

**LIQUID CRYSTALS WITH INCLUSIONS:
FERRONEMATICS AND LIVING LIQUID
CRYSTALS**

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**DEPARTMENT OF PHYSICS
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JANUARY 2024

LIQUID CRYSTALS WITH INCLUSIONS:
FERRONEMATICS AND LIVING LIQUID CRYSTALS

by

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Submitted

in fulfilment of the requirements of the degree of *Doctor of Philosophy*

to the



Indian Institute of Technology Delhi

January 2024

To my family

Certificate

This is to certify that the thesis titled “Liquid Crystals with Inclusions: Ferronematics and Living Liquid Crystals” being submitted by Mr. Aditya to the Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy in Physics is a record of bonafide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which to the best of my knowledge has reached the required standard.

The material contained in this thesis has not been submitted in part or full to any other University or Institute for the award of any degree or diploma.

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Acknowledgements

I wish to take this opportunity to thank all the amazing people that I have come across during my stay at the Indian Institute of Technology Delhi (IITD).

First and foremost, I extend my heartfelt gratitude to my supervisors, Prof. Varsha Banerjee and Prof. Sanjay Puri for having faith in me. They introduced me to a diverse set of interesting problems that have helped me understand the intricacies of the subject. They always encouraged me to think on my own and help me mature as an individual. I thank Prof. Banerjee for her constant guidance and help. Her dedication, work ethic, pursuit of perfection, and positive attitude will always be a source of inspiration for me. I have immensely benefited from our casual interactions and scientific discussions. I want to express sincere gratitude to Prof. Puri, for his invaluable insights and unwavering support. His extensive experience, clear thinking, and ground-up approach have played a crucial role in refining the direction of my work. Our weekly discussions with him were highly stimulating, and I always looked forward to meeting him, time and again. I have been fortunate to have both Prof. Banerjee and Prof. Puri as my supervisors. There is much for me to learn from them.

I extend my sincere appreciation to Pradeep Kumar Yadav (JNU, Delhi) for his significant contributions to the latter part of this thesis. Our collaboration has proven to be highly productive, and I have gained significant knowledge from our scientific interactions.

I am thankful to my research committee members at IITD, Prof. V Ravishankar, Prof. Sujin Babu and Prof. Rajesh Khana, for their critical evaluation

of my research work. Their inputs at different stages of research have provided valuable insights. I would like to express my gratitude to the numerous individuals with whom I had the privilege of interacting during my visits to conferences and workshops. These valuable exchanges and discussions have enriched my understanding and expanded my horizons in the field. I extend my heartfelt thanks to the broader academic and scientific community, whose research and findings have served as a foundation upon which this work was built.

My teaching assistant roles at IITD greatly improved my scientific knowledge and presentation skills. I am thankful to Profs. Varsha Banerjee, Rohit Narula, and Vikarant Saxena for giving me these opportunities, and it has been a fantastic experience working with them.

I gratefully acknowledge the University Grant Commission (India) and IITD for financial support. I would like to express my appreciation to IITD for providing a conducive research environment and resources essential for the successful completion of this work. In particular, I thankfully acknowledge the IITD HPC facility for computational resources.

It was a lovely experience working with my colleagues Arunkumar Bupathy, Manish Anand, Konark Bisht, Nishant Birdi, Pradeep Kumar Yadav, Dorothy Gogoi, Anuj Kumar Singh, Parbati Saha and Ritik Rajak. They have become very close friends whom I will always remember fondly. I thank Nishant for the critical reading of this thesis. I would also like to thank my friends Anubhav, Sooryansh, Chandan, Hemant, Preeti, Shivani, Gautam and Himanshu for their help, cooperation and goodwill. I also want to extend my heartfelt appreciation to Sonali Katoch for her constant encouragement throughout this journey. I will always cherish the wonderful time spent at IITD with all these people around.

Lastly, I wish to express my deep gratitude and love for my family members, Surender Singh, Kamla Vats, Upender Kumar, Sunita Vats and Hirthvi Vats, for their understanding, unconditional love and care. My parents have been my mainstay during this period. Their sacrifices, unflinching support and understanding are what made everything possible for me.

Aditya

Abstract

Inclusions or doping have played a significant role in the advancement of modern industry and technology. The introduction of specific elements has exhibited the ability to modify the intrinsic characteristics of compounds, resulting in elevated performance and enhanced functionality. In this thesis, we examine two types of inclusions in nematic liquid crystals: ferronematics and living liquid crystals. Ferronematics involve suspensions of magnetic nanoparticles within a nematic liquid crystal medium. This is an example of a system with passive inclusions. Living liquid crystals, conversely, combine living entities or bacteria with nematic liquid crystals. These living particles are self-propelled resulting in an inherently non-equilibrium system. We study the role of inclusion-nematic coupling on the equilibrium and non-equilibrium properties of these contemporary systems.

