Issue: ***July 2010***

Einstein, Right or Wrong...But Forever Relevant

by Jessica Tanenbaum

Four physicists intent on measuring the precise speed of a single dust particle? Sounds like idle curiosity taken to the extreme, a parody of how scientists spend their time.

Yet in constructing a special device to measure the random nanometer-scale movements of a tiny bead, University of Texas physicist Mark Raizen and three of his colleagues weren't joking around, nor were they carrying out a frivolous exercise. Instead, this Texas team was testing ideas about Brownian motion proposed a century ago by Albert Einstein, physicist extraordinaire.

Brownian Motion

In thinking about Brownian motion, it may help to remember that underneath the placid surface of the world we experience, a 24-7 atomic-scale dance party rages away.

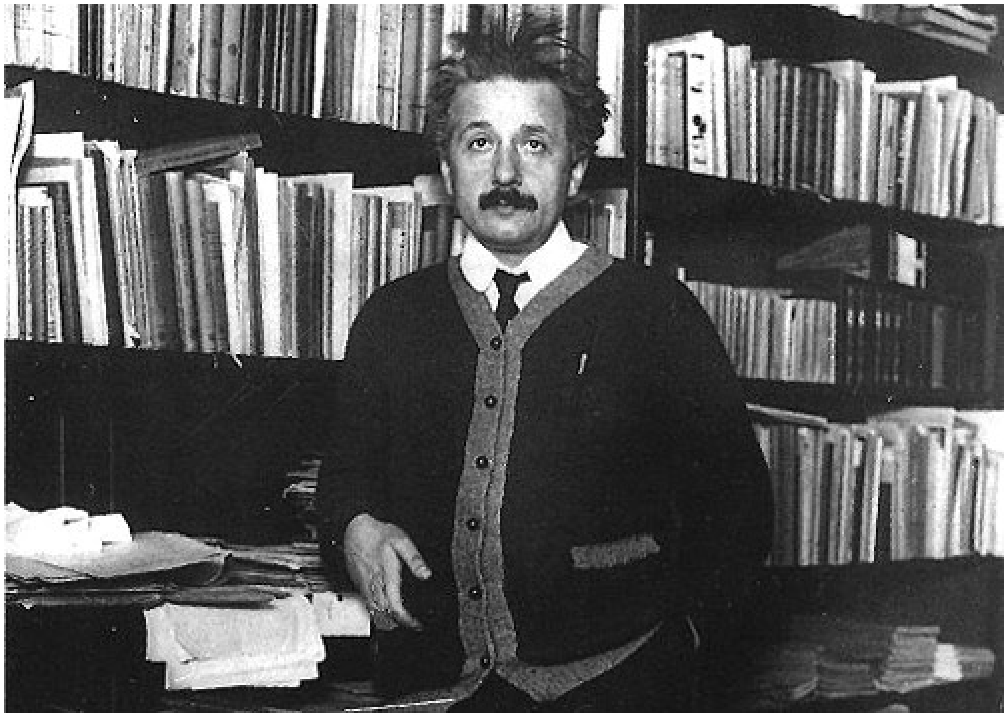
Brownian motion, this busy bumper-car activity of molecules and atoms, isn't normally visible because it occurs at scales far smaller than an ordinary microscope can capture. That, of course, raises the question — why is the phenomenon named for observations that Scottish botanist Robert Brown made with his microscope in the 1820s? Brown quite obviously did not have anything we would consider high-tech at his disposal.

He was, however, with the microscope available to him able to notice that small pollen particles appeared to jiggle in a dish of water. We now know the explanation for this strange activity: a teeming throng of water molecules battered against the much larger pollen, causing it to jiggle noticeably. The larger pollen particles unwittingly became tour guides to the roiling underworld of molecules and atoms.

Enter Einstein

Nearly a century after Brown published his findings, Einstein put forward some of his own ideas about Brownian motion. Of course, Einstein is most famous today for his special and general theories of relativity: insights into the deep connections between light, energy, gravity, and spacetime. But Einstein made important contributions to many other areas of physics. Along with a handful of other scientists in the first decade of the twentieth century, Einstein was intrigued by the idea that the orderly, predictable world we experience might be far more random and chaotic at the level of individual atoms and molecules. For instance, Einstein understood that heat, a phenomenon we perceive as part of our daily lives, is fundamentally the average energy of wildly wiggling molecules. This insight is fundamental to the part of physics known as "statistical mechanics," which codifies the laws that connect orderly macroscopic phenomena to random molecular motion. But, in the first decade of the twentieth century, these connections were still being established. Einstein's work on Brownian motion was an important step toward our modern understanding of statistical mechanics.

