Delhi Technological University

Department of Applied Physics

Optical Tweezers

Mid-term Evaluation Project Report

(EP-302) Fiber Optics

A Project by:-

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Acknowledgement

We would like to express our sincere gratitude towards our respected professor, Mrs. Gurjit Kaur for encouraging us and providing us with the opportunity to expand our subject knowledge by working on this project.

Her continued support & valuable criticism along with her guidance have been huge contributions towards the successful completion of this project.

Abstract

In this project we have done a detailed study on the discovery of "Optical Fiber Tweezers" or simply "Optical Tweezers" pioneered by Dr. Arthur Ashkin who received the 2018 Nobel Prize in Physics for his work. Optical tweezers are essentially scientific tools that make use of the principles of optical trapping by using beams of laser light to hold/transport microscopic or sub microscopic materials. Optical tweezers are nowadays employed in a multitude of applications in numerous fields, some of which include microbiology, medicine & quantum optics.

In this project we attempt to simulate a working model of optical tweezers & hence observe the dynamics of particles in optical tweezers.

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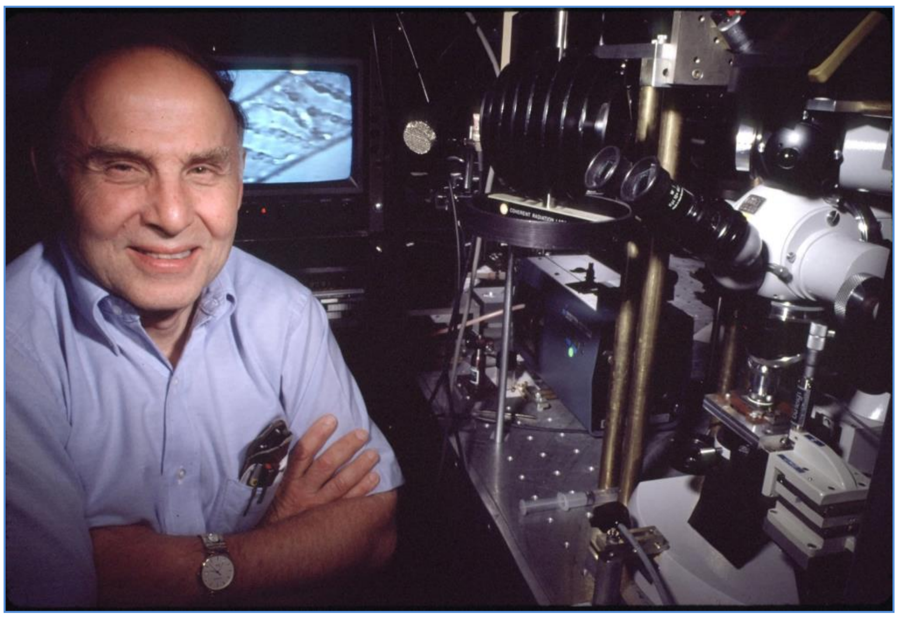
An Introduction to Optical tweezers

Optical tweezers are scientific materials that use beams of laser light to hold/transport microscopic or sub microscopic materials. Optical tweezers are nowadays employed in a multitude of applications in numerous fields, some of which include microbiology, medicine & quantum optics.

Optical tweezers were pioneered by Dr. Arthur Ashkin who received the 2018 Nobel Prize in Physics for his work in developing Optical tweezers.



Dr. Ashkin at Bell Labs in 1988. He was 96 when he was awarded the 2018 Nobel in physics. Credit...Nokia Bell Labs, via Reuters

The working principle of Optical tweezers is based around a phenomenon known as the Radiation pressure of light (the ability of light to exert a force on matter) & the different types of optic forces that arise from this phenomenon.

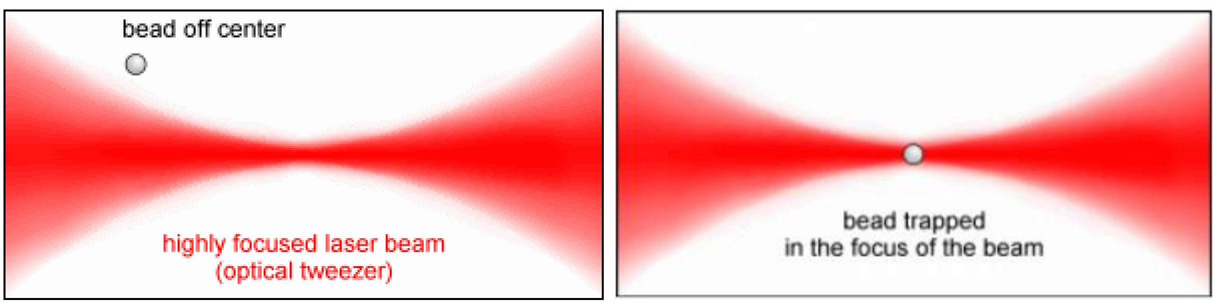
The momentum transfers that occur as a result of the pressure exerted by electromagnetic radiation on matter are integral concepts on which the process of optical trapping is based.

Radiation Pressure of Light

As we are all well aware, Electromagnetic Radiations of energy, *E=hv* are known to possess some momentum, *p=E/c*

From this we may draw the conclusion that momentum can be transferred from electromagnetic radiation to objects through a range of interactions for example: refraction & reflection. This momentum transfer will evidently lead to a pressure being applied onto the object surface on which the EM radiation is incident. This gives rise to the idea of "Radiation Pressure of Light"

Radiation pressure is defined as the pressure exerted by electromagnetic radiation on matter. Radiation pressure of light is caused due to the change in momentum that takes place at the interface of media with differing refractive indices.



In 1970, Arthur Ashkin demonstrated that dielectric particles can be accelerated and trapped by radiation pressure

The figure shown above gives an intuitive picture of how radiation pressure from a highly focused laser beam is used to hold a micro-bead in the focus of the beam.

The phenomena of radiation pressure was actually recognized as early as around the year 1619 by Johannes Kepler who observed that comet tails would always be pointing away from the direction of the sun. This effect occurred due to the radiation pressure exerted on the cloud of particles that the comet tails were composed of.

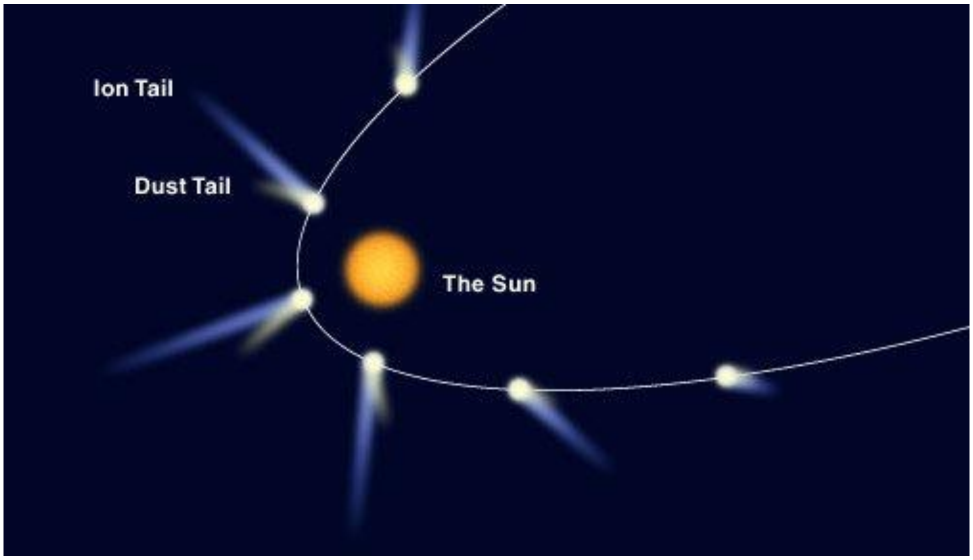


Figure that demonstrates the effect of radiation pressure of sunlight on comet tails

The force from sunlight on the small dust particles pushing them away from the sun is greater than the force of gravity acting in the direction toward the sun. As a result, the ion tails (containing charged particles) point straight away from the sun, while the dust tails curve towards the orbital path.

The reason as to why the dust tail path differs from the ion tail direction is due to the fact that the larger particles in the dust tail don't possess an electric charge & are not affected by the solar wind. Instead, the dust particles shed from the comet are repelled by the Radiation pressure force of the sunlight and lag behind the comet.

A recent space-flight application of radiation pressure that has emerged is solar sails. Solar sails refer to spacecrafts which are propelled using the momentum gained as a result of radiation pressure exerted by sunlight.

Solar sails make use of flat, low mass, large reflective surfaces (essentially mirrors) & also do not require any propellant apart from solar radiation from the sun. Due to this the ratio of allocated weight for payload to the weight of the spacecraft is higher & hence solar sails are more efficient as compared to other currently used methods of space-flight.

