

## ARPES on strongly correlated 4f materials: Unveiling novel temperature scales at their surfaces

Denis Vyalikh

Donostia International Physics Center, 20080 Donostia/San Sebastián, Basque Country, Spain

IKERBASQUE, Basque Foundation for Science, 48011 Bilbao, Spain

[www.ikerbasque.net/en/denis-vyalikh](http://www.ikerbasque.net/en/denis-vyalikh)

[denis.vyalikh@dipc.org](mailto:denis.vyalikh@dipc.org)

For a long time, Rare-Earth (RE) intermetallic materials have attracted considerable interest because of their rich and exotic properties including complex magnetic phases, valence fluctuations, heavy-fermion and Kondo behavior and non-Fermi-liquid properties. At the heart of the involved physics is the delicate interplay between itinerant electrons and the lattice of localized 4f 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 4f and itinerant electrons, these materials serve the models for studying exotic physics within the non-centrosymmetric Si-T-Si-RE surface-silicide block. Within this block, the strength of spin-orbit coupling (SOC) can be tuned by choice of suitable transition metal (T) atoms. It gradually increases by exchanging Co (3d) for Rh (4d) and further for Ir (5d). As a competing ingredient, exchange magnetic interaction may be exploited by inserting elementary 4f magnets like Gd as the RE component. Because the orbital moment of the Gd 4f 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 4f moments to a certain angle relative to the surface normal may be achieved by coupling to a 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 4f shell as Yb or Ce. This gives the opportunity to explore the interplay of the 2D electrons with 4f moments within a 2D Kondo lattice in the presence of spin-orbit coupling and a non-centrosymmetric environment.

Our ARPES experiments have realized the most of such scenarios and demonstrated quite nicely that the Si-T-Si-RE surfaces of the  $RET_2Si_2$  materials serves as a versatile playground for studying the fundamental properties linked with  $f$ - $d$  interactions at reduced dimensionality. It represents a kind of construction kit with Rashba spin-orbit coupling, Kondo interaction, crystal-electric fields and magnetic exchange with different strengths as building blocks. Their mutual combination gives the opportunity to design systems for different scenarios and to study the physics of 2D electron states in the presence of these competing interactions. The most interesting experimental results, which unveil the novel temperature scales at the surfaces of  $RET_2Si_2$  materials and which are linked with the aforementioned scenario will be presented.

### Bibliography

- [1] G. Bihlmayer et al., Rashba-like physics in condensed matter, *Nature Reviews Physics* **4** 642 (2022).
- [2]. D. Yu. Usachov et al., Cubic Rashba Effect in the Surface Spin Structure of Rare-Earth Ternary Materials, *Physical Review Letters* **124**, 237202 (2020).
- [3]. S. Schulz et al., Emerging 2D-ferromagnetism and strong spin-orbit coupling at the surface of valence-fluctuating  $EuIr_2Si_2$ , *npj Quantum Materials* **4** 26 (2019).
- [4]. A. Generalov et al., Spin orientation of two-dimensional electrons driven by temperature-tunable competition of spin-orbit and exchange magnetic interactions, *Nano Letters* **17** 811 (2017).
- [5]. S. Patil et al., ARPES view on surface and bulk hybridization phenomena in the antiferromagnetic Kondo lattice  $CeRh_2Si_2$ , *Nature Communications* **7** 11029 (2016).
- [6]. A. Chikina et. al., Strong ferromagnetism at the surface of an antiferromagnet caused by buried magnetic moments, *Nature Communications* **5** 3171 (2014).
- [7]. D. V. Vyalikh et. al.,  $k$ -dependence of the crystal-field splittings of 4f states in rare-earth systems, *Physical Review Letters* **105** 237601 (2010).