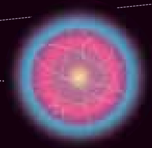
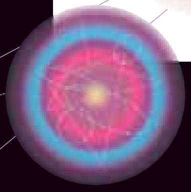
The hunting of the Quark

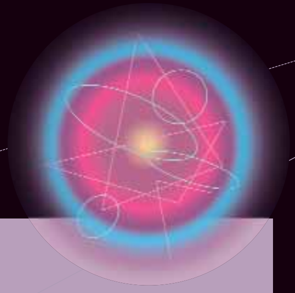
By John Svetlik

It is something of a paradox: to study the smallest known constituents of the universe, one needs big science.

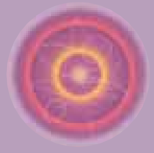


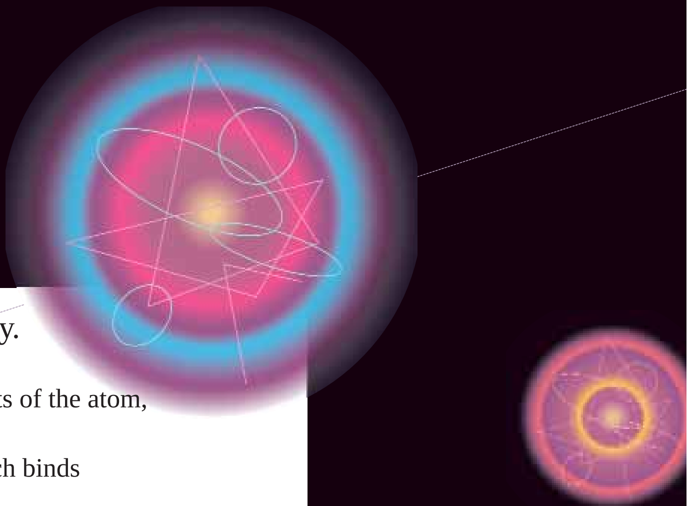


Particle physics is an enterprise on a grand scale, requiring laboratories full of technology, large teams of scientists, and budgets to match.



But in this century, the study of atoms and their bits and pieces has paid off. Nobel prizes have gone to the pioneers, and practical applications such as Mri (magnetic resonance imaging) have made it out of the laboratory and into hospitals where they are used to help people.

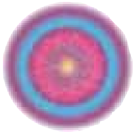




Ricardo Alarcon and Joseph Comfort are part of the quest to understand the smallest bits of the material world.

Both are experimental nuclear physicists at Arizona State University.

They lead teams of scientists and graduate students to explore the constituents of the atom, from the relatively familiar proton and neutron, to the less familiar pion which binds the protons and neutrons inside the nucleus. Alarcon and Comfort are looking even deeper.



They want information about the quarks and gluons which vibrate beneath the surface of the proton and neutron. The work involves an enormous variety of tasks. Like other researchers, the ASU physicists must write detailed proposals, compete for funds and the use of accelerator facilities, build particle detectors, write computer software to analyze data, and coordinate large teams of people to achieve a common goal.

It simply is not easy to get information from inside the atomic nucleus. Light waves are far larger than the size of the nucleus. Scientists use electron microscopy to “see” the arrangement of atoms inside a crystal. Proton and electron accelerators are the much larger “microscopes” that physicists use, paradoxically, to probe the much smaller atomic nucleus. The “pictures” physicists look at are either one form of detector, or the imprint of computer visualizations of data from the detectors.

Alarcon and Comfort explain that the only known effective technique for exploring this infinitesimal world is a process of creative destruction. Massive particle accelerators are used to fire subatomic projectiles at atomic targets. Equally large and sophisticated detectors are designed to capture the products of the resulting collisions.

The particle physicist’s main effort is devoted to finding ways to reconstruct what happened in these collisions. The process is similar to a police officer who, arriving at an accident scene, must try to reconstruct the sequence of events that led to the skid marks, broken glass, and mangled metal.

Experiments conducted by Alarcon and Comfort can last from two weeks to two months. For them to be successful, several things must occur at the same time. The detector must be operating at good efficiency, capturing as many of the events (atomic collisions) as possible. The detector can be as much as 30 feet high. It must be aligned exactly to within a millimeter in space. The computer software running the show must be bug-free. Even the weather must cooperate. Beam time, as it is called, is hard to come by, and the times when everything works are highly valued.

