INDUCE NANOSTRUCTURES WITH ELECTRIC FIELDS

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With special thanks to my advisor: Wei Lu

Abstract

This semester, I induced different nanoparticles with electric fields to observe their behavior under the guidance of Professor Wei Lu. The objective was to see what kind of effect AC voltage, DC voltage, and frequency had on the nanoparticles. Also, I wanted to see if chains would form between the nanoparticles, thereby enhancing their performance in applications such as solar cells, electronics, and energy storing devices etc. In order to conduct these experiments, I created a setup where nanoparticles of Carbon and Lithium Manganese Dioxide suspended in a dielectric solution were put into a 1mm wide slit. I used an AC/DC power supply, function generator, power amplifier, electrode setup, and an inverted microscope to see the actual particles. After several experimental trials of creating an electric field around these particles, I concluded that higher DC voltages and AC voltages with lower frequencies (~1 Hz) caused the different nanoparticles to move in the dielectric solution. The higher the voltage and lower the frequency (in the case of AC voltage), the more rapidly the particles would move in the solution. Furthermore, chains could be seen forming within Lithium Manganese Dioxide particles.

Keywords: nanoparticles, electric field, self-assembly, dipole

Background

Nanoparticles and nanotechnology are currently intense areas of scientific research as they have a wide range of applications such as energy storage devices, electronics, biomedical devices, and solar cells, etc. However, many of these applications require the nanoparticles to form ordered structures so that they can perform at an optimal level. In terms of ordered structures, self-assembly is a very promising approach to integrating nanoscale building blocks into structures. The electrostatic interaction between the particles has been of specific interest because of its long-range effect and simplicity of control. One particularly notable phenomenon is that dispersed spherical particles can acquire electric dipole moments and line up into chains parallel to an applied electric field. In this instance, the dipolar interaction between particles is of utmost importance. Figure 1 illustrates the relationship between electric fields and dipole moments, where \( p_i \) is the dipole moment of a nanoparticle, \( d_i \) is the diameter of the same nanoparticle, \( \epsilon_m \) is the permittivity of the medium, \( \alpha_i \) is the permittivity ratio, and \( E \) is the electric field strength.
Fig. 1. Strength of dipole moment is highly dependent on strength of the electric field. The permittivity ratio will dictate which direction along the electric field the nanoparticles move.

Before conducting the experiment and observing the behavior of the particles, it was important to better understand how exactly how the particles moved under dipole interaction and viscous force. Equation 1 below shows what forces will determine how the particles move.

\[ m_i a(t) = F_i^E + F_i^D + F_i^R(t) \]  

Eq. 1

Where \( m_i \) is the mass of the particle, \( a(t) \) is the acceleration of the particle, \( F_i^E \) is the force from the electric field, \( F_i^D \) is the drag force, and \( F_i^R(t) \) is the random force.

One should also consider the interactive energy between dipoles. Equation 2 below shows the parameters that the energy between dipoles depend on. Where \( U \) is the energy between the dipoles, \( p_1 \) is the dipole moment of the first dipole, \( p_2 \) is the dipole moment of the second dipole, and \( \theta \) is the angle between the two dipoles.

\[ U \sim p_1 * p_2 (1 - 3 \cos^2(\theta)) \]  

Eq. 2

The important parameter to point out is \( \theta \) because the orientation of the two particles will determine how much energy is between them. If the angle between the particles is small and close to 0 degrees, then the particles line up vertically, parallel to the direction of the electric field. Figure 2 illustrates how the orientation between the two particles will determine how much energy is between the particles.
Fig. 2. The larger the angle between the particles, the more energy between them. A 90 degree angle between the particles will have them oriented perpendicular to the direction of the electric field. If the angle between the two particles is 0 degrees, then they are oriented parallel to the direction of the electric field, thereby lowering the energy between them.

