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Angular momentum generation by scattering: alignment and rotation of microobjects

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Abstract

Using a focussed laser beam, it is possible to trap and manipulate microscopic particles. Scattering by the particle in the trap results in a force acting on the particle, due to the transfer of momentum from the trapping beam. Similarly, the transfer of angular momentum through scattering generates an optical torque, which can be used to rotate or align trapped microscopic particles.

We examine the basic processes involved in the transfer of angular momentum in scattering, and show that geometrically simple non-spherical particles can be aligned and rotated merely by using a plane-polarised Gaussian beam.

1 Introduction

Optical forces have been widely used to trap and manipulate microscopic particles for many years [1]. More recently, there has been strong interest in the rotation of microscopic objects, trapped or otherwise. The ability to generate optical torque introduces the possibility of true three-dimensional manipulation, including controlled rotation and alignment as well as translation and confinement, offering a new degree of control of microparticles, including living cells or parts thereof, or fabricated microobjects. This is of interest not only for simple manipulation, but also for the use of rotation as a tool to probe microscopic properties of fluids or biological specimens [2], and the possibility of developing optically powered and controlled micromachines [3, 4].

Optical torques result from the transfer of angular momentum from the trapping beam to a particle through scattering. A number of different mechanisms have been used to achieve rotation. Although these methods have proven useful, they have serious limitations with respect to general applicability.

- **Absorption of a helical beam**
  Since helical Laguerre-Gaussian (doughnut) beams carry orbital angular momentum [5], the absorption of light results in the absorption of angular momentum [6, 7]. Since absorption is required, three-dimensional trapping may be difficult to achieve, and heating places strong restrictions on practical applications. Control can also be difficult to achieve.

- **Absorption of circularly-polarised light**
  The spin angular momentum carried by circularly-polarised light can be absorbed to generate torque [8]. Although it is simpler to produce such a beam than to produce a helical beam, the problems due to using absorption remain, especially for biological applications.
- **Using birefringent particles as microscopic waveplates**
  Since birefringent materials can act as waveplates, changing the polarisation state, and thus the angular momentum, of transmitted light, strong torques can be generated without absorption or heating [9, 10]. This method is, obviously, restricted to birefringent particles.
- **Using specially fabricated particles**
  Specially fabricated particles can be used as optical "windmills" for torque generation [11, 12]. The rotation results from the incident light being preferentially scattered either clockwise or anticlockwise relative to the particle axis.

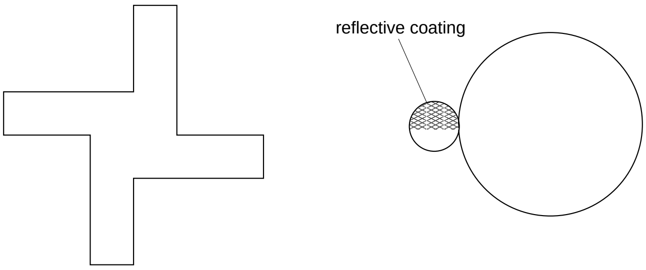

Figure 1: Optical "windmills".

- **Using specially shaped beams**
  Interference between a Laguerre-Gaussian beam and a plane wave produces an interference pattern with spiral arms. Non-spherical trapped objects will align along the spiral arms. Since this spiral pattern can be rotated, it can be used to rotate trapped objects as well [13]. Similarly, a multiple beam trap can also be used to produce a multi-armed trap for the rotation of elongated objects [14]. It is not always convenient, or even possible, to produce such beams in specific applications. The decreased intensity gradients due to increased spot size can also make trapping problematic.

None of these methods can be considered generally applicable, as they either require absorption, which is generally undesirable in trapping, especially for biological purposes, or special types of particles or beams. A non-absorptive technique for rotating non-restrictive types of particles in simple beams is highly desirable.

