Optical Properties of DeVries Liquid Crystals and a Look at Ultra Thin Freely Suspended Smectic Films

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Liquid crystals exist as a fourth state of matter. They are anisotropic and due to this order, they affect light that passes through them, making them ideal candidates for optical study. By employing a basic technique for measuring a liquid crystal's birefringence and tilt angle, one is able to study a number of other properties such as the electroclinic effect. In addition, smectic liquid crystals have been studied intently because of their ability to create stable ultra-thin films of quantized layer thickness. These thin films have been studied due to the fact that they are an ideal system for investigating two dimensional textures of biomembranes, hydrodynamics and interaction between inclusions. These 2D systems have been used to determine hydrodynamic properties such as mobility, viscosity, diffusions coefficients, etc [1]. This discussion will first take a look at the optical analysis that has been done on mainly DeVries liquid crystals and then continue on to describe the experimental process behind studying ultra thin freely suspended films along with some preliminary results.

I. INTRODUCTION

Liquid crystals have become extremely prevalent in modern society. This fourth phase has many distinctive properties that make it very useful in a number of different technologies. Their current uses can be found in the display industry and have entirely transformed the way screens, whether on your computer, cell phone, or TV, are built. Also liquid crystals can be found in a variety of different biological systems in the human body, which makes them a source of medical research as well. One increasing area of study is that of 2D liquid crystal films, much like a soap bubble, that can serve as a model of biological membranes such as the lipid bilayer of cell walls and the surfactant film of the lungs. These areas are what make liquid crystal research a rapidly growing area of study worldwide.

FIG. 1: The structure of two layers of smectic A and smectic C calamitic liquid crystals. The **z** director represent the layer normal, where the **n** director represents the molecular field vector. The angle between the two directors is known as the tilt angle [16].

II. BACKGROUND & THEORY OF LIQUID CRYSTALS

Historically, the standard phases of matter have been crystal, liquid, and gas. In the crystalline phase, a material has both positional and orientation order. Materials in the liquid phase have no such order and diffuse randomly. However, some substances exist that exhibit order between both a crystal and liquid. This order can vary in type and magnitude and within the liquid crystal phase itself there are many sub-phases, or mesophases, "these phases are grouped together and called liquid crystals" [10]. All phases have some orientation order, and some phases such smectic A and smectic C have positional order in which the liquid crystal molecules align themselves in layers as illustrated in Fig. 1.

There are various types of liquid crystals. Calamitic phases are formed by rod-shaped molecules, while discotics are formed by disc-like molecules. Then, characteristically, there are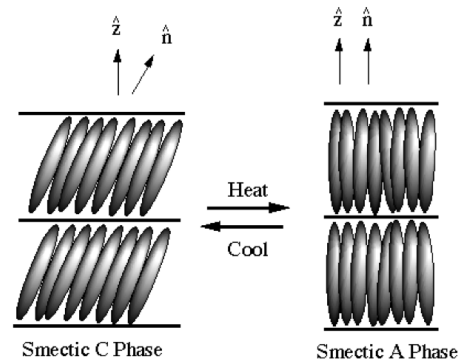 thermotropic liquid crystals that, "change phases with temperature and are often composed of a single type of molecule [11]. Lyotropic materials form, "liquid crystal phases only when mixed with a solvent of some kind [10]. The mesophase of a lyotropic liquid crystal is dependent on the concentration in the solvent. All liquid crystals are anisotropic, meaning at least one molecular axis is unique. For the purpose of this paper we will talk about thermotropic calamitic liquid crystals.

Beyond the general group of thermotropic calamitic liquid crystals, in the optical experiment, the materials used were what are considered de Vries liquid crystals. This type of material is unique in two ways. First of all, de Vries materials do not experience layer shrinkage when transitioning from smectic A to smectic C. This is an unusual effect and it has been theorized that this could cause a destruction of the layer order in certain cases. In addition, de Vries materials lack a nematic phase about the smectic A phase. This can cause issues aligning the

samples because materials that lack the nematic phase often do not generate large defect free regions.

Two of the main characteristics that define smectic liquid crystals are birefringence, Δn, and tilt angle, Θ. By analyzing of these and their responses to temperature and applied electric field, we can contribute to the on-going research into how these de Vries liquid crystals behave as a whole.

As a liquid crystal material decreases in temperature from the isotropic or liquid phase to a solid it can go through a number of different transitions unique to these materials. In the de Vries materials that we have been researching, the samples first experience the smectic A and smectic C phases. When the sample is in the smectic A phase, the molecules are aligned along the layer normal. However, when it transitions into smectic C, the molecules tilt at an angle, Θ, from the layer normal. This movement of the molecules is the tilt angle that we are trying to measure with our experiments. This tilt is not directionally unique. The molecule is energetically free to move around the axis of the layer normal. This in turn creates what can be called a "tilt cone". The magnitude of the tilt angle in the sample alters the optical changes that the liquid crystal makes to the incident light. As the sample is cooled, the angle from the layer normal increases until it approaches its maximum tilt possible.

