Bose-Einstein Condensation:

A Double Pot of Gold

by David E. Pritchard, based upon an interview with Virginia Esau

Why Atomic Physics

In 1963, I joined Norman Ramsey's atomic physics group because I was interested in working with Daniel Kleppner, who was then a young assistant professor in his group. At that time, most physicists viewed atomic physics as being dead, or at least in the doldrums. I thought the recently invented laser would change that. In those days we had a few fixed frequency visible lasers, but it seemed likely that eventually we were going to be able to make all colors of light. After I became an assistant professor at MIT in the early 70s, the continuous, narrow frequency, tunable dye laser became available commercially, making all colors available for the first time.

Lasers are bright enough to exert light forces on atoms that would cause a substantial acceleration, but the laser needs to be tuned to compensate for the changing Doppler shift as the atom slows. The first dramatic advance in slowing atoms down was made by Bill Phillips (PhD '76), and his group at NIST. They used a magnetic field to tune the atoms as they slowed, rather than the laser. This work led to his Nobel Prize in 1997. Phillips slowed atoms down from a thousand meters a second to a few meters a second. Steven Chu at Bell Labs, who shared the '97 Nobel Prize with Phillips, showed that you could use the light forces to slow down atoms even further to milli-Kelvin temperatures, an effect called optical molasses.

Perspective on 20th Century Atomic Physics

Most of the new atomic physics advances in the first three quarters of the 20th century had been concerned with developing techniques to control the *internal* quantum state of the atom. I. I. Rabi received the Nobel Prize for his resonance method, with which you could controllably change the atom from one quantum state to another. Then came the separated oscillatory fields method—for which Norman Ramsey won the Nobel Prize 1989—with which you controllably put the atom in a superposition of two different internal quantum states and then read out what state it was in later. This allowed the measurement of the transition frequency to much higher accuracy. Resonance, in turn, led to nuclear magnetic resonance and to spin echoes, together forming the basis of magnetic resonance imaging. Rabi was Ramsey's thesis advisor; Ramsey was Dan Kleppner's, and Dan was mine.

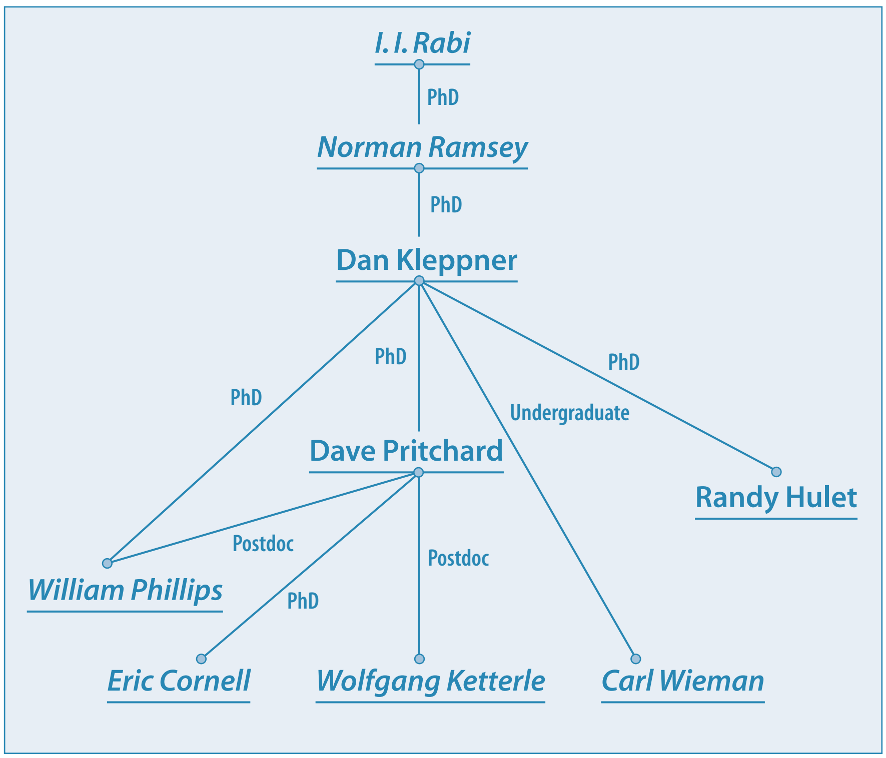

FIGURE 1

Family tree of atomic physicists. Nobel laureates in italics.

