# Colloidal Interactions in Chiral Nematic Liquid Crystals

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***Abstract*—**
**Liquid crystals are promising host media for reconfigurable self-assembly of nano- and micro-sized colloidal particles. Colloidal inclusions induce elastic distortions in the long-range molecular alignment of liquid crystals. Particles embedded in these structured media interact with each other via elasticity-mediated interactions to minimize elastic energy due to these distortions. We have explored the physical underpinnings of these interactions for colloidal particles in homeotropic chiral nematic cells. In our experiments, a Chiral Nematic Liquid Crystal is mixed with colloidal microspheres that have different vertical surface anchoring boundary conditions. This mixture is then examined under a microscope and colloidal interactions are probed using holographic optical tweezers. Using the laser tweezers, the particles are moved closer or farther away from each other to set the initial conditions. Once the laser is turned off, motion of the particles is recorded using video microscopy and center-to-center colloidal separation vs time data are extracted using particle tracking software. From these data, we determine elastic forces and interaction potentials and demonstrate that for the studied particles the interactions are repulsive at large distances but attractive at short distances.**

## I. Introduction

Liquid crystals colloids are prepared by adding plastic particles in Chiral Nematic Liquid Crystals. When micro-particles are introduced into liquid crystal media, different kinds of distorted structures are formed around the particles [0]. These distorted structures depend on the surface morphology and the anchoring strength of the particles. Hence particles embedded in structured media interact with each other via elasticity-mediated interactions to minimize elastic energy due to these distortions. The interaction between colloidal particles in the liquid crystal is studied with the help of laser tweezers [1].

Colloidal particles interact and assemble together [2]. Interactions between particles include three kinds: always repelling, always attracting, or attract at a close distance and repel at a farther distance.

The liquid crystal used is a mixture AMLC-0010 obtained from AlphaMicron, Inc. A dopant is added into the AMLC mixture to create a chiral nematic liquid crystal. The amount of doping determines the pitch of the chiral nematic liquid crystal. The dopant used is S-811, obtained from AlphaMicron, Inc. A cyno component nematic liquid crystals is also added approximately 1-3% (in present case E-31) to obtain three photon floursence [3]. Different kinds of polyamide can be used to achieve a homeotropic alignment [4].

## II. Method

### *A. Preparing the Samples*

Micro slides and cover slides are washed with Alconox Detergent in the supersonic bath for two hours. The slides are then rinsed with de-ionized water, acetone, and isopropyl. Two kinds of polyamide were used separately to coat the slides: SE-1211 and SE-5661. Both polyamides were mixed in a 1:4 ratio with Solvent for SE-1211 and Solvent for SE-5661 respectively. Polyamide is mixed with plastic colloidal particles, and is then coated on cover slides to study interaction between surface attached particles and free particles. A G3P-8 Spin Coater from Specialty Coating Systems is used to spread the polyamide onto the slides. The microslides were spincoated with the polyamide mixture, and the cover slips were spin-coated with the polyamide-spacer mixture. After spin-coating the polyamide onto the slides, the coated slides were baked at 100°C for approximately an hour.

The microslides are then glued to the cover slips with the polyamide coated surfaces facing each other. Optical glue mixed with 15μm spacers is used to glue the slides together. The slides are then put under a UV lamp for approximately 15 minutes so that the glue bonds. The slides are then ready to be filled with the liquid crystal sample.

The liquid crystal mixture was prepared at different pitches. To mix the chiral liquid crystal, the equation below was used.

$$HTP = \frac{1}{c_{ch} \times pitch}$$

The helical twisting power (HTP), a quality of the of dopant S-811 in AMLC, is 10.47/μm. By determining what pitch is wanted, the concentration of the dopant ($c_{ch}$) is determined. The nematic liquid crytal is then mixed with the determined amount of dopant to create the chiral liquid crystal.

