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Exploring the evolution and future of ESR-STM: An interview with Andreas Heinrich

Professor Andreas Heinrich is a pioneer in the field of scanning probe microscopy and a leading figure in the development of Electron Spin Resonance Scanning Tunneling Microscopy (ESR-STM). His groundbreaking work has enabled researchers to probe and manipulate individual spins with unprecedented precision. In this interview, Andreas shares insights into the origins, challenges, and future directions of ESR-STM, offering a glimpse into the next frontiers of atomic-scale magnetic measurements.

Could you share how the idea of combining ESR with STM first emerged? What was the motivation behind this approach?

For my postdoc, I went to the U.S. to work with Don Eigler, who was at the time the premier expert in working with individual atoms on surfaces. My task was to extend this technique to spins – building an STM that operated at lower temperatures and in magnetic fields so we could observe spin behavior.

The key idea behind ESR-STM came later, in 2007, at a winter physics conference in Aspen, Colorado. There, I met Arzhang Ardavan, a professor at Oxford and an expert in ensemble-based ESR, particularly in molecular qubits. As we were both avid skiers, we bonded over that, and during our discussions, we realized that it should, in principle, be possible to combine STM's spatial resolution with the energy resolution and control offered by ESR. That moment marked the conceptual birth of ESR-STM – but it would take another seven years of work before we successfully demonstrated it in 2015 [1].

What were some of the major technical challenges in implementing ESR-STM, and how were they overcome?

Back in 2007, STM was already capable of probing single spins using inelastic tunneling spectroscopy. Other researchers, primarily the group of Roland Wiesendanger in Hamburg, had developed spin-polarized STM, which was another way of accessing spin properties. However, STM inherently lacks time resolution, which made combining it with ESR a challenge.

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One major hurdle was achieving the necessary gigahertz frequency control. STM traditionally works with steady-state tunneling currents, so we had to modify the wiring and electronics to introduce fast electrical pulses. Sebastian Loth, a postdoc in my group at the time, played a key role in this effort, successfully implementing the infrastructure needed for ESR-STM. Another challenge was finding the right system where we could reliably drive ESR transitions with STM's localized electric fields. Once those steps were completed, we had a functional ESR-STM setup, but it took years of incremental progress to get there.

Your team developed a comprehensive ESR-STM tutorial available online. What inspired you to create this resource, and how do you see it benefiting the scientific community?

When you develop a new technique, you have two options: you can either keep it to yourself, limiting competition, or you can share it openly to build a research community. I've always preferred the latter approach.

We wanted to make sure that other groups didn't waste time on technical details like choosing the right cables or assembling the right circuit components. Initially, we invited researchers to visit our lab in Korea to learn ESR-STM firsthand. However, when COVID-19 prevented travel, we pivoted to creating a YouTube tutorial. This turned out to be a highly effective way to share knowledge with minimal effort on our part. Our students and postdocs contributed their expertise, making it a collaborative and successful outreach effort [2].

What do you see as the most exciting open questions in ESR-STM, and where is the field headed in the next five to ten years?

Predicting a decade ahead is difficult, but over the next two to three years, several key directions are emerging. Since the first ESR-STM paper, about 14 groups worldwide have successfully implemented the technique, with at least 10 more actively working on it.

Currently, most ESR-STM studies are conducted on a single material – a thin film of magnesium oxide (MgO) grown on silver. About 98% of results use this system, which means we need to expand to different insulators and spin systems, including molecular spins. Another breakthrough is the development of ESR sensors that are attached to the STM tip rather than the sample. This "lab-on-a-tip" approach, developed in collaboration with the group of Stefan Tautz from Forschungszentrum Jülich, allows us to measure magnetic and electric fields with atomic-scale spatial resolution and ESR sensitivity [3]. It also frees us from being limited to specific sample materials, opening doors to studying complex surfaces like 2D magnetic materials, and other exotic quantum systems.

Can ESR-STM eventually be used to study more complex systems, such as biological molecules or buried interfaces?

I personally prefer working with “dead things”: well-defined, static systems like atoms on surfaces. In biological systems, complexity increases exponentially, making them more challenging to analyze.

That said, our new tip-based ESR sensor provides a way to investigate more complex systems. One promising direction involves studying endohedral fullerenes – carbon cages that encapsulate magnetic atoms. These systems are ideal because the encapsulated spins are shielded from their environment, making them stable and well-defined, yet challenging to probe directly with STM.

Going further, applying ESR-STM to buried interfaces, where interesting quantum phenomena often occur, is a goal for the next several years. This will require overcoming technical barriers, such as operating with multiple samples in the same system, but it’s an exciting avenue for future research.

The future of ESR-STM seems incredibly promising. Thank you for sharing your insights, Andreas. The Bunsen Society community will surely appreciate learning more about this technique.

My pleasure! I look forward to seeing more researchers engage with ESR-STM and take it in new directions.

ESR-STM has already revolutionized our ability to study and manipulate individual spins at the atomic scale, but its full potential is still unfolding. As researchers continue to push the boundaries of this technique, new materials, novel applications, and unexpected discoveries are sure to emerge. With ongoing advancements in instrumentation and methodology, ESR-STM will remain at the forefront of nanoscale science, providing deeper insights into quantum phenomena and expanding our understanding of the microscopic world.

References

[1] S. Baumann, W. Paul, et al.: Electron paramagnetic resonance of individual atoms on a surface, *Science* 2015 **350**(6259), 417-420.

[2] IBS Center for Quantum Nanoscience: ESR-STM Tutorial, Copyright © 2025, https://tutorial.qns.science/.

[3] T. Esat, D. Borodin, et al.: A quantum sensor for atomic-scale electric and magnetic fields, *Nature Nanotechnology* 2014 **19**, 1466–1471.

Prof. Dr. Andreas J. Heinrich

Professor Andreas Heinrich is a world-leading researcher in quantum measurements at the atomic scale. He pioneered spin excitation and single-atom spin resonance spectroscopy with scanning tunneling microscopes, enabling high-resolution access to quantum states. Currently, he is the director of the Center for Quantum Nanoscience at the Institute for Basic Science in South Korea and a distinguished professor at Ewha Womans University. His contributions to the field have been recognized with numerous awards, including the 2024 Honorary Citizen of Seoul title, the 2023 Humboldt Research Award, and the 2020 Heinrich Rohrer Medal.

The art of SPM

Artist: **Nelly Nembot & Marius Muhle (Carl von Ossietzky University Oldenburg)**

SPM technique: **Substrate-generation/tip collection mode of scanning electrochemical microscopy (SG/TC-SECM) using pulsed amperometric detection.**

Investigated System: **Gas-diffusion electrode for Li-air battery. The color scale highlights the noise to create the impression of a decorative maze.**

Title: ***“The maze of gas diffusion electrodes“***