Attosecond Photoelectron Spectroscopy of Metal Surfaces

C.-H. Zhang* [1], **U. Thumm*** [2]

*JRM Laboratory, Kansas State University, Manhattan, KS, 66506-2604, USA

Synopsis We calculate the time delay between photoemitted conduction-band and core-level electrons of a tungsten surface [1].

Attosecond photoelectron (PE) spectroscopy can be used to study the electronic dynamics of different groups of electrons in solids. In this setup, electrons are photoemitted by an attosecond XUV pulse and streaked by a delayed femtosecond IR laser pulse. Such an experiment was carried out by Cavalieri *et al.* [2] on a W(110) surface and shows a relative delay of 110 ± 70 as between the detection of PEs that are emitted by absorption of a single XUV photon from $4f$-core and conduction band levels.

We investigated the mechanism behind this observed relative delay in the PE spectra, describing the XUV photo-release as a one-step single-electron transition from an initial Bloch wave $\Psi_{\mathbf{k}_i}(\mathbf{r},t)$ to an IR-field-dressed damped final Volkov wave $\Psi^V_{\mathbf{k}_f,\kappa}(\mathbf{r},t) = \Psi^V_{\mathbf{k}_f}(\mathbf{r},t)\chi(\kappa,z)$ with the damping factor $\chi(\kappa,z) = e^{\kappa z}$ for $z<0$ and 1 for $z>0$. Here $\mathbf{k}_i$ is the crystal momentum, $\mathbf{k}_f$ designates the (unstreaked) final momentum of the PE, $\kappa = 1/\lambda$ the damping parameter, and $\Psi^V_{\mathbf{k}_f}$ the usual Volkov wave. The PE emission probability in the dipole-length gauge for the interaction with the XUV electric field $E_X(t)$ is

$$P(E,\tau) = \sum_{\mathbf{k}_i} \left| \int dt \langle \Psi^V_{\mathbf{k}_f,\kappa} | z E_X(t) | \Psi_{\mathbf{k}_i} \rangle \right|^2 \quad (1)$$

where E is the final PE kinetic energy and τ the delay between the XUV and IR pulse. We use a jellium wavefunction for the conduction band and a tight-binding wavefunction with zero bandwidth for the core-level electrons. The relative delay $\Delta\tau$ is visible in the center-of-energy $\bar{E}(\tau) = \int P(E,\tau)EdE / \int P(E,\tau)dE - E_c$ of the two spectra (Fig. 1), where E_c is the spectral peak position without the IR field.

Our calculated time-resolved PE spectra depend on the transport of photo-released electrons inside the solid, agree with the experiments of Cavalieri *et al.* [2], and demonstrate that the observed temporal shift is caused by the interference of core-level PEs that originate in different layers of the solid and experience a temporal modulation by the streaking field. We further show how this temporal shift is controlled by the mean free path of the core-level PEs and that the observed 110 as shift is obtained in by choosing $\lambda = 5$ Å.

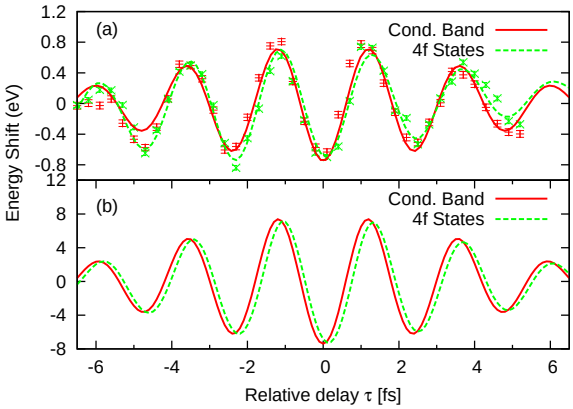

Fig. 1. Streaked electron spectra for photoemission from CB and $4f$-core levels of a W(110) surface: $\bar{E}$ as a function of the delay between the XUV and IR pulse. (a): Experimental results of Fig. 3b in Ref. [2]. The damped sinusoidal curves are fits to the raw experimental data (points with error bars). (b): Calculated results showing a relative shift of $\Delta\tau = 110$ as between the two groups of electrons.

References

[1] C.-H. Zhang, and U. Thumm, *Phys. Rev. Lett.* **102**, 123601 (2009).

[2] A. L. Cavalieri *et al.*, *Nature* **449**,1029 (2007).

[1]E-mail: chhzhang@ksu.edu
[2]E-mail: thumm@phys.ksu.edu