

An Introduction to Liquid Crystals

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An Introduction to Liquid Crystals

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*This book is dedicated to my family:
to my grandparents, Tommaso and Carmela Frate,
to my parents, Richard and Mary DiLisi,
to my siblings, Rick DiLisi, Carla Solomon, and Jennifer Newton,
to my wife, Linda,
to my daughter, Carmela,
and
to the wonderful creatures who inhabit our home.*

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Preface

Liquid crystals make today's modern world of technology possible. Flat-screen TVs, lightweight laptop computers, cellular phones, automotive dashboards, and a wide variety of electronic instrument panels all have liquid crystal displays (i.e. 'LCDs') embedded in their construction at some level. When you make copies at the office, a liquid crystal display provides the interface between you and the copier. When you watch the local morning talk show while pacing anxiously in the dentist's waiting room, you are probably watching a light-weight, wall-mounted liquid crystal monitor to get your information. When you pull out your cellphone to show friends and relatives selfies from your latest vacation, be sure to thank the technologies buried within the phone's liquid crystal screen for the rich colors and clear images that you see.

Practically every display technology in use today relies on the flat, energy-efficient construction made possible by liquid crystals. These displays provide visually-crisp, vibrantly-colored images that a short time ago were thought only possible in science fiction. Although liquid crystals are known mainly for their use in display technologies, they also provide many diverse and useful applications: adaptive optics, electro-optical devices, films, lasers, photovoltaics, privacy windows, skin cleansers and soaps, and thermometers [1–4]. The striking images of liquid crystals changing color under polarized lighting conditions are even on display in many museums and art galleries—true examples of '*science meeting art*.' Although liquid crystals provide us with visually stunning displays, fascinating applications, and are a rich and fruitful source of interdisciplinary research, their full potential may yet remain untapped.



At the Tate Liverpool Museum of British and International Modern and Contemporary Art, the exhibit '*Liquid Crystal Environment*,' is made by placing thermotropic liquid crystalline samples on five projectors fitted with polarizing filters and projecting their images onto two walls. The slides are heated and cooled to induce phase changes within the samples. The slides are also rotated atop their projectors. The phase changes and rotation of the samples are accompanied by vivid shifts in color that create the illusion of movement.

This book stems from the introductory section of my PhD thesis titled, ‘*Oligomeric Liquid Crystals: Viscoelastic Properties and Surface Interactions*’ [5]. Although the experimental techniques explored in the thesis focused on measuring the impacts of the molecular length and shape on the elastic deformations of various liquid crystalline systems, its introduction provides a solid foundation of liquid crystals for the novice investigator. When the thesis was written, the introduction nicely summarized the basic underlying physics, classifications, and properties of these fascinating systems ... today, it still does. Thus, I have taken this material, updated the content and diagrams, and packaged it into this introductory-level text. Finally, I highlight that two entirely new features have been added to the treatment. First, like any specialized field of study, research into liquid crystalline systems has its own lexicon. Thus, the etymology of all newly-defined, specialized terms has been included in this text. Research shows that students learn and retain information when such words, especially in STEM-fields, are accompanied by etymological and historical origins. Personally, I simply find that knowing the roots of new terminology, especially as I attempt to absorb the nuances of a new field of study, makes for a richer and more meaningful learning experience. Secondly, given the growing popularity and utility of liquid crystals, I have added a final section on the experimental techniques used to probe these systems.

References

- [1] Kopp V I, Fan B, Vithana H K M and Genack A Z 1998 Low-threshold lasing at the edge of a photonic stop band in cholesteric liquid crystals *Opt. Lett.* **23** 1707–9
- [2] Schmidt-Mende L, Fechtenkotter A, Mullen K, Moons E, Friend R and MacKenzie J 2001 Self-organized discotic liquid crystals for high-efficiency organic photovoltaics *Science* **293** 119–22
- [3] Bushby R J and Lozman O 2002 Photoconducting liquid crystals, current opinion in solid state & material *Science* **6** 569–78
- [4] Collings P J and Hird M 1997 *Introduction to Liquid Crystals* (Milton Park: Taylor & Francis)
- [5] DiLisi G A 1992 Oligomeric liquid crystals: viscoelastic properties and surface interactions *PhD Dissertation* Case Western Reserve University

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Charles Rosenblatt, PhD, Professor of Physics, Case Western Reserve University, and Ohio Eminent Scholar in Condensed Matter Physics. As my graduate advisor, Chuck guided the research from which my PhD dissertation sprang and from which this book evolved. Without Chuck’s subtle physical insights, experimental expertise, and mentorship, this book would not be possible. Much of the work appearing in these pages was the result of countless sleepless nights by the students studying in Chuck’s Liquid Crystal Research Group. Special thanks goes to my former lab-mates, **Zili Li**, **Minhua Lu**, and **Karl Crandall**, as well as to **Ian Nemitz**, on whose dissertation committee I served. Now scattered across the globe, these folks brought laughter to the daily grind of laboratory work. A finer crew was never assembled.

