MACROSCOPIC DYNAMICS OF FERRONEMATICS AND FERROGELS

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Introduction

A ferrofluid is a colloidal suspension of ferromagnetic mono-domain, nano-sized particles in a liquid carrier. It is "superparamagnetic", that means it shows a strong paramagnetic response in an external magnetic field and a high saturation magnetization at rather low field strength. If the carrier fluid is a mesogenic liquid, magnetic liquid crystals like ferronematics [1,2], ferrosmectics etc. can be produced. Such materials combine the electro- and elasto-optical properties of the mesophases with the magnetic-field controllability of ferrofluids. Ferrogels have been obtained by dissolving the magnetic particles in polymer solutions with subsequent crosslinking. They can be superparamagnetic and isotropic [3] as well as ferromagnetic and anisotropic [4,5]. Here, shape and volume changes induced by magnetic fields are of major interest for applications (artificial muscles).

Ferronematics I

We derive hydrodynamic-like equations to describe the static and dynamic macroscopic behavior of these materials. The macroscopic description of ferronematics differs from that of ordinary nematics in several ways. First, the magnetic susceptibility anisotropy is dramatically enhanced, thus allowing for a convenient orientation of ferronematics in external magnetic fields [6]. In addition there are several dynamic crosscouplings, which are linear in the field. These effects are present in principle already in ordinary nematics, but generally neglected there, since they are assumed to be very small. In ferronematics, however, the response to external fields is very much enhanced and there is a good chance that they are observable. Examples are [7] reversible (Hall-like) heat, concentration and electric currents, reversible contributions to flow diffusion and director relaxation, as well as a dissipative analog of the flow alignment effect. We discuss, how these dynamic linear field effects can be measured directly. Since these measurements may be difficult to perform, we propose to measure the influence of the new effects on some standard instabilities, like Rayleigh-Bénard and Saffmann-Taylor, where they lead to qualitatively new behavior [8]. For the former, with an external magnetic field parallel to the temperature gradient, we find above threshold a flow of vorticity along the field direction – besides the usual convection rolls perpendicular to the field. This leads to an effective flow oblique to the rolls (in the homeotropic director orientation) and to oblique rolls (the roll axis is oblique to the director) for the planar case (the director fixed by an additional electric field). For the Saffmann-Taylor instability of a circular interface between air and the ferronematic liquid in a Hele-Shaw cell the evolving fingers rotate if a magnetic field perpendicular to the interface is applied. Since these effects are linear in the field, they will act in opposite direction when the field is reversed. This allows to discriminate them from those field effects due to the intrinsic field dependence of material parameters, since the latter is quadratic in the field and invariant under field reversal.

Ferronematics II

On a third level of describing ferronematics suitable also for high frequencies the magnetization is taken into account as an independent degree of freedom. It is non-hydrodynamic in the superparamagnetic case (the truly ferromagnetic case has not been observed yet, although it is possible in principle [9]). Although magnetization and director are rigidly related to each other in equilibrium, this is not necessarily true in non-equilibrium situations. The standard hydrodynamic procedure reveals [10] that there is not only a static coupling between magnetization and director orientation, but also a dynamic one. In addition, there are reversible and irreversible couplings between flow and magnetization (and director rotations). Some of these couplings only exist, if an external field is applied (or if a spontaneous magnetization is present). They lead to qualitative changes in the sound spectrum and the rheological response to shear, in particular to a magnetic field dependence of sound damping and a coupling between sound and shear flow for almost all wave vector directions. We also investigate the response to an applied oscillating shear flow below the magnetic relaxation frequency. This allows to study the influence of the magnetic degree of freedom on the director dynamics. In an external field the absorption peak due to the director dynamics is shifted to a finite frequency that scales roughly with the third power of the field strength.

Ferrogels

We deal here with the isotropic and paramagnetic ferrogels only. In ferrogels the elastic degree of freedom takes over a role similar to the nematic one in ferronematics [11]. The magnetoelasticity comes in the form of magnetostriction and through the magnetic part of the Maxwell stress and makes the system anisotropic in an external magnetic field. This gives rise to a field contribution of the sound spectrum at low frequencies that depends on the angle between field and wave vector. Various dynamic couplings of the elastic degree of freedom with the magnetization and flow are found. In the high frequency limit (above the magnetic relaxation frequency) the sound velocities are shifted due to those couplings. In addition we propose an experiment, where in a field gradient an oscillating temperature gradient produces a shear deformation perpendicular to both, the field and the temperature gradient.

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