Faculty of Arts and Sciences
University of Pennsylvania
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A Supplement to Almanac

FAS reports

Physics: From Quarks to Solar Cells

Even people who have trouble recalling the parts of the atom can't help but leave David Rittenhouse Lab or the Laboratory for Research on the Structure of Matter with enthusiasm for the work of Pennsylvania's physicists.

Nobel Laureate J. Robert Schrieffer's codiscovery of the theory of superconductivity is just the beginning of a long list of fascinating contributions by the 43 physicists in this department. Their work ranges from developing a new standard for the volt to synthesizing a material that may provide inexpensive solar cells for powering our homes. It includes catching collapsing stars and helping to discover the fourth quark, one of the basic particles of the universe.

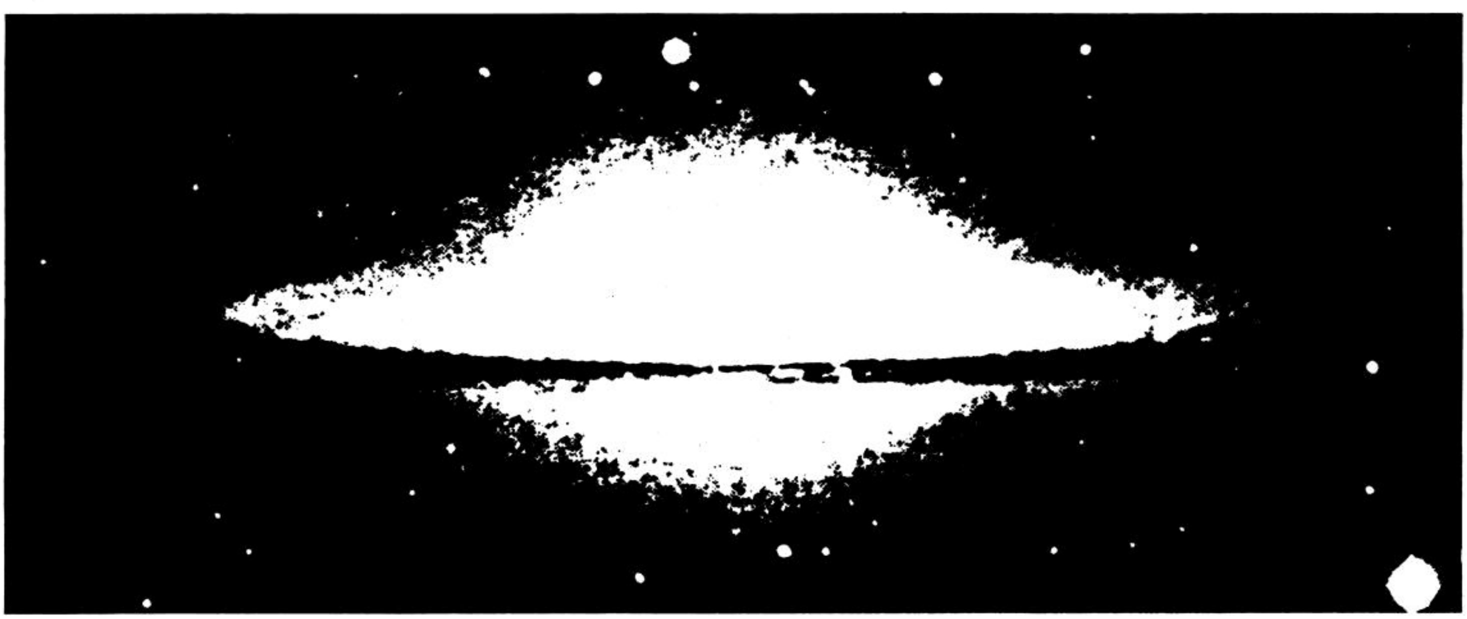
This one department, which attracts $4.7 million to the University each year in federal funds, contributes one third of the Faculty of Arts and Sciences' research budget. In addition to the 43 members of the teaching faculty, the department has 20 research faculty members and a professional staff. They work in three major areas: particle physics, nuclear physics and condensed matter (solid state) physics. In each of these areas, there are both theoretical physicists and experimental physicists.

Research, according to Department Chairman Walter D. Wales, is coupled with a heavy emphasis on teaching. There are 90 graduate students and 12 to 15 majors in each undergraduate class. Each term 1200 to 1300 undergraduates are enrolled in physics courses. All of the faculty teach introductory courses and each term half of the faculty members conduct undergraduate laboratory sections.

