One-Dimensional Optically Bound Arrays of Microscopic Particles

S. A. Tatarkova,* A. E. Carruthers, and K. Dholakia

School of Physics and Astronomy, University of St. Andrews, St. Andrews KY16 9SS, United Kingdom

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A one-dimensional optically coupled array of colloidal particles is created in a potential well formed by two counterpropagating Gaussian light beams. This array has analogies to linear chains of trapped atomic ions. Breathing modes and oscillations of the center of mass are observed. The stability of the array is in accordance with the Kramers model.

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Introduction.—The organization and manipulation of colloidal and biological matter at the microscopic level can be achieved using light forces. Gradients of the optical field can induce dielectric spheres of higher refractive index than their surrounding medium to be trapped in three dimensions in the light field maxima [1,2]. Such ''optical tweezers'' allow physicists to test several fundamental phenomena. Examples include thermally activated escape from a potential well [3], stochastic resonance phenomena [4], and various studies in colloid physics [5]. Recently the predetermined creation of arrays of microscopic particles, using light forces, has resulted in intense world-wide interest. Holographic methods [6], the phase contrast technique [7], the use of nonzero order light modes [8], and spatial light modulator technology [9] have successfully been used to create particle arrays in two and three dimensions. In 2D the light potential allows predesignated trap sites to be occupied by the particles of interest. Such tailored optical landscapes can give insights into mechanisms at the atomic level or, for example, the pinning of magnetic flux lines in type-II superconductivity [10].

Light forces may wholly dictate the assembly of a microscopic system and create analogs to atomic systems [10–12]. There have been a few observations of such ''optical binding'' notably by Golovchenko and coworkers [11,12]. They investigated systems where the interaction of coherently induced dipole moments of the spheres were said to interact to bind matter. Light forces may act to optically bind matter. These forces can organize microscopic particles with the prospects of studying ''optical molecules'' or systems in soft condensed matter physics. This topic has been controversial but potentially offers an important mechanism to self-assemble matter.

In this Letter we demonstrate the creation of one-dimensional coupled arrays of microscopic colloidal particles. An important distinction in our work is that the light forces that confine the particles also dictate the interparticle spacing due to light refocusing and may be deemed a form of optical binding [11,12]. Buican *et al.* [13] have studied optical guiding in a Gaussian beam and indicated the potential for creation of such regularly spaced particles. We provide a physical explanation of the creation and dynamics of the chain. We infer directly from our results quantitative information about the optical trap potential and trap oscillation frequency. Stability of the array is also investigated.

Atomic ion chains are deemed strong candidates for quantum computing. Chain dynamics can affect decoherence in these systems. Thus creating an analogous model with microscopic particles may offer valuable insights into similar dynamics at the atomic scale. Though our array separation is determined by light forces, it shows analogous behavior to a system of linear atomic ions where electrostatic forces dominate [14]. As particles in our optical trap can be considered harmonically bound, such systems can exhibit excitations, similar to those of atomic ions, including a center-of-mass motion and breathing modes. We observe such behavior in our experiments.

Experiment.—A continuous wave Ti-sapphire laser operating at 780 nm provides the trapping laser light. The beam was expanded and split into two equal (~ 25 mW) counterpropagating components which were then focused into a rectangular glass cell with their respective beam waists approximately 150 μm apart along the common axis far from walls. The focal length of the focusing lenses was 50 mm, the waist sizes were approximately 3.5 μm, and the cell outer dimensions were 5 mm $\times$ 5 mm $\times$ 20 mm. The cell was filled with uniform silica monodispersed colloidal microspheres in water of diameters 2.3 and 3 μm (Bangs Laboratories, Inc.). A microscope objective ($\times 20$, NA $= 0.4$, Newport) placed orthogonally to the laser beam propagation direction projected scattered light onto a charge-coupled device camera.

