Comprehensive Control of Atomic Motion

Mark G. Raizen

Recent work provides a general two-step solution to trapping and cooling of atoms. The first step is magnetic stopping of paramagnetic atoms with the use of a sequence of pulsed fields. The second step is single-photon cooling, which is based on a one-way barrier. This cooling method is related intimately to the historic problem of "Maxwell's Demon" and subsequent work by L. Szilard. Here, I discuss the connections between single-photon cooling and information entropy. I also outline future application of these methods to fundamental tests with hydrogen isotopes.

Trapping and cooling of atoms in the gas phase has been a major area of research for over 30 years, motivated by the possibility of more precise spectroscopy, tests of fundamental symmetries, and the study of many-body physics. To date, the standard method has been laser cooling, which relies on momentum kicks that are imparted to atoms by repeated cycles of photon absorption followed by spontaneous decay (*1*). Despite the enormous success of laser cooling, it has been limited to a rather small set of atoms in the periodic table because of two constraints. First, a simple two-level transition is required so that an atom can absorb a resonant photon and spontaneously decay back to the same state, enabling many cycles of the process. Second, the transition must be accessible with tunable lasers. These two constraints exclude most of the periodic table, as well as any molecules, because of the generally complicated multi-level energy structure. To sharpen this point, the simplest atom in the periodic table, hydrogen, is not amenable to laser cooling because of the lack of appropriate lasers in the far-ultraviolet region of the spectrum. The case of hydrogen is already compelling for fundamental physics: Precision spectroscopy of hydrogen isotopes (H, D, and T) would benefit enormously from trapping and cooling methods. Such methods would also enable precision measurement of beta decay of atomic tritium and would enable a breakthrough in the long-standing quest to study anti-hydrogen. Why should we be interested in general methods beyond hydrogen? One reason is that they could be an attractive alternative to standard laser cooling, especially for light alkalis such as lithium or sodium. Another reason is that there is a growing list of atoms that have been proposed for fundamental tests or applications (several examples are As, Co, Dy, Fe, Ga, In, and Ra). One thing is clear: Comprehensive methods of cooling and trapping will stimulate the scientific community to study other atoms, and it is very likely that these will lead to new discoveries. In this article, I review recent results that provide a comprehensive two-step solution to trapping and cooling of almost any atom in the periodic table. I then describe how these methods will be applied to the special case of hydrogen isotopes.

From Room Temperature to Sub-Kelvin

The starting point for atoms in the laboratory is typically room temperature, where they are often in the solid phase. They can be converted to the gas phase either by heating in an oven or by laser ablation. The first question is how to cool the atoms from room temperature to a fraction of a degree Kelvin without the advantage of laser cooling. Rather than answer that directly, I follow with another question: What is the one property of atoms that is nearly universal? The answer is magnetism. Nearly all atoms (in their ground or first metastable electronic state) exhibit paramagnetism due to an unpaired electron in the outer orbital. This has led to cooling of atoms by using helium as a cryogenic buffer gas and then

