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Observing Orbital Angular Momentum Transfer from Electron Vortex Beams to Matter

Hannah DeVyldere
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Observing Orbital Angular Momentum Transfer from Electron Vortex Beams to Matter

Hannah DeVyldere

A THESIS

Presented to the Department of Physics
LINFIELD COLLEGE
McMinnville, Oregon

In partial fulfillment of the requirements
For the Degree of
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Thesis Acceptance

Linfield College

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ABSTRACT

It is possible to produce electron beams with non-zero orbital angular momentum. Such beams, known as electron vortex beams are theoretically able to transfer their orbital angular momenta to matter, causing the matter to rotate. Nanoparticles in an aqueous solution were observed with an electron vortex beam to detect the transfer of orbital angular momentum in a low-friction environment. Observing the transfer of orbital angular momentum to particles in solution is difficult due to the necessity of imaging the particles through a liquid and the random movement of particles in the solution. Thus orbital angular momentum transfer to matter could not conclusively be observed in this environment. Initial data, observations, and a discussion of ways to eliminate particle movement, increase image quality, and reduce uncertainty of particle movement while observing orbital angular momentum transfer are discussed. Research was conducted in the Material Science Institute at the University of Oregon under the advisement of B. McMorran.
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Chapter 1

Introduction

1.1 Electron Vortex Beams

Electron beams are used in nearly every aspect of the electronics industry to troubleshoot electronics components which have sizes on the nanometer scale. As the components of microchips are too small to be seen with a light microscope, electron microscopes are used to further the research which will allow the components to be more effective or reduce their size even further. Unique electron beams with discrete quanta of orbital angular momentum (OAM) could be especially useful in the electronics and manufacturing industries. Electron beams with OAM, called electron vortex beams, could be a way of providing angular momentum to micro-motors and manipulating nanoscale components. Such beams could also be applied to create nanoparticle-trapping devices or could be used in the investigation of mesoscopic surface interactions and nanoscale viscosity measurement. Electron beams capable of transferring
OAM to matter pose unique opportunities for viewing and manipulating materials in the manufacturing of ever-advancing technology.

For physicists and material scientists, electron vortex beams provide an avenue with which to study the phenomena of OAM. OAM is primarily understood in the context of nuclei-bound electrons, however electrons in vortex beams are free electrons which are considered to have intrinsic OAM [1]. Investigation into vortex beams could give fundamental insight into the phenomena of orbital angular momentum and also provide an avenue to determine how electrons interact and transfer momentum to matter in electron-particle or electron-atom interactions.

Electron vortex beams are special electron beams in which the wavefronts of each electron’s wavefunction have a helical shape while moving forward in time. In 1992 Allen et al. [2] mathematically showed that optical vortex beams possess a property known as orbital angular momentum. Similar to light, electrons are both a particle and a wave. Electron optics exploits the parallel between light and quantum particles and the same proof showing optical vortex beams carry OAM can be extended to show the same is true for electron vortex beams.

Experimentally, Verbeek et al. [2] demonstrated the transfer of OAM from an electron vortex beam to matter by focusing the beam onto a nanoparticle on a dry substrate. Verbeek et al. observed the nanoparticle rotate under the beam’s illumination. The work presented here was conducted with the goal of
demonstrating OAM transfer from electron vortex beams to nanoparticles in an aqueous solution, and reproducing the results reported by Verbeek et al..

Transmission electron microscopes (TEMs), electron diffraction gratings, and liquid flow cells were used to perform the experiment, while TEM images and their correlating Fast Fourier Transforms (FFT’s) were analyzed to determine the results of the experiment.
Chapter 2

