Dynamical spin reversion with spin polarized current

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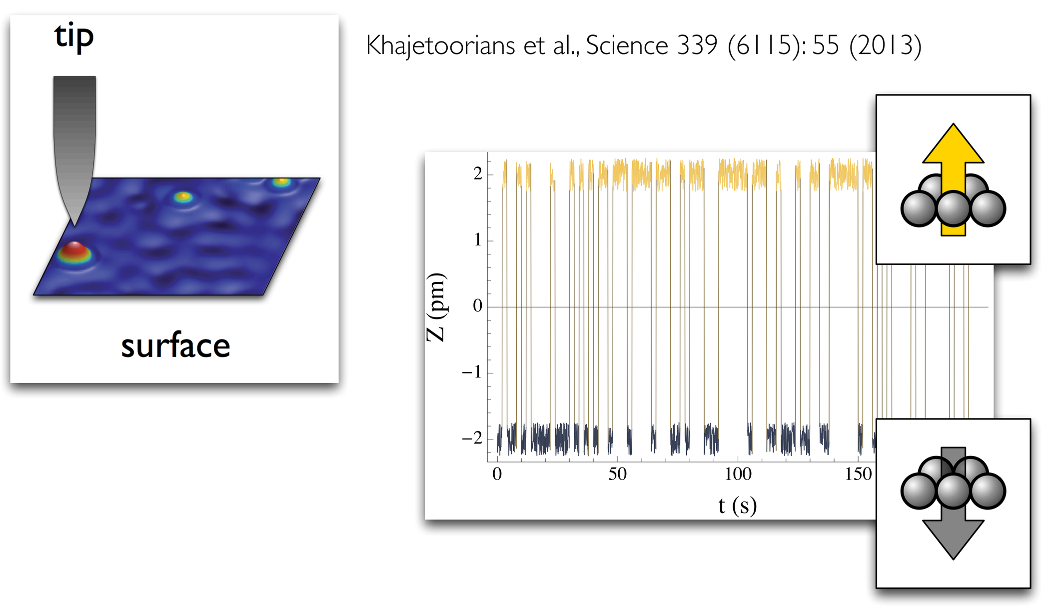
Introduction

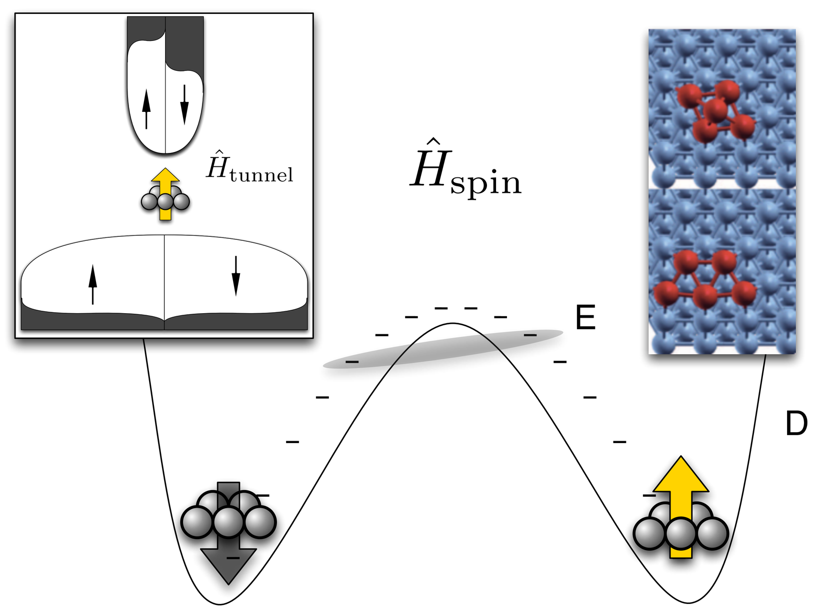
Understanding the time evolution of a magnetization reversal process is crucial for the ongoing developments in logical spin structures. In our study based on a master equation approach we relate the dynamical properties of a quantum spin driven out of equilibrium to the excitation and relaxation processes involved. As a specific case our theoretical study provides inside into the dynamical switching processes between two fully spin polarized states of a Fe cluster absorbed on a Cu surface, probed with a spin polarized scanning tunneling microscope[1]. In this setup the polarized current switches the spin of the cluster between the two polarized states across an anisotropy barrier. Rates for the intermediate excitation and relaxation processes are calculated by taking into account cotunneling between the cluster and tip/surface. Excitation of the cluster arises due to inelastic spin transfer from the electron source.

