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**INTERPARTICLE INTERACTIONS AND
POLARIZATION EFFECTS IN COLLOIDS**

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Abstract

The physics of simple colloidal systems is usually dominated by three independent length scales: the particle size, the average interparticle distance, and the range of the interparticle potential. The dispersed particles typically have characteristic dimensions in the range 5 - 100 nm, often with spherical or cylindrical symmetry. Dispersion densities vary over volume fractions ranging from 0.5 to 10^{-4} , with the corresponding mean interparticle distances ranging from about 1 to 10 diameters (in spherical systems). The interaction potential may be very short ranged (hard sphere), very long ranged (Coulomb or dipolar), or anywhere in between (screened Coulomb), and the correlations exhibited in the dispersion may be gas-like, liquid-like or crystalline, depending on the range of the potential relative to the interparticle distance. This rich phase behaviour is responsible for the remarkable importance of colloidal studies in many areas of condensed matter physics and biophysics, but it poses often intractable problems in

developing the statistical mechanical descriptions necessary for an understanding of scattering data from colloids. This paper will review the considerable recent progress in this field, in the context of SANS experiments on colloids in which the potentials are dominated by either screened Coulomb or magnetic dipolar interactions; in the case of magnetic colloids (ferrofluids), the use of polarization analysis will also be discussed.

1. Introduction

Colloidal dispersions (such as polymer latices, ceramic oxide sols, microemulsions, surfactant solutions or ferrofluids) exhibit a remarkably rich variety of complicated phase behavior. To understand the fundamental reasons for the interesting macroscopic properties of these systems, we need to know how the particles are ordered at the microscopic level, and how this order is influenced by such parameters as the size and volume fraction of particles, and, in the case of electrostatically stabilized dispersions, the surface charge, the electrolyte concentration, and the relative permittivity of the dispersion medium at the temperature of interest. However, most of the fundamental studies of the properties of colloids, and in particular their stability, have been undertaken using dilute dispersions, which often exhibit bulk phenomenology totally different from that of concentrated suspensions. In the case of non-Newtonian rheological behaviour, for example, the particle density in a dilute suspension may be too low to make a significant contribution, compared with the solvent viscosity, whereas in a concentrated suspension shear-thinning and shear-thickening regimes are related to shear-induced changes in the microscopic structural correlations between particles. In the past decade, new theoretical and experimental

techniques have been developed which allow detailed microscopic analysis of the structures present in dispersions at concentrations of practical interest. One of the most powerful techniques which has evolved is small-angle neutron scattering (SANS), which is able to study bulk materials in which multiple scattering renders the routine use of x-ray scattering methods intractable, or which may be opaque to light (so that only surface structures are visible). The technique permits *in situ* determination of colloidal dispersion structure under a wide variety of experimental conditions, and it is particularly well-suited to the study of magnetic colloids, because of specific features of the neutron-magnetic interaction.

2. Concentration Regimes

Colloidal dispersions are generally concentrated, in the sense that the solution properties are strongly influenced by interactions between particles. To quantify this notion of "concentrated," consider a suspension in which the average volume per particle is $1/n$, where n is the number density of particles in the suspension. Let this volume be represented by a cube of side d , so that d would be the average separation between particles if they were equally spaced. In a hard-sphere system, the range of the interaction is the diameter, σ , of the spheres. We expect this system to exhibit features associated with concentrated behaviour once d becomes comparable with the range of the potential, or when $\sigma/d \approx 1$. Now let the spheres develop a charge, for example by ionization, with the resulting total ionic strength of the suspension corresponding to a Debye screening length, λ_D . In this case, the onset of concentrated behaviour will occur when

$$(2\lambda_D + \sigma) \approx 1$$

(1)

Eq. (1) shows that in a colloidal dispersion there may, in fact, be three regimes of concentration, in each of which we may expect different behaviour: $\lambda_0 \gg \sigma$, $\lambda_0 \approx \sigma$ and $\lambda_0 \ll \sigma$. The presence of several length scales, each of which may be independently varied, will be of fundamental importance in the discussion throughout this paper. A case of particular importance is when one of the length scales dominates all the others. This length may be thought of as the ruler with which we measure distances in the dispersion, and apparently different dispersions may often have identical structures when each is measured with its own particular ruler; this leads to scaling relations which offer powerful means of computing certain classes of colloidal dispersion structure. The central task in analyzing scattering from colloidal dispersions is to relate the structure on the length scale of interest to the interparticle potential of corresponding range. In this paper we shall concentrate on two cases of great practical importance for which this theoretical problem may be solved analytically to a good approximation, namely dispersions of spherical particles interacting via either electrostatic or magnetic interparticle potentials. For completeness, we mention another case of interest for which some progress has been reported, namely dispersions in which there are short-ranged attractive interactions (Hayter & Zulauf, 1982; Fisher, 1986).

