

Dynamics of microparticle launching and loading into optical traps

KWAN SEOB PARK,^{1,2} KIANA MALMIR,² GLENN E. HOLLAND,²
MARTIN Y. SOHN,^{2,*} AND THOMAS W. LEBRUN^{2,3} 

¹Theiss Research, La Jolla, CA 92037, USA

²Physical Measurement Laboratory, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA

³thomas.lebrun@nist.gov

*martin.sohn@nist.gov

Abstract: Levitated optomechanics is opening new opportunities for quantum measurement in mesoscopic systems and for understanding the transition between quantum and classical mechanics. But loading microparticles into optical traps for measurements in vacuum remains an obstacle to the development of the field, in part because the process of launching particles so that they can be efficiently trapped remains poorly understood. We measure the dynamics of particle motion from vibrational excitation and launch from a surface to trapping in air. We demonstrate the direction of launch from a resonantly vibrating glass coverslip to be highly anisotropic and the measured escape velocity of tens to hundreds of millimeters per second to be insensitive to the amplitude of vibrational excitation. For a single particle launched repeatedly, escape velocities less than 50 mm per second are trapped with the highest probability. Trajectories from the launch point to the trap are found to follow a roughly two-step process in air: rapid deceleration due to drag, followed by drift into the trapping region that is accurately modeled by the Stokes-Einstein relation. These results illuminate the launch process in air, supporting the development of controlled launching of microparticles to enable application in a vacuum. This also enables selecting particles for trapping to optimize characteristics such as shape or Mie spectra, as well as repeated measurement of single particles to ensure reproducibility.

© 2026 Optica Publishing Group under the terms of the [Optica Open Access Publishing Agreement](#)

1. Introduction

Trapping and manipulating particles using focused optical beams, also called single beam gradient traps or optical tweezers, has become widely used for diverse experiments in biophysics, colloid science and also more recently in fundamental research in quantum physics [1–5]. Quantum state preparation in nanoscale or microscale particles can enable exploration of quantum phenomena in mesoscopic systems, providing insights into the transition from classical to quantum mechanics.

However, loading particles into traps in air or vacuum remains an obstacle to progress in the field. Current approaches frequently require air to damp particle motion, requiring further pumping during trapping to achieve vacuum operation. The ability to select particles based on size or morphology and to repeatably launch and trap a single particle is also frequently absent, potentially limiting reproducibility of measurements. Some processes that would be used to probe trapped particles, such as Mie scattering, are extremely sensitive to particle shape and size, highlighting the interest of selecting particles for study.

Here we report continuous measurement of particle motion demonstrating three phases of launch from a surface prior to trapping: vibrational excitation and release, deceleration due to Stokes' drag, and drift to a trap under optical forces. The launch direction is found to be highly asymmetric, with the average direction and launch velocity of ≈ 80 mm/s. The launch velocity is also insensitive to the vibrational amplitude of the launcher. The measurements are repeated multiple times for a particle to distinguish variations in launch conditions. Data after launch also

demonstrates rapid deceleration consistent with Stokes' law followed by drift to the trap region that is well described by particle mobility under the optical force. This work is intended to enable the development of controlled launching systems to allow repeatable launching in vacuum of particles selected for size, shape, or other characteristics required for applications in quantum measurement.

This work focuses on particle launching from a vibrating surface as originally reported by Ashkin [6] and applied by multiple groups [7–10]. Particles are dispersed on a glass coverslip that is vibrationally excited to overcome the force of adhesion and free the particles from the carrier. However, a range of launching methods have been reported. Nebulization techniques that spray particles encapsulated within liquid droplets towards the trap focus are widely used [11,12]. These can have the advantage of simplicity, though load-lock systems which separate the particle launching area from the main trap region may be required to limit contamination [13,14]. Vibrational launching methods based on Laser-Induced Acoustic Desorption (LIAD) [15–18] and Piezoelectric Transducer Excitation (PTE) [6–10,19–27] also offer simplicity as well as reduced contamination. Laser-Induced Acoustic Desorption can launch smaller particles with high speed [10]; however, in high-vacuum conditions the greater speed poses a potential drawback as insufficient energy dissipation may lead to failures in particle trapping. Despite this challenge, LIAD has been successfully used for the direct loading of particles into traps within high vacuum environments through the utilization of Paul traps and temporal adjustments of trap potentials [16]. Piezoelectric Transducer Excitation, with a lower launch speed compared to LIAD, reduces the energy dissipation that needs to be added in high vacuum environments. Successful loading has been achieved by using slowing beams for energy dissipation [9] and thin-film coatings with low surface energy on the substrate to reduce the stiction force [10]. Despite these efforts, loading methods often exhibit randomness. While consistent trapping of individual microparticles in air using piezoelectric excitation is well known, the details of the process remain unclear [25]. Understanding the launching mechanism is important for developing controlled launching in air and vacuum, and for the ability to trap particles with selected characteristics from within a population on a substrate.

2. Experiments

2.1. *Measuring particle motion during loading into the trap at atmospheric pressure*

To observe the particle trajectory during launch, two laser beams were used (Fig. 1): a measurement beam (635 nm wavelength) focused on the surface of the glass slide and the trap beam (1064 nm) focused approximately 60 μm above the surface. The beams are coaxial and directed vertically, defining the z axis and the principal optical axis.

Each beam is coupled to a separate quadrant photodetector, which measures the radial and axial displacement of the particle from the beam focus. The measurements cover a range of $\pm 7.5 \mu\text{m}$ radially and up to 120 μm along the z -axis. This measurement range is much larger than the excursions typical for trapped particles. As a result, we use the detection signals with the particle far from focus where the detector response can become nonlinear, and cross coupling in the response to nominally orthogonal degrees of freedom can be observed. These errors are measured and compensated to first order where the data is used for quantitative measurements, as described in the [Supplement 1](#). While data is collected from both detectors for the entire trajectory, we concentrate on launch using measurements with the red beam focused at the launcher surface. Simulations were also used to analyze the drift region between the foci of the measurement and trapping beams where measurement errors increase.

We consider the loading process as divided into three stages illustrated in Fig. 1. In the first stage, the vibration of the glass slide frees the particle from the surface. Subsequently, the initial kinetic energy of the particle is reduced to nearly thermal energies due to air friction, after which the particle drifts into the trap driven by the optical force of the trap beam.

