8 Read the passage below and answer the questions that follow.

Optical Tweezers

In early 1970s, Arthur Ashkin first reported the observation of micron-sized particles being accelerated and trapped in stable optical potential wells by utilising only the radiation pressure caused by continuous laser. This led to the development of a single-beam, gradient force optical trap, commonly known as Optical Tweezers.

Optical tweezers have since been used in fields ranging from fundamental physical sciences to biology, performing single molecule force and motion measurements, and non-invasively manipulating objects such as DNA and live single cells.

Optical tweezers have the ability of applying pico-newton forces to micron-sized particles. In such systems, transparent dielectric particles made of glass or polystyrene are commonly used as they have higher index of refraction than their surrounding medium (typically liquid), thus attracting them toward the region of maximum laser intensity.

An optical trap uses forces exerted by a highly focused monochromatic laser beam in order to trap and manipulate microscopic dielectric objects. The beam is focused through a microscope objective lens in order to produce a narrow beam waist as shown in Fig. 8.1. Dielectric particles suspended in the surrounding liquid medium will be attracted to the centre of the beam waist and towards the optical axis as shown in Fig. 8.2, where it is the region of maximum laser intensity. The laser intensity decreases with distance from the optical axis.

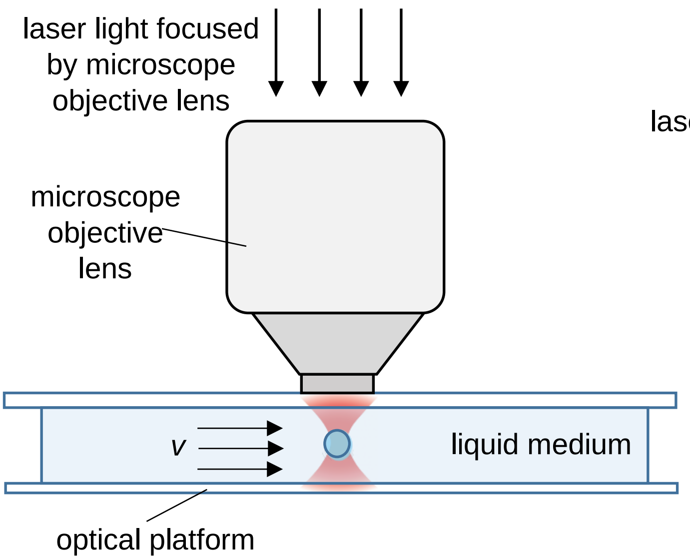

Fig. 8.1

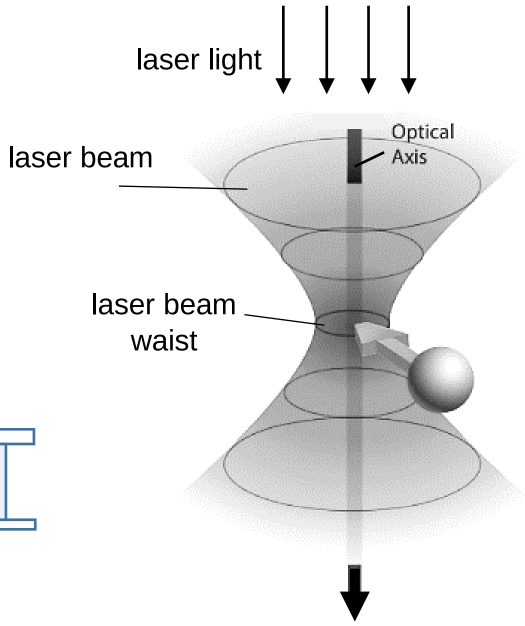

Fig. 8.2

For particles of radius much larger than the wavelength λ of the laser, the Mie scattering approach is utilised. The laser beam is made up of a stream of photons. Some incident photons are reflected by the dielectric sphere, while the rest are refracted through the dielectric sphere. The reflected and refracted processes lead to a change in the momentum of the photons, producing a resultant force on the sphere, which is proportional to the light intensity of the incident laser. With a dielectric sphere of refractive index larger than that of the liquid medium, the refracted light will induce a force in the direction of the intensity gradient, causing the sphere to move towards the centre of the beam waist.

Using the Mie approach, geometric optics is used for the calculation of optical forces. A simplified ray diagram of the refracted laser beam is shown in Fig. 8.3, where two beams G and H pass from a liquid medium through a polystyrene sphere. The sphere experiences a net force towards the centre of the laser waist beam due to both refracted and reflected beams of beams G and H. The sphere will then be stably trapped, with the centre of the sphere aligned with the optical axis.

The force due to the reflected beam may be taken to be negligible, compared to that due to the refracted beam.

