Laser Cooling of Atoms

The concept of radiation-pressure cooling of atoms was independently suggested in 1975 for the case of a gas of neutral atoms by Hänsch and Schawlow, and for atomic ions bound in an electromagnetic trap by Wineland and Dehmelt. While the notion that momentum exchange from a photon moving in the opposite direction could slow an individual atom was well understood, until this time no one had come up with a means for producing an aggregate cooling of a larger ensemble of atoms (a gas). If all atoms in a hot gas absorb photons, then some will be heated and some cooled, and the ensuing equilibrium temperature is not lowered. The general feature of the cooling concepts is that a gas of atoms or ions can be cooled by ensuring that photon absorption takes place preferentially when the atoms or ions are moving against the flow of photons from a laser.

In 1978, following these ideas, Wineland, Drullinger, and Walls performed their seminal experiment [1] in which they demonstrated the very first radiation-pressure cooling below ambient temperature of any atomic species. The key to the experiment was the variation in photon absorption associated with the Doppler frequency shift. They used a collection of positive magnesium ions contained in an electromagnetic trap subjected to laser radiation near the ~280 nm resonance of the magnesium ion. When this laser radiation was tuned slightly below resonance, cooling to below 40 K was observed. For this particular tuning, those ions with motions opposing the laser radiation are Doppler shifted toward resonance and are more likely to absorb photons, thus slowing their motions. Ions moving away from the source are Doppler shifted further from resonance and are thus less likely to absorb photons. Since the re-radiation from this excited state is symmetric, the net effect averaged over the ensemble of atoms is a cooling of the gas of ions. The very next year, Wineland and Itano [2] published a paper providing the first detailed theoretical analysis of laser cooling, which served as the foundation for the rapid development of this field. In ensuing years, they improved their methods and soon cooled ions to millikelvin temperatures.

This experimental demonstration stimulated the development of a large number of ion-cooling groups around the world and encouraged others to attempt to cool neutral atoms. In fact, it was only a few years later (in 1982) that a beam of neutral atoms was cooled by Bill Phillips and his collaborators at NIST (as described elsewhere in this volume). These ideas have contributed significantly to atomic-clock technology. Clocks using both trapped ions [3] and cooled neutral atoms [4] have now demonstrated frequency uncertainties of a few parts in 10^{15}, an improvement of an order of magnitude over conventional atomic-clock technology. Further improvements will certainly be demonstrated over the next few years. The potential of the cooled-ion standards can be appreciated by recognizing that, for a small group of ions, the systematic frequency shifts are now understood at an uncertainty level of 1 part in 10^{18}.

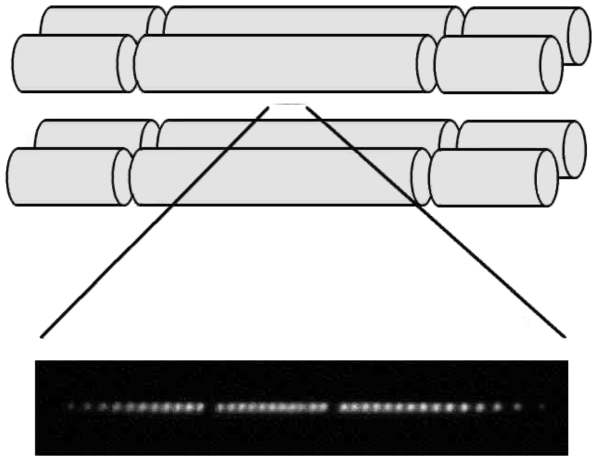

Fig. 1. A schematic diagram of a linear ion trap using alternating and static electric fields to confine linear arrays or "strings" of ions. The expanded ultraviolet image at the bottom shows the fluorescence image of an array of positive mercury ions.

Based on this early work, NBS established an Ion Storage Group in Boulder; the Group now includes five full-time staff members and a number of postdoctoral associates, guests, and students. After the initial cooling experiments, the methods were improved, but particularly striking results were obtained by cooling at the sideband frequency created by the periodic motion of the trapped ions. Using this method, the Group achieved, for the first time, cooling to the zero-point energy of motion [5,6], the fundamental limit for any cooling technique.

A unique aspect of the ion-cooling work has been the ability to do experiments with individual atoms. The NBS Group developed remarkable techniques that allowed them to observe and control both the motional and internal quantum states of individual ions, and thereby to confirm experimentally some of the fundamental concepts upon which quantum mechanics is based. For example, they observed individual quantum transitions of a single ion with 100 % probability [7], performed Young's classical light interference experiment with radiation scattered by two ions [8], performed absorption spectroscopy on a single ion [9], observed fundamental quantum-projection noise [10], and demonstrated a "Schrödinger-cat" entangled superposition state of an atom [11]. The ability to control completely the states of ions has led them to show that properly coupled ions can perform simple quantum-logic operations [12]. While the realization of a useful quantum computer faces severe obstacles, the projected performance of such a computer is so great that many groups worldwide have now begun to pursue this objective. The NIST Ion-Storage Group continues to work at the forefront of this field.

Another important line of work that grew out of this program has been the study of the behavior of larger groups of ions that form what are called nonneutral plasmas [13]. The NIST Group has cooled these plasmas to the point where they exhibit liquid and even crystalline behavior [14]. The surprising thing is that these cooled plasmas exhibit behavior analogous to that of very dense, hot neutron stars. In addition, they can be controlled well enough to allow precision studies of fundamental equilibria and dynamical behavior.

Fig. 2. The three physicists involved in this first laser-cooling experiment. Pictured from left to right are Dave Wineland, Bob Drullinger, and Fred Walls.

The three NIST-Boulder authors of this seminal paper continue to work in the Time and Frequency Division in Boulder, and each has become a world leader in a key program within the Division. Dave Wineland heads the Ion Storage Group, which continues to open up new areas of research based on trapped, laser-cooled ions. Of most recent note is his world leadership in the area of quantum logic and entangled quantum states. In recognition of his many accomplishments, Wineland has been elected a Member of the National Academy of Sciences, a Fellow of the American Physical Society and a Fellow of the Optical Society of America. He has been awarded a long list of honors, including the Davisson-Germer Prize of the American Physical Society, the William F. Meggars Award of the Optical Society of America, the I. I. Rabi Award of the IEEE, the Einstein Medal for Laser Science of the Society of Optical and Quantum Electronics, the DOC Gold and Silver Medals, NIST's Samuel Wesley Stratton Award and NIST's Edward Uhler Condon Award. Following the ion-cooling experiment, Bob Drullinger contributed to the optical frequency measurements that led to the redefinition of the meter, then went on to lead the development of NIST-7, an optically pumped cesium-beam frequency standard that became NIST's primary frequency standard in 1993. This is clearly the most accurate atomic-beam standard ever built. For this work he was awarded the DOC Gold Medal and the I. I. Rabi Award of the IEEE. Fred Walls went on to lead the development of a passive hydrogen maser of exceptional merit. He then shifted to the development of low phase-noise and amplitude-noise electronics of importance to time-and-frequency metrology and to the accurate measurement of spectral purity. He has become the world leader in this field, and in recognition of this leadership was elected a Fellow of the American Physical Society. He has also been recognized with the very first Time and Frequency Award given by the European Frequency and Time Forum, the I. I. Rabi Award of the IEEE, three DOC Silver Medals, IEEE's Millennium Medal, and NIST's Edward Bennett Rosa Award.

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