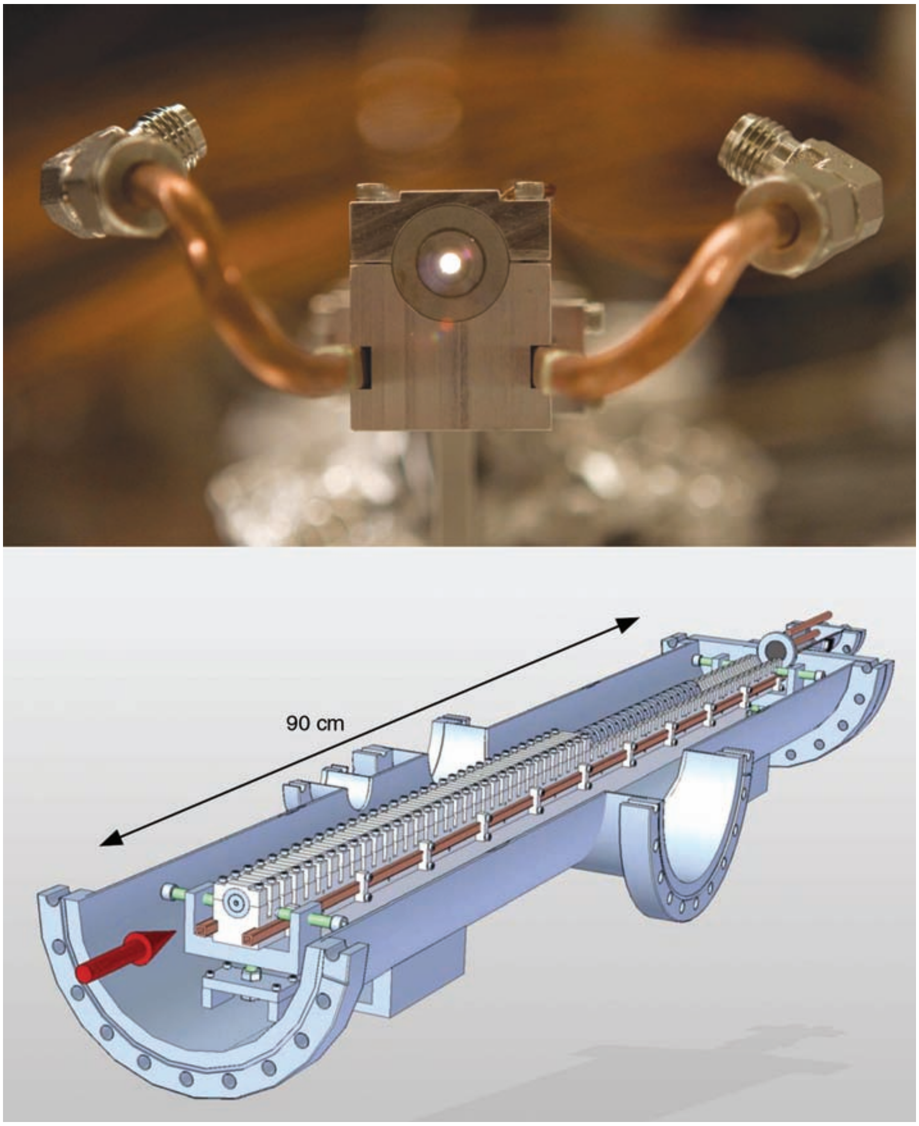

Fig. 1. Experimental set-up for the atomic coilgun. (**Top**) Photo of the assembled coilgun, head on and illuminated from the back. (**Bottom**) Schematic of the 64-stage coilgun.

Center for Nonlinear Dynamics and Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA. E-mail: raizen@physics.utexas.edu

trapping them magnetically at a field minimum created inside the cryostat. This method, known as buffer gas cooling, can work on any paramagnetic atom or molecule and has been used in a range of experiments over the past decade (*2–4*). The drawbacks of this method are the high cost and complexity of cryogenic methods and the limited optical access. It has been recognized that it would be extremely valuable to be able to trap atoms at similar temperatures, but in a simple vacuum chamber that can afford better optical access.