3. Charge Stabilized Dispersions

Thermal interparticle collisions in a dispersion would lead to coagulation if the dispersion were not suitably stabilized in some way. One of the most common methods is to use ionizable particles, which all develop a like charge, so that collisions are prevented by electrostatic repulsion;

such dispersions are called *charge stabilized*. The particles may also be protected from coagulation by *steric stabilization*, in which a mechanical barrier is placed around the particle, often in the form of a polymer coating. From the theoretical viewpoint, such neutral particle dispersions may be treated as a limiting case of charge stabilized dispersions, and we therefore only need a description of the latter.

Under a wide variety of conditions, the pair interaction potential, $U(r)$, between monodisperse, spherical colloidal particles separated by a distance r in a charge-stabilized suspension may be taken as the electrostatic part of the DLVO potential (Verwey & Overbeek, 1949; Medina-Noyola & McQuarrie, 1980; Beresford-Smith et al. 1985):

$$U(r) = z^2 \exp[-(r-\sigma)/\lambda_D] / [4\pi\epsilon_0\epsilon r(1+\sigma/2\lambda_D)^2] \quad (2)$$

Here, σ is the particle diameter, z the net charge on the particle, and λ_D the Debye length in the dispersion medium of dielectric constant ϵ . The Debye length, which determines the range of the interaction, depends on the counterions present (due to ionization of the colloidal particles) as well as on any added salt.

Dispersion structures are constantly fluctuating under the influence of thermal (Brownian) motion, and particles which form a strongly ordered neighbour shell about a given particle at one instant may be totally unrelated to one another at a later time. The description of such fluid structures is therefore probabilistic in nature, and is generally given in terms of the pair distribution function, $g(r)$, which is a measure of the likelihood of finding two particles separated by a distance r ; $n g(r)$ is the local density of particles at a distance r from a given particle.

If two particles cannot interpenetrate, no neighbour can be found

closer than the distance of closest approach, σ , so $g(r < \sigma) = 0$. At the other extreme, the density of particles at a great distance from a given particle will be indistinguishable from the bulk density, and $g(r \rightarrow \infty) = 1$. The general problem of calculating charge-stabilized dispersion structure for particles of diameter σ at density n lies in finding $g(r)$ (or its Fourier transform, $S(Q)$ - see below) for $r > \sigma$, given the potential (2). This formal problem was first treated in the mean spherical approximation of Lebowitz and Percus (1966) by Waisman (1973) for the case of a Yukawa potential. A fully analytic solution was given by Hayter & Penfold (1981a,b), using an approximation whose validity was later extended by Hansen & Hayter (1982). The approximation proposed by the latter authors, known as the rescaled mean spherical approximation (RMSA), takes advantage of the length scaling discussed in §2, while retaining the fully analytic nature of the original solution; in the limit of neutral particles it reduces to the hard sphere result (Ashcroft & Lekner, 1966). All of these methods use a one-component model basis (see e.g. Hayter, 1983), in which the colloidal particles are considered to be the only finite-sized objects present. They also treat the dispersion medium (including any small ions present) as a *uniform background*, which is equivalent to allowing the counterions to penetrate the dispersed particles; at high concentration, this is equivalent to a reduction in the effective charge on the particle. It turns out to be straightforward to correct the RMSA for this effect, by using z^* and λ^* in eq. (2), in place of the actual values z and λ_D where, at a volume fraction $\eta = \pi n \sigma^3 / 6$,

$$z^* = z / (1 - \eta)$$

and

$$k^* = k - 2\eta^{1/3} \ln(1 - \eta)$$

(3)