Fast relaxation is caused by coupling to the surface. We control the ratio between excitation and relaxation by changing the voltage between source and drain or varying the coupling of the cluster spin to the electron reservoirs. From the investigation of transient dynamics and the stationary limit, the current driven switching between the two fully spin polarized states can be expressed by a lifetime and an occupation probability. Both quantities are directly related to the in- and out-of-plane anisotropy of the cluster spin. Comparison between theory and measurement allowed us to extract the magnetic parameters unknown to the experiment. We also discuss the influence of temperature and external magnetic fields.

Current driven switching



Theoretical method



A master equation approach is used to describe the dynamic switching behavior of a spin created by an iron cluster, which is constructed on a copper surface. Inelastic coherent spin flip processes are taken into account in this method.

cluster spin Hamiltonian

$$\hat{H}_{\text{spin}} = g\mu_B B\hat{J}_z + D\hat{J}_z^2 + E\left(\hat{J}_x^2 - \hat{J}_y^2\right)$$

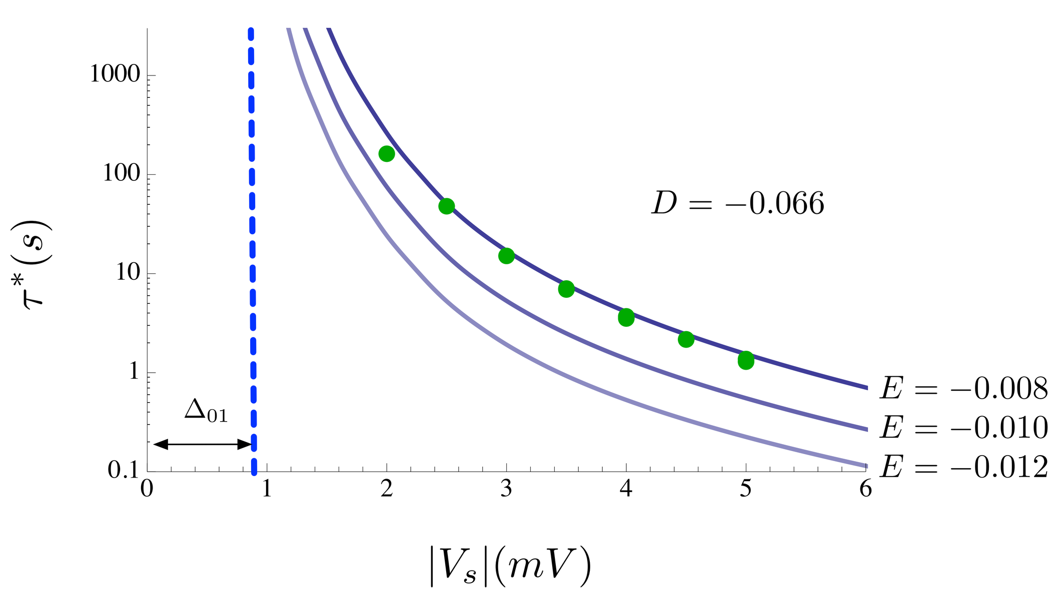
Appelbaum Hamiltonian

$$\hat{H}_{\text{tunnel}} = \sum_{rr'kk'\sigma\sigma'} v_r v_{r'} a^{+}_{rk\sigma} \frac{\sigma\hat{\mathbf{J}}}{2} a_{r'k'\sigma'}$$

