ESF PESC Exploratory Workshop

Liquid Crystal Colloid Dispersions

Bled, Slovenia
28-38 August 2003

SCIENTIFIC REPORT

Meeting convened by

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1. Executive Summary

The ESF Exploratory Workshop on Liquid Crystal (LC) Colloid Dispersions was attended by 38 leading scientists in the field from Europe and also from the United States and Japan. In addition there were 11 participants from the University of Ljjubjana who attended on a daily basis.

The meeting was convened for three full days and allowed a detailed scientific discussion of the current state-of-the-art in liquid crystal colloids and a review of the new opportunities in the field.

1.1 Background to the meeting

Over the past 10 years there has been growing interest in LC colloidal suspensions. It is found that colloidal particles of the order of micron in size experience an additional interaction when suspended in a nematic LC which arises from the distortion and defects they create in the nematic elastic field [Stark:01]. The interactions lead to self-assembly into a range of new structures (eg [Poulin:98, Poon:01, Petrov:01]). The detailed form of the macroscopic interactions depends upon the structure of defects and the way in which they interact, with both the surfaces in the system and each other. There is also interest in the flow properties associated with colloidal particles embedded in a liquid crystal host [Stark:01]. Colloidal suspensions of water droplets in nematic liquid crystals have been studied experimentally [Poulin:97, Loudet:00]. Liquid crystal in water dispersions have also been studied using copolymer stabilisers and generated curvi-linear aligned phases.

Director anchoring at the surface of a colloidal particle gives rise to complex defect structures. The precise behaviour of an isotropic droplet in a nematic matrix depends upon (i) the boundary conditions at the particle and the container (ii) the elastic constants of the nematic (iii) the anchoring energy of the nematic at the liquid interface (iv) the size and shape of the particle and (v), in the case of a liquid droplet, the strength of the surface tension. The balance of these properties is strongly temperature dependent and may lead to interesting phase behaviour. Poulin reports that the defect structure around a droplet changes from a quadrupolar to a dipolar configuration as the temperature is reduced. However the defects are difficult to describe within macroscopic theories of liquid crystals since they introduce local modifications to both the density and the order tensor (ie the order parameter is reduced and biaxiality is observed). The precise description of the structure and energy associated with a nematic defect is a complex problem which must be considered at a range of length scales. For this reason the study of these materials requires contributions from theories (eg [Fukuda:02]) and simulations (eg [Ruhwandl:97, Andrienko:01, Yamamoto:01, Care:03]) at the molecular, mesoscopic and continuum levels. There is also interest in the response of LC colloids to external fields. The coupling of elastic and electric phenomena in liquid crystal colloids may lead to new phenomena and field-responsive fluids of technological interest in display applications or as electro-rheological fluids.

1.2 Content of the meeting

The presentations at the meeting fell approximately into the following areas

- Particle assemblies induced by LC elastic field and/or nematic-isotropic phase separation
- Modelling of colloid-nematic and colloid-colloid interactions and dynamics
- Substrate-substrate interactions and substrate-induced effects
- Particle assemblies in lamellae/chiral structures
- Anisotropic colloidal particles in nematics
- Theories of compositional structure in LCs

More detailed information of the presentations is given in the next Section 2. The meeting also included discussion on the next important directions. The meeting was concluded with a round-table discussion and the following areas were identified

I) use of smaller particles *ie* moving from micron to nano particles, possibly leading to microphase separation
II) use of anisotropic particles *eg* carbon nanotubes, metallic fibres, bio-molecules
III) use of new materials for the particles; these may, for example, be chosen to respond to external fields – *eg* metallic particles
IV) the influence of capillary condensation of isotropic and nematic phases in colloid assemblies
V) a wider range of LC mesophases (eg chiral)

It was agreed that the new directions may yield materials which could be exploited for sensors, actuators, switchable materials, photonic materials, encapsulation, displays and very high strength, lightweight, materials. These materials may have applications in a wide range of industrial sectors including displays, pharmaceutical, cosmetics, structural materials, electronics, and robotics.

It is therefore clear that the field is rich with possible new directions and that there is considerable potential for breakthrough in the development of new materials. A key element of the field is the cross fertilisation of ideas; thus ideas which have been developed in thermotropic systems are now being explored in lyotropic materials.

As a direct result of the meeting, a proposal is to be submitted in November, 2003, for a Marie Curie Research Training Network which will explicitly address many of the opportunities identified at the workshop. This will involve ten centres in seven countries in Europe. There was also agreement that other funding routes would be explored in order to exploit the new ideas which are emerging in the field. The proceedings of the meeting are currently being refereed and edited and will appear in the Journal of Phyics: Condensed Matter.

