Laser Tweezers and Orbital Angular Momentum Photons

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Abstract: A photon can be considered both a particle and a wave in quantum mechanics. Quantum optics deals with such quantum mechanical properties of a photon. One such property that has been of particular interest recently is that of light's momentum, specifically its linear momentum and orbital angular momentum (OAM). Light carrying both types of momentum are of particular utility to the life sciences. Linear momentum (LM) photons have the ability to directly manipulate particles. For example, photons with these properties can be used to separate one specific particle from a group. One can then more closely observe its properties. OAM photons have the potential to unravel DNA strands using the torque of the photons to further observe certain specific physical properties. Light carrying OAM has also shown promise in the field of information technology as a new means of sending large amounts of data over long distances securely and extremely quickly. Because photons behave quantum mechanically, the encryptions are much more difficult to decode, and since the information is being sent as light it clearly travels at the speed of light. This paper will provide background on the quantum optics of particle manipulation and the results from experimental studies performed on this topic. The results show evidence of light with both types of momentum being created and used to manipulate particles. We generated light with both types of momentum, trapped particles with optical tweezers, and measured the force on the particles with a high speed video camera, optical tweezers, and computer programs that we used to track the particles.

Introduction

Light is a fairly complex notion to discuss as it has properties that are odd and unfamiliar in everyday applications. Energy from light is quantized, meaning that it comes in discrete allowable amounts (there are certain amounts of energy that are "not allowed") as realized by Maxwell Planck in 1901. Then in 1905, Albert Einstein realized that light must be made up of particles called photons that carry momentum [1]. Photons can be thought of as particles and waves, hence wave-particle duality as discovered by Arthur Compton upon shining a beam of light through a carbon sample and noticing that upon exiting, the light had a longer wavelength. The scattered photons transfer momentum to the carbon resulting in lower energy and longer wavelengths [2].

Light has three different types of momentum: spin angular momentum, orbital angular momentum, and linear momentum. This paper will be focusing on orbital angular momentum (OAM) and linear momentum (LM). Quantized OAM of photons was discovered in 1983 by Miller and Wheeler [3], and readdressed relatively recently in 1992 by L. Allen, et al. It was discovered that if a beam of light was phase shifted causing it to have a certain phase dependence, it would carry OAM. The OAM photon beam has a helical wavefront as opposed to the plain wavefront of the LM photon beam. The LM of photons is responsible for propagating the photons through space. Since photons follow the rules of relativity, the momentum is $p = h/\lambda$ where h is Planck's constant and λ is the wavelength of the light [4].

Light's momentum can be used to manipulate miniscule objects. In 1970, Arthur Ashkin et al. used light to trap dielectric particles leading to the invention of the optical tweezer [5]. A different experiment used OAM photons to straighten out the individual strands for further observation using the characteristic torque of the photons [6]. Another experiment, performed by Liu and Zhang, used LM photons to manipulate biological cells and stretch or organize them [7]. Due to the importance of LM and OAM of light, the goal of the experiment was to create separate beams carrying both types of momentum and then use those beams to manipulate particles.

Equipment and Experimental Setup

The first important piece of equipment we utilized was a spatial light modulator (SLM). This piece of equipment is a tiny LCD screen that was used to project a binary $\ell = 1$ (quantum number) forked diffraction grating in order to phase shift the photons and create OAM photons. The SLM was connected to a computer through a VGA cable acting as a second monitor of the computer. For the gratings used in this experiment, multiple existing MatLab codes were referenced and pieced together to get the forked diffraction gratings [8][9].

The second important piece of equipment we used is optical tweezers which essentially is a modified microscope to allow the laser light to enter the microscope and be reflected by internal semi-transparent mirrors to the sample stage. The laser light is then used to manipulate the particles. Since the particles are larger than the wavelength of the laser, ray optics can be used to describe the particle trapping mechanics [10]. For example, consider a particle is within the radius of the beam but is displaced a certain distance x left of the center of the LM photon beam (having the strongest intensity). At this position the rays of light that are interacting with the particle are more intense to the right than they are to the left. As these light rays enter the particle, they are refracted out in a direction towards the center of the particle in the x direction. This means that if a ray enters on the left side of the particle, it will be bent slightly to the right upon exiting and vice versa for a particle entering on the right side. Since light is a particle, the change in direction is a change in momentum which is a force that is exerted on the particle pulling it into the "trap" or center of the beam and then keeping it in that position following Newton's first law of motion. For laser tweezers using OAM photons uses the same mechanics but since the wavefront is helical, the center of the beam changes position going around in a circle of constant radius making the particles rotate.

