Observation of a single-beam gradient force optical trap for dielectric particles

A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and Steven Chu

AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received December 23, 1985; accepted March 4, 1986

Optical trapping of dielectric particles by a single-beam gradient force trap was demonstrated for the first reported time. This confirms the concept of negative light pressure due to the gradient force. Trapping was observed over the entire range of particle size from 10 μm to ~25 nm in water. Use of the new trap extends the size range of macroscopic particles accessible to optical trapping and manipulation well into the Rayleigh size regime. Application of this trapping principle to atom trapping is considered.

We report the first experimental observation to our knowledge of a single-beam gradient force radiation-pressure particle trap.[1] With such traps dielectric particles in the size range from 10 μm down to ~25 nm were stably trapped in water solution. These results confirm the principles of the single-beam gradient force trap and in essence demonstrate the existence of negative radiation pressure, or a backward force component, that is due to an axial intensity gradient. They also open a new size regime to optical trapping encompassing macromolecules, colloids, small aerosols, and possibly biological particles. The results are of relevance to proposals for the trapping and cooling of atoms by resonance radiation pressure.

A wide variety of optical traps based on the basic scattering and gradient forces of radiation pressure have been demonstrated or proposed for the trapping of neutral dielectric particles and atoms.[2-4] The scattering force is proportional to the optical intensity and points in the direction of the incident light. The gradient force is proportional to the gradient of intensity and points in the direction of the intensity gradient. The single-beam gradient force trap is conceptually and practically one of the simplest radiation-pressure traps. Although it was originally proposed as an atom trap,[1] we show that its uses also cover the full spectrum of Mie and Rayleigh particles.

It is distinguished by the feature that it is the only all-optical single-beam trap. It uses only a single strongly focused beam in which the axial gradient force is so large that it dominates the axial stability. In the only previous single-beam trap, the so-called optical levitation trap, the axial stability relies on the balance of the scattering force and gravity.[5] In that trap the axial gradient force is small, and if one turns off or reverses the direction of gravity the particle is driven out of the trap by the axial scattering force.

There were also relevant experiments using gradient forces on Rayleigh particles that did not strictly involve traps, in which liquid suspensions of submicrometer particles acted as an artificial nonlinear optical Kerr medium.[6]

The physical origin of the backward gradient force in single-beam gradient force traps is most obvious for particles in the Mie size regime, where the diameter is large compared with λ. Here one can use simply ray optics to describe the scattering and optical momentum transfer to the particle.[7,8] In Fig. 1a) we show the scattering of a typical pair of rays A of a highly focused beam incident upon a 10-μm lossless dielectric sphere, for example. The principal part of the momentum transfer from the incident light to the particle is due to the emergent rays A', which are refracted by the particle. Successive surface reflections, such as R_1 and R_2, contribute a lesser scattering. For a glass particle in water the effective index m, equal to the index of the particle divided by the index of the medium, is about 1.1 to 1.2, and the sphere acts as a weak positive lens. If we consider the direction of the resulting forces F_A on the particle that are due to refraction of rays A in the weak-lens regime, we see as shown in Fig. 1a) that there is a substantial net backward trapping-force component toward the beam focus.

Figure 2 sketches the apparatus used for trapping Mie or Rayleigh particles. Spatially filtered argon-laser light at 514.5 nm is incident upon a high-numerical-aperture (N.A. 1.25) water-immersion microscope objective, which focuses a strongly convergent downward-directed beam into a water-filled glass cell. Glass Mie particles are introduced into the trap by an auxiliary vertically directed holding beam,[5] which lifts particles off the bottom of the cell and manipulates them to the focus. Rayleigh particles are simply dispersed in water solution at reasonable concentrations and enter the trapping volume by Brownian diffusion. A microscope M is used to view the trapped particles visually off a beam splitter S or by recording the 90° scatter with a detector D.