Kelly Craig is one of Comfort’s ASU graduate students. She tells of a time last summer when the electron beam at the Massachusetts Institute of Technology’s Bates Laboratory had to be shut down temporarily. Everyone in Boston was running air conditioning during a heat wave. The large power draw from the accelerator would have caused a brown-out.

A better understanding of nature’s building blocks has been a goal of scientists for many centuries. Alarcon and Comfort study the dynamics of the atom’s nucleus. They want to know how the nucleus changes through time.

In the language of traditional nuclear physics, there are only three main nuclear particles: protons, which carry a positive charge; neutrons, which have no charge; and pions, which carry the “strong force.” Although the positive charge of the protons causes them to repel each other, the exchange of pions between nucleons (neutrons and protons) creates an attractive force strong enough to over come the protons’ electric repulsion.

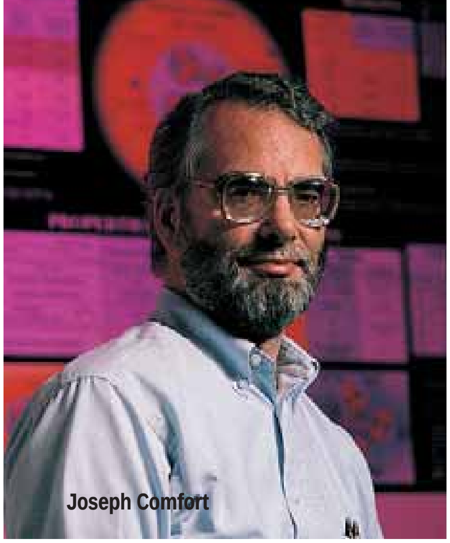
During the past two decades, as scientists discovered more and more “elementary” particles, it took the invention of a new theory, and a new set of particles, to make sense of the new subatomic zoo. The new particles are called quarks. According to quark theory, the proton and neutron are not themselves elementary particles. Each actually are made of three quarks.

The quark theory provides a new and convincing way to understand the structure of elementary particles. However, scientists still do not know how elementary particles transform into other particles, or what effect the dynamics quark interaction has on them. Alarcon and Comfort are looking for evidence of how quarks interact with each other.

Comfort often works at the Meson Physics Facility (LAMPF) in Los Alamos, New Mexico. Los Alamos physicists have devised a method to “polarize” targets. Polarizing means controlling a particle’s “spin.”

For the physicist, spin also is known as quantum angular momentum; it is one of the intrinsic properties of an atom.

Think of an atom as a spinning top. The top has angular momentum–a tendency to keep spinning–which also keeps it upright. Electrons, protons, and neutrons have a similar property. They also have just two states: $+1/2$ and $-1/2$. Think of these states as analogous to clockwise and counter-clockwise.



Joseph Comfort

JOHN C. PHILLIPS PHOTO

Comfort is looking for evidence to assess "charge independence." Mediated by pions, the strong force holds the bits of the atomic nucleus together. Researchers think that this strong force is not affected by electrical charge in any unusual way. But, at present, the experimental evidence for the hypothesis is inadequate.

"The data are a mess," Comfort says. The Asu physicist hopes that the greater precision of the spin-controlled experiment will help.

At Los Alamos, Comfort and his colleagues send beams of pions into a target of butanol. Butanol contains a large number of hydrogen atoms. Hydrogen is a useful target because it has just one proton and one electron.

Using strong magnets, microwaves, and intense refrigeration, Comfort's research team can orient protons in the target either spin "up" or spin "down." They then fire beams of negative pions at the target. Neutral pions are emitted and make signals in large detector arrays.

Alarcon and Comfort are working on a similar experiment at the National Institute for Nuclear Physics and High-Energy Physics (Nikhef) in Amsterdam, Holland. At Nikhef, researchers fire a high-current beam of electrons through a polarized target of deuterium gas. Deuterium also is known as "heavy hydrogen." In a bit of scientific serendipity, they are getting two experiments for the price of one.

Alarcon wants to find the exact distance at which the nucleons in deuterium begin to repel one another. Comfort wants to know how much energy it takes to push them apart. Both answers can be found by analyzing the same data.

Alarcon looks for the rare events when a high-energy electron knocks a whole deuterium nucleus into the detectors, and is itself detected. The process is called elastic scattering, because all the kinetic energy contained in the nucleus elastically returns as kinetic energy. By analyzing the energy levels, Alarcon hopes to calculate the closest distance nucleons can get to one another inside the nucleus.