Lastly, the chiral nematic liquid crystal is mixed with colloidal material. The colloidal materials used are 6μm plastic particles of the first kind with strong surface anchering, and 6μm plastic particles of the second kind with weak surface anchoring. Both are from AlphaMicron, Inc. The first kind of plastic particles are black in color, and the second kind of plastic particles are white in color. The fundamental difference in the particles lies within the plastic material, not the color. Yet the color allows us to distinguish between the different plastic colloids. Therefore, the plastic colloids will be further referred to as black spacers and white spacers. The spacers are mixed in vials of water so that the concentration of white particles is diluted. A small amount of the liquid is put into the centrifuge for about six minutes. The water can then be removed from the vial without removing all the spacers. The chiral nematic liquid crystal is then mixed in to the spacers vial. The final mixture is put in the sonic bath for at least five hours to mix the substance thoroughly.

Samples of the chiral liquid crystal and black spacer mixture were created at 18.7μm, 20μm, and 24μm. Samples of the chiral liquid crystal and white spacer mixture were created at 18.1μm, 20μm, and 24μm. Samples were filled with the colloidal chiral nematic liquid crystal mixture, and then epoxy glue was used to seal the sample. Hence the cells with different ratio of $\frac{d}{p}$ are prepared where d is distance between the glass plates and p is the pitch. The resulting number should be between 0.5 and 1 for the cell to have the opportune alignment.

The interaction between particles was studied with the help of Holographic Optical Tweezer (HOT) set up by recording the movie at 15 frames/second. Once data is recorded, the movies are converted into image sequences and analyzed in ImageJ using the plugin wrMTrck by Jesper S. Pedersen. The distance between particles is calculated with respect to time and the velocity was calculated at each point.

Two main forces determine the interaction of the particles. A balance between a drag force and the elastic force cause the particles to attract or repel. The elastic force is noted below:

$$F = \pm \frac{A}{r^n}$$

The A is a constant, r is the distance between the particles, and n determines whether the particle is dipolar, n being 4, or quadrupolar, n being 6.

Stokes Law is used to determine the drag of the particles in the liquid crystal:

$$F = -6\pi\eta v R$$

The R denoted in this equation is the radius of the particles, η is the viscosity of the liquid crystal, and v is the velocity of the particles. The viscosity is assumed to be a constant, so the drag equation can be written : $F = -\zeta \frac{dr}{dt}$ where ζ is a constant. An approximate value of η=30mPa•s is used [5].

## B. *Microscope Examination*

An Olympus microscope is used for examined the samples. All the videos used for analyzing were recorded at either 60X or 100X. An infrared laser tweezer system is used for manipulating the colloidal material. The colloids used in the experiments are either stuck to the surface of the glass, or are free floating particles. The particles are also not part of cholestic finger.

Once two particles are found, the laser tweezers are used to pull the particles closer and observe the interaction. If the particles attract, the laser tweezers are used to pull the particles farther away from each other until the particles repel. If the particles are initially repelling, the laser tweezers are used to push the particles closer to find the distance at which they begin to attract. Some particles will only repel, and some particles will only attract. These interactions must be recorded.

The structure of the colloidal material in the liquid crystal is also important to note, as it predicts the interactions between the particles. Particles exhibit two main structures: dipolar and quadrupolar. These structures are observed by cross-polarized images and images of the particles with a retardation plate.

## III. Results

### A. Potential Energy

An interaction between a particle stuck to the surface and free particle in an15µm thick, homeotropic aligned cell filled with 18.7 µm pitch LC and 6 µm black particle is recorded and shown in Fig 1.

Figures 1a and 1b display attracting and repelling interactions respectively.