Theory

2.1 Electron Wavefunctions

Electron probability distributions are described by wavefunctions, \( \psi(x, t) \), which quantum mechanics tells us fully describes the state of electron in coordinate space. As has been observed in many experiments since the 1920’s, the wavefunction characterizes the wave nature of electrons. In coordinate-space and prior to detection, electrons are described as being distributed over some space with varying probability instead of being found at a single point. The wavefunction describes this probabilistic distribution across space and serves as a way of mathematically describing the complex and inherently quantum mechanical properties of electrons.
Though the outcome of any individual experiment cannot be determined, the wavefunction description produces accurate probabilistic predictions when an experiment is repeated multiple times. By squaring the wavefunction of an electron bound to a nucleus, for example, the probability of the electron being found at a specific distance from the nucleus can be determined. A wavefunction can also reveal information regarding the allowable states of an electron through the use of operators. States refer to specific conditions of a particle or system at a given time. For example, an electron possessing five units of energy is in a specific energy state, while an electron which has two units of energy is in a different energy state. Operators are mathematical representations of the various measurements that could be made on a system (in this case an electron). For instance, an electron bound to a nucleus has specific energy levels (energy states) that it is allowed to be in. These energy levels can be found by applying a total-energy operator (known as the Hamiltonian, \( \hat{H} \)) to the wavefunction of the electron and determining the solutions to the resulting differential equation. Applying an operator to a wavefunction simply involves performing a set of mathematical operations (e.g. multiplying by \( x \), taking the derivative with respect to \( x \), etc.). When applied, if the resulting equation can be expressed as the original wavefunction multiplied by a constant, the eigenvalue, then that constant is the value of the measurement taken (e.g. \( \hat{H} \psi(x, t) = 5\psi(x, t) \), the electron possesses
5 units of energy). Wavefunctions provide means with which to predict the behavior and properties of quantum systems as they are acted upon and evolve. In this thesis, the angular momentum operator, $\hat{L}_z$, will be applied to determine the amount of OAM associated with the wavefunction of the electrons in the vortex beam.

### 2.2 Electron Interference

In quantum theory, prior to detection, electrons are described as having some distribution across space, instead of being at a single point. This distribution allows for the phenomenon of wave interference. Interference is a property of all waves and describes one aspect of how waves interact. The classic example is water waves. Figure 1 show two types of interference; constructive interference and destructive interference.
Figure 2.1: (a) Constructive interference of two wave peaks. (b) Destructive wave interference of a peak and a trough. Red and blue represent individual waves and the purple waves represent the combination of the two waves.

Figure 2.1a shows an example of constructive interference. When the peaks of two waves meet, the result is a bigger wave. When the lowest part of a wave meets the peak of another wave, the result is the annihilation of both the peak and the trough into some intermediate as seen in Figure 2.1b. Wave interference occurs with all waves from matter waves such as air and water to electromagnetic waves (light) to electron waves.

As exemplified in the double slit experiment performed with electrons [3], quantum particles are able to interfere with themselves. For electrons, the peaks and troughs refer to the probability amplitudes (e.g. the extrema of the wave represents a highly probable location for finding the electron). This implies that different parts of the same wave interact, changing the distribution of the particle in space and therefore altering its wavefunction.
For waves travelling along a similar axis, interference can be seen when two or more waves are in or out of phase with each other.

**Figure 2.2:** Illustration of wave interference with (a) in phase waves, (b) 180° out of phase waves, and (c) 90° out of phase waves. Notice that waves with zero phase shift add together to produce a wave with twice the amplitude. Waves with some nonzero phase shift produce a wave with amplitude between 0 and <2 times the original amplitudes.

When two waves are out of phase with each other they destructively interfere and their combined amplitude is diminished. When two waves are perfectly in phase the combined amplitude is magnified. In each case the amplitudes of the interfering waves are added together.
The spatial distribution of electrons and the ability of electrons to interfere with themselves are the basic concepts necessary to understand what electron vortex beams are and how they are engineered.

2.3 Electron Vortex Beams

Electron vortex beams are beams of electrons in which each electron’s wavefunction has a unique helical shape that is preserved as it propagates. In such beams, the electron’s probabilistic distribution perpendicular to the direction of propagation is not a typical gaussian distribution, but has been transformed via interference so that highly probable locations for the electron lie at some point along a ring.

Vortex beams are engineered by passing a Gaussian (a normal, or bell distribution) electron beam through a forked diffraction grating such as the one shown in Figure 2.3 and Figure 2.4.
**Figure 2.3:** Atomic force microscope image of a 1 OAM forked diffraction grating used to create electron vortex beams. The dark lines represent the milled troughs in the diffraction grating which impart phase shifts to the electrons (reproduced from Pierce et. al 2013)[12].