Some liquid crystal phases, including smectic phases, are birefringent. This means that when light passes through a liquid crystal, the light is subject to two different optical axes. The light then interacts differently depending on which axis it is polarized along. The two optical axes in liquid crystals are called the fast and slow axes. The fast axis lies perpendicular to the molecules. The electrons have limited mobility along this axis and ultimately this causes a low index of refraction. Conversely, the slow axis lies parallel to the molecules and the electrons are able to freely move. When the sample is in the smectic A phase, the liquid crystal is uniaxial and only one axis causes an effect. However in smectic C, it is higher primarily because the molecules are more aligned along the director than the Smectic A phase. In normal smectic materials, there is only a small increase in birefringence from Smectic A to Smectic C, but in de Vries materials there is a very large increase. This As the light travels through the sample, propagating at different rates, it becomes out of phase. The birefringence refers to the difference of the two indices of refraction, Δn. The width of the sample and the specific birefringence cause the light rays to go out of phase a certain extent. Thus when the light that passes through cross polarizers is recombined upon leaving the sample the light is linearly polarized, but it is rotated from its original orientation.

What makes the deVries liquid crystals that we study so unique is that fact that when they experience a phase transition, the volume does not change between Smectic A and Smectic C. This is a very advantageous property of devices utilizing ferro- and antiferroelectric liquid crystals [7]. It is much easier to deal with a sample of constant volume that one which varies as a function of temperature or phase.

III. OPTICAL PROPERTIES SETUP

In order to measure the qualities needed to indentify these characteristics one needs a microscope, camera, temperature controller and oven, as well as a function generator. Other than the raw physical tools needed, we also use a basic C program to control and write the temperature data and a collection of Matlab scripts to collect and analyze data. All of the required tools were already available and set up in Dr. Fernsler's laboratory so it was simply a matter of implementing the experimental procedures that will be described later and taking data to perfect the process.

This summer we used a method designed by Saipa and Giesselman to measure tilt angle and birefringence. The overall setup contains the sample that is analyzed inside of an temperature-controlled oven. This oven is placed between two polarizers mounted on a microscope and a monochromator is used to filter out all light except that of a specific wavelength. Finally a CCD camera is connected to the microscope and interfaces with a computer. The data from the photodiode is compiled in Matlab over a specific area that the user defines. The data is then written to an Excel file with a user created filename. The temperature controller on the oven is also automated and is set to take data every second.

The method developed by Saipa and Giesselman takes 4 different sets of data. You take a temperature sweep for each of the following: first have the polarizers crossed with the smectic layer normal aligned with the polarizer, then rotate the sample 45 degrees with the polarizers still crossed, then uncross the polarizers and take data with the sample both aligned and rotated 45 degrees again [6]. These measurements provide us with the values of I1, I2, I3, and I4 which, along with the thickness of the sample and know wavelength, allow us to calculate the birefringence and tilt angle using the equations provided in Saipa and Giesselman's article. The raw data that comes out of the experiment is then analyzed in a program, analyzing.m. This plots the intensity as a function of temperature and ultimate will plot intensity as a function of both temperature and applied electric field.

IV. RESULTS OF BIREFRINGENCE AND TILT ANGLE MEASUREMENTS FOR W652

By employing the method developed by Saipa and Giesselman, the birefringence and tilt angle were measured directly and for one sample the smectic helix was visible. The analysis done on this data included a Matlab smoothing function to reduce the noise of the data.

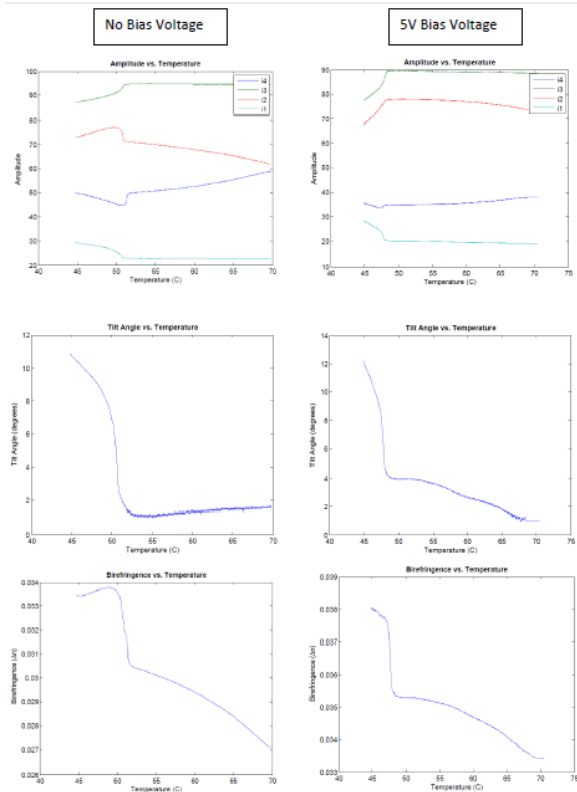When observing the original data in Fig. 2 one apparent effect that we did not correctly account for is a

FIG. 2: Experimental results of the W652 deVries liquid crystal. The left column is the data corresponding to a full run with no external applied field. The right column corresponds to a 1.25 V/micron electric field applied perpendicular to the layer normal.

resistive heating within the cell that causes a shift in the melting temperature of the sample. This effect is only present under an applied field. The melting point itself is not changing, but a differential between the temperature of the oven and the temperature of the sample arises due to this resistive heating. Thus, when running the experiment a second time, the temperature will be run over a slightly longer range and will be shifted according to the magnitude of the resistive heating.

