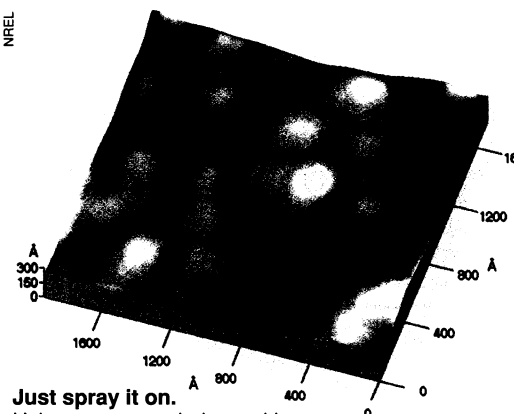
ference on Lasers and Electro-Optics in Anaheim, California, in June, Bimberg's team reports lasing measurements up to room temperature (300 K). Researchers in the two teams say they are still unsure why these temperature differences occur. But they suspect it may have to do with subtle differences in growth conditions or vertical spacings between dots.

Amnon Yariv, a quantum dot laser expert at the California Institute of Technology in Pasadena, calls the new results "a very interesting development," as they bring commercial quantum dot lasers a step closer to reality. And Bimberg and Madhukar are now working to take additional steps. The lasers

NREL



Just spray it on.
Using a spray technique with nanoclusters, scientists can make smooth thin films.

for both groups currently emit light at a wavelength near 1 micrometer. And down the road the researchers hope to grow larger dots that would produce light at wavelengths of 1.3 micrometers, which can be used to transmit data through fiber optic cables.

Film stars

Laser-makers aren't the only ones benefiting from semiconducting nanoclusters. At the National Renewable Energy Laboratory in Golden, Colorado, David Ginley and his colleagues are using such atomic clumps to make polycrystalline thin films: sheets of semiconducting crystals used to conduct electrical charges over large areas in devices such as solar cells and computer displays, or that are patterned into wires on chips.

The cheapest way to produce thin films is to spray them on, but spraying usually produces defects and gaps that lower a film's ability to conduct electricity. As a result, this fabrication process has been restricted to thicker films, which are deep enough so that gaps typically don't go all the way through. But more material costs more money, so thick films are expensive. That's where nanoclusters come in. By smoothing out the spray process, "nanoclusters allow you to transition spray technology to the thin-film range," says Ginley.

Nanoclusters solve the basic problem of spray deposition: the large size of the grains in the starter solution, which measure about 1 to 2 micrometers in diameter, or roughly the same thickness as the thin films themselves. "It's like putting down a layer of boulders next to one another," says Ginley. Even when packed tightly together, gaps remain between neighboring particles. His lab's solution: smaller particles that pack more closely. In the 9 October 1995 issue of *Applied Physics Letters*, Ginley and his colleagues reported spray-painting solutions containing 2- to 3-nanometer-sized cadmium-telluride (CdTe) nanoclusters to make smoother, virtually defect-free thin films.

Just making semiconductor nanoclusters that small wasn't easy. To synthesize their tiny CdTe clusters, the researchers started by dissolving cadmium- and tellurium-containing compounds in two separate solutions of an organic solvent known as alkylphosphines. When they mixed these solutions, the cadmium and tellurium began agglomerating into clusters. By carefully controlling the temperature and the concentration of the reactants, the researchers ended up with 2- to 3-nanometer particles coated with a layer of alkylphosphine molecules, which prevent neighboring clusters from clumping together.

Next, they sprayed a thin layer of the cluster-filled solution onto a substrate heated to at least 250°C. The hot substrate burned off the particles' thin organic coating and fused neighboring particles into a thin, smooth layer. A first look at these layers with an atomic force microscope shows that the films have no gaps and are at least 250 times smoother than conventionally sprayed polycrystalline thin films.

The researchers have yet to measure the electrical performance of these films, but have used them to construct working solar cell prototypes. And Paul Alivisatos, a professor of chemistry at the University of California, Berkeley, calls the new film-making technique "a very good idea," because it makes it much easier to create high-quality polycrystalline films over large areas, which could lower the cost of any device that uses them.