**Figure 2.4:** Cross-sectional illustration of the electron diffraction phase grating in Figure 2.3. The grating imparts a phase shift to the electron’s wavefunction. The phase shift imparted is determined by the thickness of the grating at the point where the wavefunction passes through (reproduced from Harvey et al. 2014)[1].
By passing an electron, which is spread out across some space, through the phase grating, sections of the electron wave acquire varying phase shifts depending on the thickness of the grating it passes through (see Figure 2.4). The electron’s wavefunction below the grating has varying phases meaning that the probability amplitude peaks and troughs are no longer all in the same plane but occur at various heights with respect to each other. At some points in space, probability amplitude troughs are now in phase with peaks causing an annihilation of the probability, while at other points peaks are in phase with midpoints slightly reducing the probability. The electron’s wavefunction after it has passed through the grating thus is able to interfere with itself. The wave interference is such that constructive interference of the wavefunction occurs at different points on a ring as the electron propagates down the optic axis. Wavefronts are surfaces over which the wave has constant phase. Constructive interference occurs azimuthally as the electron beam propagates, creating a wavefunction in which the wavefronts are helical. Constructive interference of multiple phases creates a ring in which the electron probability is high. While constructive wave interference swirls down the optic axis, destructive interference creates a void at the center of each vortex beam. Thus the wavefronts of an electron vortex beam’s wavefunction as it moves down the optic axis is helical. Figure 2.5 is a representation of how electron vortex beams are produced.
Figure 2.5: A Gaussian electron beam passing through a forked phase grating. The resulting interference below the grating produces multiple beams with the zeroth order beam possessing zero OAM and the remaining orders exhibiting $m\hbar$ of OAM (reproduced from McMorran et al 2011)[11].

Figure 2.5 shows an electron beam passing through a diffraction grating beneath which the resulting interference creates multiple vortex beams. The helical shape shown is a representation of the wavefunction’s wavefronts as the beam propagates. The diffraction order is denoted by $m$, which when multiplied by $\hbar$, the fundamental quanta of angular momentum, gives the amount of orbital...
angular momentum associated with each individual beam. The zeroth order beam, 
\( m = 0 \), thus has 0 OAM associated with it.

The forked shape of the electron diffraction grating gives rise to the specific shape of the electron beam’s probability-amplitude wavefronts. Reverse engineered using simulated holographic techniques [5], the forked diffraction grating has one more slit on the top half of the grating than on the bottom half. The added wavefront from the top of the grating is responsible for the helical shape of the electron’s wavefunction. Increasing the number of slits on one side of the diffraction grating would increase the OAM associated with each vortex beam.

2.4 Orbital Angular Momentum

Since it is first introduced while describing the motion of an electron around a nucleus, OAM is often associated with orbiting motion. It can be difficult, then, to see how free electrons not orbiting any particular object may also possess this property.

The wave function of the electron vortex beam can be described by

\[
\psi_f (r, z, \varphi) = F(r, z)e^{im\varphi}
\]  

where \( F(r, z) \) describes the radial and z components, \( e^{im\varphi} \) describes the azimuthal component (angular motion perpendicular to the axis of propagation) of the wave function, and \( m \) is the diffraction order. To determine the presence of
orbital angular momentum, the $z$-component orbital angular momentum operator, $\hat{L}_z$, can be applied to the wavefunction. In the Schrödinger representation the orbital angular momentum operator in the $z$-direction (along the beam axis) is $\hat{L}_z = \frac{\hbar}{i} \frac{\partial}{\partial \phi}$. Applying this operator to the vortex beam wavefunction it can be seen that

\[ \hat{L}_z \psi = \hbar \frac{\partial}{\partial \phi} \left[ F(r, z) e^{im\phi} \right] \]  

(2a)

\[ \hat{L}_z \psi = m\hbar F(r, z) e^{im\phi} = m\hbar \psi, \]  

(2b)

Thus the angular momentum associated with an electron in $m$th order diffraction is $m\hbar$.

Mathematically it is clear to see that vortex beams carry orbital angular momentum, but physically the electron is not spinning around an axis. Electrons in an electron vortex beam are modeled in spatial dimensions as moving linearly down the optic axis. To understand where the orbital angular momentum comes in it is necessary to look not at the electron’s behavior in position space (or how we model it in space), but rather at its wavefunction. Orbital angular momentum is a purely quantum effect and can be thought of as a measurement of how much the probability distribution of the electron is swirling about in time. Thus the helical nature of the probability amplitudes as the beam propagates, can be thought of as

---

1 In a TEM electromagnetic lenses do actually cause the electrons to move azimuthally. However, this spatial movement is not included in the model of the wavefunction of the electron beam and thus the mathematical findings are still valid.
the “source” of the OAM. This makes it more similar to spin angular momentum than the OAM normally associated with beams of electrons.

