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HIGH ENERGY PHYSICS

The Ultimate
Structure
of Matter and Energy

April 1979

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U.S. Department of Energy
Office of Energy Research
Division of High Energy Physics

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Cover Photo: *Proton with 300 GeV energy producing charged particles in the 30-inch Hydrogen Bubble Chamber at the Fermi National Accelerator Laboratory.*

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U.S. Department of Energy
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Acknowledgement

This report on the present status of high energy physics is the result of the efforts of a small writing group headed and inspired by Professor Victor F. Weisskopf, Massachusetts Institute of Technology. The goal was to communicate the reasons for the current excitement in the scientific community—the recent progress and achievements, their significance, and outstanding research opportunities in this field.

The other members of the writing group were: Sheldon Glashow, Harvard; Thomas Ferbel, Rochester; and Peter Wanderer, Brookhaven National Laboratory; with valuable contributions from Martin Deutsch and Francis Low, Massachusetts Institute of Technology; William Kirk, Stanford Linear Accelerator Center; and Frank Sciulli, California Institute of Technology.

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I. Introduction

High Energy Physics, or Elementary Particle Physics, is a part of basic science. The aims of basic science are discovery, insight and understanding of the workings of our natural environment and the laws that govern it.

Particle physics plays a central role in basic science because it tries to answer the following fundamental questions: What are the primal constituents of all matter and energy in the universe, and what are the laws governing the behavior of those constituents that let them combine and form matter as we see and observe it?

The search for the ultimate constituents of matter is as old as our Western culture. The Greek philosophers pondered this problem. But not until the 18th century, when the scientific method was highly developed, did some preliminary experimental results of that search begin to appear. The chemists found that matter is made of atoms and molecules: the oxygen atom is the smallest unit of oxygen, the silver atom is the smallest unit of silver. But nothing was known at that time about the nature of the atom. Only at the beginning of our century was the internal atomic structure uncovered, and the reasons found why atoms have the properties they exhibit, why oxygen atoms form gases at room temperature and silver atoms form into metal.

The following sections sketch some of the principal discoveries and insights and their development up to today. They show how one layer after another was discovered by penetrating farther into the structure of matter.

EMERGING UNDERSTANDING OF BASIC STRUCTURE OF MATTER

Each atom was found to consist of a nucleus surrounded by electrons. The atomic nuclei were found to consist of neutrons and protons; the neutrons and protons appear to consist of quarks. This is where we are today. Every new step into the structure of matter revealed a host of new and unexpected phenomena, particles and forces. In the atomic realm, we face phenomena such as the formation of chemical compounds, emission and absorption of light, electric and magnetic effects, and the properties of materials such as metals, minerals and liquids. In the nuclear realm we encounter nuclear reactions, fission, fusion and a new fundamental force of nature, the nuclear force. In the subnuclear realm we find a host of ephemeral short-lived entities, such as mesons and baryons; we find anti-matter, particle creation and annihilation, and we see peculiar strong forces in action. With every step, nature reveals to us new processes, new phenomena and new forces, and deepens our understanding of familiar ones.

The deeper we go, the larger and more powerful are the required instruments of observation, and the costlier the research becomes. At the deepest level, we investigate the behavior of matter under very unusual conditions that are realized naturally only in the interior of exploding stars, or perhaps at the very beginning of the universe, during the so-called Big Bang. Such conditions are difficult to reproduce in the laboratory. But as the observed phenomena become more and more unusual and differ more markedly from those of our immediate environment, we get acquainted with completely new forms of material behavior. We get nearer to the very nerve center of nature, and closer to answers to the kind of questions that man has asked since he began to find his way in nature.

II. The Mounting Energy Scale

At the beginning of this century, experiments on what was then elementary particle physics were carried out on table tops: they were simple and inexpensive. Today, enormous accelerators must be used in order to continue the search for the basic constituents of matter; annual U.S. expenditures for elementary particle physics are counted in the hundreds of millions of dollars.

In order to understand the need for larger and larger accelerators, it may be instructive to consider an outrageous analogy. Suppose that we were obliged to study the structure of a *peach* simply by shooting small projectiles, such as BB's, at it. (The analogy is apt because atoms and their constituents are so tiny that this method of study is practically the only one available to us. For peaches, of course, there are simpler ways.)

A beam of very slow BB's would simply bounce off the peach. By measuring the pattern of scattered BB's, we could learn the *size* of the peach and that it is *round*. Faster BB's would lodge within the peach, perhaps causing the production of a secondary product: we could learn that the peach is *soft* and *juicy*. With a more powerful BB gun, most of the projectiles would pass straight through the peach. Some, however, would change their direction to emerge from the peach at large angles. How would we understand this? We might conjecture the existence of a small hard "*pit*" within the peach. A detailed study of the large-angle scattering of high-energy BB-peach collisions would reveal the size, shape, and weight of the pit. Of course, the pit itself has structure too. A still more powerful BB gun is needed to shatter the pit and reveal the kernel within . . .

Let us emerge from the analogy to the real world of atoms and atomic constituents. To study the structure of matter, the projectiles should be chosen to be as simple as possible: hydrogen nuclei (protons), electrons, particles of light (photons), etc. Furthermore, there is a fundamental law of physics that says: the smaller an entity, the higher are the energies involved which hold its component parts together. Therefore, we need higher energies to find out the structure of smaller entities.

The unit of energy we use is called the "electron volt," denoted by eV, which is the amount of energy an electron gets in crossing a voltage difference of one volt. One electron-volt is a very typical energy for atoms and molecules, and thus for the micro-processes that make up our every-day life. A flashlight battery, for example, is nothing but a 1.5-eV electron accelerator. It costs less than a dollar. The largest electron accelerator now

in operation is located at Stanford in California. It accelerates electrons and positrons to energies in excess of 20 billion eV. Volt-by-volt the accelerators are much cheaper than flashlight batteries, but they still cost a great deal. Let us briefly consider what is revealed of the structure of the microworld as we ascend the ladder of increasing energy.

