Magnetization Relaxation and Geometric Forces in a Bose Ferromagnet (arXiv:1303.6791)

Jogundas Armaitis, Rembert Duine, and Henk Stoof
Institute for Theoretical Physics, Utrecht University, The Netherlands
E-mail: j.armaitis@uu.nl

Abstract

We construct the hydrodynamic theory for pseudospin-1/2 Bose gases at arbitrary temperatures. This theory describes the coupling between the magnetization, and the normal and superfluid components of the gas. In particular, our theory contains the geometric forces on the particles that arise from their spin's adiabatic following of the magnetization texture. The phenomenological parameters of the hydrodynamic theory are calculated in the Bogoliubov approximation and using the Boltzmann equation in the relaxation-time approximation. We consider the topological Hall effect due to the presence of a skyrmion, and show that this effect manifests itself in the collective modes of the system. The dissipative coupling between the magnetization and the normal component is shown to give rise to magnetization relaxation that is fourth order in spatial gradients of the magnetization direction.

Introduction and Motivation

In metallic ferromagnets, magnetization dynamics leads to forces on quasiparticles of geometric origin called **spin motive forces**. Furthermore, spin textures with nonzero chirality, such as the skyrmion lattice, induce the so-called **topological Hall effect**. In addition, the coupling between magnetization and quasiparticles has also been shown to give rise to novel forms of **magnetization relaxation** in this case. A prominent example is inhomogeneous Gilbert damping. This effect is important in clean solid-state systems. We therefore expect these effects to be particularly important for gases of ultracold atoms, that, in contrast to conventional condensed-matter systems, are free of impurities. Finally, even though there has been a lot of research activity concerning spinor Bose gases, a theory that describes simultaneously **all phases** of ferromagnetic spinor Bose gases and includes both geometric and dissipative coupling between superfluid, ferromagnetic order parameter and quasiparticles is lacking. We have put forward such a theory.

Hydrodynamic Theory

We choose to work in the hydrodynamic regime, where the coupling between the magnetization, and the normal and superfluid components of the gas is controlled by a gradient expansion. This approach is valid in the regime where local equilibrium is enforced by frequent collisions. Describing a ferromagnetic Bose gas requires considering **three phases: unpolarized normal fluid, normal ferromagnet and superfluid ferromagnet**. These three phases have different sets of relevant hydrodynamic variables, that have to be taken into account in order to fully describe the behavior of the system. The conserved quantities are the total particle density n, the total particle current j, the magnetization density $M^\alpha = Pn\Omega^\alpha$ and the energy. In the hydrodynamic approach we write for each conserved quantity a continuity equation (except for the energy, which we ignore for simplicity):

$$\partial_t n + \boldsymbol{\nabla} \cdot \boldsymbol{j} = 0$$

$$\partial_t \left(Pn\Omega^\alpha\right) + \boldsymbol{\nabla} \cdot \left((\boldsymbol{j}^{\perp}_{\text{spin}})^\alpha + (\boldsymbol{j}^{\parallel}_{\text{spin}})^\alpha \right) = 0$$

$$m\partial_t \boldsymbol{j} + m\boldsymbol{\nabla} \cdot \boldsymbol{\Pi} + n\boldsymbol{\nabla} V - Pn\boldsymbol{E} - P\boldsymbol{j} \times \boldsymbol{B} = 0$$