Growing role

Nanoclusters are shaping other technologies as well. Researchers around the world are studying nanoclusters for use for environmentally friendly batteries, high-quality color copiers, and high-density magnetic data storage. Even these applications, Siegel suspects, are just the tip of the nanocluster iceberg: "We've started at the top and have discovered some very important applications already. But there are many more to come." This small world has big horizons.

–**Robert F. Service**

PHYSICS

Clusters Whip Light Atomic Nuclei Into Shape

Exactly one century ago, scientists knew nothing about the innards of atoms. But while experimenting with uranium in 1896, the French scientist Henri Becquerel discovered radioactivity, a phenomenon hinting that atoms were made of smaller particles. Some of the particles Becquerel detected, researchers learned later, were alpha particles: two protons and two neutrons glued together by one of the fundamental forces of nature, the strong force. And today, 100 years after Becquerel found clues to their existence, alpha particles are producing dramatic insights into the structure and behavior of atomic nuclei.

While many such models of nuclear architecture portray protons and neutrons—together known as nucleons—packed solidly together or stacked in concentric shells, researchers have theorized that the nuclei in the lightest elements, such as carbon or oxygen, look like alpha particles clustered in triangular shapes or tetrahedra. Now recent experimental and theoretical work by several groups of British and American physicists indicates that at high energies, the alpha particles in some of these atomic nuclei, such as carbon or magnesium, can form "nuclear molecules," where one cluster of alpha particles orbits around another, and even bizarre long chains.

And in the case of the carbon nucleus, the clustering has triggered a debate over the carbon state that plays a key role in the nuclear transformations that forge carbon and a whole chain of heavier elements in the interiors of stars. Says cluster theorist Brian Fulton of Birmingham University: "Without the existence of this cluster, carbon would not exist, and therefore we would not exist." But just what that cluster looks like is now open to question, as experiments point to both a chain and a triangle shape.

This emerging cluster of results has excited the research community. Says nuclear physicist Alan Shotter, head of physics and astronomy at the University of Edinburgh in Scotland, "While nuclear clustering in light nuclei at low energy has been known for some years, recent research shows that such clustering can also exist at higher energies. This clustering seems to be related to exotic nuclear shapes, which is not only fascinating in its own right but is also providing a valuable new insight into how a complicated physical system like a nucleus can be explained in much simpler terms." Physicists ordinarily need a great many variables to describe systems that contain many particles, but nature has simplified matters by grouping clusters of these particles together. Indeed, these groupings have also intrigued condensed matter theorists, who have discovered that alpha cluster models can be applied outside the nucleus to atomic systems such as clusters of sodium atoms, where they can be used to study electronic behavior.

Beating the nuclear shell game. In the quantum realm of an atomic nucleus, of course, structure isn't just a packing problem; it also reflects a system of energy states. In nuclei of heavy elements, for instance, the strong force brings the particles so close together that they no longer behave as separate entities but as one, like a liquid droplet. In lighter elements, the particles are distinct, and the nuclei have an onionlike structure: The energies of their nucleons are lowest when they are arranged in concentric shells.

But when it comes to the lightest elements—starting with helium, which has two protons and two neutrons (one alpha cluster), and moving up to magnesium, which has 12 and 12—physicists playing this shell game run into trouble. Fulton explains: "Although the shell model works for the lowest energy states of light nuclei, at higher energies light nuclei tend to deform quite easily." To keep nucleons in separate shells, he says, physicists have to put them through some far-fetched quantum mechanical contortions: "In these cases the shell model isn't so appropriate: The calculations become hideously complicated."

