Final Report
Biaxiality in Nematic and Smectic Liquid Crystals

DOE-BES grant # DE-SC-0001412

Principal Investigator: Satyendra Kumar, Kent State University

Co-Principal Investigators: Quan Li and Dena M. Agra-Kooijman, Kent State University
Mohan Srinivasarao, Georgia Institute of Technology
Alejandro Rey, McGill University

Research Period Covered: 09/01/2009 - 08/31/2016
Report Date: 01/24/2017

During the award period, the project team explored several phenomena in a diverse group of soft condensed matter systems. These include understanding of the structure of the newly discovered twist-bend nematic phase, solving the mystery of de Vries smectic phases, probing of interesting associations and defect structures in chromonic liquid crystalline systems, dispersions of ferroelectric nanoparticles in smectic liquid crystals, investigations of newly synthesized light sensitive and energy harvesting materials with highly desirable transport properties. Our findings are summarized in the following report followed by a list of 36 publications and 37 conference presentations. We achieved this with the support of Basic Sciences Division of the US DOE for which we are thankful.

I. Twist Bend Nematic Phase

The structure of the relatively new twist-bend nematic liquid crystal (LC) phase has attracted much attention in recent years due to the interesting chemistry of molecular structure of mesogens that form this phase, scientific interest in understanding its structure, and measurements of order parameters and structure of this phase. The project team has applied several techniques to make direct measurements of the phase structure, order parameters, cone angle and pitch of heliconical structure of this unique phase. Three-step multi-scale modeling scheme was developed to characterize LCs. Quantum chemistry calculations determine the molecular structure of LC, the infrared (IR) and Raman spectra, and atomic charges. Among the important inferences drawn from our results are:

(a) the molecular orientation distribution function (ODF) changes shape from pure Gaussian to volcano-like as it transitions from the nematic to twist-bend nematic phase. The classical Meier-Saupe formalism satisfactorily explains the ODF in the nematic phase, but a series expansion in terms of Legendre polynomials is needed in the twist-nematic phase.

(b) Order parameters $<P_2>$ and $P_4>$ were measured with x-ray and Raman techniques, as functions of temperature and are in good agreement with reported indirectly inferred values from other techniques.

(c) The cone or the tilt angle follows a simple power law with exponent of 0.25 and increases from zero in the nematic phase to about 25 degrees deep inside the phase. The results from x-ray and polarized Raman methods are in excellent agreement with each other, and with semi-quantitative optical measurements.

(d) Molecular packing simulations performed using the MOLPAK software provided order parameters $\langle P_2 \rangle$ and $\langle P_4 \rangle$ based on Zannoni's methodology and density functional tight binding calculations, which agree very well with experimental findings, in Fig. 6.

(e) In addition to the known calamitic bimesogens, a bent-core mesogens was synthesized which exhibited the twist-bend nematic phase. X-ray and freeze fracture transmission electron microscopy of this phase were used to confirm its structure.

The project team made significant contributions to the understanding of this unique phase via publications of six peer reviewed papers [1-6] and five conference presentations [T1-T5], one of them [T3] was invited.

II. Solved -- the Mystery of de Vries Smectic Phases

For the past more than 37 years the mystery of the de Vries smectic-A and -C phases has prevailed and managed to baffle researchers. These phases show essentially a constant layer spacing while the measured optical properties revealed changing optical birefringence associated with increasing molecular tilt in the smectic-C phase with respect to the smectic layers. Using a microfocus x-ray beam at synchrotron facilities and in our laboratory, we were able to obtain x-ray diffraction results from essentially a single crystal domain and obtain unprecedented information about these phases. The results showed that:

(a) The molecular tilt measured with x-rays is precisely the same as obtained with optical methods. This debunked a prevalent belief that “optical tilt” in these materials is different from “x-ray tilt”.

(b) Orientational order parameters $\langle P_2 \rangle$, $\langle P_4 \rangle$, and $\langle P_6 \rangle$ in the two smectic phases were measured as functions of temperature. None of the order parameters become negative proving that the molecular distribution function is distorted Gaussian and not volcano-like as has been believed for nearly four decades! X-ray results conducted by Kent State researchers were in excellent agreement with Raman measurements of these parameters performed by the Georgia Tech group.

