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Optical angular-momentum transfer to trapped absorbing particles

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Particle rotation resulting from the absorption of light carrying angular momentum has been measured. When absorbing CuO particles ($1-5\,\mu$m) were trapped in a focused ''donut'' laser beam, they rotated, due to the helical phase structure of the beam. Changing the polarization of the light from plane to circular caused the rotation frequency to increase or decrease, depending on the sense of the polarization with respect to the helicity of the beam. Rotation frequencies were obtained by Fourier analysis of amplitude fluctuations in the backscattered light from the particles. [S1050-2947(96)08908-1]

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In this article, we report on the transfer of both orbital and spin angular momentum from a polarized Laguerre-Gaussian (LG) mode laser beam to macroscopic particles. The angular momentum carried by light can be characterized by the ''spin'' angular momentum associated with circular polarization [1] and the ''orbital'' angular momentum associated with the spatial distribution of the wave [2].

To our knowledge, first experimental observation of the torque on a macroscopic object resulting from interaction with light was by Beth [1] in 1936, who observed the deflection of a quartz wave plate suspended from a thin quartz fiber when circularly polarized light passed through it. An experiment was proposed in 1957 [3] to measure radiation torque using microwave radiation, and measurements of light torques were made in 1966 [4]. The experiments of Allen [4] showed that the torque on a suspended dipole due to circularly polarized radiation increased linearly with the intensity of the light. Recently, Allen *et al.* [2] have shown that a Laguerre-Gaussian laser mode has a well defined orbital angular momentum, and proposed an experiment analogous to the experiment of Beth, to observe the torque on suspended cylindrical lenses arising from the reversal of the helicity of a LG mode. In 1995, He *et al.* [5] observed transfer of angular momentum from a linearly polarized LG mode laser beam to absorbing particles. Micrometer-sized CuO particles were trapped in a focused ''donut'' beam, and observed to rotate when viewed through an optical microscope. The direction of the particle rotation was found to be determined by the direction of the helicity of the beam.

We present measurements of rotation frequency of micron-sized black CuO particles trapped in a donut laser beam, for different states of polarization of the incident beam. The measurements clearly show that an absorbing particle trapped and rotating in a focused plane-polarized donut laser beam rotates faster if the beam is changed to circularly polarized with spin of the same sense as the helicity of the donut, and slower if the beam is changed to circularly polarized with spin of the opposite sense to that of the helicity. The magnitude of the change in rotation frequency agrees with that expected from theory [6], within the accuracy of the experiment.

The transfer of angular momentum from light to an absorbing particle can be understood using classical electromagnetic theory. The torque due to the polarization of the light on a particle that absorbs power P_{abs} is $\Gamma_{\sigma_z}=P_{abs}\sigma_z/\omega$, where σ_z is ± 1 for circularly polarized light and 0 for plane-polarized light and ω is the frequency of the light. Our experiments were conducted using what is essentially a LG mode, which has an angular dependence of $e^{-il\phi}$, where l is the *azimuthal mode index*, or *charge* [7]. Such beams have a donut shape with a central zero. Even when plane polarized, the field has a helical structure due to the $e^{-il\phi}$ term. The torque on an absorbing particle, which absorbs power P_{abs}, from a plane-polarized LG mode beam, determined using electromagnetic theory [2], is $\Gamma_l=P_{abs}l/\omega$. In the paraxial limit, the torque on the particle due to both the polarization and the helical Poynting vector of the LG mode is simply [2]

$$\Gamma=\frac{P_{abs}}{\omega}(l+\sigma_z). \tag{1}$$

More intuitively, the light torque can be seen to arise from the angular momentum of photons. Each photon of energy $\hbar\omega$ can be assigned a ''spin'' of $\sigma_z\hbar$. The LG modes can be seen as eigenmodes of the angular-momentum operator L_z [2] and thus carry an ''orbital'' angular momentum of $l\hbar$ per photon. The angular momentum carried by a photon of a polarized Laguerre-Gaussian mode is then $(l+\sigma_z)\hbar$. When this is multiplied by the number of photons absorbed per second, the same resulting torque is obtained as that found using electromagnetic theory.

