Topologically Enabled Optical Nanomotors

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Abstract: We show that tailoring the topology of the phase space of the light-particle interaction is a powerful approach to manipulate particle dynamics. In this manner, we find that optically asymmetric (Janus) particles can become stable nanoscale motors in a light field with zero angular momentum.

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Recent years have shown the importance of topological aspects to a number of optical phenomena, including topological order in photonic structures, general optical vortices, and other robust phenomena in optics (e.g. optical bound states in the continuum)[1]. Similarly, shaping the topology of a beam of light can enable unique abilities of light to manipulate matter. For example, light that carries angular momentum (spin or orbital) can cause objects to rotate[2-4]. To date, the most common and relevant uses of light to control nanoparticles necessitate manipulation of the phase front of the light beam; such approaches can be particularly sensitive to scattering or have small active volume, thus limiting their applications.

While shaping the topology of a beam of light has opened opportunities for particle manipulation, here we propose a more fundamental, and powerful, approach. By tailoring the topology of the phase space of the *light-particle interaction* we can facilitate new kinds of manipulation of the position and orientation of a particle. Combining the phase-space topology with the appropriate particle asymmetry further enables dynamics that usually requires shaping of the beam of light itself. In this manner, we find that optically asymmetric (Janus) particles can become stable nanoscale motors even in a light field with zero angular momentum. Such precessing steady states arise from topologically-protected anti-crossing behavior of the vortices of the optical torque vector field.

The system under consideration consists of a plane, linearly-polarized electromagnetic wave of the form $\boldsymbol{E} = \hat{x}E_0 \exp(ik_0 z - i\omega t)$ impinging on a Janus particle consisting of a dielectric (silica) core with one half coated with a thin layer of gold (Fig. 1a). We calculate the force ($\boldsymbol{F}$) and the torque ($\boldsymbol{M}$) that light exerts by integrating the Maxwell stress tensor around a boundary enclosing the particle. For an asymmetric particle such as a Janus particle, the scattering of light strongly depends on its orientation with respect to the incident beam. In the damped regime, we can approximate the evolution of the particle orientation as[5] $d\boldsymbol{P}/dt \approx \frac{1}{c_{rot}} \boldsymbol{M}\times\boldsymbol{P}$. For a $1\mu m$ silica particle, half-coated with a thin layer of gold (60nm) and subjected $\lambda = 1064nm$ light, the streamlines of the vector field $\boldsymbol{N} \equiv \boldsymbol{M}\times\boldsymbol{P}$ are shown in Fig. 1b. We observe multiple vortices of the vector field $\boldsymbol{N}$, each vortex characterized by its topological charge/index defined by[6] $q = \frac{1}{2\pi}\oint_C d\boldsymbol{l}\cdot\nabla_l \gamma(\boldsymbol{l}), (q \in \mathbb{Z})$ where $\boldsymbol{l}$ is the spherical line element, $\gamma(\boldsymbol{l}) = \arg[N_\phi(\boldsymbol{l}) + iN_\theta(\boldsymbol{l})]$ is the angle of the vector $\boldsymbol{N}$, and C is a contour around the vortex center in the counter-clockwise direction. Note that q must be an integer. In our system we observe $q = \pm 1$ vortices: +1 charges correspond to attractors (green circles) and the unstable extremum points at the poles ($\theta = 0^o, 180^o$, indicated by horizontal blue lines – here the gold cap faces directly away/towards the light beam); -1 charges are saddle points, shown as red stars. The stable orientations / attractors (green circles) are of two type. First, along the high symmetry directions where the particle orientation vector $\boldsymbol{P}$ is in the xz plane, we identify four stable orientations where the net torque is zero ($|\boldsymbol{M}|$=0). In addition to these high symmetry equilibria, we also observe four other orientations where the net torque is not zero ($|\boldsymbol{M}|\neq 0$): these correspond to a phenomenon where a particle spins steadily with a fixed angular momentum while being illuminated by a linearly polarized plane light wave which has zero angular momentum (both spin and orbital).

The nature of such precessing states is best illustrated by varying the wavelength of the incident plane wave light beam, with the polarization unchanged. This progression is shown in Fig. $1c_1$-c_7. As we increase the wavelength, a rich vortex map emerges. In particular, we observe the approaching of two +1 charges (gray arrows, Fig. $1c_1$). A further small increase in wavelength first brings these charges together and finally repels them away from the high symmetry edge (Fig. $1c_3$). As the particle orientation leaves the high symmetry direction, no symmetry requires the net torque to be zero. This gives rise to a spinning attractors – a result of the avoided crossing of two +1 charges – and explains the unexpected precessing states identified in Fig 1b (for $\lambda = 1064nm$). Increasing the wavelength causes the spinning attractor to traverse the phase space, eventually returning (in a similar case of an avoided crossing) to the high symmetry direction (Fig. 1c$_7$).

