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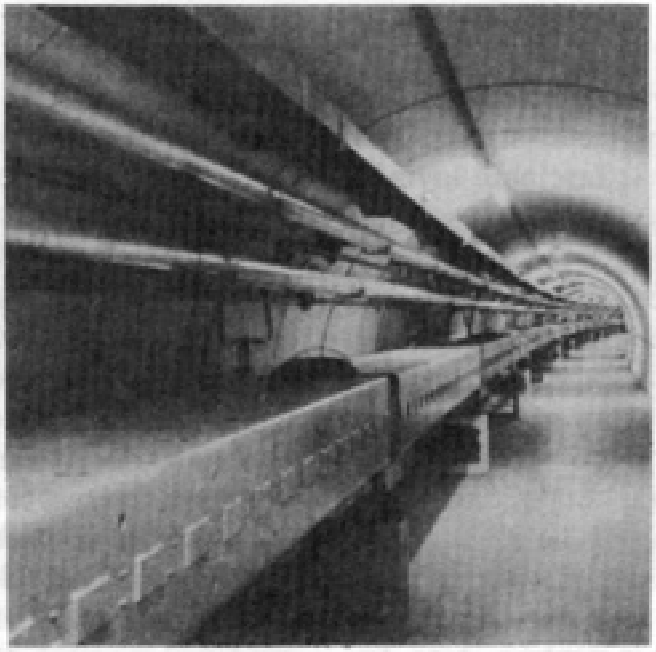
What Makes Atoms Tick?

By: Earle Holland

In the world of basic physics, there is a wonderful paradox.

Physicists spend hundreds of millions of dollars to build the giant, building-sized machines needed to search for the smallest parts of nature.

But even when the switches are thrown on the huge cyclotrons and linear accelerators they've built, the physicists only see tracks on a photographic plate, clicks on a detector — proof of where a particle has been.


Fermilab

It's like finding the fossilized footprints of ancient man, evidence that our ancestors had been there. That's the closest physicists can hope to come in their search for the fundamental particles in nature.

Among these are "quarks." All of the particles that make up a class of hadrons — or so the theory goes — are composed of quarks, always thought to be in pairs or triplets. It's the way these combinations are formed, what charge they carry, how they interrelate, that is ultimately responsible for the diversity of the universe.

Scientists are fairly sure that the particles are there. But believing is much easier than proving. And keeping track of the variations of this new sub-sub-atomic world has become a science itself.

The quarks come in flavors, curiously labeled **up, down, strange, charmed,** and **bottom**. They come in colors, too — red and blue — but you wouldn't recognize them as colors. The labeling is purely arbitrary, assigned on the whim of the researchers who work with them.

The best known of the hadrons are protons and neutrons, but there are also pions, lambdas, and others. There's another class of fundamental particles called leptons. Physicists also ponder the relationships of positrons, bosons, mesons, gluons, muons, and neutrinos.

But it is the quarks that make up the nuclei in the atoms which make up the molecules which make up all that we are and all that we know.

It's a race among scientists, tinkerers at heart, who are rushing to take the atomic nucleus apart like an alarm clock to see if they understand what makes it tick.

Inside the Van de Graaf Laboratory at The Ohio State University Research Foundation, a team of physicists hurl sub-atomic particles together at nearly one-tenth the speed of light.

These microscopic collisions and the debris they leave offer clues to the composition of the atom and, more precisely, its nucleus.

"We take some energetic particle like a proton or a neutron and crash it into the nucleus," explains Hershel Hausman, Ohio State physics professor. "Something happens inside the nucleus and pieces come flying out.

"By studying these pieces, we try to reconstruct the nature of the particles that were inside that nucleus before we hit it, and understand how it is put together."

This is the thrust of nuclear and particle physics today. These infinitesimal projectiles hurled at atomic targets are yielding a cornucopia of different particles.

A key to understanding the universe is locked inside the atomic nucleus.

But physicists from Isaac Newton to Albert Einstein to their present-day descendants look for an orderly universe, one that's put together from simple parts. And a bushel basket of different particles tends to confuse this order.

So the theory exists that the fundamental particles are the basic building blocks and of these, the quarks seem the most basic. Quarks, so the theory says, exist in combinations, bound together by the "strong" force, one of four such fundamental forces governing the universe.

'Free quarks' shake current theories

But recent Stanford University experiments seem to dispute this. "Free quarks," those existing singly rather than in pairs or triplets, were observed. The finding is enough to shake the current understanding of how the nucleus is put together. But this work hasn't been duplicated to date.

"It's an incredibly difficult experiment to do," explains Richard Boyd, physics professor. Physicists are professional skeptics. Until we've seen this confirmed in another way, we're not very willing to accept it."

So physicists Boyd, Hausman, Timothy Donoghue, S. Leslie Blatt, Harold Suiter, and Larry Dries set about trying to verify the Stanford results and look for free quarks, this time using Ohio State's huge Van de Graaff generator in a way it never had been used before.

While the Van de Graaff generator has been used for nuclear physics for years, Boyd realized that the more than 15-year-old machine could be used as a detector of the free quarks — if they are there.

The generator normally serves as a source of particle beams for the physicists' experiments. To do this, gases are pumped into the top of the massive device where they are heated by radio frequency (RF) power. This causes collisions between the atoms; the bits and pieces from these collisions produce the particles. These are then accelerated to high speeds and form the beam.