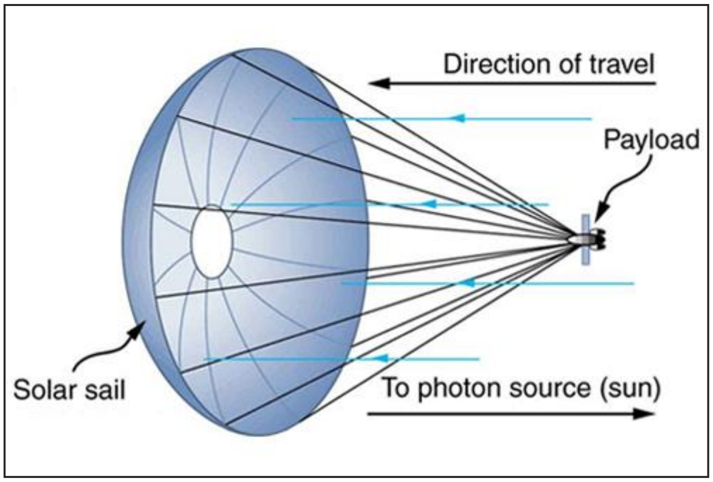


Fig: Solar sails have been proposed that use the momentum of sunlight reflecting from gigantic low-mass sails to propel the spacecraft about the solar system. Source: https://courses.lumenlearning.com/physics/chapter/29-4-photon-momentum/

Calculating Radiation pressure from momentum of an electromagnetic wave

As per Maxwell's theory of electromagnetism, we know that an EM wave carries some momentum, characterised by a momentum flux:

$$d\left(\frac{d\vec{P}}{dt}\right) = \vec{S}\, dS$$

Where, S denotes the Poynting vector which represents the energy flux or irradiance of a plane electromagnetic wave & dS denotes the element of area normal to $\vec{S}$

The radiation pressure, P_R may then be given as:

$$P_R = \frac{\langle S \rangle}{c} \text{ [Units: Nm}^{-2}\text{]}$$

Also,

$$P_R = \frac{I}{c} \text{ , where I is the incident irradiance}$$

$$\text{So the Radiation pressure} = \frac{Energy\ transferred\ per\ second\ per\ unit\ area}{Speed\ of\ Light,\ c}$$

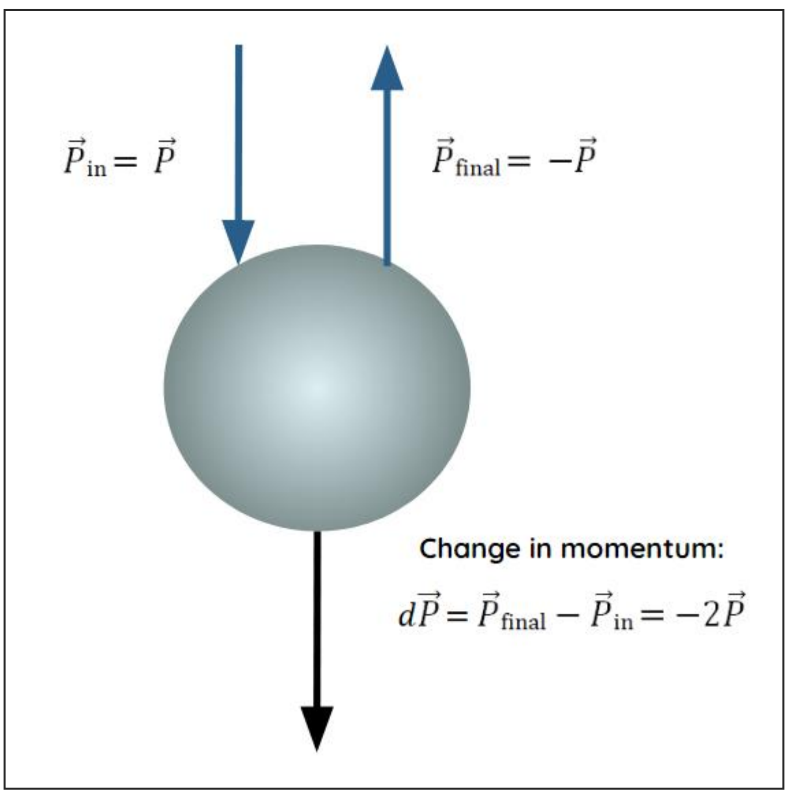
The effect caused as a result of radiation pressure in terms of forces in general is difficult to detect on larger scales as radiation pressure forces are extremely miniscule forces (of the order of 10^{-12} N)

Approximation of Radiation Pressure Forces

An attempt at approximating the radiation pressure force from commonly used laser beams has been made as shown below:

Let us first consider a system of a single beam of photons incident on a micro bead. Microbeads are microscopic spheres made out of materials with a higher refractive index than the medium in which optical tweezers are being used. These usually have diameters of the order 10^{-6} m (or 1μm).

We consider that the beam diameter, d is greater than the wavelength, λ of the light rays used (d>λ). It is also assumed that the microbead perfectly reflects the incident waves (Reflection coefficient, R=1).



As seen in the figure above, if the initial momentum of the light wave, $\vec{P}_{\text{in}}$ is equal to a certain amount say, $\vec{P}$. Then the final momentum of the light wave, $\vec{P}_{\text{final}}$ is equal to $-\vec{P}$ given that perfect reflection without any absorption occurs.

The change in momentum, $d\vec{P}$ is then given by $\vec{P}_{\text{final}} - \vec{P}_{\text{in}}$

$$\text{So, } d\vec{P} = -2\vec{P}$$

We know that the force is characterized by the rate of change of momentum & hence the force generated by radiation pressure is given as follows:-

$$\vec{F} = \left(\frac{d\vec{P}}{dt}\right)$$

Substituting the value of $d\vec{P}$ into this equation we obtain:

$$\vec{F} = \frac{d}{dt} 2\vec{P}$$

As mentioned earlier, the energy, E of the photon is given by $E = Pc$
Or alternatively the momentum, $P = \left(\frac{E}{c}\right)$

Substituting this into the expression of radiation pressure force, we get

$$\vec{F} = \frac{2}{c}\frac{dE}{dt}$$

Calculating derivative of energy, E with respect to time we obtain the power of the light source represented by W.

$$\vec{F} = \left(\frac{2W}{c}\right)$$

The equation obtained above gives the radiation pressure force exerted by a single photon. The power range of most conventionally used TEM_{00} Gaussian lasers is of the order of (2.5-4.0) x 10^{-19} W (this corresponds to power output of a single photon from the laser, not to be confused with actual power of laser).

Let us consider an example where power = 2.5 x 10^{-19} W

Substituting this value into the equation we find that the force exerted by a single photon onto the microbead would be around 1.67 x 10^{-27} N. A force of this magnitude would have an insignificant effect on the microbead & would be incapable of holding the microbead in position. However, lasers do not produce just a single photon, so for a TEM_{00} Gaussian laser beam the number of photons, $n \approx 10^{15}$ photons

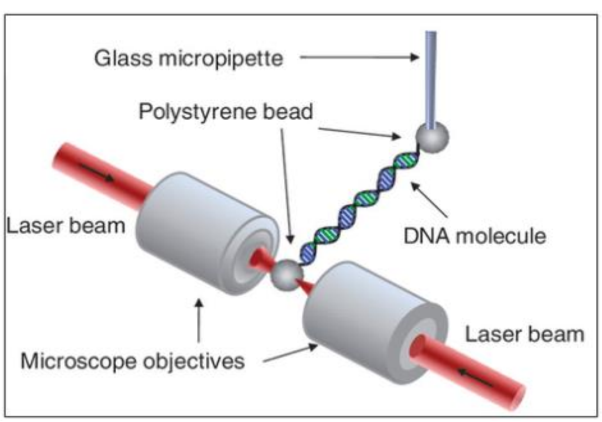
For $n = 10^{15}$ photons, the radiation pressure force produced by the laser would be:

$$\vec{F} = \left(\frac{2W}{c}\right) n = (1.67 \times 10^{-27}) \times (10^{15}) = 1.67 \times 10^{-12} \text{ N or } 1.67 \text{ pN}$$

So most conventially used lasers the forces produced due to radiation pressure are of the order of piconewtons.

How are piconewton forces useful in the study of certain fields?

A force of the magnitude of piconewtons may seem insignificant; however optical tweezers are used to perform delicate operations on extremely small scales. On these scales, forces of the order of piconewtons are significant enough to play a major role. For example studying the properties of micron-sized dielectric particles or manipulating single molecules such as DNA require nanometer precision and the ability to measure forces with piconewton accuracy. Such tasks are possible only due to the piconewtons sensitivity that optical tweezers operate within.



Schematic diagram of optical tweezers being used to trap and stretch single DNA molecules

Optical Forces

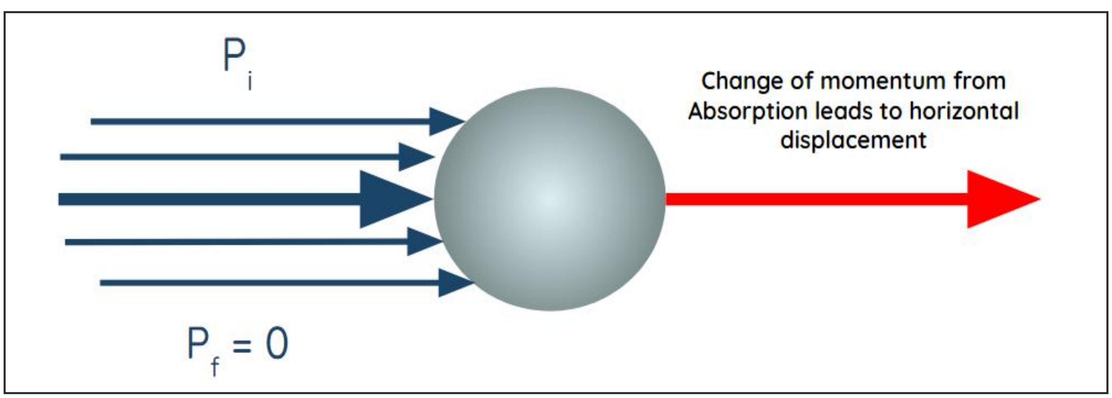
Optical forces are key components that play essential roles in the mechanism of optical trapping. Light generates mainly 3 types of optical forces: **Absorption** forces, **scattering** forces & **gradient** forces. The introduction of the concept of gradient force and scattering and absorption force is an important milestone in optical trapping.

Ray-optics can be used to describe the effects of a strongly focused laser beam over a transparent dielectric particle, whose index of refraction is greater than the surrounding medium.

In general, given that the particle is μm sized if $F_{gradient} > F_{scattering}$ then the particle gets successfully trapped.