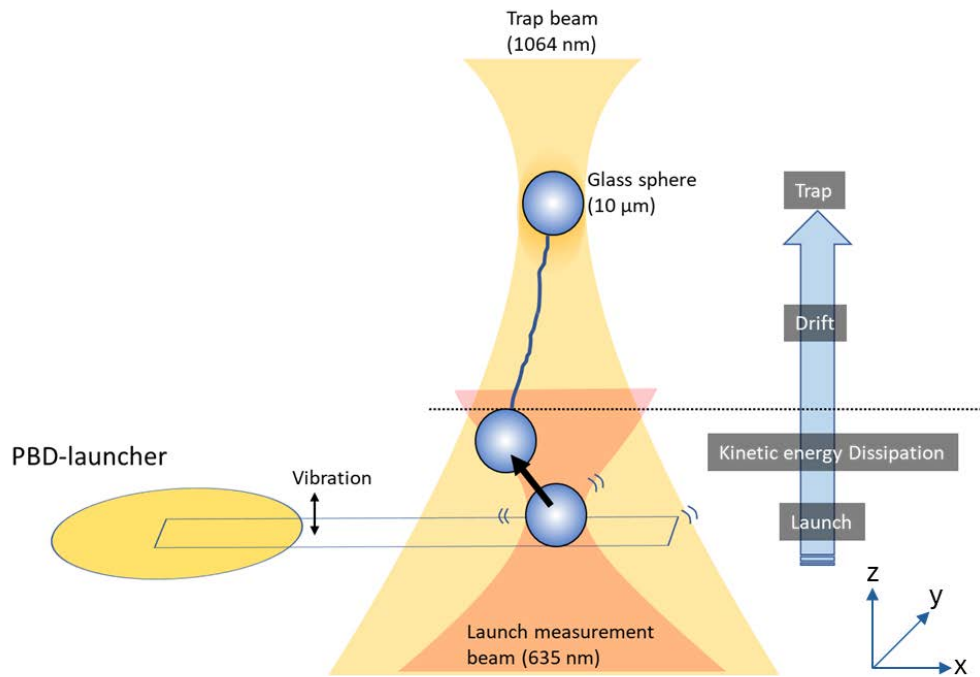


Fig. 1. Vibrational launching mechanism for particle loading into trap by a piezo bimorph device (PBD).

2.2. Optical tweezer setup

For particle trapping, a 1064 nm laser beam, represented as a yellow line in Fig. 2, was focused onto the trapping region above the launcher surface through an aspheric lens with a numerical aperture (NA) of 0.41 located below the glass slide of the particle launcher. The low range of NA used in this instrument allows operation as a single-beam gradient trap or a levitation trap. We don't distinguish here, because the focus is on launch and drift into the trap. Simultaneously, a 635 nm laser beam, indicated as a red line in Fig. 2, was focused on the surface of the glass slide approximately 60 μm below the trapping region to monitor the particle movement during launch. Both the 1064 nm and 635 nm beams scattered from the particles were collected by the aspheric lens located above the glass slide of the particle launcher. These beams were then separated by a dichroic mirror. The 635 nm beam is projected onto a Quadrant Photodiode (QPD) and a photodetector (PD), while the 1064 nm beam is also directed onto a QPD (see Fig. 2). The two QPDs measured the x and y displacement of the particles at the glass surface and trapping region using back focal plane detection [28]. Movement of the particle in x and y changes the position of the beam on the QPD, while z motion changes the intensity of the beam on the photodetector. A white light source (WL) and complementary Metal-Oxide-Semiconductor (CMOS) camera was used for imaging particles on the surface. Glass spheres [Duke Standards, Dry Borosilicate Glass Microspheres 9010 (see Disclaimer section), $(9.9 \pm 1.1) \mu\text{m}$ diameter] were used for trapping and launched in air by the particle launcher, which consists of a glass slide bonded to a piezo bimorph device (PBD).

2.3. Vibrational launcher

The PBD-launcher [PUI Audio, Inc., DigiKey PN: 668-ABLF2746B-ND (see Disclaimer section)] is briefly described here and will be the subject of a separate publication [Holland, *et. al.* to be published]. The piezo bimorph induces vibrations in the glass slide through an applied AC

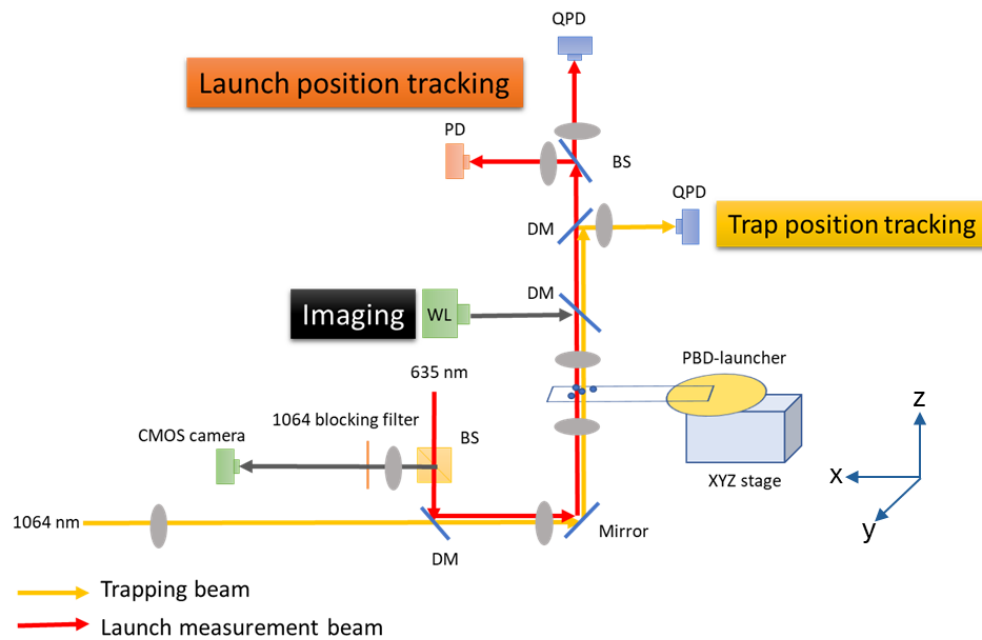


Fig. 2. Schematic of the experimental setup. PD: photodetector, BS: beam splitter, DM: dichroic mirror, QPD: quadrant photodetector, WL: white light source.