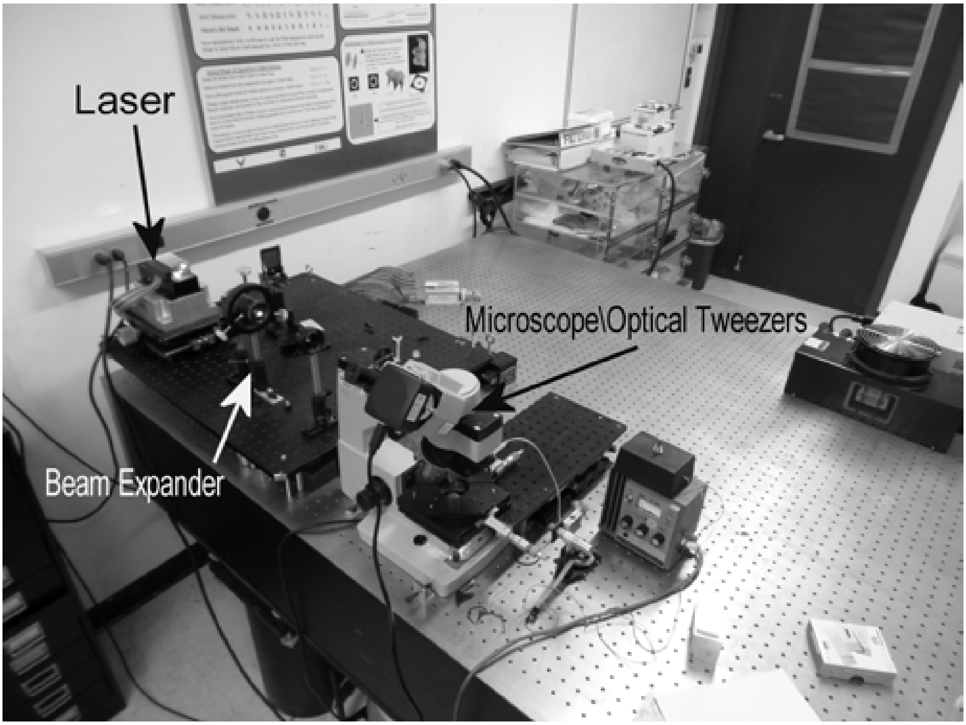

Figure 1: The setup used for the linear momentum particle trapping phase of the experiment.

The first part of the experiment was achieving trapping of particles with LM photons. The green 532 nm wavelength laser beam was directed through a 10x beam expander then through the microscope towards 2 micrometers, 1 micrometer, and 0.5 micrometers (in diameter) polystyrene particles. These particles were prepared on a sample slide with deionized water and placed on the stage of the microscope. The motion of the particles near the center of the laser beam was recorded with a high quality 1024x770 resolution, 50 fps video camera. The recordings started when the particles were too far away from the beam to feel a force, but the random Brownian motion of the particles (random moving due to the vibrating water particles) moved the particles into the range of the laser beam. The computer program that converted the video in .wmv format to individual jpeg files of each frame was the VeryDoc Video to GIF Converter. Then the images were loaded into the Able Particle Tracker program that tracks the movement of the particles based on the pixels. Then, this information was put into an Excel file and interpreted. We used a conversion of 13 micrometers per pixel and found the radius (√x2 + y2) and velocity (v = Δr/Δt). The acceleration of the particle going into the trap was also found (a = Δv/Δt) and the Brownian motion forces that were acting on the particle were found using the Langevin equation:

$$m\ddot{r} = -y\dot{r} + F(r) + \sigma\xi(t)$$

where m is the mass, determined from the density equation with the density of polystyrene being 1:05g/cm3, and are the acceleration and velocity of the particle, respectively, γ is the scalar friction constant, F(r) is the total force on the particle, σ is the amplitude of the fluctuating force, and (t) is the equation governing the fluctuations of the random force [10]. The γ term can be found using the equation γ = 6πηa, where η is the viscosity of the liquid, in this case water, and ais the radius of the particle. The σ(t) is found using experimental data.
For this particular experiment, the data indicated that |γ| >> |m| allowing equation 1 to be rewritten as:

$$m\dot{r} = F(r) + \sigma\xi(t)$$

From this, the force can be solved by subtracting the experimental dependent value, σ(t), from the right and left sides of the equation. The (t) can be found by recording the motion of the particle without the influence of the laser beam and calculating the average force.

Following our investigations of photons with LM we next considered photons with quantized amounts of OAM. Initially we verified that proper OAM beams were producible (the projection of the beam resembled a donut) [4]. The setup remained the same as before, except for an SLM placed between the laser and the beam expander and the addition of an aperture to ensure only one maximum of the beam entered the microscope. The data analysis process was the same as for the LM beam. The only difference was an additional calculation for torque since the particles were rotating [11].

