Observation of Radiation-Pressure Trapping of Particles by Alternating Light Beams

A. Ashkin and J. M. Dziedzic
AT&T Bell Laboratories, Holmdel, New Jersey 07733
(Received 14 November 1984)

The new principle of radiation-pressure trapping of neutral dielectric particles by means of alternating light beams was demonstrated in an optical levitation experiment. Stable trapping of micron-sized spheres was observed due to alternating scattering-force fields under conditions where stable cw trapping was not possible. Application of this principle to neutral-atom trapping as a means of circumvention of the optical Earnshaw theorem is suggested. A new stable cw optical trap for spheres was also discovered.

PACS numbers: 32.80.−t, 42.60.−v

We demonstrate the first example of a stable alternating-beam radiation-pressure particle trap for neutral dielectric particles in an optical levitation experiment using micron-sized dielectric spheres. The newly proposed principle of alternating-beam trapping of neutral dielectric particles, including atoms, by radiation pressure[1] is based on a dynamic effect and uses only the scattering-force component of the radiation pressure. Such scattering-force traps were recently conceived as a means of overcoming the limitations of the optical Earnshaw theorem.[2] This theorem states that stable cw trapping of dielectric particles using only the scattering force is not possible. The scattering force is the simpler of the two radiation-pressure force components[3–6] acting on a neutral particle. It acts in the direction of the incident light beam and is directly proportional to the light intensity. The second force component, the so-called gradient force, points in the direction of the optical intensity gradient and is proportional to the strength of the optical gradient. It is well known that stable cw trapping of dielectric particles is possible with use of the gradient force.[3–6] Indeed, it is a corollary of the optical Earnshaw theorem that all stable cw traps must rely on the gradient force. Stable alternating-beam traps of the general type demonstrated here are expected to have distinct advantages[1] over cw traps for trapping of neutral atoms and macroscopic Rayleigh-size particles. For atoms, large-volume traps (~ 1 cm^3) are predicted with greatly reduced optical cooling problems and well depths of ~ 1 K. The well depth and volume of these new traps are thus quite compatible with the energy and density of atomic beams slowed by the scattering force of radiation pressure.[7]

The originally proposed alternating-light-beam trap[1] using only the time-varying scattering force is shown schematically in Fig. 1. It consists of a pair of identical coaxial TEM_{00}-mode Gaussian beams A and B with foci f_A and f_B located symmetrically about the trap equilibrium point O. Action by the gradient force is assumed to be negligible. This can be achieved by placing O well into the far field of the beams A and B, or, for atoms, by tuning the beams to exact resonance. This removes the possibility of cw trapping. The light intensity in A and B is further assumed to vary sinusoidally in time as $I_{A,B} = |\mathbf{I}_{A,B}| \sin \Omega t$, where $|\mathbf{I}_{A,B}|$ is the peak amplitude of A or B and Ω is the frequency. Thus the beams switch periodically from the situation of Fig. 1(a) where A and B are in the so-called forward direction to that of Fig. 1(b), a half-cycle of Ω later, where A and B are exactly reversed. This causes a corresponding periodic reversal of the direction of the net scattering force as shown at representative points P and Q of Figs. 1(a) and 1(b). Trapping based on alternating scattering-force fields in this geometry was proposed in direct analogy with ac electrodynamic ion traps[8–10] where the dynamic stability is governed by the Mathieu equation. Indeed the shape of the scattering-force fields near the origin O in Fig. 1 are closely hyperbolic,[1] as are the electric fields of quadrupole ion traps. The detailed particle motion in alternating-field traps consists of the so-called oscillatory micromotion at the driving frequency Ω superimposed on a slower oscillatory macromotion in response to the average stable trapping potential that exists about the zero-field equilibrium point O.