In conclusion, it was felt that the meeting had been very successful; delegates commented that they had found the meeting enjoyable and very informative. It has led to much stronger links between the research teams across Europe, links which will be greatly enhanced if the bid for a research network is successful.

2. Scientific content of the workshop

In the following sections we summarise the scientific content of the meeting in a number of broad, thematic areas**.**

The work in these sections is attributed to the author who presented the work at the workshop; however it is important to note that most of the presentations arose from the work of larger research teams; a fuller attribution is given in the attached booklet of abstracts.

2.1 Keynote presentations

D. Weitz (Harvard, USA) opened the workshop with wide ranging review of current progress in the field of liquid crystal colloidal dispersions and also described recent results using micro-fluidics methods to generate monodisperse distributions of droplets in LC matrices.

H. Stark (Kontsanz, Germany) addressed two aspects of liquid crystal colloid dispersions. He first considered the Stokes drag of a single particle in a nematic environment which is a central quantity in the dynamics of colloidal dispersions. Due to the director configuration around the particle, the Stokes drag is anisotropic and highly non-linear. Secondly, he discussed particles suspended in a nematic liquid crystal above the nematic-isotropic phase transition. They are surrounded by a nematic wetting layer. Based on the harmonic approximation for the Landau-Ginzburg-de Gennes free energy, it can be shown that these wetting layers give rise to a Yukawa-type, strongly attractive pair potential for large particle distances. Its range and strength are easily tunable by temperature and therefore it provides an ideal model system for studying flocculation transitions and aggregation in colloidal suspensions.

J-I Fukuda (Japan) presented results from an adaptive mesh refinement scheme, in which fine grids are generated only around the defect core region where fine resolution will be necessary. Simulation results were presented for the dynamics of a nematic liquid crystal around a particle when external perturbations such as an electric or magnetic field are imposed. The simulations recovered the experimental observation that a hedgehog defect is transformed to a Saturn ring when an electric field is applied. He also discussed the dynamics of topological defects together with the orientation profile under the application of uniform hydrodynamic flow.

2.2 Particle assemblies induced by LC elastic field and/or nematic-isotropic phase separation.

Mitov (Toulouse, France) demonstrated the long-range ordering of nanoparticles assemblies which adopt the helical configuration of the cholesteric liquid crystalline phase. They used glass forming cholesterics and the platinum nanoparticles formed periodic ribbons (Figure 1) which mimic the well-known fingerprint cholesteric texture. Surprisingly, the nanoparticles do not decorate the original cholesteric texture but create a novel helical structure with a larger pitch. They showed that the

distance between the ribbons is directly correlated to the pitch. This inherent length scale becomes a simple control parameter to tune the structuring of nanoparticles.

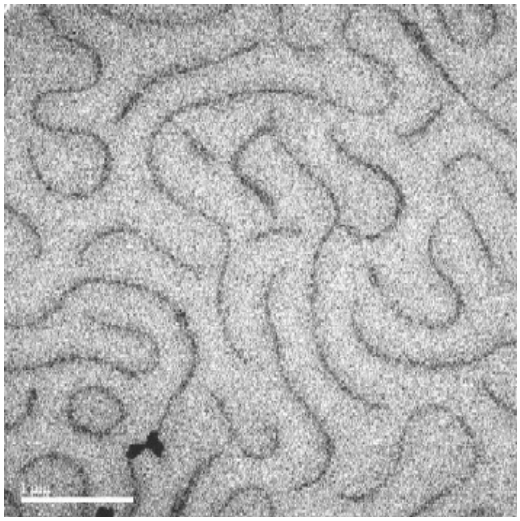

Figure 1: Ribbon-like organization of platinum nanoparticles in accordance with the cholesteric fringerprint texture. The distance between ribbons is directly related to the helical pitch / the molecular chirality of the liquid crystal

O. Mondain-Monval (Bordeaux, France) described recent work on the use lyotropic liquid crystals and colloids to structure the growth of mineral and/or hybrid inorganic-organic materials. Figure 2 shows preliminary results for mineral capsules grown in liquid crystal reversion emulsions.

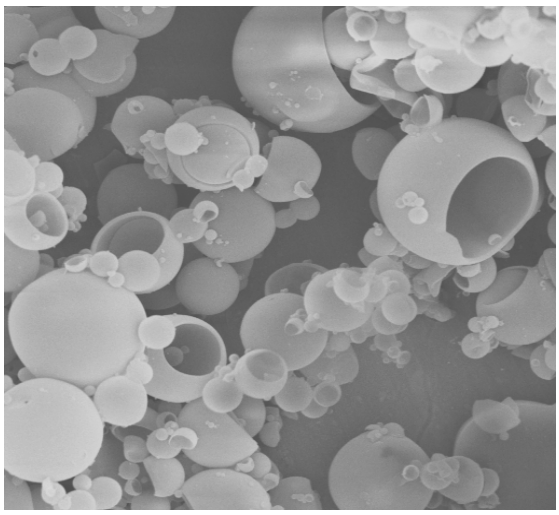

Figure 2 Preliminary mineral capsules grown in liquid crystal reverse emulsions.

