The Richtmyer Memorial Lecture: Bose–Einstein Condensation in an Ultracold Gas

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The following article is a written version of the Richtmyer award lecture given to the annual meeting of the American Association of Physics Teachers in January 1996. I discuss the basic idea of Bose–Einstein condensation in a gas and how it has been produced and examined. To cool the atoms to the point of condensation we use laser cooling and trapping, followed by magnetic trapping and evaporative cooling. These techniques are explained, along with the signatures of Bose–Einstein condensation that we observe. I also discuss how very similar laser cooling and trapping techniques have been incorporated into undergraduate laboratory experiments.

I will cover two topics that at first glance would appear to be quite different: (1) the achievement of Bose–Einstein condensation (BEC) in a very cold gas[1] and (2) the development of simple and inexpensive techniques for cooling and trapping atoms using the forces of laser light. This second topic has led to the development of experiments for undergraduate lab courses, which involve laser spectroscopy,[2] and laser cooling and trapping.[3] What ties the two topics together is that most of the techniques which are used in the undergraduate lab experiments are also used in the research which has produced BEC. Thus, these experiments allow undergraduates in a laboratory course to become involved with physics that is at the forefront of current research. Many people, at Colorado and elsewhere, have contributed to the work I will discuss. At JILA/University of Colorado there is a substantial group[4] of students, postdocs, and faculty who have been working on these projects, particularly BEC, for many years, with Eric Cornell and myself as the coleaders. The work I will discuss is primarily the results of these efforts.

This talk will be organized in the following sections: (I) introduction to BEC in gas, (II) laser cooling and trapping—basic concepts and simple inexpensive embodiments for BEC and undergraduate labs, (III) magnetic trapping and evaporative cooling of laser-cooled samples, and (IV) BEC results and conclusions.

I. INTRODUCTION TO BOSE–EINSTEIN CONDENSATION IN A GAS

It is well known that there are two types of objects in nature, fermions, which have half-integer spin, and bosons, which have integer spin. The fermions are unsociable, and thus only one fermionic object, or fermion, can occupy a single quantum state. In contrast, bosons are sociable, and not only is it possible for multiple bosons to occupy a single state, but they prefer to do so. The common example of this phenomenon is the laser, which works because photons are bosons. Although all the constituents of atoms (neutrons, protons, and electrons) are fermions, if they are assembled such that the total spin of the atom is an integer, the atom will be a boson. Although atoms can be either bosons or fermions, an examination of the periodic table reveals that when they are in their lowest electronic state, most atoms are bosons.

Atoms of a gas, when held in a container as shown in Fig. 1, can have only particular quantized energies. However, for any normal macroscopic container the spacing between these energy levels is extremely small ($\sim 10^{-25}$ erg$\approx$1 nK). As long as the sample is "reasonably hot," say, more than a few μK above absolute zero, whether the atoms are bosons or fermions has little effect on the macroscopic properties of the sample. In either case the probability of any given energy level being populated is extremely small, and the atoms can be considered to be much like small classical ball bearings bouncing around inside the container. At very low temperatures, however, a profound and dramatic effect takes place, as first pointed out by Einstein in 1924.[5]

The history of this subject actually goes back to the work of Bose, which preceded Ref. 5. Bose was trying to understand the blackbody spectrum in terms of photon statistics. He realized that he could predict the correct spectrum if he made an assumption about when photons did, or did not, have to be counted as separate particles. Essentially this was saying that they obey what we now know as Bose statistics. Einstein learned of this work and took the further step of postulating that atoms as well as photons should obey these statistics, and he went on to write down the now familiar Bose–Einstein distribution formula for an ideal gas.[5] He noticed, however, that this formula has the peculiar property that at very low, but finite temperatures, it predicts that all the atoms will go into the lowest energy level of the container. This prediction is now known as Bose–Einstein condensation and is discussed in every textbook on statistical mechanics.

Although this is normally discussed in terms of chemical potentials, a more visual way to understand the condition for BEC is to think in terms of the de Broglie wavelength, λ_{DB}. As the temperature is reduced, the de Broglie wavelength of each atom becomes larger. When the sample is so cold that the de Broglie wavelengths are larger than the interparticle spacing, the atoms begin to fall into the lowest-energy state in the container, as illustrated in Fig. 1b. Thus the actual condition for BEC is a requirement on the phase-space density. The condition usually given in the texts for an infinite homogeneous ideal gas is that $(\lambda_{DB})^3 n > 2.6$, where n is the atomic number density. Although this does not apply exactly to our case of a finite inhomogeneous system, it is fairly close and provides a good indicator for the necessary temperatures (and hence λ_{DB}) and densities that must be achieved.

BEC is a very strange material in a number of respects. First, there are a large number of atoms in a single quantum state. As such, the atoms are indistinguishable in every re-

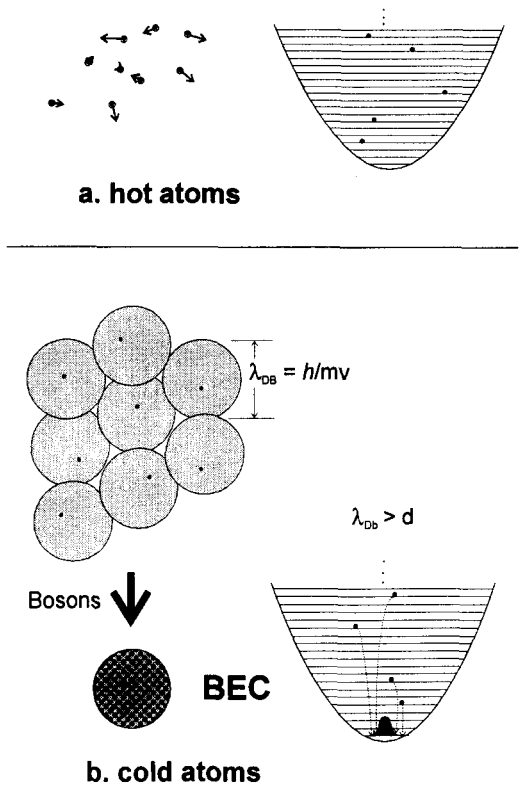

Fig. 1. (a) The energy of hot atoms is very large compared to the spacing of the quantized energy levels in a macroscopic container. For either bosons or fermions there is a very small probability of any given level being occupied. (b) When bosons are cooled sufficiently that the de Broglie wavelength, λ_{DB}, is larger than the spacing between atoms, d, the atoms fall into the lowest-energy state in the potential. All the atoms occupying that state are indistinguishable and thus occupy the same region in space.

spect and, hence, cannot be considered as separate individual atoms. They have lost their identities as independent atoms and have now fused into a sort of "superatom." Second, the transition to BEC is nonintuitive because, before the transition, the atoms are very far apart compared to their atomic "size." The average separation is 10 000 times the Bohr radius; therefore, the interactions between them, in the usual sense of electrons pushing up against each other, are extraordinarily small by any measure. However, they still know, through some strange quantum statistical sense, that it is time to all jump into the ground state. Finally, BEC represents a macroscopic population of a single quantum state and thus provides a macroscopic sample of material that is completely nonclassical in its behavior.

