The drawback is that only limited kinds of experiments could be carried out with such beams.

Meanwhile, in the lower energies, but still in the tens of billions of electron volts, three countries are considering proton accelerators in the 40 to 45 Bev range, with their chances of funding an open question. Japan aims at 42 Bev, France at 45 and West Germany at 40.

Although scientists see justification for the Japanese machine because of Japan's geographical isolation and its need to build a sound base in high energy nuclear physics, many question the wisdom of spending money on the French and West German accelerators, already outclassed by the Russian 70 Bev even before they are out of the design stage.

All of these machines accelerate protons, but in the range above one billion electron volts there is also a whole host of large instruments, mainly for electrons, but at least one for neutrons—Canada's Intense Neutron Generator—and one that could be adjusted for any nuclei ranging from hydrogen to uranium—the Omnitron at the University of California.

Electron Accelerators

	Status	Energy (Bev)
Germany		
1. Bonn	1967 in use	2.3
2. Hamburg	1964 in use	6.25
Italy		
3. Frascati	1959 in use	1.1
Japan		
4. Tokyo	1961 in use	1.3
Sweden		
5. Lund	1960 in use	1.2
USSR		
6. Yerevan	1967 test	6
7. Tomsk	1964 in use	1.3
UK		
8. Daresbury	1966 in use	4
USA		
9. Cambridge	1962 in use	6.28
10. Cal Tech	1952 in use	1.5
11. Cornell	1964 in use	2.1
12. Cornell	1967 test	10

Oak Ridge National Laboratory

Virtually all proton accelerators are circular, as are the high energy electron machines. However, there are some, notably the two-mile LINAC at Stanford University, in a straight line.

Scientists now estimate that, for large accelerators, the cost is about $2 million per billion electron volts.

Whether straight or circular, all accelerators operate generically in the same way. The particles are injected into an evacuated tube, sped along by the application of external energy at short intervals, focused into a tight beam by magnets, then hurled at a target to see what nuclear debris results. From such nuclear footprints scientists have learned much (but never enough) about the structure of matter.

To observe subatomic particles, physicists use the scattering of radiation. X-rays and gamma rays, actually different names for a photon of light, or quantum, gave scientists their first method for checking on the reactions taking place within atomic nuclei, long before man-made accelerators were built. Now they use beams of particles generated to carefully controlled energies.

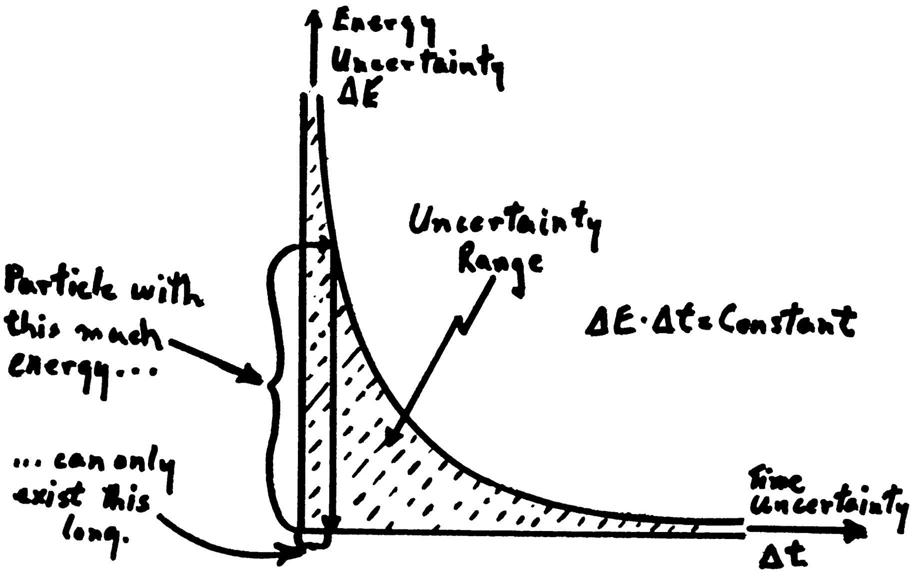
When nuclear particles are used as light to examine fine details of nuclei, their wavelength is of utmost importance—that of the bombarding particle must be sufficiently short to show structural detail.

The higher the energy, the shorter the wavelength; that is why machines of higher energy are needed to unlock the basic secrets of the structure of matter. Scattering enters because nuclear particles cannot be seen directly, but their existence and properties can be deduced from the way the incident radiation, the bombarding particles, is scattered by the target nuclei.