### 2.5 Fast Fourier Transforms

Fast Fourier Transforms (FFTs) are a way of displaying spatial information in terms of the frequency of repeating artifacts on an image. Every repeating pattern can be created by summing sine and cosine waves of various frequencies and amplitudes. A Fourier transform exploits this feature of repeating patterns to turn data presented in the time or spatial domains into frequency and amplitude data of repeating trends. Figure 2.6 shows an example of a repeating pattern being decomposed into its constituent sinusoidal waves each with varying amplitudes. The blue axis is the frequency domain which gives amplitude and of the various frequency which make up the initial pattern.

![Figure 2.6: A Fourier transform of a two-dimensional input signal (red). The component sine waves are represented by their frequency on the length of the frequency axis (blue) with the amplitude represented along the vertical axis (reproduced from Barbosa 2013) [13].](image-url)
In the experiment FFTs were applied to images. The value (how dark/light the image is at each point) serves as the amplitude and repeating values create a pattern to be decomposed into sinusoidal waves. The amplitudes and frequencies of all the waves necessary to recreate the original image are then mapped onto a two-dimensional image where bright spots (called stars in this thesis) indicate regular periodicity in the image analyzed.

If the periodic low and high values become closer together the stars on the FFT get further apart. Similarly if the repetition of values becomes more spread out the stars on the FFT will move nearer the center. If the pattern of the image rotates, it is expected that the bright stars on the FFT would rotate as well. In the experiment rotation of the FFT was an important indicator for determining the rotation of the particle.

2.6 Torque

OAM transfer from an electron vortex beam to a nanoparticle would cause the particle to experience a torque. The total torque on an object in an $m$th order electron vortex beam can be calculated as

$$
\tau_{beam} = \sum_{m=\infty}^{m=\infty} P_{m\rightarrow m'} (m - m') \frac{h}{e} \tag{3}
$$

where $m$ is the initial angular momentum of a vortex electron, $m'$ is the angular momentum of a vortex electron after the sample, $P_{m\rightarrow m'}$ is the probability that an
electron will have a change in angular momenta equal to \((m - m')\), \(I\) is the current of the beam, \(g\) is the percent of the vortex beam projected on the particle, and \(e\) is the charge of an electron.
Chapter 3

Experimental Setup

Gold nanoparticles suspended in an aqueous solution were placed in the path of an electron vortex beam with +1 OAM to detect the transfer of OAM from electron beams to matter. Gold was chosen because of its crystalline structure and relatively high atomic contrast. The nanoparticles were suspended in solution to reduce friction which could impede the rotation of the particle.

3.1 Transmission Electron Microscopes

A transmission electron microscope (TEM) was used to create the electron vortex beams and separate the diffraction orders. A TEM operates by focusing a high energy (80-300 keV) electron beam at a very thin sample (approx. 10-200 nm thick). Atoms are mostly empty space with the nucleus occupying approximately 1/100,000 of the atom’s volume. Thus, most of the electrons in the beam are transmitted through the sample with no scattering. Some electrons do however
scatter off the nuclei of the sample, deflect at high angles, and are not transmitted. Electrons from the electron beam also scatter off the electrons of the sample (although this phenomena in thin samples is not nearly as consistent as electrons scattering off the nuclei). This leaves a shadow below the sample where electrons in the beam scatter off the nuclei or other electrons in the sample. This shadow pattern is what composes the image of the TEM. TEM images contain information about the three-dimensional makeup of the sample and give information of features not just at the surface of the sample but throughout its volume.

Parts of a TEM are shown in Figure 3.3: An electron gun for extracting and accelerating the electrons, electromagnetic lenses which focus the beam and magnify the image, a stage which holds the sample, and a charge coupled device (CCD) camera for detecting the electrons which form the image.

A slightly modified TEM setup was used to conduct the experiment. An electron diffraction grating was added to the second condenser aperture of the TEM above the sample. A specific type of specimen holder was also utilized to hold the aqueous solution. A simplified diagram of the TEM used in the experiment is shown in Figure 3.1.
Figure 3.3: Simplified diagram of the experimental setup in the TEM. (a) Electrons are extracted from the electron source and (b) focused through a series of lenses. (c) The electron beam passes through the electron diffraction grating and a helical shape is imprinted onto the wavefunction of each electron. The electron beam carrying OAM is then incident upon the liquid cell in the object plane of the TEM. (d) The image is then magnified by subsequent electromagnetic lenses and projected onto the (e) phosphorous plate or CCD camera at the bottom of the TEM.
The electron beam in Figure 3.3 is focused or spread using electromagnetic lenses prior to going through the electron diffraction grating. Below the grating the electron beam, now with helical wavefronts and carrying orbital angular momentum, is incident on the sample in the liquid cell. The image of the liquid cell’s contents is then magnified through more electromagnetic lenses before being incident upon a phosphorous plate. Phosphorous releases light when hit by an electron which allows the image to be seen by the naked eye. Additionally if the phosphorous plate was lifted a CCD camera connected to the computer allows for the digital collection, storage and processing of the image.

