THE INFLUENCE OF NANOPARTICLES ON THE KERR EFFECT AT THE NEMATICP ISOTROPIC PHASE TRANSITION

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THE INFLUENCE OF NANOPARTICLES ON THE KERR EFFECT AT THE NEMATIC- ISOTROPIC PHASE TRANSITION

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Thesis

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ABSTRACT

Nanoparticles can affect some physical properties of liquid crystals. We investigate the influence that nanoparticles have on the Kerr coefficient by measuring the electric field Kerr effect (induced birefringence proportional to the square of the applied electric field), above the nematic-isotropic transition temperature by using various concentrations of cerium dioxide (CeO$_2$) nanoparticles in 4-octyl-4’-cyanobiphenyl (8CB) liquid crystal. On cooling toward the nematic-isotropic transition temperature $T_{NI}$ the nematic correlation length increases (but does not diverge because the transition is first order). When the correlation length is of the same order as the characteristic distance between the nanoparticles, the nematic fluctuations are disrupted and the Kerr coefficient will no longer increase as rapidly with decreasing temperature as predicted by Landau-DeGennes theory.
ACKNOWLEDGMENTS

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1.1 Liquid Crystals

Liquid crystals are fascinating materials that have more than the usual three physical states of matter. They show several different phases between liquid and solid. Due to their sensitivity to an electric field and changing temperature, they are in a lot of different electrical products from liquid crystal displays to smartphones.

There are several different types of molecule that form liquid crystals, for instance rod-like or disk-like molecules. Rod-like molecules are usually made of two or more aromatic rings that shape the rigid rod and flexible amphiphilic chains (Figure 1.1).

![Figure 1.1 A typical liquid crystal molecule with two aromatic rings.](image)

The main focus of this thesis is on liquid crystals with rod-like molecules.
1.2 Nematic and isotropic phases

A liquid crystal is in the isotropic phase when there is no long-range positional or orientational order. In other words, there is no preferred direction in the isotropic phase. As the temperature cools down, liquid crystals can show another phase, which is called the nematic phase. Liquid crystals' molecules in the nematic phase align in a preferred direction. This direction is referred to as the director $\hat{n}$ [1].

There are other, for example smectic, phases at lower temperatures, but that is not relevant to this thesis.

![Figure 1.2 a) Nematic phase, b) Isotropic phase. There is no long range order in the isotropic phase, but there is orientational order in the nematic phase.](image)

1.3 Anisotropy and birefringence

The uniaxial liquid crystals have anisotropy in some of their physical properties, such as dielectric permittivity and refractive index.

The dielectric tensor, when the director is along the $z$-axis, is given by
\[
\tilde{\varepsilon} = \begin{bmatrix}
\varepsilon_\perp & 0 & 0 \\
0 & \varepsilon_\perp & 0 \\
0 & 0 & \varepsilon_\parallel
\end{bmatrix}
\]  

(1.1)

and \( \Delta \varepsilon = \varepsilon_\parallel - \varepsilon_\perp \) is the dielectric anisotropy.

It should be noted that uniaxial liquid crystals have two indices of refraction, ordinary, \( n_o = \sqrt{\varepsilon_\perp} \), and extraordinary, \( n_e = \sqrt{\varepsilon_\parallel} \), and their difference, \( \Delta n = n_e - n_o \), is the optical birefringence.

1.4 The nematic order parameter

The nematic order parameter \( Q \) is a tensor, which can describe the nematic-isotropic phase transition. The order parameter describes the symmetry of the phase in a way that \( Q \) is zero for the isotropic phase (complete symmetry).