Alarcon and Comfort are part of a team installing a new detector at the Bates/Mit Laboratory in Boston. The detector is known as Oops, short for Out-Of-Plane Spectrometer. Using Oops, the scientists hope to learn about the dynamics of quarks within the nucleon (protons or neutrons). They will focus studies on a bit known as the "delta particle."

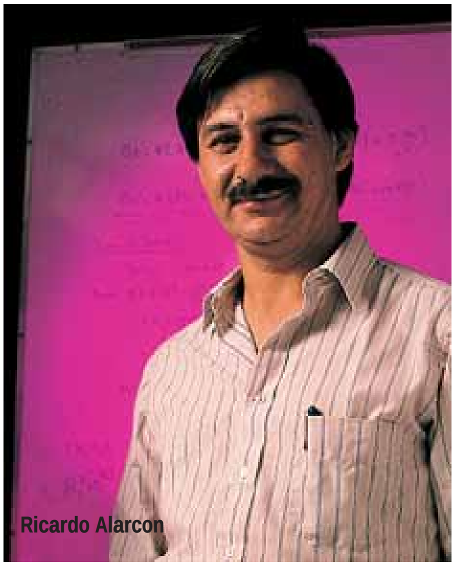
"The delta particle is the first excited state of the nucleon," Comfort explains. "In the language of quarks, one of the quarks 'flips its spin.' As a result, the nucleon as a whole changes from a spin 1/2 to a spin 3/2. Ordinarily, the spins of two quarks cancel each other out," he adds.

The delta particle is about a third more massive than either the proton or neutron. It also is very unstable, decaying quickly into a pion then back into a nucleon. Alarcon and Comfort want to know how this transition occurs. What exactly are the quarks doing?

If it is possible for a quark's spin to simply flip, they'll get one type of data. If the transition is more complex, they should see evidence of that more complex mechanism.

Alarcon's excitement for his chosen profession is evident as he speaks. "Our detectors are much better than they used to be. We can now get very precise information about the events," he says. "The fact that we can control spin will give us much better data, better than ever before."

In any particle physics experiment, capturing the collision events is always a matter of statistics. Many electrons pass undisturbed through a target. Many others create ordinary events that already are well understood. But a few will be different and interesting.



Ricardo Alarcon

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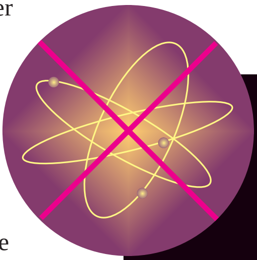
Much of the effort expended by experimental physicists is devoted to increasing the number of these interesting events. But they can not be increased to the point where the detectors become so deluged with particles that nothing can be discerned. At Bates and Nikhef, scientists often direct electrons into a circulating ring where they can pass many times through a very thin target. Using this technique, the researchers generate a fairly well-spaced flow of events. Electrons that pass through a target the first time can come around for a second try.

Both Alarcon and Comfort look forward to working at a new facility in Virginia known as the Continuous Electron Beam Accelerator Facility (Cebaf). The new accelerator will provide a continuous, high-current polarized beam of electrons. The continuous beam will allow scientists to conduct a variety of experiments that should build a wealth of new data about the heart of the atom.

Experimental particle physics research at Asu is supported by the National Science Foundation. For more information, contact Ricardo Alarcon, Ph.D. or Joseph Comfort, Ph.D., Department of Physics and Astronomy, College of Liberal Arts and Sciences, 602.965.3561



The Subatomic World

How would you describe an atom? The most popular picture is that of a tiny solar system, with the atomic nucleus as a solid, planet-like sphere orbited by one or more electrons in a series of concentric rings. The image is simplistic, and wrong. Particle physicists know that the actual bits and pieces of which atoms are made–the protons, neutrons, and electrons–do not act much like any objects or processes with which we are familiar.

Some physicists talk about the "wave/particle duality" of the subatomic. In that scenario, sometimes an electron acts like a particle, other times it acts like a wave. Others scientists explain that

The Long Haul

PHOTO COURTESY RICARDO ALARCON, PH.D.

(Front row from left) Physics graduate students Alaine Young, Kelly Craig, Nels Freed, and Cristoph Mertz, along with post-doctoral researcher Steve Dolfini (back), help assemble the OOPS detector at MIT/Bates.

