Giant Atoms Cast Long Shadow

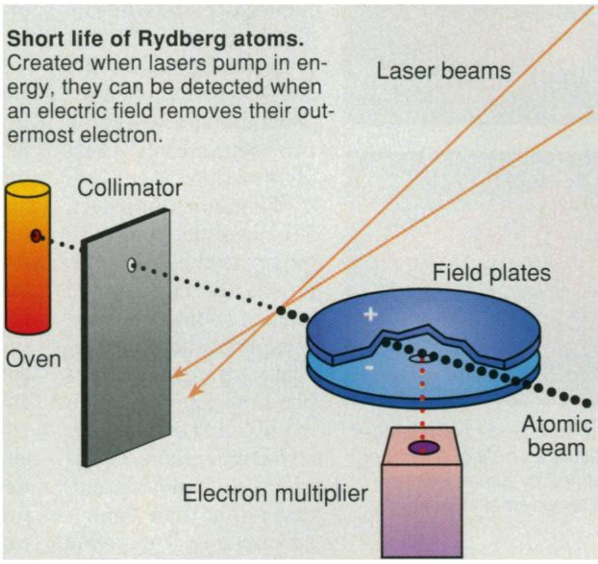
Atoms swollen with energy can serve as supersensitive detectors. They also probe the shadowy realm where the quantum world of the atom gives way to the familiar classical world

"To the best of my knowledge, we have made the largest atoms in the world," says Ken Smith, director of the Quantum Institute at Rice University, noting half in jest that he would hate to see that claim in print. These atomic behemoths—known as Rydberg atoms—are so big that thousands of other atoms can buzz around within their borders. The biggest ones Smith and his colleagues have made so far have a diameter 10,000 times that of an ordinary atom. At up to 20 micrometers across—the size of a fine grain of sand—says Smith, "you could just about see them if they were solid."

Created in the laboratory, where they live for a few milliseconds inside vacuum chambers, Rydberg atoms acquire their girth when one or sometimes two of their electrons are excited to very high energy levels, displacing them far from the nuclear core. It is not so much the size of Rydberg atoms that interests researchers, however, as it is the curious behavior of their outermost electrons. Being so distant from the nucleus, the electrons have only the most fragile ties to it, and a number of laboratories are exploiting this effect to detect subtle electric fields and probe chemical reactions that ordinarily proceed too fast for study.

But for a slowly growing community of atomic, molecular, and optical physicists ("AMO" scientists, as they call themselves), Rydberg atoms have a deeper fascination. If you could watch the outermost electron's motion, you might catch glimpses of a nostalgically unquantum-mechanical looking path. Rather than the fuzzball of probable location expected in the quantum-mechanical picture of the atom, you sometimes might see an electron circling a nucleus in a well-defined, planetlike circle or ellipse. It seems that rumors of the death of Niels Bohr's solar-system model of the atom, which the Danish physicist put forth in 1913 when classical mechanics still held sway, were premature.

What's more, researchers skilled with lasers and electric and magnetic fields can plot out itineraries for these electrons that include both semiclassical and quantum mechanical territories, making Rydberg atoms into systems for studying the shadowy border where quantum-mechanical behavior somehow morphs into the everyday, classical behavior found on larger scales. They are "stepping stones" from the quantum to the classical worlds, says John Yeazell of Pennsylvania State University, who has found evidence in Rydberg electrons of one of the most complex classical behaviors: chaos, in which the electron's motion becomes hard, even impossible, to predict, like a marble on a roulette wheel. Such exercises are allowing researchers to test the Correspondence Principle, Bohr's 80-year-old conjecture that the quantum and classical descriptions of nature somehow match up—something physicists now have to take as "a matter of faith," says AMO physicist Daniel Kleppner of the Massachusetts Institute of Technology.



Short life of Rydberg atoms. Created when lasers pump in energy, they can be detected when an electric field removes their outermost electron.