(c) The director tilt in the smectic-C phase decreases as the smectic-A phase is approached from below and follows a power law with an exponent of 0.12, eventually vanishing at the transition the untilted smectic-A phase.

(d) The three orientational order parameters in the smectic-C phase increase with decreasing temperatures and as a consequence of effective apparent molecular length increases. This increase compensates for the expected decrease in smectic layer thickness due to increasing tilt. This results explains the lack of change in smectic layer spacing while molecular tilt increases.

This work was published in five [7-10] papers and was a subject of seven [T6-T12] conference presentations, two of these were invited [T6, T11] and one plenary [T10] talk delivered at the 25th International LC conference.

III. *Chromonic Liquid Crystals*

The aggregate size in several chromonic liquid crystal systems are found to depends on concentration, temperature, and pH. These aggregates, at sufficiently higher density, undergo orientation ordering and form the *N* and the middle (*M*) LC phases. Three different models of aggregation were proposed for disodium chromoglycate (DSCG) and water solutions, ranging from simple columnar aggregation, chimney-like, to threadlike associations.

A. In order to **determine which of the three models is valid**, x-ray and optical studies were conducted at Kent State, Georgia Tech, and McGill University. We have unequivocally demonstrated that: (a) *The aggregates are simple columnar assemblies* of dye molecules with a separation of 3.4 Å, (b) Lateral separation between the assemblies is concentration and temperature dependent, varying from ~ 35 to 42 Å in the *N* phase and from 27 to 32 Å in the M phase, (c) The columnar aggregates consist of ~23 molecules in the *N* phase, 3-10 times higher in the *M* phase, (d) The scission energy in the N phase is ~ 7.19 ± 0.14 k_BT (15 wt%), 2.73 ± 0.4 k_BT (20 wt%), and 3.05 ± 0.2 k_BT (25 wt%), and (e) Solutions of all concentrations undergo a spinodal decomposition at ~ 40 °C, resulting in DSCG-rich regions with the *M* phase and water-rich regions in the *N* and isotropic phases. This work has provided much needed clarity and revealed the spinodal decomposition that appears to be responsible for the differences in various published phase diagrams.

B. The newly developed ***Differential Dynamic Microscopy*** (DMM) technique was deployed to determine the splay, twist, and bend elastic constants. We were able to circumvent the difficulties associated, *e.g.*, with the use of an external field with the DDM method. The measured relaxation rates in our laboratory are of the same order of magnitude as obtained from defect dynamics of SSY in rectangular capillaries in collaboration with *Rey* at McGill.

C. ***Multiscale simulations*** of nematic LC under cylindrical confinement with strong anchoring revealed defect textures that emerged which were used to determine key viscoelastic properties of the chromonics. Using liquid crystal elasticity and differential geometry to derive the "disclination elastica", we have demonstrated that the solutions can be classified in terms of the classical Euler elastic including solitons, periodic, and monotonic solution. The simulation results are then compared with experimental results. Theory-experimental loop was used to estimate the rotational viscosity and orientational diffusivity.

D. ***The escape in the third dimension*** was observed > 12 h after a capillary was filled and a transition to the double helix configuration of two line defects started. The two disclination lines twisted around an imaginary tube with a pitch 1.7 times larger than the diameter of capillary. We observed nucleation of tactoids that, *contrary to the expectation, are not isotropic*. Sufficiently large anisotropy in the elastic constants drove the transition from a deformation free ground state to a doubly twisted structure and resulted in spontaneous symmetry breaking with equal probability for left and right handedness. Using the measured spontaneous twist angle, *the saddle splay elastic constant for CLC was calculated for the first time*.

A total of 10 peer reviewed papers [13-23] and 14 presentations [T13-T27] were made at professional conferences. Five of the talks were Invited.