As much as his work on relativity, Einstein's thinking about Brownian motion bears the mark of a vivid and idiosyncratic imagination. Whereas Einstein-the-relativity-theorist imagined traveling on a light beam, Einstein-the-Brownian-motion-theorist invites us to imagine riding a Brownian particle — a miniature bucking bronco. What if we could measure the instantaneous velocity of this particle as it traveled on its collision course? According to Einstein, the particle's shape and size would be irrelevant to its velocity.



Caltech

In a 1907 paper, physicist Albert Einstein asserted that recording the instantaneous velocity of a Brownian particle would be an impossible technical challenge. According to Einstein, "we must conclude that the velocity and direction of motion of the particle will be already very greatly altered in the extraordinary short time θ, and, indeed in a totally irregular manner. It is therefore impossible — at least for ultramicroscopic properties — to ascertain $\sqrt{\overline{v^2}}$ by observation."

This insight has been incorporated into statistical mechanics through what's known as the "equipartition theorem." Certain special forms of the theorem might be familiar. For instance, high school chemistry students often learn that for ideal gases, E = 3/2(*n*RT), where E is energy, *n* is moles of an ideal gas, R is the gas constant, and T is temperature in Kelvin. This is an equipartition theorem, a statement relating a system's total temperature to average molecular energies.

It's important to realize that Einstein's own theory of Brownian motion accurately describes that motion only under certain conditions — in particular, under longer timescales when collisions between molecules occur relatively infrequently. Einstein's theory applies to the situation when collisions happen not too often, so that after a particle bumps into another and ricochets off at a certain velocity, it will have time to start to slow before the next collision. When collisions happen more frequently, the particle doesn't substantially lose energy between collisions, and its behavior follows a different pattern. While Einstein succeeded at describing a longer timescale of Brownian motion, French physicist Paul Langevin, a contemporary of Einstein's, published equations that accounted for both long and short timescales of Brownian behavior. The challenge for Raizen and colleagues was to make a device that could capture both.

Why Einstein Should Stick to Theoretical Physics

Never tell an experimental physicist that something is too difficult to measure. In a 1907 paper, Einstein asserted that recording the instantaneous velocity of a Brownian particle would be an impossible technical challenge. He wasn't arguing that it was impossible *in principle* to record a Brownian bumper course — only that we'd never *actually* reach the level of precision required to follow a particle making so many collisions so quickly. In effect, Einstein was inviting experimentalists to prove him wrong.

