Interactions between a pinned ferromagnetic vortex and individual nitrogen-vacancy spins

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Introduction
Ferromagnetic vortex domains produce strong, localized, rapidly-tunable magnetic fields which may be useful for nanoscale spintronic or quantum information processing devices. Here, we map out how pinning affects the motion of a vortex, and subsequently the interaction of the vortex with individual nitrogen-vacancy spins.

Ferromagnetic vortex domains

Ground state magnetization of a soft ferromagnetic disk:
- in-plane magnetization: circulating about core
- out-of-plane magnetization at vortex core (~10 nm diam.)

Vortex core position controllable via in-plane magnetic field:

Rigid vortex model — vortex core moves in effective potential:

\[ U \approx \frac{1}{2} k r^2 - k \chi_0 (H_{xy} + H_y y) \]

Increasing \( H_y \)

No pinning:

With pinning:

Pinning results in:
- Jumps in vortex position vs. \( H_y \)
- Hysteresis/bistability

Mapping the vortex pinning potential

Combined MOKE/NV spin microscopy:

- Differential MOKE microscopy measures difference in \( \mathbf{M} \) between two values of \( H_{cold} \) [1]
- \( \Delta M \), centered at the vortex core provides a measure of vortex core displacement \( \Delta y \).

1. Sweeping \( H_{cold} \) reveals vortex displacement \( \Delta y \):

\[ \Delta y (\text{arb.}) \]

\[ H_{cold} (\text{A/m}) \]

2. Sweeping \( H_{cold} \) reveals vortex displacement \( \Delta y \):

\[ \Delta y (\text{arb.}) \]

\[ H_{cold} (\text{A/m}) \]

3. Positions of jumps yield effective pinning potential:

\[ V_{\text{eff}} (y) \text{ (eV)} \]

\[ y (\text{nm}) \]

4. Verify pinning potential by simulating \( \Delta y \) vs. \( H_{cold} \):

\[ \Delta y (\text{arb.}) \]

\[ H_{cold} (\text{A/m}) \]

5. Map pinning potential by rastering vortex core with a static field:

\[ \Delta y (\text{arb.}) \]

\[ H_{cold} (\text{A/m}) \]

Coupling the pinned vortex to NV spins

- Sweep vortex position using magnetic field.
- Measure spin splitting of NV ground states with optically-detected magnetic resonance (ODMR).

Jumps in NV spin splitting identified with transitions between pinning sites found from MOKE measurements:

Conclusions
- Differential MOKE microscopy yields vortex displacement vs. applied field, from which an effective pinning potential can be extracted.
- NV spins in a nanoparticle are split by several 100 MHz as the vortex approaches.
- The NV spin splitting changes mainly by discrete jumps associated with transitions of the vortex from one pinning site to another.