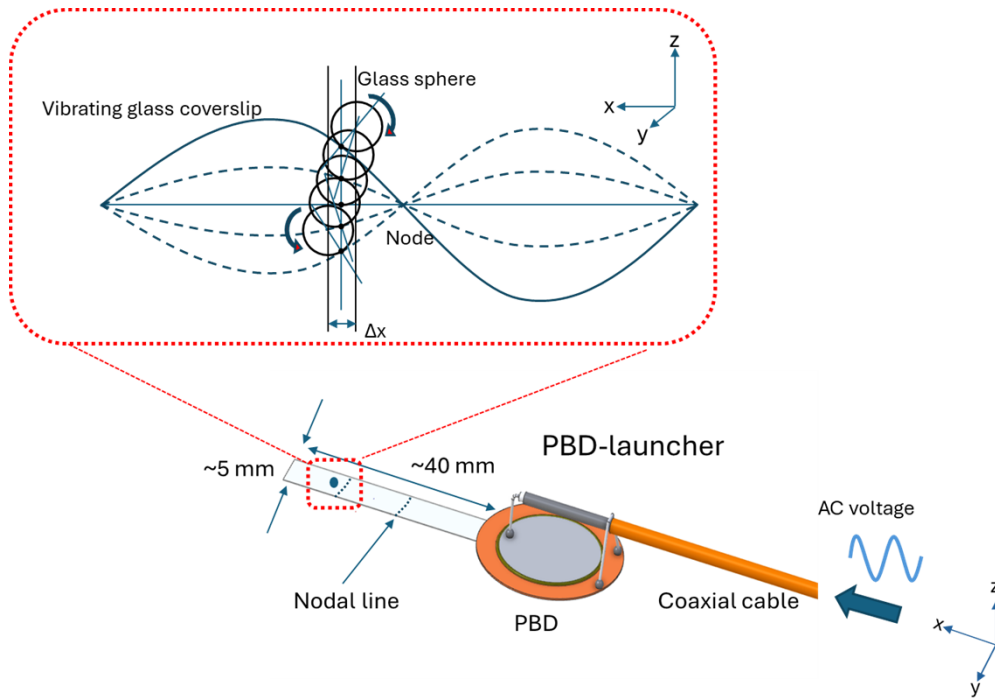


Fig. 3. Illustration of the launcher and the vibrating glass substrate. The inset shows that a vibrational mode of the glass slide in general gives motion in both z and x or y. The actual modal pattern of the glass slide is not measured here.

voltage. The vibrating glass slide exhibits multiple resonances and the frequency and the modal patterns of each depend on the slide's shape and size. To identify the resonant frequencies, we applied excitation voltages of ≈ 3.4 V peak to peak, ranging from 1 kHz to 100 kHz, selecting the ≈ 31 kHz frequency due to its pronounced vibrations of the glass slide. Subsequently, this frequency was used for excitation. When the excitation signal is applied to the PBD, particles on the surface vibrate driven by the motion of the launcher surface. As depicted in the inset of Fig. 3, this motion generates both vertical and horizontal particle motion even in firmly adhered particles. Depending on a particle's position relative to a node, varying degrees of horizontal and vertical motion are expected while the particle is on the surface. Although both square and sine waves can serve as excitation signals, a square wave was found more effective for launching.

Particles were launched using the following procedure. The particles were drawn from the storage container using a capillary tube and scattered onto the launcher's uncoated glass coverslip. A particle is selected using the CMOS camera and moved into the red beam focus using the XYZ stage connected to the launcher. The PBD was excited with a square wave at ≈ 31 kHz and ≈ 1 V amplitude to study particles bound to the surface or ≈ 5 V to launch particles. The QPD signal in the red beam channel is monitored during excitation to measure launcher dynamics and particle launch. After particles are trapped and measured, they are dropped back to the surface by blanking the trapping beam and can be relaunched. All of the data presented here is taken with the same particle [7,29]. A second particle was used for the measurements presented in the Supplement 1.

3. Results and discussion

3.1. Particle motion on the surface

Figure 4 shows the motion of a particle on the glass surface during weak vibrational excitation to prevent particle detachment. It demonstrates two different cases: a particle firmly attached to the launcher that shows the launcher dynamics and a particle whose adhesion to the surface is disrupted during excitation, making it a good candidate for launching. In Fig. 4(a), the particle is firmly stuck to the launcher. The excitation signal (grey curve) is applied in the time interval between 2 ms and 5 ms, during which particle vibration in the x direction increases to more than 500 nm, while vibration in the y direction also increases but remains smaller. The x and y amplitudes will depend on the mode of the glass slide excited and the position of the particle relative to the nodes and antinodes of the mode. Calibration of the particle position measurement was performed by measuring the displacement of a particle adhered to the launcher slide with no excitation while the slide's position is scanned in x, y and z. Displacement values for a 20 μm shift of the slide are taken from the closed-loop positioning system with a relative uncertainty of 5% as given by the manufacturer.

The ring-up and ring-down signals in Fig. 4(a) correspond to the launcher's movement, showing the time required for the launcher to store vibrational energy. The quality factor (Q) of the system was determined to be 280 by averaging the Q calculated from the ring up and ring down curves.

The magnitude of the ring down signal was fitted using the function $D(t) = a \cdot e^{-\left(\frac{\omega}{2Q}\right) \cdot (t-t_{\text{end}})}$, where $D(t)$ represents the amplitude of the vibration at time t , a is the initial amplitude determined from the maximum value of the ring-down signal, ω represents the frequency, and Q is the quality factor. The parameters t_{start} and t_{end} denote the beginning and the end of the excitation signal, respectively. These are not treated as free parameters in the fitting process but are set to known values determined by the timing of the data acquisition. An example of this fit is shown in Fig. 4(a). For validation, the ring up signal was also fitted using $D(t) = a \cdot (1 - e^{-\left(\frac{\omega}{2Q}\right) \cdot (t-t_{\text{start}})})$. The standard deviation of the individual position measurements before excitation is 8 nm in x and y. The imprecision in the z-direction is much larger, almost 600 nm, due to the increased range and reduced sensitivity for axial versus radial detection in this geometry. As a result, the

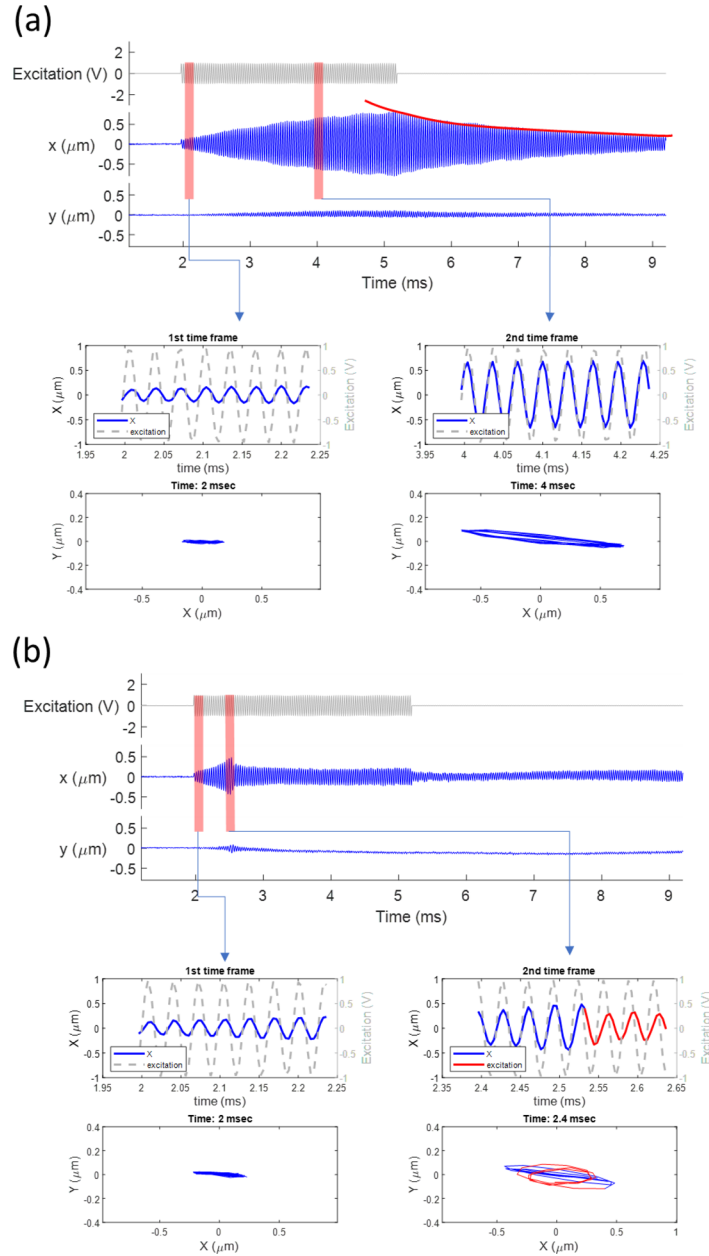


Fig. 4. Measured particle motion on the vibrating glass substrate. (a) The measured displacement of the particle, which is firmly stuck on the glass substrate. (b) The measured displacement of the particle, which is more weakly attached to the glass substrate.