Figure 1a

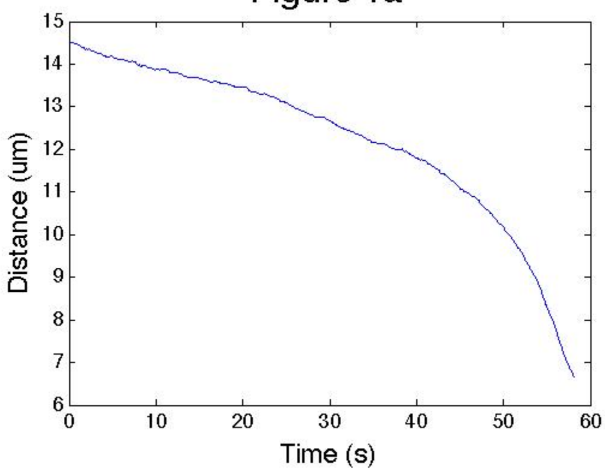



Figure 1b

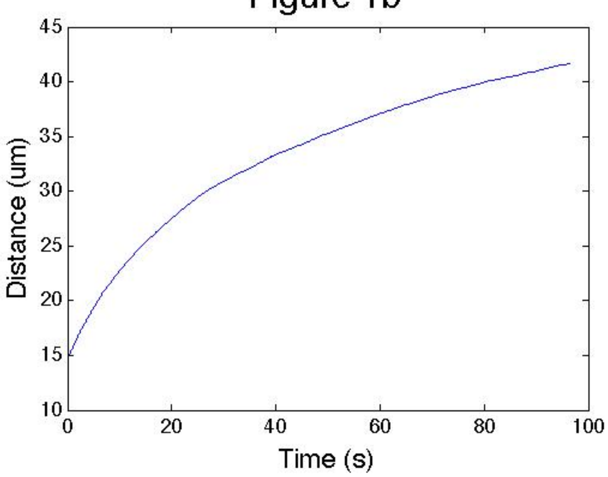
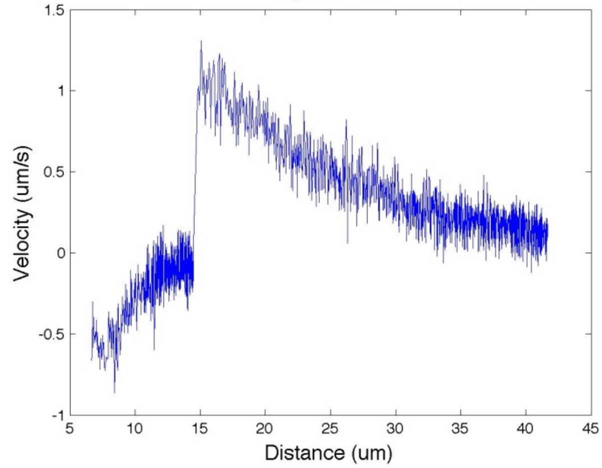


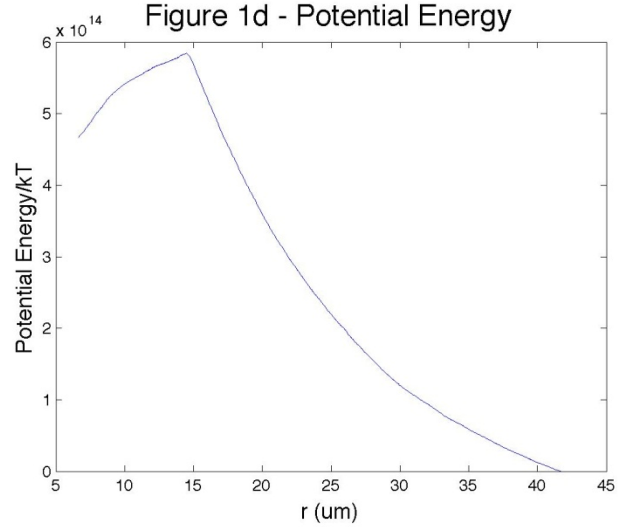

Figure 1c displays the velocity-distance relation for the particles including both the attracting interaction and the repelling interaction.

Figure 1c




As stated above, force $F = 6\pi\eta v R$ between two interacting particles was calculated from velocity data. To get potential energy as a function of distance following equation has been used as such: $U = -\int F dr$. With this calculation, the following graph is produced.