Future developments of this approach may have a range of possible applications in, for example, encapsulation and the growth of porous mineral networks.

B. Zalar (Ljubljana, Slovenia) discussed the instability of micro-emulsions in nematogenic solvents. Microemulsions of spherical DDAB/water inverse nanomicelles in nematics have recently been claimed to exhibit a 'transparent

nematic' phase. The question whether this is a true thermodynamic phase, or a demixing transition, is still open. In the vicinity of the I-N transition of the pure 5CB, two visually distinguishable phases coexist on the low temperature side: an isotropic or possibly transparent-nematic one, and a nematic one. In order to characterize these phases in more detail, deuteron NMR spectroscopic studies were performed and also imaging investigations. The temperature dependence of the opacity of the samples of various sizes was also investigated visually with a digital camera. Below T_{NI}, NMR imaging experiments detected two spatially separated phases: a lower mass density isotropic phase with high concentration of micelles and a nematic phase with vanishing concentration of micelles. The volume fraction of the isotropic component decreases upon cooling. Simultaneously, the concentration of micelles in this phase increases. The phase separation process strongly depends on the cooling rate and on the size of the sample. Similarly, when heated up back to the isotropic state, the characteristic time for the remixing of the micelles significantly increases in large samples. The observations support the phase separation scenario with a mechanism driven by elastic forces arising from the geometrical incompatibility among spherical micelles and elongated LC-molecules. Within the present study, it was not possible to identify the formation of the transparent nematic phase. This conclusion was in agreement with the arguments presented by Bellini.

T. Bellini (Milan, Italy) described work on water in oil microemulsions, in which the oil component is the isotropic phase of a thermotropic liquid crystal (LC), display demixing transitions of various types in the proximity of the nematic transition of the pure LC compound. The coexisting phases are either both isotropic, and differing in the concentration of water-surfactant droplets, or one of them is nematic. The phase behavior of a DDAB-water-5CB mixture, which was studied with various techniques, is very rich and combines features of the lyotropic systems with those of the isotropic-nematic transition of thermotropic LC. It is found that the demixing transitions are anticipated, on the high T side, by increase of droplets density fluctuations and decrease of their collective diffusion, indicating the presence of attractive interactions mediated by growing paranematic fluctuations. The results presented by Bellini prompted discussion on the “transparent nematic” phase reported by Yamamoto and Tanaka in a composite nematic liquid crystal (penthyl-cyanobiphenyl, 5CB), double tailed ionic surfactant (didodecyldimethylammonium bromide, DDAB), and water system. However, the Bellini's results contradict the notion of a “transparent nematic” phase and support a different interpretation: that upon cooling from an isotropic phase resembling an ordinary microemulsion of inverse micelles, the system undergoes a demixing transition in which the micelle-poor phase develops long range nematic order. The delegates at the meeting supported this latter interpretation of the "transparent nematic" phase.

Jean-Christophe Loudet (Bordeaux, Franece) presented findings on the formation of ordered colloidal structures from bulk demixing in liquid crystalline materials. The presence of topological defects and elastic distortions around the inclusions induce long-range attractions and short-range repulsions which control the ordering of the microdomains and stabilize them against coalescence. The ordering can be controlled on large-scale by simply controlling the macroscopic alignment of the liquid crystal. The influence of an external electric field was discussed.

J Cleaver (Edinburgh, UK) presented results on the phase kinetics of ternary systems consisting of a liquid crystal, a small molecule simple liquid such as hexane and PMMA colloidal particles. Under suitable quenching these systems form waxy solids as the colloidal particles form a metastable particle network. Cleaver presented experimental results for the kinetics of the network formation and showed that it was strongly dependent upon the presence of the hexane and how it was absorbed upon the PMMA particles.

D Cleaver (Sheffield, UK) presented results from a computer simulation study of a colloidal particle immersed in a solvent comprising liquid crystalline rod-shaped particles and a 10 % number concentration of small spherical additives. The presence of the coloidal is found to induce qualitative changes in the phase behaviour of the rod-sphere mixture. When the colloidal particle favours radial anchoring, it is found that the small spheres spontaneously aggregate to form a droplet which resides in the equatorial plane of the colloidal particle. When the colloidal particle favours tangential anchoring, however, the small spheres aggregate to form droplets at each of the boojums seen experimentally. These findings confirm expectations that small additives should preferentially reside in disordered regions, but also reflect the competing influence of surface tension effects.