Atomic, molecular, and optical (AMO) scientists used light forces and other electromagnetic forces to slow atoms down, cool them off, and trap them, in order study their internal states more precisely. But I saw the goal as getting full control over the *external* quantum mechanical degrees of freedom of atoms. This theme dominated atomic physics for most of the last quarter of the 20th century.

Atom Traps

As an immediate goal, I viewed atom cooling as the way to slow atoms enough to trap them in available magnetic fields or with available light forces. Ions had already been trapped and cooled, now we could do the same for atoms. At that time, I had been studying light forces in the context of atom optics—using them to coherently manipulate the translational state of atoms. Out of this work came a realization on my part that a proof published by Gordon and Ashkin at Bell Labs was wrong. They called it the "optical Earnshaw's theorem," which was interpreted as preventing you from using radiation pressure to trap an atom at one point in space. While I was explaining this theorem to Eric Raab (PhD '88), I realized that there was a chink in their argument. That afternoon we invented a way to disprove this theorem in one dimension. Then we collaborated on several ideas with Carl Wieman [SB '73. Thesis advisor: Dan Kleppner]—who was one of the three Nobel Prize winners in 2001—which resulted in our publishing a joint paper on ways around the theorem.

Eric Raab and I were trying various ideas to make atom traps with light pressure. Unfortunately, none of them worked, seemingly because the laser beams used for them lacked symmetry. In desperation I turned to a proposal by Dalibard for a symmetrical arrangement. We realized that we could make a three-dimensional trap using three pairs of opposing beams along x, y, and z axes. We also realized that Steve Chu had about 98% of the apparatus we needed to make this trap. All we had to do was change the polarization of the light beams that he had been using, and also put on a weak magnetic field in order to modify the light forces so that they would push the atoms back towards the center of the trap. We applied this idea to Chu's "molasses" and it worked the first time we tried it. It was just the most visual thing you ever saw. You would turn the polarizers, or turn up the magnetic field, and you would see diffuse cloud of atoms collapse into a very bright millimeter-size ball. Subsequent measurements showed that that bright ball had atoms that were cooled a thousand times below 1°K, to milli-Kelvin temperatures. You could let the atoms go and recapture them to see how long it took for them to escape as a crude measure of how slow they were going. This magneto-optic trap (MOT) *enabled* the field of cold atom physics: you could produce quite dense samples of very cold atoms, and do experiments with them. It became the workhorse of the field: at one point 10 of the 14 atomic physics assistant professors in the U.S. were using the MOT.

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Realizing that atom traps were going to be a big part of the future, we built and demonstrated a complex configuration of magnetic fields that could trap atoms in a region of space with a fairly uniform magnetic field. After I published the trap idea in 1983, it turned out that the same magnetic field configurations had been invented 20 years earlier, to confine plasmas, by a Russian, Ioffe. This Ioffe-Pritchard magnetic trap is absolutely stable, and if you put atoms in it, they do not heat up at all. It overcomes one of the negative sides of a light-force-trap, the heating due to photons bouncing off the atoms. During a collision, the photon gets scattered in a random direction, imparting a little kick to the atom, and preventing the atom from cooling down too far. The limiting temperature is of the order of a hundred microkelvin.

You can do a lot of physics with a gas of independent cold atoms, but the use of light forces to cool atoms had the ultimate goal of cooling the atoms controllably into a single quantum state. This was done in ion traps by brute force: by figuring out very clever cooling methods and making the trap very stiff so that the lowest energy state was separated from the other ones. Ultimately Dave Wineland at NIST-Boulder was able to cool ions into a single quantum state.