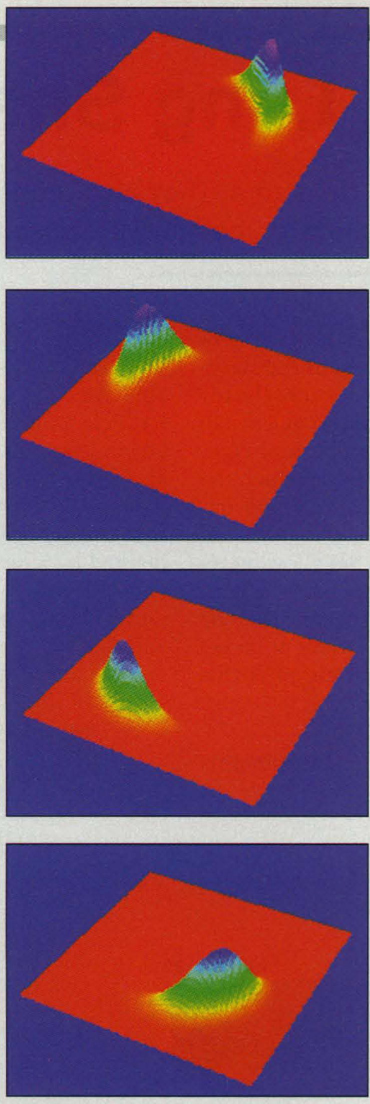
From space to the laboratory

This isn't the first time that these swollen atoms have stolen the spotlight. Named for the 19th century Swedish spectroscopist Johannes Rydberg, who labored for decades to make sense of the absorption and emission patterns of atoms, Rydberg atoms were long understood as a theoretical possibility. They were first detected in interstellar space in 1965, when radio astronomers picked up emissions from hydrogen atoms implying that they had been excited into long-lasting Rydberg states. The first laboratory evidence for Rydberg atoms showed up a few years later at Argonne National Laboratory, with the discovery that electrons in barium gas went on absorbing energy well after researchers thought they should have been kicked out of the atoms altogether.

In the 1970s, the advent of precisely tunable dye lasers enabled researchers to make Rydberg atoms routinely, pushing electrons out to larger and larger orbits. Peter Koch, an AMO physicist at the State University of New York, Stony Brook, who was part of that research wave, remembers this era as marked by a lot of "chest-thumping," with people trying to make bigger and bigger atoms. "This was the first time over new ground when almost everything you discovered seemed astounding," adds Keith Macadam of the University of Kentucky. Another advance in laser development, this one partly based on ultrashort-pulse lasers, has generated the ongoing, second wave of Rydberg science. "This is ushering in a new and exciting time," Macadam says, because pulses as short as a billionth or trillionth of a second long make it possible to take snapshots of Rydberg electrons' paths.

As a starting point for making Rydberg atoms, you can in principle use any atom in the periodic table. In practice, however, most researchers opt for atoms of alkali metals—including sodium, potassium, and rubidium—which have a lone outer electron that is easily boosted into a higher energy state. The typical experiment begins when a rarefied supply of these atoms is sent into a vacuum chamber, where lasers pump energy into the outer electron. In quantum-mechanical language, the electron's principal quantum number, n, goes up. And when n goes up, the size of the atom goes up exponentially.

To detect a Rydberg electron, now held to the nucleus by a mere thread of a bond, researchers then send in another laser pulse or use an electric field to flick the barely bound electron from the atomic core. This creates a positively charged ion and a free electron, which are readily detectable. The amount of energy required to create the ion is a measure of the energy of the Rydberg electron. Moreover, because laser pulses can be relatively short compared to the time it takes a Rydberg electron to orbit the distant nuclear core, researchers can monitor the electron by ionizing batches of Rydberg atoms at varying intervals after their creation, resulting in a movie of the electron's complex motion.