Not able to disprove Stanford experiment

A huge magnet at the bottom of the generator bends the beam, filters out specific components, and then aims it at one of the seven major pieces of particle detection apparatus. "We did our experiment well in excess of the sensitivity needed to test the assertion of the Stanford experiment and we didn't find anything," Boyd explains.

"We can't say that they were wrong. We were only able to span a restricted range. It's possible that the Stanford researchers could be seeing quarks outside our range.

"So we're not able to disprove them. On the other hand, we were able to reasonably, convincingly reject what may well be the most likely hypothesis" for the existence of free quarks, Boyd says.

But the point, Hausman adds, is that OSU physicists were able to use the Van de Graaff generator as a mass spectrometer that was two orders of magnitude more sensitive than would be required to detect the quarks.

Other tests for the Stanford effort

Other experiments are on the drawing board for the Ohio State team in hopes of understanding the Stanford work. To find the free quarks could upset modern particle theories.

"The Stanford result is so crucially important that, if it is right, we really want to know it as soon as possible," Boyd says.

The Van de Graaff generator is the largest of its type in the country. First built in 1963 with support from the National Science Foundation, it accelerates particles within the beam to energies of seven million volts, roughly one-tenth the speed of light.

"It's the black box from which we get our beams of particles to probe the nucleus," explains Donoghue.

Back in 1970, Donoghue and his research group made a unique addition to the Van de Graaff — equipment that focuses on a specific property of the proton beam.

While other major developments to do the same thing were underway at laboratories in this country and in Germany and Russia, only the Ohio State project was successful. "We did some very innovative things that made the project a success," Donoghue says.

An unexpected finding at OSU

This work has allowed the OSU team to pursue some very fundamental questions regarding the nucleus. Some of their studies have suggested that, in some nuclei, the very strong force between a pair of neutrons in the nucleus may be slightly different than the strong force between a pair of protons.

The finding implies that the two are not the same, as had been thought, and therefore the charge symmetry of nuclear forces may not be the same in all systems. "That is a very important result, if confirmed," Boyd says.

To understand our universe in all its vastness we need to understand the tiniest particles of which it is made.

In another group of experiments, Hausman investigated another kind of symmetry within nuclear interactions. That work produced information about a kind of nuclear structure — called a "doorway state" — that lasts only a billionth of a billionth of a second — a micro-instant long enough to provide a glimpse into the nucleus.

Work early last year brought Leslie Blatt and the other physicists an unexpected finding that physicists never thought existed and that may lead to a better understanding of one of nature's foremost powers — the "strong nuclear force" that binds together atomic nuclei.

Blatt detected the existence of a "second harmonic giant resonance," a new form of nuclear excitation. This new phenomenon can be described this way: A ringing bell radiates sound energy at one fundamental frequency. But it throws off energy at specific multiples of that initial frequency. These are called harmonics.

An atomic nucleus, like the bell, radiates energy when it is bombarded with positively charged particles, or protons. Instead of sound waves, the nucleus gives off gamma rays strongly at one specific frequency.

Secrets locked inside atomic nucleus

While harmonics in sound are quite common, scientists hadn't predicted them from the atomic nuclei. But this is precisely what Blatt's group found. "The original phenomenon — called the giant resonance — has been observed for some 30 years. Now we have discovered strong radiation at a second frequency approximately double that of this fundamental frequency," he says.

"And we suspect that the excited atomic nucleus may radiate in a harmonic pattern of several multiples of the fundamental frequency."

In a sense, the entire challenge now rests with the secrets locked inside the atomic nucleus. There lies the key to much understanding. A unique comparison can be made between the micro-universe of the atom and the macro-universe of space.

Boyd is looking at the precise chain of reactions that allow the burning of stars. The specific fusion process has long been a curiosity to physicists. For normal stars, the process is fairly well understood.

But for the newer oddities of the universe—the heavy neutron stars and the black holes that fascinate laymen and scientists alike—the process isn't that clearcut.

Because these objects are so dense, the nuclei of the individual atoms are fused together into one big nuclear mass. On the periphery of these stars, it's a different story.

In normal stars, Boyd says, the probability of collisions between nuclei and random particles allows for such meetings perhaps only once in, say, a million years. But in neutron stars, he adds, matter is so dense that collisions occur every few seconds.

In the laboratory, Boyd and others are looking at sections of the intricate nuclear process of fusion that takes place on the surface of stars, trying to understand the fueling of these stellar fires.

But other experiments lie ahead. The proton, a positively charged particle, has long been thought to be stable, immune to the radioactive decay of other particles. Boyd and Donoghue are planning an experiment that provides a fundamental test of the theory.

"It's still an open question whether protons are unstable or not. If, in fact, we find out that the proton is unstable and we can get a rough idea of its lifetime, then we can say that the theory which predicts that the proton is unstable has satisfied a crucial test of its validity.

"Proton lifetime experiments are perhaps the hottest experiments being done in physics today," Donoghue says.

Free quarks, proton decay, other possible fundamental particles—these are the treasures physicists are hoping to find. It's like peeling layer after layer on an onion, continually discovering something new each time.

And the layers are, perhaps, endless.

"What Makes Atoms Tick" is reprinted from "Quest" a quarterly publication of the Ohio State University.

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