\( Q_{\alpha\beta} \) is the general form for a uniaxial order parameter where axes \( \alpha \) and \( \beta \) are chosen in a way that the tensor is diagonalized,

\[
Q_{\alpha\beta} = \begin{bmatrix}
Q_1 & 0 & 0 \\
0 & Q_2 & 0 \\
0 & 0 & -(Q_1 + Q_2)
\end{bmatrix}
\]  

(1.2)

The macroscopic order parameter for a uniaxial nematic liquid crystals is,

\[
Q_{\alpha\beta} = S(n_\alpha n_\beta - \frac{1}{3} \delta_{\alpha\beta})
\]  

(1.3)

where the magnitude is the scalar order parameter \( S \):

\[
S = \frac{3}{2} \langle \cos^3 \theta \rangle - \frac{1}{2} = \langle P_1(\cos \theta) \rangle
\]  

(1.4)
Here \( n_a \) are the director components, \( \theta \) is the angle between the long molecular axis and \( \hat{n} \), and \( P_2(\cos \theta) \) is the second Legendre polynomial [1,2]. Most liquid crystals that are known are microscopically uniaxial, so it is more common to use the scalar \( S \) as the order parameter rather than \( Q \). For completely aligned nematics \( S = 1 \), for disordered isotropic states \( S = 0 \), and \( S = -\frac{1}{2} \) corresponds to a disk-like uniaxial phase.

1.5 Landau-DeGennes theory of the nematic-isotropic phase transition

The Landau theory introduces a free energy as a function of the order parameter near the nematic-isotropic phase transition temperature that can explain the system. The Landau-DeGennes theory is a mean field theory that is applied to the nematic-isotropic phase transition [2]. The Landau-DeGennes free energy density of uniaxial nematic liquid crystal can be written as:

\[
f = \frac{1}{2} AS^2 - \frac{1}{3} BS^3 + \frac{1}{4} CS^4 \tag{1.5}
\]

where \( A = a(T - T^*) \), \( T \) is the absolute temperature, \( T^* \) is the lowest temperature where the isotropic phase is stable, and the coefficients \( B \) and \( C \) are assumed to be constant near \( T^* \)[1,2].
1.6 Three elastic constants and the distortion energy

In the nematic phase the distortion energy equation describes the short-range state of distortion with the director $n$ as the variable [1].

$$F_d = \frac{1}{2} K_1 (\text{div} n) + \frac{1}{2} K_2 (n \cdot \text{curl} n)^2 + \frac{1}{2} K_3 (n \times \text{curl} n)^2 \quad (1.6)$$

where $K_1$, $K_2$ and $K_3$ are three elastic constants that are related to basic types of deformation which are splay, twist and bend, respectively. These constants must be positive so that the undistorted nematic correspond to a minimum of the free energy $F_d$. 

Figure 1.3 Three elastic deformations a) splay, b) twist, and c) bend.
1.7 The orientational fluctuations and the correlation length

The value of the order parameter can be affected by any local disruption in the system, for instance, thermal fluctuations [2]. Therefore a term is added to the Landau-DeGennes free energy density expansion (1.5). The higher terms can be neglected because of the small value of the fluctuating scalar order parameter in the isotropic phase. Therefore the free energy density becomes,

\[ f = \frac{1}{2} a \left( T - T^* \right) S^2 + d (\nabla S)^2 \]  

(1.7)

It is advantageous to use the Fourier component of the order parameter,

\[ S = \int S_q e^{i \vec{q} \cdot \vec{r}} \, d^3 r \]  

(1.8)

then the free energy density in terms of Fourier component is given by,

\[ f_q = \frac{1}{2} a \left( T - T^* \right) S_q S_{-q} + d \left( q^2 S_q S_{-q} \right). \]  

(1.9)

Using the equipartition theorem,

\[ \left[ \frac{1}{2} a \left( T - T^* \right) + dq^2 \right] \langle S_q S_{-q} \rangle = k_B T \]  

(1.10)

we find,

\[ \langle S_q S_{-q} \rangle = \frac{k_B T}{\frac{1}{2} a \left( T - T^* \right) + dq^2} \]  

(1.11)

When equation (1.11) is transformed back into the real space it can be seen that the order parameter has a decay proportional to \( e^{-\gamma} \).
\[ \xi = \left( \frac{d}{\frac{1}{2}a(T - T^*)} \right)^{\frac{1}{2}} \] (1.12)

Where \( \xi \) is the correlation length, which is the range of distortions by local fluctuations [2]. The correlation length in the isotropic phase near the nematic-isotropic transition temperature at \( T_c \), the critical temperature, is about 25 nm and 3° above \( T_c \) it is about 5 nm [3].