When looking at the sample with no field applied, the tilt angle is approximately zero at the high temperatures in the smectic A phase and upon transitioning into the smectic C phase exhibits a constant increase in the tilt. On the other hand, when there is a field applied, it causes there to be a small induced tilt in the smectic A phase due to the polarity of the deVries molecules. Thus there is an overall increase in the tilt angle as a function of time.

Finally, the most interesting effect can be seen in the birefringence measurement. As expected, the birefringence increases slowly during the smectic A phase and the changes drastically upon reaching the A to C transition point. The unique part is the fact that the birefringence then decreases after the transition point as can be seen

in Fig. 2. This is brought about by the smectic C helix in which the liquid crystal molecules rotate around the tilt cone from one layer to the next effectively creating a helical structure. This helix makes it so that the incident light does not experience one uniform molecular director and thus does not experience as great of a birefringence. This result was verified via the bias voltage measurement. By applying a field to the material, it unwinds the helix and once again creates a uniform molecular director. As can be seen in the last birefringence measurement taken with the voltage, it does not decrease after the smectic C transition which does imply that the helix was successfully unwound and that it was indeed the effect that was observed in the original measurement.

When taking measurements of tilt angle and birefringence, an additional characteristic that can be calculated, the critical exponent for the mean square tilt fluctuations. This critical exponent is directly related to the heat capacity exponent α,

$$(\delta\theta)^2 \approx t^{1-\alpha} \qquad (1)$$

where t is the reduced temperature near the smectic A-smectic C transition $t = (T - T_{AC}/T_{AC})$ where T_{AC} is the transition temperature. In order to make this analysis, the log of the intensity and tilt angle is taken which will result in a linear behavior. Using a fit of the data, the slope of the linear relationship is found to be the critical exponent. A full analysis of this characteristic has not been made on the newer W652 material, but preliminary results showed an $\alpha \approx 0.25$. This is a reasonable value to consider and when the raw log data was considered a strong linear relationship was observed.

V. ELECTROCLINIC EFFECT

The ultimate goal of applying the experimental procedure developed by Saipa and Giesselmann is to measure the electroclinic effect in a variety of deVries materials. As is discussed above, by applying an electric field the birefringence of a material can be altered. The electroclinic effect is a tilt in the optic axis induced by an applied field. In studying de Vries liquid crystals, it has been seen that they have an unusually large electroclinic effect in the smectic A phase close to the transition.

Depending on the waveform, frequency, and magnitude of the voltage applied, the birefringence will vary differently. By measuring this dependence, a better understanding of how liquid behave can be achieved. The ability to make these measurements accurately was just reached in the lab at Cal Poly, however the framework to analyze such measurements has not be created, thus there is no data yet available for this property. The data to be collected will be compared to the theory developed by Cal Poly faculty member Dr. Saunders in his recently published article "Modeling the field control of the surface electroclinic effect near continuous and first-order
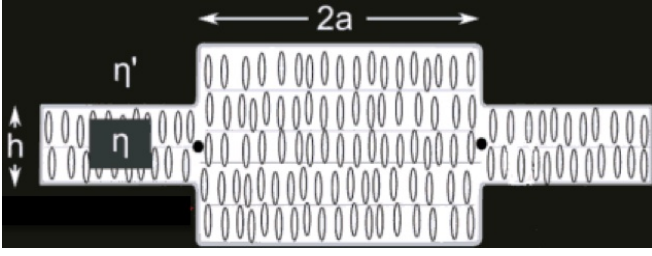
FIG. 3: The layer structure of a 5 layer smectic A island on a 2 layer background film.

smectic A* to smectic C* transitions" in the Physical Review journal. This will be one of the important areas of research to be conducted in the lab in the future.

VI. BACKGROUND & THEORY OF THIN FILMS

Freely suspended ultra-thin liquid crystal films have been studied in depth because of the ability make films with a thickness of several nanometers over an area of a few square centimeters, "making them the thinnest stable condensed matter system for probing surface effects or two-dimensional hydrodynamics" [5]. Thin films have future application in biological systems as they parallel many characteristics and behaviors of biological membranes such as lung surfactant [9]. By understanding liquid crystal films and characterizing specific materials we are able to further the pursuit of advancements such as artificial biological membranes which could save the lives of those who are born without them.

The word smectic comes from the Greek *smēktikos*, "having the properties of soap" [8]. Smectic materials create stable layers and this, "layering tendency of smectics make it easy to form homogeneous, ultra-thin freely suspended films that are quantized in thickness... and are stable for many hours (or days if not disturbed)" [5]. A standard film consists of a center area with uniform layer thickness and a thicker meniscus. In order to study hydrodynamic interactions, thicker, pancake-like domains (islands) can be created [12] in these idealized 2D systems.

