Q 22: Nuclear and X-Ray Quantum Optics

Time: Tuesday 11:00–13:00 Location: P 11

Invited Talk Q 22.1 Tue 11:00 P 11

Exploring nonlinear optics with x-rays — •Dietrich Krebs — Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

Using modern synchrotron and free-electron laser (FEL) sources, it has become feasible to study a wide range of nonlinear processes in the x-ray regime. With it comes the possibility to transfer ideas from parametric nonlinear optics as well as quantum optics to shorter wavelengths, for which we will explore examples in this talk. Processes of interest comprise x-ray-optical wavemixing (XOWM) that can combine diffractive imaging capabilities with spectroscopic sensitivity for new material diagnostics. As such, we have recently demonstrated the applicability of nonlinear crystallography using x-ray-optical difference-frequency generation to spatially reconstruct the valence response in diamond at sub-Angstrom resolution. Processes deriving from spontaneous x-ray parametric down-conversion (XPDC), on the other hand, can provide access to quantum features of light-matter interaction. As an example, we showcase a series of experiments, in which we found that non-degenerate XPDC allows access to polariton-formation in the extreme-ultraviolet (EUV) and soft x-ray spectral ranges. Recent developments have also shown renewed interest to extend XPDC into the degenerate regime, aiming to produce energetically equal x-ray photon pairs as a resource of entanglement. While these examples still face substantial challenges regarding their efficiency, they provide a promising outlook for the future of x-ray quantum optics.

Q 22.2 Tue 11:30 P 11

Nuclear excitation in ^{229}Th using paraxial light fields — •Tobias Kirschbaum, Janek Bergmeier, Alexander Franz, and Adriana Pálffy — Julius-Maximilians-Universität Würzburg, Germany

The paraxial wave equation (PWE) provides a variety of solutions depending on the specific geometry such as Laguerre Gaussian (cylindrical) and Hermite Gaussian modes (cartesian). Among others, these modes are characterized by their spatially inhomogeneous intensity profiles which render them attractive to atomic physics applications. For instance, such beams can be used in quantum metrology to minimize the unwanted light shift in atomic clock transitions [1, 2]. A compelling alternative for these atomic clocks is the ^{229}Th nucleus which has a long-lived first excited state at ≈ 8.4 eV [3]. It is thus intriguing to investigate the interaction of thorium with different paraxial light fields.

In a first step, we have investigated the interaction of ^{229}Th with non-paraxial and spatially inhomogeneous Bessel modes [4]. Here, we build upon that work by considering paraxial light fields which are also spatially inhomogeneous. We thereby address the temporal and spatial dynamics for ^{229}Th in solid-state and ion targets using solutions of the PWE in cylindrical, cartesian, and elliptical coordinates.

[1] R. Lange *et al.*, Phys. Rev. Lett. **129**, 253901 (2022).
[2] A. Peshkov *et al.*, Ann. Phys. **535**, 2300204 (2023).
[3] C. Zhang *et al.*, Nature **633**, 63-70 (2024).
[4] T. Kirschbaum *et al.*, Phys. Rev. C **110**, 064326 (2024).

Q 22.3 Tue 11:45 P 11

Coherent vortex pulse propagation in ^{229}Th:CaF$_2$ — •Alexander Franz, Tobias Kirschbaum, and Adriana Pálffy — Julius-Maximilians-Universität Würzburg, Am Hubland, 97074 Würzburg, Germany

In recent years, the isomeric transition in ^{229}Th has emerged as a promising candidate for the development of a nuclear clock [1]. One of the possible approaches for realizing such a clock involves embedding ^{229}Th nuclei into VUV-transparent crystals. In this work, we investigate from theoretical side the driving of the nuclear clock transition in ^{229}Th-doped crystals using Bessel beams, a form of light with helical wavefronts and spatial degrees of freedom. Due to the magnetic dipole character of the clock transition, such beams offer new control degrees of freedom compared to standard plane waves [2]. We study nuclear forward scattering of a resonant Bessel beam pulse propagating through the crystal, analyzing the resulting temporal and spatial intensity patterns. To this end, we extend an existing formalism developed for plane waves to Bessel beams [3]. We consider scenarios involving a single nuclear transition and multiple simultaneously driven transitions, as well as different orientations of the quantization axis. This approach opens a way to determine the relative distribution of different directions of quantization axes inside the crystal.

[1] C. Zhang *et al.*, Nature **633**, 63-70 (2024).
[2] T. Kirschbaum *et al.*, Phys. Rev. C **5**, 064326 (2024).
[3] Y. V. Shvyd'ko, Phys. Rev. B **59** 9132 (1999).

