Reports

Optical Levitation of Liquid Drops by Radiation Pressure

Abstract. *Charged and neutral liquid drops in the diameter range from 1 to 40 microns can be stably levitated and manipulated with laser beams. The levitation technique has been extended toward smaller particles (about 1 micron), lower laser power (less than 1 milliwatt), and deeper traps (greater than ten times the particle's weight). The techniques developed here have particular importance in cloud physics, aerosol science, fluid dynamics, and optics. The interactions of the drops with light, the electric field, the surrounding gas, and one another can be observed with high precision.*

We report here on a study of the optical levitation of charged and neutral liquid drops with laser beams. The techniques developed here have particular importance in cloud physics, aerosol science, fluid dynamics, and optics. Optical levitation is based on the ability of light to stably trap nonabsorbing particles by the force of radiation pressure (*1*). In this technique a continuous-wave (cw) vertically directed focused TEM_{00} Gaussian-mode laser beam not only supports the particle's weight but pulls the particle transversely into the region of high light intensity on the beam axis. Once the particle is trapped, one can manipulate it by moving the beam about. This levitation technique has been demonstrated for glass spheres and other nonabsorbing particles (*1, 2*). Applications of levitation and radiation pressure have been discussed (*3*).

The proposed application of levitation to cloud physics and aerosol science is a natural extension of the technique, since progress in these fields has hinged crucially on studies of the interactions of single particles (*4*). A comparison of optical levitation with other techniques that have been used in these sciences for manipulating particles, such as electrodynamic suspension, acoustic suspension, the use of wind tunnels, and suspension on fine wires, indicates that only optical levitation has the combined ability to handle the drops ($\sim$ 1 to 40 μ) found in natural clouds with such simplicity, high positional stability, ease of manipulation, and ease of observation. The advantage of this technique results from the depth of the optical trap, its highly localized nature approximating the particle size, and the ease with which the beam can be moved in space. We will discuss specifically how we generate charged and neutral drops in the 1- to 40-μ diameter range, trap them singly and in small clouds in the light beams, move them about, measure their charge, and observe their interactions with the electric field, light, one another, and the surrounding gas.

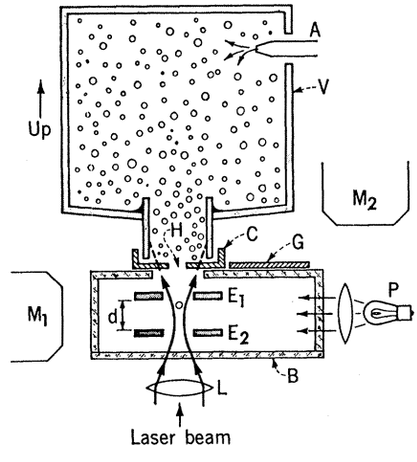

Fig. 1. Sketch of the experimental apparatus. Dimension d is $\sim$0.6 cm.

Figure 1 is a sketch of the basic apparatus. A vertically directed cw laser beam is focused by a lens L and introduced into a glass box B from below. The beam is aligned with a hole H, about 0.5 mm in diameter, located in a sliding roof cover C. A liquid droplet cloud is sprayed into a large storage vessel V with an atomizer A where it can settle slowly by gravity. Some drops fall through the hole and enter the light beam where, if their sizes are in the correct range, they can be trapped and levitated. With microscope M_1 one can view the levitated drops from the side. The drops are not only seen by scattered light from the levitating beam but are visible in silhouette against the projection lamp P. The enlarged view from M_1 is projected on a screen for ease of observation and height measurement. Two plane electrodes E_1 and E_2 with a narrow slit, which allows the beam to pass through, can be used to apply an essentially uniform electric field to the particles. Once drops have been collected by the beam, one can stop the rain of particles by pushing the sliding roof cover C aside with the sliding glass plate G. Thus, without opening the box to significant disturbing air currents, the source can be removed and replaced by a transparent plate for viewing with microscope M_2 from above.