One electron volt (eV) is truly mundane. It is the energy of a single photon of visible light, or of a simple chemical reaction such as a flame on a gas stove. When the pot boils over, the flame turns yellow. The sodium in the salty brew has been made to emit its characteristic light; sodium atoms have received a few eV of energy from the flame. The various kinds of atoms emit or absorb photons of specific colors or energies. Such observations ultimately led to the revolutionary development of quantum mechanics in the early part of this century, which led to the understanding of atoms and molecules.

One thousand electron volts (keV) is a typical x-ray energy. X-rays consist of photons just as visible light does, but photons of much higher energy. They can be produced easily enough to be available to the neighborhood dentist. Experiments with x-rays have told us much about the inner structure of atoms. Moseley discovered his famous law in 1913 by studying the energies of x-rays associated with the different elements. This law tells us that the atoms of the elements differ in the number of electrons within each atom. Quality was reduced to quantity. Moseley's law was an essential key to the structure of the atom, leading to the almost magically successful predictions of the properties of chemical elements. It was x-ray experimentation that helped to change chemistry from an art to a science.

One million electron volts (1 MeV)—now we are talking about energies a thousand times larger than x-rays. Radioactive substances such as radium or thorium emit energetic rays called alpha rays, beta rays, and gamma rays. Typically, these radioactive emanations have energies of several MeV.

Ernest Rutherford, in 1910, used such small and energetic particles as probes of the atom's structure. As in the tale of the peach, he detected the existence of occasional large-angle deflections of his projectiles when they collided with gold atoms. He concluded that there must exist something very small, hard, and heavy within the atom. He had discovered the atomic nucleus.

The atomic nucleus remained an enigma until 1932 when the neutron was found, whereupon the science of nuclear physics took off. The nucleus was recognized to be made of protons and neutrons held together by the nuclear forces. Nuclear power, nuclear weapons, and radiomedicine followed quickly in its wake.

One billion electron volts (1 GeV) has been the workhorse energy of the elementary-particle physics of the past 25 years. Originally, such energies

were accessible only by the study of cosmic rays—occasional particles visiting upon the Earth from outer space. Cosmic ray experiments led to the discovery of a number of new short-lived particles in the 30's and 40's. But high energy cosmic particles are few and far between. Accelerators provide a far more copious source of multi-GeV particle beams, which can be controlled and used to conduct precise experiments.

III. What Did We Find At The High Energy Frontier?

When those high energy particle beams were directed at matter, physicists were surprised and puzzled by the unexpected variety of previously unknown particles that emerged from the collisions. With the construction of large accelerators in the United States, a veritable population explosion of new particles took place. By the mid-60's more than 100 species were identified; they were called "hadrons" and fell into two subgroups: "mesons" and "baryons." All of them are extremely short lived; they exist only for less than a hundred-millionth of a second. They decay quickly through various kinds of radioactive processes into more familiar particles such as protons, electrons and photons.

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Furthermore, when they collide in the target, those tremendously energetic beams produce a lot of "antiparticles" together with particles. Antimatter is a common occurrence in this realm of phenomena. Of course, antimatter does not last long either; whenever it gets in touch with ordinary matter, the two combine explosively into some form of energy. Still, it is possible to collect stable particles of antimatter (antiprotons or antielectrons) in the form of powerful beams within evacuated tubes where they are prevented for some time from hitting ordinary matter. Antimatter beams serve as a tool to study the miraculous properties of this alternate form of matter.

So many newly discovered particles could not all be elementary. They were bound to be different composites of some simpler units. It was in 1963 that Murray Gell-Mann and George Zweig postulated the quark. It was assumed then that there were just three kinds of quarks, and that all the various observed hadrons were made up of quarks and antiquarks in different combinations. Indeed, the hundreds of newly-observed sub-nuclear particles could be considered as composites of quarks. As the Greeks had believed, Nature was frugal after all.

At first, only a few physicists accepted the quark hypothesis. It was successful in classifying the many observed short-lived particles: mesons seemed to be quark-antiquark combinations, baryons seemed to consist of three quarks. But there was no solid evidence for the true existence of quarks. Today, the picture has changed, due to another experiment in the tradition of Rutherford and the peach, done in 1968. Electrons of several GeV were made to collide with hydrogen nuclei by a group of M.I.T. and Stanford physicists doing their research at the Stanford Linear Accelerator Center (SLAC). Again, there were simply too many large angle deflections of the electrons. There had to be something hard and pointlike within the proton. Here at last was convincing evidence for the existence of quarks.

One trillion electron volts (1 TeV) is the next frontier. No sooner had it been generally acknowledged that quarks must exist, than it was found that there were more than just three kinds of quarks. Thanks to experiments done at Brookhaven National Laboratory (BNL), at Fermilab, at SLAC and abroad, it is now known that there are at least five quark species. There are good reasons to believe that even more must exist. Perhaps, in the end we will learn that there are just six kinds of quarks, and we are approaching a natural end to our inquiry into the structure of matter. Perhaps there are more than six. Perhaps it will be found that quarks are not elementary at all; then the story goes on, and we are not yet near the end of our search for the ultimate building blocks of matter. Only the high energy frontier of the future can provide the answers.

IV. The Families of Quarks and Leptons

Ordinary atoms of matter consist of a nucleus surrounded by electrons. Today the electron still seems to be a truly fundamental entity; the nucleus does not. The nucleus is made up of neutrons and protons. Once, these particles were thought to be fundamental, but today we know they are not. Neutrons and protons are made up of quarks. To form neutrons or protons requires only two kinds of quarks, called u-quarks and d-quarks. Thus, the ingredients of ordinary matter are these:

Nuclear ingredients	{	u-quarks
		d-quarks
extra- nuclear ingredients	{	electrons
		neutrinos

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Working inside the complex particle detection system used at the Stanford Linear Accelerator Center to study the annihilations of electrons and positrons. The series of experiments done with this detector resulted in the discoveries of the J/ψ particle, the tau lepton and new mesons containing charmed quarks.

A fourth particle slipped into the above list: the neutrino. It is not really a constituent of matter, but it is necessary to make things work. Neutrinos (symbolized by the Greek letter ν , or nu) are crucially involved in the processes of radioactivity. They also played a crucial role in the primordial processes that produced all the chemical elements from hydrogen, and continue to do so in the process that makes the sun shine. Without neutrinos, Spaceship Earth, if it existed at all, would be a cold and dreary lump of frozen hydrogen.