Results

The for the LM photon beam, the 2 micrometers and 1 micrometer polystyrene particles were sufficient to get data for and for the OAM photon beam, the only valid data was for 1 micrometer as the 2 micrometers particles were too large to be trapped. For both LM and OAM beams, the 0.5 micrometer particles were too small for the camera to track properly since it did not have enough resolution. The average force that was exerted on the particles was then calculated as described above. For the LM beam and the 1 micrometer particles, the average trapping force was 2.30x10-13 N and for the 2 micrometer particles it was 1.86x10-13 N. After subtracting the force due to Brownian motion which was 3.27x10-14 N for 1 micrometer particles and 7.02x10-14 N for 2 micrometer particles, the forces due to the photons alone was 1.97x10-13 N and 1.15x10-13 N respectively.

For the OAM beam, overall it was difficult to obtain valid data. The particles tended to escape the trap easily and ended up only rotating somewhat without having a clear center that was circumnavigated. Fortunately, a few of the runs did produce useful data. The average trapping force was 1.25x10-14 N and the torque imparted on the particles was 6.18x10-21 Nm.

The LM graphs below illustrate the data on plots

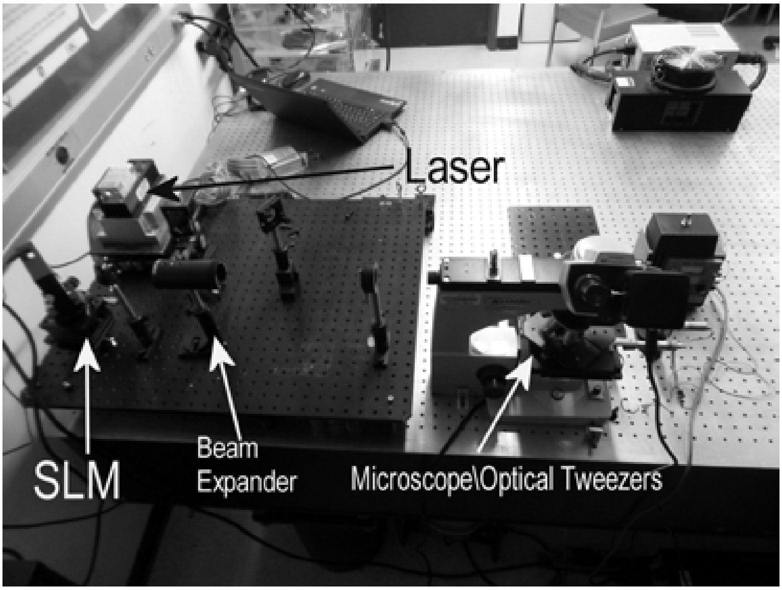

Figure 2: The setup used for the orbital angular momentum particle trapping phase of the experiment

in Excel that have been fit with the polynomial line of best fit. The LM plots demonstrate that particles within a certain radius of the beam from the laser are affected by the force. The OAM plots demonstrate that the particles are confined within a certain radius.

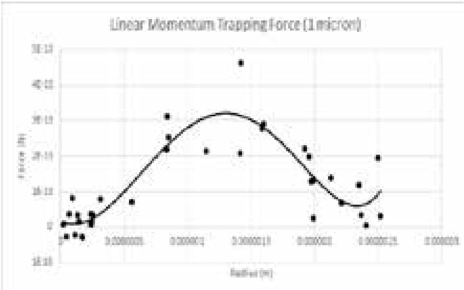

Figure 3: One Micrometer Particle Linear Momentum Trapping Force

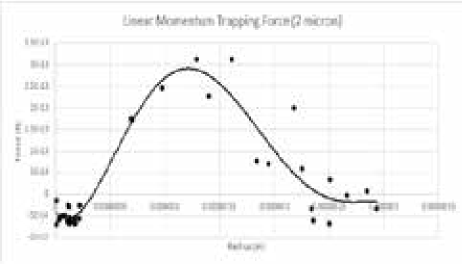

Figure 4: Two Micrometer Particle Orbital Angular Momentum Trapping Force

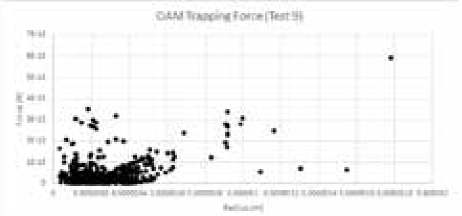

Figure 5: One Micrometer Particle Orbital Angular Momentum Trapping Force

Conclusions

Overall, this experiment was successful. It was clearly evident that photons with LM exert a force and although it is a small force. For particles on the order of 10-6 m or smaller, this force is fairly significant on the order of 10-13 N. Also, beams of photons with OAM were successfully created using a simple SLM and forked diffraction grating code. The only issue that we encountered was with the OAM photon setup. After further research, it was determined that there was difficulty trapping particles using photons with OAM for two reasons: we had access to lasers that were too weak (not high enough intensity), and our particles were too large. The video camera did not have high enough resolution to track particles smaller than 1 micrometer; therefore, we determined that a video camera with higher resolution would also be necessary to improve this experiment.

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