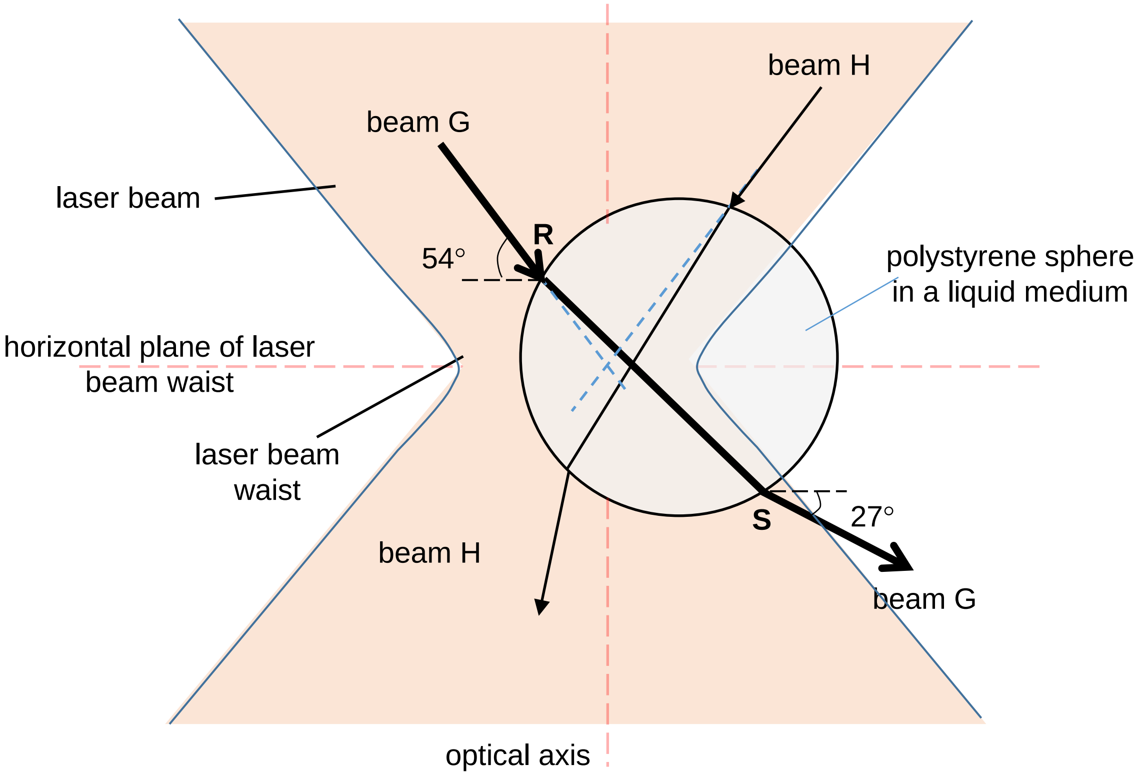

Fig. 8.3 (Reflected beams not drawn)

When the centre of a trapped sphere is displaced by a small displacement Δx from the equilibrium position, there is a restoring force F which obeys Hooke's law where

$$F = k\Delta x$$

and k is the trap stiffness.

The restoring force F can be determined using the Stoke's method, by allowing a fluid of known velocity v to flow past the sphere and measuring the corresponding displacement Δx as shown in Fig. 8.4. The viscous drag F_{drag} acting on the sphere is given by the relationship

$$F_{\text{drag}} = 6\pi r\eta v$$

where r is the radius of the sphere, η is the fluid viscosity and v is the velocity of fluid flow.

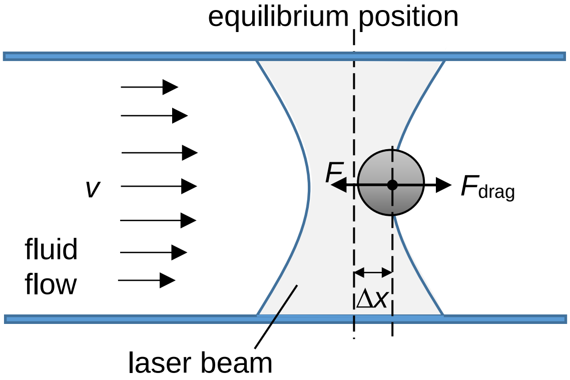

Fig. 8.4

The optical trap can then be calibrated to obtain the trap stiffness k for molecular force measurements.

(a) Suggest why opaque particles are not used for optical tweezer manipulation.

....

....

....[1]

(b) A laser of wavelength 603 nm is used for trapping polystyrene spheres.

With reference to Fig. 8.3, laser beam G with photons of total momentum p_i in unit time is incident on the sphere at R at an angle of 54° to the horizontal, and exits at S with total momentum p_f in unit time at an angle 27° to the horizontal.

