

Role of exchange field in all-electric electron spin resonance STM of single atoms and molecules

P. Busz,^{1,2,3} D. Tomaszewski,¹ J. König,³ J. Barnaś,^{1,2} and J. Martinek¹

¹*Institute of Molecular Physics, Polish Academy of Sciences, Poznań*

²*ISQI, Faculty of Physics and Astronomy, AMU, Poznań*

³*Faculty of Physics and CENIDE, University of Duisburg–Essen*

Ongoing progress in scanning tunneling microscopy (STM) has opened the possibility of achieving quantum-coherent control of individual surface spin impurities using all-electric electron spin resonance (ESR–STM) [1]. Despite the fast-growing number of experimental results obtained using this technique, which is crucial for quantum information processing and spintronics, the mechanism underlying magnetoelectric coupling in ESR–STM remains unclear. To address this issue, we present a theoretical description [2-5] that incorporates a mechanism of virtual particle exchange between a magnetic tip and a localized Anderson impurity, inducing a bias- and gate-voltage-dependent effective exchange field. We employ the GKLS equation approach, which provides results equivalent to those obtained by the real-time diagrammatic technique for a quantum impurity coupled to noncollinearly magnetized electrodes. We derive an effective Bloch-like equation describing complex spin dynamics in the presence of spin-polarized currents in various relevant limits, including both the sequential and cotunneling regimes. We show that the dc current reflects electrically controlled projections of the induced spin, enabling local single-spin readout in spin-polarized STM. The predicted bias-controlled resonance shifts, related to the peculiar voltage dependence of the induced exchange field, have been reported in recent experiments [6,7], revealing the exchange-interaction mechanism governing ESR–STM. In another ESR–STM experiment [8], the authors suggest the observation of the Hanle effect predicted by our model [2] and confirm the presence of the exchange field as a main determinant of the peak shape appearing in conductance close to zero external magnetic field. The Hanle effect corresponds to a decrease in spin accumulation in a quantum impurity due to spin precession in a static magnetic field and provides a means to determine the local exchange field and the spin relaxation time from dc magnetoresistance measurements. We present a more detailed and extended analysis of this phenomenon, facilitating experimental interpretation. We also discuss spin-pumping effects that can offer a possible explanation for the dc current observed experimentally at zero bias.

References:

- [1] S. Baumann, W. Paul, T. Choi, C. P. Lutz, A. Ardavan, *et al.*, *Science* **350**, 417–420 (2015).
- [2] P. Busz, D. Tomaszewski, J. Barnaś, and J. Martinek, *JMMM* **588**, 171465 (2023).
- [3] P. Busz, D. Tomaszewski, and J. Martinek, *Phys. Rev. B* **111**, 125415 (2025).
- [4] J. Reina-Gálvez, M. Nachtigall, N. Lorente, J. Martinek, *et al.*, *Phys. Rev. B* **112**, 245408 (2025).
- [5] P. Busz, D. Tomaszewski, J. König, J. Barnaś, and J. Martinek, in preparation.
- [6] X. Zhang, J. Reina-Gálvez, D. Wu, J. Martinek, A. J. Heinrich, and C. Wolf, arXiv **2412.03866**.
- [7] P. Greule, W. Huang, M. Stark, K. H. Au-Yeung, J. Schwenk, *et al.*, arXiv **2507.13699**.
- [8] S. Kovarik, R. Schlitz, A. Vishwakarma, D. Ruckert, *et al.*, *Science* **384**, 1368–1373 (2024).

Supported by NCN Grant No. 2020/36/C/ST3/00539.