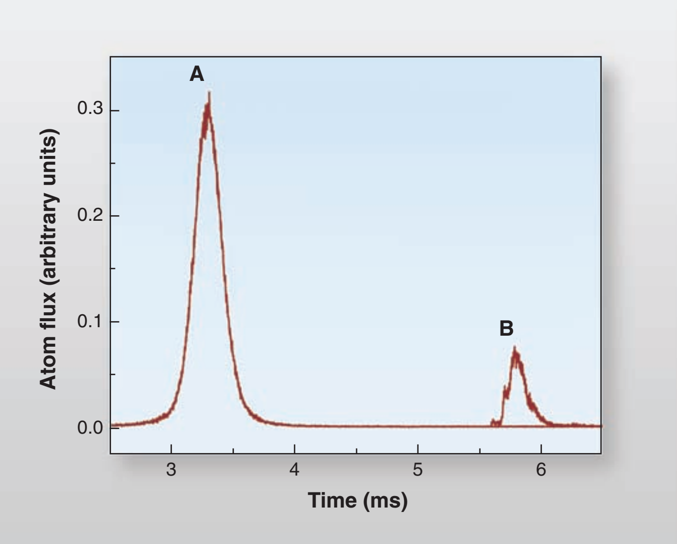

Fig. 2. Magnetic stopping of a supersonic beam of metastable neon with an atomic coilgun. The metastable atoms are detected in time-of-flight, and their delay after the firing of the valve is measured in milliseconds. The initial distribution (**A**) had a velocity of 447 m/s. The final distribution (**B**) had a velocity of 56 m/s that was required to direct the atoms to the detector (*13*).

The starting point for these experiments is the supersonic molecular beam, which has been the workhorse of physical chemistry for many years (*5*). In these devices, a high-pressure (multi-atmosphere) inert gas expands through a small aperture into vacuum and undergoes adiabatic cooling. The properties of such beams are notable, as they are nearly monoenergetic, with a relative velocity spread of less than 1% of the mean velocity. In the co-moving frame, the temperature of the gas is in the range of tens of millikelvin. This distribution is clearly nonthermal, as it has a large forward velocity. Supersonic beams are typically operated in a pulsed mode with an actuated valve so that vacuum can be maintained without too large a gas load. The pulsed source is therefore a "bullet" of gas-phase atoms traveling down the chamber at a very well-defined velocity, launched at the precise opening time of the valve. The supersonic beam serves as a universal platform for cold but fast atoms or molecules: The carrier gas can be "seeded" with another species if it is already in the gas phase. Alternatively, atoms or molecules can be entrained into the flow near the output of the supersonic valve by laser ablation of a nearby target. Further downstream (typically 10 cm or more), the two species decouple collisionally as they expand, and the density drops. This led us to propose that paramagnetic atoms could be stopped with the use of a series of pulsed electromagnetic coils (*6*). The principle of magnetic deceleration is conceptually simple and bears close resemblance to a coilgun, which is used to launch macroscopic ferromagnetic projectiles by fast switching of electromagnetic coils. The atomic coilgun also has some similarities to the Stark decelerator, which uses pulsed electric fields to stop supersonic beams of polar molecules (*7–9*).

For the case of atoms, they can be classified in terms of their response to external magnetic fields. Atoms in low-field–seeking states minimize their potential energy by going to a lower magnetic field. Consider an atom entering an electromagnetic coil, climbing a potential hill and slowing down. When the atom reaches the top of the magnetic hill, the magnetic field is suddenly switched off. Due to conservation of energy, the amount of the kinetic energy lost is equal to the energy shift, induced by the magnetic field. In the ideal operation of the atomic coilgun, the width of the velocity distribution is not changed, but the mean velocity in the laboratory frame is removed. This is not a cooling process but simply a translation in velocity space. After stopping the atoms, they can be confined in a magnetic trap. The timing of the coils can be optimized following the method of phase stability, as first developed for synchrotrons (*10*, *11*). There is a trade-off between the number of stages in the coilgun and the total flux of atoms that can be stopped. In general, a low phase angle corresponds to turning off the coils before the atoms reach the peak magnetic field, making the process more stable. Following the conceptual development and design stage, the coilgun was constructed, and the experimental set-up is shown (Fig. 1). A beam of metastable neon, as well as a beam of molecular oxygen, were stopped (*12–14*), and representative data with neon is displayed (Fig. 2). Parallel and independent work demonstrated stopping of atomic hydrogen (*15–17*).

Once the atoms are stopped, they can be trapped in static magnetic fields that create a field minimum. Such coils are used to store ultracold atoms after laser cooling and are the typical starting point for Bose-Einstein condensation experiments. The simplest configuration is to have two coils with currents running in opposite directions, known as an anti-Helmholz pair. This creates a point in the center where the magnetic field is zero and increases in all directions.

