Atomic-Scale Quantum Information Science with Spins on Surfaces

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The desire to probe and control individual quantum systems has driven significant scientific and engineering advances in quantum coherent nanoscience. Meanwhile, single atoms and molecules on surfaces have been extensively studied in search of novel electronic and magnetic functionalities. These two research paths came together when it was clearly demonstrated that individual spins on surfaces can be coherently controlled and read out in an all-electrical fashion [1]. The enabling technique is the scanning tunneling microscopy (STM) combined with electron spin resonance (ESR) [2], which provides unprecedented coherent control at the Angstrom length scale.

In this talk, I will present our new approach to controlling and detecting 4f electrons carried in a single erbium (Er) atom on a surface [3]. The Er atom, positioned at the oxygen binding site of MgO/Ag(100), possesses a suitable ground state that interact efficiently with microwave fields. By using ESR-STM, we successfully drove and detected spin resonance signals from the single Er atom in an all-electrical fashion. Due to the highly protected nature of the 4f electrons, the ESR signals were read out indirectly through a sensor spin that is decently coupled but significantly detuned from the Er spin. This indirect detection of 4f electrons extends the capability of STM to harness a wider range of spin states in a coherent manner. Furthermore, we have recently succeeded in functionalizing the STM tip with spin-polarized magnetic atoms and an ESR-active molecular spin center [4], which allows us to use this STM tip as a mobile ESR sensor and facilitate precise detection of electric and magnetic fields at the atomic level. Our work broadens the approaches for tailoring spin structures on surfaces with atomic precision in the realm of quantum information science and quantum sensing.

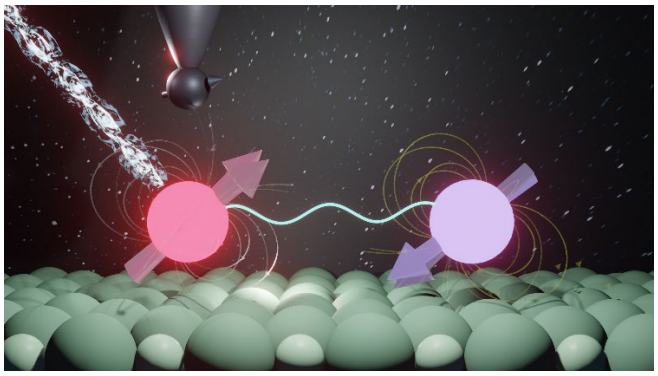

Figure 1, Atomic spin structure built with atomic precisions, characterized with high energy resolution, and coherently manipulated using a scanning tunnelling microscope (STM) combined with electron spin resonance (ESR).

[1] S. Baumann *et al.*, *Science* **350,** 417 (2015).
[2] Y. Chen *et al., Adv. Mater.* **35**, 2107534 (2022).
[3] S. Reale et al., Nat. Commun. **15**, 5289 (2024).
[4] T. Esat et al., Nat. Nano. (2024).