Absorption Forces

As discussed previously, light rays possess a particular energy & momentum. When light rays are incident on a non-perfect reflecting surface (Reflection coefficient, $R < 1$) then absorption at the interface between the two may occur. To satisfy the laws of conservation of momentum & energy, the object gains momentum equal to the energy of the light waves absorbed.



As shown in the figure above, absorption leads to the microbead experiencing a force due to the abrupt momentum change of the incident light rays. The bead experiences a force which causes it to gain momentum equal to that lost by the incident light rays. The force the microbead experiences as a result of absorption is known as the Absorption force.

The force due to absorption creates a few difficulties in the process of optical trapping as perfectly reflecting micro beads are difficult to manufacture due to their small size requirements. The absorption force can lead to the horizontal displacement of the microbead out of the focus of the laser beam being used. To counteract these issues a vertical experimental setup of the optical tweezers was proposed. In the proposed setup, the force of gravity would balance out the absorption forces & the microbead could be held in focus of the laser.

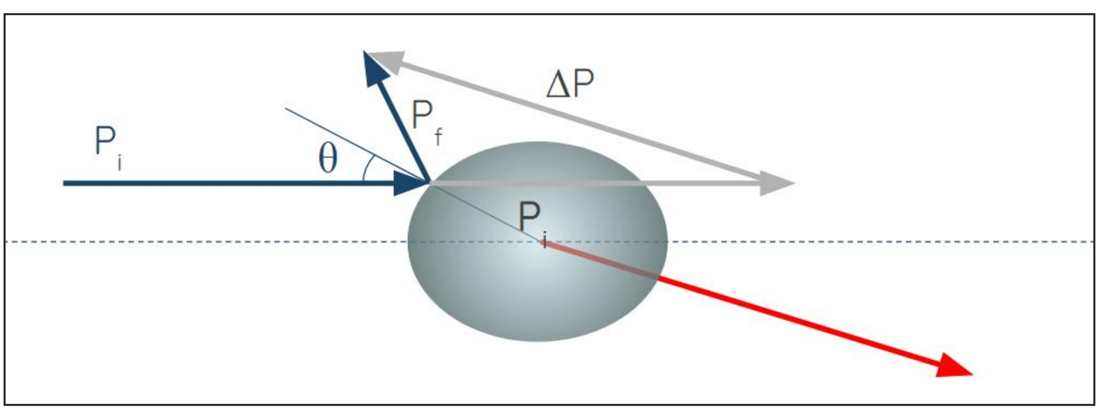
Scattering Forces

The scattering force pushes away the particle along the beam propagation direction. There are 2 types of scattering forces namely: Reflection forces & Refraction forces.

These both involve well versed concepts of reflection & refraction of light

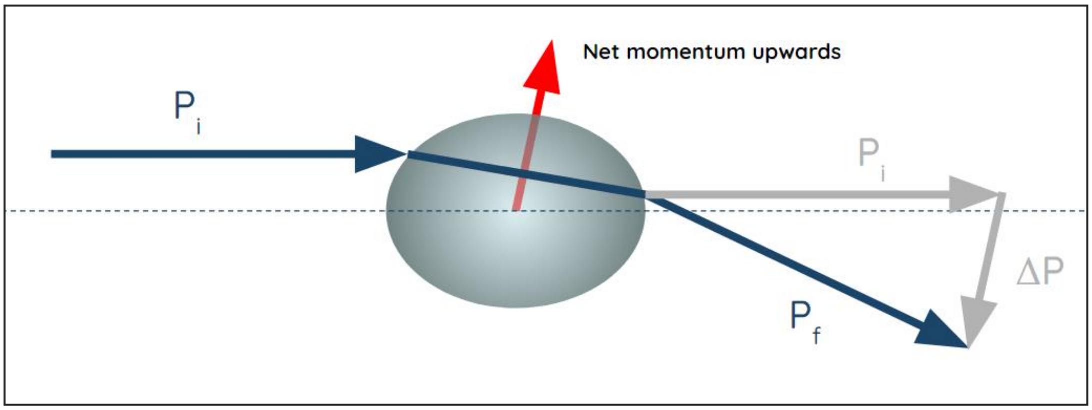
Reflective Forces:

These occur as a result of the light imparting a certain amount of its momentum to the microbead. The momentum gainied by the microbead is equal to $\Delta P = (P_f - P_i)$. The figure shown below demonstrates the direction of momentum change, & hence force applied due to reflection.



Refractive Forces:

These occur during refraction when the direction of light is changed after it passes through an object of higher refractive index than its surroundings. Since the direction & hence the momentum of light is being changed, the refracting object also experiences a momentum change opposite to the direction of momentum change of the light beam.



As demonstrated by the figure shown above, the microbead reflects the incident beam of light downwards & hence experiences a net momentum upwards in doing so.

However refractive scattering forces if utilized appropriately, form the basis of gradient forces which are required to hold microbead structures in the focus of optical traps.

Gradient Forces

Gradient forces play a crucial role in making the optical tweezing process possible. Gradient forces emerge as a result of the gaussian intensity profile of commonly used lasers in optical tweezers. The previously discussed TEM_{00} focused laser beam has a gaussian intensity profile, for which the region of higher intensity is toward the propagation axis.

There are mainly 2 types of Gradient forces:

(i) Lateral Gradient Force &

(ii) Axial Gradient Force

Lateral Gradient Force

The lateral gradient force causes the microbead to experience a net force towards the higher intensity region of a gaussian profile laser. From fig. shown below, it may be observed that for a gaussian profile laser beam the region of highest intensity lies at the center of the beam. So gradient forces contribute to "trapping" the microbead at the center of the laser beam.

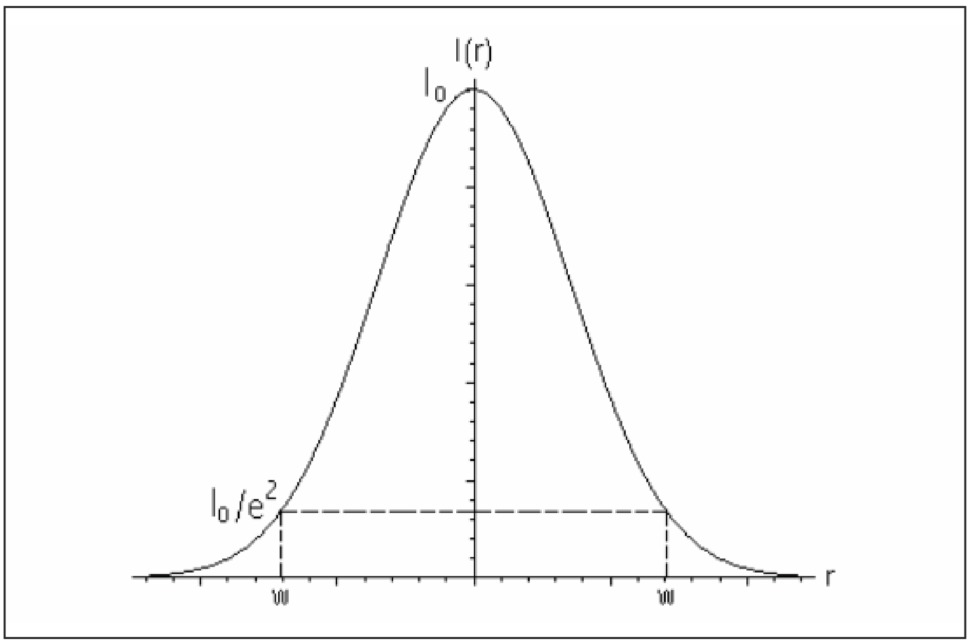
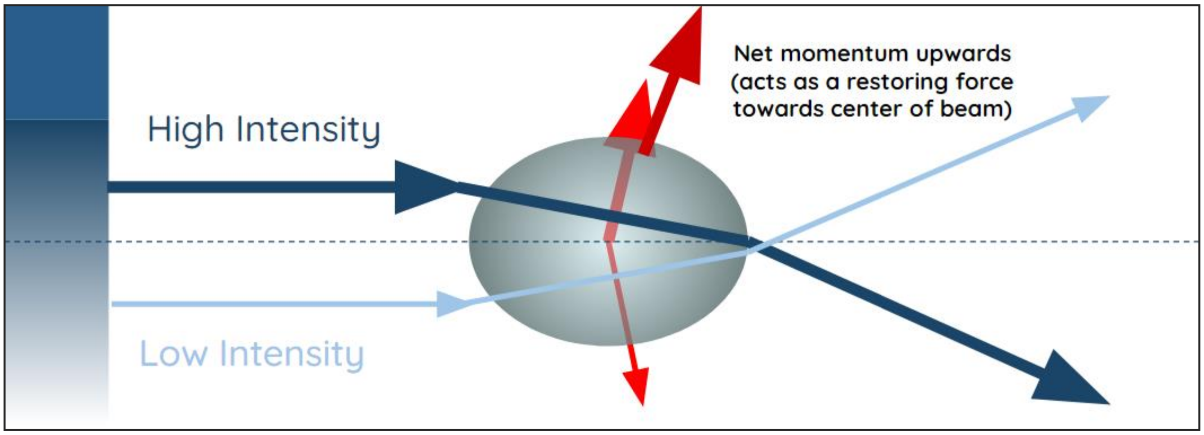


Fig: Intensity profile of a Gaussian laser beam.

When beams of both high intensity & low intensity are incident on a microbead they get refracted as shown in the ray diagram below. As explained earlier in the refractive forces section (Page 13) the microbead thus experiences a force both upwards & downwards. Since the beam of higher intensity has a higher concentration of photons being refracted, the microbead experiences a greater overall momentum upwards. So the net gradient force experienced by the microbead in response to the incident beams, would be towards the center of the gaussian beam since the highest intensity is at the center. The gradient force thus produced on the microbead always acts to pull the microbead into the center of the gaussian laser. This force is known as the lateral gradient force.

