Forces in Aharonov-Bohm optical setting: supplementary materials

SERGEY SUKHOV, VEERACHART KAJORNDENKUL, JOHN BROKY, AND ARISTIDE DOGARIU*

CREOL, The College of Optics and Photonics, University of Central Florida, 4000 Central Florida Boulevard, Orlando, Florida 32816, USA

*Corresponding author: adogariu@creol.ucf.edu

Published 3 December 2014

This document provides supplementary information to "Forces in Aharonov-Bohm optical setting,"

<http://dx.doi.org/10.1364/optica.1.000383>. © 2014 Optical Society of America

<http://dx.doi.org/10.1364/optica.1.000383.s001>

1. Experimental Setup and Procedure

Monodisperse suspensions of latex microspheres were prepared by diluting the 2 μm diameter-polystyrene microspheres (Polysciences, Inc.) into water (ultrapure water, 24.7 M Ω cm resistivity, <5 ppb total organic carbon). The suspensions were sonicated to prevent the aggregation of particles using Ultrasonic Cleaner (Cole-Parmer Instrument Company). A small drop of the suspension (2 μL) released from a pipette (Corning Lambda, 2-20 μL) was enclosed by two glass coverslips with two side-sticky tape inserted as a spacer. This effectively prevents the evaporation of the solution and the external perturbation from air currents.

In the experiment, the monochromatic light from a CW laser (wavelength, 532 nm; optical power, 3.9W; Coherent Genesis CX Series model) was split by non-polarizing beam splitter into two laser beams travelling along two different optical paths and thus illuminating the prepared sample placed on a prism as depicted in Figure 4a of the main text. A quarter-wave plate (QWP) was rotated to control the polarization state of one incident beam travelling in one arm. The two split laser beams were focused by two cylindrical lenses with focal length $L_1 = 60\text{mm}$, $L_2 = 150\text{ mm}$ creating overlapping linear trap and elliptical spot at the surface of the upper coverslip. The linear trap formed by the cylindrical lens L_1 limits particles' motion to one direction. The elliptical shape of the spot created by cylindrical lens L_2 helped in increasing of overall intensity. Note that the long focal distance of this lens

does not disturb much the circularity of polarization. A positive lens L_3 with focal length 100mm was also inserted into one arm to adjust an effective focal length and the radius of the final focused beam. In the experiment, due to radiation pressure forces, the polystyrene particles were pushed along optical beams against the upper coverslip and subsequently stably confined within the linear trap.

The motion of the polystyrene particles was imaged by a 20x objective and recorded by a CCD camera (Andor sCMOS) at a frame rate of fourteen frames per second for 40 min. The relatively high frame rate ensures that the displacement of the particle between consecutive frames is smaller than or equal to the characteristic length of a oscillation period of a transversal force F_{AB} . A notch filter (532 nm, OD4, from Edmund) was used to remove the residual laser light scattered onto the microscope objective. During the experiment, the sample was also illuminated in transmission by an incoherent red light-emitting diode light source for imaging purposes.

2. Image and Data Processing

We determine the periodicity of the existed oscillating force F_{AB} distribution based on the measurement of small displacements of polystyrene particles.

A large number of images (35000 frames) was recorded to carry out the statistical analysis of particle displacements. A pre-tracking algorithm was

implemented in MATLAB software. The algorithm determined the locations of particles' centers in every individual frame with accuracy ≈ 30 nm that is much better than oscillation period of the F_{AB} force (282nm) by evaluating the cross-correlation between the recorded image and a pre-determined function approximating the particle shape. The histograms of the relative particle positions within single pixel (not shown here) are relatively flat confirming that the particles position recovery truly had subpixel accuracy.

Linking particles from different frames into trajectories (tracking) was performed with MATLAB code developed in M. Kilfoil's laboratory [1]. The ensemble averages of the x -component of particle displacements were calculated over different finite sized regions of ≈ 840 nm along y_o and $8\mu\text{m}$ along x_o (Figures 4(a),(b) of the main text). The finite size of averaging region along x_o is determined by alignment accuracy in our experimental setup. The random Brownian displacements were averaged out because of the large ensembles of particle displacements used in this procedure.

In a final processing step, the fast Fourier transform (FFT) of the average particle displacement was computed to isolate the oscillating spatial frequency of the force distribution. The FFT was performed within a square window which was scanned across the distribution of the average particle displacement. Lastly, an average was then taken over all the FFT results. This Fourier transform was implemented in order to suppress the low-frequency noise in particle displacements. The same procedure was repeated for different image sections along the x -direction followed by averaging the resulting spatial frequency spectra of particle displacements.

In the final spatial frequency spectrum, the background noise was approximated by the curve fitting and then was subtracted to obtain the data shown in Figure 4(c) of the main text. The error bars indicated in Figure 4(c) represent the uncertainty that arises from all averaging processes. This also includes the transformation of error bars from one domain to another through a Fourier transform operation [2].

3. Optical Forces Exerted on a Dipole Particle

One can discuss the mechanical consequences of the light-matter interaction by starting directly from the Lorentz force exerted by electromagnetic fields on

matter. In this way, the effect of the interaction on the field itself is not explicitly described.

Let us examine the situation depicted in Figure 1 of the main text where two mutually coherent plane waves are incident onto a spherical particle. The first wave is circularly polarized $\mathbf{E}_1 = E_{01} \frac{1}{\sqrt{2}} (\hat{\mathbf{e}}_x \pm i\hat{\mathbf{e}}_y) e^{-ikz}$ while the second one $\mathbf{E}_2 = \hat{\mathbf{e}}_z \exp(iky) E_{02}$ is linearly polarized along z . It is clear that $\mathbf{E}_1$ and $\mathbf{E}_2$ do not interfere. Thus, the total field does not have intensity maxima and minima and, consequently, there are no gradient forces. Considered separately, $\mathbf{E}_1$ and $\mathbf{E}_2$ waves create only forces along z - and y -directions, respectively. We note that the system consisting of a sphere and two orthogonal plane waves is symmetric with respect to inversion of x -axis and asymmetric with respect the handedness of circular polarization.

The x -component of the electromagnetic force acting on a dipole-like particle (the F_{AB} force discussed in the main text) is given by [3]

$$F_x = \frac{1}{2} \text{Re} \left(\mathbf{p} \frac{\partial \mathbf{E}^*}{\partial x} \right), \text{ where } \mathbf{p} = \alpha_e \mathbf{E} \text{ is the induced}$$

dipole moment and $\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$ is the total field. A direct inspection of the field distribution shows that $\partial(\mathbf{E}_1 + \mathbf{E}_2)/\partial x = 0$ which means that $F_x = 0$. Therefore, one concludes that, for a dimensionless vortex the transversal component of force F_x is absent.

References

1. Y. Gao, and M.L. Kilfoil, "Accurate detection and complete tracking of large populations of features in three dimensions," *Opt. Express* **17**, 4685-4704 (2009).
2. J. Schoukens and J. Renneboog, "Modeling the noise influence on the Fourier coefficients after a discrete Fourier transform," *IEEE Trans. Instrum. Meas.* **35**, 278-286 (1986).
3. P. Chaumet and M. Nieto-Vesperinas, *Opt. Lett.* **25**, 1065-1067 (2000).