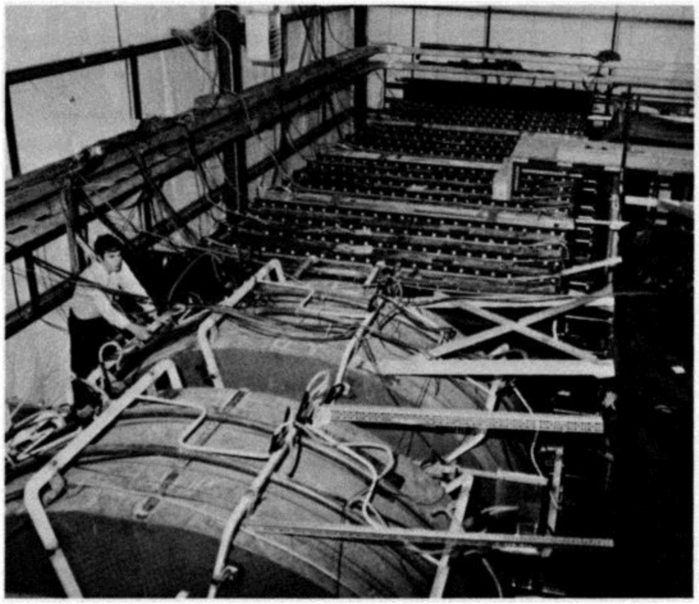
Outside the classroom, these physicists are working on problems that may at first seem far removed from our day-to-day world, but often turn out to have some fairly clear practical implications. The work of E. Ward Plummer exemplifies this kind of research. He is studying catalytic reactions—how molecules react on the surface of certain metals. His work concerns such problems as what happens to the electrons in these reactions and where the atoms sit on the surface of the metal. Working with theoretical physicists J. Robert Schrieffer and Paul Soven, he has found out that a carbon monoxide molecule stands up straight on the surface when it is binding to nickel, whereas nitric oxide on nickel cants over at a 25 degree angle.

In such seemingly small differences in molecular posture, there is information potentially worth millions in the chemical and energy industries. These catalytic reactions, in which the metal surface channels the reaction, allow oil processors, plastic manufacturers and others to speed up the desired reaction by as much as a million times while slowing down undesirable reactions that could occur. Thus Plummer's work is quite likely to provide information that engineers can use to improve these reactions, thereby improving the way we process oil or make plastics.

In the following pages are other examples of physics research, which may lead to solutions to our energy problems or a better understanding of how the universe was created.



Toward Life's Most Basic Elements



Top view of an earlier version of the experiment, designed to study the interactions of neutrinos with matter. The experiment involved a collaboration of physicists from the Fermi National Accelerator Laboratory, Harvard University, the University of Pennsylvania and the University of Wisconsin.

In one of man's basic quests in physics, he looks deeper and deeper into the atom to understand just how it is composed and what binds it together. This search has led scientists to two major discoveries in the past decade, and Alfred K. Mann's group at Pennsylvania has been instrumental in both. Their experiments helped to turn up the missing pieces in a long sought theory to unify two of the four basic forces in the universe. They also helped to identify the fourth quark, one of the basic particles of matter. These discoveries took place in experiments at a high energy particle accelerator in Batavia, Illinois, where protons with an energy of 400,000,000,000 electron volts split atoms into what scientists believe may be their most fundamental parts.

Less than a century ago scientists thought that atoms were the smallest particles in the universe. Today they believe that an atom is composed of electrons and two kinds of quarks—an up quark and a down quark, which combine to form protons and neutrons. A number of other fundamental particles have also been identified in cosmic rays striking the earth from outer space and in reactions produced at high energy accelerators; among these are neutrinos, particles that have no mass or charge and are released when neutrons decay into protons and electrons.

The interactions among these particles of the universe are controlled by four basic forces: the gravitational force, the electromagnetic force, the strong force and the weak force. The gravitational force is comparatively feeble and has little impact on the particles in the atom. The electromagnetic force both draws objects of different electrical charges together and holds the negatively charged electrons to the positively charged nucleus to form the atom.

The strong or nuclear interaction holds the nucleus of an atom together. It is several hundred times stronger than the electromagnetic force, but operates within a very short distance—usually only with particles next to it in the nucleus.

The weak force is at work in the interaction between electrons, neutrinos and muons, particles which behave like an electron and frequently occur in cosmic rays. This force is responsible for normal radioactivity.

To shatter the atom in such a way that the fundamental particles are freed and the forces can be studied, Mann and other particle experimentalists go to one of a half dozen high energy accelerators, such as the one at Fermilab in Batavia, Illinois. Here they spin a beam of protons one millimeter wide around a circle that is one and a quarter miles in diameter. They then shoot this proton beam down a straight mile-long run to hit a target one foot long and one inch in diameter. As you can well imagine, a rather powerful reaction takes place. While many particles come out of this reaction, many decay almost instantly, and still others are trapped in earth banks beyond the target. The particles necessary for the experiments continue another mile until they strike the detector.

Particle physicists since the early 20th century have been trying to form one unified theory that would explain the weak and the electromagnetic forces together. By the late '50s particle theorists had proposed some plausible possibilities. These theories, however, were contingent on something that had not thus far been observed, the weak neutral current.

Mann and his colleagues began looking for this neutral

Creating a New Standard for the Volt

When you find the notation 120 V on the bottom of your toaster, thank Donald N. Langenberg and his colleagues for their series of experiments that established a new standard measurement for the volt, which was adopted by the United States in 1972.

This practical discovery was one of a number of new measurements that came out of experiments in an area of superconductivity called the Josephson effects. Superconductivity is a phenomenon in which many metals lose all electrical resistance at temperatures near absolute zero and thus become perfect conductors of electricity. In 1962 a British graduate student named Brian Josephson developed a theory that predicted how superconducting electron pairs could move from one superconductor to another, passing through a layer of insulation only five or ten atoms thick. Scientists would have expected this insulator to stop the flow of such electron pairs almost completely. Josephson predicted that if direct current was applied to this sandwich composed of two superconductors separated by a thin insulator, it would produce an alternating current through the insulator. Today the sandwich of superconductors filled with an insulator is called a Josephson junction. Josephson developed an equation to describe this effect. He said that the frequency of the alternating current would equal twice the charge on an electron divided by Planck's constant times the dc voltage applied to the system, or as physicists say, $f = 2eV/h$.

current. They could demonstrate that such a current existed if they could create a reaction where a neutrino interacted with the nucleus of an atom and then emerged from the reaction still as a neutrino. Such a reaction would have to involve a weak neutral current.

