Free-falling nanoparticle helps to detect tiny forces

A miniature mechanical sensor works by repeatedly dropping and catching a particle.

Free-fall experiments are the stuff of scientific legend. Galileo is said to have dropped cannonballs from the Leaning Tower of Pisa to demonstrate to his students that gravitational acceleration is independent of mass. And Isaac Newton often recounted the tale of the falling apple that inspired him to think about gravitational forces over longer distances. (There's no evidence, however, that the apple landed on his head.)

Now Erik Hebestreit, his PhD adviser Lukas Novotny, and their colleagues at ETH Zürich have shrunk the apple drop to the nanoscale regime.[1] By levitating a silica nanoparticle in an optical trap, as shown in figure 1, and briefly releasing it, they can measure the effect of gravity or any other static force that acts on the particle.

The measurement is sensitive to forces as small as 10 attonewtons, or half the weight of the 136 nm particle. (It's also the gravitational force between two 80 kg people separated by 200 km.) Although the precision remains modest, with error bars on the order of 20% of the force being measured, the technique can be used to study the largely uncharted territory of short-range, static, nanomechanical forces.

Inspired by interferometry

The nanoparticles aren't the smallest objects to have been observed in free fall. Two decades ago, Steven Chu and colleagues studied falling atoms in an atom interferometer.[2] (See PHYSICS TODAY, November 1999, page 20.) By capitalizing on the cooling and trapping techniques that had won Chu a share of a Nobel Prize (see PHYSICS TODAY, December 1997, page 17), they measured the acceleration due to gravity with a precision of three parts in a billion—easily enough to observe the twice-daily oscillations due to Earth's tides. (See the article by Markus Arndt, PHYSICS TODAY, May 2014, page 30.)

In 2015 Andrew Geraci and Hart Goldman presented an idea for a similar matter-wave interferometer based not on an atomic cloud but on a solid nanosphere, whose delocalized wavefunction

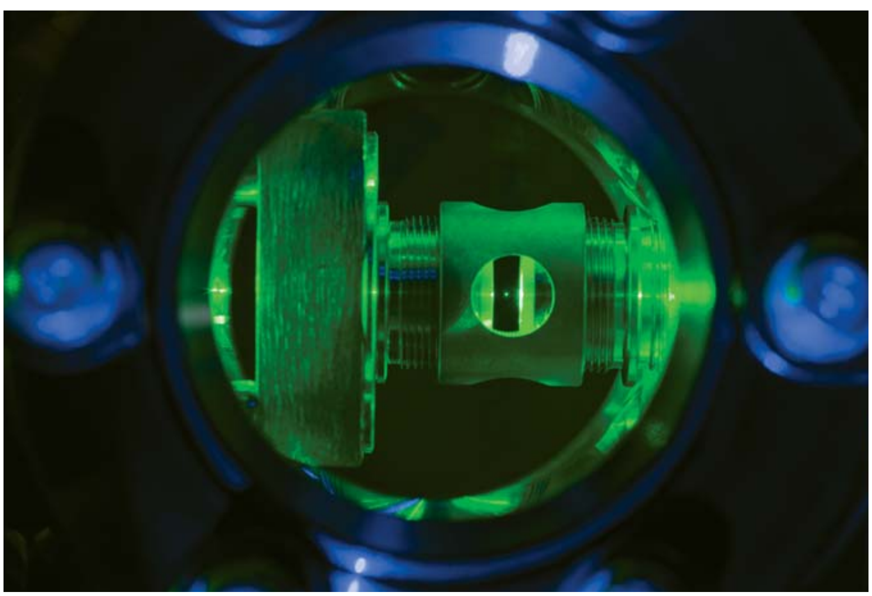

FIGURE 1. AN OPTICALLY LEVITATED NANOPARTICLE, visible here as a tiny green dot on the center line of the vacuum chamber, is the basis for a nanomechanical force sensor. (Photo by Rozenn Diehl and René Reimann, ETH Zürich.)