However, this very simple result is restricted to the paraxial approximation. Barnett and Allen [6] have developed a general nonparaxial theory, using a mode which is a general LG mode in the paraxial limit. The simple dichotomy between orbital and spin angular momentum that exists in the paraxial limit is no longer found. Instead, the results of Barnett and Allen imply that the torque will be

$$\Gamma=\frac{P_{abs}}{\omega}\left\{(l+\sigma_z)+\sigma_z\left(\frac{2kz_R}{2p+l+1}+1\right)^{-1}\right\}. \tag{2}$$

Here p and l are the mode indices, k is the wave number, and z_R is a length term, which in the paraxial limit is associated with the Rayleigh range [6]. As the beam becomes

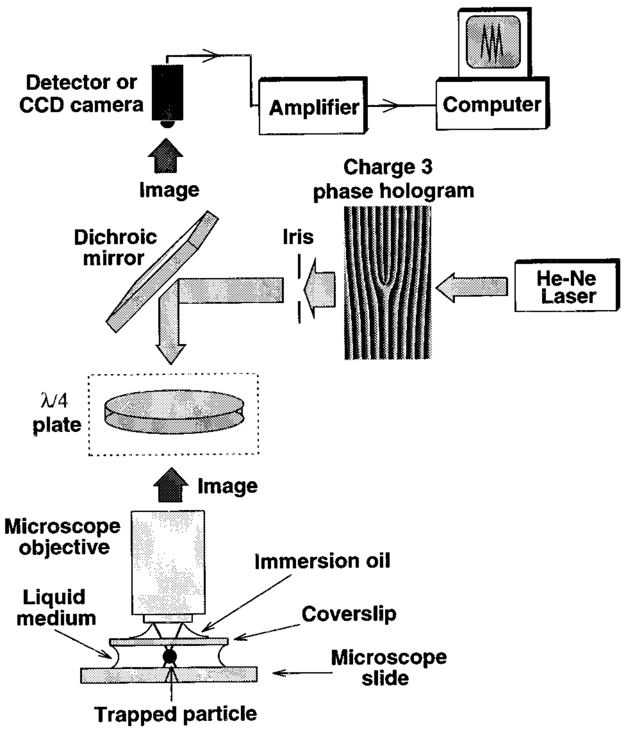

FIG. 1. Experimental setup for observation of optical angular-momentum transfer.

more strongly focused, the mixed term in Eq. (2) becomes more significant. However, if the laser beam were focused to one wavelength across, the most this term could contribute would be 20%, and substituting values appropriate to our experiments, the contribution for our laser beam (which closely approximates a Laguerre-Gaussian LG_{03} mode in the far field) focused to a 2-μm waist is only 4%. Thus we expect to observe the torques on a particle trapped in a LG_{03} mode laser beam of left-circular, plane, and right-circular polarization to be approximately in the ratio 2:3:4.

The quantity P_{abs} can, in principle, be determined from the surface area and absorptivity α of the particles and the beam profile [5]. A body rotating in a viscous fluid also experiences a viscous drag torque which is proportional to the angular velocity $\omega_{particle}$. An equilibrium angular velocity will be reached when the two torques balance, so the rotation angular frequency can be used as a measure of the optical torque.

The essential result to be tested in our experiments is thus that the angular momentum carried by photons of a left-circularly polarized, plane polarized, and right-circularly polarized charge-3 donut beam is in the ratio 2:3:4 (for a right-helical beam). This translates to the angular velocity of a particle trapped in such a beam changing in the same 2:3:4 ratio as the polarization is changed.

Our experiments were performed using an *optical tweezers* setup, as shown in Fig. 1. A Gaussian (TEM_{00}) beam from a 17-mW He-Ne laser was passed through a computer-generated phase hologram [8], which produced a beam closely approximating a Laguerre-Gaussian LG_{03} mode in the far field [7]. This donut beam was then introduced into an optical microscope. A quarter-wave plate was introduced into the beam path directly before a 100× microscope objective (N.A. 1.3), which focused the donut beam to a waist approximately 2 μm in diameter.

As explained above, the objective of this experiment was to determine if transfer of spin angular momentum from light to absorbing particles is observable on a macroscopic scale. The $\lambda/4$ plate, (as shown in Fig. 1) was used to change the polarization of the donut beam. Since the reflectivity of the beamsplitter used to direct the laser beam into the microscope objective is polarization dependent, the $\lambda/4$ plate was placed directly before the objective, after the beamsplitter, in the beam path. The polarization was checked after the objective lens using an analyzer, and the power of the beam was measured for each polarization (left- and right-circularly polarized and plane polarized.) The laser power varied less than 1% between different polarizations. The $\lambda/4$ plate was also carefully positioned so that the beam alignment into the objective did not change when varying the state of polarization of the incoming beam, since poor alignment can cause unstable trapping and thus affect the rotation speed of trapped particles. The samples of absorbing particles (CuO of sizes up to 20 μm, in kerosene mixed with oil to optimize the stability of the trap) were placed between a glass microscope slide and coverslip.

