6 Read the following article and answer the questions that follow.

Optical Tweezers

Light as a particle, photon, carries energy and momentum.

In 1970, Arthur Ashkin discovered that by using light from a tightly focused laser beam, you can effectively trap and even move microscopic particles. This led to the development of “optical tweezers”, which allow scientists to study microscopic and even nanoscopic materials, including particles the size of just a few atoms.

In recent years, optical tweezers have been successfully used to study a variety of biological systems, including trapping single viruses and characterising biological motors within cells. Hence, in 2018, Arthur Ashkin was awarded the Nobel Prize in Physics for his groundbreaking work on optical trapping.

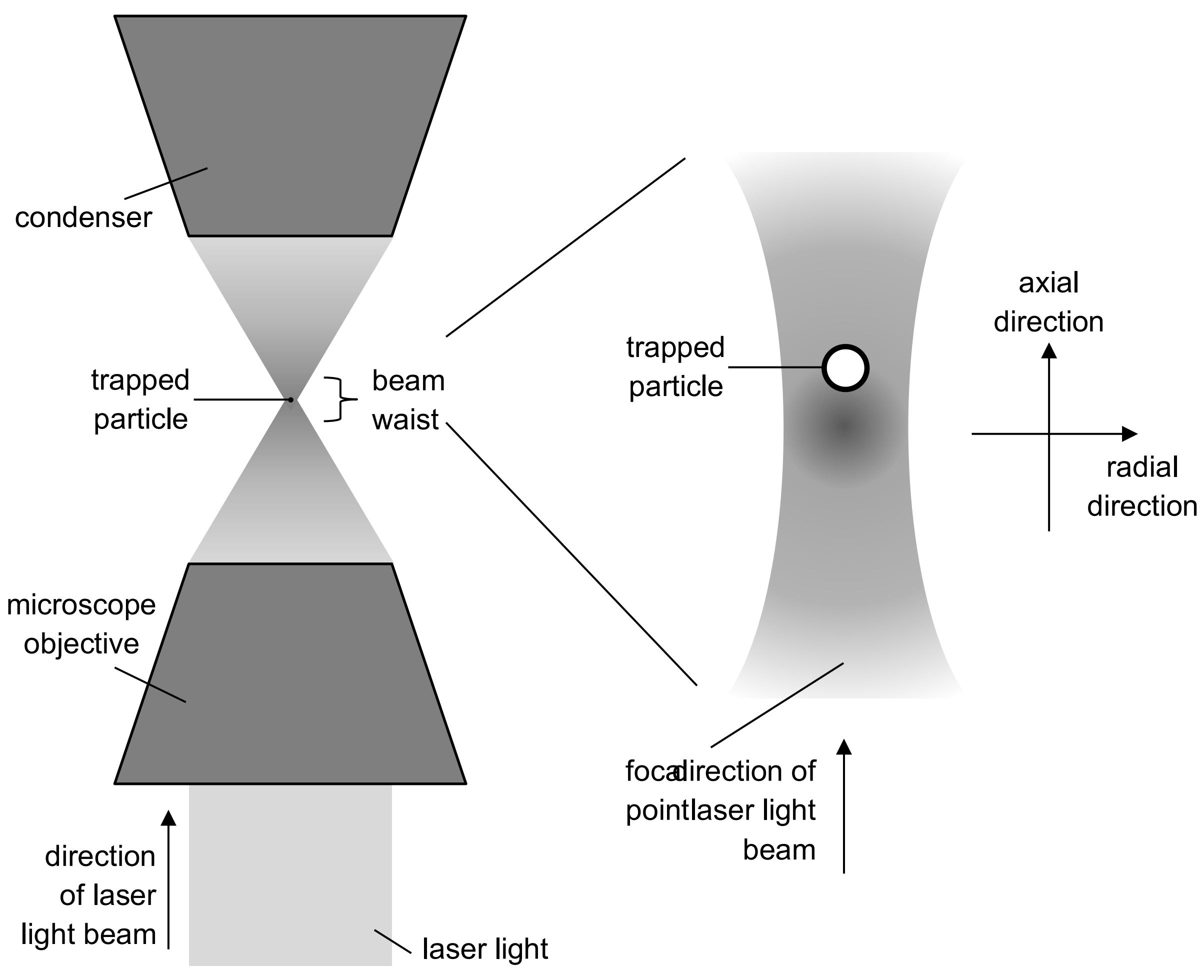


Fig. 6.1 **Fig. 6.2**

In a general optical tweezer setup, as shown in Fig. 6.1, parallel laser light is passed through a microscope objective, which focuses the laser at its focal point. The beam then diverges and enters a condenser. This forms the “beam waist” (the narrowest part of the focused laser beam), which is where the particle will be trapped, as shown in Fig. 6.2.