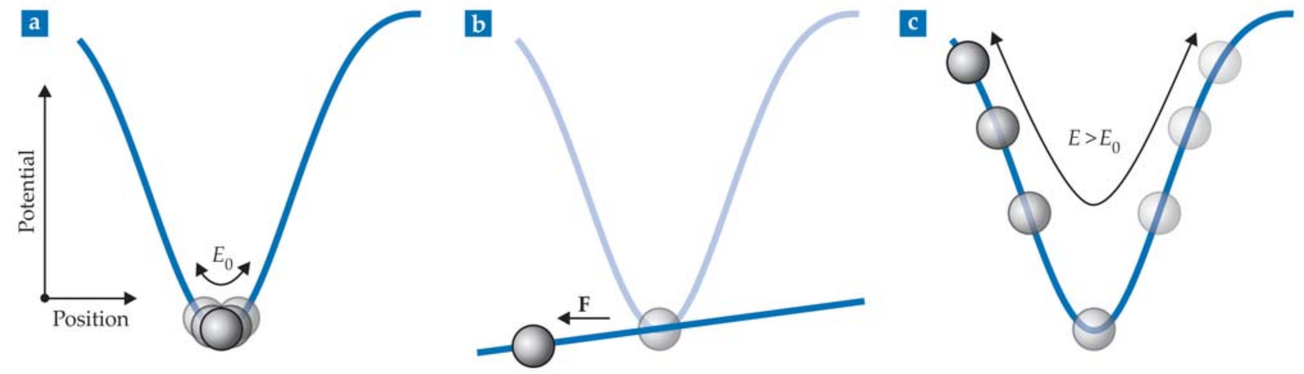

FIGURE 2. IN THE FORCE-SENSING SCHEME, the nanoparticle begins **(a)** in the center of a harmonic optical trap with a small but nonzero energy E_0. The trap is turned off **(b)**, and the particle moves away from the trap center under a static force **F**. When the trap is turned back on **(c)**, the particle oscillates with a greater energy *E*. The particle's diameter and displacement are both on the order of 100 nm; the displacement is exaggerated here for clarity. (Adapted from ref. 1.)

interferes with itself.[3] According to their analysis, the interferometer would be sensitive to the gravitational attraction between the nanosphere and a nearby micron-sized object, an interaction that could reveal short-range deviations from Newton's law of universal gravitation.

It was a bold proposal. To achieve such exquisite sensitivity, experimenters would have to cool the nanosphere into the quantum ground state of an optical trap—a feat that's still outside current capabilities.

Nevertheless, the ETH Zürich researchers were inspired by the idea. If they could implement a nanoparticle free-fall experiment, even without cooling the particle to the ground state, they could clear some of the other experimental obstacles to realizing Geraci and Goldman's proposal. And they could create a nanomechanical sensor that would be useful in its own right. "It was the next achievable step," recounts Martin Frimmer, an author on the new paper.

Catch and release

The principle of the scheme, illustrated in figure 2, is simple to state. A nanoparticle is held in the center of a harmonic optical trap. The trap is turned off for a fraction of a millisecond, during which the particle moves under the static force **F**, which may or may not be gravity. When the trap is reactivated, the particle is no longer near the center, and it oscillates with a large amplitude, which the researchers measure with high precision.

The final oscillation energy *E* depends on both **F** and the fall duration τ. It also depends on the particle's velocity $\mathbf{v}_0$ at the instant the trap is turned off. Because the initial oscillation energy E_0 is small but nonzero, $\mathbf{v}_0$ is also generally nonzero—and unpredictable.

To minimize that source of uncertainty, the researchers repeat the drop-and-catch process thousands of times for several values of τ. If $\mathbf{F} = 0$ and the particle's movement is characterized solely by $\mathbf{v}_0$, then the average *E* (essentially the average squared displacement) is proportional to τ^2. A nonzero **F** introduces a τ^4 term; by fitting the data, the researchers extract **F**.

The nanomechanical world holds many surprises, however, and the net force that acts on the particle isn't always the force one hopes to measure. For example, the usual means of rapidly switching a laser beam on and off is with an acousto-optic or electro-optic modulator. Mechanical shutters are far too slow. An AOM or EOM doesn't switch the beam all the way off but rather attenuates it by a factor of around a thousand. The residual intensity in the optical trap is enough to overwhelm the measurement of a weak static force. To reduce the trapping power to an acceptably low level, the ETH Zürich researchers used an AOM and an EOM in series, switched on and off at the same time.

Electrostatic forces posed another technical challenge. By necessity, the optical trap is positioned right next to a glass lens. And glass, being a dielectric, is prone to harboring excess surface charge. The resulting electric field turned out to be surprisingly large: several hundred volts per meter, enough to exert a force of many tens of attonewtons on a particle with a single excess elementary charge.

The researchers found no practical way to eliminate that stray field. (Says Frimmer, "There's really no such thing as 'no field' in the real world.") But they did find a way to reliably discharge the nanoparticle: by exposing it to a swarm of charged particles in tandem with an AC electric field. When the nanoparticle stops oscillating under the driving field, its charge is zero, and the experiment is ready to proceed.[4] As a proof of principle that their method could also measure applied electrostatic forces, the researchers endowed the nanoparticle with an extra electron, measured the force of the residual and applied fields, measured the force of the residual field, and subtracted.

Casimir–Polder and van der Waals

Plenty of force-sensing schemes, typically based on mechanical resonators, have far better sensitivity and precision than the nano-apple drop.[5] But they're limited to measuring time-varying forces. Some forces, such as gravity, are inherently static, and others are difficult to turn on and off.

Of particular interest is the crossover between van der Waals and Casimir–Polder dispersion forces. The van der Waals force between closely spaced atoms is a nonrelativistic quantum effect mediated by the exchange of virtual photons. For larger objects and greater separations, relativistic effects come into play, as analyzed by Hendrik Casimir and Dik Polder: The nonzero propagation time for the virtual photons becomes important, and the force scales differently as a function of distance. (See the article by Steve Lamoreaux, PHYSICS TODAY, February 2007, page 40.) The boundary between the nonrelativistic and relativistic regimes is expected to be found on a size scale of tens to hundreds of nanometers—a scale that, until the ETH Zürich researchers' work, had been stubbornly difficult to explore.