1.8 Liquid crystal interactions with electric and magnetic fields

The liquid crystal molecules have strong and micro to millisecond responses to applied external magnetic or electric fields. The molecules try to align parallel to the field when the material has positive diamagnetic or dielectric anisotropy, though they would try to align perpendicular to the field if the material has negative diamagnetic or dielectric anisotropy. The free energy density has an extra term in the presence of an external field [4,5]. Let us assume that there is an applied external electric field so that the free energy density is given by,

\[ f = \frac{1}{2} AS^2 - \frac{1}{3} BS^3 + \frac{1}{4} CS^4 - \frac{1}{2} \bar{E} \cdot \bar{D} \] (1.13)

since \( \bar{D} = \varepsilon \bar{E} \), where \( \varepsilon \) is dielectric permittivity. We can write,

\[ \frac{1}{2} \bar{E} \cdot \bar{D} = \frac{\bar{E} \cdot \varepsilon \bar{E}}{2} \] (1.14)

\[ = \frac{E_0^2}{2} \left[ \sin^2 \theta \cos^2 \theta \varepsilon_\perp + \sin^2 \theta \cos^2 \theta \varepsilon_\parallel + \cos^2 \theta \varepsilon_\parallel \right] \] (1.15)
\[ \frac{E_0^2}{2} \left[ \varepsilon_{\perp} \sin^2 \theta + \varepsilon_{\parallel} \cos^2 \theta \right]. \tag{1.16} \]

By using \( \Delta \varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} \), this is equal to

\[ \frac{1}{2} \tilde{E} \cdot \tilde{D} = \frac{E_0^2}{2} \left[ \varepsilon_{\perp} \sin^2 \theta + (\varepsilon_{\perp} + \Delta \varepsilon) \cos^2 \theta \right] = \frac{E_0^2}{2} \left[ \varepsilon_{\perp} + \Delta \varepsilon \cos^2 \theta \right] \tag{1.17} \]

Here the first term is a constant, which can be omitted, substituting \( \cos^2 \theta \) from equation (1.4). We find,

\[ \frac{1}{2} \tilde{E} \cdot \tilde{D} = \frac{E_0^2}{2} \Delta \varepsilon \left( \frac{2}{3} S + \frac{1}{2} \right). \tag{1.18} \]

By omitting the second term, which is a constant, we find our electric field term for the free energy density,

\[ f = \frac{1}{2} AS^2 - \frac{1}{3} BS^3 + \frac{1}{4} CS^4 - \frac{1}{3} \Delta \varepsilon E_0^2 S \tag{1.19} \]

From equations (1.7) and (1.19) the free energy density for our system in the isotropic phase would be,

\[ f = \frac{1}{2} a (T - T^*) S^2 + d(\nabla S)^2 - \frac{1}{3} \Delta \varepsilon E_0^2 S \tag{1.20} \]

1.9 Outline

In this thesis, the influence of nanoparticles on the Kerr effect was experimentally investigated. Chapter 2 has two different parts. In the first part, the response of liquid crystals to an applied field is introduced. In the second part, nanoparticles in liquid crystals, in general, are introduced. At the
end of Chapter 2 we define the question that we studied. In Chapter 3 are details of our experimental setup and our Kerr effect data. Chapter 4 is the summary and conclusion.
2.1 The response of isotropic liquid crystals to applied field

An external field can induce molecular alignment of an isotropic liquid crystal, which generates induced optical birefringence due to the anisotropy of the liquid crystals. If the applied field is an electric field, it is called Kerr effect and in the case of a magnetic field, Cotton-Mouton effect. There is a measurable increase in the field-induced birefringence when a system in the isotropic phase is getting closer to the nematic-isotropic transition temperature.