Single-Photon Cooling

After the atoms are magnetically trapped, the next question is how to cool them further, from

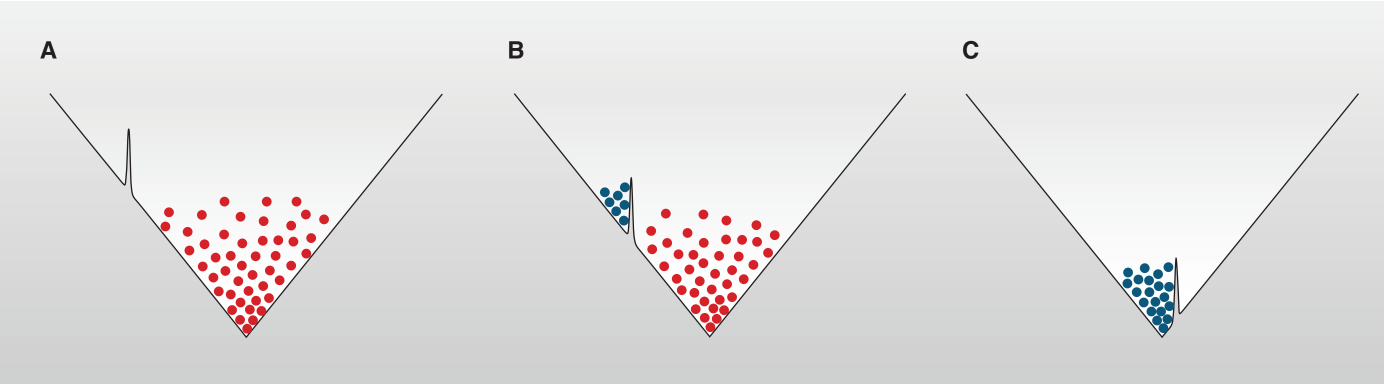

Fig. 3. Illustration of single-photon cooling in one dimension. The potential is from a magnetic trap. The one-way wall is swept from the left, catching atoms near their classical turning points. As they cross the wall, the atoms change state, as indicated by the change in color from red to blue. In (**A**), the wall is to the left of all of the particles, in (**B**), some particles are captured, and in (**C**), all of the particles are captured.

tens of millikelvin. This temperature is still very far from the limits reached by laser cooling and would not be very interesting without a way to go lower. One possible approach is to use evaporative cooling, whereby the hottest atoms are ejected from the trap, and the remaining atoms reequilibrate by collisions. However, in most cases, the initial density produced with this method is small, resulting in very long re-equilibration times and making it impractical to realize evaporative cooling during the trap lifetime. The other potential problem with evaporative cooling is that the trapped, low-field–seeking atoms can collide and change to high-field seekers that are ejected from the trap.

The approach I took was inspired by a seemingly unrelated question: Is it possible to make a barrier or wall for atoms that is "one-way"? In other words, atoms impinging from one direction can pass through, whereas atoms coming from the other directions are turned back. This one-way operation occurs in nature; for example, ion channels in cell membranes that regulate flow and maintain osmotic pressure. The question is posed here with respect to atoms in gas inside a vacuum chamber, which is quite different than anything that occurs in biology. Surprisingly, the answer is yes, as was shown in a series of papers four years ago (*18*–*21*). The basic construction is to combine a conservative potential with an irreversible step. The conservative potential is, in general, created by electromagnetic fields, which hold the atoms away from the walls of the vacuum chamber. The two viable possibilities are magnetic fields or light. The former was discussed earlier in the context of the atomic coilgun. The latter is most familiar in the context of optical tweezers. These are focused beams of light that create an attractive or repulsive potential for atoms, depending on whether they are tuned to the red or blue of an atomic transition. The irreversible step for an atom is absorption of light at a specific wavelength, followed by spontaneous decay to a different internal state.

