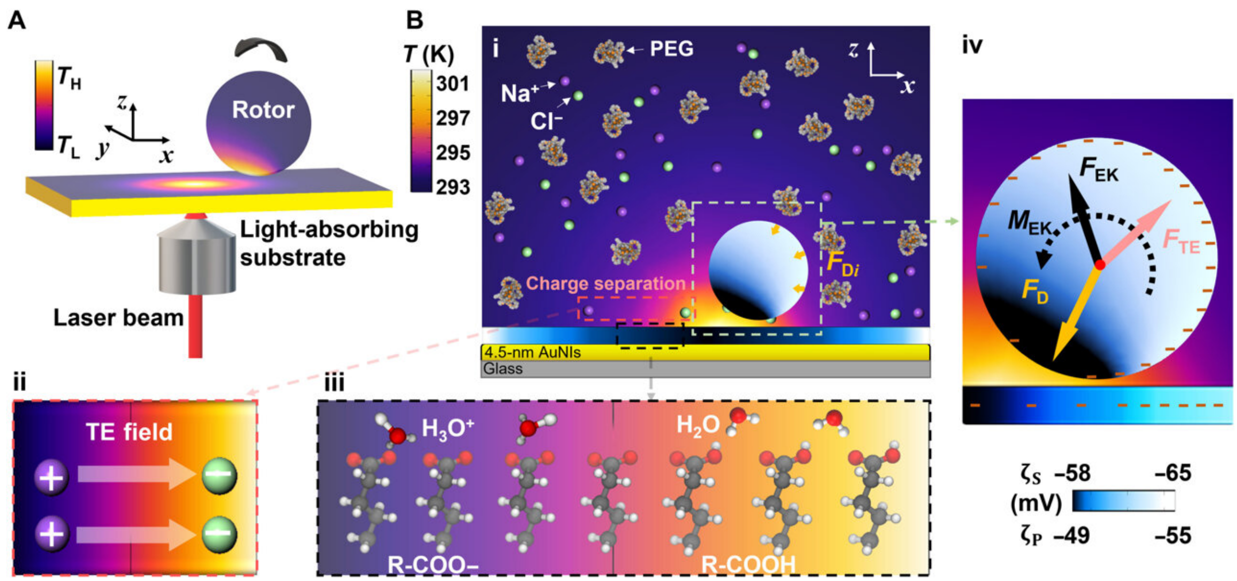
Universal optothermal micro/nanoscale rotors

July 1 2022, by Thamarasee Jeewandara



Working mechanism of light-driven out-of-plane rotation of micro/nanoscale rotors. (A) A simplified schematic illustrating the experimental setup and operation for OTER of micro/nanoparticles. (B) Working mechanism of OTER: (i) In the nonuniform temperature field, Na+ and Cl− ions and PEG molecules diffuse to the cold region. Yellow arrows indicate discrete depletion forces (FDi) acting on the rotor, which lead to a total depletion force (FD) in (iv). (ii) A TE field is created by the separation Na+ and Cl− ions owing to their different thermodiffusion coefficients. Gray arrows indicate the direction of the TE field. (iii) The temperature field also affects the dissociation of carboxylic function groups, thus the surface charges on the substrate. (iv) Optothermal forces and torque on the rotor: In the steady state, the gradient distribution of PEG molecules generates an attractive depletion force (FD) on the particle. A repulsive force (FTE) is generated from the TE field. A thermo-electrokinetic force (FEK) is from the 11-mercaptoundecanoic acid–coated plasmonic substrate with nonuniform thermo-responsive surface charge (from −65 to −58 mV). The surface charge of most particles also varies with the temperature due to their ionized acid groups on the surface. For instance, the local surface charge of a carboxylic functionalized polystyrene (PS) particle ranges from −55 to −49 mV. The "−" symbols indicate the temperature-dependent distributions of negative charges on the surface of the particle and substrate. The light-irradiated regimes with the higher temperature feature the lower charge density. A net torque, MEK, can be generated on the particle at the certain position where a balance is reached among FD, FTE, and FEK. The optical power is 78.4 μW. The red dot marks the centroid of the particle. Credit: *Science Advances* (2022). DOI: 10.1126/sciadv.abn8498