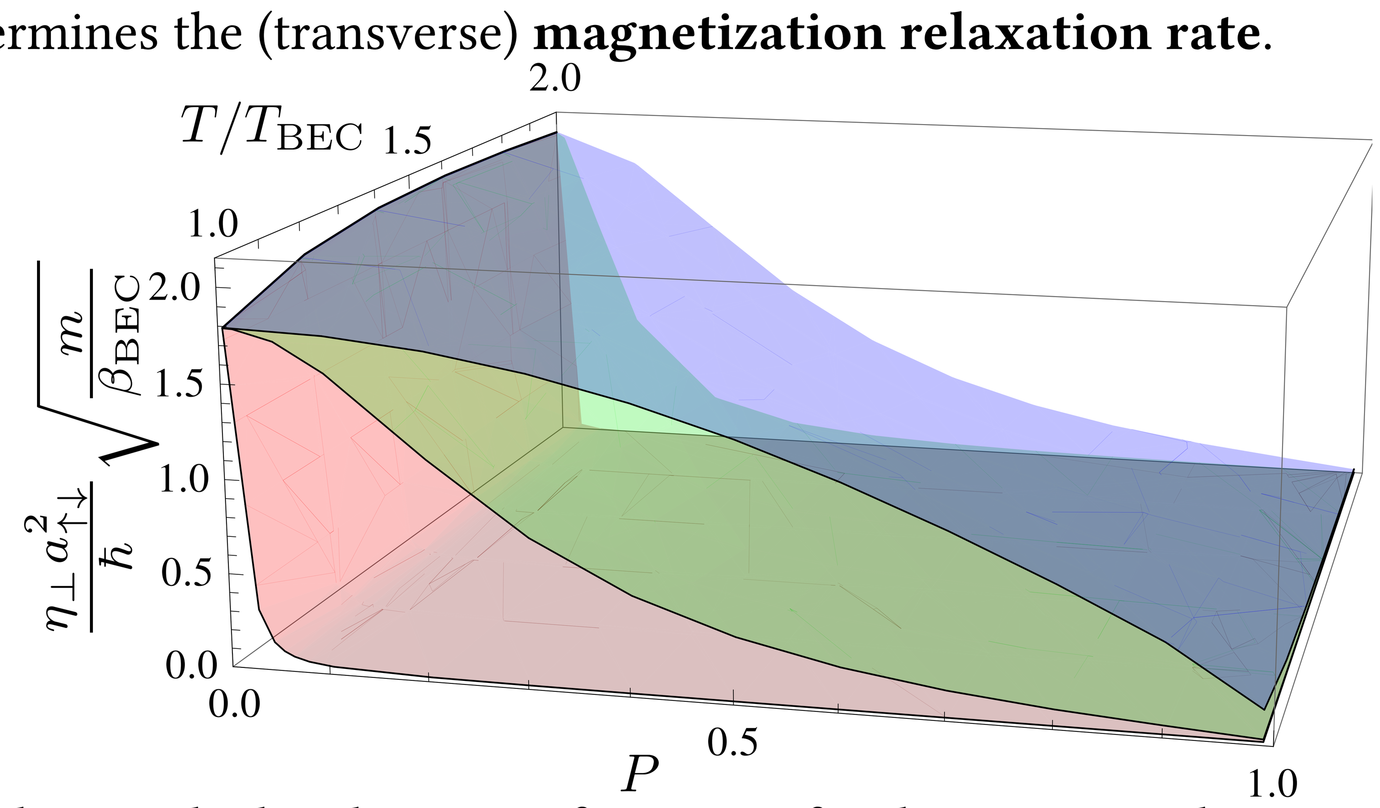
where m is the particle mass, Π is the energy-momentum tensor, V is the trapping potential, and P is polarization. We have also introduced the spin currents as well as artificial electric and magnetic fields due to the **Berry curvature**. All the input parameters for the theory have been determined microscopically from the relaxation-time approximation (magnetization relaxation) and Bogoliubov theory (the other parameters).

Spin Currents and Relaxation

In the ferromagnetic phase, one can define longitudinal (parallel to the magnetization direction) $(\boldsymbol{j}^{\parallel}_{\text{spin}})^\alpha = P\boldsymbol{j}\Omega^\alpha$ and transverse