Figure 1b) is a photograph of a 10-μm glass sphere of index about 1.6 trapped and levitated just below the beam focus of a ~100-mW beam. The picture was taken through a green-blocking filter using the red fluorescence of the argon laser beam in water in order to make the trajectories of the incident and scattered

0146-9592/86/050288-03$02.00/0

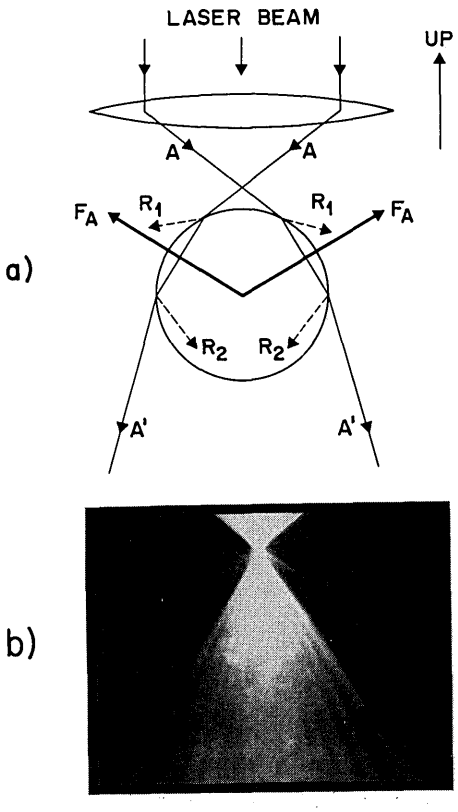

Fig. 1. a) Diagram showing the ray optics of a spherical Mie particle trapped in water by the highly convergent light of a single-beam gradient force trap. b) Photograph, taken in fluorescence, of a 10-μm sphere trapped in water, showing the paths of the incident and scattered light rays.

beams visible. The sizable decrease in beam angle of the scattered light, which gives rise to the backward force, is clearly seen. The stria in the forward-scattered light arise from the usual Mie-scattering ring pattern.

Next consider the possibility of single-beam trapping of submicrometer Rayleigh particles whose diameter $2r$ is much less that λ. Although we are now in the wave-optic regime, we will again see the role of the strong axial gradient in producing a net backward axial force component. For Rayleigh particles in a medium of index n_b the scattering force in the direction of the incident power is $F_{\text{scat}} = n_b P_{\text{scat}}/c$, where P_{scat} is the power scattered.[9] In terms of the intensity I_0 and effective index m

$$F_{\text{scat}} = \frac{I_0}{c}\frac{128\pi^5 r^6}{3\lambda^4}\left(\frac{m^2-1}{m^2+2}\right)^2 n_b. \qquad (1)$$

The gradient force F_{grad} in the direction of the intensity gradient for a spherical Rayleigh particle of polarizability α is[6]

$$F_{\text{grad}} = -\frac{n_b}{2}\alpha\nabla E^2 = -\frac{n_b^3 r^3}{2}\left(\frac{m^2-1}{m^2-2}\right)\nabla E^2. \qquad (2)$$

This Rayleigh force component, in analogy with the gradient force for Mie particles, can be related to the lenslike properties of the scatterer.

As for atoms,[1] the criterion for axial stability of a single-beam trap is that R, the ratio of the backward axial gradient force to the forward-scattering force, be greater than unity at the position of maximum axial intensity gradient. For a Gaussian beam of focal spot size w_0 this occurs at an axial position $z = \pi w_0^2/\sqrt{3}\,\lambda$, and we find that

$$R = \frac{F_{\text{grad}}}{F_{\text{scat}}} = \frac{3\sqrt{3}}{64\pi^5}\frac{n_b^2}{\left(\frac{m^2-1}{m^2+2}\right)}\frac{\lambda^5}{r^3 w_0^2} \geq 1, \qquad (3)$$