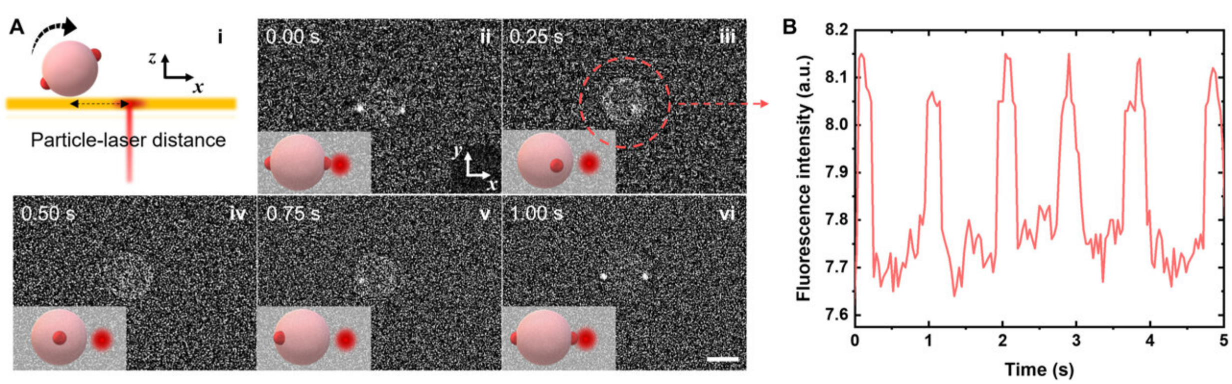
The fundamental rotation of micro and nano-objects is crucial for the functionality of micro and nanorobotics, as well as three-dimensional imaging and lab-on-a-chip systems. These optical rotation methods can function fuel-free and remotely, and are therefore better suited for experiments, while current methods require laser beams with designed intensity profiles or objects with sophisticated shapes. These requirements are challenging for simpler optical setups with light-driven rotation of a variety of objects, including biological cells.

In a new report now published in *Science Advances*, Hongru Ding and a research team in engineering and materials science at the University of Texas at Austin, U.S., developed a universal approach for the out-of-plane rotation of various objects based on an arbitrary low-power laser beam. The scientists positioned the laser source away from the objects to reduce optical damage from direct illumination and combined the rotation mechanism via optothermal coupling with rigorous experiments, coupled to multiscale simulations. The general applicability and biocompatibility of the universal light-driven rotation platform is instrumental for a range of engineering and scientific applications.

Opto-thermoelectric rotation

By regulating the rotation of micro- and nanoscale objects, researchers have proven effective functionalities across precise nano surgery, vacuum friction and microfluidic flow control. Light-driven micro- and nanorotors are a promising fuel-free option, although such devices have remained challenging to build on because they need simpler and low-power optics to achieve light-driven rotation. Ding et al proposed opto-thermoelectric rotation (OTER) in this new work, to generate electrokinetic force, depletion force and electric force based on simple and low-power optics.

The research team achieved the rotation of spherically symmetric and homogenous micro and nanoparticles via a single Gaussian laser beam positioned away from the rotors, to reduce the damage caused by direct light illumination. By combining the experiments with multiscale simulations they revealed optothermal rotation via electrokinetic interactions between micro- and nanoparticles, and the substrate with thermo-responsive surface charge. As proof of concept, the team showed how the OTER strategy could rotate objects of different sizes, materials and shapes to regulate the incident light and surface chemistry.

