Towards Entanglement of Free-Electron Pairs and Free-Electron–Bound-Electron Systems

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Free-electron quantum optics [1] explores quantum-coherent interactions between free-electron wavepackets, light, and matter, enabling ultrafast and deep-subwavelength studies of quantum correlations. A central achievement of the field has been the realization of electron–photon entanglement [2–5]. Beyond this, theory has predicted entanglement between free electrons and bound electrons [6,7], as well as between pairs of free electrons through long-range Coulomb interactions [8]. While classical correlations between free-electron pairs were recently observed experimentally [9,10], direct evidence of residual entanglement remains elusive [8]. Likewise, free-electron–bound-electron entanglement has yet to be experimentally demonstrated [11,12].

In this talk, I will show that entangled free-electron pairs leave distinct signatures in the emitted light that directly depend on their quantum state [13], providing a route for optical detection of free-electron entanglement. I will then discuss recent experiments showing that Coulomb-entangled electron pairs driven by external laser fields exhibit characteristic two-dimensional quantum-walk–like energy-correlation patterns [8], clearly different from separable states. Next, I will present a new mechanism in which elastic interactions with electromagnetic fields generate entangled electron energy-comb states [14]. Finally, I will discuss how engineered electromagnetic environments can strongly enhance free-electron–bound-electron interactions [15,16], bringing experimental observation of this form of entanglement closer to reality.

References

[1] R Ruimy, A Karnieli and I Kaminer, Nat. Phys. **21**, 193 (2025)

[2] O Kfir, Phys. Rev. Lett. **123**, 103602 (2019)

[3] G Arend, G Huang, A Feist, *et al.*, Nat. Phys. **21**, 1855 (2025)

[4] J-W Henke, H Jeng, M Sivis and C Ropers, arXiv:2504.13047 (2025)

[5] P Rembold, S Beltrán-Romero, A Preimesberger, *et al.*, arXiv:2502.19536 (2025)

[6] R Ruimy, A Gorlach, C Mechel, N Rivera and I Kaminer, Phys. Rev. Lett. **126**, 233403 (2021)

[7] Z Zhao, X-Q Sun and S Fan, Phys. Rev. Lett. **126**, 233402 (2021)

[8] O Tziperman, D Nabben, R Ruimy, *et al.*, Nat. Phys. **22**, 763 (2026)

[9] R Haindl, A Feist, T Domröse, *et al.*, Nat. Phys. **19**, 1410 (2023)

[10] S Meier, J Heimerl and P Hommelhoff, Nat. Phys. **19**, 1402 (2023)

[11] M Kolb, T Spielauer, T Weigner, arXiv:2509.13904 (2025)

[12] J M Grzesik, D Catanzaro, C Roques-Carmes, *et al.*, arXiv:2508.13112 (2025)

[13] A Karnieli, N Rivera, A Arie and I Kaminer, Phys. Rev. Lett. **127**, 060403 (2021)

[14] R Ruimy, *et al.*, in preparation

[15] A Karnieli, S Tsesses, R Yu, *et al.*, Sci. Adv. **9**, add2349 (2023)

[16] J M Grzesik, A Karnieli, C Roques-Carmes, *et al.*, arXiv:2601.21385 (2026)