To simplify matters, physicists turned to clusters. In the early 1960s, David Brink at the University of Oxford sharpened a model originally proposed by Princeton University's John Wheeler, which suggested that carbon, with 12 nucleons, was an equilateral triangle of three alpha clusters. With all angles between the particles equal, the energy of the nucleus would be lowest, making this the most stable arrangement. Oxygen, with 16 nucleons, was a tetrahedron: Again, all the angles would be equal. This model didn't explain, however, why beryllium—with eight nucleons—was unstable, breaking into two alphas, while carbon and oxygen nuclei were more stable. Brink's version, which extended to other nuclei as well, also portrayed them as clusters with geometric symmetries. But it predicted their nuclear binding energies and stability more accurately.

Elegant though such work was, it was still theory. There was some indirect experimental evidence supporting this view, from work by physicist Allan Bromley. In the early 1960s, working at an accelerator facility in Chalk River, Canada, Bromley scattered carbon nuclei off each other and obtained data suggesting that the nuclei momentarily stuck together in an intermediate excited state, with each set of 12 nucleons combining into magnesium-24. This short-lived "nuclear molecule" was the first piece of data hinting that atomic nuclei could be made from smaller but identical groups of particles. Although Bromley's detectors also found alpha particles among the final debris, they were not accurate enough to demonstrate connections between the alphas and any higher level of nuclear organization.

DARESBURY LABORATORY

Catching a cluster. In the 1980s, researchers at Daresbury Laboratory in England used this scattering chamber to detect cluster structure in various nuclei.

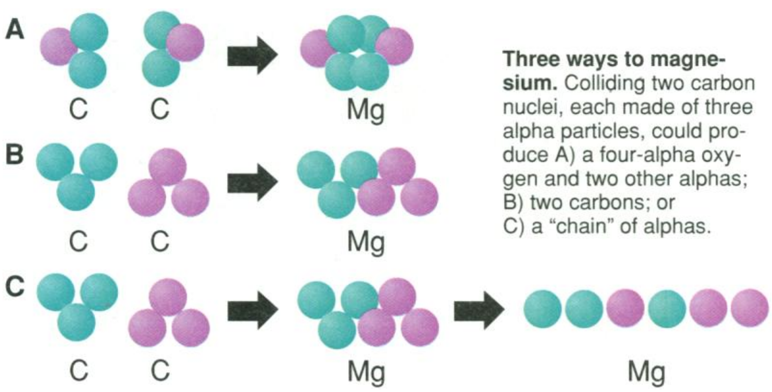
In the 1980s, new detectors were developed that could accurately pinpoint the position of particles emitted from a nuclear reaction and the direction from which they came. Using the tandem Van de Graaff accelerator at the Nuclear Structure Facility (NSF) at Daresbury, a team of British physicists, including Fulton and Bill Rae from Oxford, started a series of experiments in 1986. And they confirmed that Bromley's nuclear molecule had smaller components.

The researchers reversed Bromley's procedure for observing this intermediate state, breaking up magnesium-24 by slamming it into a barrier instead of trying to combine two carbons. By measuring the direction and energy of the twin carbon nuclei emerging from the breakup, the team could derive the energy and angular momentum of the excited nuclear molecule that immediately preceded them. Says Fulton: "What we found was that the spin varied in just the way that you would expect for a little quantum-mechanical rotor. The classical [mechanical] picture would be two carbons orbiting each other."

Taking clusters to the stars. Because Brink's models indicated that carbons themselves were composed of three alphas, the physicists suspected that alphas were basic units of organization. And Rae had developed a model taking this cluster idea a step further: He predicted that while carbon has a triangular alpha structure in its lowest energy state, if its energy was boosted it could form a relatively stable excited state in which the three alphas lie side by side in a chain. This state has an excitation energy close to 7.6 million electron volts (MeV). And that energy has implications that resonate throughout the universe, for it plays a key role in the standard theory about the creation of the elements.

Astrophysicists have long assumed that heavy elements are created by fusion in the thermonuclear furnaces of stars. The chain reaction begins when two nuclei of the lightest element, hydrogen, fuse into helium. Two helium nuclei combine to form unstable beryllium-8, which survives just long enough to interact with another helium to make carbon-12. Carbon is the route to all the other elements, as various numbers of nucleons are added. But in the early 1950s, the renowned astrophysicist Sir Fred Hoyle pointed out that the helium-beryllium reaction was too slow to account for all the carbon estimated to exist in the universe. This was a real roadblock.