Figure 1d - Potential Energy




### B. Black Spacers vs. White Spacers

Interactions in samples filled with the black spacer mixture are compared to the interactions in samples filled with the white spacer mixture.

The first two samples compared are a 20µm pitch, 6µm black spacer, 15µm thick, homeotropic aligned, free particle interaction and a 20µm pitch, 6µm white spacer, 15µm thick, homeotropic aligned, free particle interaction. The plots below show the distance as the particles attract, and the distances as the particles repel.

Figure 2a - White Spacers

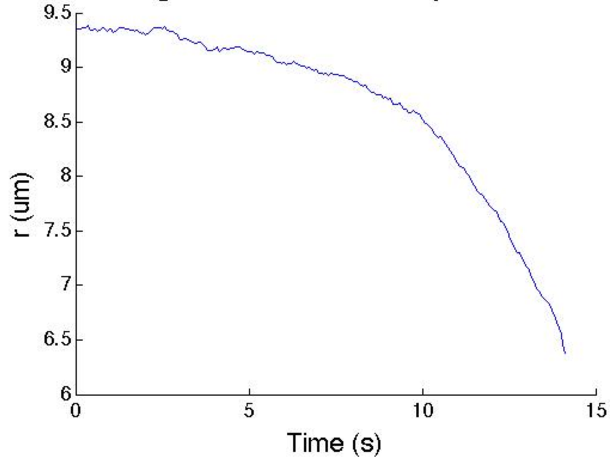



Figure 2b - White Spacers

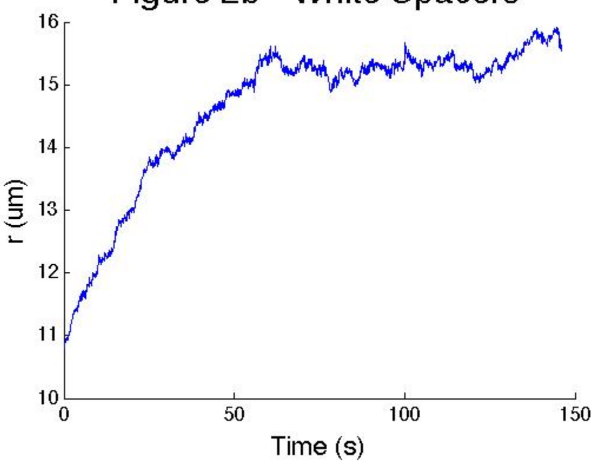



Figure 2c - Black Spacers

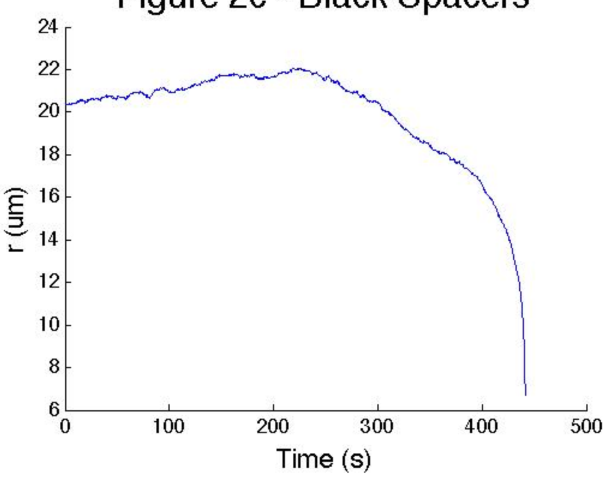
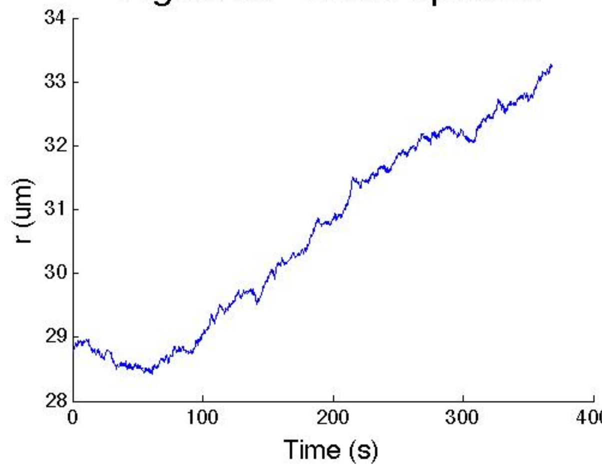