They created a beam of neutrinos for this experiment at Fermilab first by striking the target with a proton beam. The particles produced in this interaction decayed quickly into electrons, muons and neutrinos. The muons and the electrons interacted electromagnetically with an earth bank between the target and the detector and were thus buried in the bank. Since neutrinos have no charge and thus interact weakly, they were the only particles to shoot right through the earth bank and continue another mile to Mann's 300-ton detector.

At first these scientists could only see a reaction where the neutrino entered the nucleus of the atom, the nucleus broke up, the neutrino disappeared, and a muon came out of the interaction. Finally in 1973, Mann and his colleagues recorded the long sought reaction in which a neutrino enters a nucleus, a reaction occurs, and a neutrino comes out. In a very different set of experiments at an accelerator in Geneva, Switzerland, this same neutrino in—neutrino out reaction was being observed at about the same time.

Once these two forces were unified, other problems arose. Until this time scientists believed there were three types of quarks; up quarks, down quarks and strange quarks, which combined in different ways to compose all the strongly interacting particles. But the weak neutral current made physicists see new interactions, and these interactions led them to suspect that at least one more quark must exist.

In 1974 Mann and his colleagues at Fermilab indirectly observed a new strongly interacting particle that had never been seen before. At the same time another new particle was observed at the accelerator at Stanford. These new particles could not possibly be composed from the three known quarks. There had to be another, heavier quark, which physicists called the charmed quark. The existence of this fourth quark made it evident that even more quarks were to be found. One, tentatively called the bottom quark, is probably five times more massive than a proton, and the sixth quark is probably more than 15 times more massive.

If all these experiments seem as elusive as a neutrino, it is important to remember the basic point: Mann and his colleagues are helping to rewrite the laws of our universe. Before their work, scientists thought that there were four forces holding our universe together. The Penn physicists have helped to unify the weak and the electromagnetic forces so that now we believe there are only three such forces. These physicists have also offered us proof of a new fundamental particle, a fourth quark, which in turn has led scientists to the notion that there are twice as many quarks as they thought there were.

To go even deeper into these laws of the universe, Mann is now developing experiments for the next generation of accelerators, which are expected to be tens of thousands of times stronger than the current equipment!

Donald Langenberg and his colleagues were able to develop a device for measuring this effect with great accuracy. This in turn gave them a far more accurate value for the ratio of two physical constants—e, the charge on an electron and h, Planck's constant. Since these constants, like the speed of light, are at the heart of a host of other measurements in physics, it is crucial to physicists to measure them as precisely as possible.

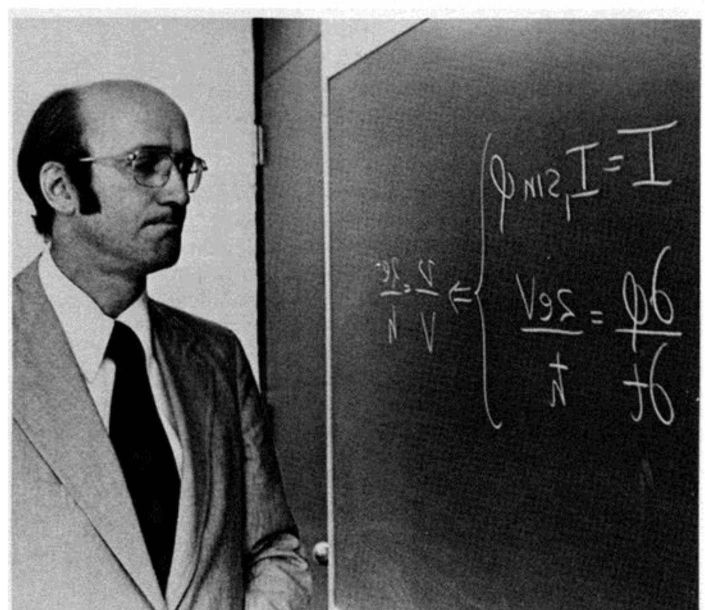
"In the end it turned out that you could do better this way by about a factor of ten, and more recently, measurement has been improved by a factor of about 100 or more," explains Langenberg.

While Langenberg's work enabled physicists to measure many other important fundamental constants more accurately, his most interesting finding—for the layman—is a new standard for the volt. The Josephson device he developed put an end to a 20-year search to replace the traditional method that relied on a precisely constructed battery.

"The volt, as a unit of electrical potential, has a well established absolute definition. But if you are going to measure things in volts in the laboratory, you have to have a way to put the volt in a bottle and carry it around," explains Langenberg.

The Josephson device is such a bottle. And thanks to this work the official U.S. laboratory volt is now defined directly in terms of the basic unit of time, the second. Those with a taste for precision will undoubtedly be pleased to learn that the U.S. legal volt is equivalent to exactly 483,593,420,000,000 cycles per second.

More recently, Langenberg has turned to the study of "non-equilibrium" superconductors. As he puts it, "A superconductor in repose is fascinating enough, but if it gets really upset, it's even more interesting. Superconductors are a little like people that way."



Donald Langenberg: the Josephson equation.