Another concept that is worth mentioning is the balance between the electric force and random force from Brownian motion. Brownian motion is the volatile movement of microscopic particles in a fluid, because of the incessant bombardment from other particles around them. In the case of my constructed experiment, the Carbon and Lithium Manganese Dioxide particles are constantly hitting each other. If the electric field is too strong, as in the applied voltage is too high, then the particle can become trapped at a local minimum. In this case, the particle does not move naturally as it would in the medium, thereby making it difficult for the particles to self-assemble. However, it is entirely possible to free the particle through thermal vibration. As the temperature increases, particles will tend to move faster, thereby freeing a trapped particle. Figure 3 illustrates better a particle trapped at a local minimum.

Fig. 3. A particle is trapped at a local minimum, unable to move either left or right because there is not enough energy to do so. Thermal vibrations can free the particle, however.

Another possibility is if the electric field is too weak and the particles lose order due to the random movement. In this case the random force is greater than the electric force and the particles fail to self-assemble once again. Equation 3 below shows that the larger the electric field, the more likely that the nanoparticles are going to self-assemble. $\lambda$ shows the balance between the random and electrical forces, $d_A$ is the diameter of the nanoparticle, $\alpha$ is the
permittivity constant, $E$ is the strength of the electric field, $\epsilon_m$ is the permittivity of the medium, $k_B$ is Boltzmann’s constant, and $T$ is temperature.

$$\Lambda = d_A^{3/2} |\alpha_A| E \sqrt{\epsilon_m / k_B T} \quad \text{Eq. 3}$$

Furthermore, Equation 4 below shows how the electric force and drag force must balance each other. Where $\tau$ is the time constant. The greater the time constant, the longer time it takes for the particles to assemble.

$$\tau = \eta / (\epsilon_m (\alpha_A E)^2) \quad \text{Eq. 4}$$

**Experimental Setup**

In order to create an electric field around different nanoparticles, I used an AC power supply, GW Instek DC power supply, GW Instek function generator, power amplifier, electrode setup, digital camera, and an AmScope inverted microscope. Figure 4 below shows a full view of the setup used. Banana plugs would either be extended from the AC or DC power supply and connected to a 4.7 kΩ resistor. A second banana plug would then extend from the resistor to the electrode setup. A third banana plug goes from the negative end of the power supply to the opposite side of the electrode setup.

**Fig. 4.** The setup for both AC voltage and DC voltage experiments.

The electrode setup can be seen in Figure 5. The inverted microscope can only be used if a setup of certain dimensions fits in the stage of the microscope. Therefore, using acrylic and the
University of Michigan machine shop, I was able to laser cut a setup of these exact dimensions. A laser cutter was used because of its precision and accuracy. Knowing that the particles are very small, they would have to be viewed in a small space where they would be clumped together and not move around everywhere, thereby increasing the chances of self-assembly. Cutting a small rectangle out of acrylic, I then created a 1mm wide slit in the middle with the purpose of putting the particles in suspended in dielectric solution. This was also created using a laser cutter. This rectangle was then taped onto a petri dish. In order to place the petri dish in the before created setup, a hole of the diameter of the petri dish was laser cut. The petri dish could then be put in the setup. In order to create the electrodes, thin copper film was used and stuck to the sides of the slit. The opposite ends of the copper film were then made stationary using brass nuts. The nuts were stuck on the setup again using acrylic and double sided tape. In this way, since electricity is conducted from the power supply to the electrodes, an electric field can be felt by the nanoparticles in the slit.

**Fig. 5.** The copper film serves as the electrodes while the nanoparticles and solution are inserted into the slit between the electrodes.

**Experimental Approach using DC voltage**

The first step was to mix the Carbon black particles in dielectric solution. In order to do this, we first obtained a petri dish and then sprayed the solution into the dish. Then, using tweezers, I moved the Carbon black particles from their container into the petri dish with the solution. After that, I used a pipet to move the solution into the slit in the setup. It is important not to add too many particles because as one can see under the microscope, clusters form and even a strong electric field will make it difficult to have any particles move. In addition, if I realized I added too little of the solution, I can always add more. However, it would be impossible to remove any of the solution once it is in the slit. Then I put the petri dish into the setup created before and put the entire thing on the stage of the inverted microscope. Figure 6 shows the Carbon black particles mixed with the dielectric solution in a petri dish.
Fig. 6. A pipet is used to remove the particles suspended in a dielectric solution.