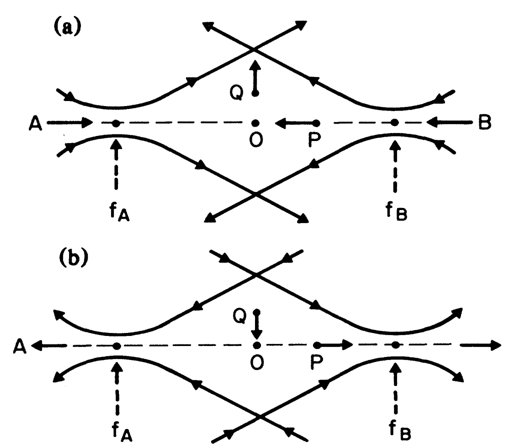

FIG. 1. Geometry of alternating-beam light trap. (a) Beams A and B in the so-called forward direction. (b) Beams A and B a half-cycle later in the reverse direction.

Figure 2 shows how we accomplish the periodic beam reversal necessary to give alternating light fields with the beam configuration of Fig. 1. Argon laser light at 5145 Å is spatially filtered by SF and split equally by polarizing beam splitter SPI into two orthogonally polarized beams, labeled forward total F_{tot} and reverse total R_{tot}. A chopper blade rotating at frequency Ω is poisitoned to switch alternately between the F_{tot} and R_{tot} beams. The beam F_{tot} is split into the two equal forward beams A_F and B_F by a 50-50 beam splitter. The beams A_F and B_F are injected into the trap through polarizing beam splitters SP2 and SP3 and focused by a pair of microscope objectives L1 and L2 to beam foci f_A and f_B. This gives rise to the beam configuration of Fig. 1(a). The beam R_{tot} is also split into two equal reverse beams A_{rev} and B_{rev} by a 50-50 beam splitter. They are focused by lenses L3 and L4 and injected into the trap through SP2 and SP3 lenses L1 and L2. The beams B_{rev} and A_{rev} are focused to the same focal points f_B and f_A with essentially the same spot sizes as the forward beams. This effectively reverses the beam configuration of Fig. 1(a) ray for ray, giving the so-called reverse-beam geometry of Fig. 1(b). In this experiment we accomplished the beam reversal in square-wave fashion with a chopper rather than sinusoidally as originally proposed.[1]

An additional movable vertical levitating beam was used for capturing, holding, stabilizing, or transporting the silicone-oil-drop particle used in this experiment. The optical absorption of the high-purity silicone oil is so low that radiometric forces[11] are negligible in these experiments. Work was performed at atmospheric pressure within a small glass box to avoid air currents. Top- and side-viewing microscopes projected enlarged views of the particle on screens for viewing and locating the particle positions in space. Attenuators (ATT)

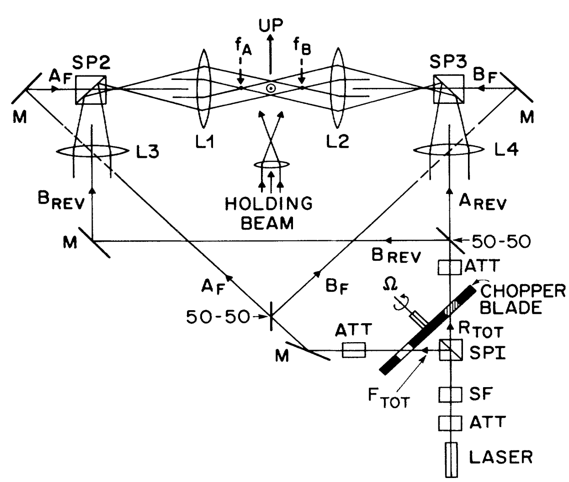

FIG. 2. Schematic diagram of the experimental setup.

and power monitors were used to adjust the beam powers.

The most direct demonstration of alternating-beam trapping using the scattering force would involve an ideal trap as in Fig. 1 where all gradient forces are negligible, cw trapping is ruled out, and only alternating-beam trapping is possible. In the levitation experiment actually performed it was difficult to reduce the radial gradient forces to a negligible value since that requires large-diameter beams with large numerical aperture and high powers. We therefore used an alternating-beam trap of the same general configuration as in Fig. 1 but with dimensions such that we still had radial stability from gradient forces. Our proof of alternating-beam stability in this version of the trap rests solely on demonstration of axial stability due to alternating scattering-force fields. Indeed, we show alternating-beam axial stability under conditions where cw axial stability is shown to be impossible.