Vance Williams, PhD, Associate Professor and Chair of the Department of Chemistry at Simon Fraser University. Dr Williams graciously supplied the striking images of liquid crystalline samples that fill the pages of this book. He stands as a true example of international collaboration in the interest of advancing science.

My able and supportive team of publishers: **Susanne Filler** and **Melanie Carlson**, from Morgan & Claypool Publishers, who turned the idea of this book into reality; **Karen Donnison**, from Concise Physics, who worked long, thankless hours to produce the figures and diagrams contained in this book; and **Chris Benson** and **Heather McKenna**, from IOP Publishing, who work magic (literally overnight) to turn the chicken scratch of the initial drafts of this manuscript into the neat, polished version you see before you.

My graduate assistant, **Alison Chaney**. Although her expertise lies in the area of School Psychology, Alison read ... and re-read ... the many iterations of this manuscript, using her eagle eyes to catch the countless typographical and grammatical errors that riddled its initial versions. Alison’s work was very necessary and much appreciated.

My friend and the finest engineer walking the planet today, **Richard Rarick**. Rick’s interests in etymology sparked my own inclusion of word-origins in this book. His craftsmanship as an engineer and dedication to the art of teaching manifest themselves in several sections of this text. Rick’s attention to detail is simply unparalleled.

Finally, my editor, friend, and chemist extraordinaire, **James DeLuca**. Chemistry is Jim’s lifeblood. His knowledge of and passion for the subject created the many anecdotes on the industrial applications of liquid crystals which are sprinkled throughout the book. Jim answered questions, emails, and phone calls with patience, clarity, and his ever-present enthusiasm.

Biographies of the Author and Editor

Gregory Anthony DiLisi



Gregory Anthony DiLisi earned his Bachelor of Science degree, with distinction, from Cornell University in Applied and Engineering Physics. He then earned his Master of Science and Doctor of Philosophy degrees in Condensed Matter Physics from Case Western Reserve University. Since then, he has taught a wide range of physics courses at the high school, undergraduate, and graduate levels. He is currently at John Carroll University, where he has held appointments in two departments—physics and education. As a faculty member, he developed over sixteen courses on topics including: computational physics, experimental physics, instructional technology, interdisciplinary science, physics for engineers, problem-solving, science and society, and science methods. As an experimental physicist, he specializes in liquid crystals and complex fluids with publications appearing in peer-reviewed journals such as: *Journal de Physique II*, *Liquid Crystals*, *Microgravity Science and Technology*, and *Physical Review A*. His research focuses on the viscoelastic properties and surface interactions of oligomeric liquid crystals as well as the stability of liquid bridges as they shift from micro- to hyper-gravity environments. In the area of science education, his research initially focused on developing problem-solving strategies and team-building skills in undergraduate engineering and science students. However, his current research focuses on using case studies as a pedagogical approach to teaching physics. In these areas, he has publications appearing in peer-reviewed journals such as: *The Journal of College Science Teaching*, *The Journal of STEM Education: Innovation and Research*, and *The Physics Teacher*. He has been the Principal Investigator of externally-sponsored research through several grants from agencies such as: The American Association of Physics Teachers, The National Aeronautics and Space Administration, and The National Science Foundation. He was chosen to be the Ohio Educator Fellow for both of NASA's *Stardust* and *Cassini* space probes and serves as a consultant to numerous educational outreach initiatives. He has authored over forty peer-reviewed journal articles and is an international speaker, having presented at numerous scientific and educational conferences of various professional societies.