Figure 2d - Black Spacers




The approximate initial distances are noted below.

| | Black | White |
|---|---|---|
| Attract distance | 20.3μm | 9.4μm |
| Repel distance | 28.5μm | 10.8μm |

*C. Free-free vs. Free-stuck to the surface particle interactions*

The next two samples compare the interactions of a sample with one particle stuck to the surface with a free particle versus two free particles interacting. The first sample is a 20μm pitch, 6μm black spacer, 15μm thick, homeotropic aligned, stuck-free particle interaction. The second sample is the same sample from figures 1 and 2, which is a 20μm pitch, 6μm black spacer, 15μm thick, homeotropic aligned, free particle interaction. The plots below show the distance as the particles attract, and the distances as the particles repel.

Figure 3a Stuck-Free

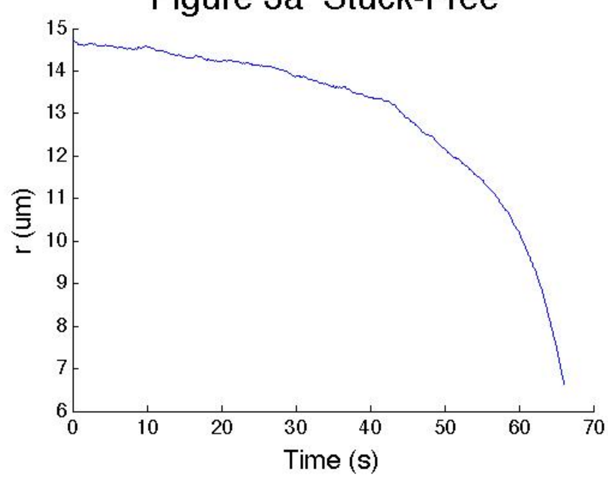


Figure 3b Stuck-Free

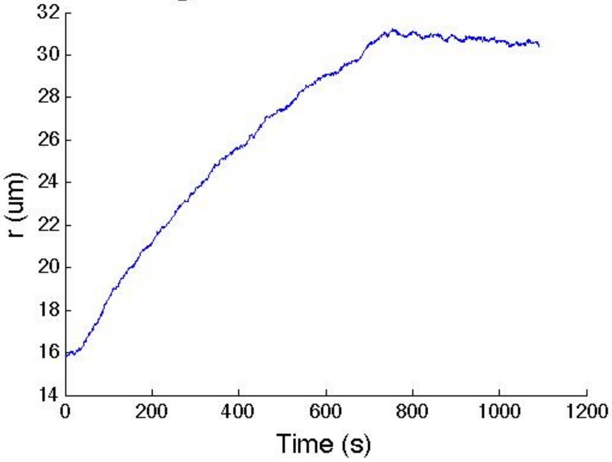



Figure 3c Free-Free