It is certainly interesting just to see BEC in a gas, but our primary motivation for this work was not simply to observe it, but rather to use it to explore the subtleties of many-particle quantum mechanics. There is some very interesting physics that can be studied through the comparisons between BEC and the other macroscopic quantum states that we all know and love,[6] particularly superfluid helium. As a liquid this is quite different from the ideal gas discussed by Einstein, but is now generally thought to be closely related to the BEC he discussed; at very low temperatures some macroscopic fraction (~10%) of the helium atoms are in the lowest quantum state. Because the atoms are very close together in the liquid, or more formally, the interparticle separation is comparable to the scattering length, this is a strongly interacting system. These strong interactions are actually responsible for much of the interesting behavior we associate with superfluid helium, but the interactions also make it much more complicated to understand the macroscopic properties of superfluid helium in terms of the microscopic interaction between two helium atoms.

BEC in a gas is the perfect tool for exploring how the microscopic interactions between atoms lead to the macroscopic properties of the many-atom quantum state. Because the atoms in the condensate are far apart compared to their atomic size, the interactions are weak and well understood and hence easily treated theoretically. Furthermore, we can readily adjust these interactions in experiments by changing the density of the gas and other parameters. Finally, as discussed below, we have very good optical diagnostics for looking at the condensate and measuring its properties. This combination of factors makes this an excellent system for studying in detail how one goes from the microscopic to the macroscopic. Much of the design of our experiment was motivated by the desire to produce BEC in a simple manner that would facilitate carrying out experiments on it to explore this area of physics.

A gaseous BEC also has a number of potential applications. It is the atomic counterpart to laser light and thus shares the primary feature that makes laser light useful, namely, very high phase-space number density. For this reason, it is likely that BEC will find many uses as well. BEC should revolutionize atom interferometry in much the same way lasers revolutionized optical interferometry, as well as other applications in which extremely high phase-space density and/or large coherence lengths of atoms are important.

Having established the motivation for this work, I will now turn to the experimental difficulties in producing BEC in a dilute gas and how they have been overcome. When you first consider how one might produce BEC, and the implication of the requirement that the interparticle spacing must be smaller than the de Broglie wavelength, you soon realize that there is a formidable challenge. The obvious approach to try first is to start with a moderately cold sample of atoms, say a few K, and then simply increase the density until the atoms condense. However, you quickly realize that this requires the atoms to be at a density approaching that of a solid, rather than the desired gas. This means the atoms will tend to see each other not as just individual friendly bosons, as they do when the separation is large compared to the atomic size, but instead as a collection of standoffish fermions. Thus this approach is clearly unsuitable. It is natural to then decide, ok, this means I have to keep the atoms far apart to have a dilute gas, so how cold do I have to make them? A simple calculation indicates that the temperature must be very cold, on the order of 100 nK. If you are a very optimistic experimentalist (or a typical theorist), you are undaunted by the mere technical details of getting a gas that cold, but there seems to be a much more fundamental problem set by the laws of thermodynamics. This problem is that no atoms want to stay a gas at such a low temperature. They want to be solids, and this is particularly true for rubidium, the atom we use, which is a metallic solid at room temperature! For this reason a number of people thought that it would be impossible to ever produce BEC in a gas and, on occasion, assured me that to do so we would have to violate thermodynamics.

Every physicist is raised to believe that you can never beat thermodynamics—often through the maxim that the three laws are "you can't win, you can't break even, and you can't

get out of the game." However, it is important to realize that while you can't beat thermodynamics if you play by its rules, it is not so hard to win if you are willing to cheat (or at least use a different set of rules), and thereby get around these oppressive laws. This is exactly what we have done to get BEC. The idea of how one can cheat thermodynamics to get BEC in a gas is a subtle and absolutely crucial concept in this work. What we actually do is avoid ever reaching a true equilibrium where thermodynamics applies. Instead we create a vapor sample that quickly equilibrates to its proper thermal distribution as a spin-polarized gas, but that takes a very long time to go to its true equilibrium state (a solid). Its equilibrium ground state is definitely going to be a little chunk of rubidium ice, but we produce conditions (low temperature and low density) so that the gas remains in its metastable supersaturated-vapor state for a long time. During this time we can produce and study a gaseous Bose condensate. Although this concept of needing to produce a sample with two very different time scales for equilibration is not widely publicized, I believe that it was the critical step for achieving BEC. Once we fully grasped this concept and its implications, the general route to BEC in a gas was clear.

The route we follow is a two-step process of cooling and trapping. The first stage uses laser light for the cooling and trapping. This is followed by a second stage that uses magnetic fields for trapping and cools by evaporation. In both stages the trapping is as important as the cooling, because it provides a "thermos bottle" that keeps the very cold atoms from coming into contact with the vastly hotter environment only 1 cm away. Historically, these technologies were developed during the 1980s as two independent fields of study. One was the development by many groups of the techniques of laser cooling and trapping,[7] with little or no concern with BEC. Simultaneously, there was a concerted effort to achieve BEC in a gas of spin-polarized hydrogen.[8] The first hydrogen BEC efforts used only traditional cryogenics, but when this approach failed, magnetic trapping and evaporative cooling were developed to continue the pursuit. In about 1989, I had the idea of combining the two technologies to produce BEC in alkali atoms by first laser cooling and trapping them, and then following that with magnetic trapping and evaporative cooling.

Before explaining in more detail these techniques and how this approach succeeded, I want to set the basic scale of the apparatus. Most people automatically associate low temperatures with large complex cryostats, dilution refrigerators, etc., but our apparatus uses none of that technology, and in fact is remarkably simple. As illustrated in Fig. 2, the heart of the apparatus is a small glass cell with some coils of wire around it. The only thing in the room that is colder than room temperature is the cooled atom cloud itself.