Bose-Einstein Condensation

With neutral atoms, there was another possibility: Bose-Einstein condensation (BEC), predicted in 1925. It was clear that if you could get the atoms cold and dense enough, the quantum de Broglie wavelength of one atom would become longer than the distance to its neighboring atoms. When the atoms get to the point where their wavelengths overlap, their fundamental indistinguishability affects the statistical mechanics of how many available quantum states there are. Satyendra Nath Bose and Albert Einstein's theory accounted for this indistinguishability. They predicted that if you have a very cold box, and you start putting in the atoms one by one, at first the atoms distribute themselves among the quantum levels of that box according to the classical Boltzmann statistics—that the states of higher energy have fewer atoms in them, but the atoms distribute themselves into many different states. However, they predicted that once you reach a certain critical density, all the additional boson atoms would go into the lowest quantum state. It might take a million atoms to reach this point, but if you then put in nine million more atoms, 90% of your sample would be in the lowest quantum state. The system would be one giant self-interacting matter wave with only a 10% admixture of "hot" atoms.

The problem was how to reach the combination of high density and low temperature needed to get to BEC. Dan Kleppner and Thomas Greytak (SB, SM '63, PhD '67) had begun using cryogenic methods to cool atomic hydrogen in 1976 with the ultimate goal to get to BEC. In 1986, their postdoc, Harald Hess (now at KLA-Tencor), convinced them to try magnetically trapping the hydrogen using a Ioffe-Pritchard trap. Hess invented a new way of cooling called evaporative cooling. He realized that if you had a dense cloud in a trap, and it had enough collisions so that some atoms escaped, the most energetic atoms would leave, cooling the gas. The atoms remaining in the trap would re-equilibrate at a lower temperature and be closer to BEC even though the total number of atoms was decreasing. By 1991, they were just a factor of 3 above the temperature needed for BEC, but they were stymied because below 100 micro-Kelvin hot atoms near the center of the trap would transfer their heat to other trapped atoms before they reached the end of the trap, where they could evaporate.

On New Year's Eve 1988, Kris Helmerson (PhD '91) and I were working frantically to finish a paper on radio frequency transitions on trapped atoms. We realized that you could use radio frequency to spill a hot atom out of a magnetic atom trap—to move it from a state that was trapped to a state that was untrapped. People call this rf evaporation: you just tune the dial on your radio frequency (rf) synthesizer and as you go to a lower and lower frequency you start to eliminate the hottest atoms, making the ones left behind colder and colder. The atoms left behind are going slower because they are colder, but the density in the bottom of the trap increases so rapidly that the collision rate increases. As you turn down the rf, you can turn it down faster and faster and still have enough collisions to maintain thermal equilibrium. In fact, this is called "runaway evaporation." Eventually, you cool them down to BEC.

Now the trouble we had was we did not know how to get enough alkali atoms in the magnetic trap to get to this evaporative stage. Although I mentioned my rf idea to Dan Kleppner, it was very difficult to implement it with the hydrogen apparatus. It turned out that the rf technique was just what they needed, as atoms could be ejected from any position in the long trap. Greytak and Kleppner used this technique when they finally observed BEC in hydrogen in 1998.

Wolfgang Ketterle

When Wolfgang Ketterle came to MIT in 1990 as my postdoc, he had done his thesis in molecular ion spectroscopy. He had then worked on flame research using lasers before he decided to return to basic research. We came up with a way to dramatically increase the density of atoms in light traps. The problem is the large scattering cross section of atoms for near-resonant light causes many problems. The light can excite the atoms causing excited-state collisions that can release enough energy to kick atoms out of the trap. Or you could have so many atoms that the trapping light would get absorbed before it gets to the center of the trap. It can also bounce from atom to atom as Carl Wieman showed, and push the other atoms out of the trap. This cross-section for the photons getting absorbed or scattered is nearly ten thousand times bigger than the cross-section for the atoms to collide, making cooling impossible.