James Joseph DeLuca



James Joseph DeLuca received his Bachelor of Science degree in bio-chemistry. He worked in the private sector as an industrial chemist for over three decades. In this capacity, he worked at PPG Industries for thirteen years, where he conducted studies of pigment durability of exterior OEM coatings. He then spent ten years at Nippon Coatings as a Laboratory Manager, where he studied proprietary micro-to-nano aqueous emulsion technology and synthesis methods. Currently, he is the QC manager at Axalta Coatings Systems—Orrville where he oversees the company's laboratory and production development. Additionally, he conducts research and development for EnVont Nanotechnologies, LLC, where he explores quantum aqueous nano-technology and a novel synthesis platform technology. In 2016, he was granted an approved United States patent for Hybrid Vehicle Systems involving synthesis methods to create an environmentally-friendly, aqueous 4–6 nm hybrid zero-valent amorphous atomic metal within crystalline mixed metal-oxide nanocrystals.

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Chapter 1

History

Liquid crystals were first discovered, by accident, in the late nineteenth century at the Karl-Ferdinands-Universität by Austrian botanist and chemist Friedrich Reinitzer (1857–1927) (see figure 1.1(a)). In 1888, Reinitzer was making esters of cholesterol for his studies of plants. While examining the properties of cholesterols extracted from carrots, he noted that cholesteryl benzoate (i.e. $C_{34}H_{50}O_2$) exhibited not one, but two melting points that were associated with ‘*birefringence*’ and vivid iridescent color changes. (The term ‘*birefringence*’ will be introduced in section 4.1. Experimental techniques to determine the birefringence of a liquid crystal will be described in section 5.4.) Strangely, cholesteryl benzoate had the optical properties of crystals, but still flowed like a liquid. Reinitzer was unsure what to do about his discovery so he wrote a letter on March 14, 1888, describing his findings to German physicist Otto Lehmann (1855–1922) at Aachen University (see figure 1.1(b)). In his letter, Reinitzer stated that at 145.5 °C, the substance appeared to be a cloudy, fully liquid melt, while at 178.5 °C, the substance became entirely clear. Reinitzer also noted that these transitions were completely reversible. Reinitzer asked Lehmann, who was one of the first researchers to combine a polarized optical microscope with a hot stage, to confirm the unusual phenomenon of two melting points. Today, the hot stage and polarized optical microscope are considered standard equipment in liquid crystal research. Lehmann, also working on materials with similar behavior, responded by labeling the substances as, ‘*flüssige krystalle*’ or, ‘*flowing crystals*.’ Thus, Lehmann coined the phrase by which these substances are now known: ‘*liquid crystals*.’

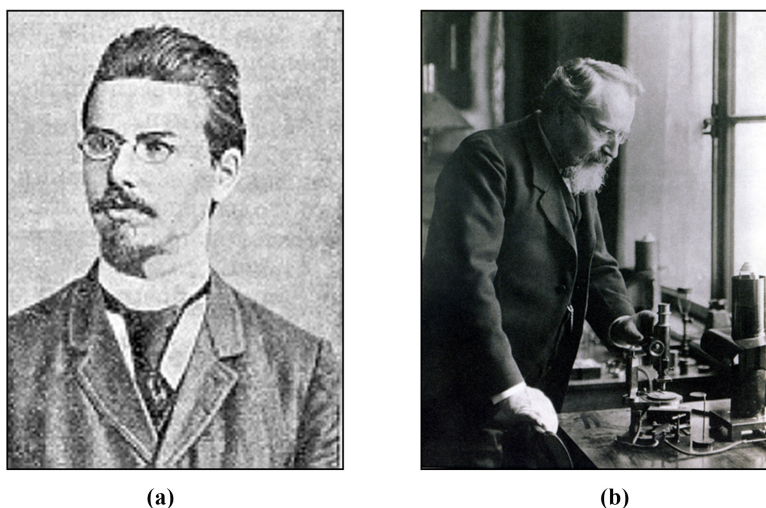


Figure 1.1. The ‘founders’ of liquid crystal research. (a) Friedrich Richard Reinitzer (1857–1927) and (b) Otto Lehmann (1855–1922).

Etymology:

The word ‘liquid’ is derived from the Latin words ‘liquere’ or ‘liquidis,’ which translate into ‘flowing’ or ‘capable of flowing.’

The word ‘crystal’ is derived from the Greek word ‘krústallos’ that translates into ‘clear ice.’