We can write \( \frac{df}{dS} = 0 \) using the free energy from equation (1.20) when the system is in equilibrium, and we can omit the second term for the moment.

This gives,

\[
0 = a(T - T^*)S - \frac{1}{3} \Delta \varepsilon E^2
\]

(2.1)

which we solve for the order parameter \( S \),

\[
S = \frac{1}{3} \frac{\Delta \varepsilon E^2}{a(T - T^*)}
\]

(2.2)

Since the scalar order parameter is proportional to induced birefringence, \( \Delta n \), we write,
\[
\frac{1}{\Delta n} \propto \frac{1}{S} = \frac{a(T - T^*)}{\frac{1}{3} \Delta \varepsilon E^2}
\]  \hspace{1cm} (2.3)

and,

\[
B = \frac{\Delta n}{E^2} \propto \frac{1}{\frac{3}{a(T - T^*)}}
\]  \hspace{1cm} (2.4)

This is how the Kerr coefficient \( B \) is defined.

Studying the behavior of isotropic liquid crystals in the presence of external fields has been the focus of many researchers [4-12]. For instance, some have worked with a magnetic field and investigated Cotton-Mouton effect [10-12], while others used electric fields and made optical Kerr effect measurements [5-9]. Probably one of the most famous experiments with a large applied field was done by Stinson, Lister, and Clark [13], which also included light scattering experiment.

2.2 Nanoparticles in liquid crystals

People have been looking at nanoparticles in liquid crystals for quite some time. The combination of the physical properties of nanoparticles with the orientational ordering of liquid crystals is very useful. On the one hand, there have been several studies on the influence of nanoparticle ordering and director distortion of the nematic liquid crystals, which usually decreases the nematic-isotropic phase transition temperature [14-17].

On the other hand, Basu and Iannacchione showed that the carbon nanotube long axis aligns with the nematic director. As a result of this, they observed that low concentrations of carbon nanotube dispersed in a liquid crystal would increase the nematic ordering [18-19]. Basu et al. also have done experiments
with liquid crystals doped with pristine graphene monolayer flakes and saw an increase in the dielectric anisotropy [20].

There are some interesting experiments that have been done with ferroelectric or ferromagnetic nanoparticles doped into liquid crystals. For instance, it has been shown that adding a small amount of ferroelectric nanoparticles into a liquid crystal can produce a strong electro-optic response [21-23].

2.3 New question: How do nanoparticles affect the nascent order imposed by an applied electric field in the isotropic phase?

The presence of the nanoparticles can influence the orientational order of liquid crystals around the nanoparticles, and may disrupted the order. If the nanoparticles are sufficiently small, they may behave similar to a chemical impurity, which would decrease the nematic-isotropic phase transition temperature like any chemical impurity would [16,24].

If there is an external electric field, having nanoparticles may cause modifications to the Kerr effect. To see an effect, the nanoparticles concentration should be sufficiently high so that the interparticle spacing can be close enough to the nematic correlation length. Close to the nematic-isotropic transition temperature, the nematic correlation length is typically 20 nm to 25 nm for most materials, but cannot diverge close to the transition temperature because the transition is first order. Further above the transition temperature (about 2° or 3°), it is typically between 12 nm to 13 nm, and well above the transition temperature (around 4° or 5°), the correlation length goes down to 5-6 nm [3].
CHAPTER III

EXPERIMENTAL PROCEDURE

3.1 Sample preparation

Samples were prepared with glass slides, which have a thin coating of the transparent electrode indium tin oxide. To clean the glass slides, they were sonicated in three steps: First in a mixture of detergent and deionized water, then in ethanol and finally with acetone to remove all organic compounds from the surface. Liquid crystal cells were constructed by using two small pieces of Mylar spacers with the thickness of 12.5 μm between two parallel glass slides. Then the cell’s thickness, d, was measured with an interferometric technique [25], the result was about 14 μm.

