Impact of surface scattering on photoelectron escape times

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What determines the precise moment when a photoelectron escapes from a solid? We demonstrate that the photoelectron escape time is not primarily determined by its inelastic lifetime but is fundamentally governed by scattering at the material - vacuum interface. This interface scattering couples *propagating* and *evanescent* partial waves–two emission channels with vastly different escape times–leading to pronounced energy-dependent variations in photoemission delays as function of final state energy. In quantum-mechanical terms, the electron simultaneously tunnels through the wall and exits through the door - and the interplay between both ways out determines the actual escape time.

To elucidate this mechanism, we first discuss the photoemission dynamics within a one-dimensional Kronig-Penney model, which clearly distinguishes the temporal behavior of propagating versus evanescent contributions. Building on this theoretical foundation, we present attosecond interferometric photoemission measurements on the topological insulators Bi_2Te_3 and Bi_2Se_3. Differential attosecond delays, i.e., relative photoemission delays between spin-orbit-split core levels (Bi 5d, Te 4d, Se 3d) - despite nearly identical final-state continua - reveal unexpectedly large relative delays of 30-100 as, far exceeding expectations from ballistic or atomic models.

Quantitative modeling within the one-step photoemission theory, combined with the Eisenbud-Wigner-Smith delay formalism, reproduces the experimental findings and attributes them to multiple scattering at the surface. This process mixes evanescent and propagating final states, establishing the interface as a timing element of photoemission.

Our results bridge two long-standing concepts - tunneling dwell times and solid-state photoemission delays - and identify *differential attosecond delays* as a robust and interpretable observable for ultrafast quantum dynamics in solids. The discovery that surface scattering alone can advance or retard electron emission by tens of attoseconds provides new theoretical and experimental access to correlation and transport phenomena at condensed-matter interfaces.