Reinitzer and Lehmann continued their correspondence and came to realize that they were observing a new, intermediate phase of matter—that is to say, a phase that had properties of both a crystal and a liquid. Reinitzer then published what is considered the first recognized research on liquid crystals: ‘*Beiträge zur Kenntnis des Cholesterins*’ (i.e. ‘*Contributions to the Knowledge of Cholesterols*’) [1]. While Reinitzer’s interest in liquid crystals waned, Lehmann continued researching the mysterious substances. Using his combination hot stage-and-polarized optical microscope, he was able to make high-temperature observations. He learned to control the conditions under which these materials changed phases and could thereby study the properties these substances exhibited while in their various phases. Lehmann’s paper, ‘*Über fließende Krystalle*’ (i.e. ‘*On Flowing Crystals*’), presented on October 25, 1889, opened a new chapter of materials research and laid the foundation of the science of liquid crystals [2].

At first, liquid crystals were thought to be something akin to ‘novelties’ or ‘curiosities’ in nature—strange, peculiar substances that were interesting to observe but that provided no practical application. However, liquid crystal research quickly flourished and since that time, thousands of organic compounds have been found to exhibit this same type of behavior [3]. In the early part of the twentieth century,

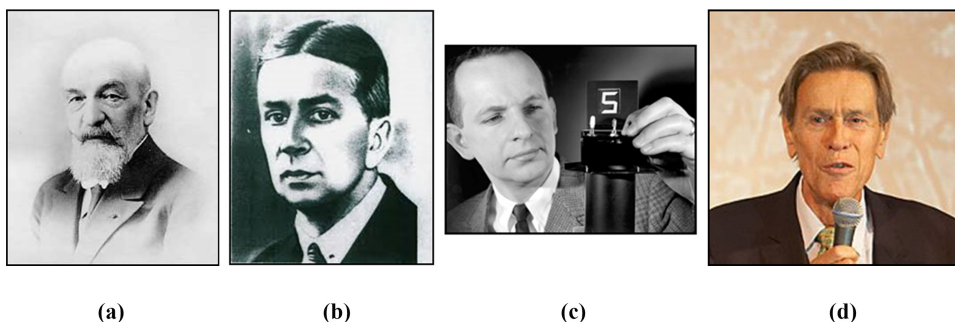


Figure 1.2. Pioneers of liquid crystal research. (a) Georges Friedel (1865–1933), (b) Vsevolod Fréedericksz (1885–1944), (c) George Heilmeyer (1936–2014) and (d) Pierre-Gilles de Gennes (1932–2007). ((d) credit: Wikimediacommons / CC-BY-SA 2.5 (<https://creativecommons.org/licenses/by-sa/2.5/deed.en>).)

German chemist Daniel Vorländer (1867–1941) began synthesizing various liquid crystalline samples and, by his retirement in 1935, determined methods for creating most of the known liquid crystals at that time. In 1922, French mineralogist and crystallographer Georges Friedel (1865–1933) published a 200 page work *‘Les États Mésomorphes de la Matière’* (i.e. *‘Mesomorphic States of Matter’*) in which he proposed the classification scheme of liquid crystalline phases that are still used today (see figure 1.2(a)) [4]. Friedel’s classification scheme will be discussed in more depth in chapter 4. In 1927, Russian physicist Vsevolod Fréedericksz (1885–1944) applied external fields to produce phase transitions in liquid crystals (see figure 1.2(b)). When a sufficiently strong electric or magnetic field is applied to a liquid crystal in an undistorted state, a phase transition will result as components of the crystal align to the field. This transition, labeled the *‘Fréedericksz transition,’* is discussed in chapter 5. Starting in the 1940s, Scottish organic chemist George Grey (1926–2013) characterized the phases of various samples under different conditions and essentially systematized the field of liquid crystals. His book, *‘Molecular Structure and the Properties of Liquid Crystals,’* published in 1962, became instrumental in laying the foundation of the liquid crystal display industry [5]. Despite Grey’s work, the high-temperature needed to cause samples to undergo various phase transitions made initial attempts at displays very impractical. Over time, chemists learned to mix various compounds to produce samples capable of operating over a wide temperature range.

Once chemists synthesized samples that could undergo these phase changes at room temperatures, practical display devices soon became possible. As a result, research into flat panel liquid crystal displays took off in the 1960s, thanks in large part to researchers at the RCA Corporation in Princeton, New Jersey. There, in 1962, physical chemist Richard Williams (1927–) was working on the concept of a TV that was light enough to mount directly to a wall. He applied a voltage to a thin layer of liquid crystals and generated *‘zones’* or *‘domains’* of striped patterns as the sample changed its alignment in response to the applied field. These *‘Williams Domains’* were the precursors of the pixels found in today’s liquid crystal displays.