The nanoparticles that we used were cerium dioxide (CeO₂) particles with polydimethylsiloxane (PDMS) coating dispersed in methylene chloride, 0.1 weight percent, which Prof. Jérôme Fresnais of Université Pierre et Marie Curie in Paris kindly prepared for us. The diameter of this nanoparticle was about 5 nm. The liquid crystal that was used in this experiment was 4-octyl-4’-cyanobiphenyl (8CB). In order to make mixtures of cerium dioxide and 8CB, the liquid crystal was weighed at room temperature, and then a small amount of cerium dioxide in the solution was added. The mixture then was placed on the hot stage with temperature about 37°C (which is lower than the methylene chloride boiling point 39.6 °C) so that methylene chloride evaporated without boiling. When all of the solvents were gone the mixture was sonicated in the isotropic phase for about two hours.
The cells were filled with the mixture in the isotropic phase and then were checked under a polarizing microscope for any visible aggregations.

Then after each measurement, we emptied the Kerr cell and cleaned it with acetone, and used it again and filled it with another mixture.

3.2 Experiment setup

The cell was placed in the optical Kerr effect apparatus, which is illustrated in figure 3.1.

Figure 3.1 a) Optical Kerr effect apparatus, optical setup. A He-Ne Laser beam ($\lambda = 632.8$ nm) passes through a polarizer, Babinet-Soleil compensator, a lens, and the Kerr cell. There is an electric field applied to the cell. The analyzer is positioned $90^\circ$ with respect to the polarizer, but both at $45^\circ$ with
respect to the projection along the vertical axis of the applied electric field. The beam is focused by another lens, and finally goes to the detector.

A beam of a He-Ne Laser with the wavelength of 632.8 nm first passes through a polarizer and a Babinet-Soleil compensator and then a lens so that the beam is focused before going into the sample. The sample was placed at a 45° angle with respect to the laser beam, (rotated around an axis perpendicular to the paper) so the optical birefringence could be measured. The cell was put in the hot stage, which was connected to a temperature controller. At the beginning of the experiment, the mixture was in the isotropic phase well above the nematic-isotropic transition temperature. The temperature was set at 46 °C and then was slowly reduced. At various temperatures, when the system was at equilibrium, an electric field at frequency 3kHz was applied across the cell, and the voltage was ramped from 3.16 V to 14.14 V. This was done so that the quantity $E^2$ was spaced evenly. The laser beam, after going through the cell, passed through another lens to be focused before going into the detector. The detector output was fed into a lock-in amplifier, which measured the optical retardation (see section 3.3). The temperature controller, the lock-in amplifier, and DMM were connected with a GPIB cable to the computer. They were controlled by MATLAB, to which data were reported. Then all data were imported to Origin and were analyzed.

3.3 Data and discussion

The first sample that we measured was pure 8CB to get our baseline. At each temperature, we collected the retardation on changing the voltage.

The optical retardation, for a sample perpendicular to the beam, is given by

$$\alpha = \int \frac{2\pi}{\lambda} \Delta n \; dx .$$  \hspace{1cm} (3.1)
But because of the tilt of the sample, the retardation is expressed as

\[ \alpha = \frac{2\pi}{\lambda} \left[ \int (n_e dz - n_o dz) \right] \quad (3.2) \]

(Note that by Snell’s law the beam splits up inside the cell.)

Here e and o refer to the extraordinary and ordinary components of the split beam as they pass through the cell. Because the experiment is in the isotropic phase, where \( \alpha \) is small, and because the Babinet-Soleil compensator is set for a retardation of \( \frac{\pi}{2} \) the induced order parameter is proportional to \( \alpha \).

We plotted optical retardation \( \alpha \) versus the square of the applied electric field for each temperature (Figure 3.2).