In our experiment lenses L1 and L2 had focal lengths of ~ 3.7 mm which focused the forward beams A_F and B_F to spot radii $w_{OF} \cong 1.2$ μm at f_A and f_B. The reverse beams were focused by 14-cm focal-length lenses L3 and L4 and then by L1 and L2 to the same foci f_B and f_A with closely the same spot radius $w_{O\,\text{rev}} \simeq 1.0$ μm. The separation between f_A and f_B was ~ 170 μm. This results in a spot radius $w \simeq 13.0$ μm at O which puts the particle at O in the far field of the beams. Since the beam diameter is comparable to the particle diameter of ~ 9.0 μm we have strong radial confinement from the gradient forces of A and B when operating with either cw or alternating-beam conditions. As we shall see, the existence of radial stability was actually a great experimental advantage. It prevented the particle from ever totally escaping from the light beams during the course of the experiment and made it possible to perform a series of stability tests with the same oil drop. The rather precise beam alignment needed for this experiment was accomplished as follows. A silicone oil drop, 9 μm in diameter, was captured in the vertical levitating beam of ~ 30 mW power by use of a spraying technique[11] and locked in a fixed position by use of feedback stabilization.[5] The four component beams of the trap were then positioned with use of the drop fixed in space as a reference.

To demonstrate alternating-beam stability we start by first determining the range of conditions within which the trap is axially stable under cw conditions. This is done by removing the stabilizer and chopper blade and transferring the particle at O to the cw trap consisting initially of the pair of equal-power forward cw beams A_F and B_F. This transfer is accomplished by gradually turning up the power of the combined forward beam pair to about 140 mW as the vertical levitating beam power is reduced to 0. We note in passing that the first stable optical trap for macroscopic particles[3] and the first proposed version of a focused-beam atom trap[12] were based on such a cw two-beam geometry. We next introduce the pair of equal-power reverse beams A_{rev} and B_{rev} and probe the range of cw stability of the trap by gradually increasing the power of the reverse beams with the forward beams still on. This adds an outward or destabilizing contribution to the net scattering force at each point P on the beam axis as shown in Fig. 1(b) while adding additional inward or stabilizing radial gradient force. At some ratio of reverse power to forward power, which in the case of ideal alignment and equal spot sizes is unity, the particle is no longer cw stable at O and escapes axially. In practice this ratio is close to unity, indicating no large deviations from ideal geometry. Fortunately the escaped particle is not totally lost but is guided along the axis by the radial gradient forces and quickly trapped at one of the strong cw traps which exist at points f_A and f_B on either side of O. The trap geometry at each of these foci consists essentially of two strongly focused opposing beams of equal power with a common beam focus whose diameter (~ 2 μm) is considerably less than the particle diameter (~ 9 μm). Although traps of this type can be understood with the simple ray model[3] they were never explicitly described in previous studies of related trapping geometries.[3,13,14] With the particle safely trapped at f_A or f_B we convert to alternating-beam operation. We transfer the particle to the vertical holding beam, insert the chopper blade, and transport the particle back to position O. With a chopping frequency Ω of ~ 500 Hz, we then gradually raise the overall alternating-beam trapping power while maintaining the measured ratio of forward-to-reverse beam powers which previously resulted in the onset of cw axial instability. In this way we successfully transferred the particle from levitation in the vertical holding beam to levitation in the alternating-beam trap at powers of ~ 140 mW in each beam pair. This observation demonstrates the existence of stability in the axial direction in an alternating-beam trap which was shown to be unstable with the very same beams under cw conditions.

