

Spin- and Angle-Resolved Photoemission Spectroscopy

by

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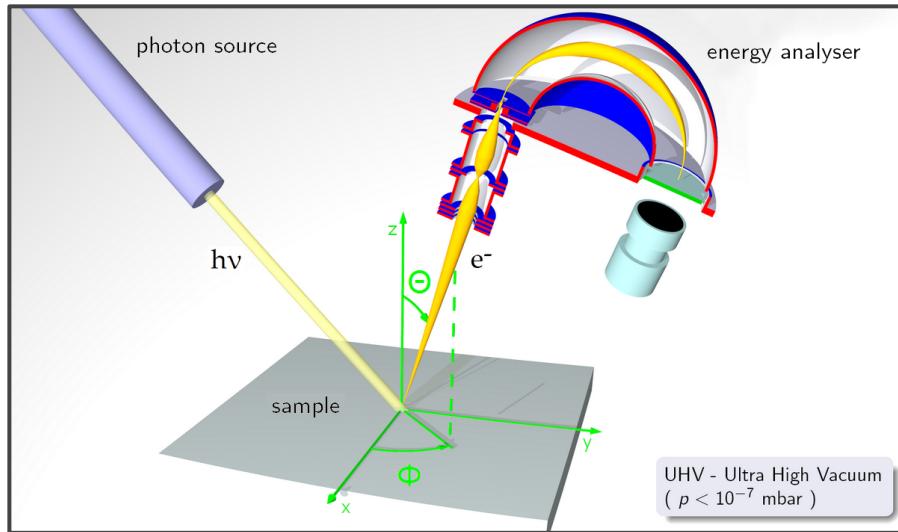


Image: ARPESSgeneral.png

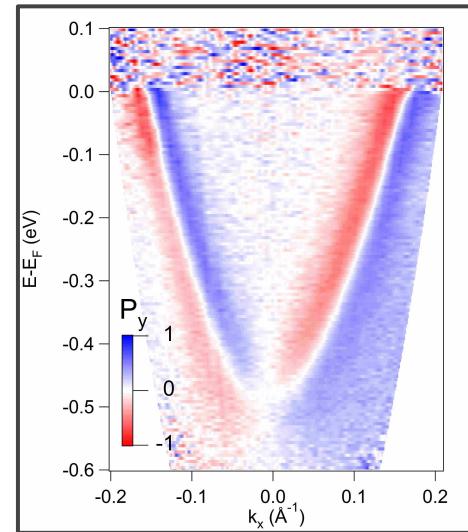
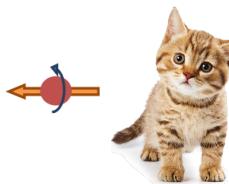


Image: AuSpinMap.png



Motivation



- Probe the electronic structure of solids.¹
- Measure the spin-resolved band structure of materials.²
- Understand emergent behaviors such as superconductivity and colossal magnetoresistance.³
- Observe complex electron dynamics at the femtosecond scale (*lasers*).⁴
- Understand the complex roles and behaviors of electronic spin in materials such as topological insulators.

1. R. Comin, A. Damascelli, "ARPES: A probe of electronic correlations", arXiv:1303.1438v1 [cond-mat.str-el] 6 Mar 2013.

2. "Lanzara Research Group." <http://research.physics.berkeley.edu/lanzara/spinarpes.html>

3. "Angle Resolved Photoemission Spectroscopy." arpes.stanford.edu

4. "Laser-based Angle-resolved Photoemission Spectroscopy." *Wikipedia*. Wikimedia Foundation, Dec. 2014.

What is ARPES?

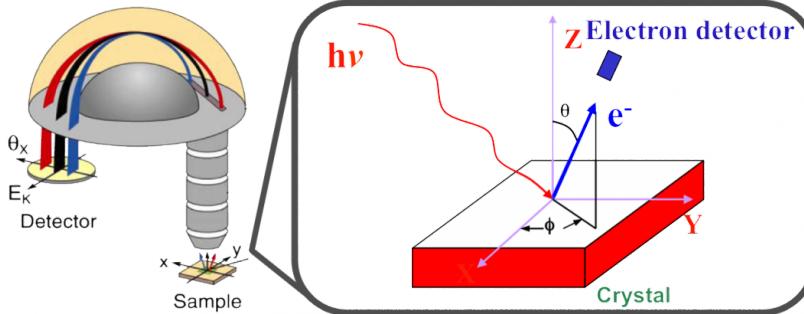
Angle-resolved photoemission spectroscopy (ARPES) is one of the most direct methods of studying the electronic structure of the surface of solids. ARPES gives information on the direction, speed and scattering process of valence electrons in the sample being studied (usually a solid) and therefore allows us to measure both the momentum and the energy of the electrons.

