PhD project: Developing a quantum thermodynamic theory for driven and heated spin systems.

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This is a theoretical physics PhD project at the University of Exeter to start in autumn 2020.

Summary: Quantum thermodynamics is a new research field, where thermodynamics is studied in the small-system size limit where fluctuations become non-negligible, weak coupling between system and environment cannot be assumed, and a fully quantum mechanical description may be needed [1]. This project is concerned with the application of theoretical tools from the fields of quantum thermodynamics and open quantum systems to the problem of modelling the dynamics, the equilibrium state, and the timescale of equilibration, of a collection of interacting spins that are strongly coupled to their environment. The aim of this project is to find analytical equations that describe the spin dynamics when they are driven by a changing magnetic field and exposed to a heated environment (with potentially multiple temperatures). These will then be used to quantify the importance of quantum mechanical and strong coupling effects in the magnetization dynamics and in the long-time steady state of the spins.

Practical motivation: The critical components of magnetic hard drives have been continually scaled down in size. Magnetic grains, which store information, are pushing below 8nm and further miniaturization faces new challenges. Magnetically hard materials are required to ensure thermal stability of the information encoded in these small bits. But the magnetic write-fields in recording heads are no longer strong enough to switch them. Heat-assisted magnetic recording (HAMR) has been proposed as a candidate technology that would enable the switching of grains by providing additional energy in form of *heat* delivered by a laser diode in the recording head. The effective inclusion of such laser diodes in the recording head is actively developed by industry and first prototypes are now available [2].

It is anticipated that this new technology will soon reach the regime where the standard theoretical tools used to model the spin dynamics are insufficient and require a rethink of the theory used. The commonly used phenomenological Langevin equation, the Landau-Lifschitz-Gilbert (LLG) equation, valid for large spin-grains will not describe the dynamics accurately at small sizes [3]. Alternative quantum Langevin equations describing the spin dynamics when undriven and in contact with a heat bath at a fixed temperature T are currently being set up by Prof Anders' and her team.

Outline of PhD project: You will begin your study with rederiving the standard LLG equation from a microscopic quantum Hamiltonian with the help of your supervisors, and assessing natural modifications of the LLG that include coloured noise rather than the standard flat Gaussian noise commonly assumed in the LLG equation. In addition to quantum effects that arise because of the quantisation of the environmental modes, you will identify quantum effects that arise because of the quantisation of the spins themselves, including any dynamic features caused by quantum coherences and quantum correlations/entanglement. Beyond environments that have a fixed temperature T, you will explore how varying the temperature of the environmental modes, i.e. “heating”, as well as changing the magnetic field affects the spin dynamics. Taking the long-time or steady state limit of the dynamics, you will aim to establish how the spin dynamics becomes equilibrated, on what timescales and assess if the steady state may include strong coupling terms described by a Hamiltonian of mean force [4]. You will identify parameter ranges where any deviations from the standard LLG model could be evident and interact with a modelling group (York) who solve the dynamics numerically, and experimental groups (Exeter) who may be able to test the new predictions.

The derived theory will help clarify how to optimally heat and drive the spin dynamics, and assess when quantum effects become important for the optimisation of the HAMR technology. The research outcomes are potentially world leading, for the first time applying fundamental physics from the emerging theory of quantum thermodynamics to solve a practical problem in magnetic materials research.

References:

[1] S. Vinjanampathy, J. Anders, *Contemporary Physics* **57**, 545 (2016).
[2] Seagate blog https://blog.seagate.com/craftsman-ship/hamr-next-leap-forward-now/ (2018)
[3] R. F. L. Evans, W. J. Fan, O. Chureemart, T. A. Ostler, M. O. A. Ellis and R. W. Chantrell, *J. Phys. Cond. Mat.* **26** 103202 (2013).
[4] H. Miller, J. Anders, *Nat. Comm.* **9**, 2203 (2018).