Optical Traps

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Introduction

In the late nineteenth century, James Maxwell proposed that light could exert an optical force, a radiation pressure. Radiation pressure is a term used to describe forces imparted to matter by absorption, scattering, emission or reradiation of light. It was not until nearly a century later that this force was demonstrated experimentally. The main reason for this long lapse between theory and experiment is because that radiation pressure is a very small force, milliwatts of power generate piconewtons of force. The creation of lasers in the 1960’s, allowed researchers to study radiation pressure easier through the use of intense collimated light. Athur Ashkin at Bell Labs in the mid 1970’s demonstrated that by focusing laser beams down into narrow beams, the laser light can create a gradient near the focal region, which can trap small dielectric objects even levitated them against gravity (Askin 1970). The term optical tweezers was used to describe this procedure of trapping objects using optical forces.

Optical tweezers are commonly used to trap objects from as small as 5 nm to greater than 10 microns (Svoboda, 1994; Ke 1999; Seeger 1991) with forces up to 100 pN (Litvinov, 2002) with resolution as small as 100 aN (Gittes, 1998). This range is ideal for investigating physical properties of both cellular and molecular biological systems such as viscoelasticity, force generation and adhesive properties. In comparison to traditional alternatives such as atomic force microscopy, micropipette and microneedle manipulation, optical tweezers are often less invasive and more compliant. The photonic gradient force can be focused on a structure within a cell (either naturally occurring or synthetic) without disturbing the plasma membrane or other cellular systems during probing. Additionally the force of the trap can be simply tuned through adjustment of the laser power. Optical traps are currently being used in situations ranging from measurement of molecular motor force generation to cellular viscoelasticity during abrupt activation events. The current uses are not limited to just an observational tool in basic science but also as a surgical tool for cellular engineers (Berns, 1998).

Theory

Optical forces are usually defined by the equation:

\[ F = \frac{Q n_m p}{c} \]

where

- \( F \) = optical force
- \( Q \) = fraction of incident power used to exert optical force
- \( n_m \) = the index of refraction of the medium the particle is in
- \( p \) = laser power
- \( c \) = the speed of light

Q is usually the main determinant for trapping force, since the medium is usually aqueous, and the laser power is limited due to the possibility of optical damage to the system or particle (Ashkin 1992). Q depends on the wavelength, polarization, mode structure, difference in refractive index between the particle and medium and the geometry of the particle. Q is equal to one for plane waves incident on a perfectly absorbing particle.

The trapping optical forces are usually broken down into 2 components: gradient force and scattering force. Scattering force is contributed to the momentum produced by the
scattering of light and acts in the direction of light propagation. Gradient force is regarded as the force created by gradient of light intensity and acts in the direction of the gradient. Laser Tweezers use the gradient force to trap particles. The gradient force used by laser tweezers is produced by the fluctuation of electric dipoles as the laser light passes through transparent materials. There are three regimes to consider for the optical forces, the Mie regime, where the object diameter is much greater than the wavelength of light, the Rayleigh regime where the diameter is much smaller than the wavelength of light, and an intermediate regime where the diameter is about equal to the wavelength. In the Mie regime (Figure 1), light refracting on the surface of a transparent material impart part of their momentum onto the material. Due to the law of conservation of momentum, the rate of change in light creates an equal and opposite rate of change. At the focal point of a laser tweezers’ system most of the gradients point towards the center of the focal point, trapping a particle there. In the Rayleigh regime, the particle can be represented as point dipoles. The scattering force is given by:

\[ F = \frac{n_m \langle S \rangle \alpha}{c} \]

Where, \( \langle S \rangle = \) time average pointing vector
\( m = \) index of particle / index of medium
\( k = \) wavenumber

and the gradient force is given by

\[ F = \frac{\alpha}{2} \nabla \langle E \rangle^2 \]

\[ \alpha = n_m^2 n^3 \left( \frac{m^2 - 1}{m^2 + 2} \right) \]

Trapping is created when the gradient force in the direction opposite of the progration of the laser light is greater than the scattering force (Kerker 1969). In the intermediate regime, calculations for the forces are much more rigorous. The time average force can be represented by:

\[ F = \left\{ \oint T_{ij} n_i da \right\} \]

\[ T_{ij} = \frac{1}{4\pi} \left[ \varepsilon E_i E_j + B_i B_j - \frac{1}{2} \left( E_i E_j + B_i B_j \right) S_{ij} \right] \]

where \( n_i = \) outward normal unit vector and the integral is over a surface enclosing the particle (Gordon 1873). These calculations are much more rigorous than the other regimes, since all six components of the electromagnetic field must be derived at the surface of the particle.

One method to measure the force of the trap is to induce an increasing and opposite force that will eventually break the trapped object free. In our experiments we used beads with simple spherical geometry in a glass capillary. Inducing a constant flow past the trapped sphere would create a known drag force on the spherical bead. At the flow rate necessary to break the bead free from the trap, the drag force could be calculated and thus the optical trapping force determined.

