New Moiré Landscapes for Atomic Spins

The interactions of the spins of single atoms with a substrate can be controlled via the moiré lattice created by depositing a 2D material on top of the substrate.

By Carmen Rubio-Verdú and M. Reyes Calvo

Atomically flat, conductive surfaces provide a crystalline environment on which single magnetic atoms can be placed and manipulated. Such surfaces provide certain advantages. Most notably, they offer an anisotropic environment that is key to defining and stabilizing the atom's spin states. However, these surfaces also have a major drawback. The interactions between the atoms and the surface electrons often lead to undesired loss of control over the atomic spin states. Sergey Trishin, Katharina Franke, and their colleagues at the Free University of Berlin now find that placing single magnetic atoms on a metallic substrate capped with a two-dimensional semiconducting material can help in controlling such interactions [1]. Because of the lattice mismatch between the 2D semiconductor and the metal underneath, a superlattice known as a moiré pattern emerges. This superstructure acts as a periodic potential that modulates how the individual atoms couple to the surface. Because that coupling governs the atomic spin dynamics, this modulation opens a new route for fine-tuning the properties of single-atom spin states. This result goes beyond the use of single atomic spins as a platform for information technologies. It also paves the way to the design of periodic magnetic artificial structures.

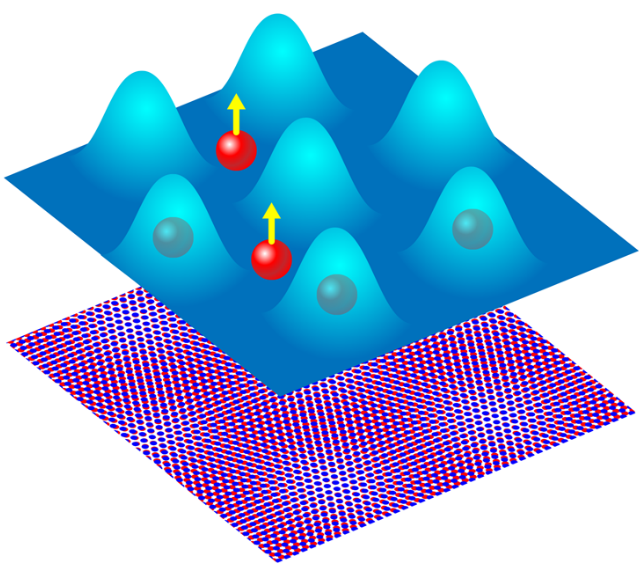

Figure 1: The moiré pattern of a single layer of MoS_2 on a gold substrate defines a periodic electronic potential that modulates the interactions of the spin of single iron atoms with the surface electrons.
Credit: APS/Alan Stonebraker

A single atomic spin represents the ultimate size limit for information storage [2]. If completely isolated from its environment, the magnetic moment shows no preferential direction. But the influence of an anisotropic environment determines the orientation of the spin magnetic moment [3]. It also splits the quantum spin energy levels, which can then be regarded as a quantum two-level system whose "up" or "down" states can be detected and manipulated [4]. Conductive surfaces have been shown to enable detection and control of atomic spins via electrical means, but the same surface electrons that make these measurements possible also induce relaxation and decoherence in the spin states. Placing a thin insulating layer of material between the single magnetic atom and the conductive substrate has been shown to achieve an optimal balance, providing the needed environmental anisotropy while limiting the strength of spin-surface interactions [**5**, **6**].

Recent research in 2D materials has led to new possibilities for designing these spin-substrate decoupling layers [**7**]. 2D materials offer an extra "tuning knob": when a single layer is stacked on top of a material that has a different lattice parameter, the lattice mismatch between the layers results in a moiré superlattice that modulates the electronic properties of the resulting heterostructure [**8**]. Trishin and colleagues show how the moiré lattice arising from the growth of a single-layer 2D semiconductor, molybdenum disulfide (MoS_2), on a gold substrate has a remarkable effect on the spin states of single iron atoms deposited on top of it [**8**]. The moiré superlattice causes the local density of electrons to vary in a periodic manner. As a consequence, individual magnetic iron atoms experience large variations in the strength of interaction with the substrate. Because of these variations, each iron atom's spin state is determined by its location within the moiré lattice. The researchers show that detection and manipulation of such spin states is possible through scanning tunneling microscopy and spectroscopy (STM/S).

An STM consists of a sharp metallic tip brought very close to the system under study, so that a tunneling current flows between them. It provides access to spectroscopic signatures at different locations of the sample, with atomic resolution. Single magnetic atoms show very different spectral signatures depending on the coupling strength of their spin with the substrate electron bath [**9**, **10**]. When the coupling is weak, the spin state is preserved, and tunneling electrons can excite the atomic spin. Conversely, a strongly enhanced interaction with the surface electrons results in the screening of the single iron atom spin; that is, the atomic spin becomes strongly correlated to the spins of the surface electrons, forming a bound system where the global net spin is zero.

The researchers examined the spectroscopic signatures of individual iron atoms randomly distributed on a MoS_2 single layer grown on top of crystalline gold. Trishin and colleagues show how, across the moiré superlattice, the coupling strength between the spin of iron atoms and the substrate underneath is modulated by the periodic electronic density. In the minima of the moiré structure, iron atoms showed spectral signatures corresponding to weak coupling. Iron atoms placed on the maxima of the moiré structure instead show spectral signatures compatible with much stronger coupling, meaning that the atomic spin becomes strongly correlated to the spins of the surface electrons, forming a bound system where the global net spin is zero.

The relevance of this result is twofold. First, semiconducting 2D layers protect atomic spins from decoherence that arises from interactions with the surroundings. Second, the moiré spatially modulates the spin state of single magnetic atoms. In the context of information technologies, this result can be exploited for controlling quantum spin states. Moreover, the variety of available 2D materials allows for the design of different moiré electronic templates, on which magnetic atoms can be placed with atomic precision thanks to STM manipulation capabilities. This sets the stage for the design of periodic artificial spin structures.

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