Absorbing particles of size 1–5 μm can be trapped above the focus of the laser beam, where the spot size is rapidly changing. This can be easily understood by considering that Poynting vector and hence the force due to radiation pressure has a component toward the center of the beam as well as one in the direction of propagation. Thus absorbing particles in a converging donut beam should experience a force trapping them in the center and pushing them in the direction of propagation, so they are pressed to the glass surface and trapped in the transverse plane.

The helical structure of the beam means that the Poynting vector also has a tangential component that causes the CuO particles to begin to rotate as soon as they are trapped [5]. The rotation frequency of particles trapped in a linearly polarized helical donut beam has previously been measured by viewing video recordings of rotating particles frame by frame. However, this method is difficult and of limited accuracy as the particles move out of focus when they are trapped and thus their images are not well defined on video. In the present experiments, the rotation frequency was measured using a photodetector positioned off center to intercept a portion of the light reflected from the rotating particle. The particles are irregularly shaped, and protruding parts of the particle reflect a ''flash'' of light onto the photodetector. The signal detected by the photodetector is then processed using Fourier transform methods, and the transform yields the rotation frequency of the particle. If the particle has two protruding parts positioned approximately opposite one another, a peak at double the rotation frequency shows up in the spectrum as well as the peak due to the actual rotation frequency. An example of such a signal is shown in Fig. 2, and the resulting spectrum is shown in Fig. 3. That the main peak shown in Fig. 3 corresponds to the rotation frequency of the particle was verified by a frame-by-frame study of a simultaneous video recording of the same particle rotating. However, the sensitivity of the reflected signal method is such that measurements may be made on less asymmetric particles than can be easily followed in video recordings. This

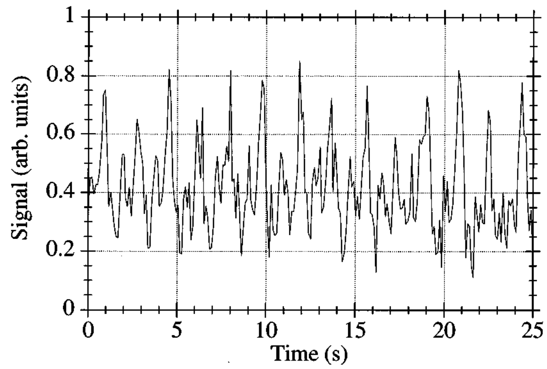

FIG. 2. Sample of raw signal detected from a rotating CuO particle. This particle has two comparatively large protrusions approximately opposite each other.

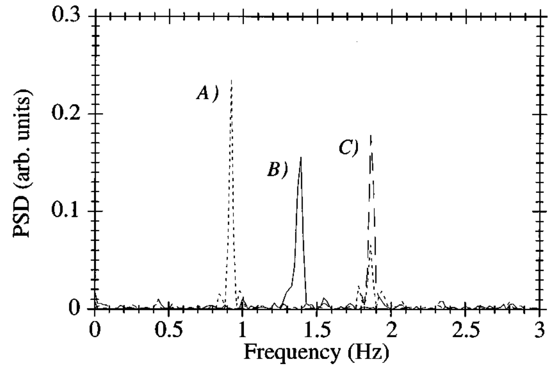

FIG. 4. Typical spectra showing the change in rotation frequency of a trapped particle as the polarization of the beam is changed. (A) is the peak corresponding to rotation in a left-circularly-polarized right-helical LG_{03} beam, (B) corresponds to a plane-polarized right-helical LG_{03} beam, and (C) corresponds to rotation in a right-circularly-polarized right-helical LG_{03} beam.

results in smoother rotation, monitored over longer periods, with a consequent great improvement in the accuracy of the rotational velocity estimates.