EBERLY *ET AL.*

Classical motion. Successive images show the calculated orbit of a Rydberg electron confined by forces from the nucleus and an external field.

Like all electrons, the Rydberg electron is actually described by a quantum wave function. But instead of spreading out into the cloudlike distribution seen in normal electrons, Rydberg wave packets have components that can travel together as a mix (or superposition) along a common planetlike orbit. That's reminiscent of the classical world, but Yeazell and his colleagues have found a more rigorous link between the behavior of Rydberg atoms and principles of classical motion.

After zapping rubidium atoms into Rydberg states, the researchers subjected them to strong magnetic fields that tweaked the far-flung electron's wave packet. "As you increase the field, you get more and more exotic [electronic] orbits, until finally you get some orbits that are not closed or regular and the system becomes chaotic," Yeazell says. When he and his colleagues applied a constant electric field and measured the probability of yanking off the Rydberg electron, they found that it displayed the mathematical hallmarks of chaos—a behavior that, although it eludes prediction, requires that the system evolve along a well-defined, classical path.

One major payoff of this kind of experiment, say physicists, is a more physical intuition into a quantum system like an atom than you could ever hope to get from quantum-mechanical calculations and theory. "As you approach the classical limit [as you do with highly excited Rydberg electrons], quantum mechanics gets harder to do theoretically," Yeazell notes. Supercomputers are getting close to being able to solve the relevant quantum mechanical equations, he concedes, "but there is a difference between having a computer program that gives you the right answer and having a physical intuition." Because chaos turns up in the bigger-than-life Rydberg atoms, he speculates, it might turn out to be a key to extending quantum mechanics further into the macroscopic world, where theorists now have to fall back on classical approximations.

Theorists have schemes for pushing the correspondence between the quantum and classical worlds even further, by coaxing the fleetingly classical wave packet into a permanent planetary orbit. Several years ago, for instance, theorists Joseph H. Eberly and Maciej Kalinsky of the University of Rochester in New York and Iwo Bialynicki-Birula of the Centrum Fizyki Teoretycznej PAN in Warsaw proposed a way to tailor the motion of Rydberg electrons so they would become a direct atomic counterpart to the motion of the two so-called Trojan asteroid clusters that lead and trail Jupiter as it orbits the sun. The asteroids cluster at points on Jupiter's orbital path where the combined gravitational forces of the two bodies create pockets of attraction.

To mimic that effect, a Rydberg electron counterpart to the Trojan asteroids also requires two sources of attraction. Eberly explains that the positively charged nucleus plays the role of the sun in providing one of those attractive centers, in this case a coulombic attraction rather than a gravitational one. To provide the second attractive force—the counterpart of Jupiter's gravity—Eberly and his colleagues apply a circularly polarized electric field. "The resulting equations governing attractions and repulsions are exactly the same as the equations governing the Achilles," the first of the Trojan asteroids to be observed, Eberly says. Both the asteroids and the counterpart Rydberg electrons are held in their respective orbits "absolutely, classically, stably," says Eberly.

This theoretical balancing act inspired other groups of theorists to discover a class of potential Rydberg orbitals in which the electrons' wave packets do not immediately disperse into quantum mechanical clouds, even when the magnetic and radiation fields used to create them are shut off. In the 15 April *Physical Review Letters*, Turgay Uzer, now of the Georgia Institute of Technology, and David Farrelly and Andrea Brunello of Utah State University argue that by immersing Rydberg electrons in both circularly polarized microwave radiation and a magnetic field, experimenters should be able to shepherd a Rydberg wave packet into a long-lasting planetary orbit. "This would literally be a Bohr atom" with the electron planet whirring stably around the nucleus-sun, Farrelly says.