with $k^* = \lambda^* \sigma$ and $k_f = \lambda_0 \sigma$. The resulting analytic approximation has been tested extensively against computer simulation data, and proves to be extremely accurate. Figure 1 shows the typical features of $g(r)$ for a dilute, deionized, charge-stabilized dispersion of a polystyrene sulfonate latex. The strongly repulsive potential prevents particles from coming into contact (the interaction potential at contact for this system would be $>40 k_B T$), and this is reflected in the fact that $g(r)$ is zero unless particles are further apart than about 13 diameters. At about 18 diameters, $g(r)$ is strongly peaked, indicating the presence of an ordered first neighbour shell, and peaks corresponding to the presence of correlated higher order neighbours remain beyond 35 diameters' interparticle separation. This dramatic degree of order in a suspension at $<10^{-4}$ volume fraction results from the very long ranged nature of the interaction under conditions of very weak screening; at only a slightly higher volume fraction, the structure will in fact crystallize.

4. SANS Applied to Non-magnetic Dispersions

The formalism for neutron scattering is similar to that for light or x-ray scattering; a detailed account may be found in, e.g. Lovesey (1984). We shall first consider non-magnetic structures, for which the probability of scattering from a given atom is simply described by an amplitude, b , which has the dimension of length; b may have either sign, negative values indicating a phase shift of π on scattering. In particular, the scattering amplitudes for hydrogen and deuterium are -0.3741 and $+0.6674 \times 10^{-14} \text{m}$, respectively, so that features may be emphasized or removed from the scattering by appropriate isotopic substitution. This is known as contrast variation, and is especially useful when the modifications can be made in the

dispersion medium alone, for example by mixtures of light and heavy water (see, e.g. Wignall, 1987).

The scattering from a colloidal particle is obtained by summing the scattering amplitudes of all atoms in the particle, weighted by the phase-shift at each atomic position in the particle. Elastic scattering of a neutron of wavelength λ through angle 2θ is accompanied by a momentum transfer of magnitude $Q = (4\pi/\lambda) \sin\theta$, which leads to a phase-shift of $\exp(iQ \cdot r)$ at position r . Restricting our attention to spherical particles for simplicity (for more detail, see e.g. Hayter & Penfold, 1983; Chen & Lin, 1987), the scattered intensity may be written as two terms, one depending only on the particle structure, and the other depending on the arrangement of particles relative to each other in the dispersion:

$$I(Q) = n \langle |F(Q)|^2 \rangle + \langle \sum_{m \neq n} \exp(iQ \cdot R_{mn}) \rangle \sum_{j(n)} \sum_{k(m)} b_j b_k \exp[iQ \cdot (r_k - r_j)] \quad (4)$$

where R_{mn} is the vector joining the centers of different particles labelled m and n , $r_{j(n)}$ is the position of atom j in particle n , and $\langle \rangle$ indicates an average over all possible configurations and sizes of the particles in the dispersion. $F(Q)$ is known as the form-factor of the particle, and depends only on the particle structure. We shall restrict discussion to monodisperse suspensions for clarity, so that

$$F(Q) = \sum_j b_j \exp(iQ \cdot r_j) \quad (5)$$

The weight factor in the average to be evaluated in eq. (4) is $g(R_{mn})^{-1}$ (since the term $m=n$ is excluded), so the term involving R_{mn} is just $n[S(Q)-1]$, where the liquid structure-factor for the dispersion is defined as

$$S(Q) = 1 + n^{-1} \langle \sum_{m \neq n} \exp(iQ \cdot R_{mn}) \rangle \quad (6)$$

For a monodisperse suspension of non-magnetic spherical particles, the

scattered intensity may thus be written

$$I(Q) = P(Q) S(Q) \quad (7)$$

where the (isotropic) single-particle scattering function is defined as $P(Q) = \langle F^2(Q) \rangle$ ($= F^2(Q)$ in this case). $S(Q) \rightarrow 1$ as $n \rightarrow 0$, so scattering from a dispersion at sufficiently low density will depend only on the particle geometry, which may therefore be measured by this type of experiment. Once $P(Q)$ has been measured, eq. (7) yields $S(Q)$ for structured dispersions, and hence provides a means of determining the interaction potential *in situ*, through our ability to compute $S(Q)$.

Fig. 2 shows some fairly typical SANS data for a dispersion of charged spherical micelles; the agreement between experiment and theory is excellent. Note that the particle scattering function $P(Q)$ determines the intensity at high Q , while the low- Q data are dominated by $S(Q \rightarrow 0)$, which is directly proportional to the osmotic compressibility of the dispersion (Egelstaff, 1969). An immediate qualitative indication of the sign of the interparticle interaction is thus given by whether $I(0)$ is depressed or augmented, relative to $P(0)$; in the present case, repulsive interactions reduce the compressibility, whereas an attractive interaction would cause $I(0)$ to increase.