signal-to-noise ratio for motion in the z-direction remains limited for small oscillations, and z-data is not used. The expanded plots show that the vibration of the particle remains in phase with the excitation signal, indicating that the particle remains firmly adhered to the substrate.

In contrast to Fig. 4(a), where the particle rings up gradually and continuously for 3 ms, the particle in Fig. 4(b) increases its amplitude of vibration more quickly. In particular, the vibrational amplitude grows at an increasing rate until 500 μs , at which point the amplitude of

vibration becomes strong enough to disrupt its adhesion to the substrate, though the particle remains attached. This is demonstrated by both the abrupt decrease in the apparent amplitude of the motion and the fact that the particle motion changes phase with respect to the excitation. The two measured particles were positioned several tens of micrometers apart, but apart from the apparent change of the adhesion were otherwise observed to vibrate in a similar manner. For small oscillations modeled by a harmonic oscillator, the observed change in amplitude and phase would indicate that the stiffness of the surface adhesion force had changed and that the particle is no longer firmly attached to the surface but is moving relative to it bound by an adhesive connection characterized by a natural frequency different from the original bond before it was disrupted. This behavior can be used to distinguish potential candidates for launching.

3.2. Launch and initial velocity

Figure 5 illustrates the complete trajectory of a particle measured from launch to trapping using the 635 nm laser. The trajectory shows launch from the glass surface, velocity damping due to Stokes' drag, and drift in the optical field into the trap. When the particle is launched, it initially experiences a high velocity, which is then reduced by Stokes' drag force, $F_d = 6\pi\eta rv$, where η is the dynamic viscosity of the medium, r is the radius of the particle, and v is the velocity. As the initial velocity decreases, the particle drifts into the optical trap due to the gradient forces of the optical field. This process demonstrates the interplay between the launch dynamics, the damping effects of air resistance, and the optical trapping forces. The noisy particle displacement data are filtered using a moving average to reduce noise in the discrete derivatives of position (see Supplement 1), so the vibration of the particle before launch is not visible. Also, in contrast to the previous figure, Fig. 5 displays both axial and radial motion. Note that the motion away from the optical axis is less than a particle radius while the vertical displacement is a few diameters. There are some obvious anomalies in the drift region, for example where the particle axial position decreases around 10 μ s. The instrumentation here is optimized for measurement of launch velocity near the surface and no attempt has been made to correct the drift data as it is not used for launch analysis.

Figure 5(a) shows the excitation signal applied to the launcher. The amplitude is higher to induce launch, but otherwise the signal remains a square wave at 31 kHz with a 50% duty cycle. After the particle is propelled from the vibrating glass, the trajectory is measured using the red beam (635 nm) until the particle is trapped (Fig. 5(c)). Three points in time are used to describe the trajectory: the launch point, the thermalization time, and entry into the trap Fig. 5(b,c). The launch point is defined as the maximum radial velocity, marked by a vertical dashed line labeled 'A' in Fig. 5(b). Measured launch velocities with successful trapping were typically less than 50 mm/s, and particles with diameters of $(9.9 \pm 1) \mu$ m moved less than 2 μ m before reaching the launch velocity. Radial velocity is used to determine the launch point because of increased sensitivity to small displacements and better repeatability.

After launch, the particle loses kinetic energy due to damping in air, eventually reaching thermal energies. We define the damping time as the period required for the radial velocity to decrease to $1/e$ or 37% of the radial launch velocity. The damping time is independent of the initial velocity and indicated by a dashed line labeled 'B' in Fig. 5(b). We also refer the thermalization time as the period required for the radial kinetic energy to decrease to within 10% of $\frac{1}{2}kT$. The thermalization time increases with launch velocity and represents the point at which the optical force begins to dominate the particle trajectory.

After thermalization, the optical force drives drift of the particle into the trap. Figure 5(c) shows the particle's entry into the trapping volume, labeled by a dashed line labeled 'C'. Figures 5(d,e) provide an enlarged view of the shaded areas in Fig. 5(b,c), respectively. The trajectory measured by the red beam during drift into the trap is shown for completeness, but it not used for the analysis here. It includes nonlinearities in response and cross coupling between radial and axial