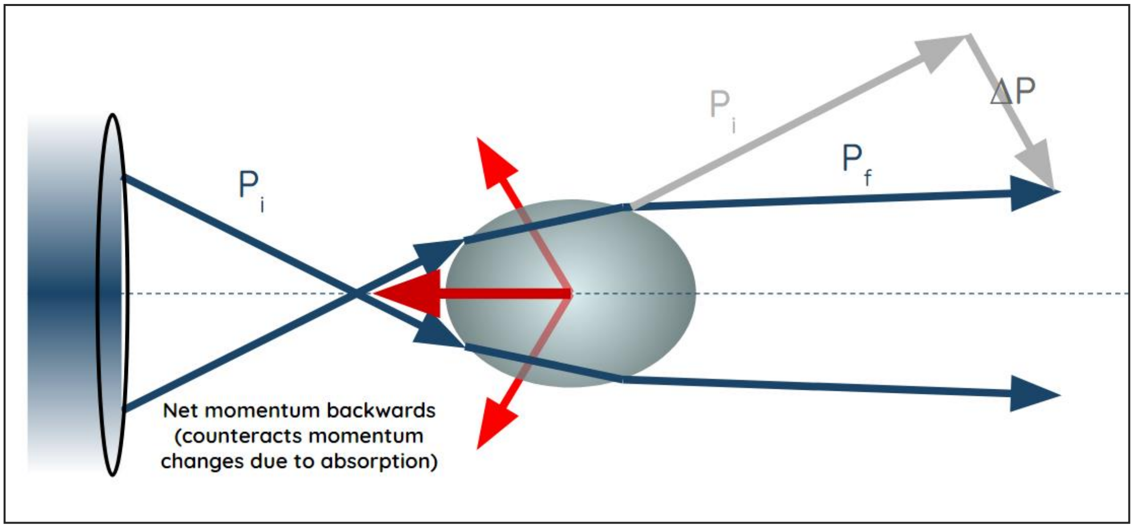


Even if small displacements of the microbead were to occur due to random disturbances, the lateral gradient force would act as a restoring force & pull the microbead back to the center of the laser beam.

Axial Gradient Force

Axial gradient forces are forces produced as a result of converging light beam being refracted through a microbead. Axial gradient forces play an important role in restraining the horizontal displacement of the microbead out of the focus of the laser caused due to absorption forces. (Page 11, “Absorption forces” section)

Dr. Ashkin discovered that a convex lens can be used to solve the problem of horizontal displacement of the microbead caused due to absorption. An Axial gradient force is introduced as a result of using a convergent beam of light



When converging beams of light are incident on the microbead structure they each get refracted and exit the microbead at wider angles than they entered. This change of direction is accompanied with a change in momentum shown by ΔP in the figure above. In accordance with the momentum conservation principle, the microbead then experiences an equal momentum ΔP but in the opposite direction. If the resultant of all the forces experienced by the microbead upon refraction of the converging light beam is calculated, the net force experienced by the microbead is observed to be towards the focus. This force is known as the Axial gradient force.

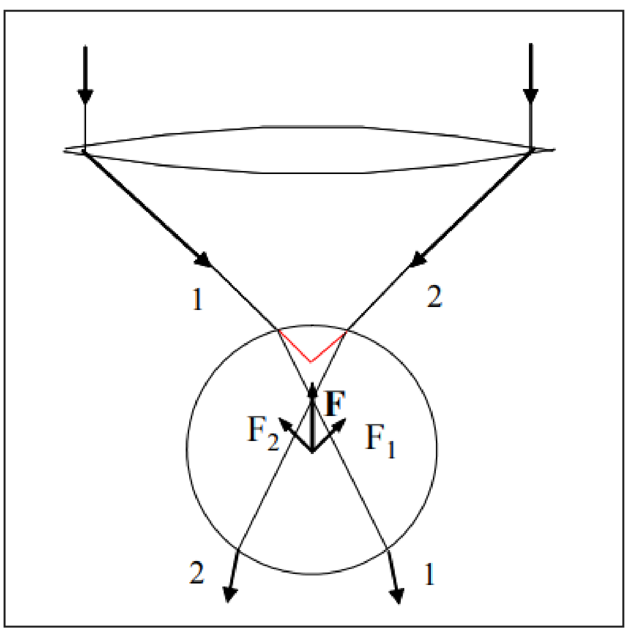


Fig: Schematic diagram showing the force on a dielectric sphere due to refraction of 2 rays of light, labeled 1 & 2.

Condition for trapping of particles:

If the gradient forces are always greater than the scattering forces ($F_{gradient} > F_{scattering}$), particles are trapped in the region near the focus. For small displacement from the laser focus, particles can be considered to be trapped in a harmonic potential well. The gradient forces act as restoring forces to effectively "trap" the dielectric particle/Microbeads.

Objectives:

The objectives that we aim to cover in this project are as follows:

- A detailed literature review on the phenomena of the radiation pressure of light which is the basis for operation of optical tweezers. Also, we will deduce an approximation for the magnitude of forces generated by radiation pressure of light & how it is useful in certain fields.

- To study the different types of forces including the different gradient forces & scattering forces which play a role in the operation of optical tweezers.

- To explore the numerous applications of optical trapping used in different areas, ranging from biomedical applications, to physics and material sciences

- To develop a working model capable of simulating the dynamics of particles in optical tweezers.

Objectives 1 & 2 have already been covered in the introduction section as seen in the previous sections. (refer to pages 5 & pages 6-11).

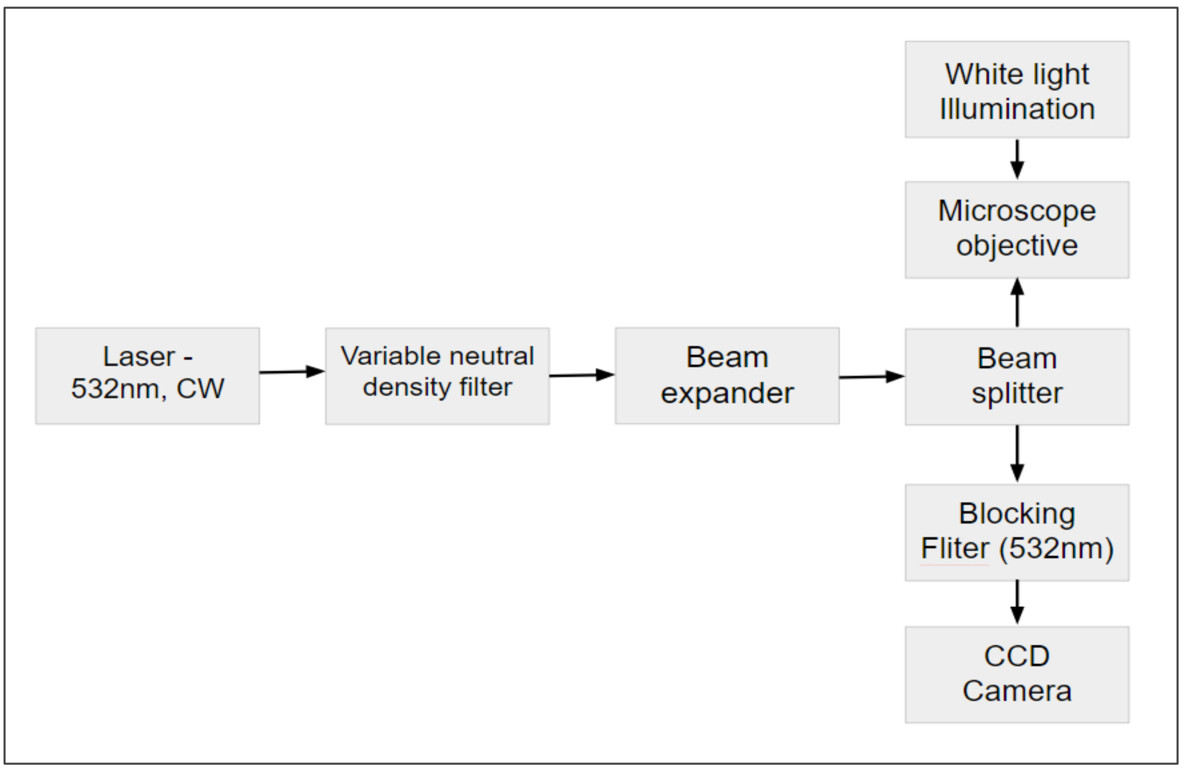
In the upcoming sections we have explored some of the various applications that optical tweezers offer aswell as the design of a simulation capable of visualizing the orientation & trajectory variations of particles of different shapes & geometries within a optical tweezer.

Design

In this section the design of optical trapping systems, optical tweezers in particular has been briefly discussed. We also take a look at the implemetation & design of an optical tweezer simulation using MATLAB.