where λ is the wavelength in the medium. This condition applies only in the Rayleigh regime where the particle diameter $2r \lesssim 0.2\lambda \cong 80$ nm. In practice we require R to be larger than unity. For example, for polystyrene latex spheres in water with $m = 1.65/1.33 = 1.24$ and $2w_0 = 1.5\lambda = 0.58$ μm we find for $R \geq 3$ that $2r \leq 95$ nm. Thus with this choice of spot size we meet the stability criterion over the full Rayleigh regime. The fact that $R < 3$ for $2r > 95$ nm does not necessarily imply a lack of stability for such larger particles since we are beyond the range of validity of the formula. Indeed, as we enter the transition region to Mie scattering we expect the ray-optic forward-scattering picture to be increasingly valid. As will be seen experimentally we have stability from the Rayleigh regime, through the transition region, into the full Mie regime. For silica particles in water with $m = 1.46/1.33 = 1.10$ and $2w_0 = 0.58$ μm we find for $R \geq 3$ that $2r \leq 126$ nm. For high-index particles with $m \equiv 3.0/1.33 = 2.3$ we find that $2r \leq 61$ nm.

The stability condition on the dominance of the backward axial gradient force is independent of power and is therefore a necessary but not sufficient condition for Rayleigh trapping. As an additional sufficient trapping condition we have the requirement[1] that the Boltzmann factor $\exp(-U/kT) \ll 1$, where $U = n_b\alpha E^2/2$ is the potential of the gradient force. As was previously pointed out,[6] this is equivalent to requiring that the time to pull a particle into the trap be much less than the time for the particle to diffuse out of the trap by Brownian motion. If we set $U/kT \geq 10$,

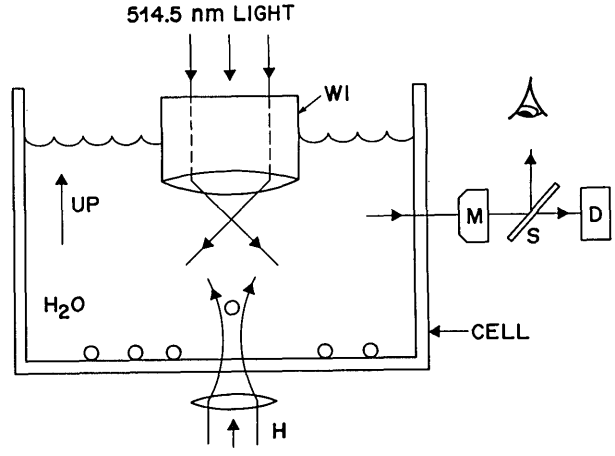

Fig. 2. Sketch of the basic apparatus used for the optical trapping of Mie and Rayleigh particles in water by means of a single-beam gradient force radiation-pressure trap.

for example, and use a power of ~1.5 W focused close to the limiting spot diameter of 0.58 μm $\cong$ 1.5λ, we find for silica that the minimum theoretical particle size that satisfies this condition is $2r$ = 19 nm. For polystyrene latex, the minimum particle size that can be trapped under these conditions is $2r$ = 14 nm. With a high-index particle of m = 3/1.33 = 2.3 the theoretical minimum size is $2r \cong$ 9 nm.

Additional experiments were performed on individual colloidal polystyrene latex particles in water. Unfortunately the particles exhibit a form of optical damage at high optical intensities. For 1.0-μm spheres with a trapping power of a fraction of a milliwatt, particles survived for tens of minutes and then shrank in size and disappeared. Spheres of 0.173 μm were trapped for several minutes with a power of a milliwatt before being lost. Particles of 0.109-μm diameter required about 12–15 mW and survived about 25 sec. With 85- and 38-nm latex particles the damage was so rapid that it was difficult to observe the scattering reliably. It was nevertheless clear that trapping occurred over full size range from Mie to Rayleigh particles.

The remarkable uniformity of latex particles was evident from the small variation of ±15% in the 90° scatter of 0.109-μm particles. Since the scattering is closely Rayleigh this corresponds to a diameter variation of ±2.4%. Subsequently we determined the size of unknown silica Rayleigh particles by comparing their scatter with the scatter from the 0.109-μm particles taken as a standard, using Eq. (1). Although the 0.109-μm particles are not strictly Rayleigh, one can make a modest theoretical correction[10] of ~1.06 to the effective particle size.