High energy physicists call the extra-nuclear particles "leptons." These particles do not sense the powerful nuclear force that holds the nucleus together. The particles listed above, two kinds of quarks and two kinds of leptons, are now regarded as making up a *family* of fundamental building blocks:

Quarks		Leptons	
u		e	
d		ν_e	

This is the "relevant" family, the particles that we know to be *needed* to make up the world as we see it around us.

The first "irrelevant" particle, called the "muon," was found in 1938. It doesn't fit into the "first family"—it appears in every way to be identical to the electron, except that it is much heavier: it weighs about as much as 200 electrons. It is a rather ephemeral entity, decaying in about a millionth of a second into an ordinary electron and two neutrinos. So-called "strange particles" (several massive particles, heavier than the muon and also short lived) were first found in the 50's, and it was to explain them that Gell-Mann and Zweig originally had to introduce a third kind of quark, called the s-quark (s for strange).

In 1961, an astonishing discovery was made at Brookhaven National Laboratory. It was learned that there was a second kind of neutrino, called the muon-neutrino, ν_μ . Electrons were associated with one kind of neutrino, whereas muons were associated with a different species of neutrino. With all these "extra" particles around, physicists saw that there simply had to exist a *second* family of fundamental building blocks, including two "superfluous" quarks and two "superfluous" leptons:

Quarks		Leptons	
s		muon	
c		ν_μ

An aerial view of the Fermi National Accelerator Laboratory shows the 4 mile main accelerator ring, the principal experimental areas, and the high rise laboratory building. It is the site of the 1977 discovery of the "upsilon" particle, first evidence for the existence of the fifth quark: the b-quark.

Once again, an extra constituent has been slipped in: the c-quark. There were good reasons to expect a fourth quark; a fourth species was indeed predicted in 1964. Not until ten years later did evidence for it show up: a particle subsequently named the J/ψ was discovered simultaneously at BNL and at SLAC and surprised everybody by having all the properties of a combination of a c-quark and a c-antiquark. The members of this second family (with the exception of the muon-neutrino) are short-lived. They and the composite particles made of them decay into the particles of the first family or into particles made up from the first family.

Since 1974 we have known of these two families of building blocks. One family relevant, essential, necessary to our understanding of matter as we see it around us; the other symmetrical family totally irrelevant, or so it would seem. Why does the second family exist at all? But alas, before we have found an answer, the balance between the necessary and the unnecessary has been upset. Yet a third family of building blocks seems to exist:

It was at Fermi National Accelerator Laboratory (Fermilab) that the first evidence appeared for the existence of the fifth quark, the b-quark: it was the discovery of a short-lived entity called "upsilon." Confirming experiments done in Germany showed that the only reasonable interpretation of this new particle is that it is made up of a fifth kind of quark, and its antiquark. The electron-positron machine at Cornell University, which will be operative soon, is ideally suited to the study of the upsilon particle and other particles made up of b-quarks.

Evidence for the third charged lepton—the tau—began to appear at SLAC in 1975. Today, due to experiments performed there and in Germany, it is generally believed that the tau, like the muon, is just like an electron but much heavier. It is some 17 times heavier than the muon and is extremely unstable. Its lifetime is probably ten million times shorter than the muon lifetime. There is also some evidence that the tau has its own kind of associated neutrino, ν_{tau} .

But the family must be completed. There are good reasons for the existence of a sixth quark called t-quark to fill out the third family. It is expected that this quark will be discovered in experiments performed at the largest electron-positron machines: PEP at Stanford or PETRA in Germany. The members of the third family, and the entities made up of them, must also be short-lived with the possible exception of the tau-neutrino.

A most important question is; how many families or building blocks are there all told? Are there just three families, or are there more? To answer this question, a really large electron-positron machine would be the ideal tool. Such an instrument has been designated as Europe's highest

priority in particle research. Design of this expensive (probably over half a billion dollars) machine has begun, and it is hoped that it might be constructed and in operation in the late 1980's. It is called LEP for "large electron-positron machine." The two "irrelevant" families cannot truly be irrelevant. In the grand scheme of nature that we cannot yet imagine, they will play an essential role. Perhaps things will get more complicated before the underlying simplicity is revealed.

The two-mile long linear accelerator at the Stanford Linear Accelerator Center. The dashed line indicates the new Positron-Electron Project, now under construction, which will provide colliding positron and electron beams at very high energies.

ISABELLE, presently under construction at Brookhaven National Laboratory. This device will be used to perform proton-proton colliding beam experiments including those searching for the heavy "photon" which carries the weak force and testing new theories of the strong force.

V. The Four Forces of Nature

To the layman, there are a baffling variety of forces in nature. To name only a few, there are the forces of gravity, the wind, the tide, and the surf. There are also the push and shove of mechanical force, the force of the motor in your car, the lift and drag on an airplane, the magical force of an electric motor, of lightning and volcano, and the lowly force that closes a clam. The elementary-particle physicist is interested in the most basic underlying forces. It is in terms of these that all other forces are ultimately resolved. Until very recently, it was thought that there were just *four* such fundamental forces:

GRAVITY is the force that rules the behavior of large objects: the universe, galaxies, solar systems, stars and planets, mountains. Indeed, it is the force of gravity that holds celestial objects together and keeps us humans tied to the earth. Newton's theory of gravity survived unchanged until the early twentieth century, when our understanding of gravity was improved by Einstein's theory.

ELECTROMAGNETISM was put together out of three seemingly very different disciplines: electricity, optics and magnetism. Maxwell performed this miraculous synthesis in the late 19th century. Electromagnetism is the force that holds the electrons bound to the nucleus to form an atom. Also, it is electromagnetism that gives rise to the forces between atoms that lets them combine into molecules, and molecules into the familiar stuff of the world. All the everyday forces such as the force of the automobile motor or even muscular force ultimately result from the electromagnetic force in the atoms. Briefly then, it is gravity that holds us to the surface of the Earth, but it is electromagnetism that makes the chemistry of our bodies function, and that makes rocks and metals solid. From the 30's to the 50's, a successful quantum theory of electromagnetism was developed, known by the acronym QED (quantum electrodynamics). Its predictions of the properties of atoms and electrons have been verified to an uncanny level of precision and have led to numerous important practical applications.