Block Diagram

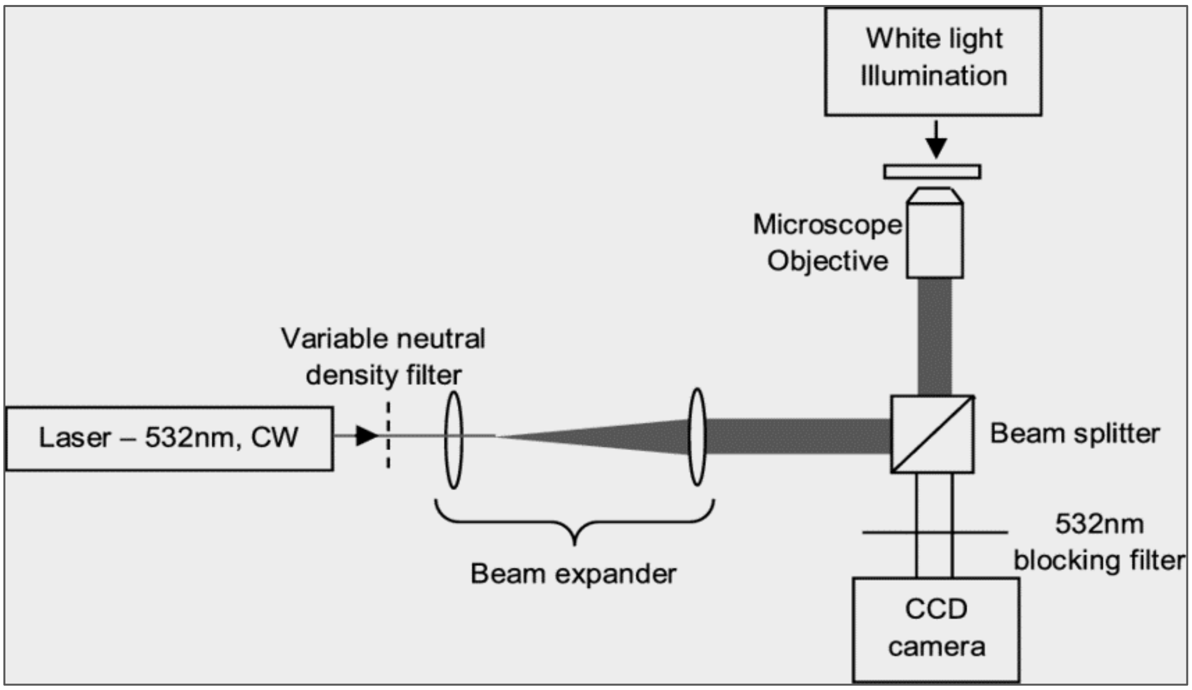
A simplified block diagram of this setup may be represented as shown below:



Block diagram of a simplified setup utilized for operation of optical tweezers

Schematic Diagram

Shown below is a typical schematic of a typical optical tweezers experimental setup used in labaratories:



Schematic diagram of a typical optical tweezer setup used in laboratory

In this setup a commercial inverted microscope (Nikon, TE2000U) forms the basis of the optical trapping system. A 532 nm continuous wave laser beam with a maximum power of 500 mW was provided by a frequency doubled Nd:YAG source and used to optically trap the beads, 532 nm being the maximum transmission wavelength for rabbit vitreous minimizing possible heating effects. Once a bead had been successfully trapped, the power of the laser beam was reduced to the minimum level at which the bead remained trapped using a variable neutral density filter.

Simulation

For the simulation aspect of our project, we have implemented a simulation of an optical tweezer trapping environment which employs a gaussian profile laser beam to confine & hold particles of different geometries.

We have implemented this simulation in MATLAB since it offers convenient toolbox packages catered for specific fields such as the Optical Tweezer Toolbox™ which we have used extensively in our program.

The Optical Tweezer Toolbox™ offers certain functions that allow for a convenient implemetation of an optical tweezer environment for microcopic particles. Some of the functions offered by this toolbox that have been utilized have been summarized below:

i) **`ott.BscPmGauss:`** This function allows us to model a gaussian profile laser beam which is used in optical tweezers. It allows us to chose & vary the polarisation, wavelength, power & other important factors of the beam.

ii) **`ott.shapes.Shape.simple:`** This function provides pre-built static models of different shapes of the micro-bead structures which would be displaced by the tweezers from which the users may utilize any desired shape.

iii) **`ott.utils.rotz:`** This function allows the users to set the intial orientation and rotational angle of the particles being manipulated by the tweezers. Often the initial orientation of the microscopic particles is a huge factor in deciding whether the particle can be held in a stable position in the focus of the laser beam.

The code for our progam Particle_dynamics.m is displayed below:-

```
% Dhruv Tyagi (2K19/EP/032) & Ayush Kumar (2K19/EP/030)
%
% Simulation of a particle moving in a Gaussian beam trap
```

```
%
% Includes configuration for sphere, cylinder and cube.
%
%

% Add the toolbox to the path (assuming we are in ott/examples)
    addpath('../');

    % Close open figures
    close all;

    % Make warnings less obtrusive
    ott.warning('once');
    ott.change_warnings('off');

    % Specify refractive indices
    n_medium = 1.33;
    n_particle = 1.57;

    % Specify the wavelength in the freespace [m]
    wavelength0 = 1064e-9;
    wavelength_medium = wavelength0 / n_medium;

    % Specify the size of the cube
    width = 1.0*wavelength_medium;

    % Select the type of particle (sphere, cylinder or cube)
    particle_type = 'cylinder';

    %% Generate beam

    tic

    beam = ott.BscPmGauss('NA', 1.25, 'polarisation', [ 1i 1 ], ...
        'power', 1.0, 'index_medium', n_medium, 'wavelength0', wavelength0);

    disp(['Beam calculation took ' num2str(toc) ' seconds']);

    %% Calculate T-matrix

    tic

```

```
    switch particle_type
      case 'sphere'

        % Describe the shape
        shape = ott.shapes.Shape.simple('sphere', width/3);

        % Specify the initial position
        x_initial = [1;1;1]/5;

        % Set a limit on the max time step, needed for stability, empirically found
        dtlim=0.001;

        % Optional parameters for drawing shape
        optargs = {};

      case 'cylinder'

        % Describe the shape
        shape = ott.shapes.Shape.simple('cylinder', [0.1*width, 0.5*width]);

        % Specify the initial position
        x_initial = [1;1;1]/2;

        % Set a limit on the max time step, needed for stability, empirically found
        dtlim=0.025;

        % Optional parameters for drawing shape
        optargs = {'noendcap', true};

      case 'cube'

        % Describe the shape
        shape = ott.shapes.Shape.simple('cube', 0.4*width);

        % Specify the initial position
        x_initial = [1;1;1]/2;

        % Set a limit on the max time step, needed for stability, empirically found
        dtlim=0.025;

```

```
            % Optional parameters for drawing shape
            optargs = {'noendcap', true};

          otherwise
            error('Unsupported particle type');
        end

        T = ott.Tmatrix.simple(shape, ...
            'index_medium', n_medium, ...
            'index_particle', n_particle, ...
            'wavelength0', wavelength0);

        [X, Y, Z] = shape.surf('npoints', 20, optargs{:});

        disp(['Calculating T-matrix took ', num2str(toc), ' seconds']);

        %% Dynamics Simulation
        % This dynamics simulation simulates the trap in some hypothetical
        % substance. It does not represent any physical system except that it
        % displays the same kind of dynamics as a trapped particle capable of
        % rotation.

        % Time the simulation
        tic;

        numt=75;                   % number of time steps
        x=zeros(3,numt);           % array of particle positions
        tvec=zeros(numt,1);        % array of times where positions are stored

        x(:,1)=x_initial;          % initial position for particle

        % Set hypothetical drag tensors for the particle
        translation_drag_tensor=eye(3)/200;
        rotation_drag_tensor=eye(3)/500;

        %save rotation matricies for drawing.
        Rtotal=zeros(numt*3,3);

        %set initial orientation [degrees].
```

```
    theta = 0;
    phi = 0;
    Rw = ott.utils.rotz(theta)*ott.utils.roty(phi);
    Rtotal(1:3,:) = Rw;

    for ii=2:numt

        % Calculate the force and the torque on the particle
        [ft,tt] = ott.forcetorque(beam, T, ...
            'position', x(:, ii-1) * wavelength_medium, 'rotation', Rw);

        % Dynamic time-stepping asymptotic with dtlim. We assume that no
        % multiplier is needed on the rotation to correct the error. There is
        % almost certainly a physically motivated choice for dt, but this method
        % seems to work well in a number of situations. Scaling factors can be
        % added if you care to, let us know what you find out!
        dt=dtlim/(1+(sqrt(sum((inv(rotation_drag_tensor)*tt).^2))));

        % Calculate new x
        x(:,ii)=x(:,ii-1)+inv(translation_drag_tensor)*ft*dt;

        % New rotation matrix using the deviation
        Rw=ott.utils.rotation_matrix(inv(rotation_drag_tensor)*tt*dt)*Rw;
        Rtotal(3*(ii-1)+[1:3],:)=Rw;

        % Store the time
        tvec(ii)=tvec(ii-1)+dt;
    end

    % Finish timing the calculation
    disp(['Simulating dynamics took ' num2str(toc) ' seconds']);

    % Create a plot of the trajectory
    figure(2)
    plot(tvec,x.')
    legend('x','y','z')
```

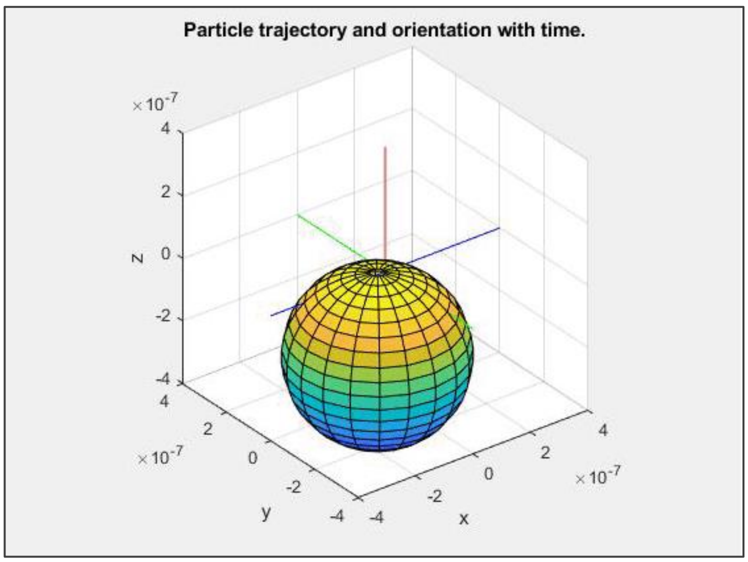
```
title('Particle trajectory in principal axes.')
xlabel('Time [simulation units]');
ylabel('Position [\lambda_m]');

%% Plotting code of rotating and translating sphere

x = x * wavelength_medium;

if exist('movieframe', 'var')
  clear movieframe;
end

for ii=1:numt
  figure(1)

  XYZt=Rtotal(3*(ii-1)+[1:3],:)*[X(:).';Y(:).';Z(:).'];
  Xt = reshape(XYZt(1, :) - x(1,ii), size(X));
  Yt = reshape(XYZt(2, :) - x(2,ii), size(Y));
  Zt = reshape(XYZt(3, :) - x(3,ii), size(Z));

  h = surf(Xt, Yt, Zt);

  hold on

  plot3([-1,1],[0,0],[0,0],'b');
  plot3([0,0],[-1,1],[0,0],'g');
  plot3([0,0],[0,0],[-1,1],'r');

  hold off
  xlabel('x');
  ylabel('y');
  zlabel('z');
  grid on
  axis equal
  axis([-1,1,-1,1,-1,1]*(width/2))
  title('Particle trajectory and orientation with time.')
  view(3)
  movieframe(ii)=getframe(1);

end
```