2.3 Modelling of colloid-nematic and colloid-colloid interactions / dynamics

R Yamamoto (Kyoto, Japan) presented results for an efficient computational scheme for simulating colloidal dispersions in LC solvent by using smooth interface. The simulations have so far been extended to dispersions in nematic and smectic C LC solvents. Work has also been undertaken to include hydrodynamics by using Leslie Ericksen type equation into the scheme.

M Telo da Gama (Lisbon, Portugal) reported investigations into the interactions between disks immersed in 2D nematics (i) analytically using the tensor order parameter formalism for the nematic configuration around isolated disks and (ii) numerically using finite element methods with adaptive meshing to minimize the corresponding Landau-de Gennes free energy or the Frank elastic free energy. For 2D nematic hosts and homeotropic anchoring conditions, Landau-de Gennes theory predicts that only quadrupolar configurations are stable. For strong homeotropic anchoring, each disk generates a pair of defects with one-half topological charge responsible for the 2D quadrupolar interaction between the disks at large distances. At short distance, the position of the defects may change, leading to unexpected complex interactions with the quadrupolar repulsive interactions becoming attractive. This short-range attraction in all directions is still anisotropic. As the distance between the disks decreases, their preferred relative orientation with respect to the far-field nematic director changes from oblique to perpendicular. Dipolar configurations were found in 2D smectic C films, a system that is similar to a 2D nematic, but where the director does not exhibit mirror symmetry, thus excluding configurations with half integer topological charges. Telo da Gama reported investigation on the interactions in this system using finite elements with adaptive meshing to minimize the Frank free energy and obtained very accurate interaction energies between disks at arbitrary separations. They found a strong repulsion at short range followed by the expected long-range dipolar interaction with a

pronounced minimum at an intermediate distance. The equilibrium director, field configuration exhibits a topological defect at the mid-point between the disks.

P Patricio (Lisbon, Portugal) described numerical methods used to calculate the free energy of colloidal particles in a 2D nematic host in situations where the nematic is non-uniform. In the first case, the non-uniformity in the nematic orientation was given by a cavity in an otherwise planar boundary. Imposing homeotropic boundary conditions, it was found that the repulsion observed between a colloidal particle and a planar wall may shift to an attraction when the cavity is present. In a second case, the nematic was subjected to a temperature gradient and exhibits a planar interface. It was found that sufficiently small colloidal particles are pinned in the interfacial region in line with recent experimental results.

C Care (Sheffield, UK) described a study of a droplet of an isotropic fluid immersed in a nematic matrix. Particular attention was paid to the deformation of the droplet and the associated defect structure of the surrounding nematic. The shape of the droplet, and the structure of the director field near to the droplet, depend upon (i) the elastic constants of the nematic (ii) the surface tension (iii) the anchoring energy (iv) the surface bending energy (v) the size of the drop (vi) the far field director structure. The results were obtained using a two dimensional lattice Boltzmann (LB) model of an interface between a nematic and an isotropic fluid. The isotropic fluid is modelled by a standard lattice Bhatnar-Gross-Krook (LBGK) scheme. The LB model of the nematic is a modified LBGK. The interface algorithm recovers the macroscopic equations, developed by Rey, which govern the dynamics of the interfacial director orientation, and the shape of the deforming interface between a nematic liquid crystal and an isotropic viscous fluid under isothermal conditions. A discussion of the role of bending energy in controlling the droplet shape was also presented. The Euler Lagrange equation which governs the shape of the droplet was presented for a simplified director field and results given from a numerical minimisation of the free energy.

M Allen (Warwick, UK) reviewed recent studies of colloidal particles in nematic liquid crystals based on molecular dynamics simulations undertaken on high-performance parallel computers. In the case of homeotropic anchoring at the surface, different defect structures were observed around a spherical colloid particle of droplet as a function of radius. The interactions between two such particles were observed and measured as a function of their separation and orientation relative to the director. For nonspherical rod-like colloids, the torque was measured as a function of angle; also the effect of proximity of the colloid to a solid surface was investigated.

2.4 Substrate-substrate interactions and substrate-induced effects

J. M. Romero-Enrique (Seville, Spain) considered the effect of a nematic solvent on the effective interaction between two colloidal particles which favour homeotropic and planar anchoring, respectively. Neglecting the effect of the nematic director field distortion at large distances, the short-distance effective interaction between colloidal particles was related to the hybrid slit pore solvation force via the Derjaguin approximation. Results were presented for the rich phenomenology that the hybrid slit presents as the anchoring potential strengths are tuned. This study was performed in the framework of the density functional theory.