![Figure 3.2 Optical retardation vs. square of applied electric field at nine different temperatures for pure 8CB sample.](image-url)
Then at each temperature the best linear fit at lower fields for each graph was plotted, and we collected the slopes (see figure 3.3 for an example).

Figure 3.3 Optical retardation vs. square of applied electric field at 40.5 °C for pure 8CB with its best linear fit. The standard error for the best fit is $3.7 \times 10^{-19} \text{m}^2/V^2$.

The slope of the best linear fit on this graph is defined as $B'$

$$B' \equiv \frac{d\alpha}{dE^2}, \quad (3.3)$$

which is proportional to the Kerr coefficient based on equation (2.4).

We then were able to plot the inverse of the Kerr coefficient versus temperature (Figure 3.4).
Figure 3.4 inverse Kerr coefficient vs. temperature for pure 8CB. The line shows the Landau-DeGennes theory prediction.

The line in figure 3.2 shows that the Landau-DeGennes theory prediction, which is, that the inverse of Kerr coefficient is directly proportional to temperature sufficiently far above $T_{Ni}$. But as this figure shows, close to the nematic-isotropic transition temperature there is a deviation from mean field theory because of nematic fluctuations. This deviation was seen first by Stinson, Litster, and Clark [13].

After the pure 8CB measurement, the cell was filled with various mixtures of CeO$_2$ and 8CB, and we looked under the microscope. For low concentrations there was no visible aggregation. However, when we looked at high concentration samples, 1 wt-% and 2 wt-%, under a microscope there were some aggregations (figure 3.5).
Figure 3.5 Four brush defects due to aggregation observed under microscope with crossed polarizers in nematic phase for 1 wt-% sample.

We measured the Kerr coefficient several times with the same Kerr cell containing the mixture of cerium dioxide and 8CB with various concentrations (Figure 3.6).

Figure 3.6 inverse Kerr coefficient vs. temperature for pure 8CB, 0.02, 0.04, 1, and 2 weight percent of CeO₂ in 8CB.
Our results show that adding CeO$_2$ nanoparticles to 8CB liquid crystal decreases the nematic-isotropic transition temperature, which we suspect it would since the nanoparticles are sufficiently small and it behave like a chemical impurity [17]. The nematic-isotropic transition temperature that we found for pure 8CB is roughly about 39.8 °C, while for the mixture of 2 weight percent CeO$_2$ in 8CB is around 35.8°C (Table 3.1).

Table 3.1 The nematic-isotropic transition temperature for different mixture of CeO$_2$ with 8CB.

<table>
<thead>
<tr>
<th>CeO$_2$ in 8CB wt-%</th>
<th>0.0</th>
<th>0.02</th>
<th>0.04</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition temperature (°C)</td>
<td>39.9</td>
<td>39.7</td>
<td>38.4</td>
<td>36.6</td>
<td>35.8</td>
</tr>
</tbody>
</table>

In Table (3.1), the nematic-isotropic transition temperature changes more rapidly with small variations in the lower concentration of nanoparticles. This suggest that at high concentrations there are more aggregates, which act more like particulate matter rather than a chemical impurity.

For our data set at 2 wt-% concentration close to the transition temperature, there is an upward curvature with decreasing temperature near $T_{\text{NI}}$ in Figure 3.6, which is different from the downward behavior that we discussed in Figure 3.4. Because the nematic correlation length increases on cooling toward the first order phase transition at $T_{\text{NI}}$, the fluctuations could be disrupted by the particles. This would prevent the Kerr coefficient from rising near $T_{\text{NI}}$. This means that the Kerr coefficient near the transition temperature is smaller than we expect from Landau-DeGennes theory and indicates that the increasing nematic correlation length is becoming comparable to the average interparticle spacing.
CHAPTER IV
SUMMARY AND CONCLUSION

In this thesis, the influence of nanoparticles on the Kerr effect was experimentally investigated. Chapter 2 has two different parts. In the first part, the response of liquid crystals to an applied field is introduced. In the second part, nanoparticles in liquid crystals, in general, are introduced. At the end of Chapter 2 we define the question that we studied. In Chapter 3 are details of our experimental setup and our Kerr effect data. And this Chapter includes our conclusion and future work.