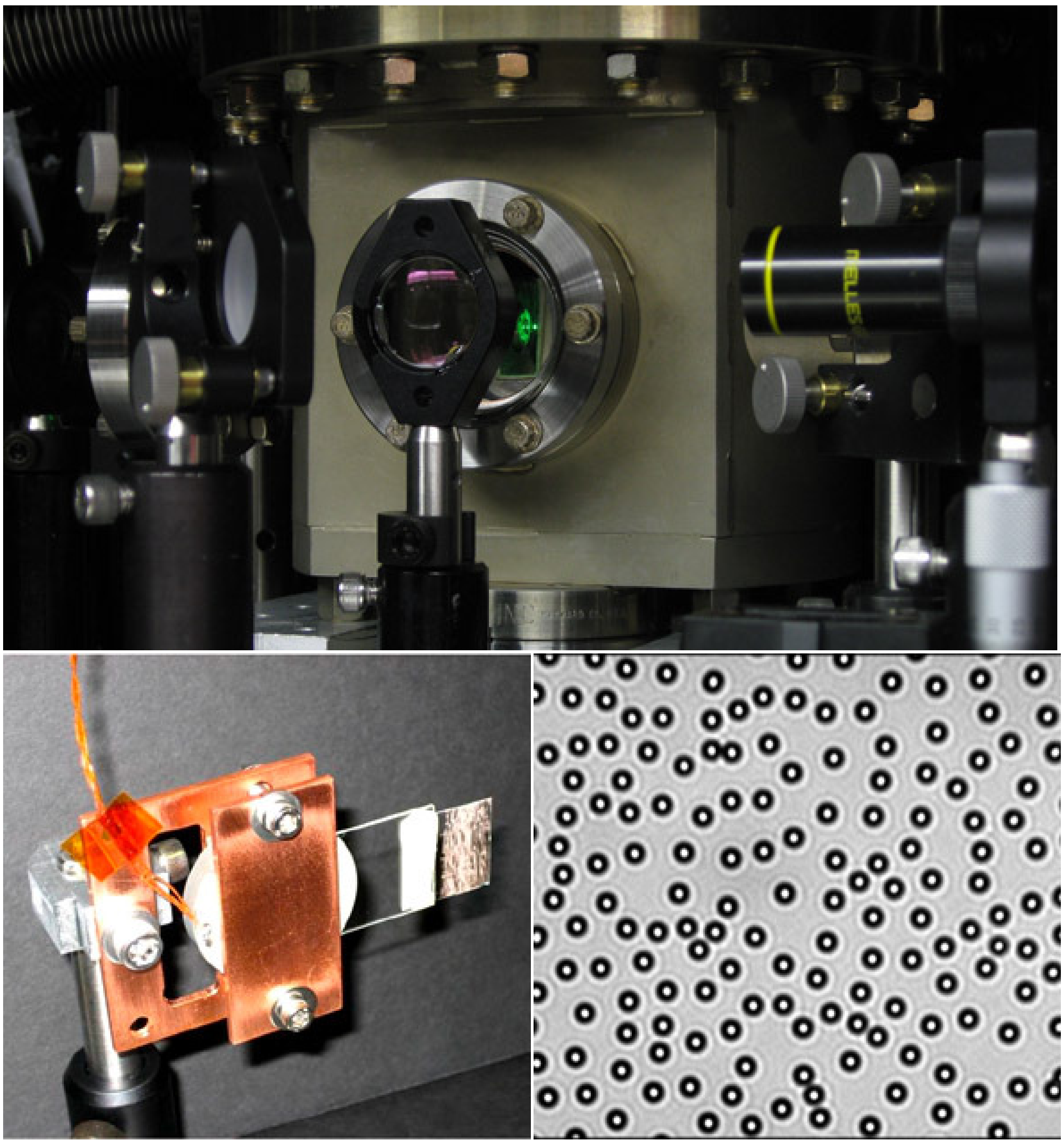
According to Raizen and colleagues, early attempts to measure the speed of a Brownian particle yielded bizarre, contradictory results. More recently, trials have faltered because they focus on particles suspended in liquid, not gas. A particle in liquid will collide with neighboring molecules more frequently than a particle in gas, since liquid is denser than gas; thus, following the changing speed of a particle in liquid is far more technically demanding.

Raizen's team in Texas came up with a creative new experimental design, starting with a gas medium for their Brownian particle. Then, using a neat trick called "optical tweezers," Raizen and colleagues successfully captured instantaneous speeds of a tiny bead levitating in gas. With their new study published in *Science*, the four physicists show that while Einstein was a visionary when it came to physics, his ability to forecast advances in technology was less impressive.

Just a Light Pinch: Optical Tweezers at Work

"Optical tweezer" technology, the key to the Raizen team's new experiment, is an application of radiation pressure, light's ability to push. Lucky for us, these pressures never amount to much (no whiplash from strobe lights, for example). But while light pressure is extremely weak, it can be tuned with extreme precision.

Seen from one perspective, the idea of radiation pressure seems perfectly intuitive: when photons strike something, they exert a force, just as one hockey player exerts a force on his rival in a body check. But from another perspective the phenomenon is paradoxical — photons are not themselves matter, and since they're massless, they have no bodyweight to use in their body checks. Not surprisingly, scientists are still studying and seeking to fully understand radiation pressure [See Laser Beam Sheds Light on Century-Long Momentum Dispute, December 2008].(Einstein himself understood that, although light lacks mass, it does have momentum that can be passed.) Radiation pressure may defy expectations, but it has also proved useful in the laboratory. The so-called optical tweezers employed by Raizen and colleagues are a prime example of an experimental tool based on radiation pressure.