When trapped, the particle experiences forces from the laser light in all directions due to reflection and refraction. These forces act as a form of restoring force so that if the particle is displaced slightly, these forces will return it back to its equilibrium position. Hence, the particle remains trapped within the beam.

The forces experienced by the trapped particle are generally categorised into two types: *gradient* forces and *scattering* forces. *Gradient* forces act in all directions on the particle and arise from the intensity profile of the beam waist – the particle experiences an attractive force towards the most intense part of the beam, which is the centre and the focal point of the beam. *Scattering* forces, on the other hand, act in the direction of travel of the laser light and arise from the reflection of light off the particle, which tends to push and displace the particle in the direction of the laser light.

Fig. 6.3 and Fig. 6.4 show the variation with displacement of the restoring forces acting on the particle along the radial direction (perpendicular to the direction of beam propagation) and the axial direction (parallel to the direction of beam propagation) respectively.

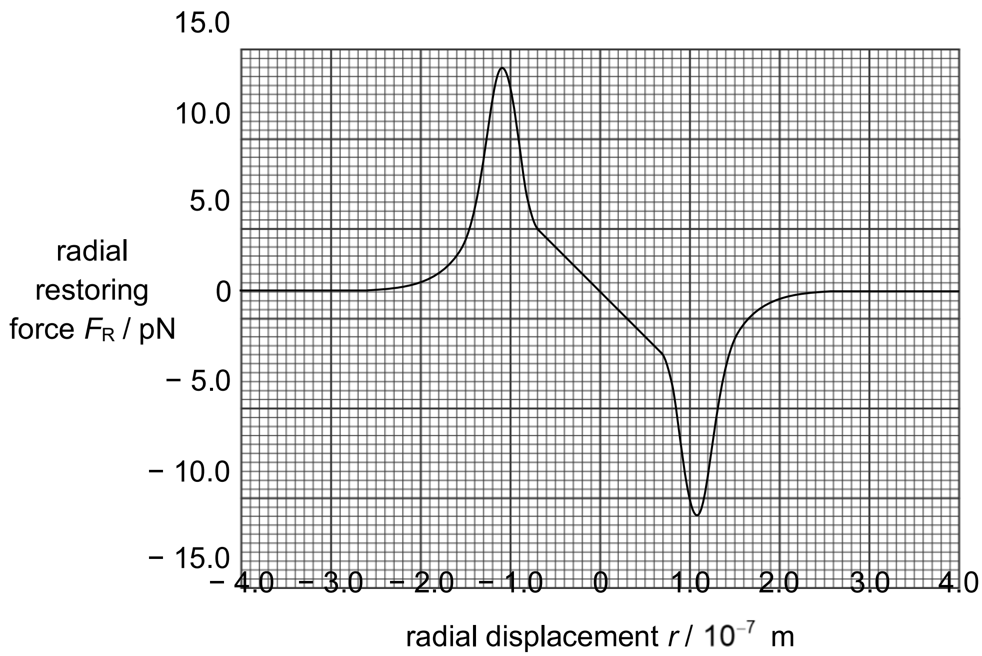
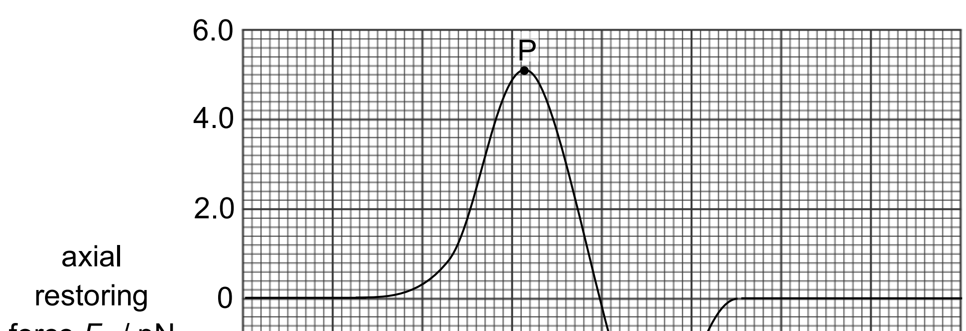


Fig. 6.3



(a) Suggest why *gradient* forces need to be larger in magnitude as compared to *scattering* forces in order for the particle to remain trapped in the beam.

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(b) If the radial displacement r of a trapped particle from its equilibrium position is small, the radial restoring force F_R experienced by the particle can be modelled using Hooke's Law for a mass on a spring, which can be expressed as

$$F_R = -kr$$

where k is the radial spring constant.