The STRONG FORCE is the third fundamental force, and it first reveals itself fully in the subnuclear world. It is the strong force that holds the quarks together to make up a proton. And it is also the strong force that holds protons and neutrons together to form nuclei. Since 1932, physicists have speculated on the nature of this force. Today, at last, we have a possible candidate for a theory of the strong force, known by the acronym QCD (quantum-chromodynamics). It is a theory analogous to electrody-

An ISABELLE superconducting magnet being assembled at Brookhaven National Laboratory. This device will be used to perform proton-proton colliding beam experiments including those searching for the heavy "photon" which carries the weak force and testing new theories of the strong force.

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ics. The quarks carry a kind of non-electric charge, and that charge produces a field of force, the strong force. One function of ISABELLE, the large colliding beam device being constructed at BNL, will be to test the predictions of QCD.

The WEAK force is the fourth and final force. It is the force responsible for the radioactive decay of many of the observed particles and nuclei. Indeed, it is the agent that causes the short life of so many of the "irrelevant" particles. It is involved in the mechanism by which the sun produces energy, and by which the chemical elements were formed from the primordial hydrogen in the interior of stars.

For many years, it has been a dream to repeat the success of Maxwell, and reduce the number of fundamental forces by a brilliant synthesis of two or more of the four. Thus it was that Yukawa tried in the 30's to unify *strong and weak* interactions. But he failed. For the last 25 years of his life, Einstein attempted the synthesis of *gravity and electromagnetism*. He too failed. Today, physicists have succeeded in putting together the *weak and electromagnetic* interactions into a single unified theory. The

suggestion was first made by Schwinger in 1956 and later in greater detail by S. Glashow that the *weak* and *electromagnetic* interactions could be put into a single so-called "gauge theory." The theory was worked out by S. Weinberg, A. Salam and J. Ward. The last essential step in the proof that such a synthesis works was given by a young Dutch physicist ('t Hooft) in 1971. Since then, some consequences of the theory have been confirmed in detail by experiment. One of the most important conclusions is the existence of special, very heavy "photons" that carry the weak interaction field in the same way that normal photons carry the electromagnetic field. These heavy photons have not yet been discovered: one needs higher energies than those available today, in order to set them free. ISABELLE may bring them forth.

There are yet more ambitious physicists who dream of the unification of three, or even of all four fundamental forces. There has been a large amount of theoretical discussion in the last five years, but a realistic theory of this kind is not yet at hand. Will it be discovered or must we go into even deeper layers of matter in order to get a unified view of the laws of nature?

VI. Some Achievements of The Past Few Years

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A few examples of what has been discovered in the last few years may serve as an illustration of the liveliness and vigor of this field of basic research. Indeed, it is astonishing how many fundamental discoveries were made and how many new insights were obtained in a relatively short period.

A. The discovery of the tau-lepton. The third electron-like object besides the electron itself and the muon was discovered at SLAC in 1975. As mentioned previously, the tau is regarded as a member of the third family of basic constituents of matter. Recent measurements at SLAC and in Germany have confirmed beyond a doubt that we face here a third type of electron, with a large mass, almost twice that of the proton.

B. The discovery of "charmed" baryons and mesons. The important discovery of the J/ψ meson in 1974 by teams at SLAC and BNL (for which Richter and Ting received the Nobel prize) suggested the existence of the c-quark, a member of the second family. In order to confirm that such quarks really exist, it was necessary to look for particles that consisted of combinations of the c-quark with other types of quarks; such objects have been discovered at BNL and SLAC in the past two years.

The double-arm particle spectrometer used in the discovery of the J/psi particle (made up of a combination of a c-quark and a c-antiquark) at Brookhaven National Laboratory. The sketch shows the paths of the electron (e^-) and positron (e^+) and the magnet and detector components that make it possible to identify the particles and determine their energy.

C. The discovery of a meson (the upsilon)—which indicates the existence of a fifth type of quark, the b-quark—was made at Fermilab. This and the first mentioned discovery have verified the existence of the third family of quark/lepton elementary particles.

D. Scattering of neutrinos by electrons. If the ideas of a common nature of weak and electromagnetic forces were correct, it would necessarily follow that neutrinos are scattered (deviated in their path) by electrons. But the effects would be extremely small. The theory predicts that for every five quadrillion (5×10^{15}) neutrinos that pass through a target consisting of about 20 tons of material, only one will collide with an electron within that target. Modern instrumentation and the skill of the physicists have made it possible to observe these tiny effects. Experiments were set up at the Fermi National Accelerator Laboratory and at CERN in Europe to test this prediction. A total of some 15 neutrino-electron collisions were observed in large bubble chambers that served as the electron targets for the high energy neutrinos. The result, which is completely consistent with the predictions of the unified theory, provides a superbly clean test of our newly found perception of nature.

E. The asymmetric scattering of electrons by deuterons. The same theory that unifies weak and electromagnetic forces also claims that the interaction between negatively charged electrons and positively charged deuterons should show very small deviations from the ordinary electric attraction between opposite charges. For a "right-handed" electron (spinning like a right-handed screw along its line of flight), the theory predicts that scattering is 0.01% less likely than for a "left-handed" electron (one that spins like a left-handed screw along its line of flight), whereas the electric interaction alone would not be different in these two cases. In a major tour-de-force, scientists from Stanford and from Yale University built a source of electrons of specific "polarization" (that is, of definite handedness), accelerated these electrons to high energy, and scattered about a trillion (10^{12}) of them from a target at the Stanford Linear Accelerator Center. Indeed, they did observe a minute but significant difference in the scattering of left-handed and right-handed electrons, precisely at the 0.01% level predicted by the new unified theory. This experiment beautifully confirms a theory that brings together two forces that were thought at one time to be disparate.