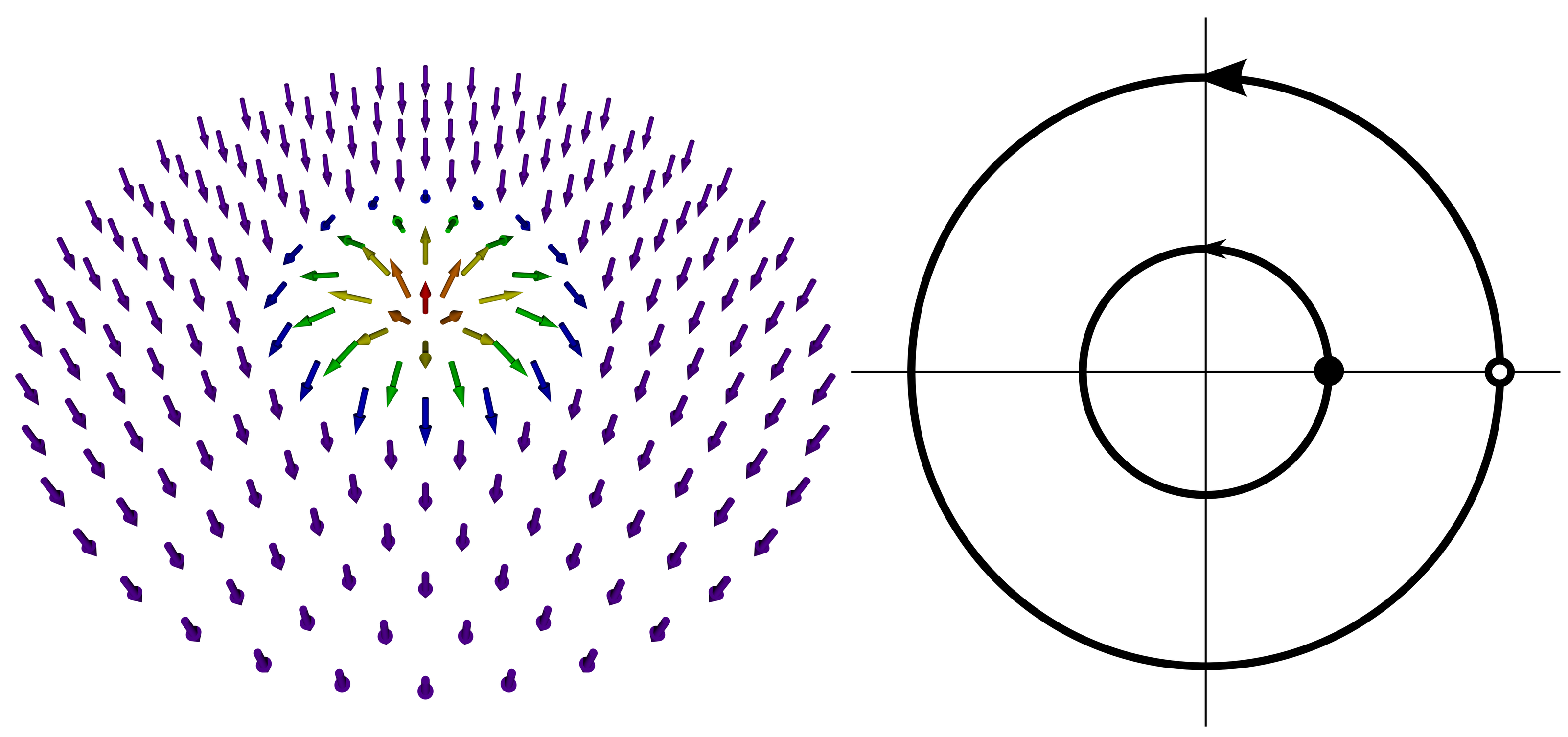
$$(\boldsymbol{j}^{\perp}_{\text{spin}})^\alpha = -\varepsilon^{\alpha\beta\gamma}\frac{1}{n}\eta_\perp \Omega^\beta (n\partial_t + \boldsymbol{j}\cdot\boldsymbol{\nabla})\boldsymbol{\nabla}\Omega^\gamma - A_s \varepsilon^{\alpha\beta\gamma}\Omega^\beta \boldsymbol{\nabla}\Omega^\gamma$$

spin currents, where A_s is the spin stiffness and $\eta_\perp$ is a parameter which determines the (transverse) **magnetization relaxation rate**.



We have calculated $\eta_\perp$ as a function of polarization and temperature (above) in the relaxation-time approximation using the fact that it is equal to the transverse spin conductivity. The three surfaces correspond to $ng_{\uparrow\downarrow}\beta_{\text{BEC}}$= 1, 0.5 and 0.1 from top to bottom. Here $a_{\uparrow\downarrow}$ is the inter-species scattering length, $g_{\uparrow\downarrow}$ is the inter-species T matrix and β_{BEC} is the inverse condensation temperature.

Baby Skyrmion



A baby skyrmion in a two-dimensional ferromagnetic cloud (left). In an isotropic trap, which has its center in the middle of the picture (right), the skyrmion (empty circle) precesses around the center of the trap. The center of the cloud (filled circle) also moves around the center of the trap. Physically, this effect is a Hall effect as it corresponds to transverse motion in response to a longitudinal force — in this case the restoring force of the trapping potential. Due to the nature of this particular spin texture, this effect is known as the **topological Hall effect**. The amplitude of the motion of the center of the cloud has been enhanced for clarity.

Discussion

To determine if the topological Hall effect can be observed experimentally, we consider a condensate of 10^4 ^{23}Na atoms in a pancake-like geometry with radial confinement of 1 Hz and perpendicular confinement of 10 Hz. The skyrmion precession frequency is then 10 Hz, and the Hall amplitude is 5 μm, which should be **observable with current experimental techniques**.

When it comes to the damping of spin waves, we consider a homogeneous ^{87}Rb gas with the density of 10^{16} cm^{-3}. At the Bose-Einstein condensation temperature and 50% polarization a spin wave with a momentum of 1 μm^{-1}, which is within the reach of current experiments, has a damping time of 0.7 s.