In the late 1960s, George Heilmeyer (1936–2014), also at RCA and working on the ‘TV-on-a-wall’ concept, continued Williams’ research and discovered several new electro-optical effects in liquid crystals. He demonstrated the first liquid crystal display, using what he called the ‘*dynamic scattering mode*,’ soon afterwards. Heilmeyer and his team are usually credited with the invention of the liquid crystal display (see figure 1.2(c)). In the 1970s, Indian physicist Sivaramakrishna Chandrasekhar (1930–2004) synthesized disc-shaped molecules for use in liquid crystal research, followed shortly thereafter by Chinese physicist Lui Lam (1944–), who did the same for bowl-shaped molecules (called ‘*bowlics*’) in the 1980s. The shapes of the components of liquid crystalline systems will be addressed in chapter 3.

By the 1990s, research into liquid crystals had clearly grown and evolved into a field rich in its potential for advancing fundamental science as well as its innovative applications beyond the realm of display technologies. As a testimony of how far the field has come in the brief time since Reinitzer’s discovery, French physicist Pierre-Gilles de Gennes (1932–2007) was awarded the Nobel Prize in Physics in 1991 for his work on liquid crystals (see figure 1.2(d)) [6]. The citation on his prize reads: ‘*for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers*’ [7]. However, to date, de Gennes is the only scientist to receive the prize in the area of liquid crystals.

References

- [1] Reinitzer F 1888 Beiträge zur kenntniss des Cholesterins *Monatsh. Chem.* **9** 421–41
- [2] Lehmann O 1889 Über fließende Krystalle *Z. Phys. Chem.* **4** 462
- [3] Chandrasekhar S 1988 Recent developments in the physics of liquid crystals *Contemp. Phys.* **29** 527
- [4] Friedel G 1922 Les États Mésomorphes de la Matière *Ann. Phys.* **9** 273–474
- [5] Gray G W 1962 *Molecular Structure and the Properties of Liquid Crystals* (Cambridge: Academic)
- [6] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [7] Nobel Media *The Nobel Prize in Physics 1991* Nobel Prize.org (15 April 2019). Retrieved from <https://nobelprize.org/prizes/physics/1991/summary/> on 4 April 2019

Full list of references

Prelims

- [1] Kopp V I, Fan B, Vithana H K M and Genack A Z 1998 Low-threshold lasing at the edge of a photonic stop band in cholesteric liquid crystals *Opt. Lett.* **23** 1707–9
- [2] Schmidt-Mende L, Fechtenkötter A, Mullen K, Moons E, Friend R and MacKenzie J 2001 Self-organized discotic liquid crystals for high-efficiency organic photovoltaics *Science* **293** 119–22
- [3] Bushby R J and Lozman O 2002 Photoconducting liquid crystals, current opinion in solid state & material *Science* **6** 569–78
- [4] Collings P J and Hird M 1997 *Introduction to Liquid Crystals* (Milton Park: Taylor & Francis)
- [5] DiLisi G A 1992 Oligomeric liquid crystals: viscoelastic properties and surface interactions *PhD Dissertation* Case Western Reserve University

Chapter 1

- [1] Reinitzer F 1888 Beiträge zur kenntniss des Cholesterins *Monatsh. Chem.* **9** 421–41
- [2] Lehmann O 1889 Über fließende Krystalle *Z. Phys. Chem.* **4** 462
- [3] Chandrasekhar S 1988 Recent developments in the physics of liquid crystals *Contemp. Phys.* **29** 527
- [4] Friedel G 1922 Les États Méso-morphes de la Matière *Ann. Phys.* **9** 273–474
- [5] Gray G W 1962 *Molecular Structure and the Properties of Liquid Crystals* (Cambridge: Academic)
- [6] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [7] Nobel Media *The Nobel Prize in Physics 1991* Nobel Prize.org (15 April 2019). Retrieved from <https://nobelprize.org/prizes/physics/1991/summary/> on 4 April 2019