Showing how the one-way wall can be used to cool translational motion is interesting. The principle of operation is best illustrated for a one-dimensional (1D) central potential (such as a magnetic trap) (Fig. 3). Initially, particles are contained in the main trap, and a one-way wall is placed in the wings. Atoms reaching that region are at their classical turning points where they have converted all their kinetic energy into potential energy. After passing through the one-way wall, they are trapped by scattering a single photon that changes the internal state. As the one-way wall is swept from the left, all of the atoms are captured. This method is called single-photon cooling, because the trapping process is accomplished via a single-photon scattering event. Laser cooling, in contrast, entails multiple cycles of scattering. A three-level model is the simplest example where single-photon cooling works; however, any multi-level structure is possible. Ironically, the only case that cannot work is a two-level atom, which is the prerequisite for laser cooling. Another point to emphasize is that although particle motion is in three dimensions, trap ergodicity can couple these degrees of freedom so that cooling in one direction can be sufficient.

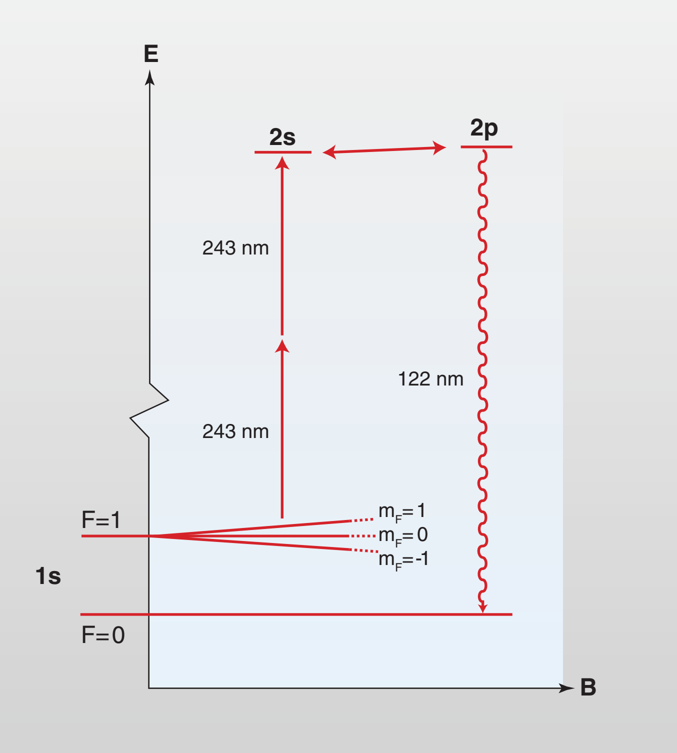

Fig. 4. Schematic of transitions in atomic hydrogen. The 1S ground state is split into two hyperfine states (F = 1 and F = 0), separated by 1.42 GHz. The F = 1 state is split into three states as a function of magnetic field, denoted with "B." A two-photon transition near 243 nm excites the atoms to the 2S state. This state is coupled to the 2P state, which decays by emitting a Lyman alpha photon near 121 nm. The energy axis is not to scale.

One proposal for the one-way barrier was a hybrid magnetic/optical approach, and this method led to efficient cooling of atoms (*22*–*24*). Subsequently, an all-optical method following the original proposal was demonstrated, although it could not be used for cooling due to the lasers being close to atomic resonance where heating dominates (*25*).

An all-magnetic approach can improve the cooling effect by providing a 2D trapping surface that catches nearly all the atoms near their turning points (*26*). Although these experiments prove the viability of single-photon cooling, they were still performed on rubidium atoms where standard laser is possible. The next step is to implement single-photon cooling for atoms that are not amenable to laser cooling. Atomic hydrogen is the most compelling case. Before describing these future directions, I make a historical digression to understand the fundamental nature of single-photon cooling in terms of information entropy.