F. Physicists at Argonne National Laboratory, in collaboration with the University of Michigan, decided to study particle properties in a special way. They argued that, because a proton is known to behave like a small spinning top, it might be profitable to collide protons on protons with the spins of the colliding protons lined up along specific directions. They developed techniques of aligning and accelerating them at Argonne's ZGS accelerator. They discovered the surprising fact that protons with aligned spins interact much more strongly with each other than when the spins are not aligned. It will be most interesting to find out what causes this abnormal behavior.

Physicists in an animated discussion of the latest results at a recent High Energy Physics Conference. Insights and understanding of the structure of matter and energy develops with steady progress in experiment and theory.

G. Progress in theoretical understanding. The progress of clearer insights into what is really going on in the subnuclear world develops slowly over long periods. The achievements in this area cannot be divided as easily into definite steps as the progress of experimental discoveries. This is why it is hard to pin down the achievements in understanding that took place in the past few years. Nevertheless, we can cite the ideas of quantum chromodynamics (QCD), which form the basis of our understanding of the strong interactions between quarks, as having been greatly developed during the past two years. It is now possible to make definite predictions on the basis of this theory; these can be compared with present and future experimental results. So far the theory has been well confirmed by these comparisons. There are still some difficulties to be overcome, such as the explanation of the apparent fact that the attractive force between quarks does not seem to diminish with increasing distance between quarks. But there is good reason to hope that even this unusual feature of the strong force will be explained by the theory.

Bending magnets of the large proton accelerator at the Fermi National Accelerator Laboratory. This accelerator is 4 miles in circumference and achieves the highest energy in the world.

VII. Particle Accelerators and Experimental Apparatus

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To find the ultimate constituents of matter, physicists require two essential items: first, highly energetic projectiles that can probe deeply into the structure within the atom, and, second, sensitive detectors that can be used to decipher that structure. The projectiles are fired by accelerators of many different types. Pioneering work in the 1930's, led by Ernest O. Lawrence, provided the impetus for the development of the immensely large and expensive present-day accelerators. During this evolutionary period, high-energy physicists have continuously refocused their field of vision. Driven by the fact that, the smaller the entities, the higher are the energies needed to get at particle structures, this very need for high energy as a powerful searchlight of the subnuclear realm constantly pressed for the development and improvement of modern accelerators. These descendants of the early "atom smashers" are not just the dull but necessary specialized tools of an exciting field. Far from it! They are extraordinary accomplishments in their own right.

The East experimental area at the Brookhaven National Laboratory. Several secondary beam pipes and associated experimental equipment are visible. Such arrangements make it possible to perform a number of experiments simultaneously at accelerators.

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In the first place, they challenge the inventiveness of the builders to the utmost, since nothing like them has ever been built before. Some of the ideas incorporated in their construction are truly great intellectual achievements. Lore and legend surround these machines, and they generate lively competition between physicists. With the successful operation of a new accelerator, there is the tremendous satisfaction of having solved intricate technological problems, and the even sweeter satisfaction of reaping a rich harvest of new scientific discoveries.

There are three types of accelerators: the linear accelerators, the synchrotron types, and the colliding beam devices. The first type produces particles of high energy by letting them move in a long straight tube and by administering many electric pushes along the way. The largest example is the Stanford Linear Accelerator Center (SLAC) in California; there the tube is two miles long: The maximum energy of the emerging electrons is 23 GeV. According to Einstein, the mass of a fast moving object is larger than that of the object at rest. The electrons at Stanford emerge with masses 46,000 times larger than ordinary atomic electrons.

At the controls of the Alternating Gradient Synchrotron Accelerator at Brookhaven National Laboratory. While accelerators are principal tools for high energy research, these complex machines are also major accomplishments in their own right.

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In the second type of accelerator, particles (usually protons) are constrained by strong magnets to move in a circular tube. They also get many electric pushes along the way until they reach the desired energy. The circular tube allows us to apply the same push many times over—every time the particle passes the point in its merry-go-round where the push is applied. At very high energies, one needs very strong magnets to make the particle beam bend around the circle. There is a limit, however, to the strength of magnets. This is why one must use extremely large circles so that the curvature can be managed by the magnets. (A fast car cannot race on a small circular race track). The highest energy protons (500 GeV) have been obtained in the four-mile ring of the Fermi National Accelerator Laboratory in Batavia, Illinois where a new project is under way to attain 1000 GeV. At 500 GeV the protons reach about 500 times the mass they would ordinarily have.

The third type of accelerator is the colliding beam device. Here the Einstein mass-energy relation is exploited. In the previously described types of accelerators the high energy beam impinges upon a stationary or fixed target: usually a piece of metal, or liquid hydrogen. In this case the impinging particles have very high masses because of Einstein's theory, whereas

The 15-foot hydrogen bubble chamber at Fermi National Accelerator Laboratory. A charged particle traversing the chamber leaves a track of little bubbles as the passing particle boils small quantities of the hydrogen liquid along its path.

the target particles have their ordinary masses. This fact reduces the efficiency of the collisions. When a truck collides with a fly, it does not transfer much of its energy to the fly! In a colliding beam device, however, both particles have high energy and consequently high masses. It is like a collision between two trucks; the collisions are much more powerful. For example, two proton beams of 500 GeV directed against each other produce collisions that are 30 times more energetic than those of one such beam with a stationary target.

At present there exists only one colliding beam device for protons, at the European Nuclear Research Center in Geneva, where proton beams of 30 GeV collide with each other. Another much more energetic device (400 GeV per beam) is under construction at the Brookhaven National Laboratory; it is called ISABELLE. There exist several devices for colliding high energy electron-positron beams. The larger ones are at SLAC (called SPEAR) and in Germany (called DORIS), each with beam energies of about 4 GeV; another of 8 GeV (called CESR) will soon be completed at Cornell University. A new device (PETRA) with electron beams of up to nearly 20 GeV has recently been built in Germany and a similar machine called PEP is under construction at SLAC.