Physics of ARPES

Photoelectric Effect

Incident light on surface ejects electrons with max K.E. of

$$E = h\nu - \phi$$



Electron Interaction Hamiltonian and Final-State Transition Probability¹

$$H_{int} = -\frac{e}{2mc}(\mathbf{A} \cdot \mathbf{p} + \mathbf{p} \cdot \mathbf{A}) = -\frac{e}{mc}\mathbf{A} \cdot \mathbf{p}$$

$$w_{fi} = \frac{2\pi}{\hbar} |\langle \Psi_f^N | H_{int} | \Psi_i^N \rangle|^2 \delta(E_f^N - E_i^N - h\nu)$$

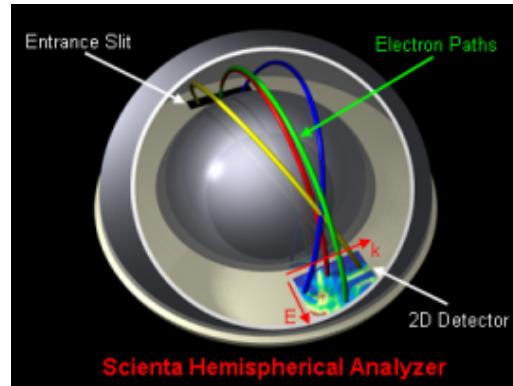
Instrumentation of ARPES

Light Source

- X-rays from a synchrotron are traditionally used.
- They have high energy and low bulk sensitivity.
- Slow data collection rate

Hemispherical analyzer

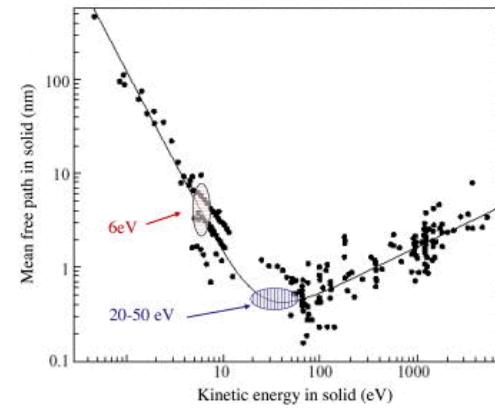
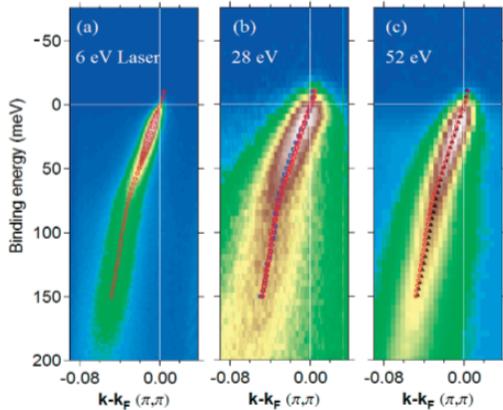
- Consists of two concentric spheres
- Voltage differentiates electrons with desired energies / momenta.
- Data is collected on a 2-D detector



Experimental Improvements

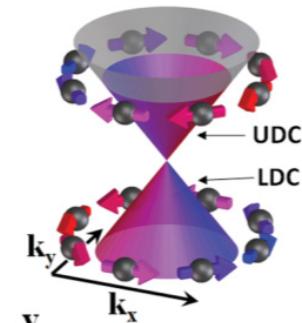
Laser Based

- strong signal
- enhanced momentum resolution
- increased bulk sensitivity



Time of Flight (TOF)

- boosts overall efficiency by multiplexing energy detection and taking full spin-resolved energy distribution curves at once. (allows measurement of spin without destroying the spatial information.)



Spin ARPES

What is it?

A method of studying properties of spin-dependent materials such as ferromagnets and topological insulators.¹

(a) Clear separation of spin-up and spin-down bands.