Here we show that non-absorbing isotropic particles, of simple shape, trapped on the beam axis, can be aligned controllably within a trap consisting of a single plane polarised TEM_{00} Gaussian beam.

2 The transfer of angular momentum

We can readily recognise that a radiation field for which a plane of symmetry exists containing a particular axis has an angular momentum of zero about that axis. Thus, helical or circularly polarised beams carry non-zero angular momentum, while plane polarised symmetric beams do not.

Since we wish to consider trapping in a plane-polarised lowest-order Gaussian beam – the most commonly used beam in single-beam traps (*optical tweezers*) – the trapping beam begins with zero angular momentum. If scattering by the trapped particle breaks the symmetry of the beam, it can introduce non-zero angular momentum to the beam, and, if so, through conservation of angular momentum, an optical torque is exerted on the particle.

If the scatterer is not symmetric across the plane of symmetry of the beam, the scattering will be non-symmetric. This is necessary, though not sufficient, for the scattered light to carry angular momentum. This will be presented in more detail.

3 Alignment and rotation of microobjects

Microobjects of simple shape, such as spheroids or cylinders produce the asymmetry required for torque generation within the trap, if they are appropriately oriented (see figure 2).

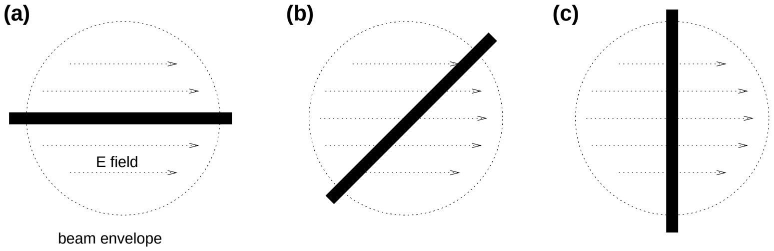

Figure 2: Thin cylinders in an optical trap. In cases (a) and (c), the symmetry of the beam is not broken, and no optical torque can be produced. These are equilibrium orientations. In case (b), the system is asymmetric, and torque generation is possible.

Generally, numerical calculations will be required to determine whether or not a particular particle can be three-dimensionally trapped, and if orientations that result in torque generation are feasible (see figure 3).

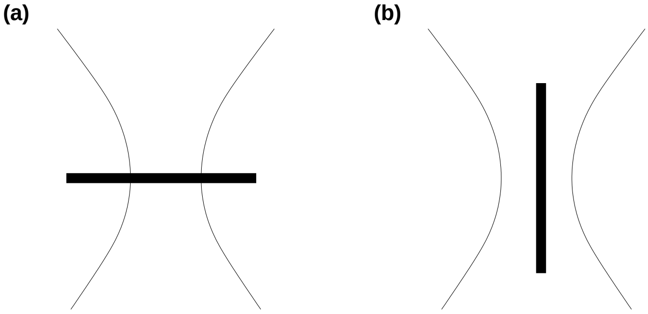

Figure 3: Alignment of elongated objects in an optical trap. Elongated objects align along electric fields, and can thus be expected to align perpendicular to the beam axis, in the plane of polarisation (a). However, elongated objects in optical traps are known to align along the beam axis (b). The actual position will depend on which effect is stronger.

Calculations of the optical force and torque acting on rod and disk shaped particles shows that the long axis of the particle aligns with the electric field of the trapping beam. This occurs for a range of particle sizes and optical properties. The results of numerical calculations of the optical force and torque will be presented.

4 Conclusion

We have shown that geometrically simple isotropic particles can be controllably aligned using a plane polarised Gaussian beam. Continuous rotation could be achieved by rotation of the plane of polarisation of the trapping beam.

This is of particular interest, since more complex schemes for alignment and rotation depend on special types of particles or beams, and cannot always be used for, for example, naturally occurring particles such as prokaryote cells, or organelles. Alignment of this nature has been observed for trapped chloroplasts [15].

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