Islands may be created in a number of ways. Simply blowing on the material or shrinking the size of the film quickly will cause islands to appear. Islands are made when smectic material is forced together and a stack of smectic layers emerge above the layer thickness of the background film as can be seen in Fig. 3. These stacks of smectic layers are bound by edge dislocation loops which, "cost energy per unit length, i.e. they have a line tension, i.e. they have a line tension $\lambda \sim \Delta N = N_i - N_b$, where N_i and N_b are the number of layers in the island and the background film respectively" [12]. Thus the islands become circular to minimize the boundary length. Islands also exhibit thin film interference, creating a wide vari-
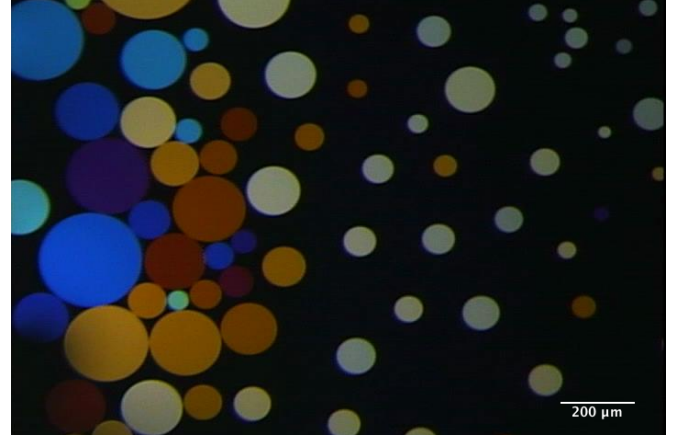

FIG. 4: A collection of islands of varying thickness. Thinner islands are grayscale and the colorful island emulsions correspond to islands above 20-30 layers where each layer is 3.1 nm thick.
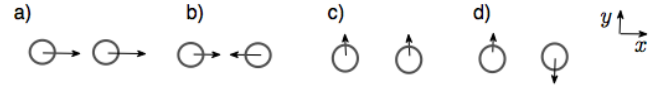

FIG. 5: The coupling effects felt by each corresponding island. The mobilities associated with each movement are as follows: a) $M_{11}^{rr} + M_{12}^{rr}$, b) $M_{11}^{rr} - M_{12}^{rr}$, c) $M_{11}^{\theta\theta} + M_{12}^{\theta\theta}$, d) $M_{11}^{\theta\theta} - M_{12}^{\theta\theta}$ [13]

ety of colors, such as can be seen in Fig. 4. This is the same effect brought on by a layer of oil on water and the colors that result from it. In liquid crystal films, the variety of color among the islands is brought on by different thicknesses. In Fig. 4, the black area is the background film, typically 2-5 layers thick, and has a very low reflectivity. The grayscale islands are thinner and thus have a higher reflectivity, but do not experience significant interference, typically 5-15 layers thick. The colorful islands correspond to much thicker domains, have high reflectivity, and are also effected by thin film interference. These islands can be anywhere from 20-100 layers and oscillate in color as thickness increases due to the interference on incident light.

When two or more islands exist in the same system, they do not remain independent of one another. Each island experiences a coupling force from the movement of the other. This force is separated into a self-component and mutual-component. In a freely suspended thin film, an island emulsion will have some mobility, μ, which describes the ease at which it can move about the film given some external force. This mobility is brought about from hydrodynamics and is dependent on the material. It can be determined by studying the velocity at which an island moves through a film given some known external
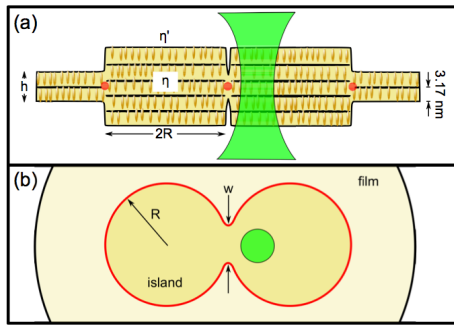
FIG. 6: Two islands in a smectic A liquid crystal film. a) A cross section of a liquid crystal island showing that it grows both above and below the background film. Each island has $N = 5$ layers and the background film has $N = 2$ layers. The red dots represent the edge dislocation loops. b) Top view of the coalesce of the two islands. A bridge forms between the two emulsions and material is exchanged until the coalescence result in one larger island [12].

force, such as gravity.

$$\mu = \frac{v}{F} \qquad (2)$$

Extending the system to two islands, the mobility can be represented by M, "where M_{11} is the self-mobility matrix and M_{22} is the mutual-mobility matrix... the only nonvanishing components of the mobility are diagonal elements M_{11}^{rr}, $M_{11}^{\theta\theta}$, M_{12}^{rr}, and $M_{12}^{\theta\theta}$" [13]. Within this coupling, M^{rr} corresponds to movement of the islands in the direction of the vector that defines their seperation, situations a) and b) of Fig. 5. Conversly, $M^{\theta\theta}$, describes the motion of the islands perpendicular to their seperation, situations c) and d) of Fig. 5. This coupling effect has been studied in detail in a one and two island system, however the collective effects that this coupling has on many island systems is still unknown.