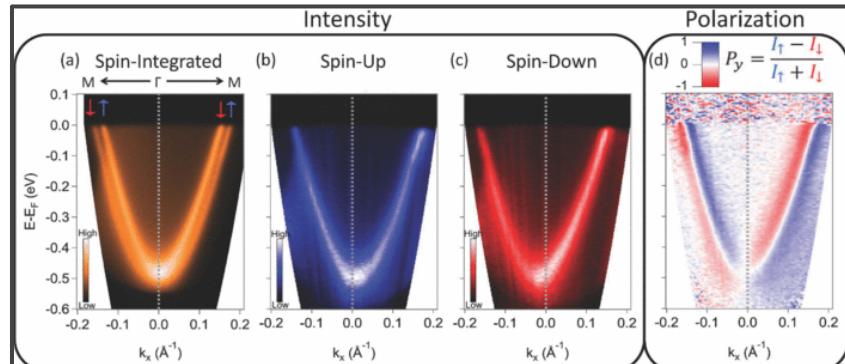
(b) Spin intensity map for **spin-up** photoelectrons.

(c) Spin intensity map for **spin-down** photoelectrons.

(d) In-plane spin polarization map as a function of binding energy and crystal momentum.

How do you do it?

Polarimetry based on low-energy exchange scattering from a ferromagnetic thin-film target.² Then integrate the polarimeter into a time-of-flight (TOF) based energy analysis.



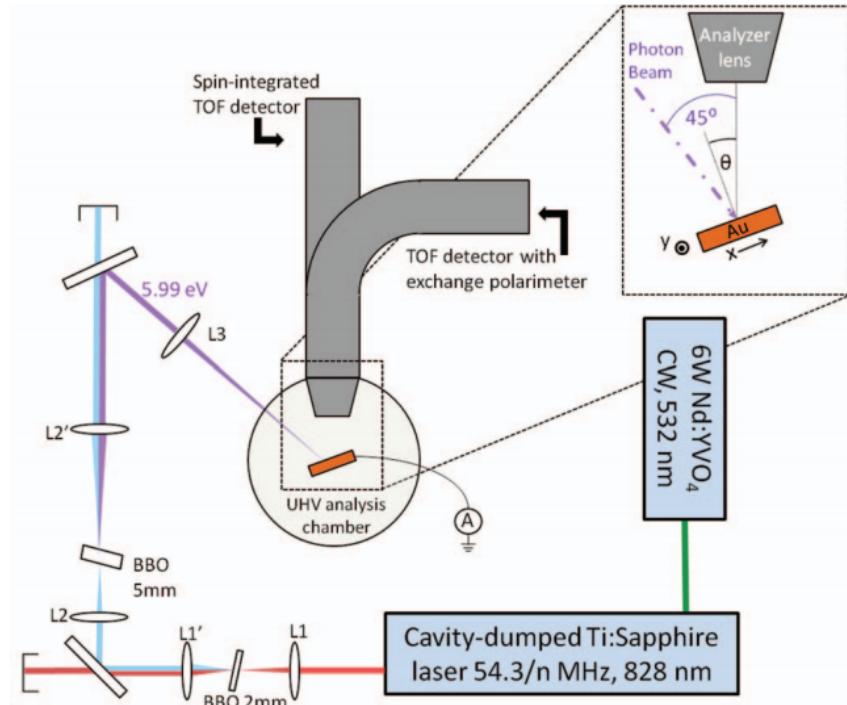
1. K. Gotlieb et al., "Rapid high-resolution spin- and angle-resolved photoemission spectroscopy with pulsed laser source and time-of-flight spectrometer," *Rev. Sci. Instrum.* **84**, 093904 (2013).

2. C. Jozwiak et al., "A high-efficiency spin-resolved photoemission spectrometer combining time-of-flight spectroscopy with exchange-scattering polarimetry," *Rev. Sci. Instrum.* **81**, 053904 (2010).

Instrumentation of Laser Based Spin TOF ARPES

Spin Detection

- Mott Detector
 - Electrons are scattered off of a gold film.
 - The direction that they are scattered indicates their spin polarization
- Thin Film Ferromagnetic Detector
 - Improved version of the Mott Detector
 - Higher scattering rates -> Faster data collection