Then in 1957, along with astronomers Geoffrey and Margaret Burbidge and Willy Fowler, Hoyle proposed a way around the obstacle. The group suggested that if carbon had an excited energy state of about 7.6 MeV, it would match, or



SOURCE: B. FULTON

Three ways to magnesium. Colliding two carbon nuclei, each made of three alpha particles, could produce A) a four-alpha oxygen and two other alphas; B) two carbons; or C) a "chain" of alphas.

"resonate" with, the combined energies of the beryllium and helium nuclei. Such resonance would facilitate energy exchange among the nuclei, speeding up the reactions and producing the needed amount of carbon. And experiments by the group indicated that carbon indeed has this resonance.

The proposal that a chain state of carbon could account for the 7.6 MeV resonance encouraged Rae and colleagues to investigate whether heavier nuclei could link alphas into chains as well. Rae's models indicated that at higher energies, even longer chains could exist, including a four-alpha chain state for oxygen-16 and a six-alpha chain for magnesium-24.

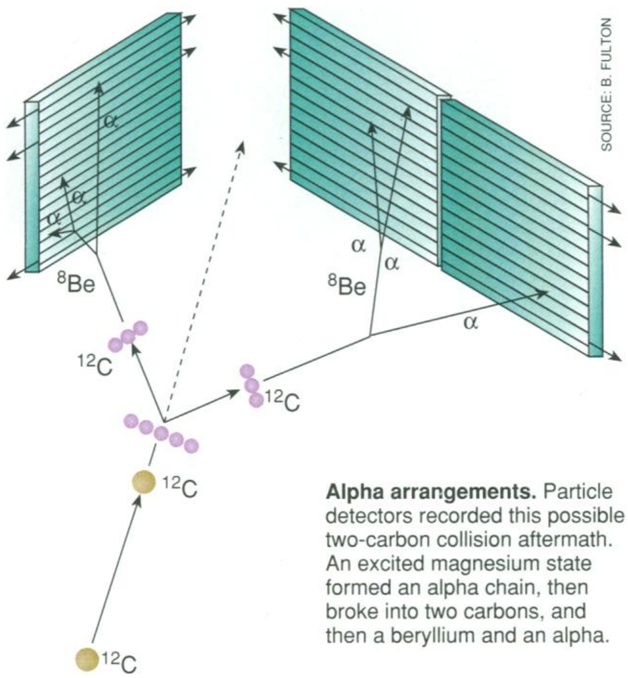
Yet these predictions were still highly speculative; scientists began to hunger for more direct evidence to back them up. So Alan Wuosmaa at Argonne National Laboratory in Illinois and Russell Betts at the University of Illinois, Chicago, decided to look for the magnesium chain state by studying the breakup of the excited magnesium created in the carbon scattering reaction.

Using Argonne's superconducting accelerator ATLAS (Argonne Tandem Linac Accelerator System), the Wuosmaa-Betts team detected six alphas coming out from the collision. By measuring their energies and angular momenta, the team could then calculate the energy and configuration of the intermediates preceding them. And in 1993 they announced they had good evidence that such intermediates formed a six-alpha magnesium chain state that was within 1 MeV of predictions.

The U.K. group—after a temporary hiatus when NSF was shut down and their equipment was moved nearly 20,000 kilometers to the tandem accelerator at the Australian National University (ANU) in Canberra—found similar evidence for a four-alpha chain in oxygen-16. "We found a sequence of states at high energies which have all the characteristics of a four-alpha chain. The moment of inertia is consistent with a very elongated structure," Fulton says.