Q 22.4 Tue 12:00 P 11

Quantum dynamics of strongly-driven interacting Mössbauer nuclei — Miriam Gerharz[1], Dominik Lentrodt[1,2], and •Jörg Evers[1] — [1]Max-Planck-Institut für Kernphysik, Heidelberg — [2]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg im Breisgau

It is an old challenge whether it is possible to fully excited an ensemble of atomic nuclei using externally applied electromagnetic fields. Motivated by recent progress in x-ray source technology and in nuclear quantum optics, in this talk, I will revisit this problem from two sides. First, I will discuss the prospects of non-linear excitation of nuclei in thin-film x-ray cavities using strongly focused x-ray pulses. To this end, we developed a comprehensive theory framework to model focused x-ray pulses in x-ray cavities, and derived the excitation enhancement via the optimization of the nuclear environment [1]. Second, I will discuss the many-body coupled dissipative dynamics of the nuclear ensemble after the excitation, using a cumulant expansion which allowed us to derive a set of nonlinear equations which is capable of efficiently modeling large nuclear ensembles for arbitrary degrees of excitation [2]. We identified a non-linear time-evolution of the nuclear dipole phase as an experimentally accessible signature for higher excitation. Our analysis further predicts finite-size effects in the nuclear dynamics of small ensembles as an interesting as-yet unexplored observable.

[1] D. Lentrodt, C. H. Keitel, and J. Evers, Phys. Rev. Lett. 135, 033801 (2025); Phys. Rev. A 112, 013711 (2025).
[2] M. Gerharz and J. Evers, arXiv:2510.00970 [quant-ph].

Q 22.5 Tue 12:15 P 11

Dynamics of x-ray waveguides in front-coupling geometry — •Julien Spitzlay[1], Hanns Zimmermann[1,2], and Adriana Pálffy[1] — [1]Julius-Maximilians-Universität Würzburg — [2]Universität der Bundeswehr München

Thin-film nanostructures containing multiple embedded layers of Mössbauer nuclei offer an intriguing platform for realizing quantum optics in the x-ray regime. These structures can be probed either in grazing-incidence or front-coupling geometry. The latter was recently demonstrated experimentally [1] and showed excellent agreement with the theoretical framework developed so far [2].

In this work, we extend this formalism to model the mesoscopic quantum dynamics of x-ray waveguides in front-coupling geometry, including configurations with multiple modes and several layers of resonant material. This approach enables the engineering of effective inter-nuclear couplings to realize hopping models [2], thereby opening the door to investigating topological photonic systems of greater complexity than achievable in grazing-incidence configurations [3].

[1] L. Lohse, et. al., Phys. Rev. Lett. 135, 053601 (2025)
[2] P. Andrejić, et. al., Phys. Rev. A 109, 063702 (2024)
[3] H. Zimmermann, et. al., arXiv:2506.10588 (2025)

Q 22.6 Tue 12:30 P 11

Exploring Topological Effects in Thin-Film X-Ray Cavities — •Hanns Zimmermann[1,2,3], Jonathan Sturm[1,3], Ion Cosma Fulga[3,4], Jeroen van den Brink[3,4], and Adriana Pálffy[1,3] — [1]Julius-Maximilians-Universität Würzburg — [2]Universität der Bundeswehr München — [3]Würzburg-Dresden Cluster of Excellence ct.qmat — [4]Leibniz Institute for Solid State and Materials Research Dresden

A promising platform for the quantum control of high-frequency photons are thin-film cavities, with one or several embedded layers of resonant nuclei such as ^{57}Fe with a Mössbauer transition at 14.4 keV. At grazing incidence, incoming x-rays couple evanescently to the cavity. In turn, the cavity field drives the nuclear transitions. The resulting nuclear response is well described by a recently-developed quantum optical model based on the electromagnetic Green's function [1].

Here, we investigate theoretically topological effects in special geometries of x-ray quantum emitters i.e. Mössbauer nuclei. We show that tailored nanostructures with multiple layers of Mössbauer nuclei can implement a non-Hermitian version of the Su-Schrieffer-Heeger (SSH) model [2]. By tuning the geometry of the structure, different topological phases can be realized. Our results demonstrate the existence of topological edge states whose presence can be identified in the x-ray reflectivity spectra or in resonant beam coupling geometry [3].

[1] X. Kong, et al. Phys. Rev. A 102, 033710 (2020)
[2] H. Zimmermann, et. al., arXiv:2506.10588 (2025)
[3] L.M. Lohse et. al., Phys. Rev. Lett. 135, 053601 (2025)

Q 22.7 Tue 12:45 P 11

Electron spectroscopy of the Mössbauer transition in 57Fe —
•K Ravi[1], E Månsson[1], L Bocklage[1,2], S Velten[1], I Sergeev[1], M Seitz[1], S Rockenstein[1], D Schmitt[3], M Kovacev[3,4], F Calegari[1,2,5], R Röhlsberger[1,6], and A Trabattoni[1,3,4] — [1]CFEL, Hamburg — [2]CUI, Universität Hamburg — [3]Leibniz University Hannover — [4]Cluster of Excellence PhoenixD, Hannover — [5]Department of Physics, Universität Hamburg — [6]IOQ, FSU Jena

Electron dynamics govern how nuclei interact with their electronic environment. In 57Fe Mössbauer isotopes, internal-conversion electrons and Auger-Meitner emission offer a surface-sensitive alternative to fluorescence for probing electron-nuclear energy exchange. Using synchrotron excitation and time-of-flight detection at PETRA III, we resolve magnetic hyperfine splitting and nuclear inelastic spectra, establishing a nuclear-electronic spectroscopy of coupled nuclear, electronic, and phononic excitations.