FAS reports

The Star Catchers

Kenneth Lande and his colleagues are catching stars—or, more accurately, little pieces of them—at their underground detector in a South Dakota gold mine.

He and four colleagues have developed a neutrino detector, a water-filled chamber that generates electronic signals when it is struck by a neutrino or another cosmic particle called a muon. The detector has three main functions. First it is designed to settle a controversy over whether a proton lives on forever or can indeed decay. Second it detects neutrinos from collapsing stars and thus provides an early warning for astronomers as to the whereabouts of collapsing stars in our galaxy. Finally, the detector identifies the sources and measures the composition of the very high energy cosmic rays striking the earth's atmosphere.

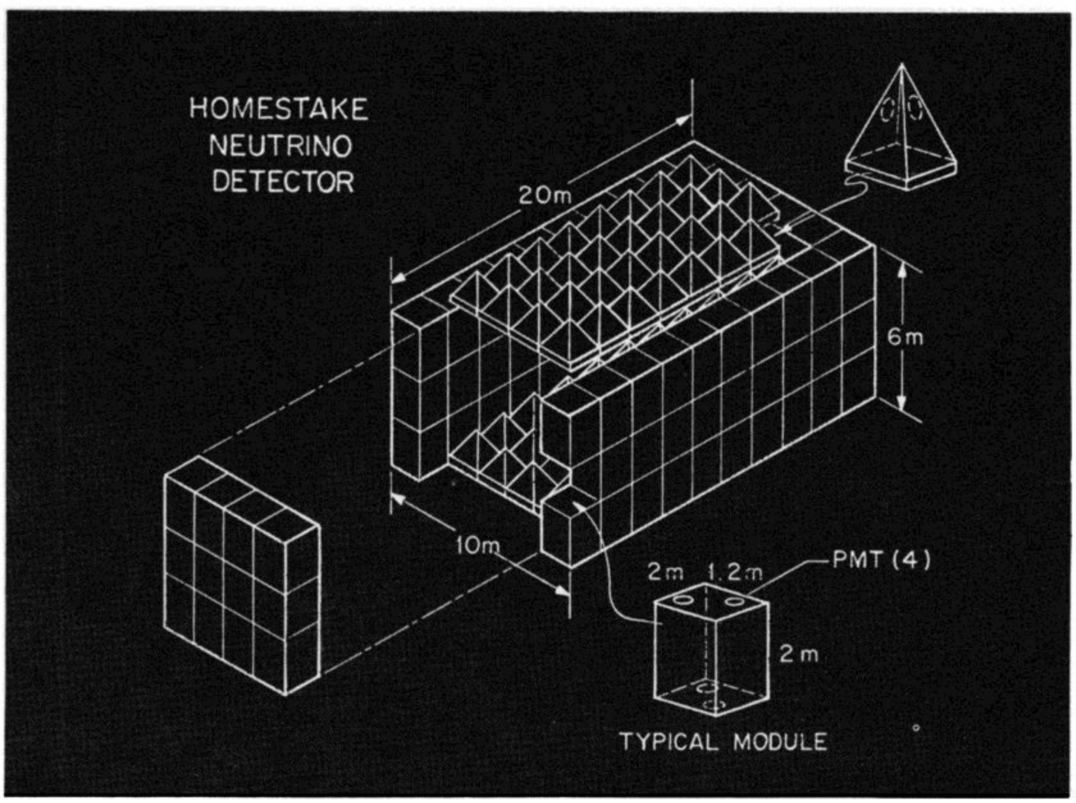
Lande's neutrino detector, located in the Homestake Gold Mine in Lead, South Dakota, is housed one mile underground, deep enough so that all cosmic particles are stopped by interactions with the earth—with the exception of neutrinos and muons. Neutrinos are particles that have no mass or charge and are produced when neutrons are created or decay. Muons are particles that behave like electrons, but are over 200 times more massive and are created when cosmic rays strike our upper atmosphere. These two particles create a reaction in the detector developed by Lande and his colleagues, William Frati, Richard Steinberg, C.K. Lee and Marianne Deakyne.

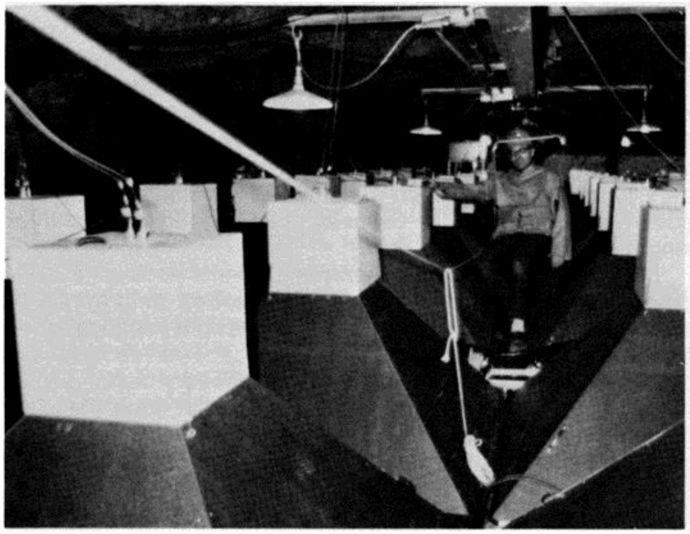
This detector consists of 1,000 tons of water, which is divided by sheets of plastic into a grid of 6 by 6 by 4-foot cubes. Within each cube are four photomultipliers, devices that turn the light flashes created by a reaction of a proton decay, a neutrino interaction or a muon traversal into an electrical impulse. The detector, coupled with elaborate computer circuitry, records what reactions are taking place and where and when they are occurring.

