Tunable X-ray Radiation from Quantum Free-electron Radiation

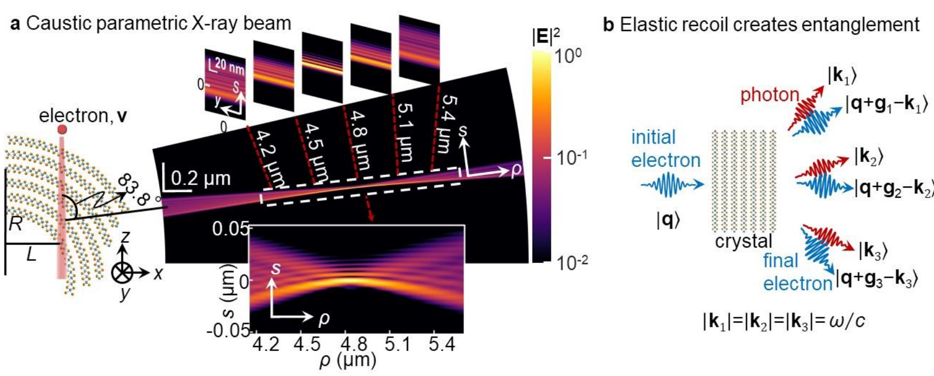
Xihang Shi[1], Michael Shentcis[1], Yaniv Kurman[1], Liang Jie Wong[2], F. Javier García de Abajo[3], and Ido Kaminer[1]

[1]Solid State Institute and Faculty of Electrical & Computer Engineering, Technion, Haifa, Israel
[2]School of Electrical and Electronic Engineering, NTU, Singapore, Singapore
[3]ICFO—Institut de Ciencies Fotoniques, Castelldefels, Spain

Tunable control of X-rays remains an open challenge with crucial implications for high-resolution X-ray spectroscopy, medical imaging, and more. However, the necessary optical elements in the X-ray regime are bulky and inefficient, strongly limiting the application of X-rays compared to the rich possibilities in the visible and IR regimes. In response, we propose a novel approach of generating tunable X-ray emission, relying on **coherent interactions between free electrons and crystalline materials**.

Coherent electron interactions are generally described by two separate processes – parametric X-ray radiation (PXR) and coherent Bremsstrahlung (CB)[1]. Both PXR and CB are intrinsically linked to the crystal structure, enabling control of the radiation via engineering of the crystal structure. We first demonstrated this scheme in transmission electron microscopes (TEMs) using van der Waals (vdW) materials[2], serving as a versatile platform for engineering X-ray sources. Our most recent developments of this approach include two schemes for creating **structured X-ray beams** using vdW heterostructures: X-ray caustics[3] and focused-X-ray beams[4]. Such beams are created directly at the sources, bypassing the need for X-ray-optical elements.

Furthermore, we also discovered a regime of electron-driven X-ray radiation in which the quantum nature of electrons and light plays critical roles in the radiation process[5]. Until our work, the classical approach was sufficient for describing free-electron radiation, with only marginal quantum corrections. We identified conditions under which an entirely new radiation mechanism emerges, driven by the entanglement between the emitted photons and the electrons.



(a) Caustic X-ray beams created via parametric X-ray radiation from electrons passing through a strained crystal structures.
(b) Free electrons scatter elastically when passing through periodic crystals, generating highly entangled electron-photon joint states.

1. Mikhail L Ter-Mikhaelyan. Electromagnetic radiative processes in periodic media at high energies. *Physics-Uspekhi* **44**, 571 (2001).
2. Shentcis, M. *et al.* Tunable free-electron X-ray radiation from van der Waals materials. *Nat. Photonics* **14**, 686–692 (2020).
3. Shi, X. *et al.* Free-electron-driven X-ray caustics from strained van der Waals materials. *Optica* **10**, 292–301 (2023).
4. Shi, X. *et al.* Free-electron interactions with van der Waals heterostructures: a source of focused X-ray radiation. *Light Sci. Appl.* **12**, 148 (2023).
5. Shi, X. *et al.* Elastic recoil imprinted on free-electron radiation, *under review* (2023).