IV. Ferroelectric Nanoparticle Dispersion in Liquid Crystals - Smectic Cocoons

Ferroelectric nanoparticles dissolved in the *N* and *SmA* LCs result in interesting modification of phase transitions, electrooptical characteristics, and optical beam-coupling efficiencies. We started an effort in this arena in collaboration with Prof. Kitzerow and Dr. Lorenz, Paderborn University. Small- and large-angle x-ray scattering studies of neat and nanoparticles doped LCs [EN18, 8OCB, and homologues of the nCB (4CB - 8CB)] were performed at synchrotron sources at the ESRF (Grenoble), APS (Argonne), and NSLS (Brookhaven). Samples in capillary tubes and planar cells were used. LCs were doped with polar and nonpolar $BaTiO_3$ particles of ~ 9 *nm* diameter.

Polar nanoparticles give rise to highly enhanced order than non-polar nanoparticles. Even in non-smectic LC such as 5CB, multilayer smectic nano-structures were induced. Surprisingly, a characteristic layer spacing of 4.5 nm was measured in all five CB homologues with nine orders of the Bragg reflection! This revealed that the nanoparticles surface potential was responsible for the formation of smectic cocoons around them. The multilayers consisted of molecular bilayers wherein the mesogens were arranged in a head-to-head assembly. The alkyl tails of the mesogenic molecules were freely movable and the tail-to-tail assembly was stabilized. Clearly a new self-assembled nanostructure is formed in which the rigid aromatic part defines the layer spacing.

This work published in four peer revised papers [24-27] and five conference presentation [T28-T32], with one invited talk.

V. Energy Harvesting Organic Semiconductors

Two different types of systems with energy harvesting possibility were investigated. These included:

(a) Several compounds synthesized by our colleagues at Kent State University and the University of Nevada at Las Vegas were investigated for the structure of their smectic phase and the dependence of charge mobility on the liquid crystal order. These systems have large pi-pi orbital overlap and excellent transport properties. This work appeared in four papers [28-31].

(b) Energy harvesting flexoelectric biological membranes were probed theoretically. One of the goals was to find the relations and impact on outer hair cells located in the inner ear of the electromechanical, rheological, and viscoelastic properties, and the spectrum of the mechanical oscillations. The model combined the flexoelectricity of a circular membrane attached to the inner surface of a circular capillary and capillary flow of contacting viscoelastic phases. The theoretical work has implications for experimental efforts to develop liquid crystal based stress-sensors. Three publications [32-34] resulted from this work.

VI. Self-Organized Liquid Crystal Nanostructures

Quan Li and his synthesis group has done in depth literature survey of scientific results related to the light harvesting phenomena in soft condensed matter (living and non-living) systems, especially, light-sensitive liquid crystal materials containing photochromic moieties. With proper design one can affect photoinduced alignment, modulation of optical path lengths, pitch of chiral structures, and interesting phase transitions. This work has led to synthesis and testing of functional materials responsive to UV, visible, and infrared irradiation. Such materials have huge potential for applications in electro-optics, photonics, and adaptive materials.

Two papers [35-36] were published in peer reviewed scientific papers, and was the subject of two keynote, one plenary and two invited talks [T33-T37].

Publications

Twist-Bent Nematic Phase

1. D.M. Agra-Kooijman, G. Singh, M.R. Fisch, M.R. Vengatesan, J.-K. Song, and S. Kumar, *The Oblique Chiral Nematic Phase in Calamitic Mesogens*, Liquid Crystals, (2017); DOI:10.1080/02678292.2016.1272141.
2. G. Singh, J. Fu, D. M. Agra-Kooijman, J.-K Song, M.R. Vengatesan, M. Srinivasarao, M. Fisch, and S. Kumar, *X-ray and Raman scattering study of orientational Order in the Nematic and Heliconical Nematic Liquid Crystals*, Accepted Phys. Rev. **E. Rapid Comm**. **94**, 060701 (2016); DOI: 10.1103/PhysRevE.94.060701
3. D.A. Peterson, J. Xiang, G. Singh, R. Walker, D.M. Agra-Kooijman, A. Martinez-Felipe, J. M.D. Storey, M. Gao, S. Kumar, O.D. Lavrentovich, and C.T. Imrie, *A reversible isothermal twist-bend nematic-nematic phase transition driven by the photoisomerisation of an azobenzene-based nonsymmetric liquid crystal dimer*, J. Am. Chem. Soc. **138**, 5283-5289 (2016). DOI: 10.1021/jacs.5b13331.
4. Y. Wang, Z. Zheng, H. K. Bisoyi, K. G. Gutierrez-Cuevas, L. Wang, R. S. Zola, and Q. Li, *Thermally Reversible Full Color Selective Reflection in a Self-organized Helical Superstructure Enabled by a Bent-core Oligomesogen Exhibiting Twist-bend Nematic Phase*, Mater. Horiz. **3**, (2016); **DOI:** 10.1039/C6MH00101G.
5. Z. Zheng and Q. Li, "*Self-Organized Chiral Liquid Crystalline Nanostructures for Energy-Saving Devices*" Chapter 14 in Nanomaterials for Sustainable Energy, Q. Li, Ed., Springer, Heidelberg, 2016.
6. Y. Wang, G. Singh, D. M. Agra-Kooijman, M. Gao, H. K. Bisoyi, C. Xue, M. Fisch, S. Kumar, and Q. Li, *Room Temperature Heliconical Twist-Bend Nematic Liquid Crystal*, CrystEngCommun **17**, 2778 (2015); DOI: 10.1039/c4ce02502d (communication, selected as hot article and highlighted in the cover).