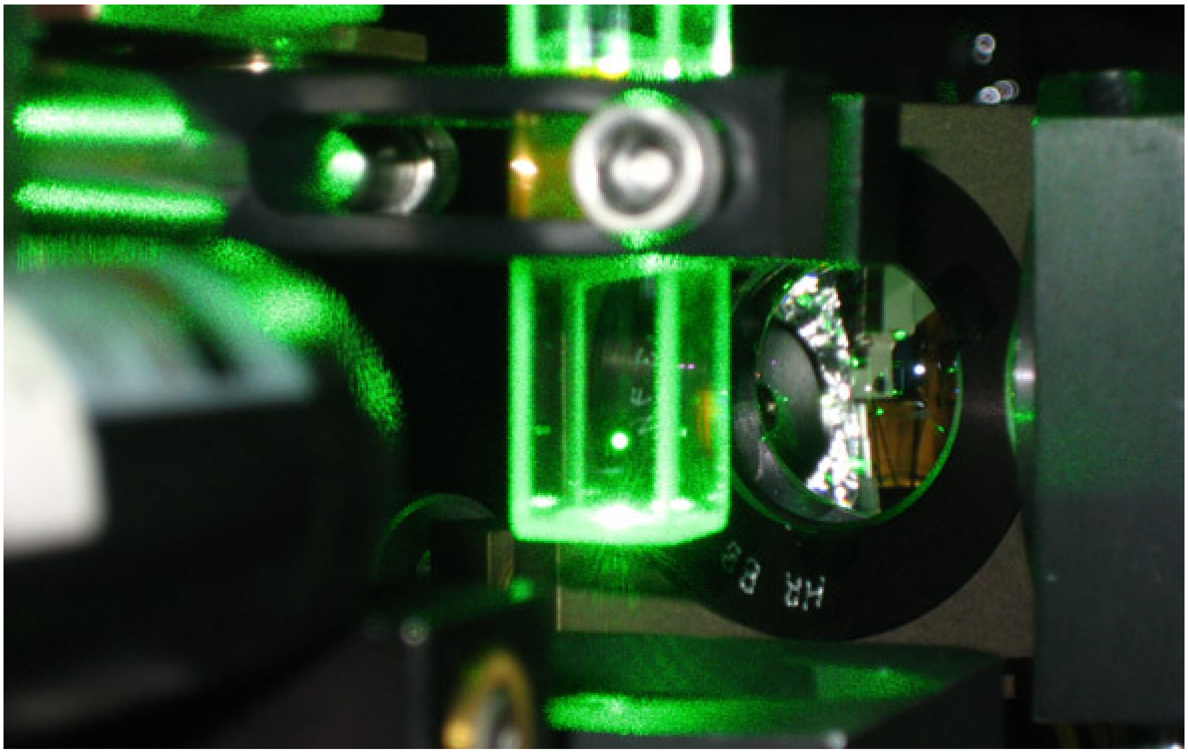


Courtesy of Mark J. Raizen

Raizen's team in Texas came up with a creative new experimental design, starting with a gas medium for their Brownian particle. Then, using a neat trick called "optical tweezers," Raizen and colleagues successfully captured instantaneous speeds of a tiny bead levitating in gas. ABOVE: The bead trapped

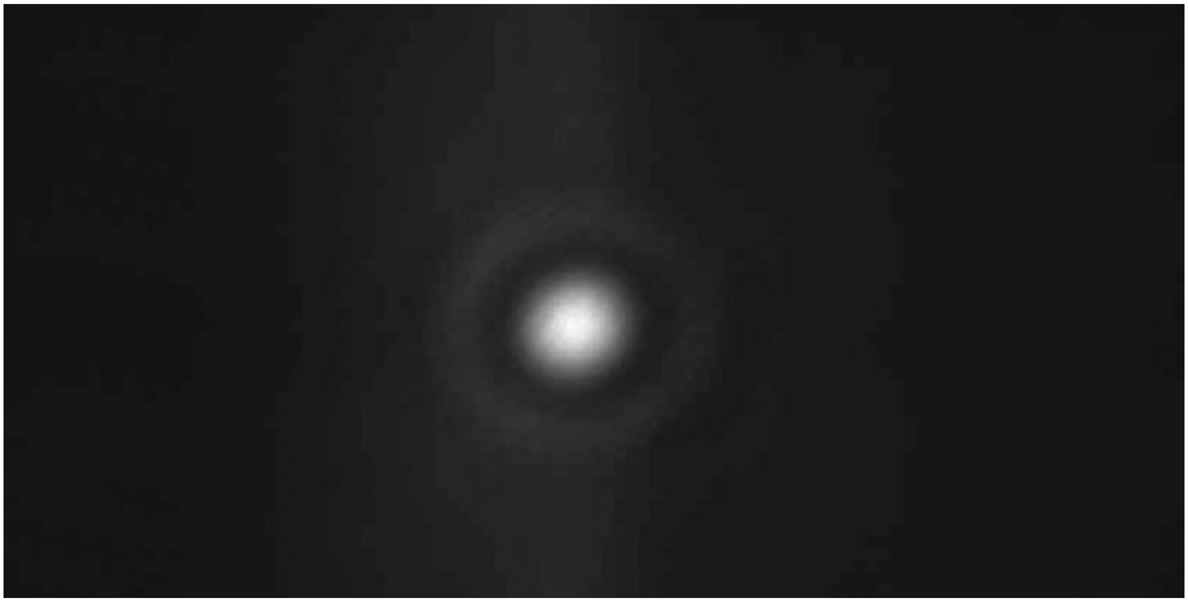
in a vacuum chamber (top); the ultrasonic shaker (left) and the beads dispersed on a slide by the shaker (right).