At the moment, Lande has the only detector in the world that might answer the question of whether a proton will always stay a proton or will instead decay into other particles. If it does decay, it doesn't do it too fast. Present theories suggest that protons might have a life expectancy of about 1,000,000,000,000,000,000,000,000,000,000 (10^{30}) years! Since Lande has over 10^{32} protons in his detector, he should be able to explore the expected lifetime range. If a proton decays after 10^{30} years, he could expect about ten protons a month to decay in his detector, one a month if protons live for 10^{31} years.

A decaying proton, Lande expects, would cause two particles to shoot out suddenly in equal and opposite directions, producing photomultiplier signals with paths beginning inside the detector rather than from its edges.

The Homestake neutrino detector is also designed to spot collapsing stars for astronomers. The current astrophysical theory holds that as the center of a star gets extremely hot, a proton and an electron come together to form a neutron and a neutrino. Since the neutron takes up much less space than the entire atom with its swirl of electrons, there is a lot of space between these newly formed neutrons. Gravitational forces then eliminate this space by shrinking the





Kenneth Lande servicing the top section of the Homestake Neutrino Detector.

star from perhaps a million miles to about ten miles across. During this process of shrinking, millions and millions of neutrinos (10^{57} to be more precise) come streaming out of the star. Soon afterward the matter left on the surface of the star is blown away creating a light as bright as the daytime sun. This explosion is called the supernova phenomenon. Next the star begins to emit pulses of radio waves and becomes a source of extremely high energy cosmic rays. This occurs in our galaxy about once every three years.

Lande is anxious to detect the burst of neutrinos from these stars. He expects such a burst to trigger many signals simultaneously in the Homestake detector as well as in other neutrino detectors located in Ohio, Switzerland and the Soviet Union. By the angles at which neutrinos enter these detectors and by the relative time of their arrival, he hopes to plot the exact origin of the neutrino burst.

"This neutrino early warning system could then alert radio and optical astronomers. In effect, it says, 'Hey, go look over there. Tomorrow you will see the supernova glow and in three weeks you will see the radio pulsations," Kenneth Lande explains. Without this warning system, it would be easy to miss these phenomena, since there is such a small chance that the telescopes would be aimed in the right direction.

While astronomers are picking up the star's radio waves, Lande's detector is set to study the cosmic rays these stars give off simultaneously. He is finding out about these rays by detecting the muons the rays create when they hit our upper atmosphere. Lande's group traces the muon particles backwards to pinpoint the spot in the sky where they were created. In so doing, they can determine where cosmic rays are coming from.

Lande and his colleagues have already made progress in catching bits of collapsing stars since their detector went into operation in January, 1979. Hopefully, their work will help answer some basic questions about these stars and thus about the nature of the universe.

A Cosmic Recipe for the Universe

Why is there matter in the universe? Why isn't it just a vast light-filled emptiness? To answer this question theoretical particle physicist Anthony Zee has developed a theory with colleagues at Princeton.

"We give a scenario, a cosmic recipe, of how the universe came about," he explains.

Zee's theories rest on the big bang theory of cosmology, the most widely accepted notion of the creation of the universe. According to this theory, the universe was originally very small, compact and hot—so hot in fact that only energy could exist. Even the nuclei of atoms had melted apart. Our 10-billion-year-old universe was created by an enormous explosion, called the big bang, which created the universe as we know it, leaving us with an expanding system that is now cooling down.

There are some phenomena that are not explained in this theory, and it is towards an understanding of two of these phenomena that Zee has addressed his calculations. First of all, he asks, where did the protons and other fundamental particles come from? From all that has been observed, the proton does not decay into other particles. Recently, however, there has been speculation by theoretical physicists that the proton does indeed decay. Second, the universe should consist of equal amounts of matter and antimatter according to the laws of physics. Antimatter, however, has been identified only in laboratories, not in nature.

Zee and his colleagues have developed calculations that trace the cooling down of the universe and explain how the cooler temperatures led to the creation of quarks, protons and other fundamental particles and to the destruction of antimatter. In the beginning, they postulate, the universe was so hot that it consisted only of energy. As the temperature dropped, however, a series of physical reactions took place that created quarks and antiquarks. A small difference in behavior between matter and antimatter known as the CP violation became important at these high temperatures. More quarks than antiquarks were produced, and ultimately the few antiquarks that were produced were annihilated. The quarks lived on, and as the temperature of the universe cooled down even further, these fundamental particles coagulated to form protons and other basic particles. Today the universe is just too cold to create quarks, protons and other particles.

Now Zee has turned his attention to another equally baffling problem: why does nature seem to repeat itself unnecessarily? Atoms are composed of three fundamental particles: up quarks and down quarks (which combine to form protons and neutrons), and electrons. Nature, however, has produced a duplicate set of these particles, which are exactly alike except that they are heavier. It now appears that there may be a third set of these basic particles even heavier than the second. Zee plans to use a branch of mathematics called group theory, which deals with principles of symmetry to get to the bottom of this. Maybe, he suggests, three sets are more beautiful than one!

Ion Sourcery and Other Discoveries in Nuclear Physics

A small one-story building between David Rittenhouse Lab and the Palestra houses a machine powerful enough to split apart the nucleus of an atom.