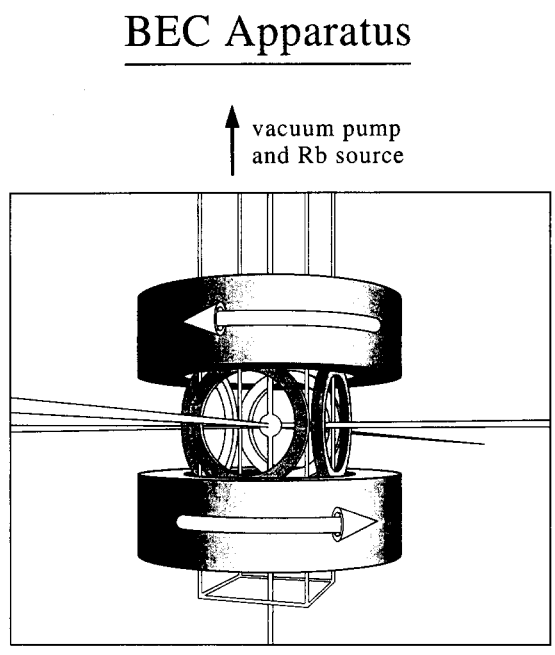

Fig. 2. BEC trapping cell. A rectangular glass cell (2.5 cm square by about 10 cm high) is attached to a vacuum pump and rubidium reservoir (not shown). Laser beams coming from all six directions go through the cell. The magnetic fields are produced by the two large coils, which have currents flowing through them in opposite directions, and the four smaller coils, which have time-varying currents, as discussed in Ref. 14.

II. LASER COOLING AND TRAPPING—BASIC CONCEPTS AND SIMPLE INEXPENSIVE EMBODIMENTS FOR BEC AND UNDERGRADUATE LABS

Now let me explain how such a simple device can be used to produce BEC. The first step in the process is to cool and trap atoms using laser light. Although cooling and trapping of atoms by light is a large subject that many groups have developed over the years,[7] I want to limit myself to discussing only a few basic ideas. The primary force we use is the radiation-pressure force that is produced when one shines resonant laser light on an atom. The atom is excited and then decays, thereby scattering the light, as illustrated in Fig. 3. Each time the atom scatters a photon, it feels a tiny kick, owing to the transfer of momentum. Of course an atom can scatter many photons per second, and so this scattering force can result in a large acceleration. To cool the atoms, one must make this force have a frictional or velocity-dependent part. This is done by using the Doppler shift and appropriate detuning of the laser frequency. As shown in Fig. 3, if the laser is tuned to the red side of the atomic resonance line, then if the atom is going toward the laser (a), it sees the light Doppler-shifted more into resonance and hence scatters many photons. This results in a large force opposing the atom's motion. However, if the atom is moving in the same direction as the laser beam (b), the Doppler-shifted light is further off resonance, so the atom only feels a small force increasing its speed. Thus if one has laser beams coming from all six directions to strike the atom, the net effect is that no matter what direction the atom is going it will always feel a force opposing its velocity, and it will be slowed down and thus cooled. Once the atoms are quite cold ($\lesssim$1 mK), there is another more complicated process, often called "Sisyphus" or "sub-Doppler" cooling, which cools them somewhat further than is possible by using the Doppler effect. This cooling arises from a fortuitous coincidence between the manner in which atoms make transitions between states, and their potential energy as they move up and down the potential hills produced by the standing-wave laser fields.

Laser light can be used not only to cool the atoms, but also to hold them away from the hot walls. To use the radiation-pressure force for this purpose it must be given a spatial dependence. This is done through the Zeeman shift of the atomic levels induced by an inhomogeneous magnetic field.

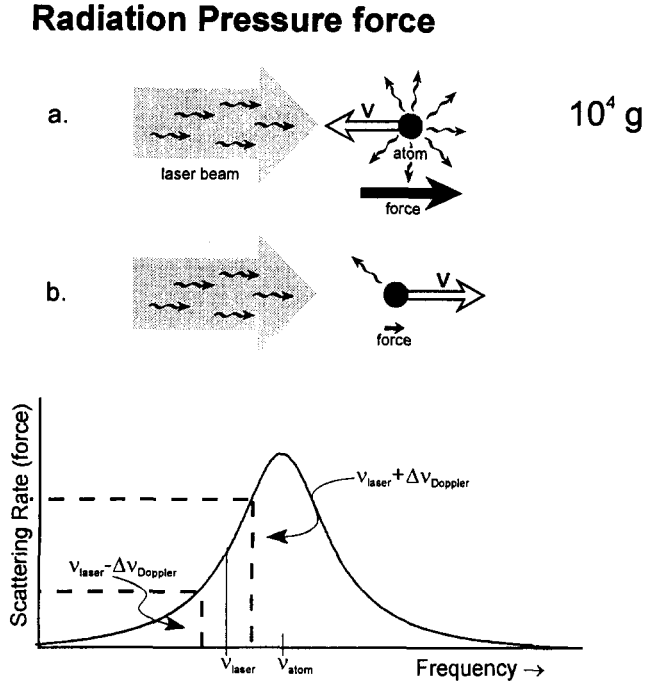

Fig. 3. The laser beam exerts a force as large as 10^4 mg on the atom by scattering photons. At the bottom is shown how the atom-scattering (or equivalently, excitation) rate depends on laser frequency. If the laser frequency is below the atom's resonant frequency as shown, then (a) when the atom is moving opposite to the direction that the light is going, the scattering rate and force are high because of the Doppler shift. (b) When the atom is moving in the same direction as the light, the Doppler shift is in the opposite direction, and so the rate is low.

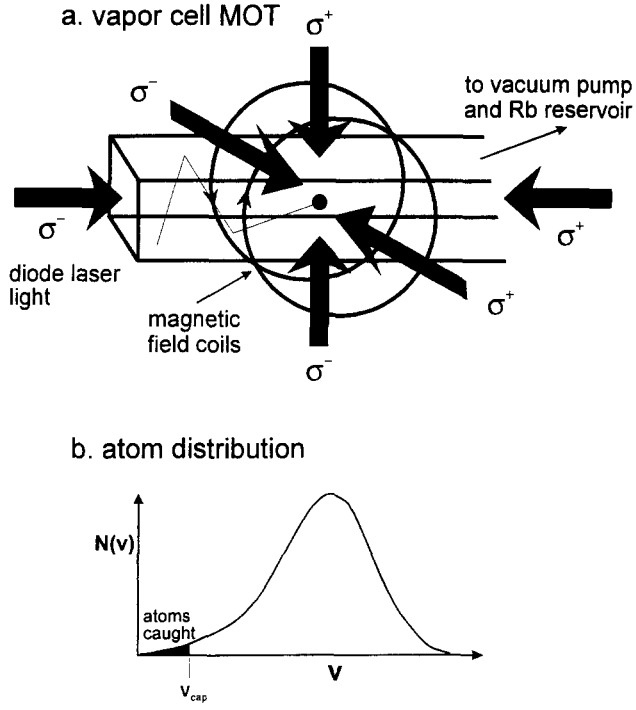

Fig. 4. (a) Schematic of a vapor-cell magneto-optic trap. A rectangular glass cell, typically 2.5 cm square, is evacuated, and then a small amount of rubidium (or other alkali) vapor is introduced into it. Six circularly polarized laser beams, with the helicities or circular polarizations shown, pass through the cell. In practice this is usually done with three beams that are reflected back on themselves through quarter-wave plates. The two circles are coils of wire that have currents flowing in opposite directions to produce the desired magnetic field gradient. (b) The Maxwell–Boltzmann distribution of the room-temperature rubidium atoms in the cell. Atoms bounce around inside the cell until they happen to come off the wall with a velocity less than v_{cap} (~15 m/s) and pass through the laser beams, at which point they are caught by the trap. After a short time, $\sim 10^7$ trapped atoms accumulate in the center of the trap, forming a small cloud. The temperature of these trapped atoms is about 10 μK.