Trapping of nominally spherical colloidal silica particles was observed by using commercially available Nalco and Ludox samples[11] diluted with distilled water. With a high concentration we quickly collect many particles in the trap and observe a correspondingly large scattering. At reduced concentration we can observe single particles trapped for extended time. Once a particle is captured at the beam focus we observe an apparent cessation of all Brownian motion and a large increase in particle scattering.

With silica samples we always observe a wide distribution of particle sizes as evidenced by the more than an order-of-magnitude difference in scattering from particles trapped with a given laser power. Particle damage by the light was not a serious problem with silica particles. The smaller particles of the distribution showed only slight changes of scattering over times of minutes. The larger particles would often decay by factors up to 3 in comparable times.

Measurements were made on a Nalco 1060 sample with a nominal size of about 60 nm and an initial concentration of silica of 50% by weight diluted to one part in 10^5–10^6 by volume. Trapping powers of 100–400 mW were used. The absolute size of the Nalco 1060 particles as determined by comparison with the 0.109-μm latex standard varied from ~50 to 90 nm with many at ~75 nm. We also studied smaller silica particles using a Ludox TM sample with nominal particle diameter of ~21 nm and a Nalco 1030 sample with nominal distribution of 11 to 16 nm. Dilutions of ~10^6–10^7 and powers of ~500 mW to 1.4 W were used. With both samples we were limited by laser power in the minimum-size particle that could be trapped. With 1.4 W of power the smallest particle trapped had a scattering that was a factor of ~3 × 10^4 less than from the 0.109-μm standard. This gives a minimum particle size of 26 nm assuming a single spherical scatterer. The measured minimum size of 26 nm compares with the theoretically estimated minimum size of ~19 nm for this power, based on U/kT = 10 and spot size $2w_0$ = 0.58 μm. This difference could be resolved by assuming a spot size $2w_0$ = 0.74 μm = 1.28 (0.58 μm) $\cong$ 1.9 λ.

Experimentally we found that we could introduce a significant drift of the fluid relative to the trapped particle by moving the entire cell transversely relative to the fixed microscope objective. This technique gives a direct method of measuring the maximum trapping force. It also implies the ability to separate a single trapped particle from surrounding untrapped particles by a simple flushing technique.

Our observation of trapping of a 26-nm silica particle with 1.4 W implies, by simple scaling, the ability to trap a 19.5-nm particle with m = 1.6/1.33 = 1.20 and a 12.5-nm particle of m = 3.0/1.33 = 2.26 at the same power. These results suggest the use of the single-beam gradient force traps for other colloidal systems, macromolecules, polymers, and biological particles such as viruses. In addition to lossless particles with real m there is the possibility of trapping Rayleigh particles with complex m for which one can in principle achieve resonantly large values of the polarizability α. Finally, we expect that these single-beam traps will work for trapping atoms[1] as well as for macroscopic Rayleigh particles since atoms can be viewed as Rayleigh particles with a different polarizability.

References

1. A. Ashkin, Phys. Rev. Lett. **40,** 729 (1978).
2. A. Ashkin, Science **210,** 1081 (1980); V. S. Letokhov and V. G. Minogin, Phys. Rep. **73,** 1 (1981).
3. A. Ashkin and J. P. Gordon, Opt. Lett. **8,** 511 (1983).
4. A. Ashkin and J. M. Dziedzic, Phys. Rev. Lett. **54,** 1245 (1985).
5. A. Ashkin and J.M. Dziedzic, Appl. Phys. Lett. **19,** 283 (1971).
6. P. W. Smith, A. Ashkin, and W. J. Tomlinson, Opt. Lett. **6,** 284 (1981); and A. Ashkin, J. M. Dziedzic, and P. W. Smith, Opt. Lett. **7,** 276 (1982).
7. A. Ashkin, Phys. Rev. Lett. **24,** 146 (1970).
8. G. Roosen, Can. J. Phys. **57,** 1260 (1979).
9. See, for example, M. Kerker, *The Scattering of Light* (Academic, New York, 1969), p. 37.
10. W. Heller, J. Chem. Phys. **42,** 1609 (1965).
11. Nalco Chemical Company, Chicago, Illinois; Ludox colloidal silica by DuPont Corporation, Wilmington, Delaware.