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14. ABSTRACT We report the development of general methods for trapping and cooling of atoms and molecules for atom optics and interferometry. The starting point of this work is the supersonic beam which produces a monochromatic, but fast beam of a noble-gas carrier gas. Atoms or molecules can generally be seeded or entrained into the supersonic beam flow. In one approach, ground-state helium atoms were slowed by reflection from Si(111) mounted on a spinning rotor. In order to stop and trap other atoms, we developed a multi-stage "atomic coilgun" consisting of					
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Report Title

Noble-Gas Atomic Interferometer

ABSTRACT

We report the development of general methods for trapping and cooling of atoms and molecules for atom optics and interferometry. The starting point of this work is the supersonic beam which produces a monochromatic, but fast beam of a noble-gas carrier gas. Atoms or molecules can generally be seeded or entrained into the supersonic beam flow. In one approach, ground-state helium atoms were slowed by reflection from Si(111) mounted on a spinning rotor. In order to stop and trap other atoms, we developed a multi-stage “atomic coilgun” consisting of miniature electromagnets with each one generating a short magnetic pulse. We were able to use this device to slow and then stop a supersonic beam of metastable neon atoms. The same apparatus was next used to stop a beam of molecular oxygen. In parallel, we have developed a general method of cooling that does not require a cycling transition and can be used to accumulate magnetically trapped atoms in an optical tweezer near the recoil temperature. This method, single-photon cooling, is based on a one-way wall for atoms and molecules. The combination of two methods provides a two-step solution to trapping and cooling that will work on most of the periodic table.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. "Towards coherent control of supersonic beams: a new approach to atom optics," A. Libson, M. Riedel, G. Bronshtein, E. Narevicius, U. Even, and M. G. Raizen, New J. Phys. 8, 77 (2006).
2. "Coherent slowing of a supersonic beam with an atomic paddle," E. Narevicius, A. Libson, M. F. Riedel, C. G. Parthey, I. Chavez, U. Even, and M. G. Raizen, Phys. Rev. Lett. 98, 103201 (2007).
3. "Towards magnetic slowing of atoms and molecules," E. Narevicius, C. G. Parthey, A. Libson, M. Riedel, U. Even, and M. G. Raizen, New J. Phys. 9, 96 (2007).
4. "An atomic coilgun: using pulsed magnetic fields to slow a supersonic beam," E. Narevicius, C. G. Parthey, A. Libson, J. Narevicius, I. Chavez, U. Even, and M. G. Raizen, New J. Phys. 9, 358 (2007).
5. "Stopping supersonic beams with a series of pulsed electromagnetic coils: an atomic coilgun," E. Narevicius, A. Libson, C. Parthey, I. Chavez, J. Narevicius, U. Even, and M. G. Raizen, Phys. Rev. Lett. 100, 093003 (2008).
6. "Stopping supersonic oxygen with a series of pulsed electromagnetic coils: a molecular coilgun," E. Narevicius, A. Libson, C. Parthey, I. Chavez, J. Narevicius, U. Even, and M. G. Raizen, Phys. Rev. A (Rapid) 77, 051401 (2008).
7. "Single photon molecular cooling," E. Narevicius, S. T. Bannerman, and M. G. Raizen, New J. Phys. 11, 055046 (2009).
8. "Comprehensive control of atomic motion," M. G. Raizen, Science 324, 1403 (2009).

Number of Papers published in peer-reviewed journals: 8.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

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(d) Manuscripts

Number of Manuscripts:0.00

Patents Submitted

Patents Awarded

Awards

W. E. Lamb Medal for Laser Science and Quantum Optics (2008).

Lewiner Distinguished Lecturer, Technion, Israel (2009).

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Adam Libson	1.00
Tomas Mazur	1.00
FTE Equivalent:	2.00
Total Number:	2

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
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Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):

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The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:

Names of Personnel receiving masters degrees

NAME

Isaac Chavez

Christoph Schaefer

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Max Riedel

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Names of personnel receiving PhDs

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1

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

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Scientific Progress

Trapping and cooling of atoms in the gas phase has been a major area of research for over thirty years. The advances in this field were enabled by laser cooling, which was recognized by a Nobel Prize in Physics in 1997. Despite the enormous success of this method, it has been limited to a small set of atoms in the periodic table. The reason for the limited applicability of laser cooling is that it requires a two-level cycling transition and one that is accessible with stabilized lasers. These constraints have excluded most of the periodic table as well as any molecules.

The potential impact of general trapping and cooling methods is great, ranging from fundamental physics and chemistry to important technological applications in atom optics and interferometry.

In the past few years, my group has pioneered new approaches to trapping and cooling. The starting point of this work is the supersonic beam which produces a monochromatic, but fast beam of a noble-gas carrier gas. Atoms or molecules can generally be seeded or entrained into the supersonic beam flow. As a first step, we developed a single-crystal mounted on a spinning rotor in vacuum to slow ground state helium by elastic reflection. The slowing in this case is purely kinematic, just as a tennis ball is slowed or stopped by a receding racket. To implement this concept experimentally, we designed a tapered titanium rod (1 meter diameter) that was mounted in the center of a vacuum chamber to a ferro-fluidic feedthrough and a motor outside the chamber. The beam velocity was 520 m/s and we reached a tip velocity of 130 m/s so that the beams was slowed by 260 m/s to approximately to half of its initial value. In the first set of experiments we used single crystal Si(111) that was passivated by atomic hydrogen. More recent experiments were performed with single crystal Lithium Fluoride which was cleaved. The advantage of LiF is that it is much more inert than Si, and can be cleaned in-situ with metastable helium atoms. While the slowing experiments worked as predicted, they cannot be generalized beyond ground state helium, as heavier atoms will either stick on impact, or undergo inelastic scattering. A more general approach was needed.