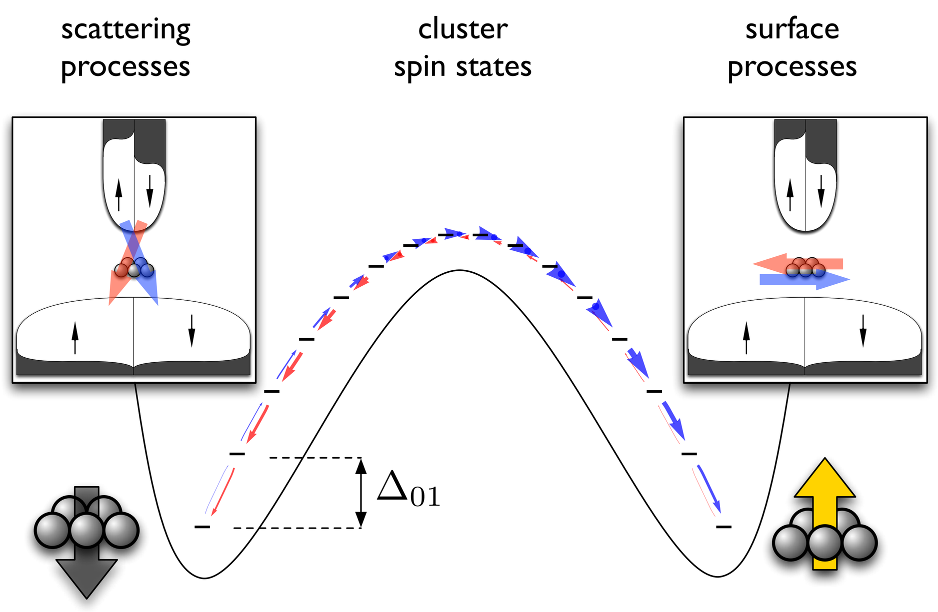
master equation

$$\frac{dP_\alpha}{dt} = \sum_\beta \left(W_{\alpha\beta}P_\beta - W_{\beta\alpha}P_\alpha\right)$$

Lifetime of current driven spin



Determination of anisotropy from spin dynamics



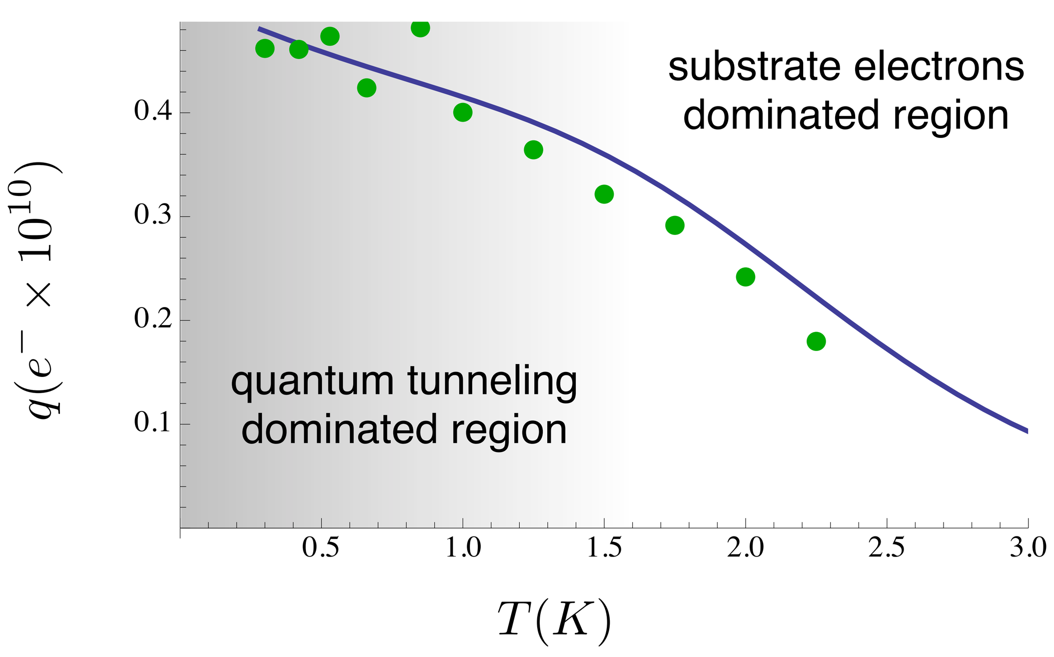
- cluster spin remains stable if the voltage drops below Δ_{01}
- onset of spin noise mainly depends on D
- slope of $\tau^*(V)$ depends on E and D