The levitated drops in general arrange themselves in order of size, with the largest closest to the beam focus. Figure 2 shows various situations. With multiple drops the upper drops are arranged in a light intensity distribution modified by the lower drops. Thus in Fig. 2b′ the upper drop is located outside the shadow cast by the lower drop and sits off-axis in the high-intensity light ring which diffracts past the lower drop. With many drops (Fig. 2, c and d) the particles become more closely coupled as a result of their effects on the light distribution and also as a result of electrostatic attractions and repulsions. Up to 20 or so drops can collect in a fixed array which undergoes rearrangement when significantly dis-

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turbed. Drops were made from various liquids. Drops of pure water in the 10- to 30-μ range evaporate so rapidly in room air that they are held only for about 30 seconds. Instead of adding water vapor to the surrounding air to increase drop life, we made drops from liquids with low vapor pressure such as silicone oil or water-glycerol mixtures with composition ratios varying from ten parts water and one part glycerol to pure glycerol. Silicone oil drops persist in this apparatus almost indefinitely. However, a pure glycerol drop with a diameter of ~ 12 μ was observed to evaporate to ~ 1 μ in 3 hours. We gradually reduced the power of the argon ion laser operating at 5145 Å from ~ 40 to ~ 0.2 mw to keep the drop from rising too high in the levitating beam as its mass decreased. The impressively low power of 0.2 mw indicates how little power is required for the levitation of particles approaching 1 μ in diameter. The 35-μ particle of Fig. 2a is held by ~ 400 mw.

The electrical charge carried by drops can be determined from a comparison of the applied electric forces with the light forces. Thus, if we displace a drop upward with an electric field, then the percentage reduction in light needed to restore the drop to its original position represents the fraction of the particle's weight supported by the field. From the weight and the applied field, one can determine the total charge. Water-glycerol mixtures are polar liquids and give drops with various charges (plus, minus, or neutral) as expected. The charges are often high enough so that a force several hundreds of times the weight of the particle, mg (where m is the mass and g is the gravitational acceleration), can be applied with reasonable fields. Nonpolar silicone oil gives drops with much less charge.

The magnitude of the restoring forces acting on levitated particles corresponds to $\sim mg$ (*2*). For larger particles (~ 40 μ) the magnitude of the restoring forces gives rise to a very stable trap. Thus it would take an air current of ~ 5 cm/sec to eject a 40-μ particle from the beam. Because of increased viscous drag, small particles (~ 1 μ) are stable up to an air current of only $\sim 3 \times 10^{-3}$ cm/sec. This makes manipulation of 1-μ drops difficult. However, it is possible to deepen these traps by orders of magnitude. By increasing the strength of the upward supporting light and balancing it with a downward electric or optical force, one can maintain levitation and increase the trap depth in proportion to the increase in light power. Fortunately this method is most useful with small drops where the levitating power is initially quite low. In practice, we have deepened traps by more than an order of magnitude by using a downward electric force. This scheme may permit the levitation of even smaller particles, possibly in the submicron range. It also has the important advantage of operating in the zero-gravity environment of space experiments. The opposite procedure of applying an upward electric force and decreasing the supporting light beam results ultimately in a transition to the Millikan type of support where uniform electric forces alone support a particle in neutral equilibrium. Although easily done for small particles (~ 1 to 4 μ), this procedure has less practical interest since we lose the advantages of stability. For larger particles where light power is a consideration and damping is not severe, partial electric support has merit. With the field uniformity of our plates we have easily supported 90 percent of a particle's weight electrically.

Potential applications of the levitation technique for single trapped drops include measurements of the rates of evaporation, condensation, charging, and neutralization. The effects of changes in the ion content and flow rate of the surrounding air and also changes in the drop itself, such as the effects of the addition of dissolved impurities (salts) and various solid nuclei, can be studied. In addition to making possible the direct observation of the drops in a high-power microscope while levitated, the levitation technique can also be used to deposit drops elsewhere for measurements.