Here in Penn's Tandem Accelerator Laboratory, five nuclear physics professors, their research associates and graduate students work with a particle accelerator called a Tandem Van de Graaff to try to figure out what is in a nucleus and what happens in nuclear reactions.

"We are studying what happens with interesting collisions," explains David Balamuth. "In some reactions particles just bounce around. Others are the realization of the alchemists' dream of changing one element into another, rearranging the nuclear particles to create new substances."

To split apart a nucleus, the physicists at the Tandem Accelerator Lab create and focus a beam of atoms with extra electrons, called negative ions. The accelerator itself is a 45-foot long gas-filled cylinder with a tube through its center from which all the air has been evacuated. The nine-million-volt electrical potential at the center of the machine draws the negative ions down the tube until they reach a velocity of at least one tenth the speed of light. The negative ions then pass through a thin carbon foil, which strips away many of their electrons and turns them into positive ions (atoms with more protons than electrons). Since they are positively charged, they are now repelled by the high-voltage terminal, which pushes them out of this vacuum tube and accelerates them again.

At the end of the tube, the beam of ions hits a target, which is about the size of a dime and looks like colored cellophane. The beam splits apart the nuclei of the substance on the target—carbon, nitrogen or another element depending on the experiment. A detector then picks up the pieces, gauging just what came out of the reaction—its direction, speed and weight.

One contribution that has brought international prominence to the Penn lab is what Department Chairman Walter Wales calls ion sourcery. This invention by Roy Middleton, director of the Tandem Accelerator Lab, is known to most as the Universal Negative Ion Source and is used throughout the world to make the negative ions needed for the accelerators. Until Middleton's discovery few materials could be made into negative ions. Now however scientists can use Middleton's discovery on almost any element they wish and can create a host of nuclear reactions that were previously impossible.

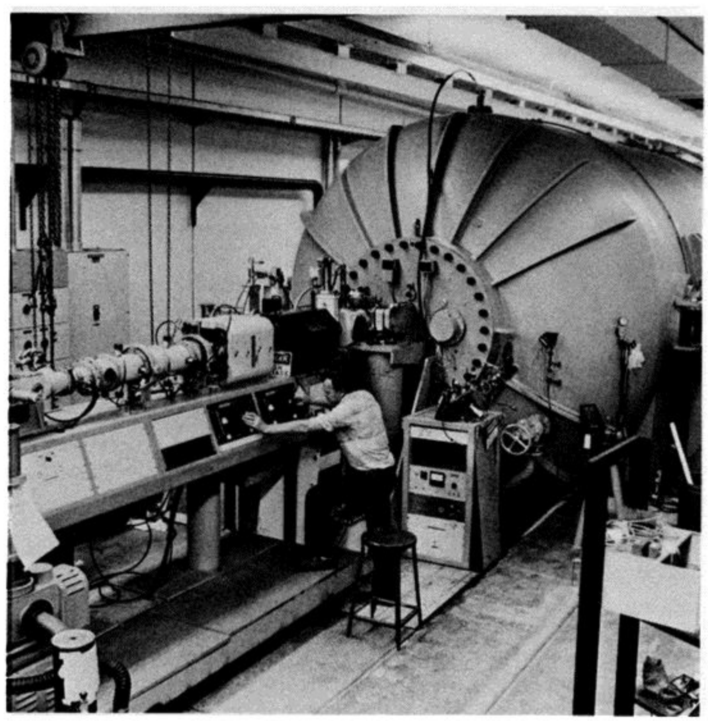
Roy Middleton, William Stephens, Robert Zurmuhle, Terry Fortune and David Balamuth, the five professors at the Lab, focus on two overall problems in nuclear physics: the structure of the nucleus, or how the particles are shaped, organized and bound together, and the nuclear reactions, or the mechanisms for changing one nucleus into another. These physicists pride themselves on the diversity of their research and the fact that they are approaching the same problems from different directions.

Physicists recently looked at the composition of nuclei with many more neutrons than protons, an interesting phenomenon that occurs in substances like uranium. These substances are hard to study, however, because their nuclei have so many particles. Therefore Penn's physicists took a comparatively light nucleus, that of beryllium, and added neutrons to it so that it simulated the heavy nucleus of substances like uranium. To do this they turned tritium, a form of hydrogen with two neutrons and one proton, into a beam of negative ions using Roy Middleton's Universal Ion Source. They collided this tritium beam with a special form of beryllium called beryllium 10. This reaction produced beryllium 12 enabling them to study this substance. They documented its mass, its behavior in an excited state, and the length of time it takes to decay.

In another important experiment, Penn's nuclear physicists accelerated carbon and bombarded an oxygen target, another reaction that was only possible because of Middleton's Universal Negative Ion Source. This reaction produces alpha paticles and magnesium in very highly excited states that should decay rather quickly . . . but don't. Penn's nuclear physicists were the first to explain this phenomenon, which is caused by the very high angular momentum of these states.

Looking to the future of nuclear physics, David Balamuth observes, "I think nuclear physics is going through a dramatic period of change at the moment. In the last 50 years, the study of nuclei has in large measure been severely limited by what is possible experimentally," he explains. "In the next 25 years, because of tremendous technological progress, it will be possible to ask truly basic and interesting questions about the structure of the nucleus."