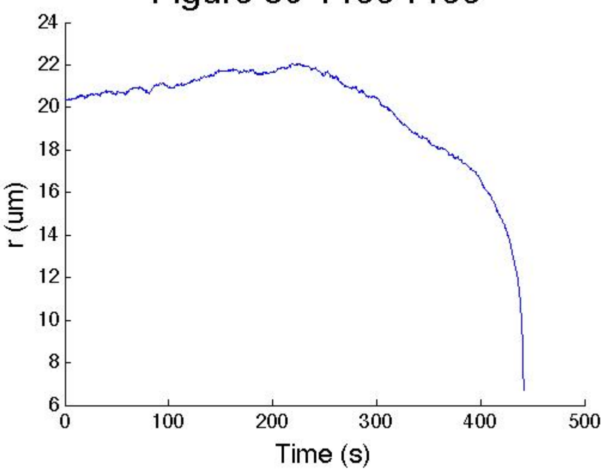
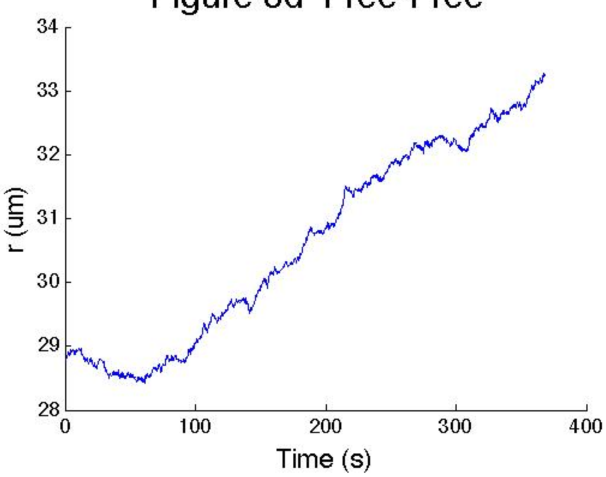



Figure 3d Free-Free




The chart below displays the approximate distance at which the particles initially began to react.

| | Stuck-Free | Free-Free |
|---|---|---|
| Attract distance | 14.6μm | 20.3μm |
| Repel distance | 15.8μm | 28.5μm |

### *D. Interactions in different pitch materials*

Samples were made with different pitch of chiral liquid crystal. Data from a 18.7μm pitch, 6μm black spacer, 15μm thick, homeotropic aligned cell with stuck-free particle interaction is compared to another stuck-free particle interaction in a 20μm pitch, 6μm black spacer, 15μm thick, homeotropic aligned cell. The second sample is the same as used figures 5 and 6.

Figure 4a 18um

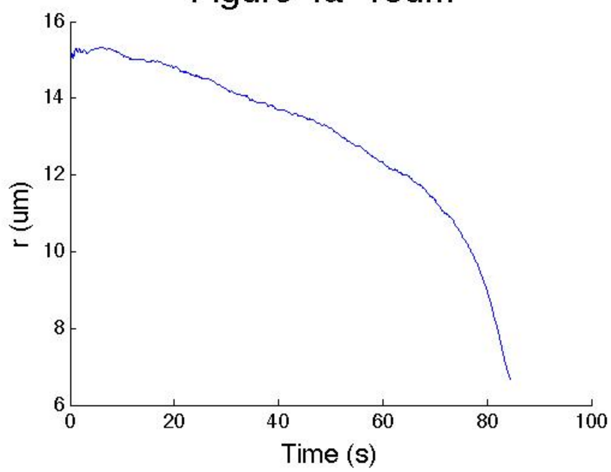
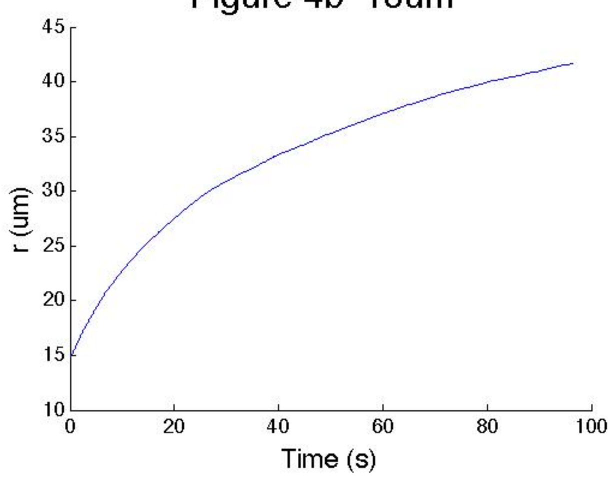
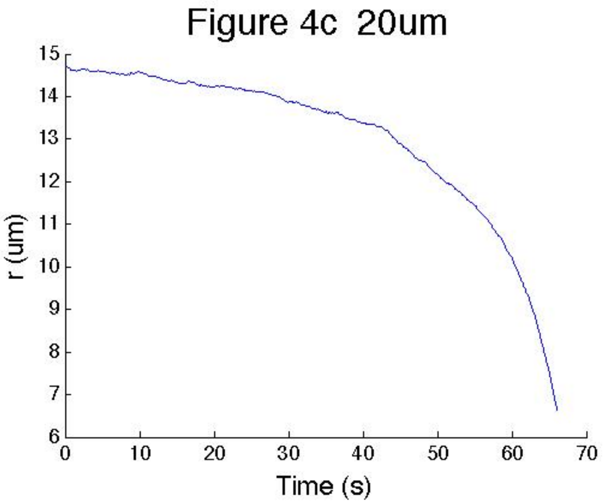
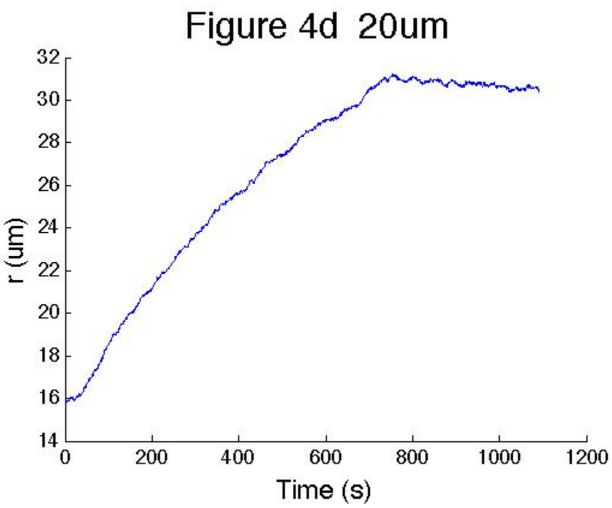