These types of study have stimulated more extensive numerical treatments which include detailed finite counterion effects, but the analytical simplicity of the RMSA tends to make it the best initial choice for data analysis (see, e.g. Bratko *et al.*, 1986; Nägele *et al.*, 1985; Belloni, 1986). Recent reviews of some of the extensive literature which has developed in the past decade may be found in Chen & Lin (1987) and Hayter

(1987). The extension to dynamic studies, using neutron spin-echo, is discussed by Hayter (1981, 1985). For completeness, we also note that while some types of polydispersity may be handled (Blum & Høye, 1977; Vrij, 1979), there is so far no general theory for polydisperse systems, nor for the general case of anisotropic particles, although a special case of anisotropy will be discussed in the next section. Some experimental progress has been made in analyzing anisotropic dispersions, however, by using an applied hydrodynamic shear to align the particles, in which case eq. (7) again applies rigorously, provided Q is replaced by Q , where the vector axes are determined by the shear geometry (Hayter & Penfold, 1984).

5. Magnetic Dispersions: Polarization Analysis.

Colloidal dispersions of super-paramagnetic particles form magnetic liquids known as *ferrofluids*. Besides being technologically important, these materials are of intrinsic physical interest, because they provide model magnetic fluid systems in which the parameters of the potential may be controlled by the experimentalist. Commonly, ferrofluids consist of cobalt or magnetite particles of about 3-15 nm diameter, sterically stabilized by a non-magnetic (possibly mixed) surfactant coating, yielding composite spherical particles whose volume is about 10 times that of the magnetic core. The interaction between the particles consists of a hard-core repulsion, a van der Waals attraction and a long-range magnetic dipole-dipole interaction between permanent moments, μ , located at the center of each spherical particle. The strength of the magnetic interaction is measured by the dimensionless reduced moment, μ^* , defined by

$$(\mu^*)^2 = \mu^2 / (k_B T \sigma^3) \quad (8)$$

where σ is the total diameter of the composite particle; μ^* is the energy (in $k_B T$ units) of maximum repulsive interaction between two particles in contact.

Correlations between particles in a ferrofluid lead to the formation of chains of particles, with the dipole moment μ parallel to the local chain direction. In an applied magnetic field, H , these chains tend to align parallel to H , so that both $g(r)$ and $S(Q)$ are anisotropic. In order to interpret SANS results from a magnetized ferrofluid, a formalism which describes the structure factor $S(Q)$ of an aligned system is therefore required. One of the theoretical attractions of ferrofluids is that a multipolar expansion of the interparticle potential is naturally truncated at the dipole term, so that one may hope to treat such a system more easily than a fluid of sterically anisotropic particles, such as a liquid crystal, in which higher multipoles remain important.

Ferrofluids are an ideal subject for study by SANS, because of the selection rules which exist for magnetic neutron scattering, and because of the possibility of combining SANS with *polarization analysis*. (For a review of the production and handling of polarized neutron beams, see, e.g. Hayter, 1978). We first consider the case of SANS from a *dilute*, monodisperse suspension of spherical ferrofluid particles in an arbitrary magnetic field, H . The presence of a magnetic moment in the scattering particle leads to a second, magnetic scattering amplitude, p , entering the problem (see, e.g. Lovesey, 1984):

$$p = \gamma r_e |M| f(Q) \quad (9)$$

where r_e ($-2.818 \times 10^{-15} \text{m}$) is the classical electron radius, M is the total

resultant moment of the particle in Bohr magnetons, $f(Q)$ is a magnetic form factor, which will be effectively unity at small Q , and γ (-1.913042 nuclear magnetons) is the magnetic moment of the neutron. For a given (single-domain) ferrofluid particle, there will now be two concentric form-factors corresponding to eq. (5):

$$F_N(Q) = \sum_j b_j \exp(iQ \cdot r_j) \quad (10a)$$

and

$$F_M(Q) = \sum_j p_j \exp(iQ \cdot r_j) \quad (10b)$$

which are referred to as the *nuclear* and *magnetic* form factors, respectively.