(i) For laser beam G, sketch a vector diagram to show the total initial momentum p_i, total final momentum p_f, and total change in momentum Δp of the photons in unit time. Label the vectors clearly.

[2]

(ii) With reference to your answer in **(b)(i)** and using Newton's laws of motion, explain how the refracted laser beam G gives rise to a force acting on the sphere.

....

....

....

....[2]

(iii) Calculate the momentum of a single photon.

momentum = ... N s [2]

(iv) Using your answer in **(b)(i)**, show that the change in momentum of one photon is 5.14×10^{-28} N s.

[1]

(v) The force on the sphere due to laser beam G is 16 pN.

Hence calculate the number of photons in laser beam G passing through the sphere in unit time.

number of photons = ... [2]

(vi) Due to laser beams G and H, the sphere experiences a net force of 19 pN towards the centre of the beam waist.

Calculate the magnitude of the force due to beam H.

magnitude of force = ... N [3]

(vii) Suggest why laser beam G produces a larger force on the sphere as compared to laser beam H.

....

....

....[1]

(c) An optical tweezer system is calibrated using the Stoke's method by trapping a polystyrene sphere of diameter 4.0 μm in liquid as shown in Fig. 8.4. Values for v and Δx are obtained from the experiment and the values are plotted on the graph of Fig. 8.5.

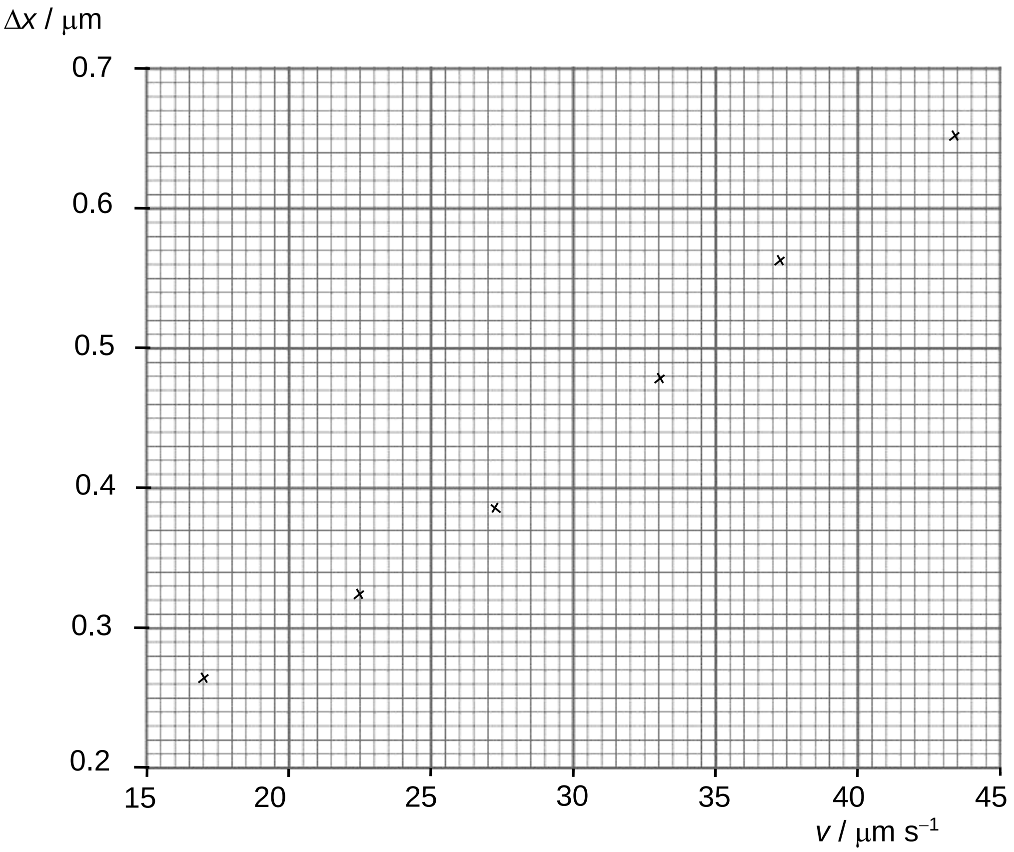

Fig. 8.5

(i) Determine the base units of viscosity η.

SI base units = ... [1]

(ii) On Fig. 8.5, draw the line of best fit for all the points. [1]

(iii) Determine the gradient of the line drawn in **(c)(ii)**.

gradient = ... [2]

(iv) Hence, determine the trap stiffness k of this optical tweezer system, given that the value of η is 0.890×10^{-3}.

k = ... N m^{-1} [2]

[Total: 20]

End of Paper