Maybe they will learn precisely what holds the atoms together. They might discover why a collision between the nuclei of carbon and oxygen leads to a third substance—magnesium. Who knows, in fact, what this basic research may teach us about how our universe is made.



View of the tandem Van de Graaff accelerator vault. The accelerator itself is inside the large pressure tank. The beam comes out through the evacuated pipe at the left of the picture.

Testing Laser-Proof Materials

Can LRSM's new organic solids help beam information to satellites in outer space? Are these organic solids the future switching gear that will replace tons of copper cable in our communications system? Or will they allow engineers to write computer circuits small enough to fit in a wrist-watch?

All of these are real possibilities with a group of organic solids now being tested by Anthony F. Garito and 15 scientists at the Laboratory for Research on the Structure of Matter (LRSM). These organic solids may be particularly useful in laser technology because they behave differently from other materials under this high intensity light. Laser light, unlike normal light, is composed of only one frequency and moves in only one direction.

The organic solids under study can withstand extremely high intensity lasers. While the inorganic counterparts of these substances shatter at levels of laser light as low as 100 kilowatts, physicists have not yet invented a laser beam strong enough to shatter these organic solids. Physicists are even more interested in the fact that these organic substances actually change the light that strikes them. When most substances are hit by a beam of light, they either reflect it or absorb it. When the substances under study at LRSM are hit by a laser beam, they can modulate the light, change its amplitude or filter it. For example, by frequency doubling they can turn a beam of red light into a beam of green light.

Garito and his group are anxious to identify as many of these changes or electro-optical effects as they can and to understand how they occur. Once these materials are better understood they can be put to use in the rapidly developing field of laser technology.

Laser beams are important in both communications and computers because they travel at the speed of light and thus can move a signal from one place to another almost instantaneously. In addition, the fibers for conducting these light impulses are much smaller than electrical circuits. Tons and tons of copper cable, for example, can be replaced by a bundle of optical fibers. To make the best use of laser technology, industry needs improved materials for getting light signals in and out of the systems that transmit high intensity laser beams to distant satellites and route beams of laser light in various directions.

Garito's group has already happened upon one interesting application for their organic solids. While they were looking at the electro-optical changes in these materials, they saw that the photons from the laser beam created an extremely efficient chemical reaction that changed the chemical identity of solids. This process, the physicists realized, could be used to make computer circuits as small as one-half a micron, about one hundredth the diameter of a human hair and smaller than any circuits thus far manufactured.

Garito's group is now working to create a thin film of this organic polymer that will be the most useful for this process, which changes the material's chemical identity. They have already modified their process to use the more effective X-rays rather than laser beams for delineating the circuits.

At the same time Garito's group is fabricating and testing over 300 different organic solids with these electro-optic properties. Their federal grants for this work range from $500,000 to $1 million a year. In addition to their work on why and how these materials change laser light and withstand high intensity beams, they are also considering the general issue of how these materials behave in a high intensity electrical field. This understanding is critical to the next generation of computers, where the dimensions will be small, the electrical field will be of very high intensity, and materials may well behave in new ways.

"To maintain high technology, we must understand what happens to condensed matter systems in the presence of an electric field. That's the very beginning of physics, and it's still with us today," concludes Garito.

Mathematical Links Between Magnets and Coffee

A primary goal of theoretical physics is to explain seemingly disparate phenomena with a single unifying theory. Such unifying theories have led to significant advances in our understanding of how nature works. In the 19th century, for example, James Clerk Maxwell explained the once distinct phenomena of electricity and magnetism with a single theory that predicted altogether new phenomena such as electromagnetic waves. In the past decades this electromagnetic force was combined with a weak force into a single unifying theory (which Penn physicist A.K. Mann helped to prove with his neutrino experiments).

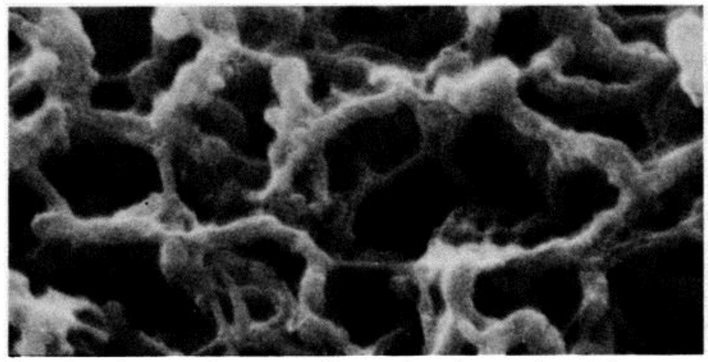
"In condensed matter physics, the fundamental interactions among particles are known. The interest and vitality of this field comes from the enormous variety of phenomena that can be produced by the 100,000,000,000,000,000,000,000 (10^{23}) interacting particles," explains Tom Lubensky.

Professor Lubensky has been studying the universal properties of phase transitions, that is, the change of a material from one state to another. As water evaporates into a gas, for example, it is undergoing a phase transition.