The outputs obtained for 3 different particle shapes i.e: i) Sphere, ii) Cube, iii) Cylinder have been shown below:

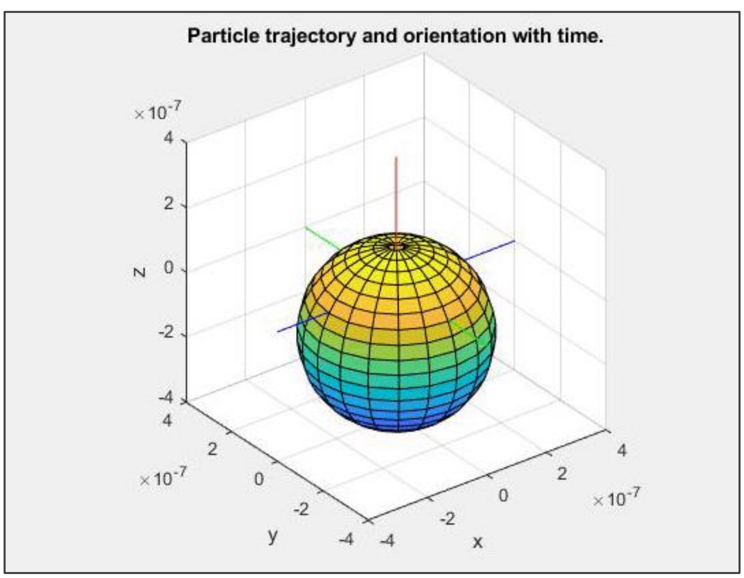
Results Obtained:

The variation of Particle trajectory & orientation of a **Sphere** shaped microstructure with time:

i) At t=0 seconds:

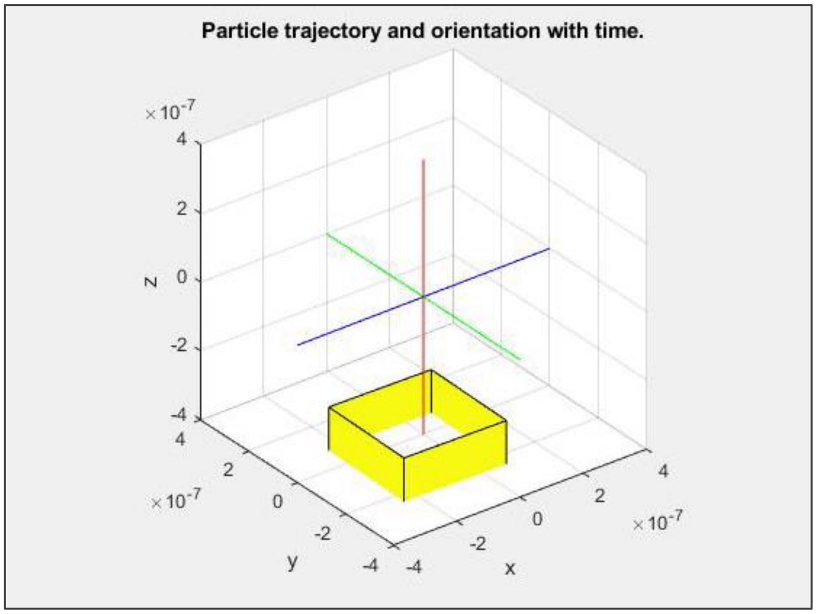


ii) At t=2.5 seconds:

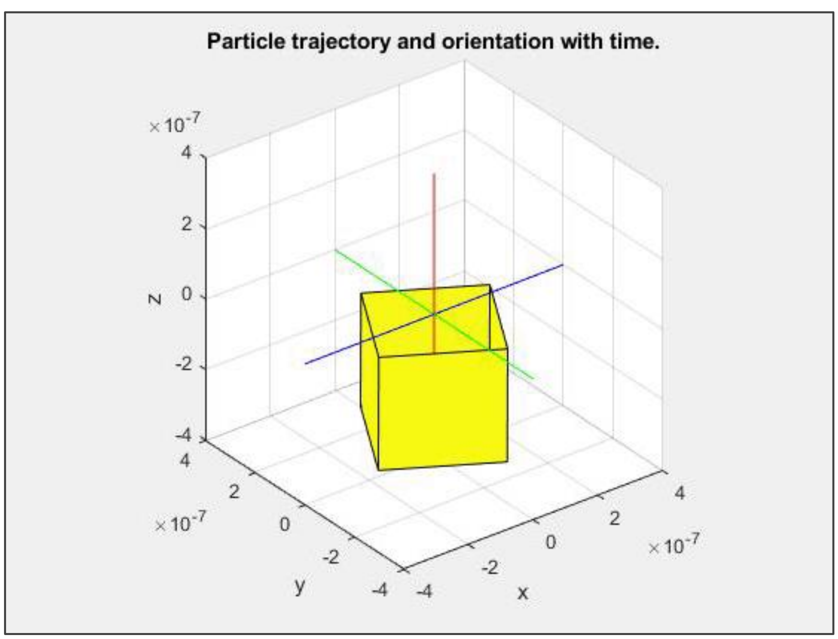


The variation of Particle trajectory & orientation of a Cube shaped microstructure with time:

i) At t=0 seconds:

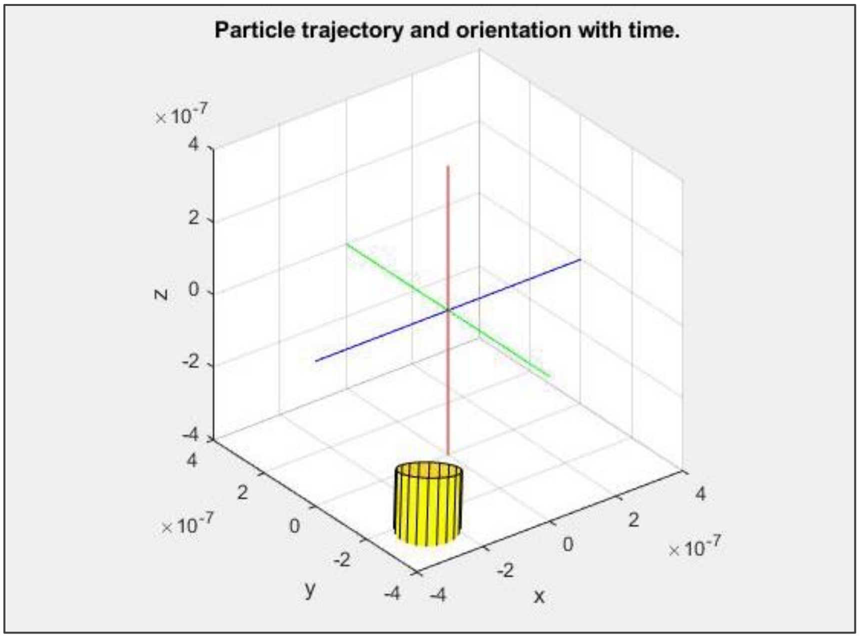


ii) At t=2.5 seconds:

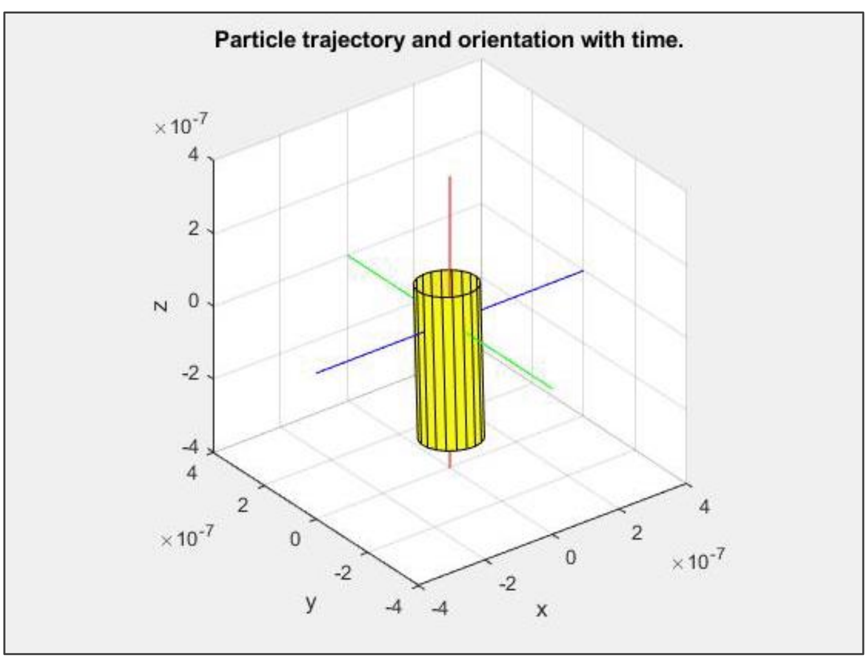


The variation of Particle trajectory & orientation of a **Cylinder** shaped microstructure with time:

i) At t=0 seconds:



ii) At t=2.5 seconds:



Applications of Optical Tweezers

In this section we give an overview of some recent applications of optical tweezers and optical forces in liquid environments. The contactless manipulation of particles promotes the use of optical tweezers in a wide variety of research fields. Here, we describe a selection of systems where optical tweezers have enabled advances in biology, micro bubbles manipulation, chiral optomechanics, nanotechnology, optical binding & several other fields.