Maxwell's Demon and the Szilard Engine

In 1871, James Clerk Maxwell proposed a thought experiment that is still a topic of controversy and discussion today (*27*, *28*). He considered a chamber with gas particles separated by a wall with a trap door. Maxwell envisaged an "intelligent being with deft hands" who could see the coming and going of particles and open or close the trap door appropriately. This creature became known as "Maxwell's Demon" and appeared to violate the second law of thermodynamics, as the Demon could lower the entropy of the gas without doing any work. The resolution to this paradox took many years to evolve, and the most important contribution was by L. Szilard (*29*). He first proposed an engine that could run from a single heat bath using the Demon, in clear violation of the second law (*30*, *31*). The resolution Szilard proposed was that the Demon collects information every time that the trap door is opened. This information, he argued, carries entropy that exactly balances the entropy decrease of the gas, thereby saving the second law. The concept that information has real physical meaning was arguably the start of modern information science. The role of information in cooling has been the topic of much discussion over the years and was the basis for stochastic cooling of charged particles in accelerators (*32*). However, the information content and overall efficiency in that case is extremely small, as only a small pick-up coil is used to detect the particle motion and a fast electronic feedback loop was required.

I now return to single-photon cooling and examine its connection with Maxwell's Demon. A theoretical analysis shows that, as each atom scatters one photon, information is provided about the turning point and the energy of that particle. A calculation of the entropy increase of the radiation field scattered from a directional laser into a random direction shows that, in fact, it exactly balances the entropy reduction of the atoms as they are trapped with the one-way wall (*33*, *34*). Therefore, single-photon cooling is a physical realization of Maxwell's Demon. The demon, in this case, is particularly simple and efficient: a laser beam that induces an irreversible process and scatters one photon from the beam. Such a demon is certainly not an intelligent being, yet it does not need an active feedback loop. The fact that the information is available and can in principle be collected is enough.

Future Directions

The possibility of trapping and cooling almost any atom in the periodic table will undoubtedly open new areas of research. The same methods should also work on any paramagnetic molecule, which will enable the study of ultracold chemistry (*26*). Here I concentrate on the simplest atom in the periodic table, hydrogen, and show that new tests of fundamental physics become possible.

Hydrogen is the most abundant element in the universe and serves as the Rosetta Stone of physics. The two other isotopes of hydrogen are deuterium, with one neutron, and tritium, with two neutrons. There is a long and rich history of experiments on atomic hydrogen and related theory. The story starts with the measurement and explanation of hydrogen spectra, one of the first major successes of quantum mechanics. The story continues with the Lamb shift and the triumph of quantum electrodynamics, still the best tested theory today. In recent years, trapping and cooling of hydrogen was accomplished with heroic efforts using a dilution refrigerator and evaporative cooling (*35*). The pinnacle of quantum control, Bose-Einstein condensation, was even achieved with hydrogen (*36*). These trapping methods have not been extended to deuterium or tritium and have now been discontinued. Further progress hinges on new methods to trap and cool hydrogen isotopes in a simple room temperature apparatus. In parallel, ultrasensitive spectroscopy on hydrogen and deuterium beams has reached an exquisite level of precision due to the advent of the frequency comb (*37*, *38*).

The methods described above are perfectly suited to trapping and cooling of all three isotopes of hydrogen. The starting point will be a supersonic beam of molecular hydrogen in a neon carrier gas. The molecules will be dissociated with a discharge near the nozzle, and the atomic coilgun will stop the atoms and confine them in a magnetic trap. In fact, hydrogen has already been stopped and trapped with a coilgun (*17*). The structure of hydrogen is ideally suited to single-photon cooling, although it requires a laser near 243 nm to drive a two-photon transition to a metastable 2S state (Fig. 4). The atoms in the $F = 0$, $m = 0$ state will be optically trapped in a standing wave of light inside a build-up cavity.

One of the first goals with trapped hydrogen isotopes will be to push the current limits of ultrahigh precision spectroscopy, especially needed for tritium. More importantly, trapping and cooling of atomic tritium may hold the key to the determination of the neutrino rest mass, one of the most pressing questions in modern physics. A recent concept paper showed how a sample of trapped ultracold tritium serves as an ideal system for neutrino mass measurement by kinematic reconstruction of the recoiling electron in coincidence with the recoiling helium ion (*39*).