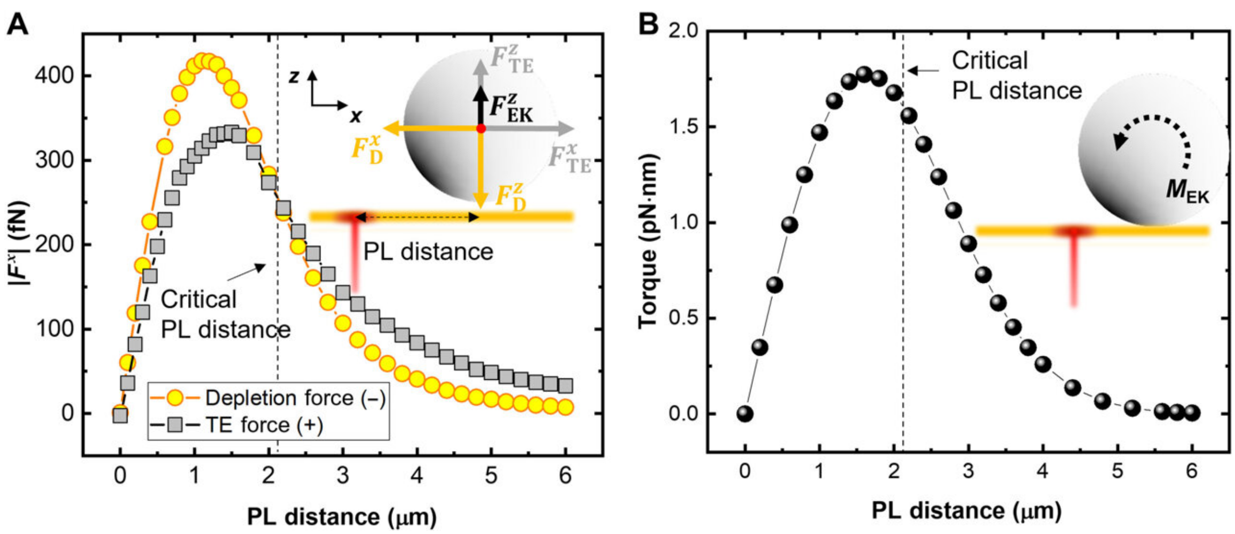


In situ optical characterization of light-driven out-of-plane rotation of a spherical microparticle. (A) (i) Schematic illustration of the out-of-plane rotation of a spherical PS particle (i.e., rotor) around an axis parallel to the substrate. The laser beam, which propagates perpendicular to the substrate, heats the region of the substrate near the particle. The particle is suspended in a 5% PEG/5% PBS solution covering the substrate. The two red beads are fluorescent nanoparticles for the visualization of the orientation change of the rotor under an epifluorescence microscope. The focal plane of the optical microscope is around 1 μm above the substrate. (ii to vi) Successive fluorescence images of a rotating 2.8-μm PS particle. Insets are schematic illustrations of the orientations of the rotor with two fluorescent nanoparticles as markers. Experimentally, two 40-nm (in diameter) fluorescent PS nanoparticles were attached to the rotor through streptavidin-biotin binding. The red point on the right side of the rotor marks the position of the driving laser beam. Scale bar, 2 μm. (B) Time-dependent fluorescence intensity measured from the rotor and its surroundings as marked in (iii) of (A). The out-of-plane rotation of the rotor leads to the periodic fluctuation of the fluorescence intensity. The intensity peaks appear when the rotation leads to both fluorescent nanoparticles in the focal plane of the optical microscope. a.u., arbitrary units. Credit: *Science Advances* (2022). DOI: 10.1126/sciadv.abn8498

Mechanism of action of universal light-driven rotors

The researchers illustrated the experimental setup and working mechanism of OTER—where a laser beam generated optothermal forces on the particles. Ding et al tailored the net force and torque via the laser power and laser particle distance for out-of-plane rotation of the micro and nano-objects. They then directed the laser beam to a light-absorbing substrate such as a porous gold film to establish a tailorable temperature field in microseconds.

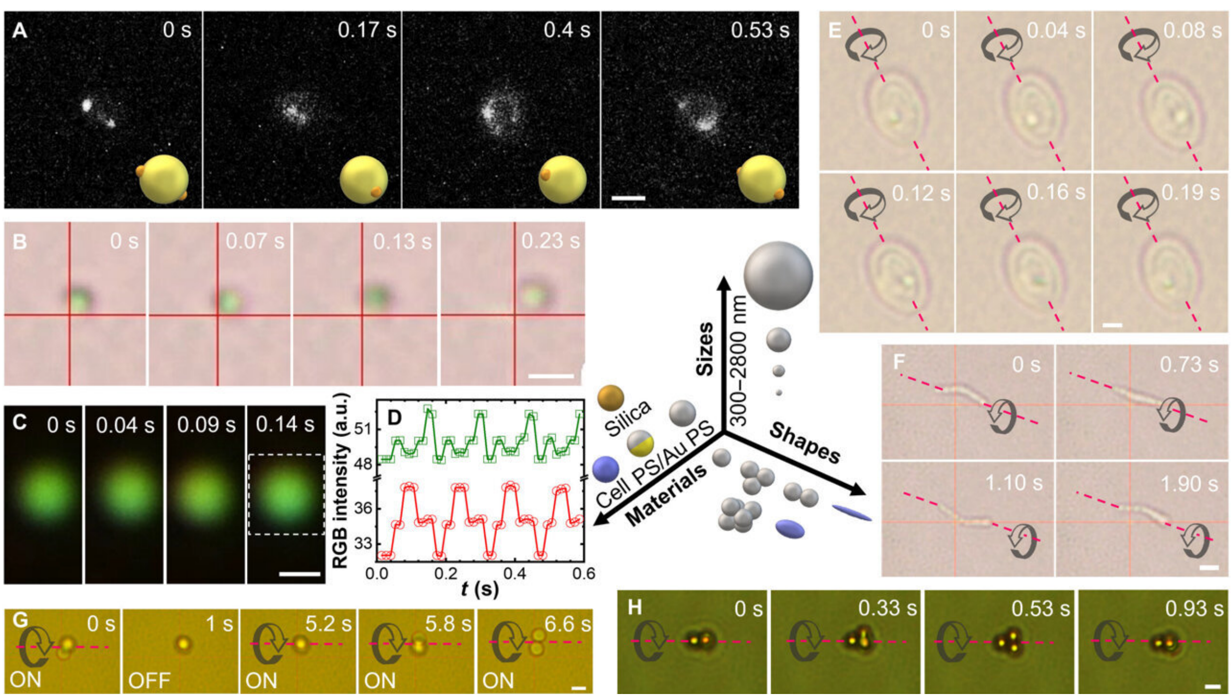
In order to optothermally generate the forces and torque required for stable rotor rotation, Ding et al added polyethylene glycol (PEG) molecules, and phosphate buffered saline into water and functionalized the substrate with carboxylic acid–terminated alkanethiol monolayers. Upon laser illumination, the team achieved a temperature rise to create a thermoelectric field in the presence of ions to drive thermo-electrophoresis of the charged rotor. They explored the surface charge gradient on the substrate to then provide an optothermally tunable electrokinetic force known as the thermoelectric force.