Using dynamical equations of motion (including diffusion), we characterize the orientation space of the particle, and established the criteria for the stability of these special orientations to rotational diffusion. Though we distinguish these findings from the effects of topological photonics found in band structures and edge states, they are nevertheless built upon topological concepts and connect the interaction of light with nano- and micro-particles to a wide range of physical phenomena including electromagnetic bound states in the continuum in photonic crystals[7], topological defects, and general vortex physics[6]. In addition, by characterizing the complete phase space of the system, we showed that the wavelength of light can directly control the location of stable orientations and the size of the corresponding attractor basins. These results show that the combination of phase-space topology and particle asymmetry can be a powerful degree of freedom in designing nanoparticles for optimal external manipulation in a range of nano-optomechanical applications.

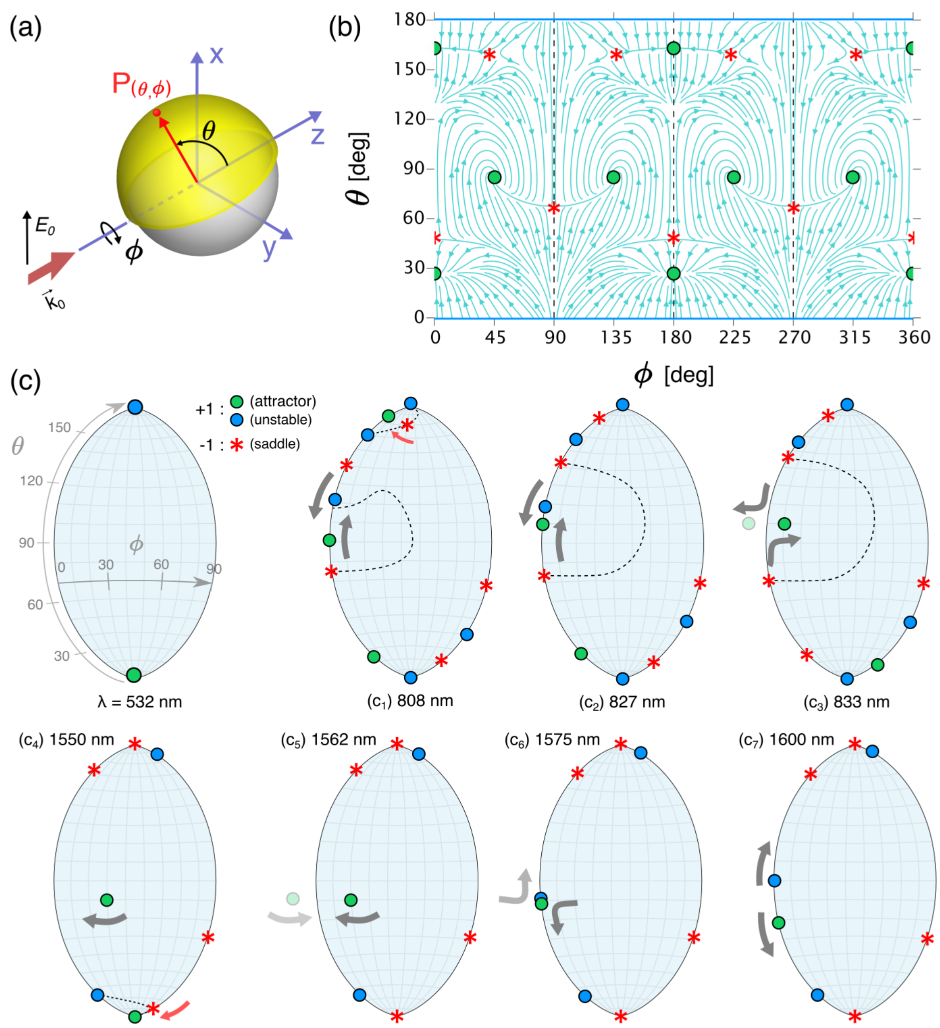

Fig.1. (a) A plane wave light beam impinges on a Janus particle (silica core, half-coated with gold). (b) Streamlines of the $\boldsymbol{N} = \boldsymbol{M}\times\boldsymbol{P}$ vector field indicate the evolution of the particle orientation in the damped regime. The vortices, denoting rotational equilibria, are shown as circles ($q = +1$) and stars ($q = -1$). (c) Varying the wavelength of light changes the vortex dynamics and gives rise to the emergence of spinning attractors as the result of an avoided crossing of two +1 charges (c$_2$, c$_6$).

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