SCANNING TUNNELING SPECTROSCOPY OF A KONDO PEAK

Project: B2

Author: Simon Gerber

Introduction

Scanning Tunneling Spectroscopy (STS) has emerged as a powerful technique for investigating the Kondo effect at the atomic scale, providing unprecedented insights into this fascinating quantum phenomenon.[1,2] The Kondo effect, which arises from the interaction between magnetic impurities and conduction electrons in metals, manifests as a sharp resonance peak near the Fermi level.[3] This resonance, known as the Kondo peak, carries a wealth of information about the electronic and magnetic properties of the system under study. STS offers the unique ability to probe this effect with atomic resolution, allowing researchers to explore the behavior of individual magnetic impurities on surfaces.[1,4] By measuring the differential conductance (dI/dV) as a function of bias voltage, STS can reveal the characteristic Kondo resonance and its response to various experimental parameters.[2,4] This article aims to provide a comprehensive overview of the methods and considerations involved in measuring and analyzing Kondo peaks using STS, highlighting both standard techniques and advanced approaches that have pushed the boundaries of our understanding of this quantum phenomenon.[4,5]

Basic Measurement Techniques

The foundation of studying the Kondo effect with STS lies in several fundamental measurement techniques.[2] The standard STS measurement involves recording the differential conductance spectrum near zero bias voltage, where the Kondo effect manifests as a sharp resonance peak.[1,4] This peak arises from the scattering of conduction electrons by the magnetic impurity, leading to a modification of the local density of states.[3,6] The shape and width of this resonance provide crucial information about the strength of the Kondo interaction and the system's characteristic energy scales.[4] STS offers the advantage of probing both occupied and unoccupied states close to the Fermi energy with high sensitivity, allowing for a comprehensive picture of the electronic structure around the magnetic impurity.[2,5] Temperature-dependent measurements form another cornerstone of Kondo studies with STS.[4,6] By performing spectroscopy at various temperatures, researchers can observe the evolution of the Kondo peak, which typically broadens and decreases in amplitude as temperature increases. This behavior is a hallmark of the Kondo effect and allows for the determination of the Kondo temperature, a fundamental parameter that characterizes the strength of the Kondo interaction. Additionally, the temperature dependence of the peak width and amplitude can provide insights into the scaling behavior of the Kondo effect, offering a window into the underlying quantum many-body physics.

Another powerful technique in the STS toolkit is the application of magnetic fields to induce splitting of the Kondo peak. When an external magnetic field is applied, the single Kondo resonance can split into two distinct peaks, with the splitting proportional to the field strength. This phenomenon occurs due to the Zeeman effect on the magnetic impurity's spin states and serves as a confirmation of the Kondo nature of the observed resonance. The field-induced splitting also allows researchers to probe the g-factor of the magnetic impurity and study the competition between Kondo screening and magnetic field effects. By systematically varying the magnetic field strength and orientation, one can map out the anisotropy of the Kondo effect and gain insights into the magnetic properties of the impurity-substrate system. Furthermore, the evolution of the split peaks with increasing field strength can reveal information about the breakdown of Kondo screening and the transition to other magnetic ground states.

Advanced Techniques

As research in this field has progressed, several advanced techniques have been developed to enhance the measurement and analysis of Kondo peaks. High-resolution spectroscopy represents a significant advancement in STS measurements of the Kondo effect. By employing low modulation voltages and implementing noise reduction strategies in the experimental setup, researchers can improve the resolution of the Kondo peak. This enhanced resolution is crucial for accurately determining the intrinsic line shape and width of the resonance, which are sensitive indicators of the underlying physical processes. High-resolution spectroscopy enables the observation of fine features in the Kondo resonance, such as satellite peaks or asymmetries, that might be obscured in lower-resolution measurements. These subtle details can provide valuable information about the coupling between the magnetic impurity and its environment, including interactions with substrate electrons, neighboring adsorbates, or vibrational modes.

Spin-polarized STM (SP-STM) has revolutionized the study of Kondo physics at surfaces by introducing spin sensitivity to the measurement process. By utilizing a magnetic tip, SP-STM allows for the direct probing of spin-dependent electronic structure, offering a new dimension to Kondo peak analysis. One of the most striking capabilities of SP-STM is its ability to induce splitting of the Kondo peak even in the absence of an external magnetic field, thanks to the exchange interaction between the magnetic tip and the surface impurity. This technique enables the investigation of spin-dependent interactions between the tip and the sample, providing insights into the magnetic coupling mechanisms at play. SP-STM can also reveal information about the spin polarization of the split Kondo state, shedding light on the complex interplay between Kondo screening and local magnetic moments. The combination of SP-STM with other techniques, such as magnetic field application, opens up new avenues for exploring the rich physics of Kondo systems under various perturbations.