Despite the name, optical tweezers are not for plucking as much as for trapping. Raizen and colleagues used a special optical tweezer device to trap and track their Brownian particle, a bead three micrometers in diameter, made of nonreactive silica. The physicists tuned two laser beams to emit light that would exactly balance out gravity, so that when the beams shone on the bead, it hung precisely in midair. And if the bead moved at all, the laser beams would be deflected, and well-positioned detectors would record this light deflection. Thus, the data from this light show allowed the physicists to calculate the instantaneous velocity of the bead. Maybe Einstein can't be blamed, at least not too much, for failing to foresee this application of 21st century technology.



Courtesy of Mark J. Raizen

Raizen and colleagues used a special optical tweezer device to trap and track their Brownian particle, a bead three micrometers in diameter, made of nonreactive silica. The physicists tuned two laser beams to emit light that would exactly balance out gravity, so that when the beams shone on the bead, it would hang precisely in midair. ABOVE: The bead trapped in midair by the laser beams. BELOW: A closeup of the tiny bead.



Courtesy of Mark J. Raizen

Raizen and colleagues didn't just want to trap the bead in place — they wanted to watch it jiggle as air molecules battered against it. But if the bead flew out of the trap entirely, the experiment would end. Through careful calibration, the experiment was designed so that most collisions with air molecules would only bump the bead slightly, allowing it to return to its original position, where the forces from gravity and the two laser beams balanced out. Of course, random jolts sometimes knocked the bead entirely out of the laser beam trap. But Raizen and colleagues could keep the bead trapped for as long as 46 hours, obtaining plenty of data to analyze.

The Upshot

By far the coolest part of the team's experiment is the science-fiction set-up: trapping a bead in mid-air with two laser beams. Since their data essentially corroborates what theoretical physicists already knew — that Einstein's understanding of Brownian motion holds only when collisions are relatively infrequent and that the Langevin equation is more general — the scientists proved that their experimental design is sound. Because Raizen and colleagues got their experimental results to match well-loved physics formulas, they can confidently continue using their unique optical tweezers. According to Raizen, the researchers soon hope to tackle quantum problems requiring even greater precision.

Mark G. Raizen: Shaking Up Physics

Mark G. Raizen is the Sid W. Richardson Foundation Regents Chair and professor of physics at the University of Texas at Austin. He earned a bachelor's degree in mathematics from Tel Aviv University in 1980, followed by two years of graduate studies in mathematics at the Weizmann Institute of Science. In 1989, Raizen completed his Ph.D. in physics at the University of Texas under the guidance of 1979 Nobel laureate Steven Weinberg and H.Jeff Kimble. Prior to joining the University of Texas faculty in 1991, Raizen did two years of postdoctoral research at the National Institute of Standards and Technology (NIST) in Boulder, Colorado. Raizen has received numerous awards and honors, holds a patent for a "squeezed state" optical device, and has published over 100 peer-reviewed papers.

Raizen's research combines theoretical physics with hands-on experimentation in an effort to slowdown and control atoms. In his research, he has creatively and intuitively borrowed ideas from disciplines ranging from chemistry to electromechanics and plasma physics.

