at a particular harmonic, n0, leads to a variety of non-classical effects, from squeezing of every harmonic to entanglement between harmonics. We then consider the solid-state systems driven by two-color (Pump-Control) fields. We demonstrate that by tuning the pump laser to control non-adiabatic transition between valence band and conduction band, one can control quantum properties of the generated light state, pathing the way for generation of quantum light state in the solid-state device by purely classical control. In addition, we explore interference between quantum light states generated at different moments controlled by the number and timing of pump lasers. Furthermore, we discuss the cases for molecule system driven by one-color and two-color fields, highlighting the role of nuclear motion during the intense light-matter interactions. We analyze how the coupling of electronic and nuclear dynamics influences the quantum light state.

[1] Lewenstein M., et al, Nat. Phys., 2021, 17:1104.
[2] Yi S., et al., Phys. Rev. X, 2025, 15: 011023.

Bo Ying, Friedrich Schiller University, Jena

Ionization of singly charged Helium ions in elliptically-polaried laser fields

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Hankai Zhang, EPFL, Lausanne

Ultrafast resonant single-particle imaging of NaI under femtosecond and sub-femtosecond X-ray pulses

We investigate the ultrafast resonant imaging response of NaI single particles. By comparing measurements obtained with 15 fs and sub-femtosecond X-ray pulses, we explore how pulse duration influences resonant scattering signals and radiation-driven electronic dynamics. To interpret the experimental observations, X-ATOM simulations are employed to model X-ray–atom interactions, including photoionization and ultrafast population evolution. The resulting time-dependent scattering cross sections provide insight into transient electronic configurations and their impact on resonant diffraction signals. This combined experimental and simulation approach enables a deeper understanding of femtosecond and sub-femtosecond X-ray matter interactions in simple ionic systems.