transition rates

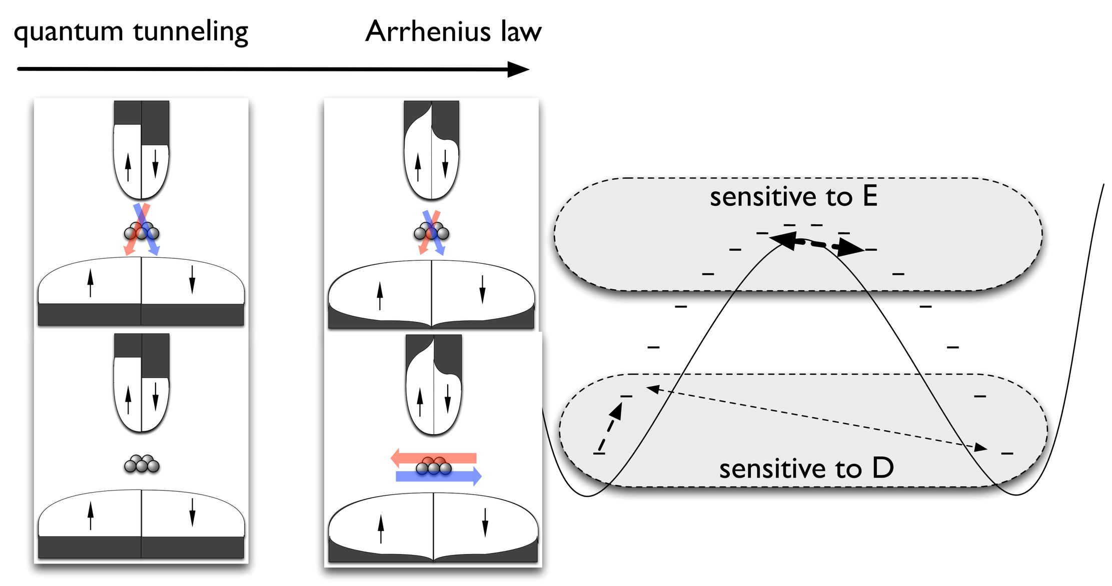
$$W_{\alpha\beta} = \pi \sum_{rr'\in\{\text{tip,surface}\}} |v_r v_{r'}|^2 \Sigma^{rr'}_{\alpha\beta}\zeta(\mu_r - \mu_{r'} - \Delta_{\alpha\beta})$$

$$\Sigma^{rr'}_{\alpha\beta} = |\langle\alpha|J_+|\beta\rangle|^2\rho_{r\downarrow}\rho_{r'\uparrow} + |\langle\alpha|J_-|\beta\rangle|^2\rho_{r\uparrow}\rho_{r'\downarrow} + |\langle\alpha|J_z|\beta\rangle|^2\left(\rho_{r\uparrow}\rho_{r'\uparrow} + \rho_{r\downarrow}\rho_{r'\downarrow}\right)$$

Temperature dependence



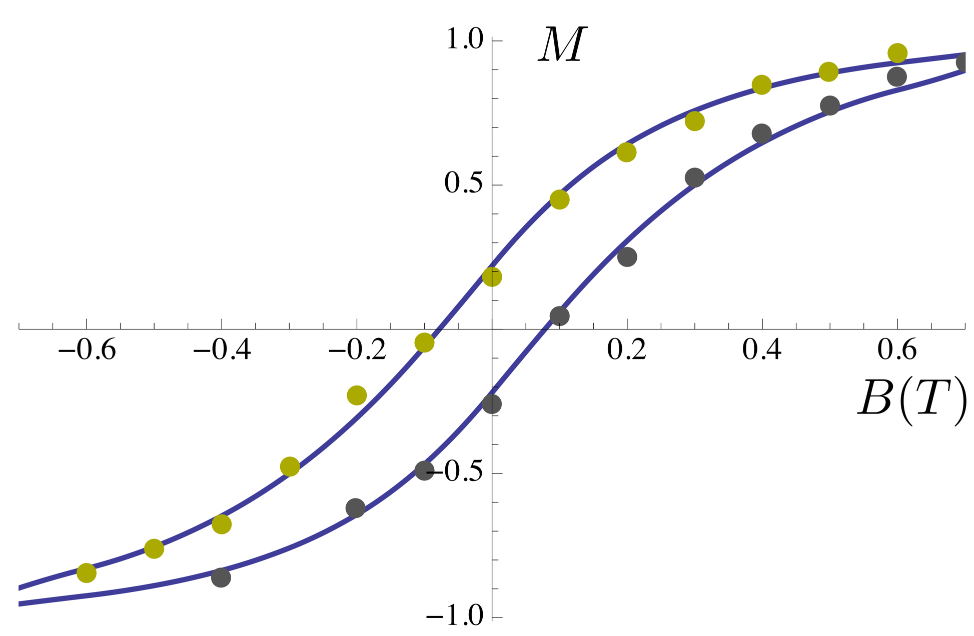
Influence of quantum tunneling and transverse anisotropy