This Zeeman shift controls the light-scattering rate (and thus the radiation-pressure force) in a position-dependent fashion. This effectively creates a potential. The atoms sit at the bottom of the potential, held there only by the laser light.

The simplest way to implement laser cooling and trapping is shown in Fig. 4. This is a so-called magneto-optic (MOT) trap in a vapor cell.[9,10] This method is so simple and inexpensive that it is now a standard experiment in the University of Colorado undergraduate physics lab course,[3] but it is also what we use for the BEC experiment. We start with a small glass cell that is attached to a vacuum pump and, intermittently, to a rubidium reservoir, so that it contains about 10^{-10} Torr of rubidium and very little other gas. Then the laser trap is added by sending in laser beams of the appropriate polarization from all six directions and applying the magnetic field. Only a few milliwatts of power are needed in each laser beam, so this light is obtained from inexpensive diode lasers, much like those found in CD players. The frequency of the light must be controlled quite precisely; this is done by using a diffraction grating to send light of a particular frequency back into the laser. A simple servo-control system, which adjusts the grating position and the laser current, locks the frequency of the laser to an atomic resonance line.[2] The final component of the MOT, a small magnetic field gradient, is produced by running currents in opposite directions through coils of wire on each side of the cell (often called "antihelmholtz coils").

The trap slowly fills up with atoms captured from the low-velocity tail of the Maxwell–Boltzmann distribution. The fastest atom that can be captured depends on the diameter and intensity of the laser beams, and this in turn determines the rate at which atoms are loaded into the trap and the equilibrium number. For our low-power, 1.5-cm-diam beams, about 10^7 atoms are captured into the trap. The time it takes to collect these atoms depends on the rubidium pressure. We use a trapping setup for the BEC experiment similar to that used in the undergraduate lab experiment. However, the undergraduate lab experiment operates with higher rubidium pressure and therefore typically fills with a time constant of 1–2 s. In the BEC experiment, it is desirable to operate at much lower pressures. In this case the time constant for the trap to fill is about 1 min. With such long fill times, the light-induced collisional loss can reduce the number of atoms collected, so a "dark spot" trap is used to suppress this loss.[11]

The layout of the undergraduate trapping experiment is shown in Fig. 5. In the normal class, it is broken up into two experiments, each of which takes three lab sessions, each of which lasts for three hours. For the first experiment, students use either of the two diode-laser saturated-absorption setups to carry out Doppler-free laser spectroscopy of rubidium.[2] In the second experiment, they lock the laser frequencies to the appropriate saturated-absorption lines and send the beams from both lasers into the trapping cell in the middle of the

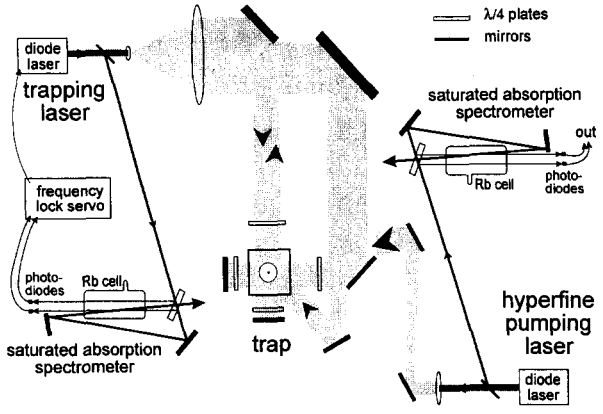

Fig. 5. Layout of the undergraduate laser spectroscopy and trapping and cooling experiments on a 4×6 ft optical breadboard. At each side are setups for carrying out saturated-absorption laser-spectroscopy experiments. In the center is the trapping cell, which uses light from both the lasers.

table to observe and study laser trapping and cooling.[3] These experiments are discussed in detail in Refs. 2 and 3.

III. MAGNETIC TRAPPING AND EVAPORATIVE COOLING

Returning to BEC, remember that the requirement is to have a large enough phase-space density; the laser-trapped sample is a major step toward this goal. After the period of atom collection, the optical trap contains about 10^7 atoms, and their temperature is about 10 μK. The good news is that this one easy step has increased the phase-space density by about 16 orders of magnitude over the original room-temperature vapor. The bad news is that this still leaves one about 5 orders of magnitude short of BEC.

Actually my original interest in BEC research grew out of my curiosity about what was limiting the densities and temperatures that could be reached in these laser traps. We studied this for several years and learned that there were several relevant processes, all of which were due to the presence of the photons.[12] In some respects the photons are rather like houseguests or fresh fish. They are very desirable to have initially, but if they stay around too long, they lose their appeal and even become downright unpleasant. In this case, a photon will "overstay its welcome" by scattering repeatedly off the atoms in the trapped cloud. Because of this, we decided it would be desirable to get rid of the photons, once we had shamelessly used them to produce a nice laser-cooled and -trapped sample. You can do this just by blocking the laser beams, but, when that is done with atoms at these temperatures, they simply reconfirm Galileo. They fall until they hit the bottom of the cell with a "thud" (admittedly, a very faint one). To save the cold atoms from this untimely end, we held them in a magnetic "safety net," often known by the less charitable term, "magnetic trap."[10] This fairly old technology uses the fact that each atom has a small magnetic moment, $\boldsymbol{\mu}$, and thus can be confined by the $\boldsymbol{\mu}\cdot\mathbf{B}$ interaction in an appropriately configured inhomogeneous magnetic field. To confine a room-temperature atom, or even a 1-K atom, in this way is fairly difficult, because it requires large magnetic fields. However, to confine an atom that has already been laser cooled to 10 μK is quite simple.

In fact, it was the ease of creating such cold, magnetically trapped samples that encouraged us to think about what more could be done with them. I was aware that shortly before we carried out this magnetic trapping, the MIT hydrogen BEC group had achieved very impressive results with evaporative cooling of magnetically trapped hydrogen atoms.[8] Although they had not quite reached BEC, they had shown that it was possible to use this technique to get large increases in phase-space density. We decided to see if we could use this evaporative cooling of our cold alkali atoms to achieve BEC.