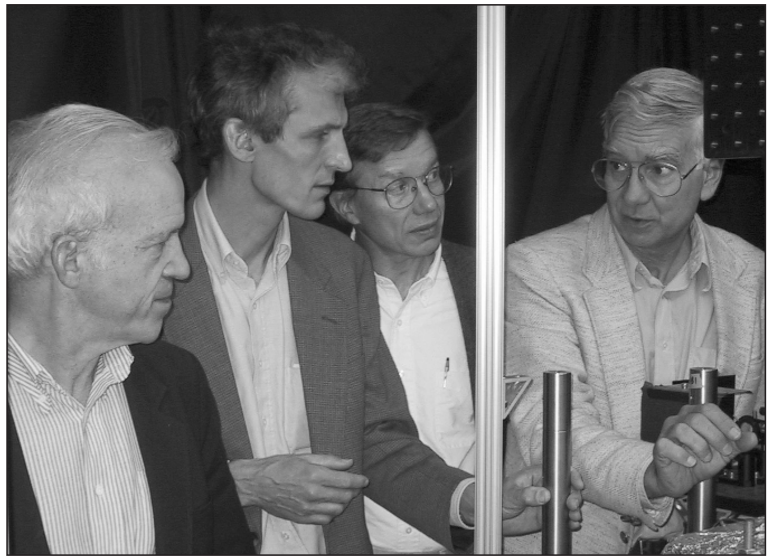

Figure 2

MIT faculty in ultralow temperature atomic physics. From left to right: Dan Kleppner, Wolfgang Ketterle, Tom Greytak, and David Pritchard, looking at the latest sodium BEC apparatus.

Wolfgang and I came up with an idea that solves this problem called the dark spot MOT. Basically, it involves hiding the atoms that have cooled off in the center of the trap by putting them in a hyperfine state that does not interact with the light. The light trap works in the upper hyperfine state, F=2. Because light-excited atoms sometimes decay to the F=1 state, a "repumper" laser beam is used to quickly return to the F=2 state where they are trapped. Our solution was to use a small piece of tape to block the center of the repumper beam. Then those atoms, which had already been slowed and trapped in the center of the trap, would just sit there because they were cold. The result was that the atoms in the center of the trap accumulated in the inactive hyperfine state for many microseconds, get repumped by light, and then become dark for more microseconds. When we took a laser that was tuned to excite atoms in F=1, the dark state, we found that there were so many atoms in that state that the light was absorbed in the first 1% of its travel across the cloud of atoms. Suddenly we had gone up a factor of about a hundred in density! We realized at that if we could switch those atoms into a magnetic trap, we would have a high enough density to start evaporative cooling. We changed our research agenda: BEC was no longer the pot of gold at the end of the rainbow; it was an attainable objective.

Wolfgang had finished three years of his postdoc with offers of faculty positions from a couple of other competing institutions. We wanted him to stay at MIT, but I was concerned that he would not be promoted to tenure unless he had a research program that was independent of mine. I said, "Wolfgang, would you like to stay here and take over this experiment?" Wolfgang agreed. He accepted the Department's offer of a faculty position. I gave him the experiment along with the two senior graduate students and the two grants that were specific to that experiment. I walked away from an experiment, but gained a great colleague.

Now at the same time, Eric Cornell (PhD '90), a former student of mine, had taken a position at JILA as a postdoc for Carl Wieman. He heard about the dark spot MOT and also realized that this was also a key to loading atoms in a magnetic trap and cooling them off with rf evaporation. Eric is very creative, and always optimistic. He was running neck and neck with Wolfgang. Every few months they would get another factor of 10 or of 50 in density, on the road to BEC.