We observed that the nematic-isotropic transition temperature decreases when the liquid crystal is doped with nanoparticles. We also saw a larger incremental effect on the transition temperature at lower concentration than at higher concentration. This is because at high concentrations there are more aggregates that behave more like particulate matter rather than a chemical impurity.

Our observed deviation of the inverse Kerr coefficient near the nematic-isotropic transition temperature from the Landau-DeGennes behavior was also observed in the same way by Stinson and Litster, and Clark [13] and Dunmur and Tomes [7]. In addition, for one measurement we saw that for the higher concentration of nanoparticles the inverse Kerr coefficient has an upward behavior, which indicates that, the Kerr coefficient is smaller than it was expected to be.

In the future, more measurements need to be done at higher concentrations to validate what we saw with 2 wt-% data. Unfortunately, we ran out of
nanoparticles after we collected the 2 wt-% data and Prof. Fresnais was unable to synthesize more particles in a timely manner.
APPENDIX

Computer program used in the experiment in MATLAB code,

clear all
close all
format long

% initials
V0=0.158;
maxtemp=46;
waite=5;
freq=3000;

inputs=input('do you want to enter new parameters? ','s');
compare=strcmp(inputs,'no');
if compare==1
else
  % gets input from the user
  V0=input('start voltage (Vrms):  ');
  waite=input('wait times (s):   ');
  maxtemp=input('max temprature(c):  ');
  freq=input('Frequency (Hz):  ');
end

% creates the dmm, lockin amp, function generator and temp_control

dmmdc=gpib('ni',0,13);
lock=gpib('ni',0,8);
tempcontrol=gpib('ni',0,11);

% opens communication with the three divices
fopen(dmmdc);
fopen(lock);
fopen(tempcontrol);

% sets the devices to return only numbers without units

fprintf(dmmdc,'F2R0T4G1X');
fprintf(lock,':FORM:ELEM READ');
fprintf(lock,'HARM2');

% will be used to store data
file='practice';

% sets the initial frequency and amplitude and temprature
fprintf(lock,cat(2,'FREQ',num2str(freq)));


fprintf(lock,cat(2,'SLVL',num2str(V0)));  
fprintf(tempcontrol,cat(2,'SETP',num2str(maxtemp)));  
pause(waite);

fulltime = clock;

year = num2str(fulltime(1));
month = num2str(fulltime(2));
day = num2str(fulltime(3));
hour = num2str(fulltime(4));
minute = num2str(fulltime(5));

filebase=cat(2,file,'_',hour,'_',minute,'_',month,'_',day,'_',year,'_.txt');

for t=[46,45,44,43,42,41,40,5,40,2,40,19.9,19.8,19.7]
    pause(waite);
    final=[];
    fprintf(tempcontrol,cat(2,'SETP',num2str(t)));
    pause(200);
    pause(waite);
    for n=1:20
        V=V0*sqrt(n);
        fprintf(lock,cat(2,'SLVL',num2str(V)));
        pause(3);
        totaldata=str2num(query(lock,'SNAP?1,2,3,4'));
        ac=totaldata(3);
        phase=totaldata(4);
        dc=query(dmmdc,'DATA?');
        dc=strrep(dc,'NDCV','');
        dc=str2num(dc);
        g=ac/dc;
        data=[V,ac,dc,g,phase,t,freq];
        final=[final;data];
    end
    final=final';
    filename=cat(2,filebase,num2str(t));
csvwrite(filename,final)
end

%closes the devices
fclose(dmmdc);
fclose(lock);
fclose(tempcontrol);

%deletes the devices
delete(dmmdc);
delete(lock);
delete(tempcontrol)
save(filename);
BIBLIOGRAPHY


