Invited Paper

Rotational levitated optomechanics with birefringent particles

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ABSTRACT

Optomechanical systems have come to the fore in the last two decades. This field focuses upon the interaction of light with matter. It can lead to new approaches for precision measurement and the study of quantum physics. Light may both probe the system and mediate a reduction in energy of the system (cooling). In this domain, levitated optomechanics has emerged as an important direction which holds a mesoscopic particle in isolation from its surroundings. This reduces dissipation. This may be performed using optical trapping, though levitation through electrostatic or other means offer interesting alternative. Exploiting the rotational degree of freedom by spinning the trapped particle adds further value. By drawing on some of the key international work, including that from my group, I will review some of particular advances made in such rotational levitated optomechanics using birefringent particles.

Keywords: levitated optomechanics, optical tweezers, optical manipulation, spin angular momentum, rotation, birefringence, limit cycle

1. INTRODUCTION

In 2018 half of the Nobel Prize in physics was awarded to Arthur Ashkin for his conception of the field of optical trapping. In 1970 he published work on a dual beam configuration for trapping, with the famous realization of the single beam optical tweezers realized in 1986[1]. All geometries of trap have found major application but the single beam optical tweezers is the most widely used and has particularly led to major advances in single molecule biophysics[2]. One feature of optical trapping. is its ability to impact across really very different areas of science. This stretches from the afore-mentioned areas of biophysics (single molecules, cells, in vivo) to include non-equilibrium thermodynamics, colloidal dynamics, microrheology and the understanding and use of structured light fields amongst other areas.

Separately optomechanics has emerged as a very important area exploring the control of optical and mechanical degrees of freedom mediated by the radiation pressure force. This broad field encompasses numerous systems and maybe augmented with the inclusion of optical cavities. The motivation for this field arises from the fact that this interaction between light and matter may remove energy from the mechanical system leading to an exquisite sensing capability for studies of both quantum physics and gravity. Levitated optomechanics is a branch of this area the interaction between light and matter with the aim of performing unprecedented levels of precision measurement. The use of a trapped particle detached from its surroundings leads to reduced dissipation and therefore minimal decoherence. This promises a host of new physics including potentially testing and going beyond the Standard Model[3]. Optical fields can add in immense value to this area as the trapped particle is isolated from its environment as the trapping occurs within a vacuum environment. The trap may control the translational and rotational degrees of freedom. In addition, one may confine a plurality of trapped particles, potentially in a three-dimensional space. The levitated particle essentially acts as an underdamped, simple harmonic oscillator and its centre-of-mass motion may be cooled by external feedback[4]. The system may also be cooled to the quantum ground state[5,6,7] affording new opportunities for studying how mesoscopic particles behave in the quantum regime.

Rotation adds an interesting degree of freedom to the levitated optomechanics toolbox. The use of rotation can be instrumental in providing experimental tests for topics such as torque sensors and quantum friction[8]. Rotation for the trapped particle may be instigated by a number of methods: we can use absorption, though deleterious heating is an

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issue. More popularly the transfer of both spin and orbital angular momentum has proved powerful for rotation in optical traps in both liquid, air and vacuum. In liquid, this has led to a deeper understanding of structured light, optical angular momentum density and has been used for viscosity measurements. More broadly the angular momentum of light is having a major impact on its mechanical effect on matter[9]. In this article we focus on spin angular momentum which has proved to be a productive method so far for spinning objects in air and vacuum based trapping and thus rotational levitated optomechanics. Spin angular momentum has been transferred both to birefringent microspheres or nanoparticle and nanodumbbell structures. In contrast to the low rotation rates seen in liquid for vaterite microspheres (10s Hz to 100s of Hz), transfer of spin angular momentum to these microspheres has led to a very high rotation rates in vacuum due to the reduced viscosity. The initial demonstration of rotation in vacuum in this way showed rotation rates of up to 5 MHz[10]. The use of silica nanoparticles, including nanodumbells of the order of 100nm in diameter, rather than larger birefringent spheres, has advanced this to the gigahertz level[11,12] which may enable highly sensitive torque measurements. We focus particularly on birefringent particles here for rotational levitated optomechanics in this article. We now progress to explain further how spin angular momentum may be transferred from light to the object, where the anisotropy of the trapped particle leads to rotational motion.

2. BIREFRINGENT PARTICLES IN VACUUM

Birefringence is a well-known optical property that can alter the polarization property of an incident light beam. Indeed, this is the basis for retardation plates that are used ubiquitously in all photonics laboratories. Circularly polarized light is well known to possess spin angular momentum and when used as an optical trap, this angular momentum can be transferred to trapped mesoscopic birefringent particles that act as miniscule retardation plates[13,14]. The circularly polarized beam both traps the particle and sets it into rotation. The particle reaches a terminal angular velocity dictated by the rotational Stokes drag which is dependent upon the particle size and medium viscosity. In the overdamped case of optical tweezers in liquid, this is a route for measuring the viscosity of biologically relevant fluids[2]. In air and vacuum, the particle can be stably confined, even at low pressures where rotation rates in the MHz regime can be achieved. For all such studies, vaterite microspheres have emerged as a promising anisotropic birefringent material. This is a polymorph of calcium carbonate ($CaCO_3$) and can be synthesised to polycrystalline birefringent spheres with a hexagonal substructure of micron-sized dimensions.