The interest in colliding beam devices is mounting but the other types of accelerators are also of great importance. True enough, the collisions they produce are not so energetic—but they produce many more of them! In the colliding beam devices, one beam hits another beam; both are very tenuous and dilute. The distance between the particles is vastly greater than in an ordinary piece of matter. In the fixed target type of accelerator the beam hits a solid or liquid target of ordinary matter in which the particles are much closer to each other and more concentrated. Many more collisions occur and it is possible to collect the particles produced by these collisions and let them emerge as secondary beams. Thus we can produce beams of strange and rare particles, such as mesons and neutrinos and antiparticles, and we can use them for interesting and important experiments. The colliding beam devices produce far too few collisions to make secondary beams intense enough to be used for experiments.

Accelerating particles is only half of the task. We also must be able to observe and distinguish the particles that emerge from the collisions; and this is done with particle detectors. A great amount of ingenuity has gone into the construction of devices that can register single particles, recognize their nature and measure their energy and other properties.

One of the most important detectors is the bubble chamber. The largest of these is the 15-foot-long chamber at Fermilab, filled with liquid hydrogen or other liquified gases. Any charged particle traversing that chamber leaves a track of little bubbles, since the passing particle boils small quantities of the liquid along its path. These tracks are photographed and we obtain such beautiful pictures of subnuclear processes as the one shown on the cover of

Scanning technician at Fermilab makes a measurement using a photograph of a particle interaction in a bubble chamber. The particle tracks are a series of bubbles initiated by the passing electrically charged particles.

this booklet. A great advantage of this device is the fact that we can exploit the results of an experiment by studying the photographs in a laboratory at a university far away from the accelerator.

Other detectors for high energy particles have been designed as a result of the rapid development of electronic devices in recent years, and their design has in turn contributed to electronic developments. Among the modern detectors are the so-called proportional chambers and drift chambers

A large neutrino detector system at Fermilab. Neutrinos interact so weakly that they require massive detectors. Large slabs of steel are interspersed with electronic detectors which record the interactions.

which utilize the ionization of gases along the path of a charged particle. So-called scintillation counters utilize the light emitted by a solid, liquid or gas upon the passage through it of a charged particle. Each of these detectors has properties which make it especially suitable for studies of specific particles or particular energies. All of them have undergone rapid improvements in precision and sensitivity since their early development, in response to the increasingly stringent requirements of experimentation at higher energies.

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All of the techniques described above are designed for detecting and analyzing charged particles through their electric effects. The detection of uncharged particles is a more difficult task. Here one is restricted to observing the effects of their collisions with electrons or protons in the material of the detector. One of the most impressive feats has been the detection of neutrinos. They interact so weakly with matter that a single neutrino has a very good chance of passing through the entire earth without making any collision. In fact, if the Fermilab neutrino beam were made to pass through the earth, we would expect 99 out of 100 neutrinos to exit on the other side unscathed! It is not surprising, therefore, that to study neutrino collisions one requires massive detectors, and great tonnage of sensitive material, as well as an intense beam of neutrinos. The 15-foot long bubble chamber at Fermilab is a particularly useful device for work with neutrinos.

VIII. Epilogue

Why are we doing all this? Why should we continue to spend about 300 million dollars a year for these apparently very esoteric activities, that are well understood only by scientists and seem to have little direct connection with the numerous practical problems of the day? No physicist or conscientious citizen can get away without thinking about these questions, and without presenting valid answers.

We believe that there are three important answers. The first one is based upon an age-old experience: rarely has there been a discovery of basic science that did not have some useful practical application. The second answer is this: basic science works at the frontier of the possible; therefore the basic researcher is constantly challenged to look for innovative ideas and to stretch the technological frontier to the utmost. The third answer is the intrinsic value of knowing the fundamental causes of what is going on in the natural world. The steady growth of this knowledge in scope and in depth is one of the great achievements and inspirations of our western civilization.

Let us be more specific in regard to these three arguments. We return to the first one: Most discoveries in fundamental science have led to strong practical use. The inverse is also true: rarely has there been an important practical technical innovation that was not based upon some insight of basic science. A colorful quote by a former industrial Research Director, H. Casimir, illustrates this point.

I have heard statements that the role of (basic) research in innovation is slight. It is about the most blatant piece of nonsense it has been my fortune to stumble upon.

Certainly, one might speculate idly whether transistors might have been discovered by people who had not been trained in and had not contributed to wave mechanics or the theory of electrons in solids. It so happened that inventors of transistors were versed in and contributed to the quantum theory of solids.

One might ask whether basic circuits in computers might have been found by people who wanted to build computers. As it happens, they were discovered in the thirties by physicists dealing with the counting of nuclear particles because they were interested in nuclear physics.

One might ask whether there would be nuclear power because people wanted new power sources or whether the urge to have new power would have led to the discovery of the nucleus. Perhaps—only it didn't happen that way, and there were the Curies and Rutherford and Fermi and a few others.

One might ask whether an electronic industry could exist without the previous discovery of electrons by people like Thomson and H. A. Lorentz. Again, it didn't happen that way.

ALVAREZ

BETHE

FERMI

FEYNMAN

GELL-MANN

LAWRENCE

OPPENHEIMER

PURCELL

RABI

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SEABORG

SCHWINGER

WIGNER

One might ask even whether induction coils in motor cars might have been made by enterprises which wanted to make motor transport and whether then they would have stumbled on the laws of induction. But the laws of induction had been found by Faraday many decades before that.

Or whether, in an urge to provide better communication, one might have found electromagnetic waves. They weren't found that way. They were found by Hertz who emphasized the beauty of physics and who based his work on the theoretical considerations of Maxwell. I think there is hardly any example of twentieth century innovation which is not indebted in this way to basic scientific thought.

Basic science contributes to technological progress by discovering new modes of material behavior that may be used for technical exploitation. There are many past examples: electricity and magnetism were once thought to be rare and unimportant side effects in nature; electric effects were seen only during thunderstorms or as tiny static effects when certain objects were rubbed against each other; magnetic effects were found only with rare minerals such as lodestone. Basic science has revealed the ubiquitous nature of electricity and magnetism in all matter, thus opening up the vast technological opportunities that we witness today.

Nuclear phenomena were first considered as exceptional occurrences in a few very rare radioactive substances. Basic science has revealed them as the properties of every atomic nucleus, thus initiating the nuclear age, which now also includes power technology and all the fruitful medical and technological applications of artificial radioactivity.