Smectics Phases and Biaxiality

7. D. Agra-Kooijman, H-G. Yoon, S. Dey and S. Kumar, *Origin of Weak Layer Contraction in* D.M. Agra-Kooijman, M. Fisch, L. Joshi, W. Ren, P. McMullan, A. Griffin and Satyen Kumar, *Dual Relaxation and Structural Changes Under Uniaxial Strain in Main-chain Smectic-C Liquid Crystal Elastomer*, Phys. Chem. Chem. Phys. **17**, 191(2015).
8. *de Vries Smectic Liquid Crystals*, Phys. Rev. E **89**, 032506 (2014). DOI: 10.1103/PhysRevE.89.032506
9. S. Kumar, Q. Li, D.M. Agra-Kooijman, M. Srinivasarao, and A. Rey, *Biaxiality in nematic and smectic liquid crystals*, proceedings of DOE Materials Chemistry Principal Investigators Meeting-2014, pp. 190-193(2014).
10. S. Dey, D.M. Agra-Kooijman, W. Ren, P. J. McMullan, A. C. Griffin, and S. Kumar, *Soft Elasticity in Main Chain Liquid Crystal Elastomers*, Crystals **3**, 363-390, (2013), DOI:10.3390/cryst3020363.

11. J. He, D. M. Agra-Kooijman, G. Singh, C. Wang, C. Dugger, L. Zang, J. Zeng, L. Zang, S. Kumar, and C. S. Hartley, *Board-like Dibenzo[fg,op]napthacenecs: Synthesis, Characterization, Self-assembly, and Liquid Crystallinity*, J. Mater. Chem. C **1**, 5833–5836 (2013).
12. Y. Wang, H.-G. Yoon, H. K. Bisoyi, S. Kumar, and Q. Li, *Hybrid Calamitic and Bent-core Dimeric Mesogens and Their Biaxial SmA and Nematic Phases*, J. Mater. Chem. **22**, 20363 (2012); DOI: 10.1039/c2jm34315k.