The same methods will also work for trapping and cooling of anti-hydrogen (*40*, *41*). In this case, the supersonic beam method cannot be used as the starting point. Instead, a beam of anti-hydrogen could be generated by launching anti-protons through a positron cloud and then stopped and cooled with our methods. Experiments with anti-hydrogen will be able to answer the simple question: Does anti-matter fall the same way as matter? Such experiments can also test charge-parity-time reversal invariance, believed to be a fundamental symmetry of nature. These examples illustrate that hydrogen and its isotopes hold the key to many unanswered questions about the universe.

In the short term, work will concentrate on optimizing the efficiency of the atomic coilgun. The first possible improvement is to mode-match the incident beam to the coilgun by magnetic focusing. I am also investigating the possibility of an adiabatic magnetic slower in which the atoms would be trapped in three dimensions throughout the entire stopping process. This would then preserve the initial phase space density, translating the atoms to rest in the laboratory frame. The case of single-photon cooling must be further developed, and the limitations of the method have to be studied. For example, the density limit has not been reached and must be studied further. A quantum analysis of single-photon cooling has not yet been developed. The temperature that can be reached is limited to the photon recoil, as opposed to evaporative cooling that has no such limit. I envisage that single-photon cooling is most suitable as the first stage, followed by evaporation in an optical trap to reach quantum degeneracy.