The researchers plan to study those dispersion forces by dropping a nanoparticle in close proximity to a vertical glass plate. By measuring the horizontal and vertical oscillations separately, they hope to determine whether the particle falls straight down or is attracted to or repelled from the plate. That experiment, however, poses yet another technical hurdle: "We'll need to deal with the optical reflection off the glass," says Frimmer. "But we're learning how to do that."

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References

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2. A. Peters, K. Y. Chung, S. Chu, *Nature* **400**, 849 (1999).
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4. M. Frimmer et al., *Phys. Rev. A* **95**, 061801 (2017).
5. See, for example, J. Moser et al., *Nat. Nanotechnol.* **8**, 493 (2013).

PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

A PUZZLING GAMMA-RAY SURVEY OF THE SUN

Gamma rays produced via thermonuclear fusion in the Sun's core are absorbed long before they reach the visible surface, or photosphere. Nonetheless, our neighborhood star glows brightly in the gamma-ray spectrum due to interactions with cosmic rays: Speedy protons passing through the solar system smash into the photosphere and unleash cascades of particles and high-energy radiation.

Theorists have struggled to model how the incoming cosmic rays and the solar magnetic fields that steer them produce the Sun's observed gamma-ray spectrum. New measurements from the *Fermi Gamma-Ray Space Telescope*'s Large Area Telescope offer the best-ever look at the Sun's gamma emissions—and reveal that theorists still have a lot of work to do.

Analyzing data collected between August 2008 and November 2017, Tim Linden of the Ohio State University and his colleagues charted gamma-ray events by their energy and their position on the solar disk. Throughout the observing period, *Fermi* detected a relatively steady flux of photons, in the tens of GeV, that was concentrated at the Sun's poles. The flux significantly exceeded that predicted by the one and only model that takes on cosmic-ray interactions with solar gas.

The picture became more complex when the researchers focused on events before 2010, when the Sun was in the minimum phase of its roughly 11-year cycle of magnetic activity. From late 2008 to late 2009, *Fermi* detected six gamma rays with energies exceeding 100 GeV, the only ones of such high energy it would see during the nine years. Those events and other pre-2010 events exceeding 50 GeV emanated mostly from the Sun's equatorial region. Linden and colleagues conclude that separate cosmic-ray-triggered mechanisms are responsible for the relatively steady, lower-energy gamma rays at the poles and the equatorial, higher-energy photons that peak at solar minimum.

The new study offers theorists a rich and puzzling data set, one that also includes an unexpected dip at 30–50 GeV in what otherwise resembles a power-law spectrum. The underlying physics may become clearer once *Fermi* completes a full solar cycle's worth of observations through the upcoming minimum; in fact, earlier this year, as the Sun continued its slide into quiescence, the telescope spotted its seventh event exceeding 100 GeV. The High-Altitude Water Cherenkov Observatory in Mexico and the IceCube Neutrino Observatory in Antarctica may also provide clues by capturing particles produced in air showers triggered by high-energy gamma rays. (T. Linden et al., *Phys. Rev. Lett.*, in press.) —AG

OBSERVING NEW GEOMETRIC PHASES IN THE LAB

Falling cats and Olympic divers share the ability to twist, spin, and reorient themselves to land on their feet or make minimal splash. To accomplish that feat, they bend and contort to make a complete loop in their body's "shape space," so their bodies end up in the same shape they started in. But in physical space, they don't end up where they started: They rotate through a finite angle. Michael Berry described that acquired rotation, a so-called geometric phase, 35 years ago for quantum systems, and the phase now bears his name. Shortly thereafter, John Hannay extended the concept to classical analogues, for which the iconic example is a bead sliding frictionlessly on a horizontal, rotating, noncircular hoop. After one rotation, the hoop returns to its starting orientation, but the bead will have moved by an angle that depends only on the hoop geometry, not on its rotation speed.

Hannay's original analysis considered only slow, adiabatic rotations. John Lindner and colleagues at The College of Wooster now generalize it to arbitrary motions, including regimes that can be readily realized in laboratory experiments. In the hoop's rotating frame of reference, the bead experiences multiple fictitious forces, of which the Coriolis and centrifugal forces are the more familiar. But it is the Euler pseudo force, arising from the hoop's initial angular acceleration, that sets the bead in motion in the hoop frame. Numerical simulations (see the figure) showed that the resulting trajectory in the lab frame (blue curve, right) can be quite complex and include multiple kinks. The researchers validated their simulations experimentally, with a cylinder of wet ice, weighted down by a steel ball, that slid around an elliptical track fashioned from 3D-printed plastic rails affixed to an aluminum sheet on a turntable. Converting a classic, idealized example into a realized experiment offers a firsthand opportunity to explore geometric phases in all their classical and quantum forms. (H. Bae, N. Ali, J. F. Lindner, *Chaos* **28**, 083107, 2018.) —RJF PT