We had general hunches as to why certain aspects of atomic physics might favor this approach to BEC, relative to the previous hydrogen work. Hydrogen was plagued by dipole–dipole spin–flip collisions that caused atoms to go into a lower-energy spin state and be lost from the trap (thus in a sense, quenching the spin-polarized metastable vapor). We felt it was likely that heavy alkalies would have similar rates for these undesirable collisions, but would probably have much larger cross sections than hydrogen for the desirable two-body elastic collisions needed to thermalize the gas for evaporative cooling. The arguments are just that the atomic magnetic moments of rubidium and hydrogen are similar and heavy alkalies are much larger, fluffier atoms. In terms of the earlier discussion, this comparison of collision rates is saying that the critical difference in the two equilibration time scales, gas thermalization versus quenching metastability, is larger in alkalies than in hydrogen. However, these ideas could only be hunches, because all of the relevant rates for alkali atoms are extremely sensitive to the exact shape of the interatomic potential[6] and, hence, were completely unknown six years ago. Much of our work over the past six years was spent in determining the good and bad collision rates. From the work of ourselves and others, in the past few years it has become clear that the original hunch was correct, and it also gave us a much better idea as to exactly what conditions were necessary in order to achieve evaporative cooling to BEC.

Although it took us several years to learn this, the key issue for successful evaporative cooling of a laser-cooled sample is simply obtaining a high enough elastic collision rate between the magnetically trapped atoms. This can be understood by considering the evaporative cooling process in more detail. As shown in Fig. 6(a) and demonstrated with hydrogen, the simplest form of evaporative cooling is to confine the atoms in a magnetic bowl and let the most energetic atoms escape over the side. When they do this, they carry away far more than their share of the energy, and thus the remaining atoms get colder. This is much like what happens when coffee cools. The most energetic coffee molecules leap out of the cup into the room, carrying away lots of energy and thereby cooling the coffee that remains in the cup. In order for evaporative cooling of a magnetically trapped gas to work efficiently, the time for the atoms to reestablish a proper thermal distribution after atoms escape the trap must be much shorter than the lifetime of the cold atoms in the trap. The trap lifetime is primarily determined by collisions with hot background atoms in the cell, and thus it is important to have good vacuum in the cell. The thermalization time is determined by the elastic collision rate, which is equal to the density times the cross section times the relative velocity. This is why the large elastic scattering cross section of heavy alkali atoms is very useful. However, it is still necessary to make the density larger than that provided by a simple laser-trapped cloud, which is transferred to the mag-

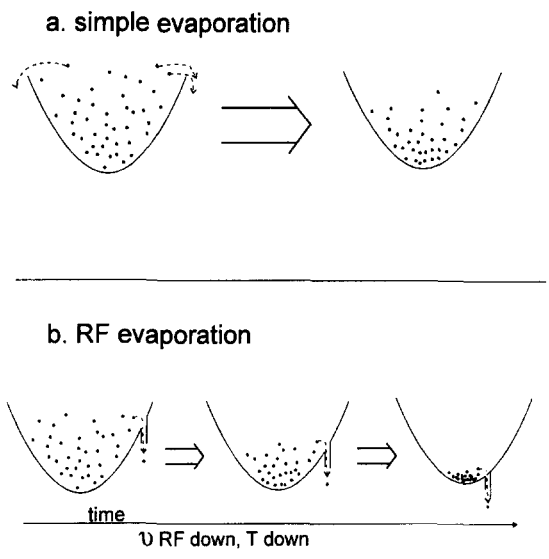

Fig. 6. Schematic of evaporative cooling of magnetically trapped atoms. The atoms are contained in a magnetic bowl. (a) In simple evaporation the most energetic atoms escape over the side, and the remaining atoms then become colder. (b) The applied rf field causes the atoms' magnetic moments to flip at the particular value of magnetic field that satisfies the resonant condition. This makes a hole at a particular position (magnetic field) in the bowl through which atoms escape. The position of the hole and the resulting atom distribution are shown for three different times during a cooling cycle in which the rf frequency is being ramped down.

netic trap. We increase the density in the magnetic trap through a variety of optical techniques to make the cloud as dense and cold as possible before it is put into the magnetic trap,[13] and then finally we squeeze the cloud as much as possible with the magnetic trapping force. The final step that gave us high enough density to make evaporative cooling work sufficiently well to reach BEC was the invention of a new type of magnetic trap[14] by Eric Cornell that provides a large amount of "magnetic squeeze" for a given current. This is the so-called "time orbiting potential" or "TOP" trap. With this final piece of technology in place, we were then able to evaporatively cool the magnetically trapped atoms to extremely low temperatures.

As shown in Fig. 6(b), we actually do not evaporate simply by allowing the atoms to escape out of the top of the trap as described above. What we actually do is apply an rf field at frequency ν, which causes the magnetic spins to flip when the resonant condition, $h\nu=(\Delta m)g\mu B$, is met. Since higher potential energy in the trap also corresponds to being in a region of higher magnetic field, this can be pictured as putting a leak in the trap at a position that is set by ν. This is very convenient since it allows us to use the rf to skim off the most energetic atoms; then as the remainder cool and settle lower in the trap, we reduce the rf frequency and skim off the top of this new distribution to continue to optimize the cooling.[14,15] In an actual cooling cycle, the rf frequency is ramped slowly to a final value that determines the final temperature of the sample.

IV. BEC RESULTS AND CONCLUSIONS

All the pieces I have described are put together in a series of steps that cool room-temperature rubidium atoms to a Bose–Einstein condensate as follows: (1) collect 10^7 rubidium atoms from the room-temperature vapor into the MOT; (2) do some tricks with the magnetic field and the laser detuning to optically get the atoms as dense and cold as possible; (3) use a single, circularly polarized laser beam to optically pump all the atoms into the $F=2$, $m=2$ spin state (the state that is confined in the magnetic trap); (4) turn off all the lasers and turn on the magnetic fields for the TOP trap; (5) ramp up the magnetic fields to squeeze the magnetically trapped sample to increase its density and elastic collision rate; (6) turn on the rf and ramp down the frequency to evaporatively cool. The initial collection (1) and the evaporative cooling (6) take roughly 1 min each, whereas all the other steps are essentially instantaneous on that time scale.