References and Notes

1. H. J. Metcalf, P. van der Straten, *Laser Cooling and Trapping* (Springer, New York, 1999).
2. J. D. Weinstein, R. deCarvalho, T. Guillet, B. Friedrich, J. M. Doyle, *Nature* **395**, 148 (1998).
3. C. I. Hancox, S. C. Doret, M. T. Hummon, L. Luo, J. M. Doyle, *Nature* **431**, 281 (2004).
4. W. C. Campbell, E. Tsikata, H. Lu, L. D. van Buuren, J. M. Doyle, *Phys. Rev. Lett.* **98**, 213001 (2007).
5. G. Scoles, Ed., *Atomic and Molecular Beam Methods*, vols. 1 and 2 (Oxford Univ. Press, New York, 2000).
6. E. Narevicius *et al.*, *New J. Phys.* **9**, 96 (2007).
7. H. L. Bethlem, G. Berden, G. Meijer, *Phys. Rev. Lett.* **83**, 1558 (1999).
8. S. Y. T. van de Meerakker, P. H. M. Smeets, N. Vanhaecke, R. T. Jongma, G. Meijer, *Phys. Rev. Lett.* **94**, 023004 (2005).
9. B. C. Sawyer *et al.*, *Phys. Rev. Lett.* **98**, 253002 (2007).
10. E. M. McMillan, *Phys. Rev.* **68**, 143 (1945).
11. V. Veksler, *J. Phys. (USSR)* **9**, 153 (1945).
12. E. Narevicius *et al.*, *New J. Phys.* **9**, 358 (2007).
13. E. Narevicius *et al.*, *Phys. Rev. Lett.* **100**, 093003 (2008).
14. E. Narevicius *et al.*, *Phys. Rev. A* **77**, 051401 (2008).
15. N. Vanhaecke, U. Meier, M. Andrist, B. H. Meier, F. Merkt, *Phys. Rev. A* **75**, 031402 (2007).
16. S. D. Hogan, D. Sprecher, M. Andrist, N. Vanhaecke, F. Merkt, *Phys. Rev. A* **76**, 023412 (2007).
17. S. D. Hogan, A. W. Wiederkehr, H. Schmutz, F. Merkt, *Phys. Rev. Lett.* **101**, 143001 (2008).
18. M. G. Raizen, A. M. Dudarev, Q. Niu, N. Fisch, *Phys. Rev. Lett.* **94**, 053003 (2005).
19. A. Ruschhaupt, J. G. Muga, *Phys. Rev. A* **70**, 061604 (2004).
20. Reference (*19*) was submitted shortly after (*18*), but the work cited in (*19*) was independent.
21. A. M. Dudarev, M. Marder, Q. Niu, N. Fisch, M. G. Raizen, *Europhys. Lett.* **70**, 761 (2005).
22. G. N. Price, S. T. Bannerman, E. Narevicius, M. G. Raizen, *Laser Phys.* **17**, 965 (2007).
23. G. N. Price, S. T. Bannerman, K. Viering, E. Narevicius, M. G. Raizen, *Phys. Rev. Lett.* **100**, 093004 (2008).
24. S. T. Bannerman, G. N. Price, K. Viering, M. G. Raizen, *New J. Phys.*, in press; preprint available at http://arXiv.org/abs/0810.2239.
25. J. J. Thorn, E. A. Schoene, T. Li, D. A. Steck, *Phys. Rev. Lett.* **100**, 240407 (2008).
26. E. Narevicius, S. T. Bannerman, M. G. Raizen, *New J. Phys.*, **11**, 055046 (2009).
27. J. C. Maxwell, in *Theory of Heat* (Longmans, Green, London, 1871), pp. 308–309.
28. H. S. Leff, A. Rex, Eds., *Maxwell's Demon: Entropy, Information, Computing* (Princeton Univ. Press, Princeton, NJ, 1990).
29. L. Szilard, *Z. Phys.* **53**, 840 (1929).
30. R. J. Scully, M. O. Scully, *The Demon and the Quantum* (Wiley-VCH, Weinheim, Germany, 2007).
31. P. A. Skordos, W. H. Zurek, *Am. J. Phys.* **60**, 876 (1992).
32. S. Van der Meer, *Rev. Mod. Phys.* **57**, 689 (1985).
33. A. Ruschhaupt, J. G. Muga, M. G. Raizen, *J. Phys. At. Mol. Opt. Phys.* **39**, 3833 (2006).
34. P.-M. Binder, *Science* **322**, 1334 (2008).
35. H. Hess *et al.*, *Phys. Rev. Lett.* **59**, 672 (1987).
36. D. G. Fried *et al.*, *Phys. Rev. Lett.* **81**, 3811 (1998).
37. J. L. Hall, *Rev. Mod. Phys.* **78**, 1279 (2006).
38. T. Hänsch, *Rev. Mod. Phys.* **78**, 1297 (2006).
39. M. Jerkins, J. Majors, J. R. Klein, M. G. Raizen, preprint available at http://arXiv.org/abs/0901.3111.
40. M. Amoretti *et al.*, *Nature* **419**, 456 (2002).
41. G. Gabrielse *et al.*, *Phys. Rev. Lett.* **89**, 213401 (2002).

42. This work is supported by NSF, the Army Research Office, the R. A. Welch Foundation, the State of Texas Advanced Research Program, and the Sid W. Richardson Foundation.

10.1126/science.1171506

Comprehensive Control of Atomic Motion

Mark G. Raizen

Science **324**, 1403 (2009);
DOI: 10.1126/science.1171506

This copy is for your personal, non-commercial use only.

If you wish to distribute this article to others, you can order high-quality copies for your colleagues, clients, or customers by clicking here.

Permission to republish or repurpose articles or portions of articles can be obtained by following the guidelines here.

The following resources related to this article are available online at www.sciencemag.org (this information is current as of March 20, 2015):

Updated information and services, including high-resolution figures, can be found in the online version of this article at:
http://www.sciencemag.org/content/324/5933/1403.full.html

This article **cites 32 articles**, 1 of which can be accessed free:
http://www.sciencemag.org/content/324/5933/1403.full.html#ref-list-1

This article appears in the following **subject collections:**
Physics
http://www.sciencemag.org/cgi/collection/physics

Downloaded from www.sciencemag.org on March 20, 2015

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published weekly, except the last week in December, by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. Copyright 2009 by the American Association for the Advancement of Science; all rights reserved. The title *Science* is a registered trademark of AAAS.