3.2 Liquid Flow Cell

A liquid flow cell TEM sample holder was utilized to hold the nanoparticle solution. Liquid cells are completely sealed cells which allow for liquid samples to be inserted into the high vacuum environment of the TEM without blocking electron current through the sample. The liquid cell, as shown in Figure 3.2, consisted of two silicon chips, one containing a 100nm spacer to create a space for the fluid. A 30nm-thick, electron-transparent window made of silicon nitride is inset into each chip allowing for the sample to be sealed without significantly reducing the electron current transmitted through the sample.
Figure 3.2: A cross section diagram of the liquid cell tip with a pictorial representation of a vortex beam incident on a gold nanoparticle. Two silicon chips, (orange) with 30nm silicon nitride membranes (green) sandwich gold nanoparticles suspended in an aqueous solution. The silicon dioxide spacer creates a space for the liquid to sit (reproduced from Greenberg et. al, 2016)[9].

The liquid cell fits inside the tip of the liquid flow cell TEM holder shown in Figure 3.3.
The liquid cell is inserted into the chip well (the rectangular cut out) in the tip of the liquid flow cell holder. The overclamp (Figure 3.3b) lies face down on top of the two chips and is secured in place with the slide lock.

### 3.3 Procedure

The experiment used 3-30 nm diameter gold nanoparticles, suspended\(^2\) in an aqueous solution and sealed in the tip of a liquid flow cell. The liquid cell was prepared by pipetting a microliter of solution onto a clean\(^3\) open-faced liquid cell chip sitting in the well of the flow cell holder. A second chip was then placed on top of the first and the overclamp on top of both the chips. The overclamp was then secured in place by a slide lock.

---

\(^2\) Ligands were used to suspend gold particles in water

\(^3\) See Appendix A for the liquid cell chips cleaning procedure.
Following the assembly of the flow cell tip, the holder was then placed in a leak check station to verify that the tip had been put together correctly and check that the silicon nitride windows were still intact. The leak checking chamber subjected the liquid cell to a vacuum similar to that of a TEM. With no leaks present the chamber was expected to reach reach $3.6 \times 10^{-6}$ mbar within 3 minutes.

Prior to the experiment, the TEM, in nanoprobe mode, was aligned and aberration corrected using a dry sample of nanoparticles on a carbon/copper substrate grid. A sealed liquid flow cell with gold nanoparticles was inserted into the object plane of the previously aligned TEM, the height of the sample was adjusted until particles in the liquid showed the least amount of contrast and thus were sufficiently in focus. The Fast Fourier Transform (FFT) was used to measure the image defocus and confirm the presence of crystalline material.

It was hypothesized that, considering the depth of our liquid cell to be between 160 nm and 300 nm, different planes would be seen moving in and out of focus as the height of the sample was changed. It was found that a particle in focus stayed in reasonable focus (atomic lattice could be clearly seen) even after changing the height of the sample 300 nm in the + and - z direction. Since no clear indicators were present in the image or the FFT showing the particle more in or out of focus, no clear conclusion could be drawn to determine the depth of the particle within the cell.
Mechanized movement of the stage (where the holder is inserted into the TEM) made scanning and maneuvering of the liquid cell possible in the viewing window. By moving the stage a particle, approximately 2nm-10nm in diameter, was chosen and centered on the viewing screen. A +1 OAM forked diffraction grating manually installed into the second condenser aperture of the TEM was inserted and aligned along the optic axis. The beam was then shifted so that the first diffraction order was centered on the viewing screen. The particle previously chosen was then maneuvered until it was centered in the dark void in the beam’s center. The intensity was then focused onto a smaller area so that the edge of the beam was just outside the edge of the particle. After verifying that the atomic lattice was still visible, a series of images were recorded to show the evolution of the particle in time. A control series of images was also taken using an un-diffracted beam spread out over the field of view.