It is now possible to estimate experimentally the depth of the axial potential well of the alternating trap. By further increasing the power of the reverse beam pair relative to the forward beam pair we add an additional axial destabilizing force component to the trap. One can increase the reverse power by $\sim 34\%$ before the alternating-beam trap goes unstable and the particle escapes axially. This is equivalent to adding a 17% reverse cw beam. Since well depth is proportional to power, this implies an alternating-beam well depth of $\sim 17\%$ of the stable cw well depth in the axial direction. It was found that the escaped particle again becomes trapped at one of the foci. Indeed, with alternating beams an average trapping force still occurs at f_A or f_B as a result of the strong viscous damping at atmospheric pressure. We were thus able to retrieve the particle and repeat all measurements three more times under cw and chopped conditions, with essentially identical results. Our experimentally observed well depth of $\sim 17\%$ of the cw well depth can be compared with ion traps. For ion traps a maximum theoretical depth of $\sim 33\%$ of the dc well depth is predicted for strictly sinusoidal harmonic traps when operating at the edge of the stability region.[1,10] In practice, operation with depths of $\sim 10\%$ is more usual.

Finally we studied the stability and alternating-beam well depth as a function of chopping frequency Ω. Stability existed from the highest frequency used (1000 Hz) down to a minimum of ~ 100 Hz. The well depth which theoretically continues to increase down to the lowest stable frequency was observed to increase down to ~ 500 Hz, where the above extensive measurements were made, and slowly decrease at lower frequencies. This decrease may result from residual beam misalignments.

We observe that particles in our alternating-beam traps remain essentially motionless when trapped. No micromotion or macromotion is seen since all particle motion is heavily overdamped at atmospheric pressure. At low pressure oscillatory effects should be seen as in electrodynamic traps for macroscopic particles[9] and in cw levitation traps.[15] The experiment described above is an excellent example of optical micromanipulation of small particles and use of levitated particles as sensitive probes of optical and other forces. Indeed, in this experiment, the single 9-μm oil drop was flawlessly transferred a total of 50 times between five different types of traps located in a region of space about $25 \times 25 \times 200$ μm^3. This occurred over a 5-h period during which the particle position was directly observed with micrometer resolution.

In conclusion, we have made the first demonstration of the principle of alternating-beam trapping of neutral particles by radiation pressure. Using alternating scattering-force fields we achieved an optical levitation trap with a considerable well depth and range of stability. This demonstration strongly suggests further use of the alternating-beam technique for trapping and cooling of neutral atoms and possibly Rayleigh-sized particles under conditions where gradient forces are totally negligible.[1] Finally, a new and useful type of strong cw optical trap was discovered at the common focus of a pair of strongly focused opposing beams of equal power.

[1]A. Ashkin, Opt. Lett. 9, 454 (1984).

[2]A. Ashkin and J. P. Gordon, Opt. Lett. **8**, 511 (1983).
[13]A. Ashkin, Phys. Rev. Lett. **24**, 156 (1970), and **25**, 1321 (1970).
[4]J. P. Gordon and A. Ashkin, Phys. Rev. A **21**, 1606 (1980).
[5]A. Ashkin, Science **210**, 1081 (1980).
[6]V. S. Letokhov and V. G. Minogin, Phys. Rep. **73**, 1 (1981).
[7]W. D. Phillips and H. Metcalf, Phys. Rev. Lett. **48**, 596 (1982)1 J. V. Prodan, W. D. Phillips, and H. Metcalf, Phys. Rev. Lett. **49**, 1149 (1982).
[8]D. J. Wineland, Science **226**, 395 (1984).
[9]R. F. Wuerker, H. Shelton, and R. V. Langmuir, J. Appl. Phys. **30**, 342 (1959).
[10]H. G. Dehmelt, Adv. At. Mol. Phys. **3**, 53 (1967).
[11]A. Ashkin and J. M. Dziedzic, Science **187**, 1073 (1975).
[12]A. Ashkin, Phys. Rev. Lett. **40**, 729 (1978).
[13]A. Ashkin and J. M. Dziedzic, Appl. Phys. Lett. **24**, 586 (1974).
[14]G. Roosen, Opt. Commun. **26**, 432 (1978).
[15]A. Ashkin and J. M. Dziedzic, Appl. Phys. Lett. **28**, 333 (1976).