(i) From Fig. 6.3, estimate the maximum displacement of the particle from its equilibrium position in which the restoring force can be approximated using Hooke's Law.

maximum displacement = ………………………….. m [1]

(ii) From Fig. 6.3, determine *k*.

k = ………………………….. N m^{-1} [1]

(iii) The particle is displaced from its equilibrium position along the radial direction such that the radial restoring force F_R can be described by Hooke's Law. It then begins to oscillate about its equilibrium position. The mass of the particle is 1.50×10^{-14} kg.

1. Using the features of the graph in Fig. 6.3, explain why the oscillation of the particle can be described as simple harmonic.

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2. Determine the frequency of oscillation of the particle.

frequency = …………………………. Hz [2]

(c) By referring to Fig. 6.3, sketch on Fig. 6.5 the variation with axial displacement z of the particle's potential energy U along the radial direction from $r = -0.5 \times 10^{-7}$ m to $r = +0.5 \times 10^{-7}$ m as it oscillates in the radial direction.

Assume U at the equilibrium position ($r = 0$) be zero.

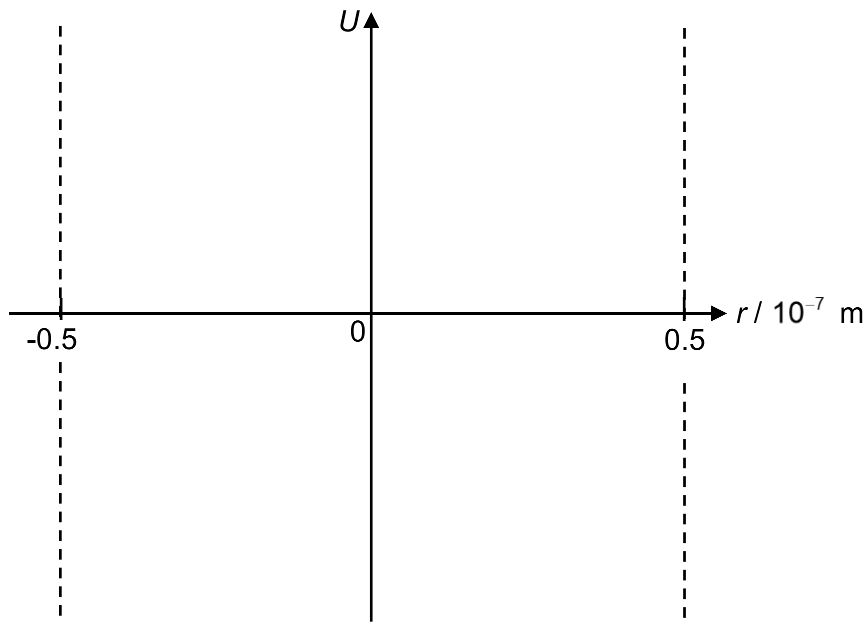

Fig. 6.5

[2]

(d) When the properties of a biological molecule like DNA are being studied, it is usually first attached to a microscopic glass bead. The bead is then immersed in a medium with a refractive index that is smaller than the refractive index of the glass bead. Following which, the bead is trapped and manipulated by optical tweezers in order to study the molecule's properties.

The restoring forces experienced by the trapped glass bead can be explained using the refraction of light through the glass bead. Fig. 6.6 shows a light ray from the laser beam being refracted as it passes through the glass bead.

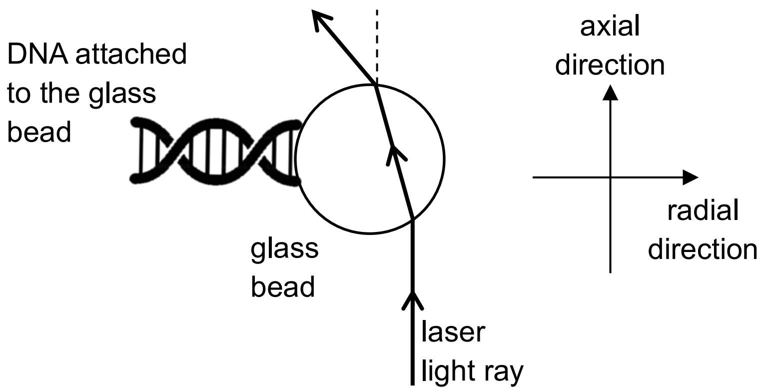

Fig. 6.6

By considering the momentum of photons and Newton's laws of motion, explain how the refraction of the light ray exerts a force radially to the right on the glass bead.