No one knows quite how to realize the conditions that the theorists stipulate. But beyond their aesthetic appeal (who wouldn't want an atom to look like a solar system?), there's an extra incentive: Researchers think they may also point to new ways to control electronic motion and energy in more conventional atoms. After all, Eberly notes, "when you think about the electrical properties of matter, the optical properties, the magnetic properties, even many of the structural characteristics, these are determined by the location of electrons in their orbits in the atoms that make up matter. ... One can easily speculate about the tremendously different properties you might get if the electrons can be held stably in wildly inappropriate locations."

Discriminating atoms

In the nearer term, researchers' growing finesse at creating, manipulating, and studying Rydberg atoms should add to their value as laboratory tools for studying other systems—quantum dots, for example. Quantum dots, sometimes called artificial atoms, are tiny specks of semiconductor materials made of thousands of atoms whose quantum-mechanical features confine electrons within their bounds like sailors stranded on an island. By controlling the dimensions and composition of the quantum dot, materials scientists can tailor their electronic properties, and that, combined with their minute size, has made them into candidates for making future-generation memory and logic chips. "An electron in a quantum dot is like a Rydberg electron," Farrelly says. In both cases, electrons are held in place via forces that act over relatively long distances—an especially long-range coulombic attraction in the case of the Rydberg atom and a bowl-like potential energy well formed in a quantum dot. So, Farrelly surmises, what researchers learn about electronic behavior in Rydberg atoms may help them predict the properties of quantum dots.

The feeble link between a Rydberg electron and its nuclear core can also lengthen the lifetime of exotic chemical species by factors of a million and more, making them long-lived enough to study. Rice's Smith, for example, has observed potassium Rydberg atoms bonding with a water molecule for microseconds—millions of times longer than ordinary potassium atoms can sustain the union, which has an unfavorably high energy. "The Rydberg electron zings by, it picks up and carries the energy away, so these stay together," explains Smith. This type of interaction, he says, enables researchers to artificially slow down chemical interactions that normally are too fleeting to measure.

Carl Kocher of Oregon State University in Corvallis thinks materials science could also benefit from Rydberg atoms. When he shoots them through the openings of a fine gold grid, they shed their outer electrons in patterns that change detectably when he covers the metal with patches of another substance just a single atom or molecule thick. He conjectures that a Rydberg-based analytical device might yield insights into the atom-by-atom growth of thin films, a booming area of materials science.

The supersensitivity of Rydberg atoms recently proved its value in another area. Building on earlier work by researchers at the Max Planck Institute for Quantum Optics in Munich, Serge Haroche's group at l'École Normale Supérieure in Paris reported recently that it had used Rydberg atoms to make direct measurements of the "graininess" of light (*Science*, 5 April, p. 34). The experiment measured subtle energy oscillations induced in Rydberg electrons by the electric field generated by individual photons trapped inside a small cavity. In ordinary atoms, any effect would be undetectable. But because the distance between a Rydberg atom's positively charged core and outermost electron is so large, the atom has an enormous electric dipole moment, which amplified the effect of the trapped field.

Technology, quantum mechanics, and the physics of electromagnetic fields aren't the only places on which the shadow of these swollen atoms is falling. First detected in space, Rydberg atoms showed up there again in 1995 when astronomers, pointing their radio telescopes at a very hot star in the constellation Cygnus, observed the first natural laser in the gases surrounding the sta (*Science*, 8 September 1995, p. 1336). The laser's wavelengths could only have come from hydrogen atoms in Rydberg states.

Such surprises have kept more than a few researchers hooked on Rydberg atoms for decades. "I have always been interested in these atoms, because they have exaggerated properties and you can use them to do things you otherwise only could dream about," remarks Thomas F. Gallagher, a University of Virginia AMO physicist. When he started studying Rydberg atoms in the mid-1970s, he says, "nobody had any conception of how many things would happen."

–**Ivan Amato**

Ivan Amato's book on materials science, Stuff, will be published early next year by Basic Books.