Chromonic Liquid Crystals

13. Xuxia Yao, Karthik Nayani, Jung Ok Park and Mohan Srinivasarao, "Orientational Order of a Lyotropic Chromonic Liquid Crystal measured by Polarized Raman Spectroscopy" *J. Phys. Chem. B., 120(19), 4508-4512(2016)*
13. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Disclination Elastica Model of Loop Collision and Growth in Confined Nematic Liquid Crystals*, Soft Matter **11**, 5455 - 5464, (2015) DOI: 10.1039/C5SM00708A.
14. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Oval-Shaped Disclination Loop Nucleation and Growth in Nematic Liquid Crystals under Conical Confinement*, Liq. Cryst. **42**, 506 (2015).
15. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Nematic Liquid Crystals under Conical Capillary Confinement: Theoretical Study of Geometry Effects on Disclination Lines*, Mol. Cryst. Liq. Cryst. **612**, 1, 56-63, (2015); DOI: 10.1080/15421406.2015.1030574
16. K. Nayani, R. Chang, J. Fu, P. W. Ellis, A. Fernandez-Nieves, J. O. Park, and M. Srinivasarao, *Spontaneous Emergence of Chirality in Achiral Lyotropic Chromonic Liquid Crystals Confined to Cylinders*, Nat. Commun. **6**, 8067 (2015); DOI: 10.1038/ncomms9067.
17. D. Agra-Kooijman, G. Singh, A. Lorenz, P. Coolings, H. Kitzerow and S. Kumar, *Columnar Molecular Aggregation in the Aqueous Solutions of Disodium Cromoglycate*, Phys. Rev. E **89**,062504 (2014); DOI: 10.1103/PhysRevE.89.062504.
18. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Theoretical Predictions of Disclination Loop Growth for Nematic Liquid Crystals under Capillary Confinement*, Physical Review E **90,** 042501 (2014).
19. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Mechanisms and Shape Predictions of Nematic Disclination Branching under Conical Confinement*, Soft Matter **10**, 3245-3258 (2014).
20. E. Soulé and A.D. Rey, *Oscillating Fronts Produced by Spinodal Decomposition of Metastable Ordered Phases*, Soft Matter **9**, 10335–10342 (2013).
21. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Disclination Shape Analysis for Nematic Liquid Crystals under Micron-range Capillary Confinement*, Mater. Res. Soc. Symp. Proc. 1526 (2013); DOI:10.1557/opl.2013.490.
22. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Theory and Modeling of Nematic Disclination Branching Under Capillary Confinement*, Soft Matter **8**, 11135-11143 (2012).

23. E. R. Soulé, A. D. Rey, *Hedgehog Defects in Mixtures of a Nematic Liquid Crystal and a Non-Nematogenic Component*, Soft Matter **8**, 1395-1403, (2012); DOI: 10.1039/C1SM06741A.

Nano-particle dispersion in Liquid Crystals – Smectic Cacoons

24. **Featured:** A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, and H.-S. Kitzerow, *X-ray Scattering of Nematic Liquid Crystal Nano-dispersion with Negative Dielectric Anisotropy*, Appl. Opt. **52**, E1-E5 (2013). DOI: 10.1364/AO.52.0000E1

25. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, M. Fernández Martínez, and H.-S. Kitzerow, *Doping a Mixture of Two Smectogenic Liquid Crystals with Barium Titanate Nanoparticles*, J. Phys. Chem. B **117**, 937–941 (2013); DOI: 10.1021/jp310624c.

26. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, and H.-S. Kitzerow, *Bilayers in Nanoparticle-Doped Polar Mesogens*, Phys. Rev. E **88**, 062505 (2013); DOI: 10.1103/PhysRevE.88.062505.

27. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, and H.-S. Kitzerow, *Doping the Liquid Crystal 5CB with Milled $BaTiO_3$ Nanoparticles*, Phys. Rev. E. **86**, 051704 (2012). DOI:10.1103/PhysRevE.86.051704.

Energy Harvesting

28. Y. A. Getmanenko, S.-W. Kang, N. Shakya, C. Pokherel, S. D. Bunge, S. Kumar, B D. Ellman, and R. J. Twieg, *5,5'-Bis-(Alkylpyridinyl-2,2'-Bithiophenes: Synthesis, Liquid Crystalline Behavior, and Charge Transport*, J. Mat. Chem. C **2**, 256-274 (2014);

    DOI: 10.1039/c3tc31522c.

29. Y. A. Getmanenko, N. Shakya, C. Pokherel, S.-W. Kang, S. Kumar, S. D. Bunge, B D. Ellman, and R. J. Twieg, *Bis(5-Alkylthiophen-2-yl)Arene Liquid Crystals as Potential Semiconductors*, J. Mat. Chem. C **2**, 2600-2611 (2014); DOI: 10.1039/c3tc32211d

30. R. Jose, T. J. Patel, T. A. Cather, D. J. Willhelm, J. Grebowicz, H. Han, P. K. Bhowmik, L. Sharpnack, D. M. Agra-Kooijman, and S. Kumar, *Thermotropic mesomorphism in catanionic surfactants synthesized from quaternary ammonium surfactants and sodium dodecylbenzenesulfonate: Effect of chain length and symmetry*, Colloids and Surfaces A **461**, 40-49 (2014); DOI: 10.1016/j.colsurfa.2014.07.037

31. R. Jose. T. J. Patel. P. K. Bhowmik, T. A. Cather, R. R. Davilla, J. Grebowicz, S. Han, D. M. Agra-Kooijman, and S. Kumar, *Room Temperature Thermotropic Liquid Crystal Phases of Novel Catanionic Surfactants Derived from Quarternary Ammonium Surfactants and Bis(2-ethyl)sulfosuccinate*, J. Colloid & Interf. Sci. **411**, 61-68 (2013),

    DOI: 10.1016/j.jcis.2013.08.045.