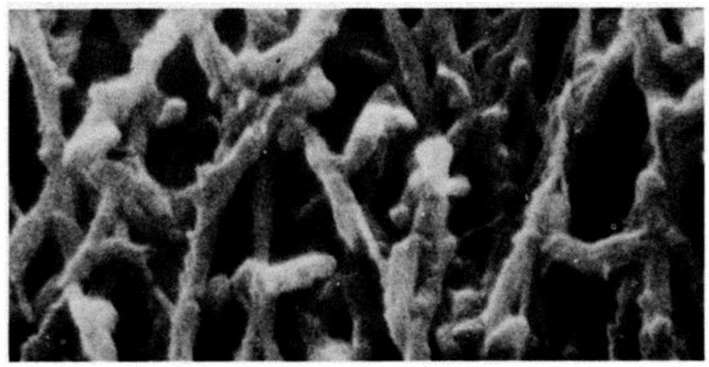
Recently physicists have studied the liquid-gas transition with the same universal theory that describes the transition from a magnetic to a non-magnetic state in an iron bar or the transition from a normal to a superfluid state in helium. These studies have been possible largely because of a sophisticated mathematical tool called the renormalization group, developed by Kenneth Wilson of Cornell. Wilson's work showed that all of these transitions share a common mathematical property in the way they develop order.

Lubensky has demonstrated how Wilson's universal theory also applies to a variety of "percolative" transitions. Percolation occurs whenever fluids flow through random networks. One example of this process is the random path that water takes down through the spaces between the coffee grounds in a drip coffee maker. Other examples are the flow of oil in porous rock and water moving through sandy soil. Mathematically the process of percolation is very similar to the formation of a gel (such as jello) or the vulcanization of rubber. In the cases of coffee and oil in porous rock, the network filling the container is the fluid passing from one end of the system to the other. In the case of a gel, a large number of small molecules react with each other to form larger molecules as time progresses. At a critical time, a container filling network forms and gives the gel its characteristic rigidity. Thus this single theory shows that such seemingly unrelated phenomena as evaporation of water, extracting oil from porous rock and making jello have much in common.

Polyacetylene: A Metallic Chameleon



Scanning electron microscope picture of as-grown polyacetylene.



Scanning electron microscope picture of oriented polyacetylene. The fibril diameter is approximately 200 Angstroms (1 Angstrom = 10^{-8}cm).

Polyacetylene makes Penn's physicists and chemists sound like magicians. They can turn this material, which looks like metallic saran wrap, from an insulator that stops the flow of electricity to a metal that permits electricity to flow freely. Out of it they can create solar cells for powering our homes with the light of the sun or rectifying junctions that change alternating current into direct current.

Even to chemists and physicists polyacetylene seems remarkable, for this organic polymer appears to conduct electricity in an entirely new way. It is thus causing physicists to introduce new concepts to the basic solid state physics of the last 40 years and is leading to the development of a whole new class of materials.

Alan J. Heeger, Professor of Physics and Director of the Laboratory for Research on the Structure of Matter, and Alan MacDiarmid, Professor of Chemistry, decided to study polyacetylene because they wanted to combine the techniques of physics and chemistry to develop an organic material that might have electronic or magnetic properties. They were attracted to polyacetylene because it is about the simplest organic polymer; it consists only of carbon and hydrogen molecules linked together in a herringbone chain. Initial solid state experiments on the substance were so interesting that Heeger and MacDiarmid brought in other scientists, including J. Robert Schrieffer, to explain some of its remarkable properties.

These scientists found that polyacetylene could respond to an electrical current in extremely different ways depending on how they made this material. By adding a small amount of chemical impurities to polyacetylene, a process called doping, Heeger and MacDiarmid have literally turned this substance into an insulator, a semiconductor and a metal depending upon the chemicals they add. This gives polyacetylene the distinction of having the largest range of electrical conductivity yet discovered. As physicists put it, its electrical conductivity can be controlled over 1,000 billion times—from 10^{-10} to 10^{+3}.

The Penn scientists have also made progress toward developing some practical devices out of polyacetylene. They have successfully constructed rectifying junctions, which are used to change alternating current into direct current. They have also made polyacetylene into solar cells, which transfer the light of the sun into electrical current. Because polyacetylene can be made fairly cheaply, there is some hope that it might be used for converting the sun's energy into electrical power that could supply electricity to homes or offices.

What really excites the physicists, however, is the fact that polyacetylene may be a one-dimensional metal. This means that it conducts electricity primarily in the direction of the polymer chain unlike other known metals, which conduct electricity in all three dimensions. Theoretical physicists have developed many concepts based on one-dimensional models of electrical conductivity, but only with the advent of polyacetylene and related organic metals did they have a chance to test and indeed validate these ideas.

"We now believe that the conduction mechanism, the mechanism that conducts charge along polyacetylene is totally different from anything people have seen before," explains J. Robert Schrieffer, who is now working on this with a graduate student, Wu Pei Su.

Schrieffer, Heeger and others believe that at low doping levels, the properties of polyacetylene are dominated by polymer excitations called solitons, which are kinks moving along the polymer chain. The moving solitons are believed to be carrying electrical current. Thus polyacetylene is the first known system in which solitons may be playing a fundamental role in carrying an electrical charge.

Schrieffer and Wu Pei Su have come up with a theory of solitons in polyacetylene, which they describe as very simple. Their theory accounts for most of the experimental effects, some of which completely disagree with the findings from the last 40 years of solid state physics. These theoretical physicists have predicted certain phenomena and are waiting for the experimentalists to see if their predictions are accurate.

Polyacetylene is already leading to the development of more new materials, now that physicists understand the physics and chemistry for making metallic or semiconducting polymers.

"It's fairly clear that it's going to be a growing and maybe very large field. Its ultimate importance will depend on what underlying science is brought out and what technology comes from it," concludes Heeger.

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