Nobody can predict what parts of the subnuclear realm may be of most practical use in the future.

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The second argument we made was this: basic science works at the frontier of the possible; the unsolved problems of science are those that cannot be solved with known and established means and methods. Therefore the basic researcher is constantly forced to look for innovative ideas and new technical devices. A few examples: high energy research has greatly advanced the technique of superconducting magnets; it has extended the art of measuring very short time intervals by large orders of magnitude; it has developed extremely sensitive and precise methods to register radiation of all kinds. Many of these methods are used today in x-ray detection—as, for example, at airport gates.

Basic research also provides a pool of young men and women who have become accustomed to tackling unexplained phenomena and who have learned to find new ways to deal with them. They have been exposed to extraordinary challenges, such as creating within the laboratory the physical conditions prevailing in exploding stars or during the Big Bang. They have worked under the most exacting conditions, in open competition with the entire scientific world community. This is why it is so important to keep a high level of basic research activity at the universities — so that the younger generation can get in touch with it and participate at a high level. More than half of the graduate

students of high energy physics find jobs in other fields where they can make use of their experiences and apply them to other fields of science and technology.

When studying the development of industrial nations, one cannot fail to make the following observations: in the first half of the nineteenth century, England was the great industrial nation, and at the same time, England produced the great names in fundamental research—Maxwell, Young, Faraday, etc. Then, in the second half of the nineteenth century and at the beginning of the twentieth, Germany began to play a leading part. It is then that one finds a galaxy of German physicists: Holmholtz, Nernst, Roentgen, Planck, Schroedinger, Sommerfeld, Heisenberg, etc. Later in the twentieth century, as the United States became the leading industrial nation, fundamental science blossomed in America. Fermi, Wigner, Oppenheimer, Lawrence, Rabi, Bethe, Purcell, Alvarez, Seaborg, Schwinger, Feynman, and Gell-Mann are only a few names illustrating this point. There is a clear connection: where there is basic science, there is industrial growth.

The third argument is this: the value of fundamental research lies not only in the ideas produced and in the phenomena discovered. There is more to it.

In the past two hundred years, mankind has found some truly fundamental causes of what is going on in the natural world and we have learned to penetrate below the surface of the phenomena that are ordinarily observed around us. Basic science has searched for and found a regular world beneath the seemingly irregular flow of natural events and has studied its laws and interrelations. This search goes on and reaches ever deeper layers of nature, finding at the same time new and unexpected forms of natural events. High energy physics is a spearhead in this endeavor; it tries to reach the deepest level of the material world.

Basic science is one of the cornerstones of our Western civilization. No other civilization has created anything like it. It is probably the major contribution of our time to the great creations of the human spirit. It is one of the positive, constructive elements in a time when so many values are undermined and overthrown.

A vigorous basic science creates a spiritual climate which affects the whole intellectual life of the nation by its influence on our way of thinking and by setting standards for many other intellectual activities. Applied sciences and technology adjust themselves to the highest intellectual standards which are strived for in the basic sciences. It is the style, the scale, and the level of scientific and technical work in pure research that attracts some of the most inventive spirits and brings the most active scientists to those countries where science is at its highest level. This is why many outstanding scientists have moved to the United States from other countries in recent decades.

The case for generous support for pure and fundamental science is as simple as this. Fundamental research sets the standards of modern scientific thought; it creates part of the intellectual climate in which our modern civilization flourishes. It pumps the lifeblood of ideas and inventiveness not only into the technological laboratories and factories, but also into other cultural activities. It is a most vital and active part of our intellectual life, a part which we all should regard with pride as one of the highest achievements of our century.

Glossary

Accelerator—A device which increases the speed (and thus the energy) of charged particles such as electrons and protons.

Alpha ray—The nucleus of the helium atom, consisting of two protons and two neutrons. Emitted from certain heavier nuclei as radiation.

Antimatter—Matter composed of 'antiparticles', i.e., antiprotons, antineutrons, antielectrons, etc. instead of the ordinary protons, neutrons, electrons, etc.

Antiparticle—Each particle has a partner, called an antiparticle, which is identical except that all charge-like properties (electric charge, strangeness, charm, etc.) are opposite to those of the particle. When a particle and its antiparticle meet, these properties cancel out in an explosive process called annihilation.

Atom—The smallest unit of a chemical element, approximately $1/100,000,000$ inch in size, consisting of a nucleus surrounded by electrons.

Baryon—A type of strongly interacting particle. The baryon family includes the proton, neutron, and those other particles whose eventual decay products include the proton. Baryons are composed of 3-quark combinations.

Beam—A stream of particles produced by an accelerator.

Beta ray—An electron or positron emitted when the weak interaction causes a nucleus to decay. The neutron, for example, decays into a proton, an electron (beta ray), and an antineutrino.

BNL—Brookhaven National Laboratory, near New York City, which operates a 30 GeV synchrotron-type proton accelerator and is constructing the 400 GeV proton-proton colliding beam accelerator ISABELLE.

Bubble chamber—A particle detector in which the paths of charged particles are revealed by a trail of bubbles produced by the particles as they traverse a superheated liquid. Hydrogen, deuterium, helium, neon, propane, and freon liquids have been used for this purpose.

Cerenkov counter—A detector of Cerenkov radiation, which is electromagnetic radiation emitted by a charged particle when it passes through matter at a velocity exceeding that of light in that material. Cerenkov counters are used to identify charged particles.

Charm—The distinguishing characteristic of the fourth type of quark, also called the c-quark. Each quark is characterized by a number of properties including familiar ones like mass and electric charge and less familiar ones, which were arbitrarily given names like charm and strangeness.

Colliding beam accelerator—When a high energy particle collides with a stationary target, a large portion of the energy resides in the continuing forward motion. Only a small portion of the energy is available for creating new particles. In a colliding beam device, collisions take place between high energy particles which are moving toward each other. In such an arrangement, most of the energy is available for creating new particles.

Cyclotron—In this type of accelerator, magnets cause particles to travel in circular orbits and to pass repeatedly through a constant-frequency alternating electric field, which adds a small amount of energy each time the particles travel through it. In these low energy machines, the time for a particle to make one orbit is constant.

