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A. Ashkin, and J. M. Dziedzic

Citation: Appl. Phys. Lett. **19**, 283 (1971); doi: 10.1063/1.1653919
View online: https://doi.org/10.1063/1.1653919
View Table of Contents: http://aip.scitation.org/toc/apl/19/8
Published by the American Institute of Physics

Optical Levitation by Radiation Pressure

A. Ashkin and J. M. Dziedzic
Bell Telephone Laboratories, Holmdel, New Jersey 07733
(Received 14 June 1971; in final form 13 August 1971)

The stable levitation of small transparent glass spheres by the forces of radiation pressure has been demonstrated experimentally in air and vacuum down to pressures ~1 Torr. A single vertically directed focused TEM_{00}-mode cw laser beam of ~250 mW is sufficient to support stably a ~20-μ glass sphere. The restoring forces acting on a particle trapped in an optical potential well were probed optically by a second laser beam. At low pressures, effects arising from residual radiometric forces were seen. Possible applications are mentioned.

This letter reports the observation of stable optical levitation of transparent glass spheres in air and vacuum by the forces of radiation pressure from laser light. The technique used involves properties of radiation pressure previously deduced from experiments on small transparent micron-sized spheres in liquid.[1] It was shown that a light beam striking a sphere of a high index of refraction in a position of transverse gradient of light intensity not only exerts a force directed along the light beam, but also has a transverse component of force which pushes the particle toward the region of maximum light intensity. This fact makes stable optical potential wells possible.[1] In contrast to magnetic[2] and electrostatic[3] feedback levitation, or electrodynamic levitation,[4] optical levitation based on the potential well provided by radiation pressure is truly stable in a dc sense with the particle at rest at the equilibrium point. In this regard, magnetically levitated superconductors[5] are similarly stable at rest.

In our experiment a single vertically directed focused cw laser beam was used to lift a glass sphere off a glass plate and stably levitate it. Figure 1 shows the basic apparatus. About 100–500 mW of 5145-Å laser light in the TEM_{00} mode is focused by a 5-cm lens and directed vertically on a selected sphere of ~15–25 μ in diameter, initially at rest in position A on the glass plate. The power is such that a force of several g is applied at A with the particle at the beam waist ($2w_0 \cong 25\ \mu$). This force is directly calculable from the index of refraction of the sphere ($n = 1.65$) as indicated in Ref. 1. This, by itself, is insufficient to break the strong van der Waals attraction to the supporting plate, which for a 20-μ sphere is ~$10^4 g$. This bond can, however, be broken acoustically by setting up a vibration with a piezoelectric ceramic cylinder cemented to the glass plate. Tuning the driving frequency rapidly through a mechanical resonance momentarily shakes the particle loose and it begins to rise up into the diverging Gaussian beam. It comes to equilibrium at position B about 1 mm above the beam waist where radiation pressure and gravity balance. A glass enclosure over the plate serves to minimize air currents. By moving the lens, the beam and hence the particle can easily be moved anywhere within the enclosure. It can even be deposited on the roof for careful subsequent examination. Figure 2 shows a 20-μ particle levitated in air and photographed by its scattered light. The particle is extremely stable and can remain aloft for hours.

Operation at reduced pressure was accomplished with a simple vacuum cell and an adjustable leak valve. Levitation down to pressures as low as 1 Torr was observed before the particles were lost. It is felt that residual radiometric forces coupled with reduced viscous air damping account for this loss. As the pressure was reduced, the equilibrium position B gradually dropped down toward the beam focus indicating the onset of an additional downward force, thought to be radiometric in origin. Due to residual optical absorption and the lenslike character of the sphere, the top of the sphere is slightly hotter than the bottom. This gives a downward radiometric force (negative photophoresis) which initially increases as the pressure is reduced. The thermal force F_{th} is proportional to $1/p$ down to ~10 Torr, where the mean free path is comparable with the sphere diameter.[6] Also, the viscosity and thermal conductivity of the gas are roughly constant for pressures down to ~10 Torr. Below this pressure, radiometric forces, viscosity, and thermal conductivity begin to decrease. Experimentally, at low pressure the particles begin to become less stable

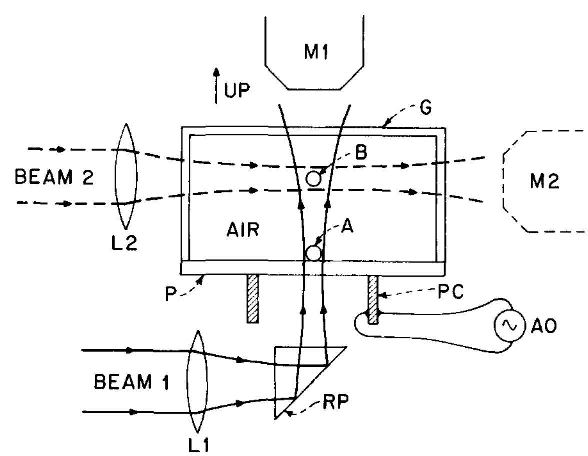

FIG. 1. Levitation apparatus. Particle at A is shaken loose acoustically and lifted to B by TEM_{00}-mode beam 1. TEM_{00}-mode beam 2 is introduced later as a probe beam to study the strength of the trapping forces. L1 and L2 are lenses, P is a glass plate, G is a glass enclosure about 1.5 cm high, RP is a reflecting prism, PC is a piezoelectric ceramic cylinder driven by audio-oscillator AO, and M1 and M2 are microscopes.