In a dilute suspension, the scattered SANS intensity will be given by

$$I(Q) = \langle |F(Q)|^2 \rangle \quad (11)$$

where

$$\begin{aligned} F(Q) &= F_N(Q) + \phi F_M(Q) \\ &= \sum_j a_j \exp(iQ \cdot r_j) \end{aligned} \quad (12)$$

with $a_j = (b_j + \phi p_j)$. Our task is to evaluate the amplitude a_j (i.e. the phase, ϕ), in $F(Q)$, and then to compute the thermal average, eq. (11), which must include an average over spin states in the neutron beam, since we now have a preferred axis system. Taking axes with $\hat{z} \parallel H$ ($\hat{z}$ denotes a unit vector), and denoting by (+) and (-) the neutron polarization states anti-parallel or parallel to $\hat{z}$, there are now four types of scattering process, namely those in which the polarization is preserved [(+)→(+), (-)→(-)], and those in which the polarization is reversed [(+)→(-), (-)→(+)]. The former are referred to as non-spin-flip (nsf) scattering, and the latter as spin-flip (sf). The four possibilities may be succinctly denoted by ($\pm\pm$) and ($\pm\mp$),

and we must take specific account of their effect on the phase factor, ϕ .

Fortunately, this problem is simplified by an extremely important selection rule in magnetic neutron scattering: only the components of $\mathbf{M}$ perpendicular to the scattering vector $\mathbf{Q}$ are effective in scattering neutrons. Moon et al. (1969) showed that, for the coherent scattering in which we are interested, the amplitudes for the four cases are:

$$a^{++} = b - pM_{1z} \quad (13a)$$

$$a^{--} = b + pM_{1z} \quad (13b)$$

$$a^{+-} = -p(M_{1x} + iM_{1y}) \quad (13c)$$

$$a^{-+} = -p(M_{1x} - iM_{1y}) \quad (13d)$$

where $M_1 = \hat{\mathbf{M}} \cdot (\hat{\mathbf{M}} \cdot \hat{\mathbf{Q}}) \hat{\mathbf{Q}}$ is the projection of the unit vector in the direction of $\mathbf{M}$ onto the plane perpendicular to $\mathbf{Q}$. It is seen that scattering from components of $\mathbf{M}_1$ parallel to $\mathbf{H}$ is *nsf*, while scattering from the transverse components is *sf*. We first consider the (usual) case of a SANS experiment with no analysis of the polarization, so that no distinction is made between *sf* and *nsf* processes. In this case, only the initial polarization matters, and eqs. (13) reduce to

$$a^{\pm} = a^{\pm\pm} + a^{\pm\mp} \quad (14)$$

We must now evaluate eq. (11) using eqs. (12) and (14), taking into account the probability of a given orientation of μ relative to $\mathbf{H}$. In general, this will require a Langevin formalism, but two cases may be written down immediately, namely the zero-field and saturating field limits. The latter is of particular interest. In a saturating field, $\mathbf{M} \parallel \mathbf{H}$, so that if we arrange the geometry such that $\mathbf{Q} \parallel \mathbf{H}$, $M_1 = 0$, and inspection of eqs. (13) and (14) shows that $a^{\pm} = b$, whereas if $\mathbf{Q} \perp \mathbf{H}$, $a^{\pm} = b \pm p$. For these two geometries, eq. (11) reduces to

$$I(\mathbf{Q} \parallel \mathbf{H}) = F_N^2(Q) \quad (15a)$$

$$I(\mathbf{Q} \perp \mathbf{H}) = [F_N(Q) \pm F_N(Q)]^2 \quad (15b)$$

where the sign depends on the initial beam polarization; in the case of an unpolarized beam, eq. (15b) averages to

$$I(Q \perp H) = F_N^2(Q) + F_M^2(Q) \quad (16)$$

The selection rule which leads to eqs. (15) thus provides an extremely simple experimental method of separating the non-magnetic and magnetic structural features of the particles in a dilute ferrofluid dispersion, by performing the same experiment twice, with the field applied first parallel, then perpendicular to Q .