P Teixeira (Lisbon, Portugal) presented a simple model for the liquid crystal matrix surrounding `soft' colloidal particles whose separation is much smaller than their radii. The work used an implementation of the Onsager approximation of density functional theory to calculate the structure of a nanometrically thin film of hard Gaussian overlap particles of elongations κ=3 and κ=5, confined between two solid walls. The penetrability of either substrate can be tuned independently to yield symmetric or hybrid alignment. Comparison was made with Monte Carlo simulations of the same system by Cleaver, Teixeira and Barmes and revealed good agreement in the symmetric case.

I.Muševič (Ljubljana, Slovenia) described the use of atomic force spectroscopy (AFS), which is based on the atomic force microscope, as an efficient method for measuring of the separation dependence of forces between two surfaces with nano-metre and pico-Newton precision. When a liquid crystal is confined between two closely spaced surfaces, the structural forces are exerted on confining surfaces due to the translational and orientational order across the liquid crystal interface. The method permits direct analysis of the orientational and translational order profile by measuring separation dependence of interfacial forces. The forces, relevant to the nematic-solid interfaces were considered, such as the van der Waals force, electrostatic force between charged surfaces in liquids as well as the structural forces including pre-nematic, pre-smectic, capillary and Casimir force. Muševič presented studies of the temperature dependence of interfacial forces of nematic liquid crystals 5CB, 8CB and 12CB on DMOAP silanated glass and saphire. They observed that the interfaces are clearly divided into two regions: the first molecular layer, which is smectic-like. It is followed by a partially ordered region that shows pre-nematic order in 5CB, pre-smectic order in 8CB and well developed layer-by layer order in 12CB. In many cases capillary condensation of a nematic and even order is observed.

2.5 Particle assemblies in lamellae

L Ramos (Montpellier, France) showed how colloidal inclusions can stabilize a network of linear defects in a cholesteric liquid crystal. This network converts the mechanical properties of a presheared sample from fluid-like to solid-like and leads to the formation of a “defect-mediated” solid. The rheological properties of these materials were measured and compared to pure liquid crystal samples. The frequency dependence of the complex shear moduli, for samples with and without inclusions, were discussed in terms of the properties of defect structure present in the samples.

A compact arrangement of lyotropic lamellar droplets (or onions) was spontaneously generated by tuning a control parameter such as the Gaussian curvature modulus of a surfactant bilayer. This converts the mechanical properties of the materials from fluid-like to gel-like. These materials exhibit an ultraslow relaxation dynamics, due to rearrangements of the lamellar droplets, which becomes slower and slower as the samples age. In the second part of the talk described the experimental investigation of the aging properties of these materials, probed by two techniques, dynamic light scattering and linear rheology. These techniques are powerful tools to investigate the aging dynamics and may be used for a large variety of materials including liquid crystal colloidal dispersions.

P. Cluzeau (Lille, France) presented evidence for self organization process of colloidal inclusions in 2D system consisting the smectic free standing films. The nucleation of the inclusions is induced by the heating of the smectic film above the bulk smectic-nematic phase transition. In such a new type of 2D emulsion, inclusions confined in the smectic membrane are constituted by another LC phase non-miscible with the smectic one. Optical analysis of the textures allows the determination of the nature of the topological defect(s) which accompany each inclusion and thus to understand the type of self-organization (chains or even two dimensional array of inclusion).

In order to check the universality of such phenomena both chiral and non chiral materials exhibiting respectively the SmC*-N* and SmC-N phase transitions were investigated. In both cases, the nucleation of inclusions was obtained. The analysis of the c-director configuration reveals that the anchoring conditions around the N* and N inclusions are different: homeotropic boundary condition for the N* inclusions while planar for the N ones. The associated topological defects are different. As a result, interactions are of dipolar type for chiral emulsion (SmC*-N*) and of quadrupolar type for non-chiral emulsion (SmC-N). In the former case inclusions self-organize in linear stable chains while in the latter one, branched chains appear. With further heating, the inclusions build structured arrays that look like 2D foam trapped in the film. Thermotropic smectic films could provide a model for biological membranes.

2.6 Anisotropic colloidal particles in nematics:

R Leheny (Baltimore, USA) described recent research on aspherical inclusions, such as nanowires, in nematics. The particles' orientational degrees of freedom introduce a variety of new issues. He reported experiments using magnetic nanowires to characterize quantitatively the orientational elastic energy of elongated colloids in nematics and to investigate how one can exploit the elastic behavior to manipulate the nanowires.

