Optical Tweezers: An Introduction

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An optical trap, or optical tweezer, is an instrument capable of exerting forces of the order of piconewtons on nano-scale particles. It is primarily used in biological and biophysics experiments where one requires fine control over molecules such as DNA or viral material. These instruments can manipulate the motion of dielectric materials sub-micron in length scale over distances of less than a nanometer. [5]

In an optical trap, the object is placed inside a viscous fluid and subjected to a beam of laser light. One can then control the motion of the object by changing the intensity profile and focus of the beam.

If the wavelength of the light used is much smaller than the size of the object manipulated, then a ray tracing argument adequately explains the function of a tweezer. In such a case, supposing the object is placed inside a beam of laser light with Gaussian intensity profile, then it will experience a net force towards the center of the beam. The refraction of the light rays through the object imparts momentum onto it. If the object is at the center of the beam, then the forces exerted by those rays incident from either side are opposite and equal, hence there is no net force. However, if the object is displaced from the central axis of the beam, the rays incident laterally closer to this axis are more intense and so impart more momentum than those further away from the center. This results in a restoring net force. This situation is depicted in fig. 1.

If the laser beam is focused through an objective, then there will be a 'waist' for the beam at the focus. Similar ray tracing arguments explain the presence of an axial restoring force towards the waist, as seen in fig. 2.

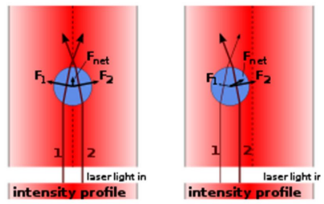

Figure 1: Lateral forces acting on the particle inside a Gaussian beam. Once the particles is displaced from the central axis, there is a restoring force due to the unequal intensity of rays incident on it. **Source**

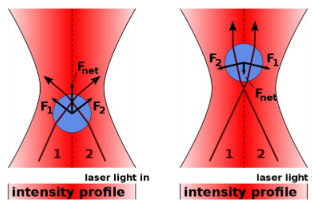

Figure 2: Axial forces accelerate the particle towards the waist of a focused beam. **Source**

On the other hand, once the particle of interest is much smaller than the wavelength of the light used, it can be treated as a point dipole in the presence of an electric field gradient.

Consider once again the particle inside a Gaussian beam of light. Assuming that the particle's dielectric response is linear through $\vec{P} = \alpha \vec{E}$, then the force acting on it is given by

$$\vec{F}(\vec{r}, t) = \alpha \left(\frac{1}{2} \nabla \vec{E}(\vec{r}, t)^2 + \frac{\mathrm{d}}{\mathrm{d}t} (\vec{E} \times \vec{B}) \right) \tag{1}$$

The time dependent components of the Poynting vector term oscillate too quickly to interact with the whole particle motion,[3] hence the time averaged force can be written

$$\left\langle \vec{F}(\vec{r}) \right\rangle = \frac{\alpha}{2} \nabla \left\langle \vec{E}(\vec{r})^2 \right\rangle \tag{2}$$

It is immediately clear from (2) that the force is indeed directed towards the region of greatest intensity.

Optical tweezers have proved to be an invaluable tool in the life sciences. They are used extensively in cell isolation and assembly [2]. They have also been used to manipulate quantum dots of about 10nm in size. [7] One of the early examples of their use in these areas is provided in a paper co-authored by Arthur Askin, who received the noble prize in 2018 for his work in the early development of optical tweezers. This paper reports "The experimental demonstration of optical trapping and manipulation of individual viruses and bacteria in aqueous solution using single beam gradient force traps."[1]

Since the motion of particles in an optical trap results from the gradient and scattering deterministic forces overlaid on top of the Brownian motion inherent to particles in a fluid, these setups have also been used to study stochastic thermodynamics in microscopic systems. [6] For example, it has been shown, using optical tweezers, that the second law of thermodynamics may be violated in small systems over short time scales.[6]

Similar methods have been used to cool atoms to tens of micro Kelvins. Trapped ions are hit with laser light tuned to just below their resonant frequency. In the atoms' frame, this light is at their resonant frequency due to the Doppler shift. Hence, the light is absorbed and imparts momentum onto the ions, slowing and cooling them in the process.[4]

References

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