DEVELOPMENTAL BIOLOGY

Receptor for Vital Protein Finally Found

Biologists, like wiretappers eavesdropping on clandestine molecular conversations, have been trying to trace protein signals as they travel from one cell to another and then to the recipient's genes, the masters of the cell's fate. But the connections in some of these communications circuits have been hard to pin down because the proteins that carry the signals are elusive. That has been the case with the "Wnt" proteins, which help trigger the growth of the cerebellum in mice and—in some cases—cancerous cell proliferation. Researchers just haven't been able to identify the receptor molecules on the cell surface that pick up a Wnt signal and relay it to the interior.

Now, however, researchers have traced a call. They have identified the receptor for one Wnt family member, the fruit fly protein Wingless. A team led by Jeremy Nathans, a molecular biologist at Johns Hopkins University, and Roel Nusse, a developmental geneticist at Stanford University, reports in the 18 July issue of *Nature* that when they inserted the gene for a novel fruit fly protein into cells from *Drosophila* embryos that were normally deaf to Wingless's signals, the cells, in essence, pricked up their ears: They initiated a chain of processes involved in cell adhesion—an event usually triggered by Wingless. That is strong evidence that the new protein, called Drosophila frizzled 2 (Dfz2), is Wingless's long-sought partner.

"It opens up a whole new set of experiments," says Harvard University developmental geneticist Andrew McMahon. With the receptor, researchers can get a clear look at the molecules that carry Wingless's signal to the nucleus and determine the exact genes that receive this signal. And that work could have broad implications, for researchers have found dozens of Wnt molecules in mice, frogs, nematodes, and humans, and the proteins have proven to be crucial regulators of development. Fruit fly embryos with defective Wingless protein, for example, have body patterning problems, failing to develop proper body segment boundaries, eyes, and—as the name implies—wings. But because the Wnt proteins are difficult to obtain in purified form for use in biochemical experiments, they had remained "orphan" growth factors, ligand molecules with no known receptors.


M. BRINK AND C. S. HARRYMAN

Wingless connection. Wingless protein (red) binds to the surface of fruit fly embryo cells engineered to make its receptor.

Nathans's laboratory had the opposite problem: a family of receptors without ligands. Nathans and co-workers Purnima Bhanot, Deborah Andrew, Jen-Chih Hsieh, Yanshu Wang, and Jennifer Macke had discovered that a receptorlike *Drosophila* protein called frizzled has a host of counterparts in birds, fish, and mammals. Biologist Paul Adler at the University of Virginia had shown in the 1980s that flies lacking frizzled suffer curious patterning defects, including wing hairs that swirl in erratic directions. "All of that got us thinking," Nathans says. Because both the Wnt and frizzled families were large, and because another protein called disheveled seemed to be a mediator of both Wingless and frizzled signals, "the Wnts seemed like a good bet" as frizzled ligands.

That bet paid off when Nathans sent his frizzled molecules to Nusse. When exposed to Wingless, some *Drosophila* cells begin accumulating a protein called Armadillo, which helps cells stick together. But cells called Schneider cells, cultured from early fly embryos and thought to resemble mammalian immune cells called macrophages, lack this ability. Guessing that the Schneider cells are missing some component of the mechanism that activates Armadillo accumulation—including, perhaps, the receptor for Wingless—Nusse and colleagues Marcel Brink and Cindy Samos Harryman inserted the gene encoding one of Nathans's new frizzled proteins, Dfz2, into the cells, then incubated them in the presence of Wingless. The cells promptly bound Wingless on their surfaces and began building up Armadillo. "That was an enormous surprise," Nusse says. "We didn't expect that simply transfecting the gene would allow the cells to respond."

With one receptor identified, Nusse, Nathans, and others are busy searching for Dfz2 homologs in mice and other animals. They are also designing biochemical and genetic experiments to discover what substances interact with Dfz2 inside the cell. "We know that the Wnts play roles in regulating cell fate," says McMahon. "Having the receptor gives us a way of probing how they work."

–**Wade Roush**