32. A. D. Rey and E. E. Herrera-Valencia, *Mechano-electric Transduction Performance of Actuation Device Based on Liquid Crystal Membrane Flexoelectricity*, Philosophical Transactions of the Royal Society A, Mathematical, Physical and Engineering Sciences, **372,** 2029 (2014); DOI: 10.1098/rsta.2013.0369.

33. E. E. Herrera-Valencia and A. D. Rey, *Stress Sensor Device Based on Flexoelectric Liquid Crystalline Membranes*, ChemPhysChem **15,** 1405-1412, (2014);

DOI: 10.1002/cphc.201300600.

34. A. D. Rey, P. Servio and E. E. Herrera-Valencia, *Bioinspired Model of Mechanical Energy Harvesting Based on Flexoelectric Membranes*, Phys. Rev. E **87**, 022505 1-12, (2013).

Self-Organized Chiral Liquid Crystalline Nanostructures

35. L. Wang and Q. Li, *Stimuli-Directing Self-Organized 3D Liquid Crystalline Nanostructures: From Materials Design to Photonic Applications*, Adv. Funct. Mater. **26**, 10-28 (2016); DOI: 10.1002/adfm.201502071.

36. H. Bisoyi and Q. Li, *Light-Directing Chiral Liquid Crystal Nanostructures: From 1D to 3D*, Acc. Chem. Res. **47**, 3184 (2014); **DOI:** 10.1021/ar500249k.

Talks/Presentations

Twist-Bent Nematic Phase

T1. Y. Wang, H. K. Bisoyi, and Quan Li, *Molecular Design and Synthesis of Heliconical Twist-Bend Nematic Liquid Crystals*, 250th American Chemical Society National Fall Meeting, Boston, Massachusetts, Aug. 16-20 (2015).

T2. G. Singh, D. M. Agra-Kooijman, M. R. Fisch, M. R. Vengatesan, J.-K. Song, and S. Kumar, *A Twist in the Nematic Phase of Mixtures of Achiral Cyanobiphenyl Dimer Mesogens*, April Meeting of the Ohio Section of American Physical Society, Kent, OH, March 27-28 (2015).

T3. S. Kumar, **Invited Talk**, *Structure and Phase Diagram of a Twist-Bend Nematic System*, 21st National Conference on Liquid Crystals, VSSD College, CSJM University, Kanpur, India, Nov. 9-12 (2014).

T4. M. Srinivasarao, K. Nayani, M. S. Park, A. Aiyar, J. O. Park and E. Reichmanis, Invited Talk, *Molecular Ordering in Polymer Based Semiconductors:Utility of Polarized Raman Spectroscopy of ordered systems*, Polymer Processing Society 2013, Mumbai, India, December 4-7 (2013).

T5. K. Nayani, M. S. Park, B.-J. Yoon, J. Ok Park and M. Srinivasarao, **Invited Talk**, *Polarized Raman Scattering for Measuring Order Parameters of Nematics*, International Conference on Raman Spectroscopy, ICORS, Bangalore, India, August (2013).

Smectics Phases and Biaxiality

T6. D. M. Agra-Kooijman, M. R. Fisch, W. Ren, P. J. McMullan, A. C. Griffith, and S. Kumar, **Invited Talk,** *Relaxation and Microscopic Structural Changes in Main Chain Smectic Liquid Crystal Elastomers,* International Liquid Crystal Elastomer Conference 2015 and Workshop on Active Liquid Crystals and Gels, Erice, Italy, October 2-7, (2015).