Concerning solid nuclei, the smallest solids that we have levitated thus far are ~ 4-μ dried latex spheres (Dow Corning). Because latex is slightly absorbing in 5145-Å light, we used ~ 1 mw of 6328-Å light to levitate the spheres. We also expect that one can grow a small crystal within a levitated drop by partial evaporation of a drop containing dissolved salts. Possibly we can evaporate the solvent completely and levitate the crystal itself, if its shape is not too extreme. The most irregularly shaped objects that we have levitated thus far are random clumps of two to five glass spheres. These invariably orient themselves in the beam. These objects, incidentally, could be

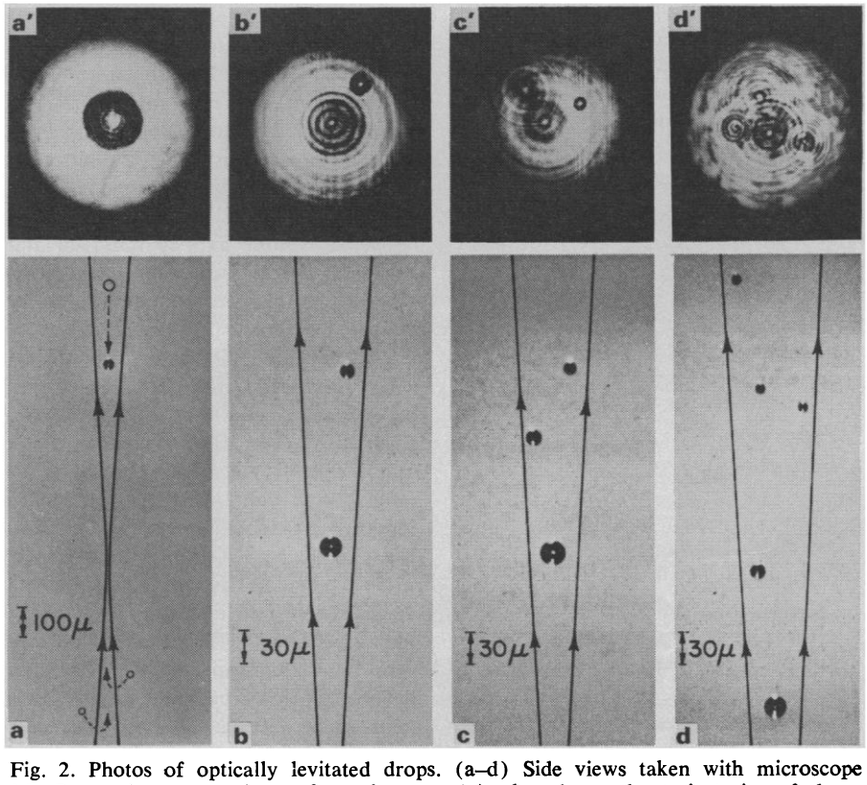

Fig. 2. Photos of optically levitated drops. (a–d) Side views taken with microscope M_1. Beam shapes are shown for reference; (a) also shows the trajectories of drops colliding with the levitated drop. (a'–d') Corresponding top views taken with microscope M_2; (a'–c') focus on the highest drop, and (d') focuses lower in the beam, showing the diffraction rings from the four lowest drops.

used for studying Mie scattering from oriented irregular particles. In addition, our observations of levitation in complex light intensity distributions, such as in Fig. 2d, as well as interesting cases of levitation of small drops in the irregularities of the light beam occurring just above splattered fallen drops lying on the cell floor, indicate that levitation does not require an extreme uniformity of geometry. Finally, concerning ice crystals, we believe that fairly regular crystals such as prisms *should* levitate and that more complex shapes *may* levitate. Possibly an electric field would orient the more platelike crystals and thus aid in levitation.

Levitation permits various drop interactions to be observed. Thus, if two levitated drops (Fig. 2b) have opposite charges, we can force them closer and closer together by applying an external field until they finally coalesce. The fused drop remains levitated at a new height with the combined mass and charge. We have also directly observed drop-drop collisions. Often a levitated drop is struck from above by a heavier drop that is drawn into the beam as it falls. Alternatively, a levitated drop can be hit from below by lighter drops that wander into the lower regions of the beam where they are drawn in, are driven upward through the beam focus, and then encounter the levitated drop (see Fig. 2a). In these encounters we have often observed drop coalescence when the partners have opposite charges and misses when the drops have like charges. Drops can grow by a factor of 4 or 5 in diameter by successive collisions.