At the end of the cooling cycle we have a nice cold sample, but since it is sitting in the dark we don't know anything about it. So we turn the light back on and look at it. When the sample is very cold, since it is sitting at the bottom of a harmonic potential, it is also very small and thus hard to see. To make the cloud large enough to see in detail we turn off the magnetic trap and allow the atoms to fly apart. For a number of technical reasons, this is better than just magnifying the image with lenses. After the atoms have spread out for 0.06 s, the cloud is much bigger, and we then take a "shadow snapshot" of it. This image is obtained by illuminating the expanded cloud with a very short pulse of laser light that is tuned to the resonant frequency of the atoms. The atoms scatter the light, thereby casting a shadow in the illuminating laser beam, and the shadow is imaged onto a CCD array (TV camera). This shadow image is the two-dimensional projection of the velocity distribution of the original cloud of atoms in the magnetic trap. From the velocity distribution we can extract the temperature and various other properties of the sample.

A set of three such pictures is shown in Fig. 7. (These data are from the work described in Ref. 1.) These correspond to three repetitions of the experiment, where the only difference is the final rf cooling frequency. In the leftmost picture, we have only cooled the atoms down to a balmy 200 nK, and what we see is a round hill, which looks like the familiar Maxwell–Boltzmann velocity distribution. At higher temperatures (not shown here), the cloud has the same shape with a larger width. We determine the temperature by extracting it from the measured velocities. The middle picture shows a cloud (~10 000 atoms) where the sample was cooled further, down to about 100 nK, and this is when things get exciting. On top of the rounded hill, a narrow spire now emerges that is centered at zero velocity. If we cool even further (right), we can produce a sample (~2000 atoms) in which the hill is completely gone, and only the narrow spire remains.

You can see how this behavior is exactly what one expects with BEC if you go back to the original concept illustrated in Fig. 1. The normal atoms that are distributed over many energy levels from the Maxwell–Boltzmann-like hill. The atoms in the lowest-energy state of the potential are the most localized in both position and velocity space, and they are centered at zero velocity. Thus as atoms condense into that state, they form a very narrow peak in the velocity distribution, which sits on top of the broader hill of noncondensed atoms. The condensate lives for 15–20 s if it is left in the dark.

There are other features of these velocity distributions that indicate we are seeing BEC. One is the peak density of the trapped cloud as a function of temperature, as shown in Fig.

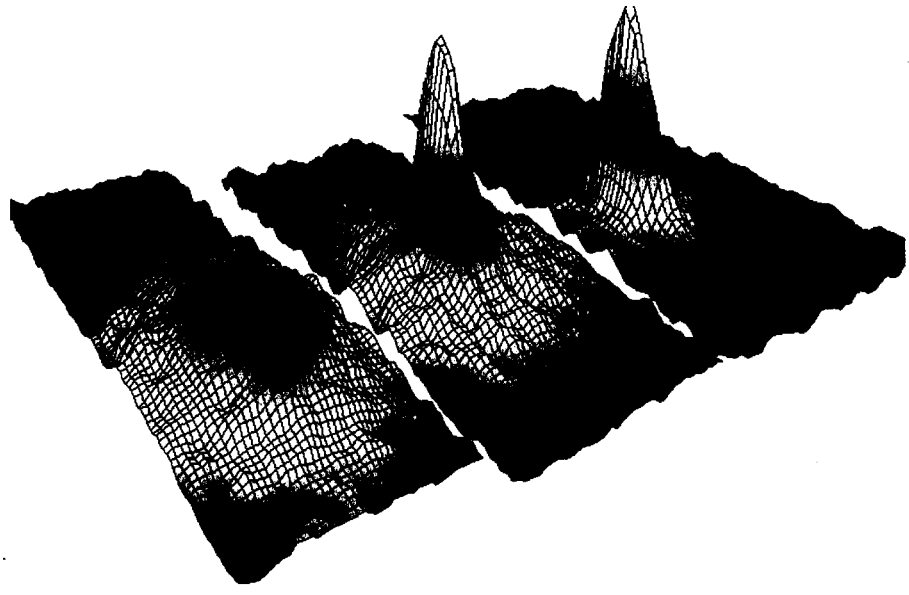

Fig. 7. Two-dimensional velocity distributions of the trapped cloud for three experimental runs with different amounts of cooling (different final rf). The axes are the x and z velocities, and the third axis is the number density of atoms per unit velocity-space volume. This density is extracted from the measured optical thickness of the shadow. The distribution on the left shows a gentle hill and corresponds to a temperature of about 200 nK. The middle picture is about 100 nK and shows the central condensate spire on top of the noncondensed background hill. In the picture on the right, only condensed atoms are visible, indicating that the sample is at absolute zero, to within experimental uncertainty. The gray bands around the peaks are an artifact left over from the conversion of false-color contour lines into black and white pictures for this publication. The original color versions can be seen on the JILA WWW home page (http://jilav1.colorado.edu/www/images.html) and the 1996 APS calendar.

8. Although we measure velocity distributions, one of the very nice features of using a harmonic trap is that we can immediately obtain the density distribution from these data just by scaling the velocity distribution by the appropriate oscillation frequencies in the trap. The figure shows how the peak density is nearly constant with temperature until it goes below 100 nK, whereupon the density jumps up very dramatically. This provides a strong indication of a phase transition, just like the condensation of steam into water.

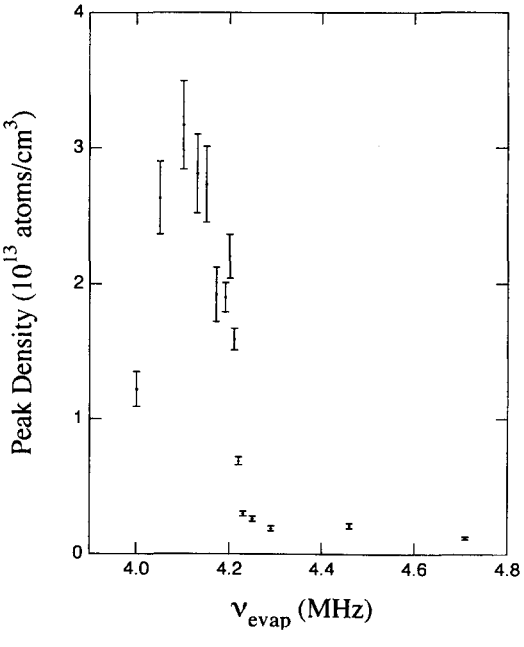

Fig. 8. A plot of the peak density of the trapped cloud as a function of the temperature, in units of the final value of the rf frequency used in evaporative cooling.[1] The sudden increase in density at 4.2 MHz corresponds to a temperature of about 100 nK. The point at the far left is lower because the rf is ramped down so far it has begun to cut away the condensate itself.