The type of magnetic trap they both had been using was not the Ioffe-Pritchard trap, but a spherical quadrupole that had been proposed by Wolfgang Paul (Nobel laureate 1989) and demonstrated by Bill Phillips. It achieves great trapping strength at the expense of a field reversal at the bottom. Atoms that come too close to this point lose their quantum sense of which state they are in and switch themselves out of the trapped state. Thus the trap has a drain at the very bottom.

This did not bother Eric and Wolfgang at first, but when the atoms got colder and colder, the atoms would cluster in this middle region and start draining. Wolfgang solved this problem by focusing a green laser that repels the atoms from the bottom of the trap. Eric spun the very bottom of the trap around in a circle. The center of the circle was a stable minimum point at which the atoms could accumulate. The zero where the atoms could change state was moved outside of the trapped atom cloud. He named this technique the time-orbiting potential trap (TOP), and with that he was able to get BEC about four months before Wolfgang.

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When Wolfgang reached BEC, he had about a hundred times more atoms than the JILA people, and he could make them approximately 10 times faster. Then he did something that I have always regarded as the height of scientific courage. He thought that the Ioffe-Pritchard configuration of the magnetic trap, because it is stable, was far better for studying BEC than the quadrupole trap. He did not have tenure. His phone was ringing off the hook with invitations to speak about his BEC, which he had observed twice. He already had a thousand times more atoms than the JILA team, yet he decided that the right thing to do scientifically was to scrap the trap he had been using and replace it the new one.

For four or five months he did not have any results. Then the new trap started working. This trap, because the magnetic field is very uniform, allows you to observe the atoms with light. Wolfgang pioneered the method of observing the atoms in the trap non-destructively. The previous method required turning the trap off, seeing where the atoms had expanded to, and observing in the middle there were lots of atoms that did not move very fast because they were in the lowest state of the trap. You could not see the actual condensate that way. Now he could see the condensate and could do experiments with the condensate oscillating in the trap, or even experiment with conditions where at first there was a BEC and then there was not. He could observe the condensate form and reform and thereby study the dynamics of its formation. The Nobel Prize Committee recognized his achievement in awarding him the Nobel Prize in Physics for 2001, which he shared with Carl Wieman and Eric Cornell.

The End of the Rainbow

Atomic physics after about 1975, has been interested in controlling the atom's external quantum state–its translational motion either as quantized in a trap or in a free-particle state. The ultimate payoff of external state manipulation is atom interferometry, which involves making and reading out superpositions of the external quantum state. Now in collaboration with Wolfgang, we are using BECs as sources of essentially motionless atoms to do various atom optics and interferometry experiments.

But now consider where the idea of controlling the quantum state of atoms can go from here. The atom sits there in your trap; it is in a given quantum state internally; it is in a given quantum state externally. If you want, you can controllable put it in an entangled superposition state involving both internal and external degrees of physics, and then read this state out. This is as far as you can go in single atoms, unless you start taking them apart and doing nuclear physics. Atomic physics has reached the end of the rainbow that guided it through the 20th century.

Future Directions: The Next Rainbow's End

For the 21st century, we have switched from a quantum reductionist approach to single atoms and have begun a quantum constructivist approach. The objective is to start building up *systems of atoms* that are assembled completely at the quantum level. BEC is of tremendous interest to condensed matter physicists because you can study collective behavior: exciting collective excitations of the condensate, making sound waves, or stirring the atoms to create vortices and vortex lattices. You can visualize them, you can observe them form in real time. For example, if a BEC is placed in a suitably tuned standing light wave, the atoms experience a periodic potential. The strength of the tunneling between adjacent minima is controlled by the light intensity. This system is a remarkably exact realization of the Mott-Hubbard model that predicts phase transitions from insulator to conductor for electrons in a periodic potential. You can turn the knob on the terms in the Hamiltonian, turn off the potential, and measure the momentum distribution of the atoms. This experiment has recently been done by Immanuel Bloch's group in Munich.