When an external force or coupling drives two islands close enough together, a smectic A liquid crystal island can experience coalescence. Coalescence means that the two islands join together into one larger island, the same effect occurs when two water droplets are brought together. This coalescence is driven by the line tension of the edge dislocation loops. The line tension may be minimized for two islands if, when they aggregate, they coalesce and become one larger circular island, minimizing the total circumference. This can be seen in Fig. 6. This coalescence may also happen with an island and the meniscus, in which the island effectively disappears from the bulk of the film. By studying how the coalescence of islands happens over time, one may understand more about the dynamics of the liquid crystal film.

VII. THIN FILM SETUP

The smectic A liquid crystal films were studied using two separate compounds. The first of which is 12160 that was synthesyzed by DisplayTech Inc., a calamitic mesogen, consisting of a mixture of 80% 2619 and 20% 2486, shown in Fig. 7 a). The second compound studied was 8CB, also a calamitic mesogen, is a very well characterized material that has been studied extensively in the field of freely suspended liquid crystal films, whose chemical structure is shown in Fig. 7 b). 8CB is used to create very thin films with a small ΔN between the islands and background film, however 8CB is not ideal for the creation of 3.5 cm diameter films and is used mainly on a 1 cm diameter film holder. 12160 on the other hand often creates thicker films that remain stable for extensive periods of time over a larger surface area.

Using reflection microscopy, these two compounds are studied in films of both 1 cm and 3.5 cm diameter. The sample is contained in a horizontal metal box with windowed covers on both the top and bottom to reduce any air flow or turbulence that may be brought about by the surroundings. The windows on the covers are angled such as to negate any reflection from the windows themselves. Each of the two film holders fit tightly inside of the sample box and may be removed and replaced in order to change the diameter of the film. Using two holes drilled in the side of the box, tubes are fed into the box which connect to two, coaxially facing, needles. These needles are connected to a handle which can move horizontally and are used to create a shear on the film. This shear is used to break larger, thicker regions into smaller regions and island emulsions. Using compressed nitrogen gas and a variable pressure valve, we are able to control the duration and magnitude of the disturbance that the air causes on the films.

On the opposite side of the film holder, a sharp piece of copper sheet is connected to another handle that can be moved horizontally across the film holder. This copper sheet is 5 cm wide in order to span the entire diameter of the larger film holder. The copper piece is used as a film spreader and is connected to an auto translation device that can draw the sheet across the opening of the film holder at a variety of quantized speeds. The speed at which a film is drawn changes the thickness of the resultant film. This method of creating ultra-thin films works well with the creation of large films, such as the 1-3.5 cm films.

The sample box with film holder is placed on a metal plate with a hole, slightly larger than the film holder, drilled into it. Below the hole, a beam splitter, lens, lamp, and black sheet of felt are used to create a reflective macroscopic view of the film that is captured by a JVC Everio camcorder. This allows for the study of the entirety of the film, however at low resolution and cannot be used on the 1 cm film holder. Above the sample box, a similar, more compact setup uses a beam splitter and light source to generate the microscopic view of the film

(a)

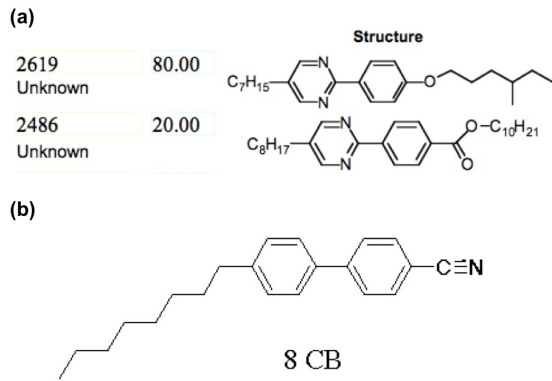| 2619 Unknown | 80.00 |
| 2486 Unknown | 20.00 |

(b)

8 CB

FIG. 7: a) Chemical structure and make up of 12160. b) Chemical structure of 8 CB.

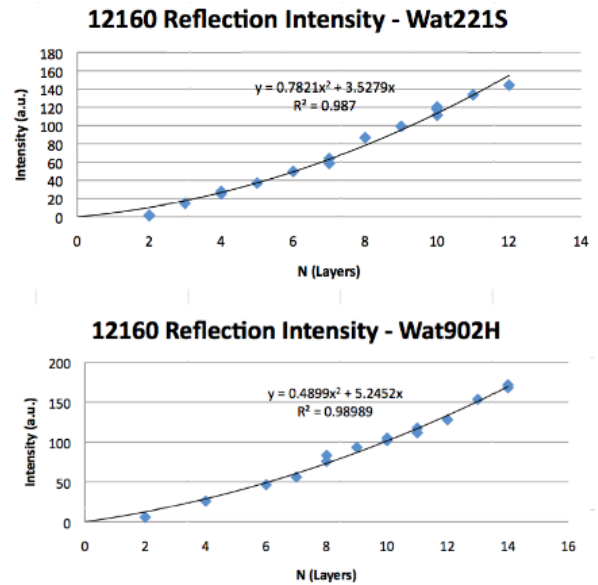FIG. 8: Experimental setup using reflection to obtain both a macroscopic and microscopic view

FIG. 9: top: calibration of reflection intensity as a function of island thickness on Watec 221S CCD camera. bottom: calibration of Watec902H Ultimate CCD camera.