We study the non-equilibrium phenomenon of domain growth after a thermal quench (or coarsening) in ferronematics. We first investigate the role of coupling on pattern formation across different dimensions. Our modelling is based on coupled time-dependent Ginzburg-Landau equations for the coupled order parameters. We consider both shallow and deep quenches from a high-temperature disordered phase. The system coarsens by the collision and annihilation of topological defects. We focus on *slaved coarsening*, where a disordered component is driven to coarsen by an ordered one. We present detailed results for the morphologies and growth laws, which exhibit unusual features purely due to the magneto-nematic coupling. To the best of our knowledge, this is the first study of this non-equilibrium phenomenon in FNs. Next, we provide a theoretical framework for the emergence of biaxial order in FNs which has been elusive for several decades in pure NLCs since

its inception in 1970. Our framework allows for the manipulation of morphologies and quantitative estimates of the biaxial order. We hope our quantification will guide the experiments to be more systematic.

The second part of the thesis deals with the study of active inclusions in the NLCs or living liquid crystals. We provide a phenomenological model to study the symbiotic pattern dynamics in this contemporary system using the Toner-Tu model for active matter, the Landau-de Gennes free energy for liquid crystals, and an experimentally motivated coupling term that favours coalignment of the active and nematic components. Our extensive theoretical studies unfold two novel steady states, chimeras and solitons, with sharp regions of distinct orientational order that sweep through the coupled system in synchrony. The induced dynamics in the passive nematic is unprecedented. We show that the symbiotic dynamics of the active and nematic components can be exploited to induce and manipulate order in an otherwise disordered system. We also numerically investigate the interplay between confinement and coupling on the pattern formation in the LLCs. The main findings of the study include dynamics states with persistent vortices in microfluidic wells, tailored morphologies with potential applications in targeted drug delivery and controlled motion of the chaotic active particles. Our work provides many ideas for manipulating active matter and liquid crystals for exciting futuristic applications. We hope that it will initiate joint experimental and theoretical investigations in LLCs.

Finally, we conclude with a discussion on the implications, future perspectives and possible extensions of the ideas developed in the thesis.

सार

आधुनिक उद्योग और प्रौद्योगिकी की प्रगति में समावेशन या डोपिंग ने महत्वपूर्ण भूमिका निभाई है। विशिष्ट तत्वों की शुरुआत ने यौगिकों की आंतरिक विशेषताओं को संशोधित करने की क्षमता प्रदर्शित की है, जिसके परिणामस्वरूप प्रदर्शन में वृद्धि हुई है और कार्यक्षमता में वृद्धि हुई है। इस थीसिस में, हम नेमैटिक लिक्विड क्रिस्टल में दो प्रकार के समावेशन की जांच करते हैं: फेरोनेमैटिक्स और जीवित लिक्विड क्रिस्टल। फेरोनेमैटिक्स में नेमैटिक लिक्विड क्रिस्टल (एनएलसी) माध्यम के भीतर चुंबकीय नैनोकणों (एमएनपी) का निलंबन शामिल होता है। यह निष्क्रिय समावेशन वाली प्रणाली का एक उदाहरण है। इसके विपरीत, जीवित लिक्विड क्रिस्टल, जीवित संस्थाओं या जीवाणुओं को नेमैटिक लिक्विड क्रिस्टल के साथ जोड़ते हैं। ये जीवित कण स्व-चालित होते हैं जिसके परिणामस्वरूप स्वाभाविक रूप से गैर-संतुलन प्रणाली बनती है। हम इन समकालीन प्रणालियों के संतुलन और गैर-संतुलन गुणों पर समावेशन-नेमैटिक युग्मन की भूमिका का अध्ययन करते हैं।