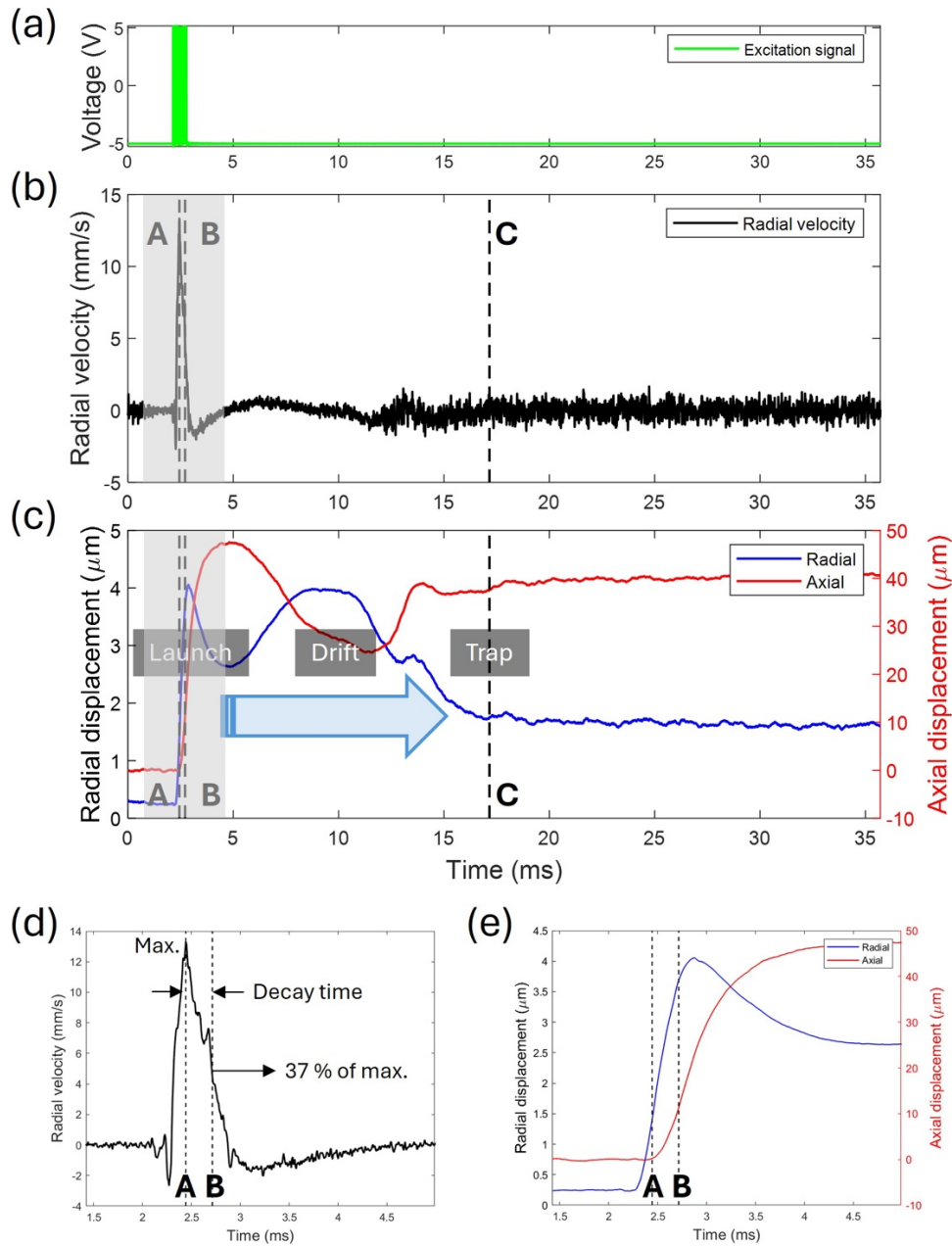


Fig. 5. Measured particle trajectories during loading into trap. (a) Excitation signal applied to the PBD. (b) Radial velocity calculated from trajectories. (c) The displacement of the particle is represented by the values along the lateral and axial axes (cylindrical coordinates). The launch velocity is defined by the maximum radial velocity. (d,e) Magnified signals showing the shaded areas in (b,c). The dashed lines labeled 'A', 'B', and 'C' represent the launch point, decay time, and trapping point, respectively.

motion that generate artifacts in the measured trajectory not fully compensated by the correction outlined in the [Supplement 1](#).

The damping time shown in Fig. 5(d) as the time required for the particle to reach the position of the dashed line labeled 'B', is $\approx 300 \mu\text{s}$, estimated by fitting the averaged radial velocity to a decaying exponential. The decay time, as calculated from Stokes' law, with the friction coefficient $\beta = 6\pi\eta r$, $\eta = 1.849 \times 10^{-5} \text{ kg}/(\text{m} \cdot \text{s})$ at 25°C yields a theoretical value of $\frac{m}{\beta} = (750 \pm 90) \mu\text{s}$, where the uncertainty is one standard deviation propagated from the one standard deviation uncertainty of the particle size distribution. The measured duration of $\approx 310 \mu\text{s}$ is much shorter than the theoretical decay time for isolated particles determined by Stokes friction [30]. Drag is known to increase significantly near surfaces. The variations in drag, known as the Faxén corrections, are different for motion parallel and perpendicular to the surface and vary rapidly with distance from the surface. Calculating the corrections is beyond the scope of this work, but the magnitude of the correction is consistent with the increased drag observed here.

3.3. Statistics of launch velocity

The launch velocity of particles is closely related to the success rate of trapping [9,10,18]. The relation between the measured trapping efficiency, launch velocity and beam power is summarized in Fig. 6. Figure 6(a) shows that the probability of trapping exceeds 80% for launch velocities below 25 mm/s and drops to 50% near 75 mm/s. These statistics are derived from repeatedly launching a single $9.9 \mu\text{m}$ nominal diameter glass particle 400 times and measuring the trajectories. Two trapping beam powers are used: 48 mW and 120 mW. Figure 6(b) demonstrates that trapping beam power does not significantly change the launch velocity measured, though it may have a small effect for the lowest velocities. As expected, trapping beam power strongly affects the trapping efficiency, with the trapping probability exceeding 95% below 50 mm/s at 120 mW (Fig. 6(c)), and falling to 60% at 48 mW (Fig. 6(d)) over the same range of velocities.

Our observations confirm that particles with lower initial velocities have a higher likelihood of successful trapping, and that higher trapping beam power leads to increased trap efficiency not only at high launch velocities but also at low launch velocities. These measurements were performed on samples exposed to laboratory conditions and not dried to reduce moisture. The measured launch velocity and probability of trapping were also found to be insensitive to the amplitude of the excitation voltage applied to the launcher. This can be understood by referring to Fig. 4(b). The launcher amplitude requires more than 15 cycles to increase to a magnitude that releases the particle. If a given amplitude of vibration is required to launch a particle, that point will be reached sooner at higher excitation voltage, but the acceleration of the particle on the launcher will be similar. Data demonstrating this is included in the [Supplement 1](#). Repeating these measurements in vacuum is expected to produce different launch velocities and much lower trapping efficiencies but the goal is to measure the launch process to develop control algorithms for launching directly in vacuum.

Note that, the launch velocities mentioned in this paper are all corrected values obtained by numerical differentiation of the position data. In our experimental setup, z-axis displacement is detected by monitoring changes in the power of the photodetector (PD). However due to cross coupling, transverse displacement can introduce variations in the z signal without axial movement. To address this cross-talk between radial and axial displacements, we employ a first-order correction for the z-axis displacement. This correction is implemented using a lookup table generated from position measurements of a glass sphere on a glass substrate. The glass sphere is positioned on the substrate connected to the XY stage and is systematically scanned by moving the stage. By collecting data from two separate XY scans, we compile a complete dataset representing the influence of motion in x and y on the measured z position. Subsequently, we correct the z signal by subtracting this value based on the XY positions, effectively mitigating the effects of transverse displacement on our z-axis measurements. This correction procedure is described in the [Supplement 1](#).