Depending on the strength of the beam, the spot size of the beam, the diffraction order used and the size of the particle, the length of the time series images was varied. For larger particles (~10nm) time series images were often taken over the course of 20 minutes with one minute intervals between each image as the movement appeared to be occurring much less rapidly than smaller (~2nm) particles. Second order beams were also used in various trials as well as higher OAM diffraction gratings (+3 and +5 OAM).
Chapter 4

Results and Analysis

4.1
Time series images of the same gold nanoparticle were taken under a +1 OAM vortex beam, a -1 OAM vortex beam, and an un-diffracted nanoprobe beam in the TEM.

Figure 4.1: TEM time series images of a +1h beam centered on a particle ~8 nm in diameter. Over the course of 7.5 seconds lattice lines are observed at varying angles.
Figure 4.1 shows selected images from a time series of images taken with the first order diffracted beam of a +1 diffraction grating focused on a particle approximately 8nm in diameter. Lattice lines are observed at multiple different angles with respect to the original orientation. This clear change in the angle of lattice lines throughout the series, suggests some form of rotation of the particle.

For a rotating nanoparticle it would be expected that the “star” pattern of FFT would rotate. However, the FFT for these images only display 2-6 “stars”, which, in various frames disappear and reappear. This, coupled with the “jumpy” nature of the rotation (the lattice appears to be oriented in one direction or tilts slightly in both the counterclockwise and clockwise directions for several frames before rapidly reorienting), makes it difficult to determine the exact behavior of the particle.

For reference, Figure 4.2 below shows selected images from the control series of a particle in an un-diffracted (OAM of the incident electron beam is equal to 0) beam.
Figure 4.2: Selected time series images of a particle imaged using an un-diffracted beam. Angles are measured from the lattice present in the t = 0 image.

Analyzing the images in Figure 4.2 it can be seen that the nanoparticle under the un-diffracted beam appears to be behaving in similar manner as when it was exposed to the first order electron vortex beam (OAM = +1). Taking a close look at the FFT for the control it was found that there were instances when the stars moved radially inward towards the center instead of spinning. This behavior could be consistent with the particle rolling, as the perceived lattice spacing of the nanoparticle would vary, changing the spatial periodicity of the image and causing a shift in the radial distance of the stars in Fourier space.
Chapter 5

Conclusion

Electron vortex beams, when focused on nanoparticles in an aqueous solution do induce rotation of the particle in some manner. The specific process responsible for this rotation has yet to be determined. As similar behavior was exhibited in the control as in the experiment it is not conclusive whether orbital angular momentum was transferred to the gold particle or not.

The rotation seen in both the control and +1 OAM time series of images could be a result of a couple of different phenomena. It is likely that there is a baseline amount of movement due to brownian motion and the vortex beam just adds a slight rotation on top of this. There also stands the possibility that the nanoparticle is rolling in conjunction with rotating. There is also the possibility that the crystal faces of the gold nanoparticle rearrange themselves under the intensity of the electron beam as has been previously observed. To bring in yet another dimension of complexity, it is common that nanoparticles have multiple
crystal faces which would allow for differing lattice lines to be confused with a single lattice line rotating.

It has also been theorized that within a liquid flow cell the intense focus of the electron beam can cause radiolysis (molecular decomposition) of the water into $\text{H}^+$ and $\text{OH}^-$ \cite{4}. The recombination of $\text{H}^+$ and $\text{OH}^-$ into water vapor could produce currents within the liquid cell \cite{5}. Zhu et al. attributed the observed rolling and rotation of nanoparticles in the liquid cell to the possible current produced by radiolysis and recombination.

As it is certainly unclear whether OAM transfer is responsible for part of the phenomena observed, future work could focus on eliminating some of the possibilities that presented themselves. Using nanorods, for instance, could help separate out rotation of the particle versus rolling. Similarly, determining the various crystal faces and lattice spacings of the particle before imaging could reduce the possibility of confusing various lattice lines. In the case that the particles are rotating at too high a rate for the existent imaging capabilities, lowering the beam current or using a more viscous solution may further allow for the minimization of jumpiness in our image data.

Although rotation from OAM transfer could not be conclusively shown through this experiment, elimination of variables, and various control experiments could reduce the possible outside causes of rotation to a few which may be
accounted for or eliminated entirely, thus allowing observation of OAM transfer to matter.
Chapter 6

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