Angle-resolved photoelectrons spectroscopy (ARPES) for investigations of strongly-correlated electrons and exotic magnetism in quasi-two-dimensional 4*f* systems

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The photoelectric effect, discovered by H. Hertz in 1887 and later, in 1906, explained by A. Einstein, forms the basis of a variety of spectroscopic techniques known as photoelectron spectroscopy (PES). Among them are ultraviolet photoelectron spectroscopy (UPS), X-ray photoelectron spectroscopy (XPS), angle-resolved photoelectron spectroscopy (ARPES), as well as spin- and time-resolved photoelectron spectroscopies [1]. Nowadays, PES is one of the most extensively used and continuously developing methods, allowing researchers to comprehensively study the electronic structure of molecules, solids, surfaces, and interfaces, and to gain insight into the dynamic and magnetic properties of the studied systems. Furthermore, PES has wide practical implications in fields such as surface chemistry and materials science, and it has significantly contributed to the understanding of fundamental principles in solid-state physics [1,2].

An introduction to photoelectron spectroscopy, with particular emphasis on angle-resolved photoelectron spectroscopy (ARPES), will be provided. Several examples from our own studies [3–15] will then be presented, illustrating how ARPES can be applied to investigate strongly correlated electrons and magnetic phenomena in rare-earth intermetallic materials. For a long time, such materials have attracted considerable interest because of their exotic properties at low temperatures, which include complex magnetic phases, valence fluctuations, heavy-fermion behavior, Kondo physics, and many others. All of these phenomena arise from the interplay between nearly localized 4f electrons and itinerant states.

In that regard, the class of RE compounds RET_2Si_2 (T is transition metal atoms) of the $ThCr_2Si_2$ type structure attracts considerable attention. Besides their unique bulk properties evolving from a delicate interplay of 4*f* and *spd* electrons, these materials serve as toy models for studying exotic physics within the non-centrosymmetric Si-T-Si-RE four layer of the Si-terminated surface. There, the spin-orbit coupling (SOC) can be tuned by choice of suitable transition metal atoms. It gradually increases by exchanging Co (3*d*) for Rh (4*d*) and further for Ir (5*d*). The SOC-based phenomena will be rather weak for Co 3*d* electrons, while they will be greatly enhanced for Ir 5*d* orbitals.

As a competing ingredient, exchange magnetic interaction may be exploited by inserting elementary 4*f* magnets like Gd as the RE component. Because the orbital moment of the Gd 4*f* shell vanishes (L = 0), the pure and large spin moment of Gd will be a strong and robust source of magnetic phenomena. A rotation of the 4*f* moments to a certain angle relative to the surface normal may be achieved by coupling to crystal-electric-field (CEF). To make use of notable CEF effects, a non-vanishing orbital moment L is needed, like for instance in Ho or Dy. Then, this option allows to implement an exchange magnetic field with different strength and orientation at the surface, which competes with the Rashba SOC field and creates additional possibilities to manipulate the properties of the 2D electrons within the considered Si-T-Si-RE system. As the next ingredient, the Kondo effect can be introduced by inserting elements with unstable 4*f* shell as Yb or Ce. This gives the opportunity to explore the interplay of the 2D electrons with 4*f* moments within a 2D Kondo lattice in the presence of spin-orbit coupling and a non-centrosymmetric environment.

It will be shown that, in general, such a Si–T–Si–RE system may serve as a beautiful playground for studying the fundamental properties of 2D electrons. These systems can be regarded as a veritable platform, with spin–orbit coupling, Kondo effect, crystal-electric field, and exchange magnetic interactions as the building blocks. Combining them provides the opportunity to design systems for different scenarios and to explore the physics of 2D electrons in the presence of these competing interactions.

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