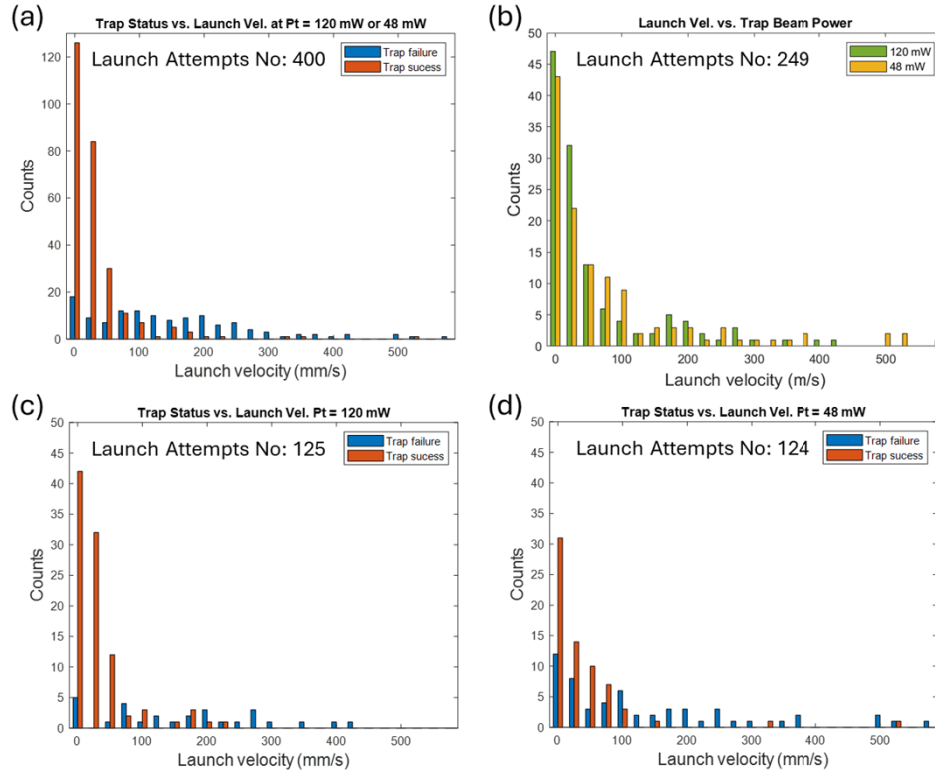


Fig. 6. Histogram of launch velocity on repeat launch attempts with a single, identical $\approx 10 \mu\text{m}$ glass particle. (a) Launch velocity distribution based on successful trapping, derived from 400 launch attempts. The term Pt in the figures represents the trapping beam power. (b) Launch velocity distributions depending on the trapping beam power. Launch velocity distribution based on successful trapping with the trapping beam powers of 120 mW (c) and 48 mW (d).

3.4. Thermalization of initial kinetic energy and drift into the trap

Measurements of particle position after launch show that the motion can be modeled as a two-step process. The first step is rapid decay of the launch velocity until the particle reaches thermal velocities due to Stokes' drag. In the second step, the particle drifts into the trap with a velocity proportional to the optical force and a mobility derived from Stokes' law.

As depicted in Fig. 1, the particle travels some distance before dissipating its kinetic energy and momentum after the launch. If the kinetic energy of the particle does not decrease sufficiently rapidly, it may move outside the trapping beam, increasing the possibility of trapping failure due to the particle not drifting into the trap. The distance the particle moves before slowing to thermal velocities is defined as the thermalization length. This length increases with initial velocity, as we show below, and is on the order of a few particle diameters.

The decay of particle velocity due to Stokes' drag can be described by the Stokes-Einstein relation. Once the particle's velocity has decayed to thermal velocities, its motion can be described in terms of drift. The drift of charged particles under the influence of a constant electric field in a gas can be described in terms of the electrical mobility as $v_{\text{drift}} = \mu_{\text{elect}} E$, where v_{drift} is the terminal drift velocity, μ_{elect} is the electrical mobility, and E is the electric field. Rewriting this in terms of force and using the Stokes-Einstein relation to express the mobility we can apply

this to drift of spherical particles driven by optical forces (F_{optical}) as:

$$v_{\text{drift}} = \frac{1}{6 \pi \eta r} F_{\text{optical}}$$

For the particles used here with diameters of $(9.9 \pm 1) \mu\text{m}$, we expect $(6 \pi \eta r)^{-1}$ to be $(5.8 \pm 0.3) \times 10^8 \text{ s/kg}$, where the uncertainty results from the uncertainty in particle diameter. Note that, the viscosity of air, η , which is a critical factor in the trapping of particles, is primarily determined by the temperature, pressure, and humidity of the air.

To model the thermalization process we used a three-dimensional Monte Carlo simulation that included the drag force from the viscosity of air and the fluctuating force from Brownian motion. The optical force was the gradient force of a Gaussian beam matching our beam geometry. The simulation involved two different launch velocities. One particle was released with no initial velocity, while the other was launched perpendicular to the z-direction with a velocity of 30 mm/s. Both particles started at $x = 0$, $y = 0$, and $z = -60 \mu\text{m}$ ($60 \mu\text{m}$ below the trap). Figure 7(a) depicts trajectories for a $10 \mu\text{m}$ diameter glass particle during loading into the trap, with and without initial velocity. After launch away from the z axis, the particle's radial velocity decays until the particle stops moving away from the axis at a maximum radial displacement of approximately $2 \mu\text{m}$ and turns back toward the axis and the trap under the influence of the optical force. To test the mobility model, we divided the velocity by the optical forces to estimate the mobility in the simulated system. The simulated mobility was found to be within less than 10^{-3} of the theoretically expected value of $1/\beta = (6 \pi \eta r)^{-1}$ over the full trajectory.

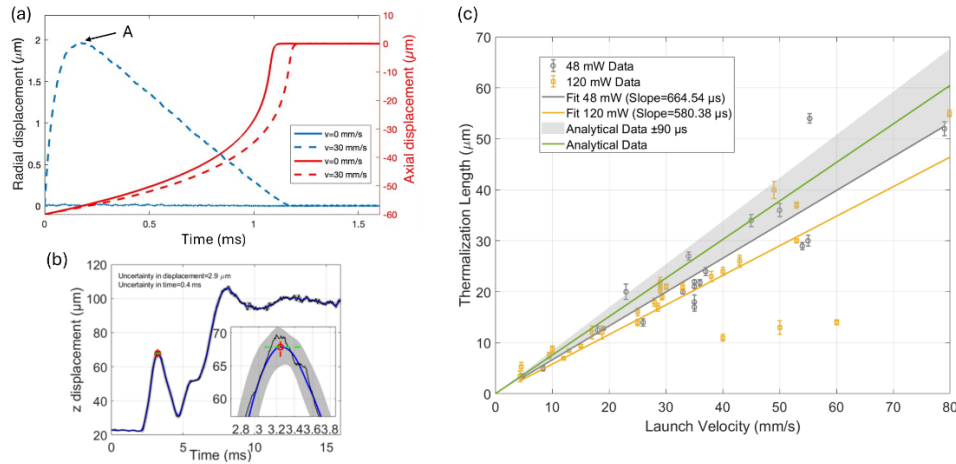


Fig. 7. (a) Simulated trajectory for a particle that is launched with no initial velocity (solid traces) and with a velocity of 30 mm/s perpendicular to the z-direction (dashed traces). (b) Ratio of simulated mobility to theoretical mobility. (c) Thermalization length determined from the experimental data along with the analytical analysis depicted by the solid line.