We proposed that paramagnetic atoms in the supersonic beam could be stopped using a series of pulsed electromagnetic coils. All atoms in the periodic table have a magnetic moment in their ground state or in a long-lived metastable state allowing the control of the atomic motion using magnetic fields. The principle of magnetic deceleration is conceptually simple: low-field seekers lose kinetic energy by moving into the high magnetic field region at the center of an electromagnetic coil. 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 Zeeman energy shift. In the ideal operation of the atomic coilgun, the velocity distribution of the atoms is not changed, but the mean velocity in the laboratory frame is removed. This is therefore not a cooling process, simply a translation in velocity space. After stopping the atoms, they can be confined in a magnetic quadrupole trap.

We used a supersonic valve developed by Prof. Uzi Even from Tel-Aviv University who has collaborated with us on the first generation of experiments. The unique features of this valve are a pulse duration as short as 10 microseconds (FWHM) at a repetition rate of 40 Hz, combined with cryogenic operation. The small gas load enables the use of compact turbo-molecular pumps instead of large diffusion pumps. The valve can operate up to 100 atmospheres leading to a supersonic beam that is very directional (half-angle of seven degrees) and very monochromatic (less than 1 percent relative spread in velocity). Starting from conical nozzles and carefully optimizing performance, together with hydrodynamic simulations, led to the development of a trumpet nozzle design. The result is a beam brightness of 4×10^{23} atoms/sr.s, an order of magnitude better than anything reported to date. The atoms in the supersonic beam have a typical velocity spread of only 10 m/s, corresponding to a temperature of about 15 mK for helium.

The paramagnetic species decouples from the carrier gas downstream from the valve where the coilgun is located. The latest generation device consists of 64 miniature coils, each driven with separate circuit and the firing sequence is computer controlled. We invested a considerable effort in the design of the coils and the related drive electronics. The goal was to reach a peak field of several Tesla with a turn-off time of under 10 microseconds with a scalable and cost-effective approach. The result is that each coil now produces a peak field of 5.2 Tesla and a turn-off time of only 6 microseconds. Each coil is driven by a discharging capacitor and switching is accomplished by a combination of an integrated-gate bipolar transistor (IGBT) and a thyristor. Recent advances in these solid-state devices make it possible to switch currents as high as 1000 A. The cost for one driver circuit is under \$25, so that a complete coilgun assembly is very simple and economical.

We chose to start with metastable neon due to the ease of detection with a micro-channel plate (MCP). A supersonic beam of pure neon was excited in a gas discharge to produce metastable atoms. The precise timing of the firing of the valve was synchronized with the firing of the slowing coils. We have also stopped a beam of molecular oxygen with the same apparatus. In parallel, a group at ETH Zurich has also been working on magnetic deceleration and has constructed a 12-stage coilgun where each coil has a peak field of 1.4 Tesla. They have used this device to stop a beam of atomic hydrogen.

The next step is to cool the atoms further, and to realize this goal, we developed a method we call single-photon cooling. The basic construction is a one-way barrier for atoms or molecules, that we proposed in 2004. Consider an optical tweezer placed near a sample of magnetically trapped atoms. We focus inside the tweezer a "depopulation" beam that is tuned to drive an electronic transition followed by spontaneous decay. The key point is that for a subset of atoms that reach this depopulation beam, the decay changes two quantum numbers simultaneously: the first is a change in magnetic quantum number to a lower value, while the second is a change in the internal state (such as hyperfine state for atoms, or rotational state for molecules). The change in magnetic quantum number has the effect that the tilt due to the magnetic trap is reduced, opening up a bound

state. The change in the other state (such as hyperfine) has the effect that those atoms cannot be re-excited by the depopulation beam as it is off resonance. This enables one-way accumulation of atoms in the tweezer near the recoil temperature. To optimize this process, the center of the magnetic trap is scanned relative to the tweezer, and atoms are captured near their classical turning points. Each atom only scatters one photon on average as it enters the tweezer trap in an irreversible process. We have shown that this cooling method is a physical realization of a proposal due to Leo Szilard from 1929 in an effort to explain Maxwell's demon in terms of information entropy.

Single-photon cooling was demonstrated experimentally on magnetically trapped rubidium atoms that were loaded from optical molasses [32]. We started with atoms in a quadrupole trap at 100 microkelvin in the $F=2$, $m=2$ ground state. We constructed an optical "cup" with five laser beams at 532 nm. The cup is placed under the magnetic trap and a depopulation beam is tuned from the initial ground state to the $F'=1$ excited state. In about 42% of the time, the atoms decay to the $F=1$, $m=0$ state where they are trapped in the optical cup. We swept the center of the magnetic trap by applying a bias current to one coil, and accumulate 10^6 atoms in the cup in 700 ms of sweep time. We observed a factor of 350x increase in phase space density. This is a large cooling effect, and further improvements are likely. We showed theoretically that single-photon cooling can be applied to molecules, and several groups are now pursuing this experimentally. The current effort in my group is to apply the above methods for trapping and cooling of hydrogen isotopes, which will enable precision measurements and new fundamental tests.

Technology Transfer