Afterwards, I turned on the microscope and tuned it until I could get a clear image of the particles. Ideally, the light of the microscope will be right over the middle of the slit in between the two electrodes because that is where the electric field is the strongest. Turning on the DC power supply, I varied the voltage until I was able to obtain a good balance between the force from electric field and force from random motion. I found this voltage to be 55 V. Figure 7 and Figure 8 below show Carbon black at 0 V and 55 V, respectively.

Fig. 7. The Carbon black particles are still at 0 V.

Fig. 8. The Carbon black particles are moving at 55 V.

The same method was applied for the Lithium Manganese Dioxide particles except a voltage of 92 V was applied. Fig.9 and Fig. 10 below show Lithium Manganese Dioxide at 0 V and 92 V, respectively. One can tell that there is also movement after the voltage has been increased.

Fig. 9. The Lithium Manganese Dioxide particles are still at 0 V.

Fig. 10. The Lithium Manganese Dioxide particles are still at 92 V.
**Experimental Approach using AC voltage**

The same methods for DC voltage experiments were applied to AC voltage except now there is use of the function generator. The banana plugs are put into the input and output ends of the function generator and AC power supply now instead of the DC power supply. Videos were taken of the two different nanoparticles as I lowered the frequency from 1 MHz to 1 Hz.

**Results and Discussion**

In the case of DC voltage, a higher voltage induced a stronger electric field, thereby making the particles move more rapidly and inducing dipole moments. This was true in both cases of Carbon black and Lithium Manganese Dioxide. Not only that, but one could tell the viscosity of the solution had a drag force on the particles. In addition, particles bumping into other particles could be seen as the random force that also influenced the motion and trajectory. However, I could not see any chains form between any of the particles.

In the case of AC voltage, a higher voltage also induced a stronger electric field. The particles again moved more rapidly but frequency had an even bigger impact. No matter how high the voltage was, if the frequency was even above 300 Hz, the particles would barely move. Table 1 and Table 2 below show the results of varying frequency and voltage on Carbon black and Lithium Manganese Dioxide, respectively.

**Table 1.** Varying voltage and frequency for Carbon Black

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Frequency</th>
<th>Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.60 V</td>
<td>1 MHz</td>
<td>None</td>
</tr>
<tr>
<td>61.70 V</td>
<td>10 kHz</td>
<td>Nearly indiscernible</td>
</tr>
<tr>
<td>58.60 V</td>
<td>1 kHz</td>
<td>Some</td>
</tr>
<tr>
<td>54.20 V</td>
<td>1 Hz</td>
<td>Rapid</td>
</tr>
</tbody>
</table>
Table 2. Varying voltage and frequency for Carbon Black

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Frequency</th>
<th>Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>190.40 V</td>
<td>1 MHz</td>
<td>None</td>
</tr>
<tr>
<td>181.60 V</td>
<td>10 kHz</td>
<td>None</td>
</tr>
<tr>
<td>176.20 V</td>
<td>1 kHz</td>
<td>Some</td>
</tr>
<tr>
<td>170.40 V</td>
<td>1 Hz</td>
<td>Some</td>
</tr>
</tbody>
</table>

Lithium Manganese Dioxide needed a much higher voltage to see any movement. Even then, there was never any rapid movement between the particles. Also, while it was difficult to see any chains form for Carbon Black, there was one instance where a chain between the particles formed for Lithium Manganese Dioxide at 170.40 V and 1 Hz. Figure 11 below shows chains forming between the particles. Once again, as in carbon black, lower frequencies would generate more movement from the nanoparticles. From this, it is hopeful that with just the right amount of particles, and a strong enough electric field, self-assembly can occur.

In conclusion, we saw that electric fields induce dipole moments inside particles. The interaction between the particles and the applied field caused the particles to move and form various structures. The electric force, viscous drag force, and the random Brownian forces together determine the motion. Results with both AC and DC electric fields show that the field strength and frequencies can be manipulated to control the motion of the particles. Higher voltages make the particles move more rapidly, as do lower frequencies. The studies suggest a promising approach of using electric field to form various small structures.