G Vroege (Utrecht, Netherlands) described work on the development and study of anisometric (rodlike and platelike) particles dispersed in various (however, until now exclusively *isotropic*) solvents. These dispersions form liquid crystal phases, because of the inherently anisotropic interactions between the particles. He gave an overview of the synthesis of colloidal aluminium (hydr)oxide particles, the resulting rodlike or hexagonal forms of the particles, the possibilities to modify them - e.g. by secondary growth or growing an additional silica layer - and the ways to stabilize them in several solvents. Examples of liquid crystal phases (nematic, columnar) in these systems was presented, as well as the resulting phase diagrams and how they may be understood. The influence of external (magnetic, gravitational) fields and particle polydispersity was discussed. He concluded by raising the question whether anisometric colloidal particles and a liquid-crystalline solvent would be a fruitful combination.

2.7 Theories of compositional structure in LCs

E Velasco (Madrid, Spain) described the application of a version of density-functional theory to a variety of problems involving smectic phases. The theory was proposed some time ago as a consistent generalisation of the Onsager theory when applied to

spatially non-uniform structures, such as smectic phases. A numerically convenient methodology has been proposed to make the theory tractable. He used the theory to analyse a model for hard spherocylinders that possess a dipole moment. Several ferroelectric phases were identified, and a global phase diagram, including nematic as well as smectic phases, calculated. Also, a generalisation of the theory was proposed to deal with mixtures of hard spherocylinders. The theory predicts an extremely rich phase diagram. In some cases a microsegregated phase, consisting of alternating layers of one or the other component, can be stabilised.

P van der Schoot (Eindhoven, Netherlands) noted that when polystyrene globules are added in very small quantities to nematic liquid-crystalline dispersions of fd virus particles in water, they self-assemble into chain-like aggregates mostly oriented along the director. At sufficiently high concentrations of the stiff, filamentous virus particles, micrometer-sized gaps appear between the globules that do not seem to disrupt the perfectly aligned assemblies. Adding amounts of globules in excess of a few grams per liter induces either a micro phase separation to a lamellar phase or a complete demixing of the constituents, depending on the concentration the virus particles. He argued that, because the polystyrene globules are much smaller in size than the nematogens, their chaining-up cannot be due to an elastic deformation of the director field, nor to Casimir-type interactions resulting from fluctuations of the director field. He argued that in this system the self-assembly of the globules into chains is likely to result from depletion interactions induced by an excluded-volume coupling to the filaments in the host nematic. The reason is that the volume a pair of spheres excludes to a filament (modelled as a rigid rod) depends on their relative orientation, leading in the nematic phase to a highly angle-dependent depletion interaction. By considering density fluctuations in nematic rod-sphere mixtures, it was argued that pre-transitional fluctuations could give rise to the structural reorganization of the assemblies at higher densities of rods observed in experiment.

2.8 Other contributions

T Schilling (Amsterdam, Netherlands) described work on the Monte Carlo simulation of LC nucleation in a system of hard spherocylinders. When a droplet of an isotropic liquid is nucleated from vapour, the shape of the droplet is generally spherical, so that the surface tension is minimized. The nucleation of liquid crystals is far more complex. Firstly the growth mechanisms for radial (with respect to the director field) and axial growth differ. An example for this is the formation of long, thin filaments rather than droplets at the isotropic to smectic transition in suspensions of hard rods. Secondly the interfacial tension between a liquid crystalline phase and the isotropic phase depends on the orientation of the particles with respect to the interface. This leads to an anisotropic surface anchoring strength and an anisotropic surface tension. Thirdly a liquid crystalline droplet can adapt its surface anchoring not only by changing its shape, but also by deforming its director field. Therefore the competition between elastic deformation and surface anchoring will influence the shape.

P Ziherl (Ljubljana, Slovenia) described a study of the mechanical properties of cubic colloidal lattices. This was based on a heuristic model based on the analogy between the dry foam and the crystalline phases of repelling particles. He discussed two systems characterized by soft short-range repulsion: (i) strongly screened charged colloids and (ii) dendrimer micelles stabilized by a fuzzy polymeric corona.

They calculated the elastic constants FCC, BCC, and A15 phase, and analyzed their dependence on the range of the soft potential as well as the density. They found that the shear moduli of the two non-close-packed lattices are considerably smaller than the corresponding moduli of the FCC lattice.

S Martin (Kontanz, Germany) described work on the use of optical tweezers to precisely control the orientation and torque of the particles in an optical tweezer using linearly or circularly polarised light. Optically birefringent spherical colloidal particles were fabricated by the light induced polymerisation of liquid crystalline droplets below the isotropic-nematic transition temperature. The application of multiple tweezers and high speed video microscopy then allows for the direct measurement of the cross-correlation functions between the various degrees of freedom in 2 or more body systems.