Loose links in the chains. In the past year, however, some of the links in the magnesium-chain story have weakened—undermining researchers' understanding of carbon's excited state in the process. Richard Freeman and his group at the Center for Nuclear Research in Strasbourg, France, produced data indicating that the same state not only decays via the two-carbon intermediate state but also into two different nuclei: an oxygen ground state of four alphas tightly packed into a configuration that resembled a sphere as much as anything, and two-alpha beryllium. Other groups working at Catania, in Sicily, and in Bombay, India, have confirmed this result. And Fulton admits it's difficult to conceive of ways that such nuclei could evolve from a long chain. "It's hard to see how a long chain of six alphas could break up into a tight spherical group of four alphas plus a couple of remaining alphas," he sighs. And the U.K. group itself also measured other breakup patterns that do not seem to correspond to a chain state.

Rae has spent the past 9 months trying to figure out what's happened to the chains. He now thinks he's beginning to get a handle on it. "This state isn't what we thought but something much more interesting," he says. Analysis of the energies corresponding to the spin and orbital motion of the magnesium intermediate, Rae says, indicates that it's not a chain but a pair of triangles orbiting one another; this arrangement is, in fact, very similar to the one theorized earlier for carbon's ground state. But this time, the evidence is more direct. Rae saw peaks in the data that had sixfold symmetry. And the most straightforward explanation for that was two carbon-12 nuclei, each a triangle of alphas with threefold symmetry. It's more energy-efficient for this configuration, which already has subgroups of alphas, to break up into a sphere and some leftovers, Rae says; a linear chain would more easily break in half. "If this model of the data is correct," Rae says, "then we have the first direct piece of experimental evidence that the carbon nucleus has a threefold symmetry—that it's made of three alpha particles."



Alpha arrangements. Particle detectors recorded this possible two-carbon collision aftermath. An excited magnesium state formed an alpha chain, then broke into two carbons, and then a beryllium and an alpha.

Recent work by some Japanese theorists supports these new ideas. At December's joint Japan–U.S. Seminar on Nuclear and Atomic Clusters, held in Honolulu, Hawaii, cluster theorist Yasuhisha Abe from Kyoto University and some of his colleagues argued that it had been unnecessary to invoke a chain state in order to account for excited magnesium in the first place. "Our viewpoint was completely different from the simple linear chain structure of the British," claims Abe. "Now Dr. Rae seems to have changed his opinion to something closer to ours. We think it's two three-alphas coupling weakly with each other, but I suspect our picture is still too simple," he adds.

New geometry. Simple or not, some of these latest ideas about the ways that light nuclei arrange themselves into clusters have caught the eyes of scientists studying larger quantum systems, such as atomic clusters. Using this approach, for instance, Marvin Cohen and Walter Knight of the University of California, Berkeley, have predicted how tiny clumps of sodium atoms, created by vaporizing the metal with a laser (a technique devised by Rick Smalley of Rice University in Texas and Vladimir Bondybey of AT&T), arrange themselves into a series of clusters with particular stable geometries. Some of these arrangements, such as tetrahedra or two-dimensional arrays, are similar to those found in atomic nuclei, and the scientists think the principles behind them might explain some unusual electronic behavior seen in such clusters.

But in the world of light nuclei, the new data on excited carbon do throw up a knotty problem: Now researchers have at least two models for the all-important Hoyle carbon resonance state, a chain and a three-alpha triangle. "It's frustrating that we still don't actually know the structure of that state," comments Fulton.

To resolve the issue, both U.S. and British groups are planning a new series of experiments to exploit more sophisticated detector systems. A new detector, the Multi Element Gas Hybrid Array, is being flown out to ANU and should be on line by July. That's the easy part. Thinking up the definitive experiments to pin down the carbon resonance state is harder. Says Betts: "We came away from the Hawaii meeting committed to doing one important experiment—which is to resolve the structure of the carbon 7.6 MeV state. Everyone believes that what Bill Rae calculates [about the carbon state] is basically right, but we don't really know what the key experiment is. We all agree that these cluster states are real, but what is missing is the smoking gun."

–Nina Hall

Nina Hall is a free-lance writer living in London.