The simple experiments described here indicate the potential of the technique for studying the important problems of droplet growth by accretion in Langmuir type collisions with the use of cloud size droplets. In more sophisticated experiments prepared target and incident drops of known size and charge, each initially held in its own optical trap, could be used. They could subsequently be placed in the same beam and be brought together at varying speeds, with an electric field or light being used as the driving mechanism. The parameters of the collision, the particle trajectories, and the detailed fluid dynamics of the drop coalescence could be observed with high-speed movie cameras viewing from different angles. Finally we have made observations on the question of the coalescence efficiency of drops making physical contact. Occasionally we observed two drops roughly equal in size come side by side in the beam and seemingly touch for seconds prior to coalescence. This result should be checked with the use of movie cameras, as suggested above.

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Human Skeletal Muscle: Properties of the "Chemically Skinned" Fiber

Abstract. *A "skinning" procedure is described for irreversibly disrupting the sarcolemmal membrane of human skeletal muscle and allowing calcium and other diffusible solutes (such as adenosine triphosphate) access to the myofilament space. Single skinned fibers give isometric tensions of about 1.5 kilograms per square centimeter when exposed to ionized calcium even after 1 to 2 weeks of storage at 5°C. For up to 5 days the preparation will sequester and, under appropriate conditions (anion substitution, caffeine addition, or magnesium withdrawal), release calcium. The regulation of intracellular calcium distribution and the calcium-induced activation of the contractile proteins are discussed and related to the morphology of human fibers and to similar processes occurring in other muscle preparations.*

The sarcolemmal membrane of human skeletal muscle fibers (*1*) becomes permeable to high molecular weight ions such as adenosine triphosphate (ATP) after 1 to 2 hours of immersion in a solution lacking ionized calcium (pCa > 9). The solution (R) contains 5 to 10 m*M* ethylene glycol-bis(aminoethylether)-*N,N'*-tetraacetic acid (EGTA), 170 m*M* potassium propionate (KPr), 2 m*M* magnesium acetate, 2 m*M* Na_2ATP, and 5 m*M* imidizole and has a pH of 7.00. The permeability changes that result from storing the sarcolemma in solution R occur at 5°C and apparently are due to physical disruption of the membrane, since only fragments of this organelle can be seen in electron micrographs of the stored fibers (*2*). The extensive disruption of the sarcolemma undoubtedly accounts for both the effectiveness and the irreversibility of the "skinning" procedure. Once the sarcolemma is sufficiently disrupted to allow the chemical constituents of the bathing medium access to the myofilament space, the fibers are referred to as having been chemically skinned.

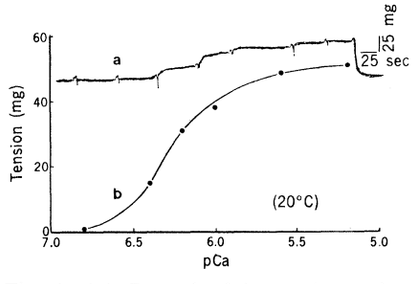

Fig. 1. (a) Record of isometric tensions given by a single skinned fiber exposed to a series of increasing Ca ion concentrations. The Ca was buffered with a total of 5 m*M* EGTA, and the final pCa was calculated as described in (*13*). The concentrations of the other bathing solution components are as in solution R (see text). (b) A tension threshold for this fiber appears at about pCa 6.7 and the maximum tension (P_o) at about pCa 5.2.

The sarcolemma of human skeletal muscle immersed in an EGTA-based solution is much more labile than the sarcolemmas of other skinned fiber preparations such as frog cardiac muscle (*3*) and frog (*4*) and crayfish (*5*) skeletal muscle. Frog and crayfish skeletal muscle exposed to an EGTA-based solution require mechanical skinning for the sarcolemma to be disrupted sufficiently to allow the chemical constituents of the bath access to the myofilament space. Frog cardiac muscle, however, becomes permeable to high molecular weight ions when exposed to EDTA (ethylenediaminetetraacetic acid), but the membrane regains its semipermeability when reexposed to millimolar concentrations of ionized Ca (*3*).

Once skinned, a 2- to 4-mm length of single muscle fiber was placed in a temperature controlled (20°C), vig-