Mechanical properties of red blood cells

Optical tweezers have numerous applications in biological sciences, ranging from single molecule studies to cell biophysics. In this section we have discussed one particularly successful application, namely the investigation and determination of the mechanical and elastic properties of red blood cells (RBCs).

Very early in the history of optical tweezers Dr. Ashkin showed that RBCs (and many other biological species) could be trapped without optical damage using and infra-red laser beam.

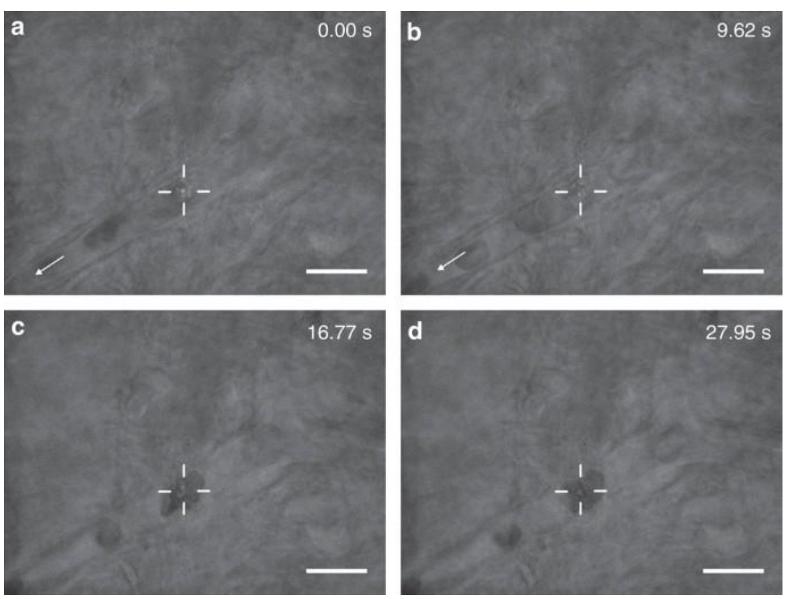
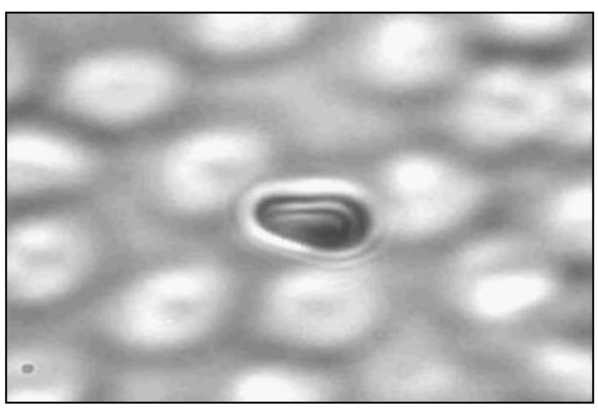


Fig: Trapping & manipulating red blood cells in living animals using optical tweezers using an infrared laser

Bronkhorst et al. showed that optical tweezers could be used to deform a red blood cell under direct trapping using a line of three optical traps to ‘fold’ the cell and observe the relaxation time. Later Liao & his team showed that RBCs could also be stretched under direct trapping, using a single beam that jumped rapidly between two locations to grip the cell.

Later theoretical work accurately calculated the optical stress distribution over the surface of an RBC osmotically swollen to adopt a spherical shape and its resulting deformation in the dual tweezers stretching experiment. By solving for the dynamic deformation of the RBC, that is, accounting for the change in shape and redistribution of optical stress as the cell deforms towards the stretched state the authors could determine the membrane mechanical properties (Young’s modulus and shear modulus) before and after treatment with N-ethylmaleimide, which is known to cause a decrease in cellular deformability. This work was further refined for the RBC in its native biconcave discoid shape. When predicting the deformation of the RBCs under optical stress it is necessary to account for both the non-linear and viscoelastic properties of the cell. By combining optical tweezers stretching with Raman spectroscopy, Raj et al. found that at large deformation the RBC must undergo a structural transformation in order to bear the high load.



(*Red blood cell in optical tweezers. Stretching and rotation.*)

Chiral optical forces

Chirality derives from the lack of mirror symmetry of an object. A chiral object exists in left- and right-handed version (enantiomers) that cannot be superimposed by translations and rotations within the space where they are embedded. Also circularly polarised light is chiral, with handedness depending on the electric field sense of rotation with respect to the propagation axis. Besides linear momentum, circularly polarised light may transfer also spin angular momentum.

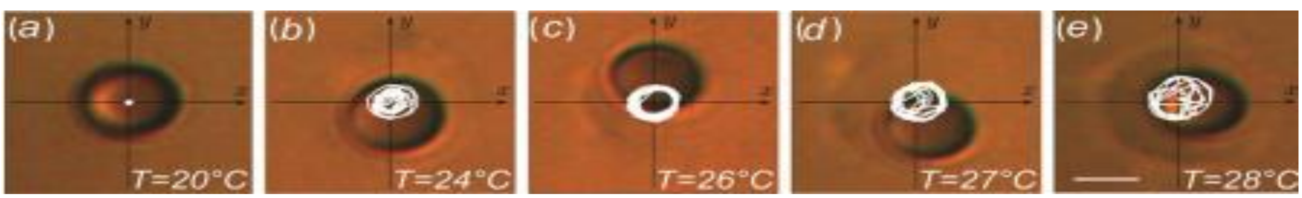
Recently, several works considered chirality-dependent optical forces on small particles aiming at all-optical separation of enantiomers. The optomechanical interaction of chiral light with mesoscopic objects has been studied in optical tweezers, giving the opportunity to investigate the transfer of spin angular momentum to birefringent particles and observe spin-dependent light-induced rotations.

Nanotechnology applications

During the last few decades much effort has gone into the miniaturization of machines down to microscopic scales, often inspired by biological systems. Optical tweezers are a powerful tool to assemble micro and nanodevices accredited to their ability of contactless manipulation. Hence optical tweezers have become a crucial tool in the miniaturization process required for devlopment of nanotechnology. Moreover, they are capable of applying and detecting extremely small (femtonewton) forces and torques yielding potential for driving nanomachines.

At the nanoscale, semiconducting, metal, and hybrid colloidal particles have been trapped and manipulated opening novel exciting possibilities for assembly, characterization and optical control of nanodevices and biomolecules. Nanodevices or micro-engines need power to operate and to be controlled. A solution to this demand can be provided by structured optical beams, carrying orbital and spin angular momentum (SAM and OAM), generated by holographic optical tweezers (HOT) or similar techniques . In particular, micro rotators and micropumps have been realized by transferring SAM and OAM to microparticles.

Another approach to power nanodevices is to emulate the working principles of heat engines. The nucleation of vapour bubbles inside silicon micro-cavities has been used to realize several microscopic heat engines with a working volume of only 0.6 mm^3. Recently, a microscopic engine powered by the density fluctuations of a critical solution has also been proposed ,where a micron-sized particle performs revolutions around the optical beam when optically trapped in a water-2.6- lutidine critical mixture. The work performed by this engine is adjustable by the power of optical trap, the temperature of the environment and the criticality of the mixture.

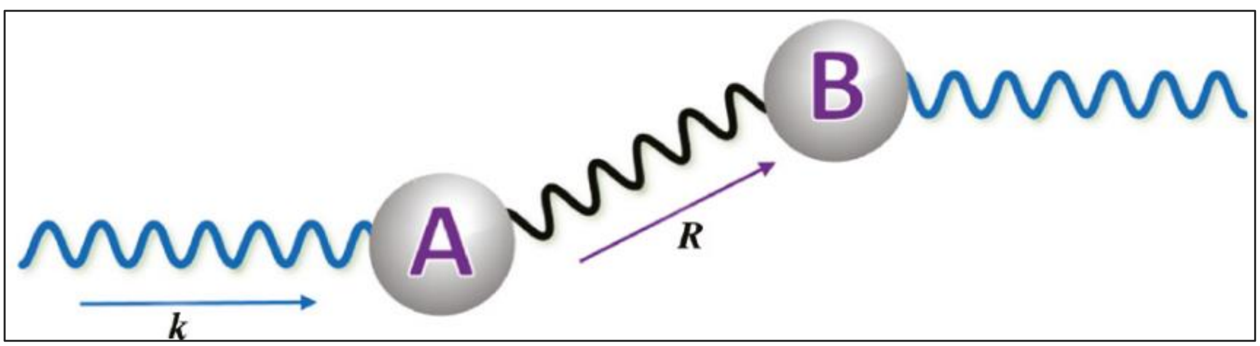


(Micro-engine powered by critical demixing. An optically trapped colloidal particle, with radius a = 1.24 µm, immersed in a water–2.6-lutidine critical solution performs rotations around the trapping beam. The performances of the engine can be tuned by adjusting the criticality of the mixture via the ambient temperature. At low temperature (a), the particle is stably trapped. When the temperature increases (b), the particle starts to rotate around the optical beam (white solid lines trajectories), reaching its maximum value for a temperature of 26° (c) with a very reproducible trajectory. A further increase of the temperature results in a decrease of the engine rotations and performances (d, e). The white bars in (e) correspond to 1 µm. Figure adapted from Schmidt et al.)