The thermalization length was measured experimentally by determining the turnaround point in the radial motion of a single particle launched 47 times. An example trajectory is shown in Fig. 7(b), and the uncertainty estimation is described in the Supplement 1. The results are plotted versus launch velocity in Fig. 7(c), with a line representing the values expected for a $9.9 \mu\text{m}$ glass sphere. The expected thermalization length is determined from the particle position as function of time. Starting from the equation of motion ($ma = -\beta v$) and integrating gives the velocity, $v(t) = v_0 e^{-\frac{\beta}{m}t}$, and the position, $r(t) = v_0 \frac{m}{\beta} \left(1 - e^{-\frac{\beta}{m}t}\right)$, as functions of time. The thermalization length is determined by solving for the time required to reach thermal velocity, $v_{th} = \sqrt{2 E_{th}/m}$,

and calculating the position at that time. The result is $r_{thermal} = \frac{m}{\beta}(v_0 - v_{th})$, a linear relation with a slope corresponding to the decay time calculated previously from Stokes' law, $(750 \pm 90) \mu s$.

The linear dependence of thermalization length on launch velocity is shown in Fig. 7(c) for two trapping powers: 48 mW and 120 mW, where the slopes of the lines give the corresponding thermalization times. The theoretical value of $(750 \pm 90) \mu s$ is also shown as a line surrounded by an error band. Here, the thermalization length is the distance the particle travels away from the initial launch point before it turns back toward the optical axis of the trapping beam. The slopes of the fit lines for the low power (48 mW) and high power (120 mW) beams are $665 \mu s$ and $580 \mu s$ respectively. This shows that the trapping beam does influence the slowing of the particle, with the thermalization time at the lower power lying just inside the error band representing the influence of particle size on the theoretical thermalization time. Though the measured values appear close to theoretical values, we note that the drag corrections discussed earlier would be expected to reduce the observed thermalization lengths and to do so anisotropically. The velocity and directionality of launch, and their dependence on the launcher excitation are the principal results that can inform the development of approaches to launching in vacuum.

3.5. Launch directionality

Similar to the thermalization length, the launch direction also influences the trapping efficiency. Variations in launch direction lead to changes in the starting point for drift within the influence of the trapping beam. Figure 8 presents a 3D map illustrating the velocity and the launch position for each of the 400 launch attempts using the same particle. In this visualization, each arrow represents an individual launch, with its position indicating where the particle reaches its peak velocity in the lateral direction and its length corresponding to the launch velocity.

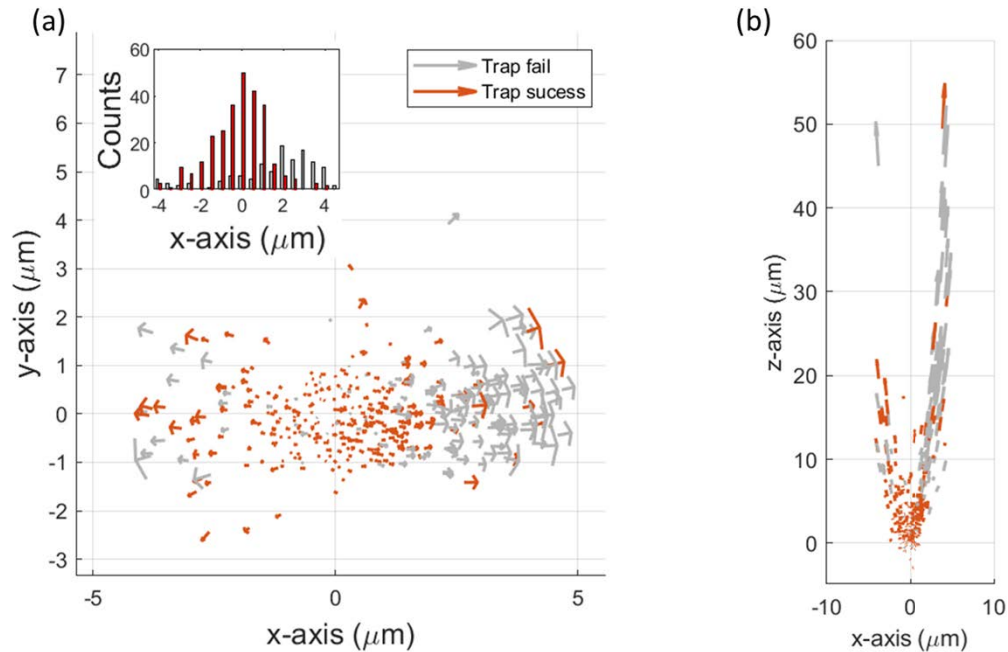


Fig. 8. Plot showing the launched position with the velocity of each launch attempt in the X-Y view (a) and X-Z view (b). The inset is the distribution of the launched positions in x-axis. The length of arrows is proportional to the velocity.

In the XY projection, a mostly consistent launch direction is observed, predominantly oriented in the x-direction rather than isotropically. Variations in the y-direction may be attributed to perturbations caused by coupled motion in X and Y as shown in Fig. 4(b). This predominant launch direction appears to reflect the geometry of the mode of vibration of the glass slide. After the launcher is excited, particles collect in areas of the slide that appear to correspond to nodes of the vibrational mode. The modal patterns can also be visualized under grazing incidence illumination. Particles are primarily launched in directions that projected onto the slide would be perpendicular to the nodal line on the glass slide bonded to the PBD, reflecting strong vibration in x-direction. Launches at higher speed exhibit lower trap efficiency and are observed at locations farther away from the center, consistent with the expectation that faster particles move further from the origin by the time the launch velocity is measured.

In the XZ projection, the vertical component of the launch velocities is shown. Again, low-velocity particles measured near the origin exhibit significantly higher trap efficiency, making them more promising candidates for controlled launch and trapping in vacuum. In a vacuum environment without air friction or damping from a control system or secondary beam, the launch velocity of particles should be minimized to the extent possible to promote successful trapping. Particles near the origin exhibit velocities on the order of a few millimeters per second (mm/s) and are potential candidates for trapping within a vacuum environment. For efficient trap loading in vacuum, it is helpful to reduce the launch velocity and to employ an external source of dissipation to slow the particle.

4. Conclusions

We measured the dynamics of glass particles during loading into an optical trap at atmospheric pressure using a custom particle launcher paired with a dual tracking system optimized for measurement near launch and near the trap. Launch velocities were found to be below 50 mm/s for efficiently trapped particles and insensitive to the amplitude of excitation. The evolution of particle motion after launch followed a two-step process of rapid deceleration due to air drag followed by slow drift into the trap determined by the optical force. Piezo bimorph induced vibrations in a thin glass slide enabled repeatable loading of identical individual particles. Our investigation revealed specific behaviors of particles weakly and firmly attached to the surface. This information suggests potential candidates for launching experiments with improved trap efficiency. The statistical analyses of launch velocity demonstrated correlations with trap efficiency, emphasizing important factors for successful trapping. We found that lower launch velocities corresponded to higher trapping efficiency, and that the power of the trapping beam did not significantly influence launch velocity. Moreover, our study explored the thermalization length, revealing a linear relationship with launch velocity. As launch velocity increased, the thermalization length extended, impacting trap efficiency by potentially causing particles to move beyond the trapping beam's optical field. Also, there is a predominant launch direction aligned with the direction perpendicular to the nodal line on the glass slide. These particle launching mechanisms will provide a foundation for future developments in trapped particle experiments conducted in vacuum environment.