The separation of the beam waists in this counterpropagating geometry allows a single sphere to be trapped in the potential well between them (see Fig. 1); there is already tight confinement in directions transverse to the beam axis. Blocking one of the beams turns this geometry into one for optical guiding [1,13]. Theoretically, we consider the interaction of dielectric spheres of radius a with a Gaussian beam of wavelength λ when the relation $a \gg \lambda$ is satisfied. Our calculations of the axial force follow those elsewhere [15–17] with the sphere radius

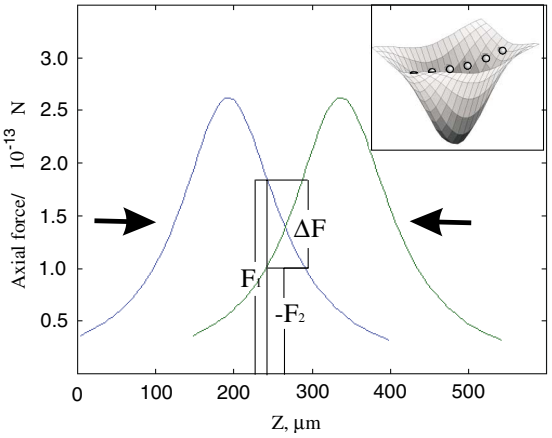

FIG. 1 (color online). Axial forces for the counterpropagating beam geometry. The peak point for each curve corresponds to the beam waist position. Forces from both beams (F_1 and F_2) are drawn as positive. The resultant axial force ΔF is the difference of two forces drawn. The inset shows how particles reside in the resulting potential well.

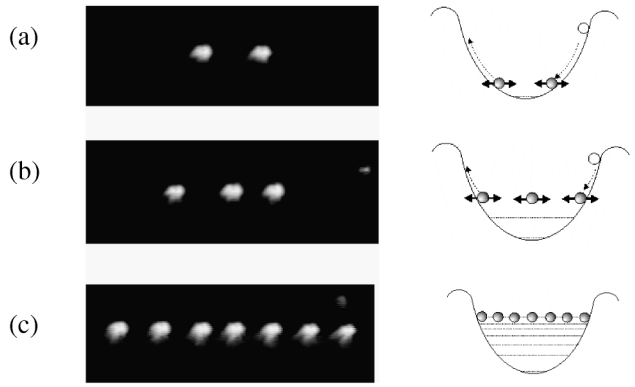

FIG. 2. Experimental data for arrays of (a) two, (b) three, and (c) seven spheres (each 3 μm in size). The diagrams on the right elucidate how we fill up the approximately harmonic potential well created by the two counterpropagating beams.

exceeding the trapping laser wavelength. The model allows us to calculate the variation of axial force along the beam propagation for our experimental parameters (Fig. 1). For collinear beams with slightly displaced waists (along the optic axis), a near parabolic optical potential results with the single equilibrium position at the minimum at the intersection of the curves in Fig. 1.

In the counterpropagating geometry, when a second sphere moves into the same trap the first (trapped) sphere (Fig. 2) is pushed from its equilibrium point. The new equilibrium position of two spheres in trap is above the bottom of the potential well with a separation between them as shown. Each sphere will experience the same value of differential force ΔF (Fig. 1) which can be calculated from the model. This process repeats each time a new sphere drifts into the trap region (Fig. 2). This behavior is observed with both 3 μm diameter and 2.3 μm diameter spheres. We stress at this point that the array length and importantly the interparticle spacing we observe is extremely long in comparison with typical distances over which electrostatic interactions occur in optical traps [5]. For two 3 μm particles we observe an interparticle separation of 48 μm [Fig. 2(a)].

For typical experimental conditions the maximum number of particles in a stable trapped array was seven. The overall array length was $\sim$150 μm in this instance. Very occasionally, we observed trapping of eight or even nine spheres though this was rather unstable with the outer spheres of the array leaving the trap region very quickly. This instability is due to thermally activated loss as the outer particles within the chain have relatively weak optical potential barriers to overcome to escape the potential well. Thermal fluctuations also caused a variation in overall array length for greater than seven spheres for these trap parameters.