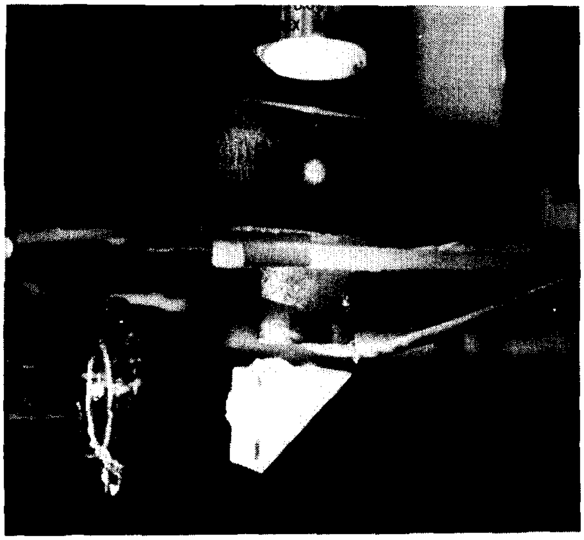

FIG. 2. Photograph of a ~20-μ transparent glass particle being levitated about 1 cm above a glass plate by a 250-mW vertically directed laser beam (shown as beam 1 in Fig. 1). The bright spot is the particle (vastly overexposed) photographed by its own scattered light. The ~90° Mie scattering from the particle is seen on a screen placed at the rear and side of the glass enclosure.

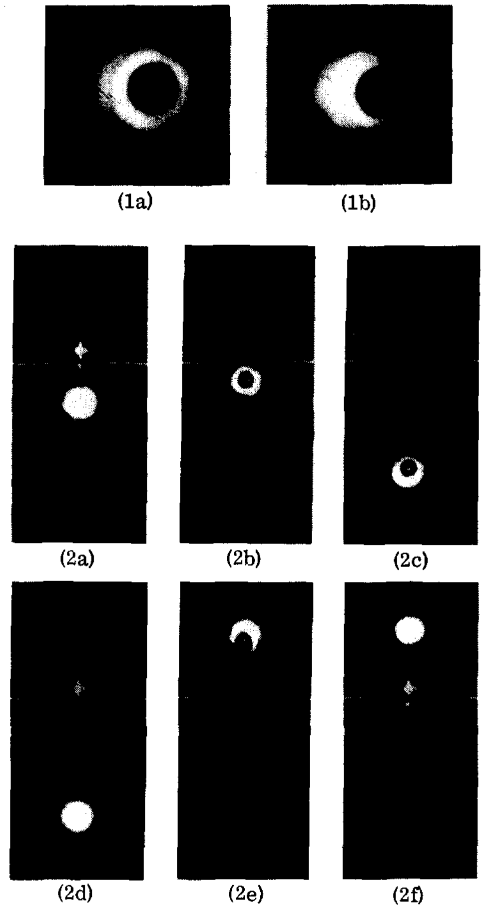

FIG. 3. Probing the horizontal and vertical trapping forces with auxiliary transverse beam 2. Top views 1(a) and 1(b) from microscope 1 show the horizontal displacement of the particle in beam 1. Side views 2(a) and 2(f) from microscope 2 show the vertical position of the particle in beam 1 as it is hit by transverse beam 2.

horizontally and vertically and even begin to spin at an increasing rate about a vertical axis prior to breaking loose from the optical trapping forces. Thus we see that even radiometric forces which are one or two orders of magnitude less than radiation pressure at atmospheric pressure can cause trouble at reduced pressure. A calculation of optical absorption in the particle, based on the estimated radiometric forces, indicates an absorption loss $\alpha \cong 5\times10^{-2}$ cm^{-1} which is quite high. The glass spheres were made commercially by the Flexolite Corp. of St. Louis, Mo. for reflectors. Since a loss of $\alpha \cong 10^{-4}-10^{-5}$ cm^{-1} is possible in glass, this thermal limitation is not fundamental.