Another interesting aspect of the data is revealed by looking down on the peaks of Fig. 7 from above, as shown in Fig. 9. This allows one to examine the isotropy of the velocity distribution. In Fig. 9(a), you can see the that contour lines of the rounded hill are essentially circular, indicating an isotropic distribution. This is just what one must have for any thermal sample, because of the equipartition theorem, which says there are equal amounts of kinetic energy in each direction. However, you can see that Figs. 9(b) and 9(c) show that the spires are not round; instead they are quite elliptical, indicating an anisotropic velocity distribution. The explanation for this is that in these figures you are actually seeing a macroscopic quantum wave function. The reason for the shape of this wave function is that the harmonic potential in our trap is not isotropic. The spring constants in the z direction are eight times larger than they are in the radial (x–y plane) direction. A simple first-year quantum mechanics calculation of the wave function of the ground state in such a three-dimensional harmonic potential will show you that the wave function is pancake shaped; it is narrower in the z direction than in the radial direction. This means that the atoms are more localized along the z direction; therefore, just from the uncertainty principle (or more formally, calculating the momentum-space wave function), you can see that an atom in this eigenstate must have a larger velocity spread in the z direction, and this is why the velocity distribution is elliptical.

It is even more enlightening to do this calculation of the harmonic oscillator wave function and quantitatively com-

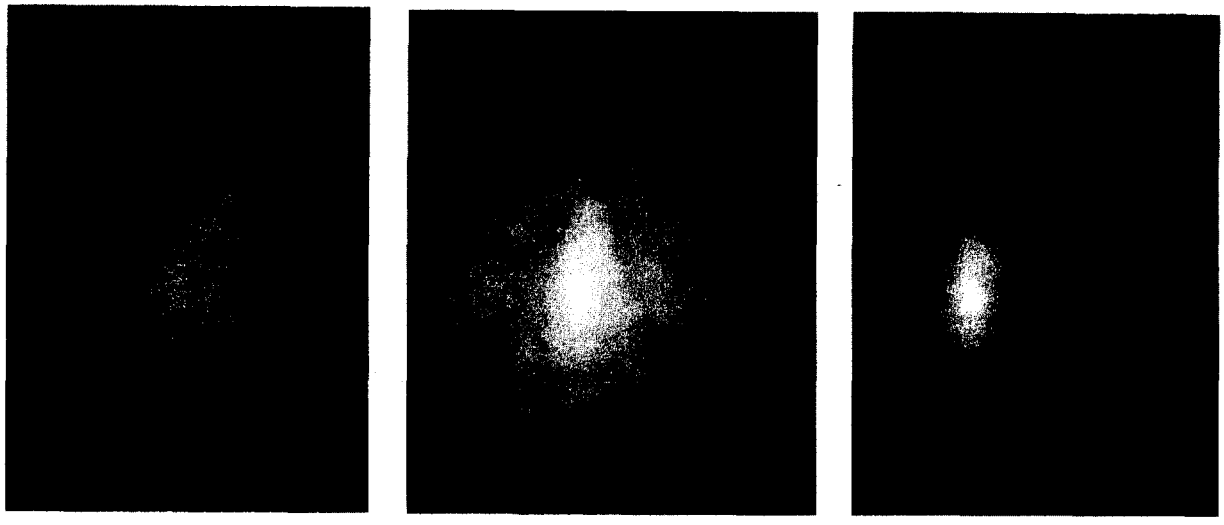

Fig. 9. Plot of x and z velocity distributions of same samples shown in Fig. 7 (Ref. 1). Images shown are negatives of actual data, so brighter corresponds to more atoms (less transmitted light). The circular distribution corresponds to a 200 nK isotropic velocity distribution; the other images show that the spread in velocity in the condensate is larger in the z direction than in x.

pare it with our data. (If you are teaching introductory quantum mechanics, you might want to consider giving this to your students as a problem.) It turns out the results do not quite agree! There is a discrepancy of about 30%. After discovering this, we got our theory friends, specifically, M. Holland and J. Cooper, to do the calculation correctly by putting in the small known interactions between the atoms.[16] This properly calculated wave function shows that the interactions distort the shape of the wave function into one that matches perfectly with the data! This is a very satisfying result because one of the primary motivations for undertaking this work was the goal of understanding in detail how the microscopic interactions affect the macroscopic behavior, and this first small step in that direction has been very successful.

To summarize, we see three clear signatures indicating that the atoms are undergoing Bose–Einstein condensation into the ground state of the confining potential. First, the velocity distribution has two distinct components, a broad thermal distribution and a narrow peak centered at zero. Second, the peak density shows a very abrupt increase as the temperature is decreased. Third, the velocity distribution is elliptical rather than round. Thus it seems rather convincing that BEC has been observed. However, the best news is that this was done is a relatively simple and inexpensive apparatus that will allow many properties of the condensate to be studied in detail. This is the goal that Eric Cornell and I set out to achieve years ago.

There are now many obvious things to study about the condensate, and we and many other groups are eagerly setting out to do this. A very abbreviated list includes looking at how the condensate scatters light and comparing this with normal atoms, investigating the dynamics of the phase transition, and determining the elementary excitation spectrum of the condensate. One particularly wants to study how all these properties depend on the microscopic interactions and how they change as we vary the interaction energy. This is straightforward to do simply by changing the density by varying the number of atoms in the trap or by adiabatically increasing or decreasing the confining potential. It will also be interesting to study different types of condensates, and it looks as though the same basic approach should work to achieve BEC in many different systems. This has already been demonstrated in sodium,[17] and other atoms will no doubt follow. The study of gaseous Bose–Einstein condensates appears likely to be a very fruitful area of physics during the next few years. Most of their properties are as yet unknown, but the basic theoretical tools exist to calculate them and we now have experimental tools for measuring them.

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I am pleased to acknowledge the help of many people in the work discussed here. These include all my students and postdocs over the last decade, and many other helpful colleagues. Although the full list is too numerous to mention I want to single out the contributions of the JILA BEC group and especially Eric Cornell with whom I have had a tremendously rewarding collaboration for many years. Gwenn Flowers and Sarah Gilbert were instrumental in helping set up and carefully documenting the undergraduate laboratory experiments, and Sarah provided constructive criticism in the preparation of this manuscript (as well as all my previous papers). The work I discussed has been supported by NSF, ONR, and NIST.

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[1]M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, "Observation of Bose-Einstein condensation in a dilute atomic vapor," Science **269**, 198–201 (1995).

[2]K. MacAdam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode laser system with grating feedback, and a saturated absorption spectrometer for Cs and Rb," Am. J. Phys. **60**, 1098–1111 (1992).

[3]C. Wieman, G. Flowers, and S. Gilbert, "Inexpensive laser cooling and trapping experiment for undergraduate laboratories," Am. J. Phys. **63**, 317–330 (1995).