Chapter 2

- [1] Next Generation Science Standards 2019 *2-PS1 Matter and Its Interactions* www.nextgen-science.org/dci-arrangement/2-ps1-matter-and-its-interactions
- [2] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [3] Friedel G 1922 Les États Méso-morphes de la Matière *Ann. Phys.* **9** 273–474

Chapter 3

- [1] Nemitz I R 2017 Liquid crystals: surfaces, nanostructures, and chirality *PhD Dissertation* Case Western Reserve University
- [2] Williams V 2019 *Liquid Crystal Microscopy* Simon Fraser University. Retrieved from lcmicroscopy.weebly.com on 31 March 2019
- [3] Priestly E 1976 *Introduction to Liquid Crystals* (New York: Springer)
- [4] Collings P J and Hird M 1997 *Introduction to Liquid Crystals* (Milton Park: Taylor & Francis)
- [5] Scutaru D, Carlescu I, Bulai E-R, Ciobanu C I, Lisa G and Hurduc N 2019 *Bent-Core Liquid Crystals: Structures and Mesomorphic Properties* (London: IntechOpen Limited)
- [6] Jakli A 2013 Liquid crystals of the twenty-first century—nematic phase of bent core molecules *Liquid Cryst. Rev.* **1** 65–82

- [7] Collings P J 1990 *Liquid Crystals: Nature's Delicate Phase of Matter* (Princeton: Princeton University Press)
- [8] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [9] Ciferri A, Krigbaum W R and Meyer R B 1982 *Polymer Liquid Crystals* (New York: Academic)
- [10] Akins R B 1991 Dielectric investigation of double glass transitions in polymers *PhD Dissertation* Case Western Reserve University
- [11] DiLisi G A, Rosenblatt C S, Griffin A C and Hari U 1992 Viscoelastic properties of a liquid crystalline monomer and its dimer *Phys. Rev. A* **45** 5738–45
- [12] DiLisi G A, Rosenblatt C S and Griffin A C 1992 Bend elastic modulus of a bent and straight dimeric liquid crystal *J. Phys.* **2** 1065–71
- [13] DiLisi G A, Rosenblatt C S, Griffin A C and Hari U 1990 Behavior of the anchoring strength coefficient near a structural transition at a nematic-substrate interface *Liquid Cryst.* **7** 353–60
- [14] DiLisi G A, Rosenblatt C S, Griffin A C and Hari U 1990 Splay elasticity in an oligomeric liquid crystal *Liquid Cryst.* **8** 437–43
- [15] DiLisi G A, Rosenblatt C S, Akins R B, Griffin A C and Hari U 1992 Anchoring strength coefficient of a monomer and its dimer at a polymer-coated interface *Liquid Cryst.* **11** 63–71
- [16] DiLisi G A, Terentjev E M, Griffin A C and Rosenblatt C S 1993 Viscoelastic properties of a bent and straight dimeric liquid crystal *J. Phys.* **3** 597–602
- [17] Solomons T W G and Fryhle C B 2013 *Organic Chemistry* (Hoboken: Wiley)
- [18] March J and Smith M B 2007 *March's Advanced Organic Chemistry: Reactions, Mechanisms, and Structure* 6th edn (Hoboken: Wiley)

Chapter 4

- [1] DiLisi G A 1992 Oligomeric liquid crystals: viscoelastic properties and surface interactions *PhD Dissertation* Case Western Reserve University
- [2] Li Z 1991 A magneto and electrooptic study of ferroelectric liquid crystals *PhD Dissertation* Case Western Reserve University
- [3] Rosenblatt C S 1978 A light scattering study of ferroelectric liquid crystal thin films *PhD Dissertation* Harvard University
- [4] Nemitz I R 2017 Liquid crystals: surfaces, nanostructures, and chirality *PhD Dissertation* Case Western Reserve University
- [5] Nemitz I R, Lacaze E and Rosenblatt C S 2016 Electroclinic effect in a chiral paranematic liquid-crystal layer above the bulk nematic-to-isotropic transition temperature *Phys. Rev. E* **93** 022701
- [6] Cheng J and Meyer R B 1972 Pretransitional optical rotation in the isotropic phase of cholesteric liquid crystals *Phys. Rev. Lett.* **29** 1240–3
- [7] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [8] Salisbury D F *New Family of Liquid Crystals Created* Phys.Org (5 October 2010). Retrieved from <https://phys.org/news/2010-10-family-liquid-crystals.html> (31 March 2019)
- [9] Ringstrand B and Kaszynski P 2013 Functionalization of the [closo-1-CB9H10]– Anion for the Construction of New Classes of Liquid Crystals *Acc. Chem. Res.* **46** 214–25
- [10] Williams V 2019 *Liquid Crystal Microscopy* Simon Fraser University. Retrieved from lcmicroscopy.weebly.com (31 March 2019)