The mechanism for formation of this array is purely due to light refocusing and subsequent balancing of radiation pressure. Any given irradiated sphere refracts the majority of incident light thus acting like a lens. This creates a secondary light radiation pressure force on an adjacent sphere, that in combination with the light radiation pressure from the focused input beams, creates a new equilibrium in which the array of spheres can reside. Each sphere in the array is "optically" coupled to each of the other spheres. We have adapted a numerical ray optics ray model [17] to calculate the equilibrium position for two spheres subject to beam waists as in the experiments separated by 150 μm. The model takes into account the fraction of incident light focused by the sphere to calculate the interparticle forces. The optical force on the second sphere due to the first is calculated to be $\sim$0.175 pN. The calculations of the model verify to within 10% the experimentally observed spacing (48 μm) and thus confirm the physical process responsible for the array generation. We also note that this explains earlier observations on two guided particles [13]. In terms of our model, spheres in the array reside in their own potential well. As an example, consider two spheres where each of the spheres focuses the light at a position approximately midway between the two spheres. In this instance this creates a situation where each of the spheres resides in one well of a double well light potential. For a greater number of spheres the idea is similar, with each sphere acting to create a new potential well within the system, forcing the particles farther up the well created by the counterpropagating beams in order to balance the forces and reach an equilibrium position. A detailed analysis will be presented elsewhere.

Electrostatic interactions could potentially play a role in the array formation. The interaction between charged spheres is based on the Derjaguin, Landau, Verwey, and Overbeek theory [5,18] which is limited by the screening length due to the atomic ions present in solution. For our

experimental parameters the screening length is very short (< 100 nm) and the electrostatic interaction restricted to a length scale of less than a micron, an order of magnitude lower than the interparticle spacing we observe. We dispersed the spheres in 1 M NaCl for some experimental runs and observed no discernible change in the interparticle spacing for our arrays, thus validating our premise that the array is created solely by light forces.

We have measured experimentally the equilibrium positions of the spheres for arrays from one to seven particles in length (Fig. 3). The form of these data is reminiscent of that for trapped atomic ions in a linear Paul trap [14]. We are able to extract detailed quantitative information from these experimental data such as the exact form of the trap potential and calculate the actual axial trap frequency. We have fitted the data in Fig. 3 in this way to a parabolic potential, determining the axial trap frequency to be approximately 300 Hz from our theory (Fig. 1) and our experimental parameters.

The lowest mode of oscillation corresponds to the center-of-mass motion of the particle chain. All of the particles move to and fro in unison in this mode. We observed center-of-mass motion of this array. When a chain of a given number of spheres was created, one of the trapping beams was blocked and the whole chain was observed to accelerate against the direction of propagation of the blocked light beam. Reintroducing the obstructed beam (within a few seconds) caused the chain to restore its initial position with a time scale determined by differential force at the current array position. Altering the laser power equivalently in both beams (no change in differential force; see Fig. 1) did not alter the sphere positions but did result in higher light scattering from the spheres. We also observed a breathing mode of the trapped particle array. One of the lenses was mounted on the precision motorized z translation stage, to vary the focal position of one trapping beam. In Fig. 4 we see the corresponding breathing behavior of a long particle chain (of 2.3 μm particles) on the z displacement of one of the lenses. The reduced light pressure force on the one side of the potential well resulted in increases in interparticle spacing. As the lens returns to its original position, the chain self-restores. The time scale of the motion is very slow as the system is heavily overdamped. The dynamics are similar to center-of-mass and breathing modes in chains of linear trapped ions [14].

In the majority of research related to optical tweezing, little attention has been devoted to the temporal stability of the trap. Factors such as local temperature fluctuations caused by light heating and local convective microflows might affect the stability of the trap. Activated escape from such a trap underpins several physical and biological processes. We loaded spheres into our trap and measured their temporal stability. A quantitative description of diffusion activated escape from a one-dimensional potential well was given by Kramers [19]. It states that average residence time is a function of potential well parameters and obeys the equation $\langle \tau_K \rangle = \tau_0 \exp(U/k_B T)$, where U is potential well depth, T is temperature, and τ_0 is the time scale responsible for restoring relaxation dynamics within the well and can be expressed, for spheres far from walls and each other, as [3,4] $\tau_0 = 6\pi\rho a/m\omega^2$, where a is sphere radius and m is the mass, ρ is water viscosity, and ω is the associated frequency of the trap. Experimentally we measured the residence time as a function of number of spheres in the trap (Fig. 5). Each escape event is random and has a low probability in agreement with Poisson statistics.