It can be estimated that the horizontal restoring forces are much stronger than the vertical restoring forces about the equilibrium point of the optical trap. This is directly observable in an auxiliary experiment in which a particle levitated in a 250-mW vertical beam 1 is illuminated by a horizontal beam 2 of adjustable power (see Fig. 1). Microscopes 1 and 2 are used to project enlarged views of the beams and particles on viewing screens. In photographs 1(a) and 1(b) of Fig. 3, taken with microscope 1, we observe the horizontal displacement of the particle in beam 1 as the power in beam 2 is increased to ~125 mW. This power almost pushes the particle out of beam 1. Thus we find a maximum transverse trapping acceleration of $\sim\frac{1}{2}g$ for beam 1. This is very large and accounts for the high degree of horizontal stability observed. The much weaker vertical stability manifests itself in microscope 2 in the sensitivity of the vertical equilibrium level to minor power fluctuations. It is interesting to note that the probe beam 2 itself can be used to stabilize the particle vertically. View 2(a) shows the particle, seen by its own scattered light as two bright sources located near the top and bottom of the particle,[7] sitting at its equilibrium level marked by the white line. Just below it is beam 2, adjusted to about 40 mW. In view 2(b), beam 2 is raised so its fringe field hits the particle, whereupon it draws the particle down into it, close to its axis. In this position the transverse stability of only 40 mW in beam 2 is sufficient to hold the particle essentially fixed vertically as the power fluctuates. In fact, it is now possible to lower beam 2 and drag the particle down many particle diameters into the region of slowly increasing vertical force [view 2(c)] before it breaks free and returns to its equilibrium position [view 2(d)]. The particle can also be lifted up, as shown in view 2(e), before it breaks free and drops back to the equilibrium level [view 2(f)]. In situations 2(d) and 2(f), where the particle returns to equilibrium, we can conveniently observe the effects of viscous damping inasmuch as the particle returns without undergoing any vertical oscillations.

Many other trapping configurations having even greater stability based on several beams are possible. For instance, a third beam, opposing beam 2, and of the same power would keep the equilibrium point on the axis of beam 1 while adding to the vertical stability. Other laser modes such as TEM_{01} and TEM^*_{01} (the doughnut mode) have been successfully used, although the TEM_{00} mode is optimum. Other particle shapes, if not too extreme, are useable, possibly even partly hollow particles. With a different launching technique, it certainly should be possible to levitate very much smaller particles, even perhaps in the submicron range. It should be noted, however, that the principles of optical levitation should not be expected to provide any significant trapping of atoms, even though the pressure of resonance radiation on atoms is quite a significant effect.[8]

The technique of optical levitation will probably have use in applications where the precision micromanipulation of small particles, free from any supports, is important such as in light scattering from single small particles (Mie scattering) or in laser-initiated fusion experiments. If the viscous damping can be further reduced, applications to inertial devices such as gyroscopes and accelerometers become possible. Measurement of low optical absorptions, absolute optical power measurement, and pressure measurement are also likely areas of application. Levitation may also provide an interesting adjunct to Millikan-type experiments on charged particles. The extreme simplicity of the technique and its remarkable stability recommend its use.

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[7] The interference observed in the 90° Mie scattering of Fig. 2 can be ascribed to the interference from these two bright sources. One can determine the particle diameter d by measuring its distance from the observing screen and the fringe spacing, since the separation between the two near-field sources is $\cong (1+\sqrt{2})\, d/2$.
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APPLIED PHYSICS LETTERS VOLUME 19, NUMBER 8 15 OCTOBER 1971

Correlation between Backward Stimulated Raman Pulse and Moving Focus in Liquids*

M.M.T. Loy† and Y.R. Shen
Department of Physics, University of California and Inorganic Materials Research Division, Lawrence Radiation Laboratory, Berkeley, California 94720
(Received 27 May 1971)

We have studied the correlation between backward stimulated Raman pulse and small-scale "filament" induced by a Q-switched laser pulse in Kerr liquids. We show that the filament is the result of a moving focus and that the backward Raman pulse is initiated by the moving focus inside the liquid cell.

In studying stimulated Raman scattering in Kerr liquids with a Q-switched laser, Maier *et al.*[1] have demonstrated that the backward Raman radiation often appears as an intense ultrashort pulse. They assume the Raman radiation is initiated from the "filament" at the end of the cell and show that the ultrashort Raman pulse results from continuous amplification of the leading edge of the pulse through interaction with the incoming fresh laser beam.[1] Recently, we have proved[2] that, with Q-switched pulses, the so-called filament[3] is simply the result of a moving focus.[4] We have also been able to correlate both forward and backward Raman pulses with the moving focal spot.[2,5] In this letter we show, from results of time-correlation measurements, that the backward Raman pulse can often be initiated from the moving focus well *inside* the cell. The experimental results agree quantitatively with predictions from the moving focus model and therefore can also be taken as a direct confirmation of the moving focus model.

To illustrate the correlation between backward Raman radiation and the moving focus, we show in Fig. 1 the U curve describing the position of the focal spot inside the cell as a function of time.[2,6] This U curve is obtained from the equation for the self-focusing distance,[7]

$$z_f(t) = K/[P^{1/2}(t - z_f n/c) - P_{cr}^{1/2}], \qquad (1)$$

where $P(t)$ is the power of the input laser pulse, and K and P_{cr} are parameters determined by the beam characteristics and liquid properties.[7] The extremely high laser intensity in the focal region initiates stimulated Raman scattering readily. Consequently, we would expect to see Raman radiation continuously initiated from the moving focal spot. However, for the backward Raman radiation, it is clear from Fig. 1 that the leading edge is initiated from the region around A, where the slope of the curve is $-c/n$. This leading edge of the Raman pulse propagating backward along the dot-dashed line intercepts the incoming fresh laser beam