3 Assessment of results and future directions

The meeting provided an excellent overview of the current state-of-the-art in liquid colloid dispersions and concluded with a round table discussion which identified the following topics as being those which will form the basis of the next steps in the field

1) magnetic particles / metallic wires / bio-molecules in liquid crystals
2) encapsulation
3) free standing films for organisation of particles
4) small particles in liquid crystals
5) microphase separation
6) nematic colloids in confined geometries
7) hydrodynamics
8) use of chemistry
9) patterned surfaces
10) liquid crystals as templates
11) mixed lyotropic / thermotropic systems or 'living lyotropics'
12) polymerisation
13) field induced structural changes
14) capillary condensation in colloid assemblies
15) nano- motors and actuators.

In addition is was agreed that there was now a good understanding of the 'transparent nematic' phase.

The set of topics above has subsequently been used as the starting point for creating a bid for a Marie Curie research training network. During the discussion in creating the proposal, topics 1, 4, 5 and 13 were identified as being of particular importance although there was support for most of the topics across the proposed network.

In addition, the proceedings of the meeting are currently being refereed and edited and will be published in the Journal of Physics: Condensed Matter.

4. Final Programme

The final programme is given in Appendix A with a copy of the Poster for the meeting which in Appendix B.

5 List of Participants

See Appendix C.

6 Statistical Information

There were 38 delegates at the meeting, with an additional 11 who attended from Ljubljana. The following statistics relate to the 38 main participants.

25 of the 38 delegates were invited to the meeting and received some ESF support for their attendance. The remaining delegates attended the meeting at full cost or were supported from other grants.

Age profile:

Research Student	3
Young scientists	27
Senior scientists	8

In this table, Young Scientists include post-doctoral workers and scientists in the early stages of their research career. Senior scientists are defined as researchers with more than 10 years research experience.

Gender profile

Male	32
Female	6

Country of origin

France	8
Germany	3
Italy	1
Japan	2
Netherlands	3
Portugal	4
Slovenia	5
Spain	2
United Kingdom	8
United States	2

This table shows that the meeting drew widely from countries in Europe and also had representation from some of the leading workers in the field from Japan and the USA.

References

[Andrienko:01] Andrienko D, Germano G, Allen MP (2001) *Phys Rev E* **63** 041701
[Care:03] Care C M, Halliday I, Good K and Lishchuk S V (2003) *Phys Rev E* **67**, 061703
[Fukuda:02] Fukuda J, Yokoyama (2002) *Phys Rev* **E66**, 012703
[Loudet:00] Loudet J C, Barois P and Poulin P (2000) *Nature* **407**, 6111
[Stark:01] Stark H (2001) Phys Rep **351**, 387
[Petrov:01] Petrov PG, Terentjev EM (2001) Langmuir **17,** 2942
[Poon:01] Poon W C K *et al* (2001) Eur Phys J **E4,** 11
[Poulin:97] Poulin P, Stark H, Lubensky T C and Weitz D A (1997) *Science* 275**, 1770**
[Poulin:98] Poulin P and Weitz D **(1998) Phys Rev** E57**, 626 – 637**
[Ruhwandl:97**]** Ruhwandl R W and Terentjev E M (1997) Phys Rev **E56**¸5561
[Yamamoto:01] Yamamoto R (2001) Phys Rev Lett **87**,075502

Appendix A Workshop Programme

ESF Exploratory Workshop

Liquid Crystal Colloid Dispersions

28th – 30th August, 2003 Bled, Slovenia

Thursday 28th August			
0845 – 9000		*L Laurent* ESF	***Opening of workshop***
0900 – 1000		D Weitz *Harvard University*	*Liquid crystal emulsions*
1000 – 1030		P van der Schoot *Eindhoven University of Technology*	*Self assembly of globules in a nematic dispersion of rods*
1030 – 1100	**Coffee**		
1100 – 1130		M Mitov *CNRS Toulouse*	*Long range structuring of metallic nano-particles in accordance with the cholesteric fingerprint texture*
1130 – 1200		B Zalar *Jozef Stefan Institute*	*Instability of micro-emulsions in nematogenic solvents*
1200 – 1230		T Bellini *University of Milan*	*De-mixing transitions in micro-emulsions formed by mixtures of DDAB, water and thermotropic liquid crystals*
1230 – 1400	**Lunch**		
1530 – 1600		M M Telo da Gama *University of Lisbon*	*Colloidal interactions in two dimensional nematics*
1600– 1630		C M Care *Sheffield Hallam University*	*Mesoscopic modelling of nematic-isotropic interfaces*
1630– 1700		P Ziherl *University of Ljubljana*	*The foam analogy: elastic constants of cubic colloidal crystals*
1700 – 1730	**Coffee**		
1730 – 1800		P Teixiera *Catholic University of Portugal*	*Density functional studies of liquid crystal interfaces*
1800 – 1830		E Velasco *Universidad Autonoma de Madrid*	*Density functional theory of hard-rod smectic phases: some recent results*
1830 – 1900		R Yamamoto *Kyoto University*	*Simulating particle dispersions in nematic liquid crystals*
1930 – 2100	**Dinner**		