T7. D.M. Agra-Kooijman, M. Fisch, and W. Ren, P. J. McMullan, A. Griffith, and S. Kumar, *Stress and Structure Relaxations in Smectic Liquid Crystal Elastomers*, April Meeting of the Ohio Section of American Physical Society, Kent, OH, March 27-28 (2015).

T8. D. M. Agra-Kooijman, M. Fisch, W. Ren, P. McMullan, A. Griffin, and S. Kumar, *Strain Dependent Relaxation of Main-Chain Liquid Crystal Elastomer*, 25th International Liquid Crystal Conference, Dublin, Ireland, June 29 - July 4 (2014).

T9. H. Bisoyi, Y. Wang, Y. Wang, and Q. Li, *Building Hybrid Rod-Like and Bent-Core Molecular Architectures to Induce Biaxiality*, 248th American Chemical Society National Fall Meeting, San Francisco, Aug. 10-14 (2014).

T10. S. Kumar, **Plenary Lecture**, *Unraveling the Mystery of de Vries Smectic Phases*, 25th International Liquid Crystal Conference, Dublin, Ireland, June 28 - July 4 (2014).

T11. D. M. Agra-Kooijman, G. Singh, H.-G. Yoon, and S. Kumar, **Invited Talk**, de *Vries Smectics: Volcano- or Sugarloaf-like Molecular Distribution Function?* 20th National Conference on Liquid Crystals, Manipal University, Manipal, India, December 15-18 (2013)

T12. H. K. Bisoyi, Y. Wang, and Q. Li. *Molecular Design and Synthesis of Hybrid Rod-like and Bent-core Liquid Crystal Dimers to Induce Biaxiality*, 246th American Chemical Society National Meeting, Indianapolis, Indiana, September 8-12 (2013).

Chromonic Liquid Crystals

T13. Mohan Srinivasarao, "Formation of monodomains of chromonic liquid crystals: A Twisted Path", International Liquid Crystal Conference, Kent State University (August 2016).

T14. Mohan Srinivasarao, "Spontaneous Emergence of Chirality in Liquid Crystals", Symposium honoring Nick Abbott in the Division of Colloid Chemistry, American Chemical Society Meeting, San Diego (March 2016).

T15. Mohan Srinivasarao, "Spontaneous emergence of chirality in achiral liquid crystalline systems" 90th Birthday Symposium in honor of Richard Stein, University of Mass, Amherst, MA, August (2015).

T16. A. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Estimation of Viscoelastic Properties from Confined Liquid Crystal Defects*, Canadian Society of Rheology, Mason Award Symposium McGill University, Montreal, Canada. , May 20(2015).

T17. A. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Disclination Loop Growth for Nematic Liquid Crystals under Capillary Confinement*, Material Research Society Fall Meeting, Hynes Convention Center - Boston, Massachusetts, USA, November 30 - December 5, (2014).

T18. M. Srinivasarao, **Invited Talk**, *Differential Dynamic Microscopy: Determination of Viscoelastic Properties of Nematic Fluids*, Institute of Non-Newtonian Fluid Mechanics (INNFM) Meeting on Rheometry and General Rheology, Lake Vyrnwy, Wales, April (2014).

T19. A. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Estimation of the Elastic Modulus of Spider Silk Using a Nematic Discliantion Shape Model*, 3rd CRIBIQ Student Symposium, Centre sur la biodiversité de l'Université de Montréal, Montreal, Canada, September 22-23 (2014).

T20. A. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Texture Transformation Process for Confined Nematic Liquid Crystals*, 10th CSACS Student Symposium, University of Montreal, Montreal, Canada, September 8 (2014).

T21. A. Shams, X. Yao, J. O. Park, M. Srinivasarao and A. D. Rey, *Nematic Liquid Crystals under Conical Capillary Confinement: Theoretical Study of Geometry Effects on*

Disclination Lines, 25th International Liquid Crystal Conference, Dublin, Ireland, 29 June - 4 July (2014).

T22. D. M. Agra-Kooijman, L. Joshi, G. Singh, S.W. Kang, P. J. Collings, and S. Kumar, **Invited Talk**, *Molecular Assembly and Ordering in Aqueous Solutions of Chromonic Mesogens*, Optics of Liquid Crystals 2013, Honolulu, Hawaii, Sept 29 – Oct 4 (2013).