Electro-osmosis is the motion of fluid induced by an applied electric field. An electrolyte in a glass capillary contains negative charge on the surface from dissociated silanol groups (-SiOH) as well as adsorption of OH⁻ groups. In the liquid, an equal and opposite charge balances the negative groups. When an electric field is applied, the ions of the double layer will travel towards one of the electrodes. Since the ions of the electrolyte are predominately of one charge, a body force of the liquid results in the direction of the migrating ions. The velocity of the fluid is given by:
\[ \nu = -\frac{\varepsilon \zeta E}{\eta} \]

where \( \varepsilon \) = electric permittivity, 8.85E-12 F/m
\( \zeta \) = zeta potential, ~0.45 mV
\( \eta \) = viscosity, ~10E-3 Ns/m²
\( E \) = electric field. Voltage/3cm

With this the drag force experienced by the particle is:

\[ F = 6\pi \mu r U \]

This derivation of drag force is valid for creeping flow situations.

\( r \) = radius of the spherical particle

**Experimental**

A 532 nm laser was used for optical trapping as displayed in the figure on the left. The light was passed through a single mode fiber, then collimated and polarized. The beam was expanded before entering the back aperture of a 1.4 NA objective. 21 \( \mu m \) internal diameter round glass capillaries were mounted on a coverslip. Aqueous fluid with appropriate concentrations of beads was initially drawn in via capillary action. 0.5240 \( \mu m \) and 1.053 \( \mu m \) polystyrene beads from Polysciences were used. Water velocity was then controlled via electro-osmosis due to the applied potential across the capillary. At predetermined laser powers, the voltage was modulated to determine the maximum drag force necessary to overcome the optical trap. The optical trap force was estimated by setting it equal to drag force experienced by the particles. The forces were found to be in the range of 3E-15 or 3E-14 N.

<table>
<thead>
<tr>
<th>Bead Size (( \mu m ))</th>
<th>Voltage (V)</th>
<th>Applied Voltage (mW)</th>
<th>Voltage (fN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5240</td>
<td>15</td>
<td>36 mW</td>
<td>3.3 fN</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>53 mW</td>
<td>5.3 fN</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>62.5 mW</td>
<td>9.5 fN</td>
</tr>
<tr>
<td></td>
<td>73</td>
<td>72 mW</td>
<td>16.1 fN</td>
</tr>
<tr>
<td>1.053</td>
<td>43.5</td>
<td>36.5 mW</td>
<td>19.2 fN</td>
</tr>
<tr>
<td></td>
<td>48.8</td>
<td>45 mW</td>
<td>21.5 fN</td>
</tr>
<tr>
<td></td>
<td>54.1</td>
<td>53 mW</td>
<td>23.8 fN</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>58.5 mW</td>
<td>28.6 fN</td>
</tr>
<tr>
<td></td>
<td>71.1</td>
<td>66 mW</td>
<td>31.3 fN</td>
</tr>
<tr>
<td></td>
<td>74.5</td>
<td>71 mW</td>
<td>32.8 fN</td>
</tr>
</tbody>
</table>

Under ideal circumstances, mW of optical power should generate piconewtons of force. Clearly as shown from the table above, in our experimental conditions mW of laser power generated far less trapping force than expected.

As it can clearly be seen, the trapping power needed to overcome the drag force should linearly dependent on the fluid velocity (Figure 3). The slopes for different sized particles will not be equal due to linear dependence on radius for drag force and cubed dependence for optical force in the intermediate regime. Therefore, the slope for 1.0 \( \mu m \) beads should be four times as great as the slope for 0.5 \( \mu m \) beads. As can be seen from the plot on the right, there is not the expected difference in slopes (slope0.5 = 1.55, slope1.0 = 0.92).
Some explanations for the differences between the observed and expected values include the fact that the laser focus not be reproduced to the same location from sample to sample due the the setup of the optical stage. Spherical aberrations created due to the cylinder shape of the capillary tube also distorted the laser focus forcing us to only be able to trap near the top of the tube. The capillary is also mounted to the surface of a glass cover slip with a thin layer of adhesive, which could create additional losses. The geometry of the adhesive was unknown and could result in changes of the laser focus as the beam transmits through it. The voltage generator used was designed to operate at high voltage, and had fluctuations in voltage output at low levels (V > 30 volts). Lastly, numerous repeated measurements on the same sample could not be done due to charging of the particles and the resultant electrophoresis. This was observed to cause particle motion in the opposite direction.

Conclusion

It was experimentally demonstrated that optical power exerted enough force on polystyrene spherical particles to create an optical trap that prevented movement during fluid flow. The optical force of the traps was determined by solving for the drag force necessary to dislodge the particle during fluid flow. In comparison with predicted and theoretical force power relationships, our results deviated. This was likely due to the many nonideal optical conditions.

It was found that trapping of the same particles on a flat glass cover slip occurred with much less laser power. It is likely then, that trapping particles in a rectangular cross-section capillary could be done with lower power resulting in calculated optical forces approaching theoretical values.
References