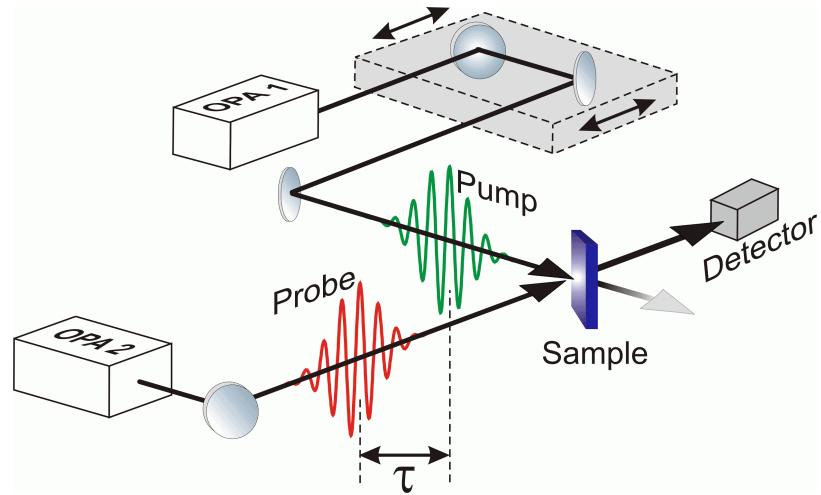
Next Step: TrARPES

What is time-resolved ARPES?

- Infrared pump pulse drives the sample's low energy electrons into a nonequilibrium state
- Ultraviolet probe pulse photo emits electrons outside the sample

What is it used for?

Analyzing the time-dependent processes involved in the relaxation of nonequilibrium electronic states with sub-picosecond precision



Conclusions & Acknowledgments

- ARPES is a useful experimental technique for learning about surface electron dynamics.
- Various improvements to ARPES such as time- and/or spin-resolution have greatly enhanced our understanding of surface physics.
- New leading research is currently being conducted by our mentor, Kenny Gotlieb, and his colleagues in the Lanzara Research Group.¹

Awesome People



← Shoutout to
Mitch's arm.

In Case We Need to Stall

"Have you heard that entropy isn't what it used to be?" - Ludwig Boltzmann

Quantum Mechanics

Heisenberg and Schrödinger in a car speeding down the freeway. Predictably, they are stopped by a traffic policeman.

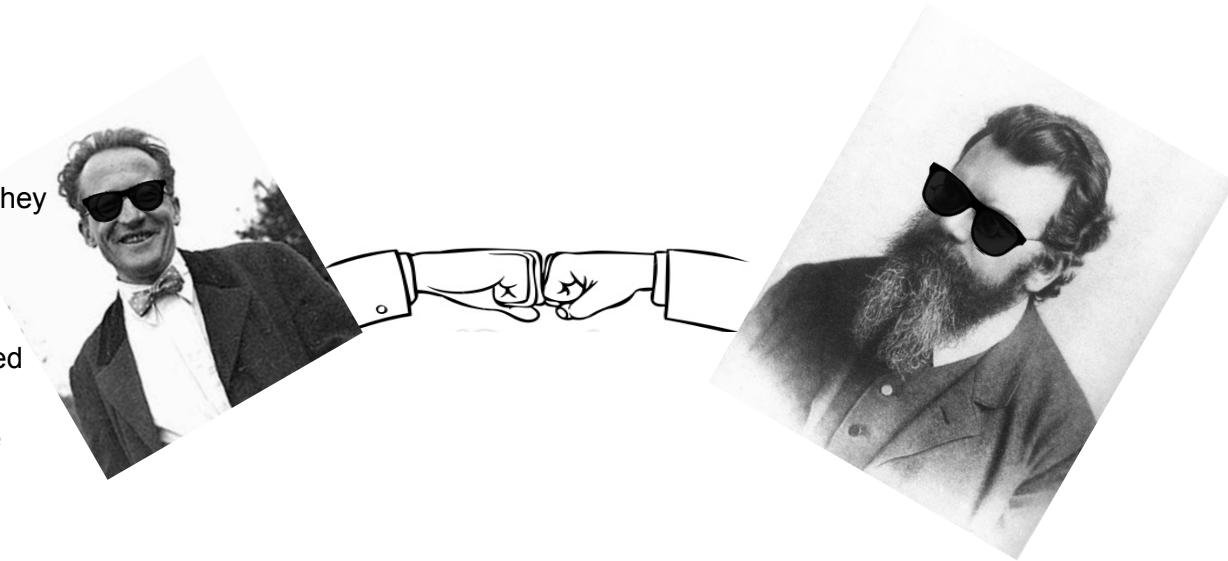
"Do you know how fast you were going?" asked the cop.

"No, but I know exactly where I was," replied Heisenberg.

Deciding to give the car an inspection, the cop opens the trunk.

"Did you know you've got a dead cat in here?" he asks.

"Well, I do now!" replied Schrödinger.



Please pass
us!!!!