VIII. CHARACTERIZATION OF 12160

Unlike 8CB, the DisplayTech liquid crystal mixture 12160 has not been characterized and thus must be tested in order to prepare for future analysis of the properties it exhibits. The first quality that must be understood is the relation between reflected intensity as a function of thickness. As was stated and shown in Fig. 1, smectic A liquid crystal form into a quantized thickness of layers. Islands that are still thin enough to be grayscale are measured to determine the intensity dependence on thickness because there are no oscillations in the interference at these lower thicknesses. Using an image with a variety of different grayscale island emulsions, each island is analyzed and an estimate thickness is allotted. The intensities are then plotted as a function of thickness and a polynomial fit is applied, as seen in Fig. 9 , that intersect the origin. Using this method, outliers are identified and adjusted as to correctly model the reflection intensity vs. thickness. These measurements are specific to the camera and settings on it. Therefore, both the Watec 221S camera was calibrated as well as a Watec 902H Ultimate on a separate reflection microscope.

Using the calibration, the viscosity of 12160 can be calculated. On a different microscopic set up with a Watec 902H Ultimate CCD camera, a thin film with emulsions is created. Emulsions are then blown on the film and manipulated by hand until one island stand alone in the film as to not be effected by island coupling. The microscope and stage are then rotated as to apply an external force using the in-plane component of gravity. A microscopic micrometer calibrates the microns per pixel conversion

through a 5x objective. This view is captured by a Watec 221S CCD camera. The microscopic view is used to study the islands as collective groups and provides a close up view of both coalescence and the coupling effects brought on by island diffusion. Although both macroscopic and microscopic views are functional, both may not be used simultaneously.

More recently, this same type of setup was built in the Cal Poly lab for the purpose of working along side the UC Boulder LCMRC group. Although it currently lacks the ideally controlled environment devoid of the influence of air flow, thermal convection, and gravity. However, a thin film of approximately 5-10 layers was created and emulsions of 10-20 layers were created on it. The film was stable and the video feed of the sample was acceptable for future measurements. With a few adjustments and the application of a concrete experimental procedure, Cal Poly will also be able to partake in the unique field of ultra thin freely suspend liquid crystal films.
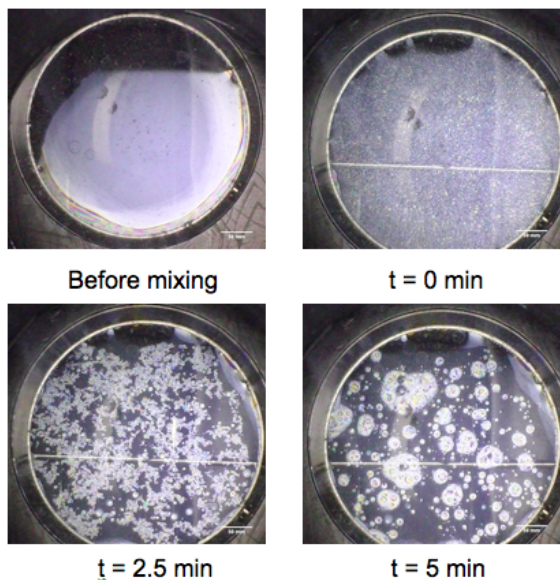
FIG. 10: A time progression of the macroscopic view, before and after the island emulsions have been blown. The needles can be seen at the center of the last three images. Also shows the time progression of coalescence on the macroscopic scale.

in order to determine the size and radius of an island for analysis. The island is then tracked over time to find the velocity of the island. Using the size and calibrated layer thickness of the island, the gravitational force is then calculated and used along with the velocity measurement to determine the mobility of the island using Eq. 2. Then, using the previous quantities and mobility, μ, the viscosity of 12160 can be determined using Eq. 3, where η is the bulk viscosity and h is the layer thickeness.

$$\mu = \frac{1}{16\pi a \eta h} \qquad (3)$$

This equation represents the three dimensional diffusion model of an island. In order for the island to fit this model it must have a radius approximately ten times the Saffman length, l_s, which is a constant of the film defined by Eq. 4 [14].

$$l_s = \frac{\eta h}{2\eta'} \qquad (4)$$

Once the viscosity of a material is known as well as the relationship between reflective intensity and thickness, the substance may be characterized and properties such as the diffusion coefficient may be calculated.

IX. CREATION OF ISLAND EMULSIONS & FILMS

The most challenging aspect of using large films is being able to reproduce the effects seen from film to film.

For this reason, a number of techniques are used to make similarly structured films and emulsions. Using a spatula, material is spread across half of the circumference of the film holder. The amount is determined by the desired thickness of the film as well as the material. For example, more 12160 may be used to create films with a large ΔN between emulsions and the background film, where as a small amount of 8CB may be used to study many islands of similar layer thickness.