Below are Raizen's June 17, 2010 responses to questions posed to him by Today's Science.

Courtesy of Mark G. Raizen

"The best scientists are 'trouble-makers' who do not accept the common wisdom at face value."

Q. When did you realize you wanted to become a scientist?

A. When I was a child I thought that I would become a medical doctor, following a long tradition in my family. At the age of ten, I visited my uncle's lab at NIH [National Institutes of Health] in Bethesda, Maryland, and decided that I wanted to do the same thing. My uncle was a medical doctor by training, but chose a research career as a biochemist. That day, I realized that I wanted to be a scientist.

Q. How did you choose your field?

A. Choosing my field was not a direct path. I have taken a long and twisted road to being a physicist.

In high school, physics was my worst subject, and I got a C in the class. I now realize it was because I was too curious, my teacher resented my constant questions, and wanted me to just memorize the book. I then turned to mathematics, where I could understand everything. My undergraduate degree is in that field. I always felt myself drawn to physics, and decided to pursue a graduate degree. My research began in theoretical physics, but then I became an experimentalist. I finally found my true calling as a research physicist and professor where I can combine theory with experiment. I wish that I could meet my high school teacher now; I am sure he would be surprised.

Q. Are there particular scientists, whether you know them in person or not, that you find inspiring?

A. My advisor, Steven Weinberg, continues to inspire me. Our relationship started 25 years ago when I was a beginning graduate student. I was in awe of Weinberg, a Nobel laureate in physics, and a great man. To be chosen as one of his students was an honor. Over the years we have become friends, and just had lunch last week!

There are many scientists from the past whom I admire. James Clerk Maxwell is a great inspiration to me, and my own research has been influenced by him. I recently found out that Maxwell was Einstein's hero, whose picture he kept on his mantle. Another role model for me is Enrico Fermi. Both Maxwell and Fermi combined theory and experiment, which has been the guiding principle of my research.

Q. When you tell people that you are a physicist studying dynamics what is their reaction? What do you think is the biggest misconception about your profession?

A. People often tell me that physics was their worst subject in high school, and my response is: mine too! This is a great icebreaker and I then find genuine interest in physics. I think that the sciences, and physics in particular, can be intimidating. My goal is to explain things in a way that anyone can understand.

Q. In an interview with Science, you mention that researchers are now looking at objects in the in-between size scale: tiny, but still composed of millions of atoms, and trying to see if quantum-mechanical states can be achieved with these objects. What factors make it more likely that "quantum mechanical" behavior will be seen in aggregations of atoms?

A. Quantum effects become important when a particle is nearly at rest. In a solid, this only happens as the temperature approaches absolute zero. We are working with a small bead of glass suspended by an optical tweezer. The internal temperature of the bead is high (near room temperature), however we can cool the center-of-mass of the bead so that as a whole it is nearly stationary. This is possible because the center-of-mass motion is extremely well isolated from the internal vibrations of the solid.

Q. What would be a prototypical example of quantum mechanical behavior of such an assemblage of atoms, versus classical behavior?

A. The "Holy Grail" is to create a superposition state, where a bead of glass is in two locations at the same time. This would realize a thought experiment known as Schr□dinger's Cat, which would defy our classical intuition. Such "Cat" states have been made in the lab, but so far have only involved a few atoms.

Q. Is there, in principle, any upper limit on the sizes of assemblages of atoms that might exhibit quantum mechanical behavior?

A. One of the main goals of current research is to study the limits of quantum behavior, and the effects of [a quantum mechanism called] decoherence.

Q. Outside of a laboratory, would one ever see such behavior (perhaps in some exotic extraterrestrial environment, for example)?

A. It is hard to imagine, but I am not going to make a prediction, as scientific reality is often stranger than science fiction.

Q. Where do you spend most of your workday? Who are the people you work with?

A. I spend most of my workday between my lab and my office. In my office, I think about the current and future experiments and I read papers. When I am in the lab, I work most closely with my graduate and postdoctoral students. During the regular semesters, I teach undergraduate and graduate classes. I enjoy holding office hours, where I typically see the best students in the class. I am invited all over the world to give lectures on our work. Many of my best ideas occur during travel, because I get some distance (literally) and, hence, perspective. I am fortunate that my wife always travels with me. We talk about my new ideas, sometimes in the middle of the night. I believe that traveling stimulates creativity, and getting away from a day-to-day routine really helps.