Figure 4b 18um






Approximate initial distances between particles are noted below.

| | 18.7μm | 20μm |
|---|---|---|
| Attract distance | 15.1μm | 14.6μm |
| Repel distance | 15.3μm | 15.8μm |

## IV. Discussion

### A. Potential Energy

The resulting potential energy graph shows that the particles attract when the slope is positive. Similarly, when the slope is negative the particles repel.

### B. Black particles vs. White particles

The black particles appear to attract at a much farther distance than the white particles. The white particles are attracted to each other at about half the distance of the black particles. Also, the white particles begin to repel at a much closer distance than the black particles begin to repel. The distance at which the white particles begin to repel is about 1/3 the distance at which the black particles begin to repel.

### C. Free-free vs. Free-stuck to the surface particle interactions

The free-stuck particles interactions began at a much closer distance than the free-free particle interactions. Although this difference is not as significant as the difference in the black versus white particle interactions, this is still an interaction worth noting.

### D. Interactions in different pitch materials

The interactions in the 18.7μm pitch material do not significantly vary from the interactions in the 20μm pitch material. The distance gap between attraction and repelling in the 18.7 μm pitch material is smaller than that of the 20μm pitch material. Yet, the numbers are incredibly close in range.

## V. Conclusion

The interaction between colloidal particles in chiral nematic liquid crystals confined between homeotropic cell geometry was studied. The energy of interaction is ~$10^6$ times larger than thermal fluctuation energy (kT) of liquid crystal molecules. The potential energy graph displays attracting and repelling interactions of a stuck and free particle. The point at which two interacting particles change between repelling and attracting is a much farther distance for the black plastic particles than the white plastic particles. Two free particles interacting also reach this point at a much farther distance than interactions between a stuck particle and a free particle. No significant difference in repelling and attracting interactions is noted between different pitched liquid crystal materials.

## Acknowledgment

I would like to thank Dr. Manoj Pandey and Dr. Ivan Smalyukh for their contributions and help. The author would like to thank the LCMRC REU Program, University of Colorado Boulder Physics Department, and the NSF for funding.

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