Once the material is placed on the film holder, the copper sheet is moved over the hole in the film holder and pull back across it in order to create a film. Again, this speed at which the film spreader is pull across affects the thickness of the film. Drawing a film fast results in a thinner film than one drawn more slowly. Often times, if starting with a faster draw speed, one can switch to a slower speed midway through pulling the film to avoid popping a thinner film as it is being stretched out.

After the film has been created, position the two coaxially facing needles over the center of the film. Slowly turn on the nitrogen gas as to not rupture the film. The pressure used to create a shear on the film is again dependent on the material, amount of liquid crystal, and size of the film. A smaller film will tend to be more stable than a larger film and one made of 12160 will withstand a higher pressure than 8CB. Moving the needles back and forth across the film will bring more material from the meniscus. If done correctly, this will result in an even distribution of island emulsions throughout the film with little to no visible meniscus, as can be seen in Fig. 10. After, the microscopic view may be adjusted to a region of interest to study the different coupling and coalescence over short and long time frames.

X. RESULTS OF THIN FILMS

Using the experimental procedure described above, large amounts of qualitative data was collected. Through a collection of images, a large data bank of videos was gathered to be analyzed. In order to study coalescence and how the average island size changes over time. As can be seen in Fig. 11, the coalescence of islands causes the average size of the islands to increase over time. The software used to obtain this data is not complete and often time breaks large islands into collections of smaller ones. However, the overall trend is still apparent.

In addition to the coalescence over time, collections of island emulsions show very apparent complex coupling interactions through general movement as well as during and after coalescence events. This coupling, brought on by the hydrodynamics of the system, can easily be seen when a larger island passes through a grouping of smaller islands. The larger island seemingly "pushes" the smaller islands out of the way without touching them. This is caused by the flow patterns that extend infront of the larger island, very similar to the patterns that can be seen when a boat moves through the water. When cou-
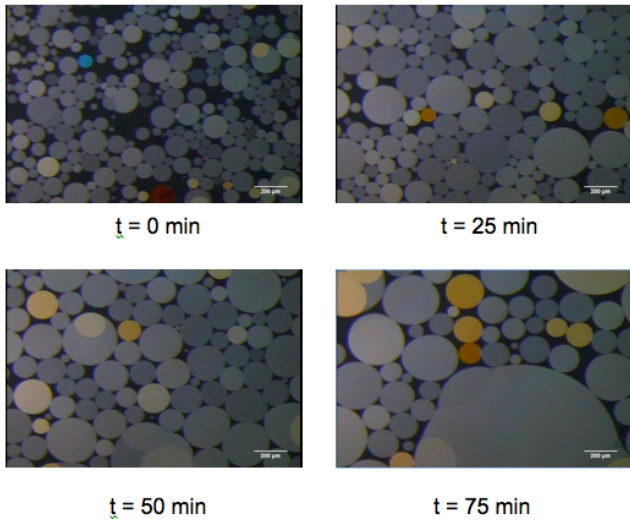
FIG. 11: Four images sampled at twenty-five minute intervals. Shows a high density of islands with similar thicknesses in 12160. One can notice the trend of increasing average island size over time.
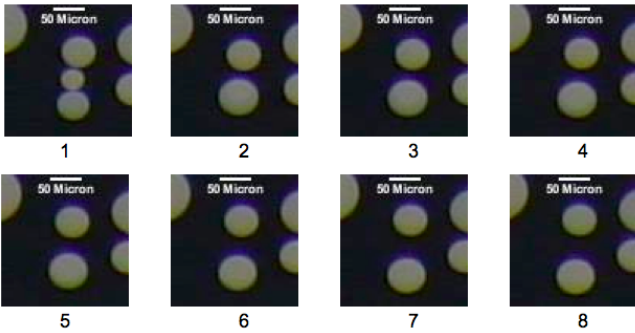

FIG. 12: Two Islands coalesce in 8CB and the movement back to an equilibrium distance is seen through the progression of 8 frame each with 1/15 second between them.
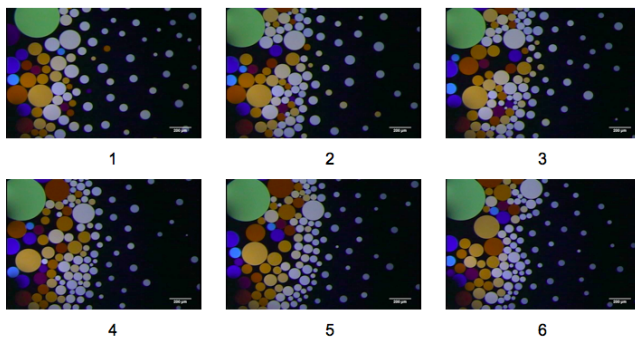

FIG. 13: A gradient of island thicknesses occurs over time in 12160, each frames is 30 seconds apart.

pling accompanies coalescence, the effect is most likely brought on by the effective eddy that is left when one island coalesces in the space occupied by another island. This leaves an open area behind the island that moves and upon coalescence, has been observed to quickly move towards its original position as can be seen in Fig. 12.