हम फेरोनेमैटिक्स में थर्मल क्वेंच के बाद डोमेन वृद्धि की गैर-संतुलन घटना का अध्ययन करते हैं। हम पहले विभिन्न आयामों में पैटर्न निर्माण पर युग्मन की भूमिका की जांच करते हैं। हमारा मॉडलिंग युग्मित क्रम मापदंडों के लिए युग्मित समय-निर्भर गिन्ज़बर्ग-लैंडौ (टीडीजीएल) समीकरणों पर आधारित है। हम उच्च तापमान वाले अव्यवस्थित चरण से उथले और गहरे दोनों प्रकार के क्वेंचियों पर विचार करते हैं। टोपोलॉजिकल दोषों के टकराव और विनाश से प्रणाली कठोर हो जाती है। हम स्लेव्ड कोर्सेननिंग पर ध्यान केंद्रित करते हैं, जहां एक अव्यवस्थित घटक को एक ऑर्डर किए गए द्वारा मोटे होने के लिए प्रेरित किया जाता है। हम आकृति विज्ञान और विकास कानूनों के लिए विस्तृत परिणाम प्रस्तुत करते हैं, जो पूरी तरह से मैग्नेटो-नेमैटिक युग्मन के कारण असामान्य विशेषताएं प्रदर्शित करते हैं। हमारी सर्वोत्तम जानकारी के अनुसार, एफएन में इस गैर-संतुलन घटना का यह पहला अध्ययन है। इसके बाद, हम एफएन में द्विअक्षीय क्रम के उद्भव के लिए एक सैद्धांतिक रूपरेखा प्रदान करते हैं जो 1970 में अपनी स्थापना के बाद से शुद्ध एनएलसी में कई

दशकों से मायावी है। हमारा ढांचा द्विअक्षीय क्रम की आकृति विज्ञान और मात्रात्मक अनुमानों के हेरफेर की अनुमति देता है। हमें उम्मीद है कि हमारा परिमाणीकरण प्रयोगों को और अधिक व्यवस्थित बनाने में मार्गदर्शन करेगा।

थीसिस का दूसरा भाग एनएलसी या जीवित लिक्विड क्रिस्टल में सक्रिय समावेशन के अध्ययन से संबंधित है। हम सक्रिय पदार्थ (एएम) के लिए टोनर-टू मॉडल, लिक्विड क्रिस्टल (एलसी) के लिए लैंडौ-डे गेनेस मुक्त ऊर्जा और प्रयोगात्मक रूप से प्रेरित युग्मन शब्द का उपयोग करके इस समकालीन प्रणाली में सहजीवी पैटर्न गतिशीलता का अध्ययन करने के लिए एक घटनात्मक मॉडल प्रदान करते हैं। सक्रिय और नेमैटिक घटकों का संरेखण। हमारे व्यापक सैद्धांतिक अध्ययन दो नवीन स्थिर अवस्थाओं, काइमेरा और सॉलिटॉन को उजागर करते हैं, जिनमें अलग-अलग ओरिएंटेशनल क्रम के तेज क्षेत्र होते हैं जो समकालिक रूप से युग्मित प्रणाली के माध्यम से घूमते हैं। निष्क्रिय निमैटिक में प्रेरित गतिशीलता अभूतपूर्व है। हम दिखाते हैं कि एएम और एलसी घटकों की सहजीवी गतिशीलता का उपयोग अन्यथा अव्यवस्थित प्रणाली में आदेश को प्रेरित और हेरफेर करने के लिए किया जा सकता है। हम एलएलसी में पैटर्न निर्माण पर ज्यामितीय बाधाओं और युग्मन के बीच अंतरसंबंध की भी संख्यात्मक रूप से जांच करते हैं। अध्ययन के मुख्य निष्कर्षों में माइक्रोफ्लुइडिक कुओं में लगातार भंवर के साथ गतिशीलता की स्थिति, लक्षित दवा वितरण में संभावित अनुप्रयोगों के साथ अनुरूप आकारिकी और अराजक सक्रिय कणों की नियंत्रित गति शामिल है। हमारा काम रोमांचक भविष्य के अनुप्रयोगों के लिए एएम और एलसी में हेरफेर करने के लिए कई विचार प्रदान करता है। हमें उम्मीद है कि यह एलएलसी में संयुक्त प्रायोगिक और सैद्धांतिक जांच शुरू करेगा।

अंत में, हम थीसिस में विकसित विचारों के निहितार्थ, भविष्य के परिप्रेक्ष्य और संभावित विस्तार पर चर्चा के साथ समाप्त करते हैं।

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List of Abbreviations

LC	Liquid crystal
NLC	Nematic liquid crystal
BNLC	Biaxial nematic liquid crystal
MNP	Magnetic nanoparticle
FN	Ferronematic
FP	Fixed-point
LSA	Linear stability analysis
LdG	Landau-de Gennes
LLC	Living liquid crystal
LRO	Long-range order
TDGL	Time-dependent Ginzburg-Landau
TT	Toner-Tu
GL	Ginzburg-Landau
LAC	Lifshitz-Allen-Cahn
LS	Lifshitz-Slyozov
CH	Cahn-Hillard
LCD	Liquid Crystal Display
BPT	Bray-Puri-Toyoki
SDM	Sub-domain Morphology