The road to a doctorate in physics can be long and difficult. Undaunted by the long haul ahead of them, Asu graduate students Carole Gaulard, John Adams, Kelly Craig, and Ed Six are enthusiastic about their choice of profession. Traveling throughout the country and around the world to get the work done is one "benefit" that every graduate student in experimental nuclear physics seems to agree upon.

Gaulard is closest to finishing her doctorate, but even she doesn't quite know when that will be. "Until you have your experiment, you don't know when you are going to finish," she explains. Her studies may require an additional three or four semesters. But that time frame will depend on her ability to get "beam time" at an accelerator facility, and then having the experiment itself go well.

Kelly Craig agrees. She has been a part of Asu's graduate physics program the longest of the students assembled in the room. "I know a very smart, hardworking person who stayed on track and took 10 years to complete the degree," she says. "And I don't think that's unusual."

Despite such a daunting prospect, "doing physics" still holds a strong attraction for Craig and her fellow graduate students.

"First of all, I really like mathematics. It's been my favorite thing forever," she explains. "Being able to do science and use my mathematics knowledge is what I like to do. In the future, I would love to be a research scientist and work in one of the major laboratories, and work with graduate students like us," she adds.

John Adams is convinced that basic research is essential for the future of society.

"Basic research of the type we do leads to Pentium microchips and other applications," he says. "Without basic research, a company like Microsoft wouldn't have boomed. The work is the cutting edge. Without basic research, without understanding more deeply how nature works, you'll just end up doing the same old stuff."

Ed Six is working on an experiment called "9112" at the Nikhef in Amsterdam. He describes his work sanguinely. "I'm basically helping out, moving this here, building that, taking data. I worked a little bit on software. But mostly, I worked on putting the detector together, changing something small, putting it back together."

Each of graduate students know they must do whatever work needs to be done. When dissertation time comes, they will accept the experiment to which they are assigned. But they have no doubt at all that they are doing the science that is right for them. Physics is where they want to be; it's what they want to do.

"Biologists work to understand living things," the students say, almost in unison. "But physicists work to understand the universe." —John Svetlik

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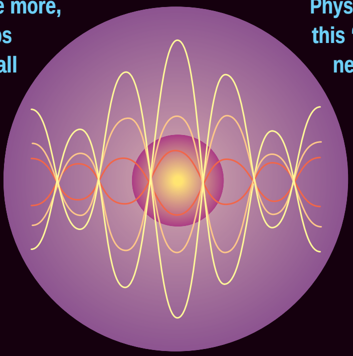
the laws of nature which exist at the infinitesimal size of atomic particles simply are different from the laws that govern airplanes, trees, baseballs, and water puddles. They describe electrons as "probability waves," or "wave packets." Electrons are are neither particles nor waves alone, but both at the same time.

Subatomic particles even react differently to energy. Add a little energy to a proton, and nothing happens. Add a little more, and the proton jumps to what scientists call a new "quantum energy level."

Think of the guitar string that vibrates only at a certain frequency. Like that string, a proton or neutron can exist only at certain energy levels, and at no others. Physicists know that it is impossible to add energy continuously to a subatomic particle. But if a particle is hit with enough energy in one burst, it will transition into a higher energy state. In fact, add more and more energy, and the result is a variety of different particles.



Physicists say that this "creation" of new particles from nothing but energy is clear evidence that mass and energy are equivalent, as Albert Einstein argued.

Protons and electrons carry electric charges. As a result, scientists can use forces such as magnetism and electricity to control, accelerate, and detect these subatomic particles.

To conduct meaningful research in this tiny world, experimental physicists such as ASU's Ricardo Alarcon and Joseph Comfort must use massive pieces of equipment known as particle accelerators.

Accelerators come in two basic types: machines that send electrons zooming into a target, and those that speed protons into atomic collisions. Each type of accelerator is used for a different purpose.

Electrons are much less massive than protons–almost 1,800 times less massive. As a result, when electrons are speeded up inside a particle accelerator, they have much less energy than a proton speeding at the same velocity. Picture a baseball and a large truck zooming along at 90 miles per hour. The baseball is the electron; the truck is the proton.

Even though electrons essentially have no mass, electron beam accelerators allow researchers such as Alarcon and Comfort to use them as tools for probing deep into the structure of the atomic nucleus.

—John Svetlik