[4]This list includes C. Monroe, N. Newbury, C. Myatt, C. Sackett, J. Cooper, M. Holland, R. Ghrist, W. Petrich, D. Jin, E. Burt, G. Flowers, M. Anderson, J. Ensher, and M. Matthews. The BEC data presented here were primarily the work of the last three.

[5]A. Einstein, Sitzungsber. K. Preuss. Akad. Wiss. 261, (1924); 3 (1925).

[6]In addition to superfluid helium, two other examples are superconductivity, and BEC in excitons. The latter work is discussed in J.-L. Lin and J. P. Wolfe, "Bose–Einstein condensation of paraexcitons in stressed Cu_2O,"

Phys. Rev. Lett. **71**, 1222–1229 (1993). For an extensive discussion of BEC in many different systems, see *Bose-Einstein Condensation*, edited by A. Griffin, D. Snoke, and S. Stringari (Cambridge U.P., Cambridge, 1995).

[7]See the following volumes for numerous articles and references on the subjects of laser cooling and trapping. N. R. Newbury and C. E. Wieman, "Resource Letter TNA-1: Trapping of neutral atoms," Am. J. Phys. **64**, 18–20 (1996) (this article also provides extensive references on magnetic trapping); C. Wieman and S. Chu, (Eds.), *Special Issue on Laser Trapping and Cooling*, J. Opt. Soc. Am. B **6** (11) (1989); *Proceedings, Enrico Fermi International Summer School on Laser Manipulation of Atoms and Ions, Varenna, Italy*, edited by E. Arimondo, W. Phillips, and F. Strumia (North-Holland, Amsterdam, 1992).

[8]For review of the hydrogen work, see T. Greytak, in *Bose-Einstein Condensation*, edited by A. Griffin, D. Snoke, and S. Stringari (Cambridge U.P., Cambridge, 1995), p. 131.

[9]E. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, "Trapping of neutral sodium atoms with radiation pressure," Phys. Rev. Lett. **59**, 2631–2634 (1987).

[10]C. Monroe, W. Swann, H. Robinson, and C. Wieman, "Very cold trapped atoms in a vapor cell," Phys. Rev. Lett. **65**, 1571–1574 (1990).

[11]M. H. Anderson, W. Petrich, J. R. Ensher, and E. A. Cornell, "Reduction of light-assisted collisional loss rate from a low-pressure vapor cell trap," Phys. Rev. A **50**, R3597–3600 (1994); "High densities of cold atoms in a dark spontaneous-force optical trap," W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, Phys. Rev. Lett. **70**, 2253 (1993).

[12]D. Sesko, T. Walker, C. Monroe, A. Gallagher, and C. Wieman, "Collisional losses from a light force atom trap," Phys. Rev. Lett. **63**, 961–964 (1989); T. Walker, D. Sesko, and C. Wieman, "Collective behavior of optically trapped neutral atoms," Phys. Rev. Lett. **64**, 408–411 (1990); D. Sesko, T. Walker, and C. Wieman, "Behavior of neutral atoms in a spontaneous force trap," J. Opt. Soc. Am. B **8**, 946–958 (1991).

[13]N. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, "Behavior of atoms in a compressed magneto-optical trap," J. Opt. Soc. Am. B **11**, 1332–1335 (1994).

[14]W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, "Stable tightly confining magnetic trap for evaporative cooling of neutral atoms," Phys. Rev. Lett. **74**, 3352–3355 (1995).

[15]D. E. Pritchard, K. Helmerson, and A. G. Martin, "Atom traps," in *Proceedings of the 11th International Conference on Atomic Physics*, edited by S. Haroche, J. C. Gay, and G. Grynberg (World Scientific, Singapore, 1989), pp. 179–197.

[16]M. Holland and J. Cooper, "Expansion of a Bose-Einstein condensate in a harmonic potential," Phys. Rev. A **53**, R1954–1957 (1996).

[17]K. B. Davis, M. O. Mewes, N. J. vanDruten, D. S. Durfee, D. M. Dvrn, and W. Ketterle, "Bose Einstein condensation in a gas of sodium atoms," Phys. Rev. Lett. **75**, 3969 (1995).

Surface charges on circuit wires and resistors play three roles

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The significance of the surface electric charge densities associated with current-carrying circuits is often not appreciated. In general, the conductors of a current-carrying circuit must have nonuniform surface charge densities on them (1) to maintain the potential around the circuit, (2) to provide the electric field in the space outside the conductors, and (3) to assure the confined flow of current. The surface charges and associated electric field can vary greatly, depending on the location and orientation of other parts of the circuit. We illustrate these ideas with a circuit consisting of a resistor and a battery connected by wires and other conductors, in a geometry that permits solution with a Fourier–Bessel series, while giving flexibility in choice of wire and resistor sizes and location of the battery. Plots of the Poynting vector graphically demonstrate energy flow from the battery to the resistive elements. For a resistor with a large resistance, the potentials and surface charge densities around the current-carrying circuit are nearly the same as for the open circuit with the resistor removed. For such resistors, the capacitance of a resistor and its adjacent elements, defined in terms of the surface and interface charges present while current flows, is roughly the same as the capacitance of the adjacent elements of the open circuit alone. The discussion is in terms of time-independent currents and voltages, but applies also to low-frequency ac circuits. © *1996 American Association of Physics Teachers.*

I. INTRODUCTION

The ideas of electric charges and potentials of conducting surfaces in electrostatics on the one hand and current flow in simple circuits on the other are disjoint topics in almost all elementary physics textbooks. Such texts usually begin electricity and magnetism with electrostatics—first, point charges, then conducting surfaces at different potentials, surface charge densities, etc. To segue into magnetism (and to treat a practical topic), the texts then discuss current flow in simple circuits—wires, resistors, batteries. Currents are described as charges in motion within the interior of the elements of the circuit, but the charges are rapidly subsumed into current densities or total currents obeying Ohm's law. In electrostatics, charges are always stationary; in circuits, charges are always in motion.

A cursory inspection of some beginning undergraduate texts[1–10] in the Berkeley Physics Library showed that only one (the new book by Chabay and Sherwood[1]) mentioned surface charges on the wires or resistors. In some, a figure showing a battery in the circuit has plus and minus signs next to the battery plates, but it is not clear whether this is a hint at charges present or only an indication of the sign of the potential at the terminals of the battery. If a text discusses the charging of a capacitor, charges do surface again on the plates of the capacitor, but there is no mention of stationary charge elsewhere on the circuit. With the early notable exception of Jefimenko's book,[11] intermediate,[12–14] or advanced texts[15–18] are no better. My book does not even treat circuits, except in a few problems associated with capacitance or inductance. It is very true that the amounts of charge