In the zero-field (paramagnetic) limit, any angle ψ between μ and H will be equally likely. In this limit (noting that $\langle \cos \psi \rangle = 0$ and $\langle \cos^2 \psi \rangle = 1/3$), the scattering will be isotropic and independent of beam polarization:

$$I(Q) = F_N^2(Q) + \frac{2}{3} F_M^2(Q) \quad (17)$$

We now return to the case of a concentrated ferrofluid, for which the scattering will be described by an equation analogous to eq. (4), but in which we can no longer take R_{mn} as uncorrelated with the particle orientation, unless all particles have the same orientation. The latter case corresponds to a saturating applied field, and we shall only consider that limit. (The approach to be taken in the general case, which is extremely complicated, has been discussed by Blum and Torruella, 1972). For the aligned case, as discussed in §4, eqs. (15) will take the form of eq. (7):

$$I(Q \parallel H) = F_N^2(Q) S_{\parallel}(Q) \quad (18a)$$

$$I(Q \perp H) = [F_N(Q) \pm F_M(Q)]^2 S_{\perp}(Q) \quad (18b)$$

where $S_{\parallel}(Q)$ and $S_{\perp}(Q)$ are the values of the structure factor, $S(Q)$, for Q parallel and perpendicular to H . The problem of calculating $S(Q)$ for an aligned ferrofluid was solved, in an approximation related to the mean spherical approximation, by Hayter and Pynn (1982), and tested by computer

simulation by Hess et al. (1984). Fig. 3 shows the pair correlation function, $g(r)$, corresponding to $S(Q)$ for a concentrated, aligned ferrofluid, computed at three volume fractions. At $\eta=0.3$, there is pronounced structure parallel to H , but little correlation in the orthogonal direction; this corresponds to the formation of chains of particles along the field direction. As the volume fraction increases, the chains become crowded together, and the anisotropy becomes dominated by excluded volume interactions ($\eta=0.5$).

So far, it has been assumed that the moments in the colloidal particles may be fully aligned by an applied field. In practice, this may not be the case at the microscopic level, thermal fluctuations giving rise to local disorder about the mean alignment direction. We may measure this effect, by adding polarization analysis to SANS. For this purpose, a polarized incident beam is used, and the polarization of the scattered beam is analyzed. It is evident from eqs. (13) that, for $Q \perp H$, *nsf* scattering only measures the component of the magnetization along the field ($\hat{z}$) direction, while for $Q \parallel H$, *sf* scattering only measures any x - y components due to fluctuations of the magnetization away from alignment with the field. Measurements of the *nsf* and *sf* scattering in the two field geometries thus provide complete information on the ferrofluid structure. An example is given in Fig. 4. The theoretical curves in the figure were obtained using form factors obtained by measurements on a dilute sample of the same material, so that the curves are *parameter free*, apart from a single normalization constant; agreement between theory and experiment is seen to be very good. It is evident that, even at the highest applied field (which is effectively at saturation), there are still thermal fluctuations of the moment direction about the field; the primary effect of reducing the field is to increase these fluctuations.

6. Conclusion

SANS is extremely well-suited to the study of colloidal dispersion structure, providing detailed information on the structure of the particles and on the interaction potential between them. In the case of magnetic dispersions, the addition of polarization analysis to the SANS technique leads to unique structural information, in which the non-magnetic and magnetic components are distinguishable model free.

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CAPTIONS FOR FIGURES:

Fig. 1. Pair correlation function $g(r)$ for a dilute ($\phi=8.4 \times 10^{-5}$), charge stabilized colloidal dispersion of polystyrene sulfonate latex particles, computed from the RMSA (—) and by Brownian dynamics simulation ($\square$).

Fig. 2. Observed ($\bullet$) and calculated (—) scattered intensity, $I(Q)$, as a function of momentum transfer, Q , for a charged micellar dispersion: 0.03 mol.dm⁻³ hexadecyltrimethylammonium chloride in D₂O at 313K. The functions $P(Q)$ and $S(Q)$ are discussed in the text.

Fig. 3. Pair correlation function $g(r)$ for a magnetized ferrofluid dispersed at three different volume fractions: $\eta=0.3, 0.4$ and 0.5 . (—) $r \parallel H$; (--) $r \perp H$.

Fig. 4. Observed ($\bullet$) and calculated (--) scattered nsf intensity, $I(Q)$, from a ferrofluid dispersion ($\phi=0.27$) for Q perpendicular and parallel to the applied magnetic field, H . (a) $H=0.5T$; (b) $H=0.25T$. Dashed lines correspond to including a slightly attractive component in the central part of the potential. Fluctuation scattering is discussed in the text.

FIG. 1

FIG. 2

FIG. 3

FIG. 4