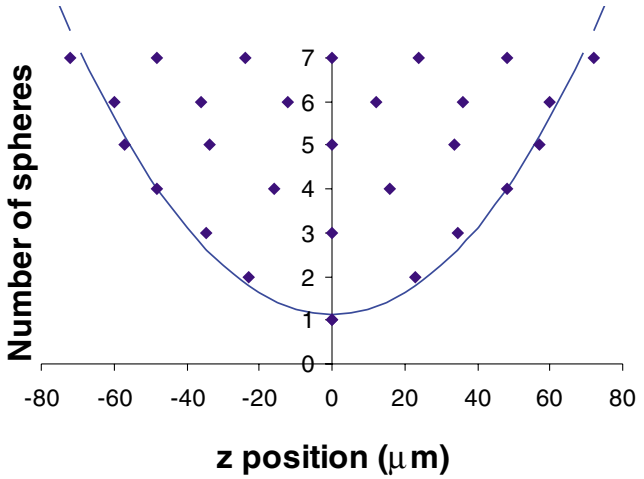

FIG. 3 (color online). Equilibrium positions for particles in the array. The parabolic fit shows the harmonic form (as expected) of the light beam potential. Notably, this allows us to extract important quantitative data about the trap (frequency, light potential).

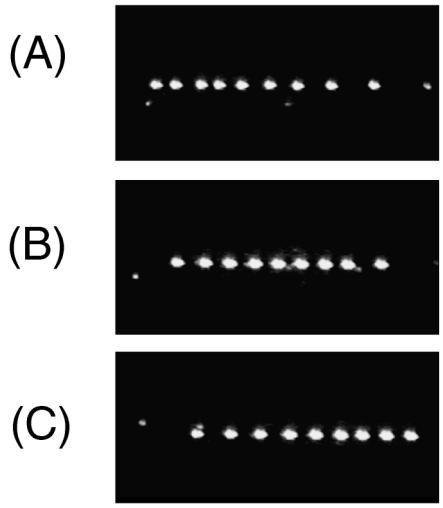

FIG. 4. Observation of a breathing mode. In (a) and (c) we see the displacement of the chain as a whole from the center with the interparticle spacing increasing as one goes farther from the center of the array.

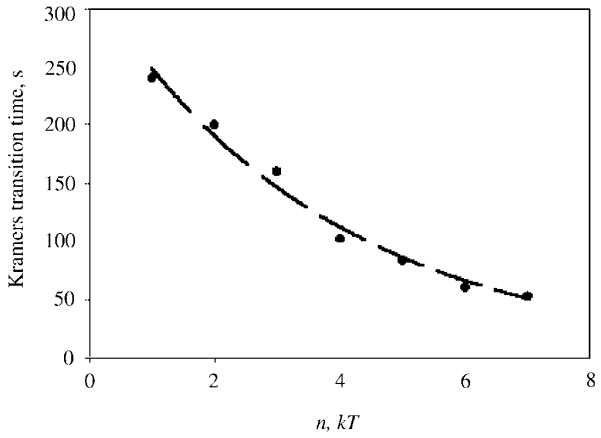

FIG. 5. Kramers transition time for the array. The main features of the observed residence times are supported by a general statistical theory showing exponential decay. The fit is appropriately described by an exponential function of the form $\langle \tau_K \rangle = \tau_0 \exp[\frac{U}{(n+c)k_B T}]$ and has the magnitude of the potential barrier $U/k_B T$ varied from 4.1 to 5.8 and $\tau_0 = 1$, $c = 16$ for particle number $n = 1, 2, \ldots 7$.

In conclusion, we have presented experimental observation and modes of oscillation of a one-dimensional optically bound system of colloidal particles that is akin to an extended line of coupled oscillators.

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*Corresponding author.
Electronic addresses: kd1@st-andrews.ac.uk; sat3@st-andrews.ac.uk

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