Funding. National Institute of Standards and Technology (70NANB24H051).

Acknowledgements. This work was performed under financial assistance award 70NANB24H051 from the National Institute of Standards and Technology, U.S. Department of Commerce. Disclaimer: The statements, findings, conclusions, and recommendations are those of the author(s) and do not necessarily reflect the views of the National Institute of Standards and Technology or the U.S. Department of Commerce.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See [Supplement 1](#) for supporting content.

References

1. G. Pesce, P. H. Jones, O. M. Maragò, *et al.*, “Optical tweezers: theory and practice,” *Eur. Phys. J. Plus.* **135**(12), 949 (2020).
2. H. Xin, Y. Li, Y. Liu, *et al.*, “Optical Forces: From Fundamental to Biological Applications,” *Adv. Mater.* **32**(37), 2001994 (2020).
3. C. Gonzalez-Ballester, M. Aspelmeyer, L. Novotny, *et al.*, “Levitodynamics: Levitation and control of microscopic objects in vacuum,” *Science* **374**(6564), eabg3027 (2021).
4. F. M. Fazal and S. M. Block, “Optical tweezers study life under tension,” *Nat. Photonics* **5**(6), 318–321 (2011).
5. C. J. Bustamante, Y. R. Chemla, S. Liu, *et al.*, “Optical tweezers in single-molecule biophysics,” *Nat. Rev. Methods Primers* **1**(1), 25 (2021).
6. A. Ashkin and J. M. Dziedzic, “Optical Levitation by Radiation Pressure,” *Appl. Phys. Lett.* **19**(8), 283–285 (1971).
7. H. Park and T. W. LeBrun, “Contact Electrification of Individual Dielectric Microparticles Measured by Optical Tweezers in Air,” *ACS Appl. Mater. Interfaces* **8**(50), 34904–34913 (2016).
8. D. C. Moore, A. D. Rider, and G. Gratta, “Search for Millicharged Particles Using Optically Levitated Microspheres,” *Phys. Rev. Lett.* **113**(25), 251801 (2014).
9. E. Weisman, C. K. Galla, C. Montoya, *et al.*, “An apparatus for in-vacuum loading of nanoparticles into an optical trap,” *Rev. Sci. Instrum.* **93**(11), 115115 (2022).
10. A. Khodaei, K. Dare, A. Johnson, *et al.*, “Dry launching of silica nanoparticles in vacuum,” *AIP Adv.* **12**(12), 125023 (2022).
11. M. D. Summers, D. R. Burnham, and D. McGloin, “Trapping solid aerosols with optical tweezers: A comparison between gas and liquid phase optical traps,” *Opt. Express* **16**(11), 7739 (2008).
12. S. Anand, J. Nylk, S. L. Neale, *et al.*, “Aerosol droplet optical trap loading using surface acoustic wave nebulization,” *Opt. Express* **21**(25), 30148 (2013).
13. P. Mestres, J. Berthelot, M. Spasenović, *et al.*, “Cooling and manipulation of a levitated nanoparticle with an optical fiber trap,” *Appl. Phys. Lett.* **107**(15), 151102 (2015).
14. M. Calamai, A. Ranfagni, and F. Marin, “Transfer of a levitating nanoparticle between optical tweezers,” *AIP Adv.* **11**(2), 025246 (2021).
15. P. Asenbaum, S. Kuhn, S. Nimmrichter, *et al.*, “Cavity cooling of free silicon nanoparticles in high vacuum,” *Nat. Commun.* **4**(1), 2743 (2013).
16. D. S. Bykov, P. Mestres, L. Dania, *et al.*, “Direct loading of nanoparticles under high vacuum into a Paul trap for levitodynamical experiments,” *Appl. Phys. Lett.* **115**(3), 034101 (2019).
17. J. Flajšmanová, M. Šiler, P. Jedlička, *et al.*, “Using the transient trajectories of an optically levitated nanoparticle to characterize a stochastic Duffing oscillator,” *Sci. Rep.* **10**(1), 14436 (2020).
18. M. Nikkhou, Y. Hu, J. A. Sabin, *et al.*, “Direct and Clean Loading of Nanoparticles into Optical Traps at Millibar Pressures,” *Photonics* **8**(11), 458 (2021).
19. T. Li, S. Kheifets, D. Medellin, *et al.*, “Measurement of the Instantaneous Velocity of a Brownian Particle,” *Science* **328**(5986), 1673–1675 (2010).
20. T. Li, S. Kheifets, and M. G. Raizen, “Millikelvin cooling of an optically trapped microsphere in vacuum,” *Nat. Phys.* **7**(7), 527–530 (2011).
21. Y. Arita, M. Mazilu, and K. Dholakia, “Laser-induced rotation and cooling of a trapped microgyroscope in vacuum,” *Nat. Commun.* **4**(1), 2374 (2013).
22. Y. Arita, M. Mazilu, T. Vettenburg, *et al.*, “Rotation of two trapped microparticles in vacuum: observation of optically mediated parametric resonances,” *Opt. Lett.* **40**(20), 4751 (2015).
23. J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, *et al.*, “Cavity Cooling a Single Charged Levitated Nanosphere,” *Phys. Rev. Lett.* **114**(12), 123602 (2015).
24. G. Ranjit, D. P. Atherton, J. H. Stutz, *et al.*, “Attonewton force detection using microspheres in a dual-beam optical trap in high vacuum,” *Phys. Rev. A* **91**(5), 051805 (2015).
25. H. Park and T. W. LeBrun, “Optical Trap Loading of Dielectric Microparticles In Air,” *JoVE* **120**, 54862 (2017).
26. C. Montoya, E. Alejandro, W. Eom, *et al.*, “Scanning force sensing at micrometer distances from a conductive surface with nanospheres in an optical lattice,” *Appl. Opt.* **61**(12), 3486 (2022).
27. H. Park and T. W. LeBrun, “Parametric Force Analysis for Measurement of Arbitrary Optical Forces on Particles Trapped in Air or Vacuum,” *ACS Photonics* **2**(10), 1451–1459 (2015).
28. A. Pralle, M. Prummer, E.-L. Florin, *et al.*, “Three-dimensional high-resolution particle tracking for optical tweezers by forward scattered light,” *Microsc. Res. Tech.* **44**(5), 378–386 (1999).
29. G. Xiao, “A PZT-assisted single particle loading method for dual-fiber optical trap in air,” *Optics and Laser Technology* **126**, 106115 (2020).
30. R. B. Harvey, “Methods of Theoretical Physics. By P.M. Morse and H. Feshbach. 2vols., Pp.xxii, 1978. 120s. each vol. 1953.(McGraw-Hill),” *Math. Gaz.* **39**(327), 80–81 (1955).