Smectic Islands also tend to arrange themselves in a gradient of thickness given some induced tilt. An undetectable tilt is apparent on the films being analyzed because as time progresses the thicker islands arrange themselves so that they are on the lower end of the film and force the thinner films towards the outer edges of the gradient as can be seen in Fig. 13. Although coalescence does effect this film, the islands are stable enough to arrange into this gradient before they coalesce.

XI. FUTURE WORK & CONCLUSION

The completion of the optical measurements process was a large breakthrough in the Cal Poly lab and opens the door for a variety of different measurements. The experiment will be expanded to include a number of different materials, but will focus almost entirely on de-Vries material. In addition, a procedure for measuring and analyzing the electroclinic effect data will hopefully be developed and applied soon. Overall, this experiment provides a basic, visual approach to characterizing liquid crystals and is a perfect way to learn the optical properties and behaviors of liquid crystals during the different phases.

A large amount of data was collected at the UC Boulder campus, however nearly all of the analysis done on it has been qualitative. The problem comes in measuring the size and positions of the different islands. Although a new Matlab program has been found that can identify the size distribution over an image, it is limited by thresholding and lacks the capability to track the islands [15]. However, it does find the location of the islands it analyzes, so by employing an existing program, the islands may be tracked. The current use of the program has been limited by time and the full potential of it is not known. Once the software is obtained to do this, the change of size distribution over time may be studied as well as the collective motion of a many island system.

In addition to the data that has been collected at this point, the effect described in Fig. 12 is still not understood. A future experiment to study this effect should use a high speed camera to watch the coalesce happen at a very high speed in order to study the dynamics of this interaction. Ideally, this effect would also be observed using the new film setup at the Cal Poly lab to verify its validity. Overall, this experiment has shown the complexity of multiple islands and the hydrodynamic interactions that they are subject too. Although analysis is needed in order to quantitatively understand what is happening in the system, qualitatively we are able to observe the complex behavior. By understanding the hy-

drodynamic qualities of these liquid crystals, they may one day be feasible medical replacements for natural oc- curring membranes, such as lung surfactant.

[1] A. Eremin, S. Baumgarten, K. Harth, R. Stannarius, Z.H. Nguyen, A. Goldfain, C.S. Park, J.E. Maclennan, M.A. Glaser, and N.A. Clark. Two-Dimensional Microrheology of Freely Suspended Liquid Crystal Films. Phys. Rev. Lett. **97**, 176001 (2006).

[2] Wikipedia. Birefringence. http://en.wikipedia.org/wiki /Birefringence. Accessed: 8 May. 2014.

[3] A.J. Levine and F.C. MacKintosh. Dynamics of viscoelastic membranes. Phys. Rev. Lett. **66**, 061606 (2002).

[4] V. Prasad, S.A. Koehler, and E.R. Weeks. Two-Particle Microrheology of Quasi-2D Viscous Systems. Phys. Rev. Lett. **107**, 268301 (2010).

[5] Z.H. Nguyen, (2003), *Smectic A Liquid Crystal Freely Suspended Films: Testing Beds for the physics in Thin Membranes*, Ph.D. Thesis, University of Colorado Boulder: United States.

[6] A. Saipa, F. Giesselmann, (2003), *A high resolution temperature scanning technique for optical studies of liquid crystal phase transitions*, Liquid Crystals, **347-353**, Vol. 29, (2002).

[7] J. Lagerwall, F. Giesselmann, (2006), *Current Topics in Smectic Liquid Crystal Research*, CHEMPHYSCHEM, **20-45**, Vol. 7, (2006).

[8] Meriam Webster. Smectic. http://www.merriam-webster.com/dictionary/smectic. Accessed: 8 May. 2014.

[9] W.R. Schief, *Liquid-Crystalline Collapse of Pulmonary Surfactant Monolayers*, Bio1physics Journal **3792**, 1302961 (2003).

[10] P. Collings and M. Hird, Introduction to Liquid Crystals: Chemistry and Physics. (Taylor & Francis, London, 1997).

[11] J. Fernsler, Reasearch - Liquid Crystals. http://www.calpoly.edu/∼jfernsle/Research/Research.html. Accessed: 26 Jul. 2013.

[12] Z.H. Nguyen, A.M. Goldfain, C.S. Park, J.E. Maclennan, M.A. Glaser, N.A. Clark, and Magdeburg Group, Coalescence, submitted to Phys. Rev. Lett. (2013).

[13] Z. Qi, T. Kuriabova, Z.H. Nguyen, C.S. Park, J.E. Machlennan, M.A. Glaser, T. Powers, and N.A. Clark, in preparation to submit, (2013).

[14] Z.H. Nguyen, M. Atkinson, C.S. Park, J. Maclennan, M. Glaser, and N. Clark. Crossover between 2D and 3D Fluid Dynamics in the Diffusion of Islands in Ultrathin Freely Suspended Smectic Films. Phys. Rev. Lett. **105**, 26304 (2010).

[15] P. Sharma, (2011), *Dynamics of interfaces*, Ph.D. Thesis, School of Natural Sciences, Tata Institute of Fundamental Research: Mumbai.

[16] J. Rego. Introduction to Liquid Crystals. http://www.csupomona.edu/∼jarego/pages/LC_intro.html. Accessed: 29 Jul. 2013.