- [11] de Gennes P G and Prost J 1993 *The Physics of Liquid Crystals* 2nd edn (London: Clarendon)
- [12] Chandrasekhar S 1977 *Liquid Crystals* (Cambridge: Cambridge University Press)
- [13] Davidson M W 2019 *Precholesteric to Cholesteric Phase Transition* Florida State University. Retrieved from <https://micro.magnet.fsu.edu/dna/pages/cholesteric1.html> (31 March 2019)
- [14] Kopp V I, Fan B, Vithana H K M and Genack A Z 1998 Low-threshold lasing at the edge of a photonic stop band in cholesteric liquid crystals *Opt. Lett.* **23** 1707–9
- [15] Muoz A, Palffy-Muhoray P and Taheri B 2001 Ultraviolet lasing in cholesteric liquid crystals *Opt. Lett.* **26** 804
- [16] Ozaki M, Kasano M, Ganzke D, Haase W and Yoshino K 2002 Mirrorless lasing in a dye-doped ferroelectric liquid crystal *Adv. Mater.* **14** 306
- [17] Cao W, Muoz A, Paffy-Muhoray P and Taheri B 2002 Lasing in a three-dimensional photonic crystal of the liquid crystal blue phase II *Nat. Mater.* **1** 111–3
- [18] Coskun S, Eran B B, Cankurtaran O and Karaman F 2009 Thermodynamics of the mixture of a liquid crystal and a copolymer of dimethylsiloxane *J. Optoelectron. Biomed. Mater.* **1** 91–102

Chapter 5

- [1] Chatelain P 1943 *Bull. Soc. Fr. Miner.* **66** 105
- [2] Zili L, DiLisi G A, Petschek R and Rosenblatt C S 1990 Nematic electroclinic effect *Phys. Rev. A* **41** 1997–2004
- [3] Zili L, Akins R B, DiLisi G A, Rosenblatt C S and Petschek R 1991 Anomaly in the dynamic behavior of the electroclinic effect below the nematic-smectic-A phase transition *Phys. Rev. A* **43** 852–7
- [4] DiLisi G A, Rosenblatt C S, Akins R B, Griffin A C and Hari U 1992 Anchoring strength coefficient of a monomer and its dimer at a polymer-coated interface *Liq. Cryst.* **11** 63–71
- [5] DiLisi G A, Rosenblatt C S, Griffin A C and Hari U 1990 Behavior of the anchoring strength coefficient near a structural transition at a nematic-substrate interface *Liq. Cryst.* **7** 353–60
- [6] Haller I and Huggins H A 1972 U. S. Pat. 3 656 834 (Cl. 350/150; G02f)
- [7] Haas W, Adams J and Flannery J 1970 *J. Phys. Rev. Lett.* **25** 1326
- [8] Creagh L T and Kmetz A R 1973 *Mol. Cryst.* **24** 59
- [9] Proust J E, Ter-Minassian L and Guyon E 1972 *Solid State Comm.* **11** 1227
- [10] Rosenblatt C S 1984 *J. Phys., Paris* **45** 1087
- [11] Horn R G 1978 *J. Physique* **39** 105
- [12] de Gennes P G 1974 *The Physics of Liquid Crystals* (London: Oxford University Press)
- [13] Oseen C W 1933 *Trans. Faraday Soc.* **29** 883
- [14] Zocher H 1933 *Trans. Faraday Soc.* **29** 945
- [15] Frank F C 1959 *Discuss. Faraday Soc.* **25** 19
- [16] Ericksen J L 1966 *Archs. Ration. Mech. Analysis* **23** 266
- [17] Collings P J and Hird M 1997 *Introduction to Liquid Crystals* (Milton Park: Taylor & Francis)
- [18] Chandrasekhar S 1977 *Liquid Crystals* (Cambridge: Cambridge University Press)
- [19] DiLisi G A, Rosenblatt C S, Griffin A C and Hari U 1990 Splay Elasticity in an Oligomeric Liquid Crystal *Liquid Crystals* **8** 437–43