Deuterium—Heavy hydrogen, the nucleus of which contains one proton and one neutron.

Electromagnetism—A long-range force associated with the electric and magnetic properties of particles. This force appears to be intermediate in strength between the weak and strong force. The carrier of the electromagnetic force is the photon.

Electron—An elementary particle with a unit negative electrical charge and a mass $1/1840$ that of the proton. Electrons surround an atom's positively charged nucleus and determine the atom's chemical properties. Electrons are members of the lepton family.

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Electron volt—The amount of energy of motion acquired by an electron accelerated by an electric potential of one volt: MeV=million electron volts; GeV=billion electron volts; TeV=trillion electron volts.

Elementary particle physics—The area of basic science whose goal is to determine and understand the structure and forces of the most basic constituents of matter and energy.

Fermilab—Fermi National Accelerator Laboratory, near Chicago, which operates a synchrotron-type 500 GeV proton accelerator. The Fermilab accelerator and associated facilities are being upgraded to 1000 GeV.

Fission—A process in which the nucleus of a heavy atom such as uranium splits into two smaller nuclei, with the release of energy.

Fusion—A process in which two light nuclei are joined or fused together to make a heavier nucleus, with the release of energy.

Gamma rays—A term used for the energetic photons that are emitted in the decay of atomic nuclei and other unstable particles.

Gauge theory—A type of general theory of forces, modeled on the immensely successful modern theory of electromagnetism.

GeV—(Giga electron volt) - A unit of energy equal to one billion (10^9) electron volts. The abbreviation BeV has also been used for this amount of energy, but currently international usage prefers Giga for 10^9 .

Gravity—The weakest of the four basic forces and the one responsible for the weight of matter and the motion of the stars and planets.

Hadrons—The family of particles consisting of baryons and mesons. These particles all have the capability of interacting with each other via the strong force.

High energy physics—Another name for elementary particle physics. This name arises from the high energies required for experiments in this field.

ISABELLE—A colliding beams accelerator under construction at BNL. Two proton beams, each with proton energies up to 400 GeV, will collide with one another at six interaction regions where experiments will be performed.

J—A particle made of a c-quark (see "Charm") and an anti-c-quark. It is also called the psi particle and is three times as massive as the proton.

Lepton—A member of the family of weakly interacting particles, which includes the electron, muon, tau, and their associated neutrinos and antiparticles.

Linear accelerator—In this type of accelerator, particles travel in a straight line and gain energy by passing once through a series of electric fields.

Meson—Any strongly interacting particle which is not a baryon. Mesons are composed of quark-antiquark combinations.

MeV—(Mega electron volt) - A unit of energy equal to one million electron volts.

Molecule—A unit of matter made up of two or more atoms.

Muon—A particle in the lepton family with a mass 207 times that of the electron and having other properties very similar to those of the electron. Muons may have positive or negative electric charge.

Neutrino—An electrically neutral and massless particle in the lepton family. The only force experienced by neutrinos is the weak force. There are at least three distinct types of neutrinos, one associated with the electron, one with the muon, and one with the tau.

Neutron—An uncharged baryon with mass slightly greater than that of the proton. The neutron is a strongly interacting particle and a constituent of all atomic nuclei, except hydrogen. An isolated neutron decays through the weak interaction to a proton, electron and antineutrino with a lifetime of about 1000 seconds.

Nucleus—The central core of an atom, made up of neutrons and protons held together by the strong force.

Particle—A small piece of matter. An elementary particle is a particle so small that it cannot be further divided—it is a fundamental constituent of matter. Quarks and leptons now appear to be the only elementary particles, but the term is often used in referring to any of the subnuclear particles.

Particle detector—A device used to detect particles which pass through it.

Photon—A quantum or pulse of electromagnetic energy. A unique massless particle that carries the electromagnetic force.

Positron—The antiparticle of the electron.

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Proton—A baryon with a single positive unit of electric charge and a mass approximately 1840 times that of the electron. It is the nucleus of the hydrogen atom and a constituent of all atomic nuclei.

Psi—A particle made of a c-quark (see "Charm") and an anti-c-quark and three times as heavy as the proton. It is also called the J particle.

Quantum Chromodynamics—A theory which describes the strong force among quarks in a manner similar to the description of the electromagnetic force by quantum electrodynamics.

Quantum Electrodynamics—The theory which describes the electromagnetic interaction in the framework of quantum mechanics. The quantum of the electromagnetic force is the photon.

Quantum Mechanics—The mathematical framework for describing the behavior of photons, molecules, atoms, and subatomic particles. According to quantum mechanics, the forces between these particles act through the exchange of discrete units or bundles of energy called quanta.

Quark—One of a small family of particles which may be truly elementary. All hadrons are believed to consist of combinations of quarks or quarks and antiquarks.

Synchrotron—A type of circular particle accelerator in which the frequency of acceleration is synchronized with the particle as it makes successive orbits. The time to orbit the machine decreases with the increase in particle energy.

SLAC—Stanford Linear Accelerator Center in Stanford, California, which operates a 23 GeV electron linear accelerator and an electron-positron colliding beams system with 4 GeV beam energies. A new electron-positron colliding beam facility (PEP) with 15 GeV beam energies is under construction.

Strange particle—The name given to particles thought to contain just one s-quark (strange quark). The remaining quarks in strange particles are either u or d quarks.

Strong force—A short range force which dominates the behavior of interacting mesons and baryons and accounts for the strong binding among nucleons.

Tau—An elementary particle in the lepton family with a mass 3500 times that of the electron but with similar properties. There are positive and negative tau particles.

TeV—Tera electron volt, a unit of energy equal to one thousand billion (10^{12}) electron volts.

Upsilon—A particle believed to be made up of a b-quark and an anti-b-quark. It is approximately ten times as massive as the proton.

Weak force—A short range force which governs the production and decay of many nuclear and subnuclear particles. It is much weaker than the strong force but stronger than gravity. In the gauge theory, the carrier of the weak interaction has a mass about 80 times the proton mass.

X-rays—Photons produced when atoms in states of high energy decay to states of lower energy.