Tip functionalization represents another frontier in advanced STS techniques for studying the Kondo effect. By deliberately attaching magnetic atoms (such as iron) to the STM tip, researchers can create a controllable magnetic probe that interacts with the Kondo impurity on the surface. This approach allows for the tuning of the tip-sample magnetic interaction, enabling studies of exchange coupling strength and its impact on the Kondo resonance. Functionalized tips can induce Kondo peak splitting through exchange interactions, providing an alternative to external magnetic fields for probing the magnetic properties of the system. The ability to manipulate the tip's magnetic properties offers unprecedented control over the measurement conditions, allowing for systematic studies of how different magnetic configurations affect the Kondo state. Furthermore, tip functionalization can be combined with atomic manipulation techniques to create and study complex Kondo systems, such as coupled impurities or custom-designed magnetic nanostructures.[4,7]

Data Analysis

The analysis of STS data is crucial for extracting meaningful physical information from Kondo peak measurements. Fitting observed Kondo resonances with appropriate theoretical line shapes forms the backbone of quantitative analysis in this field. Common fitting functions include the Fano line shape, which accounts for the interference between tunneling into the discrete Kondo state and the continuum of substrate states, and the Frota function, which often provides a better description of the intrinsic Kondo resonance. These fits yield important parameters such as the resonance width, which is related to the Kondo temperature, and the q-factor in the case of Fano fits, which provides information about the nature of the tunneling processes. Advanced fitting procedures may incorporate additional effects, such as spin-orbit coupling or crystal field splitting, to provide a more comprehensive description of the system. Deconvolution techniques play a crucial role in accounting for instrumental broadening effects, which can obscure the true width and shape of the Kondo resonance.

The analysis of temperature and magnetic field dependences adds another layer of complexity and richness to Kondo peak studies. Tracking the evolution of fit parameters with temperature allows for the extraction of scaling laws and provides a test of theoretical predictions for Kondo systems. Similarly, analyzing the magnetic field-induced splitting can yield information about g-factors, magnetic anisotropies, and the competition between Kondo screening and Zeeman effects. In SP-STM measurements, careful analysis of the spin-dependent tunneling spectra can reveal the spin structure of the Kondo state and provide insights into the mechanisms of spin-flip processes. As the field advances, new analytical tools and theoretical frameworks continue to be developed to handle the increasing complexity of Kondo systems studied by STS, including multi-impurity configurations, non-equilibrium effects, and coupling to other degrees of freedom such as vibrations or superconductivity.

Conclusion

Scanning Tunneling Spectroscopy has established itself as an indispensable tool for studying the Kondo effect at the atomic scale, offering unparalleled spatial resolution and the ability to probe individual magnetic impurities. Through a combination of basic measurement techniques and advanced approaches, STS provides a comprehensive view of Kondo physics, from the fundamental properties of single impurities to complex, coupled systems. The ability to perform temperature-dependent measurements, apply magnetic fields, and utilize spin-polarized probes has greatly expanded our understanding of how Kondo systems behave under various conditions. The development of high-resolution spectroscopy and tip functionalization techniques has pushed the boundaries of what can be observed and manipulated at the atomic scale. As researchers continue to refine these methods and develop new analytical approaches, STS will undoubtedly play a crucial role in unraveling the mysteries of quantum many-body physics at surfaces. The insights gained from these studies not only advance our fundamental understanding of quantum phenomena but also pave the way for potential applications in fields such as quantum computing and spintronics. As we look to the future, the continued evolution of STS techniques promises to reveal new facets of the Kondo effect and related quantum phenomena, driving forward our exploration of the quantum world at its smallest scales.

References

1. Madhavan, V. et al. (1998). Tunneling into a Single Magnetic Atom: Spectroscopic Evidence of the Kondo Resonance. Science, 280(5363), 567-569.
2. Chen, C. J. (2021). Introduction to Scanning Tunneling Microscopy (3rd ed.). Oxford University Press.
3. Liang, W. et al. (2002). Kondo resonance in a single-molecule transistor. Nature, 417(6890), 725-729.
4. Ternes, M. (2015). Spin excitations and correlations in scanning tunneling spectroscopy. New Journal of Physics, 17(6), 063016.
5. Bonnell, D. A. et al. (2001). Scanning Tunneling Microscopy and Spectroscopy: Theory, Techniques, and Applications. Wiley-VCH.
6. Hewson, A. C. (1993). The Kondo Problem to Heavy Fermions. Cambridge University Press.
7. Barja, S. et al. (2019). Identifying substitutional oxygen as a prolific point defect in monolayer transition metal dichalcogenides. Nature Communications, 10(1), 3382.