Friday 29th August			
0900 – 1000		H Stark *University of Konstanz*	*Stokes drag and the effect of nematic wetting layers in liquid crystal colloids*
1000 – 1030		S Martin *University of Konstanz*	*Hydrodynamic coupling of liquid crystalline colloidal particles*
1030 – 1100	**Coffee**		
1100 – 1130		P Cluzeau *CNRS Lille*	*Interaction and self-organisation of endogene inclusions in liquid crystal membranes*
1130 – 1200		L Ramos *University of Montpellier*	*Defect network, mechanical properties and aging dynamics in lamellar materials*
1200 – 1230		R L Leheny *Johns Hopkins University*	*Colloidal wires in nematics*
1230 – 1400	**Lunch**		
1530 – 1600		M P Allen *University of Warwick*	*Molecular simulation of colloidal particles in nematic liquid crystals*
1600– 1630		J M Romero-Enrique *Imperial College*	*Nematic-mediated interaction between colloidal particles with opposing anchoring: a Derjaguin approach*
1630 – 1800	**Poster Session & Coffee**		
1800 – 1830		T Schilling *FOM*	*Liquid crystal nucleation in a system of hard spherocylinders*
1830 – 1900		D Cleaver *Sheffield Hallam University*	*The effect of spherical additives on a liquid crystal colloid*
2000 – 2200	***Conference Dinner***		

Saturday 30th August		
0900 – 1000	J Fukuda *Japan Science and Technology Corporation*	*Dynamics of a nematic liquid crystal around a spherical particle*
1000 – 1030	P Patricio *University of Lisbon*	*Colloidal interactions in two dimensional liquid crystals*
1030 – 1100	**Coffee**	
1100 – 1130	G J Vroege *Utrecht University*	*Liquid-crystalline behaviour in dispersions of colloidal rods and platelets*
1130 – 1200	O. Mondain-Monval *Centre de Recherche Paul Pascal*	*Mixed colloids-surfactant systems*
1200 – 1230	J van Duijneveldt *University of Bristol*	*Small angle X-ray scattering from 5CB-laponite compounds*
1230 – 1400	**Lunch**	
1530 – 1600	J-C Loudet *University of Pennsylvania*	*Behaviour of colloidal particles dispersed in liquid crystal solvents: aligned emulsions from bulk demixing and response to an electric field*
1600– 1630	P Poulin *University of Bordeaux*	*Dispersion and alignment of carbon nanotubes*
1630– 1700	I Musevic *University of Ljubljana*	*Structural forces at nematic-solid interfaces*
1700 – 1730	**Coffee**	
1730 – 1830	Closing Summary and Discussion	
1930 – 2100	**Dinner**	

Appendix B Workshop Poster

ESF Exploratory Workshop on

Liquid Crystal Colloid Dispersions

August 28 - 30, 2003

Bled, Slovenia

(http://www.fiz.uni-lj.si/~zumer/LC-Colloid-Bled03.htm)

Colloidal dispersions within a liquid-crystalline host exhibit many novel structural, rheological and optical properties, which are very interesting both from scientific perspective and for potential applications. The colloidal particles disrupt the orientational ordering of the liquid crystal, thus inducing interparticle forces, which may be quite different from those mediated by an isotropic fluid. These forces have been shown to lead to a variety of exciting structures. The purpose of the meeting is to bring together the researchers interested in experimental, theoretical and simulation studies of these materials. The meeting will cover the following topics: phase structures, mechanical properties, optical properties, rheological properties, ageing and ageing dynamics, theory (interactions, defects, structures etc.), simulations (molecular and mesoscale), new directions.

Organising Committee:

Chris Care, Sheffield Hallam University, Sheffield, UK
Doug Cleaver, Sheffield Hallam University, Sheffield, UK
Philippe Poulin, CNRS, Pessac, France
Primož Ziherl, University of Ljubljana, Ljubljana, Slovenia
Slobodan Žumer, University of Ljubljana, Ljubljana, Slovenia

Meeting venue: IEDC, Bled School of Management

Appendix C - Final List of Participants

	Title	First Name	Last Name	Affiliation 1	Affiliation 2	Street Address	City	Postal Code	Country	Telephone	Fax	E-mail
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45	Dr.	Alenka	Mertelj	J. Stefan Institute								
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47	Prof.	Mika	Vilfan	J. Stefan Institute								
48	Dr.	Boštjan	Zalar	J. Stefan Institute								