Optical Binding

Optical binding is a laser-induced inter-particle force that exists between two or more particles subjected to off-resonant light. It is one of the key tools in optical manipulation of particles. Distinct from the single-particle forces which operate in optical trapping and tweezing, it enables the light-induced self-assembly of non-contact multi-particle arrays and structures. Whilst optical binding at the microscale between microparticles is well-established, it is only within the last few years that the experimental difficulties of observing nanoscale optical binding between nanoparticles have been overcome.

The laser-induced optical force that exists between two or more micron- or submicron-sized particles, when subjected to a moderately intense off-resonant laser light at optical frequencies, is commonly known as optical binding. For studies in pursuit of optical nanomanipulation, it is worth recognising a need for those particles to also be individually supported by a localising force, most often the force of optical tweezers or trapping by the self-same laser beam. For example, in the case of laser tweezers the particles are localised in a microscale volume, commonly supported in a passive liquid support medium to offset the effect of gravity. It is with such particles, already held almost stationary in an optical field, that optical binding exerts its effect as a stabilising influence on inter-particle separations. This is an effect that can still be significant at inter-particle separations on the order of a few multiples of the optical wavelength.



(*Optical binding between nanoparticles A and B separated by a displacement vector* ***R****. Identical input and output photons of wave vector* ***k*** *are depicted in blue, a virtual photon in black.*)

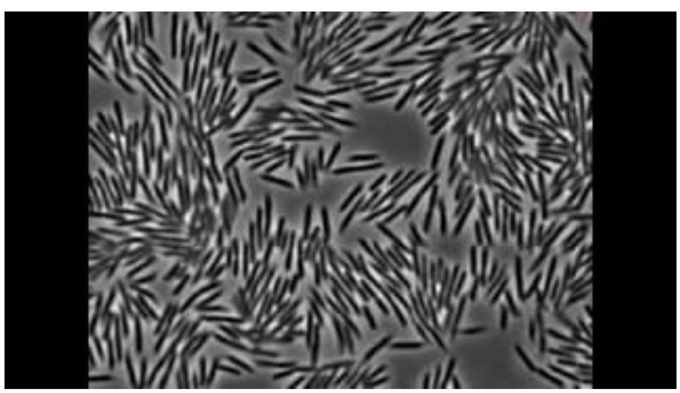
Active matter

Recently, optical tweezers have proved extremely useful for the characterization of active matter systems and the study of the interplay between optical forces and thermophoresis.

Thermophoresis is a phenomenon observed in mixtures of mobile particles where the different particle types exhibit different responses to the force of a temperature gradient.

Active matter systems are those systems constituted by natural and artificial objects capable of self-propulsion. Thanks to their ability in converting energy to propulsion, these systems show behaviours like swarming and the emergence of other collective properties due to far-from equilibrium interactions. This self-propelling behaviour is due to the interplay between random fluctuations (responsible for Brownian motion) and active swimming that drives them into a far-from equilibrium state. Although self-propulsion is a well-known feature in microorganisms to explore environments for nutrients or to escape from toxic substances, a lot of effort is still put in the realization of artificial self-propelling nano and microparticles. Two typical examples of self-propelling particles are artificial Janus particles and biological bacteria such as Escherichia coli, both of them well characterised by optical tweezers.

Furthermore, optical tweezers can be also employed to synchronize collective behaviour of active particles. In particular, this feature has been used to realize a self-assembled fluid pump by trapped active Brownian particles. Optical tweezers can be also employed to perturb the environment of active matter modifying their collective behaviour.



Active matter is composed of large numbers of active "agents", each of which consumes energy in order to move or to exert mechanical forces. Such systems are intrinsically out of thermal equilibrium. Unlike thermal systems relaxing towards equilibrium and systems with boundary conditions imposing steady currents, active matter systems break time reversal symmetry because energy is being continually dissipated by the individual constituents. Most examples of active matter are biological in origin and span all the scales of the living, from bacteria and self-organising bio-polymers to to schools of fish and flocks of birds. The image shown above is a swarm of E coli exhibiting collective motion.

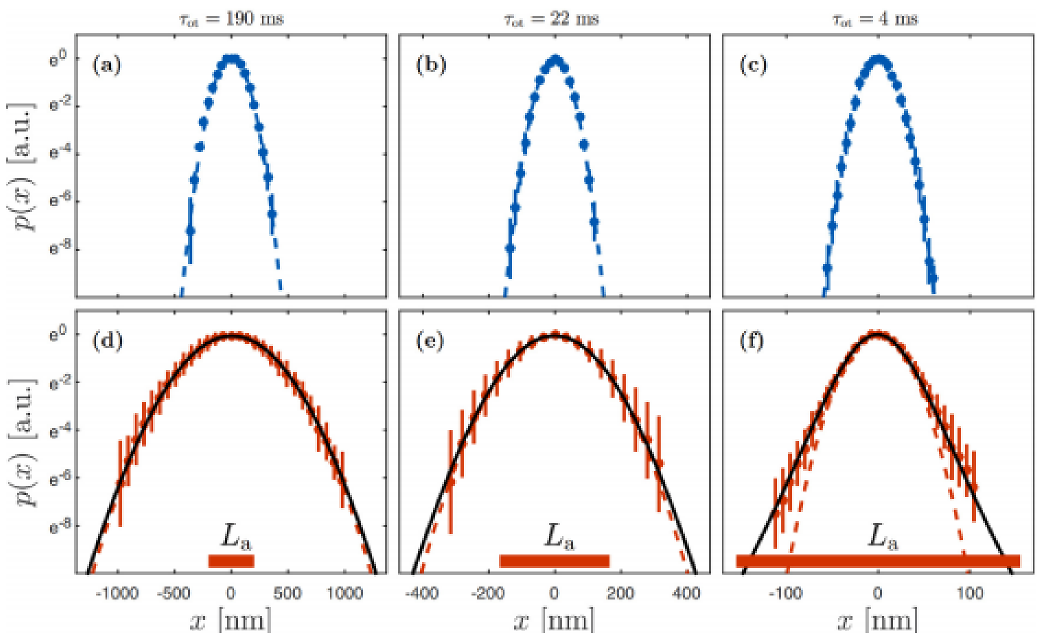
Stochastic thermodynamics

Optical tweezers can also be employed as a very powerful tool to unveil and characterize the statistical properties of micro and nanoscopic systems. Here Brownian noise and large thermal fluctuations play a crucial role by introducing stochasticity. In particular, the dynamics of optically trapped particles results from the interplay between deterministic optical force fields and Brownian motion, which introduces a well-defined noisy background. Therefore, optically trapped particles can be employed as probes to investigate statistical physics phenomena, whose dynamics are driven by both random and deterministic forces, ranging from biomolecules to nanodevices.

One of the biggest advances that can be achieved by applying stochastic thermodynamics to microscopic systems is the possibility to recover information about an equilibrium state of the system from measurements where the system is off equilibrium instead of just averaging the fluctuations out.

Stochastic thermodynamics can be successfully applied to different systems, such as living matter. For example, biomolecules are often coupled, with active baths, due to molecular motors inside the cytoplasm. This coupling is thought to lead to anomalous diffusion within the cytoplasm, a phenomenon that is largely not yet understood.

Recently, the behaviour of an optically trapped particle, immersed in an active bath, has been investigated by digital video microscopy to show a transition from Boltzmann to non-Boltzmann statistic (see fig. shown below). This transition takes place whenever the characteristic scale of an optical trap becomes comparable to the characteristic correlation length of the active noise. A consequence of this transition is that non-equilibrium relations such as the Jarzynski equality and Crooks fluctuation theorem cannot be applied in active baths according to their classical formulation. Although this behaviour is unexpected in active system, its investigation is crucial to develop better models for living and far-from equilibrium systems.



(Emergence of crossover from Boltzmann to non-Boltzmann spatial distributions for a trapped particle in an active bath. Dots represent the distribution of an optically trapped particle, while dashed lines correspond to Gaussian distributions. in the case of not active bath, for increasing values of the stiffness (a)=k = 0.42 fN nm−1, (b)=k = 3.6 fN nm−1 and (c)=k = 22 fN nm−1, the particle becomes more confined and its spatial distribution remains Gaussian. Vertical lines represent the error on six acquired trajectories. When the particle is trapped in an active bath, as the stiffness increases the particle is confined within a length scale comparable to the persistence length in the active bath (La red bar). In this case the particle distribution deviate from Gaussian and can be fitted with a heavy-tailed q-Gaussian distribution (solid black line) with (d) q = 1.013, (e) q = 1.023, and (f) q = 1.142 Panels (d and e). Figure adapted from Argun et al. [253]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Conclusion & Scope

To conclude, through this project we were able to learn about the mechanism & theory behind optical trapping & manipulation. We were able to understand the importance of optical tweezers in today's world a key tool for the contactless manipulation of a wide variety of samples at the micro and nanoscale. We discussed some fundamental aspects of the theory and experimental practice of optical tweezers with a focus on a selection of applications in biology, nanotechnology, and chemistry.

After almost 50 years since the pioneering experiments by Arthur Ashkin on optical forces on microparticles,this exciting field is still acquiring momentum expanding its treads to exciting developments from the life sciences , to nano engines , and quantum technologies.

Device applications are already being pursued. It has already been shown how optically induced forces can play a critical role in determining precise and consistent inter-particle separations of deposited silver nanoparticle chains and arrays onto solid substrates in so-called "optical printing" – a potentially important fabrication technique for creating new photonic devices.

The future scope of optical tweezers in fields of microbiology & nanophotonics appears to be a truly bright prospect.

Once again we would like to thank our professors Dr. Than Singh Saini & Dr. Ajeet Kumar who gave us the opportunity to work on this project & further our knowledge on the topic to its current state.

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