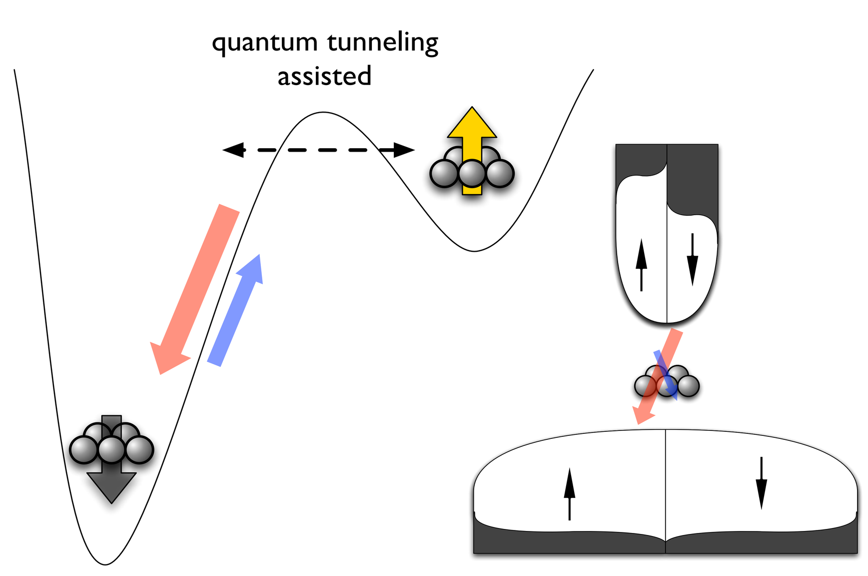
- $T \geq 2$K Arrhenius behavior is recovered by model
- no constant transition rate in low temperature regime, thus quantum tunneling alone is not the key mechanism
- fully magnetization reversal due to quantum tunneling requires additional spin-flip processes due to half integer spin of the iron cluster
- nonequilibrium-induced quantum tunneling prominent at low temperatures closer to the top of the barrier
- shape of the shoulder depends on the size of the transverse anisotropy E

$$\zeta(\mu_r - \mu_{r'} - \Delta_{\alpha\beta}) = \frac{\mu_r - \mu_{r'} - \Delta_{\alpha\beta}}{1 - \exp\left(-\frac{\mu_r - \mu_{r'} - \Delta_{\alpha\beta}}{kT}\right)}$$

Magnetization behavior



Field driven switching and comparison with dynamics



- Zeeman energy favours ground state pointing parallel to B
- E effectively lowers the barrier for transitions into ground state
- asymmetry at $B = 0$ results from the spin polarized tunneling current created by the magnetic tip
- stationary limit and nonequilibrium magnetization are related to life times $\tau^\pm$ via equation of motion for strong relaxation

equation of motion

$$p_{++}(t+dt) = p_{+-}(t)\frac{dt}{\tau^-} + p_{++}(t)'\left(1 - \frac{dt}{\tau^+}\right)$$

solution

$$p_{++}(t) = \frac{\tau^+}{\tau^+ + \tau^-} + \frac{\tau^-}{\tau^+ + \tau^-}\exp\left(-\left(\frac{1}{\tau^+} + \frac{1}{\tau^-}\right)t\right)$$

[1] Khajetoorians *et al.*, *Science* **339** (6115): 55 (2013)
[2] Loth *et al.*, *Nature* **6**: 340 (2010)
[3] Delgado *et al.*, *Phys. Rev. Lett.* **104**, 026601 (2010)
[4] Krause *et al.*, *Science* **317** (5844): 1537 (2007)

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