Q. What do you find most rewarding about your job? What do you find most challenging about your job?

A. The most rewarding aspect of my job is making new discoveries. Being a mentor to students is personally rewarding. I have graduated so far 20 Ph.D. scientists, and they have all gone on to successful careers.

I currently supervise 10 Ph.D. students in my group and they are all part of the Raizen family. My philosophy about science and mentoring students is described in a recent article entitled "Atom Stopper." [For article, see www.utexas.edu/ opa/ blogs/ research/ 2010/ 04/ 26/ atom-stopper/.

Q. What has been the most exciting development in your field in the last 20 years? What do you think will be the most exciting development in your field in the next 20 years?

A. Our work over the past five years has been the most exciting time in my career. We have solved the general problem of trapping and cooling any atom in the periodic table. This will lead to basic tests of fundamental physics, and will also have real applications to society.

Q. How does the research in your field affect our daily lives?

A. Our recent work opens the door to efficient isotope separation, especially important in medicine. This could lead to new cancer treatments which were not available due to the extreme cost of enriched isotopes. We have also developed a method of nanolithography which will impact laser technology, lighting, and solar energy.

Q. For young people interested in pursuing a career in science, what are some helpful things to do in school?

What are some helpful things to do outside of school?

A. The most important thing to do in school is to keep asking questions, even if it irritates your teacher. A good teacher will be delighted by such students. Learning by rote memorization is the kiss of death to discovery. In that regard, the best scientists are "trouble-makers" who do not accept the common wisdom at face value. Never lose your curiosity! Outside of school, try to get involved with research, especially in the summer. I have a high-school student in my lab this summer, and she is working with two undergraduates. Lastly, READ. This includes, literature, history, classics, and not just science. Reading will open your mind to the world around you.

Discussion Questions

In the physics of everyday objects that we learn in high school, momentum is considered to be the product of mass times velocity; clearly, if light does not have any mass, momentum has to mean something else when applied to photons. Try to find out a little about how momentum is understood in connection with photons, and in what ways the concept is similar to, and in what ways different from, the momentum of high school physics.

Journal Abstracts and Articles

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites).

"Measurement of the Instantaneous Velocity of a Brownian Particle." www.sciencemag.org/cgi/ content/ abstract/ science.1189403.

Bibliography

Cassidy, David. "Einstein on Brownian Motion," [accessed June 24, 2010]: www.aip.org/ history/ einstein/ essay-brownian.htm.

"Instantaneous Velocity in Brownian Particles Observed, a Century after Einstein Said it Would Be Impossible." *ScienceDaily* (May 20, 2010) [accessed June 24, 2010]: www.sciencedaily.com/ releases/ 2010/ 05/ 100520141206.htm.

Lemons, Don S. "Paul Langevin's 1908 paper 'On the Theory of Brownian Motion.'" *American Journal of Physics* (November 1997) [accessed June 24, 2010]: www.physik.uni-augsburg.de/ theo1/ hanggi/ History/ Langevin1908.pdf.

"Optical Tweezers: an Introduction." Explanatory website hosted by Stanford University [accessed June 24, 2010]: www.stanford.edu/ group/ blocklab/ Optical %20Tweezers %20Introduction.htm.

Raizen, Mark G., Tongcang Li, et al. "Measurement of the Instantaneous Velocity of a Brownian Particle." *SciencExpress* (online advance publication for *Science*) (May 20, 2010) [accessed June 24, 2010]: www.sciencemag.org/ cgi/ content/ abstract/ science.1189403.

Keywords

Brownian motion, Albert Einstein, statistical mechanics, equipartition theorem, optical tweezer, Mark G. Raizen

---

Modern Language Association (MLA)

Citation:

"Einstein, Right or Wrong . . . But Forever Relevant." *Today's Science*. Facts On File News Services, July 2010. Web. 8 July 2010. <http://192.168.0.52/article/s1800085>.

For further information see Citing Sources in MLA Style.

Facts On File News Services' automatically generated MLA citations have been updated according to the *MLA Handbook for Writers of Research Papers*, 7th edition.

American Psychological Association (APA)

Citation format:

The title of the article. (Year, Month). *Today's Science*. Retrieved Month Day, Year, from Today's Science database.

See the American Psychological Association (APA) Style Citations for more information on citing in APA style.