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Characterization of Spin Ice Physics Using Capacitive Torque Magnetometry

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Introduction

The quest for novel quantum phases that show collective degrees of freedom and topological excitations is one of the central themes in condensed matter physics. In recent years research on geometrically frustrated systems has intensified as the macroscopically degenerate ground state manifolds host a large density of states that can be manipulated, and emergence of unusual low temperature properties when perturbations are applied is expected. The spin ice, analogue to water ice, forms the foundation of many exotic noncollinear spin textures, and it hosts a highly dynamic magnetic Coulomb phase with quasiparticle excitations equivalent to magnetic monopoles [1]. Investigations of thin films of spin ice systems such as $Ho_2Ti_2O_7$ (HTO) are beginning to emerge [2,3], yet the traditional tools for characterization of spin ice physics, such as neutron scattering and specific heat measurements, are not well suited for thin film (i.e., very small sample) investigations. The PI has developed torque magnetometry for characterization of spin ice physics in pyrochlore titanates, showing that specific spin textures of the spin ice state can be distinguished using this technique.

Experimental

Capacitive torque magnetometry measurements using a home-built device, consisting of a sample affixed onto a flexible Cu-Be cantilever that forms the top plate of a parallel plate capacitor, were performed on single crystals and thin films at the SCM1 and SCM2 facility, and in Cell 7 at the NHMFL.

Results and Discussion

Capacitive torque magnetometry measurements as a function of applied field direction and strength for a single crystal of HTO are presented in Fig. 1a). The response shows a clear angular dependence with zero-crossings indicating alignment of the field with the crystallographic directions of the crystal. The exact angular dependence can be modeled by simply calculating the torque response for one unit cell of HTO for the various possible phases in the system (in the [100]-[110]-[010] plane: $Q = 0$ with $B \parallel \langle 100\rangle$, $Q = X$ with $B \parallel \langle 110\rangle$ [4,5]) and the transitions between them, which require multiple spin flips. Fig, 1 b) shows the 11 T data from Fig. 1a) and calculated torque curves for the $Q = 0$ and $Q = X$ phases (solid lines). It is clear that the system resides mostly in the $Q = 0$ phase, as expected, and that a transition from $Q = 0$ to $Q = X$ to $Q = 0$ occurs when the field is applied along the <110> family of directions. This transition involves a sequence of spin flips each leading to a measurable change in the torque, the dashed lines correspond to calculated torque curves after each consecutive spin flip.

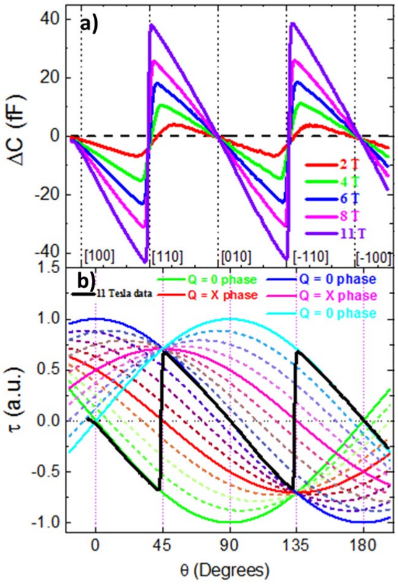

Figure 1: Capacitive torque as a function of angle for a single crystal measured at T = 0.5 K, i.e., below the spin freezing temperature. a) angular sweeps where B rotates from [100] → [110] → [010], for applied fields ranging from 2 → 11 T. b) Calculated normalized torque curves compared with sample-volume-scaled normalized torque data from panel a. The solid lines are calculated torque curves for the stable phases of the spin ice state [4,5], while the dashed curves represent calculated torque curves for transient states, i.e., states following from a sequence of spin flips.

Conclusions

These results demonstrate the ability to use torque magnetometry to construct field dependent phase diagrams of the spin ice state detailing transitions between specific spin textures. The torque technique is sensitive enough to characterize spin ice physics in thin film samples, providing opportunities to investigate if spin ice physics and associated monopole excitations are preserved and/or altered when pyrochlore titanates are grown in thin film geometries, exposing the material to strain and reduced dimensionality.

Acknowledgements

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References

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