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(e) A photon of wavelength 960 nm enters the glass bead and undergoes refraction, as shown in Fig. 6.7. It enters the glass beads at the angle of 32° to the axial direction. It leaves the glass bead with the same wavelength but at 10° to the axial direction.

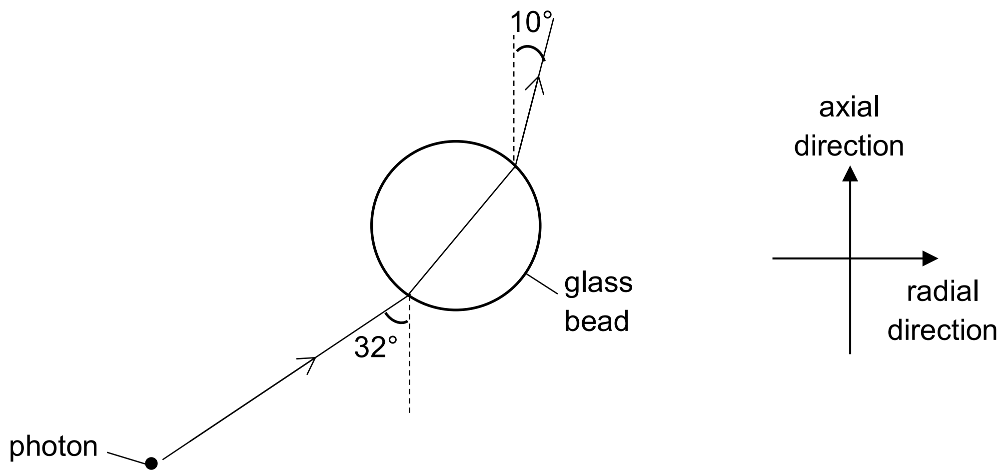

Fig. 6.7

Calculate

(i) the momentum of the incident photon,

momentum = ………………………… kg m s^{-1} [2]

(ii) the magnitude of the impulse of the photon in the axial direction,

impulse = ………………………… kg m s^{-1} [2]

(f) Parallel light rays are converged sharply by the microscope objective lens as it enters the glass bead. The lights are refracted as it comes through and out of the other side of the glass bead. This results in the light going out to travel more along the axial direction, as illustrated in Fig. 6.8.

A force due to this refraction of light will act on the glass bead along the axial direction.

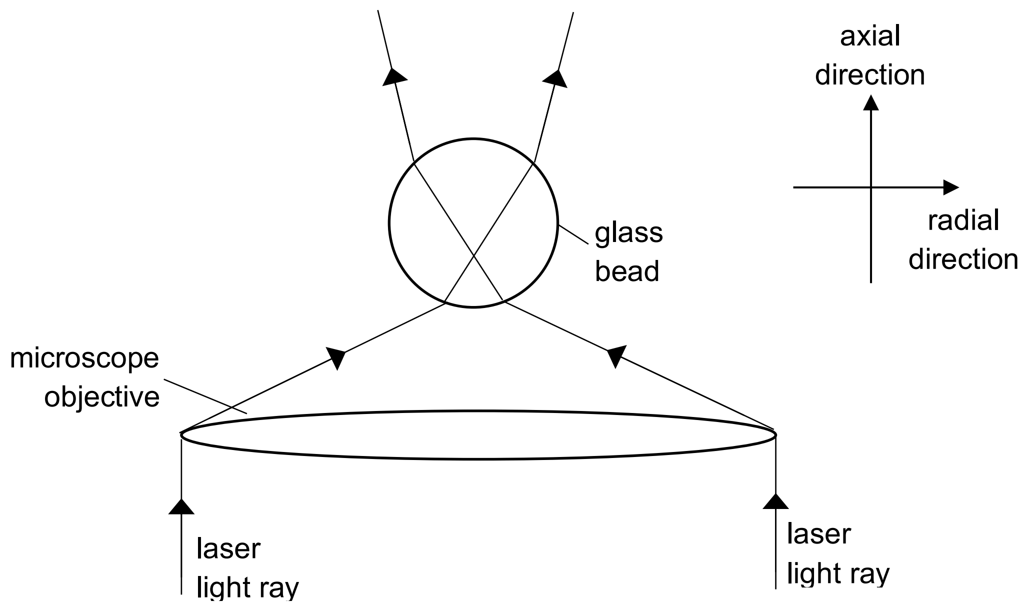

Fig. 6.8

Referring to Fig. 6.4, the maximum axial restoring force indicated with point P has a higher magnitude than that indicated with point Q.

Suggest why this is so.

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End of paper