T23. M. Srinivasarao, **Invited Talk**, *Imaging in Materials Science: New Stuff in Old Places*, Summer School on Soft Matter Interfaces held at Changwon National University, Changwon, South Korea, July (2013).

T24. M. Srinivasarao, Jung Ok Park, Beom-Jin Yoon and Karthik Nayani, **Invited Talk**, *Differential Dynamic Microscopy: Its Applications to the Study of Dynamics of Complex Fluids*, BGER (Building Global Engagements in Research) International Research Symposium, Swansea University, Wales, UK, February (2013).

T25. A. Shams, S. Gurevich and A. D. Rey, *Defect Pattern Formation in Liquid Crystals under Confinement*, Canadian Association of Physicists Congress, Université de Montréal, Montreal, Canada, May 27-31 (2013).

T26. S. Kumar, **Invited Talk**, *Revisiting the Structure of Mesophases of Chromonic Systems*, D.M. Agra-Kooijman, and G. Singh, 19th National Conference on Liquid Crystals, Thapar University, Patiala, India, Nov. 21-23 (2012).

T27. A. Shams, and A. D. Rey, *Modeling of Disclination Loops in Bent-core Liquid Crystals*, CSACS Student Symposium, Centre Culturel, Université de Sherbrooke, Sherbrooke, Canada September 12 (2012).

Ferroelectric Nano-particle dispersion in Liquid Crystals – Smectic Cacoons

T28. A. Lorenz, D. M. Agra-Kooijman, N. Zimmermann, H.-S. Kitzerow, D. R. Evans, S. Kumar, *Bilayer gelation in nanoparticle-doped nCB-homologues*, International Liquid Crystal Conference 2014, Dublin, Ireland, June 29 – July 4 (2014).

T29. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, and H.-S. Kitzerow, *Nanoparticle Induced Smectic Phase with Unusual Layer Spacing in 4-cyano-4'-pentylbiphenyl and Several Homologues*, 46th Biennial Meeting of the German Colloid Society, Paderborn, Germany September 23 – 25 (2013).

T30. A. Lorenz, **Invited Talk**, *X-ray Diffraction: From Fundamentals to Uses in Liquid Crystal Research*, I-CAMP 13th Summer School on Liquid Crystals, Cambridge, UK, June 26 – July 6 (2013).

T31. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, and H.-S. Kitzerow, *Liquid Crystal Multilayers Adsorbed on Nanoparticles with Unusual Layer Spacing in 5CB*, British Liquid Crystal Society Annual Meeting, Cambridge, UK March 25 – 27 (2013).

T32. A. Lorenz, N. Zimmermann, S. Kumar, D. R. Evans, G. Cook, and H.-S. Kitzerow, *Multilayers with Unusual Layer Spacing in Nanoparticle Doped 5CB*, 40th Topical Meeting on Liquid Crystals 2013, Paderborn, Germany, March 20 – 22 (2013).

Self-Organized Chiral Liquid Crystalline Nanostructures

T33. Q. Li, **Keynote Talk**, *Light-Directing Self-Organized Chiral Liquid Crystalline Nanostructures: From 1D to 3D Photonic Crystals*, 5th Symposium on Liquid Crystal Photonics, Beijing, April 22-26 (2016).

T34. Q. Li, **Keynote Talk**, *Light-Directing Self-Organized Liquid Crystalline Nanostructures: From 1D to 3D Photonic Crystals* at SPIE Photonics West, San Francisco, California, Feb. 7-12 (2015).

T35. Q. Li, **Invited Talk**, *Self-Organized Liquid Crystals for Photonics and Energy*, 25th International Liquid Crystal Conference, Dublin, Ireland, June 29-July 4 (2014).

T36. Q. Li, **Plenary Talk**, *Stimuli-Directing Liquid Crystalline Nanostructures: From Photonics to Energy*, 2014 International Conference on New Energy and Sustainable Development, Beijing, June 13-15 (2014).

T37. Q. Li, **Invited Talk**, *Light-Directed Self-Organized Liquid Crystalline Nanostructures: From Photo Display to Dynamic Photonics*, 2013 Gordon Research Conference on Liquid Crystals, Maine, June 16-21 (2013).