A quantum computer is a system of atoms where every single one of the bits can be separately controlled and interrogated on the quantum level. As atomic physicists we can see single atoms with lasers. We can put them in a trap, couple them together, and interrogate them. This is a promising route to realize quantum computers. We may be able to contribute to nano-fabrication using this quantum control of atoms. Instead of trying to get smaller and smaller instruments to controllably deposit or remove materials, we may be able to fabricate structures on the nanometer length scale by controlling the quantum state of atoms and putting them into a quantum system exactly where we want them.

Wolfgang and I have collaborated on building an apparatus that can transport the BEC from the rather constrained environment where it is made (coils, laser beam, etc.) to another chamber a foot away where we can experiment with it. We have already put the BEC in simple atom waveguides—little configurations of wires that are microfabricated on a chip. The wires make a magnetic trap like a long Ioffe-Pritchard trap, so the atoms have a guide that is about 100 microns above the surface. The atoms travel in that guide and maintain their quantum coherence, thus making fiber-atom waveguides, analogous to optical waveguides. I hope we will be able to use these guided waves to do interferometry this year.

Personal Reactions

For me, the number one thrill has always been the moment when our small band of scientists finally attains the first definitive data on something new and risky, like atom diffraction, atom trapping, single ion trapping, or an atom interferometer. This often follows several years of building, getting no signal at all, trying to figure out why or to guess what is wrong without sufficient data, rebuilding, trying it a different way. Then suddenly, one night, it works—generally so well you wonder how you failed to observe the robust signal in all those previous attempts. The second thrill would be seeing people learn from this experience, go off to explore, then bring forth their own discoveries. Dan Kleppner, Tom Greytak, and I attended the Nobel Prize ceremony in Stockholm last winter, where Eric, Carl, and Wolfgang received their prizes in Physics. I cannot help but remark on the interconnectivity of the work of scientists, mentioned and not mentioned in this article, who contributed to reaching BEC. Thirdly, having colleagues like Dan and Wolfgang who are wonderful physicists and companions, is a tremendous piece of luck: all good scientists do not always have such generous spirits as colleagues. And finally, having our groups in a top-ranked department in a stimulating environment like MIT, having an umbrella of advice and administration from RLE, makes me feel extraordinarily fortunate. Having all this, my family, and my very special wife Andrea makes me feel blessed.

DAVID E. PRITCHARD, *Cecil and Ida Green Professor of Physics, has been a crucial link in the atomic physics chain that extends from Nobel laureates I. I. Rabi and Norman Ramsey, to more recent Nobel Prize winners William Phillips, Steven Chu, Eric Cornell, and Wolfgang Ketterle. Born in New York City, Pritchard graduated from the California Institute of Technology (BS, 1962) and Harvard University (PhD, 1968), and came to the MIT Department of Physics first as a postdoctoral associate, becoming an Assistant Professor in 1970.*

Pritchard was awarded the 1991 Broida Prize of the American Physical Society and is a Fellow of the American Academy of Arts and Sciences. His memberships include the National Academy of Sciences, the American Association for the Advancement of Science, the American Physical Society, and the Optical Society of America. He has published over one hundred papers in refereed scientific journals, has two patents, has received over 100 invitations to speak at national or international meetings, and is involved in a leadership capacity in numerous professional activities and organizations.

Before her retirement last year, VIRGINIA ESAU *was an Administrative Officer at MIT for fourteen years, first in the Center for Materials Science and Engineering, and afterward in the Department of Physics. She is now managing the space and renovation projects for the Department on a part-time basis. Prior to coming to MIT, Ms. Esau designed and managed the Boston College School of Nursing computer facility while administering its centralized personnel, fiscal, and communications systems. In addition to developing and implementing the Town of Brookline Title I Outreach to Parents program, she edited educational materials for workshops on racial issues.*

Ms. Esau graduated from Boston University, spent her junior year in Denmark with the Scandinavian Seminar, and has done graduate work at Harvard University and Boston College.