Viscosity is not typically a function of surrounding gas pressure but in this instance, this changes at the point when the mean free path of the gas becomes comparable to particle size. At this point we see a fall in viscosity, which does become pressure dependent, and concomitant rise in rotation rates of the trapped object. In a circularly polarised trapping beam, vaterite crystals of a few microns in diameter can be rotated at rates of up to 5MHz in modest vacuum environments (10^{-3} mbar)[10]. Vaterite particles of similar size have been trapped and rotated at even lower pressures[15].

3. ADVANCED DYNAMICS OF BIREFRINGENT PARTICLES

Vaterite shows intriguing dynamics not only in circularly polarised light but also when it is placed in a linearly polarized beam. In this case the particle motion is governed by a nonsymmetric coupling between rotational and translational degrees of freedom. The non-conservative nature of the optical forces leads to interesting trajectories of particle motion. As the particle both translates and rotates, it follows as trajectory that returns it to its initial starting co-ordinates and an exchange of energy between the optical field and the particle occurs. We have to include the thermal forces present and as a consequence, some of these particle trajectories grow to become increasingly coherent. Energy can be transported from the trapping light field to the particle and subsequently dissipated into the surrounding gas. Intriguingly vaterite violates time-inversion symmetry[16] linking this behaviour to the concept of a photonic time crystal[17]. This coherent, stable motion of vaterite in a linearly polarised beam is of value in developing high precision sensors: When parametrically driven, these oscillating vaterite particles can exhibit an ultranarrow linewidth of 2.2 μHz and an ultrahigh mechanical quality factor in excess of 2×10^{8} [16].

When considering a dynamical system and its equilibrium point, oscillatory behaviour can be observed in the stability when varying a critical parameter and may the result in a Hopf bifurcation[18]. A limit cycle around this point of equilibrium may appear: this is a closed trajectory in phase space and may be considered as an asymptotic limit of adjacent oscillatory trajectories in the system. These cycles have been of interest in numerous dynamical systems including in the study of action potentials in neuroscience, glycolosis and electrical circuits showing nonlinearity.

In the field of levitated optomechanics, we have recently seen such limit cycles in the particle dynamics. In this instance, the bifurcation parameter is the viscosity of the surrounding environment and a Hopf bifurcation can result at a critical point. At such a bifurcation the trapping point loses its stability and limit cycles emerge whose amplitude grows with decreasing viscosity (our critical parameter). In essence, the nonconservative forces exponentially intensify small perturbations inherent within the system. These considerations have led to a more detailed understanding of why a rotating vaterite microparticle may remain stable in a circularly polarized optical trap in vacuum whereas silica particles on equivalent size may be ejected[19,20]. The underlying physics is based on the role of azimuthal spin forces arising from the trapping beam. These may drive the particle's centre-of-mass motion past equilibrium. For the case of vaterite which is birefringent, the force is orientation dependent and can even exert itself such that it opposes the incident momentum. As vaterite spins at high rates, the effective (i.e. rotationally averaged) azimuthal spin force is arrested to a high degree. Overall, this leads to an increase the trap stability for vaterite relative to that of an equivalent sized isotropic microsphere, such as silica[20]. The behaviour of vaterite contrasted with the behaviour of silica particles that underwent significantly larger orbits in their limit cycles and were expelled from the trap. In this study, not only were we able to observe limit cycles of the vaterite motion, but we could cool them using parametric feedback cooling[4] to millikelvin temperatures. This has potential applications for studies of observing limit cycle oscillations in the quantum regime.

4. MULTIPLE BIREFRINGENT PARTICLES IN VACUUM

As levitated optomechanics has advanced researchers are now seeking to trap and manipulate multiple particles in tandem in vacuum. There is a desire to achieve simultaneous cooling of multiple trapped particles. By drawing inspiration from experiments with cold neutral atoms and atomic ions, where an actively cooled object can be used to sympathetically cool another we recently embarked on sympathetic cooling for mesoscopic particles. Recently, sympathetic cooling of two charged (non-birefringent) particles held in a Paul trap was described[21]. Coulomb forces provide strong interactions between particles, they may also couple strongly to the environment. An optical approach would circumvent this issue as well as lending itself to optical cooling of the centre-of-mass motion. To this end, in our recent studies we confined two birefringent trapped particles with control over the inter-particle separation. In this case, whilst holding two particles, we performed parametric feedback cooling upon one of them while observing the behaviour of the adjacent trapped particle[22]. Two such rotating microparticles trapped in close proximity may exhibit optical binding: This is an interaction mediated by light scattering whose strength is dependent on the inter-particle separation[23]. More broadly, such ‘‘optically bound matter’’ may lead to self-organized systems[23,24]. In our case, this showed a purely optical route for sympathetic cooling wherein both the directly cooled particle and the adjacent trapped particle achieved temperatures below 1K[22].

5. CONCLUSIONS AND FUTURE OUTLOOK

Levitated optomechanics has emerged as a powerful platform for studying quantum physics with potentially "high" mass particles and promises to shed new light on the classical-quantum interface as well as develop exquisite new sensors[3]. With the interest in multiple particles, potential studies of entanglement and topological studies are foreseeable based on the varying and nonreciprocal optical interactions between levitated objects[25]. Rotation of particles in vacuum, including birefringent particles, has made an important contribution in this field. This has led to a new understanding of the light-matter interaction, creating some of the fastest man-made objects on Earth, the observation of cooled limit cycles, generated advanced sensing capabilities and laid the groundwork to observe quantum friction and quantum synchronisation.

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