Quantitative analysis and modeling of OTER of single spherical rotors. (A) Simulated magnitudes of depletion force and TE force along the x axis on a 2.8-μm PS particle as a function of PL distance in a 5% PEG/5% PBS solution. As marked by the dashed line, a balance between depletion force and TE force (i.e., zero net force) is reached at a critical PL distance of 2.1 μm. Inset: Schematic illustration of force analysis for the light-driven rotor in the xz plane. The red and white circles represent the laser spot and the rotor, respectively. (B) Simulated torque (MEK) acting on the rotor as a function of PL distance. The torque at the critical PL distance (2.1 μm) is around 1.6 pN·nm. Credit: *Science Advances* (2022). DOI: 10.1126/sciadv.abn8498

Characterizing and modeling opto-thermoelectric rotation

Ding et al studied the rotation behavior of light-driven rotors by using optical microscopy. They acquired better examination of rotation behavior by labeling a polystyrene microparticle with two fluorescent nano-beads with streptavidin-biotin binding for the out-of-plane rotation of the particle driven by a laser. The observed off-axis rotation protected the delicate rotors, including live cells from damage caused by high power optical illumination. The team further incorporated finite element analysis, molecular dynamics, and finite difference time domain simulations to analyze the working forces of opto-thermoelectric rotors. The scientists calculated the opto-thermal forces and torques acting on the rotor as a function of particle-laser distance and conducted a series of experiments and simulations to understand the impact of electrokinetic force, depletion force and thermoelectric force by tuning the surface charge of the substrate and components of the solution.



General applicability of OTER to a variety of rotors with diverse shapes, sizes, and materials. (A) Successive fluorescence images of a rotating 1-µm PS particle labeled by fluorescent nanoparticles for the rotation visualization. (B) Successive optical images of a rotating 500-nm PS/Au Janus particle. (C) Successive dark-field optical images of a rotating 300-nm PS/Au Janus particle. (D) Real-time RGB intensity of the dark-field optical images of the Janus particle. The white dash rectangle in (C) marks the selected area from which the RGB intensity is recorded. (E) Successive optical images of a rotating yeast cell. (F) Successive optical images of a rotating B. subtilis. (G) Successive optical images of a rotating dimer composed of two 2-μm silica particles. “ON” and “OFF” indicate that the laser beam is turned on and off, respectively. (H) Successive optical images of a rotating trimer composed of three 1-μm PS particles. The dash lines and black arrows represent the rotation axes and directions, respectively. Scale bars, 1 μm (A, B, E, F, and H), 500 nm (C), and 2 μm (G). Solutions, 15% PEG/5% PBS (A to C, G, and H) and 5% PEG/5% PBS (E and F). Credit: *Science Advances* (2022). DOI: 10.1126/sciadv.abn8498

Applications of OTER

Ding et al showed the impact of OTER on biological cells and synthetic particles of diverse materials, sizes and shapes. They displayed the rotation of nanoscale rotors such as polystyrene-gold Janus particles by using dark-field optical microscopy. The OTER method is also applicable to live cells including live strains of fungi, bacteria and even human cells in cell culture media containing ions. Additionally, the method is suited for rotors with complex architectures including out-of-plane rotation of particle dimers, trimers, and hexamers. Using the method, Ding et al envision accurate regulation of the rotor and laser beam to accomplish 3D profiling of biological cells and synthetic particles of high resolution.

Outlook

In this way, Hongru Ding and colleagues harnessed thermo-diffusion of ions and molecules in solutions to develop a thermoresponsive charge at solid-liquid interfaces. The opto-thermoelectric strategy allowed the rotation of micro- and nanoscale objects in a liquid environment with simple and low-power optics. The method is superior to existing conventional techniques with universal applicability for image sensing and biomedical applications. The team expect the optothermal approach to play a significant role in in vitro biological studies to rotate cells and synthetic particles in native biofluids with ions and biomolecules.

More information: Hongru Ding et al, Universal optothermal micro/nanoscale rotors, *Science Advances* (2022). DOI: 10.1126/sciadv.abn8498

Jonghoon Ahn et al, Ultrasensitive torque detection with an optically levitated nanorotor, *Nature Nanotechnology* (2020). DOI: 10.1038/s41565-019-0605-9