The sequence of the experiment was as follows: CuO particles were trapped using a plane-polarized donut beam. The photodetector was used to measure the reflected light, and the signal was sampled at 20 Hz for a period of 100 sec. The $\lambda/4$ plate was then rotated to give left-circularly polarized light while the particle remained trapped, and the signal was again sampled. This procedure was repeated for right-circularly-polarized light and again for plane-polarized light, in that order. In this way, the rotation frequency for a particular particle was obtained for each polarization. Variations of the order in which the polarization was changed were also used. For each experiment, the first and final data sets were taken with the laser beam in the same polarization state, to ensure that any systematic increase or decrease in rotation speed would be evident. The spectra obtained (Fig. 4) clearly show an increase or decrease in rotation speed of the particle due to the circular polarization of the light. The rotation frequency increases when the helicity of the electric field vector (due to the circular polarization) has the same direction as the helicity of the Poynting vector (due to the donut mode), and the decrease in rotation frequency corresponds to the case where the torque due to polarization opposes the torque due to the Laguerre-Gaussian mode. To verify this observation, the hologram which is used to produce the Laguerre-Gaussian mode was turned around, reversing the sense of the helicity of the Poynting vector. The trapped particles now all rotate in the opposite direction to the previous situation, and are slowed down by the polarization which previously caused an increase in rotation frequency and sped up by the polarization which previously slowed them down. Spectra obtained for this orientation of the donut are of the same quality as that shown in Fig. 4.

We have plotted the fractional increase or decrease in rotation frequency due to circular polarization against the rotation frequency for plane-polarized light in Fig. 5. From this graph we see that the proportional change in rotation speed in going from plane-polarized light to left- or right-circularly-polarized light is between 20% and 45%.

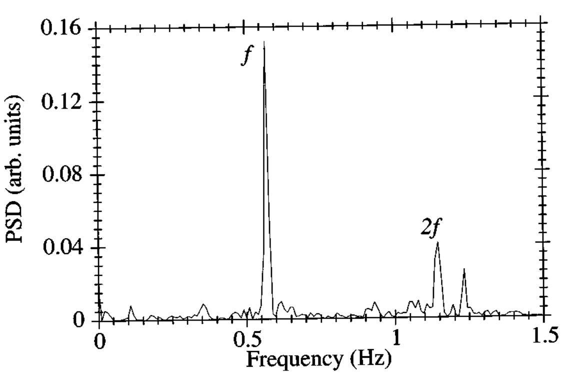

FIG. 3. Spectrum obtained from a CuO particle with two protrusions resulting in strong peaks at both f and $2f$, where f is the actual rotation frequency of the particle. That f is indeed the true rotation frequency of the particle was verified by observation of a video recording made simultaneously with the taking of the data shown in Fig. 2.

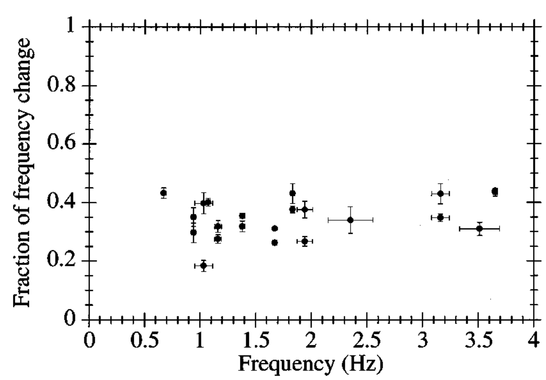

FIG. 5. Plot of fractional change in rotation frequency vs rotation frequency for CuO particles. The change in rotation frequency is due to rotation of a $\lambda/4$ plate by 45°, changing the polarization of the beam from plane polarized to circularly polarized. The error bars reflect the uncertainties in frequency measurements on the individual particles.

According to theory for the donut beam of charge 3, we expect to observe the torques on an absorbing particle trapped in a donut beam with left-circularly, plane-, and right-circularly-polarized light to be in the ratio 2:3:4 approximately. However, static friction between the particle and the slide can affect the ratio. As the particle size increases, we expect the torque required to initiate rotation to increase, causing all rotation frequencies to be reduced by approximately the same amount. This will have the effect of enlarging the proportional frequency change, which was indeed observed in our data.

In spite of this, the results show that, independent of frequency over a 4:1 range, the fractional frequency changes observed cluster about the expected 0.33 figure. Although the spread in values is too great to allow an accurate estimate of the correction term in Eq. (2) it can certainly be seen not to be dominant. Since, in practical terms, ours is a very strongly focused beam, this suggests that the simple paraxial result that the total angular momentum of the field is a simple sum of orbital and spin components will be adequate in the great majority of cases.

The results also provide further proof that the rotation previously reported [5] is the result of optical angular-momentum transfer rather than, say, some thermal effect, as such effects certainly could not be polarization sensitive in this way.

Our experiments show that the rotational speed of small absorbing particles trapped in a focused laser beam depends on the polarization of the light. The dependence is consistent with the transfer of angular momentum to the particles from a field exhibiting two forms of angular momentum— an orbital component associated with the helical phase structure of the donut beam, and a spin component associated with circular polarization of the light— as expected for a paraxial Gauss-Laguerre mode.

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