

## ***PHOTOELECTRON SPECTROSCOPY***

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### ***1. INTRODUCTION***

Most properties of materials reflect, directly or indirectly, the nature of their electronic states. Electrons interact with the ions – and therefore feel the translation symmetry of the lattice – but also, namely in interesting materials, with other electrons. This leads to complex correlated states. Not surprisingly, the most straightforward way to investigate electronic properties is to remove the electrons from the solid, and to measure them far from the interacting system. This is the general idea of a photoemission experiment. Perhaps more surprisingly, such a simple measurement contains crucial information on the interacting system. The purpose of this chapter is to illustrate this simple and powerful idea.

The impressive results obtained over the past four decades, and the huge number of experiments performed every year, demonstrate that photoemission has reached the venerable status of a standard probe of the electronic properties of solids. And yet, new and exciting developments, often associated with synchrotron radiation, are reshaping the practice and scope of the technique, bridging the gap with conventional "thermodynamic" probes of the electronic states. The forefront of research has moved from studies of the band structure on the eV scale, to the investigation of elementary excitations, electronic instabilities, and new exotic properties of correlated systems, at the meV range and with high momentum resolution. In this perspective, this chapter gives only a very brief account of traditional aspects of photoelectron spectroscopy, while it addresses, with examples from the recent literature, the spectral properties of correlated electron systems. For a broader view and a much more detailed description of the technique the reader is referred to some excellent reviews [1,2].

This chapter is organized as follows: section 2 gives a brief qualitative description and an intuitive interpretation of a photoemission experiment. Section 3 presents a discussion of a photoemission spectrum based on the simple and widespread 3-step model. Correlation effects and their manifestation in the spectral properties are introduced in section 4. These ideas are illustrated by selected case studies in section 5.

## 2. WHAT IS PHOTOEMISSION?

Photoelectron spectroscopy (PES) is a photon in-electron out experiment (figure 1). The interaction of a monochromatic beam of UV or soft X-ray photons with a sample generates photoelectrons with a broad distribution of emission angles and kinetic energies. The target may be indifferently a solid, a liquid or a gas, but in the following we will implicitly consider the more common case of a solid. The emitted electrons are then collected over a broad (angle-integrated PES, or simply PES) or a narrow (angle resolved PES or ARPES) acceptance angle. The subsequent measurement of the distribution of kinetic energies, typically performed by an electrostatic analyzer, yields a *spectrum* or *energy distribution curve* (EDC). The EDC represents the number of photoelectrons measured as a function of kinetic energy within the energy and angular acceptance windows of the analyzer. The measured intensity depends in a non-trivial way on various parameters that can be controlled, at least in principle, independently. They include the energy, polarization and incidence angle of the photon beam, the orientation and temperature (and magnetization etc.) of the sample, the collection angle and the angular acceptance window of the analyzer. A measurement of the spin may be added to the energy analysis, but the specific topic of spin-resolved PES and ARPES, which is of obvious interest in the study of magnetic systems, will not be covered here.

In this chapter we will address the crucial question: "*What kind of information is contained in a photoelectron spectrum?*" at various levels of sophistication. From the outset our physical intuition suggests that a PES spectrum must reflect the energy distribution of electrons inside the solid. When a photon is absorbed, its energy is transferred to an electron, which "jumps" from its initial state at energy  $\varepsilon_i$  to an excited state. If the photon is sufficiently energetic, the final state lies above the vacuum level and the photoelectron can escape from the solid. Energy conservation then determines the kinetic energy  $\varepsilon_k$  of the photoelectron

$$\varepsilon_k = \varepsilon_i + \hbar\Omega - \phi \quad \{1\}$$