Scattering is a general term given to the collisions between two or more particles. There are two kinds: elastic and inelastic.

In elastic scattering, the particles react somewhat like billiard balls, ricocheting off each other but leaving the point of interaction with the same overall energy of motion. In inelastic scattering, one or more of the particles absorbs some of the incident energy, either raising it to a higher energy state or forming an entirely new particle. Energy has been changed into mass.

The more massive the particle being created, the higher the price tag, both in terms of energy and money. ◈



Meson creation: energy conservation can be broken if lifetime is short.

THE THEORY

Plethora of particles

Theorists look to higher energies for clues in their search for simplicity

by Carl Behrens

At a recent Washington, D.C. meeting of the American Physical Society, Dr. Murray Gell-Mann spoke before a huge crowd of scientists. Using complicated mathematics he described his efforts in past months to simplify and organize his theoretical picture of the world of elementary particles.

"It's not as simple as we hoped it might be," he concluded. "We'll have to change the picture and try again."

Theoretical physics has never been simple, but some stages are more puzzling than others. Right now, physicists are faced with an uncomfortable amount of information, with no clear way of fitting it all together in a simple pattern.

Most of this information has come from experiments with high energy accelerators. And the common belief among high energy physicists is that much higher energies are going to be needed before a really simplifying principle is upheld.

High energy physics is clogged with several major problems:

- Too many "particles we might do without," as one text on the subject puts it. The population of unexplained particles has risen to more than 200.
- Too many unexplained rules. Physicists have found that particle interactions take place so that certain quantities or factors remain unchanged; but why those factors are conserved remains a mystery.
- Too many theories or models that explain some phenomena well but don't extend to others, and don't lead to simplifications the way earlier theories have.
- More difficult experimental problems, coming from the need to measure shorter distances, shorter times and stronger forces.

Four kinds of forces operate on the particles that make up the physical world: electromagnetic, nuclear forces, both strong and weak, and gravity, which so far is of little significance to particle physicists.

Particles are characterized by having either a net unit electric charge—the charge on an electron—or no charge at all, but never a fractional charge. A charged particle always exerts an electric force on other charged particles; when it is moving, it also exerts a magnetic force. Both kinds of force arise from the charge, and act together as electromagnetic force.

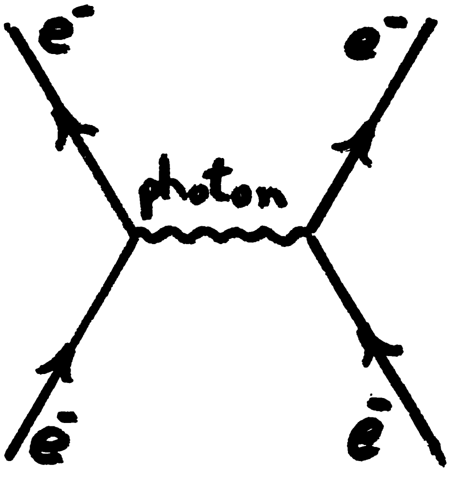
During the first four decades of this century, the nature of electromagnetic forces was elaborated to a highly satisfactory degree, using the theory of quantum mechanics. With it, atomic structure and the table of chemical elements were clarified and explained, atoms were described and chemical reactions were seen to be electromagnetic in character.

Electromagnetism's quantum theory also explained the nature of light, a problem that had bothered physicists for centuries. Light was seen to be a combined electric and magnetic field, propagated through space as a wave.

In the process of explaining how the force worked, however, physicists had to accept some concepts about the nature of matter that appeared to run wildly against common sense.

- Light was found to act sometimes like particles, other times like waves. The only way to resolve this difficulty was to invent a particle, called a photon, that had no mass but contained energy and moved at a fixed speed with a wave motion.
- Not only do massless particles like photons move like waves; to explain what they see physicists later had to conclude that all matter does. The frequency of the wave motion depends on the mass and velocity of the body, and for anything larger than an atomic particle, the frequency of vibration is too high to be detected, which is why the phenomenon had never been observed.
- Matter—mass—is interchangeable with energy; it can be destroyed or created.

These and other assumptions explain the behavior of electromagnetic forces. But these theories themselves created problems where the atom's nucleus is concerned: Since electromagnetic theory dictates that like electric charges repel each other, why don't the protons in the atomic nucleus fly apart? Some other, stronger forces must operate within the very short distances of the nucleus, forces which disappear as distances increase.



Electrons swap a photon, separate.

In the 1930s and '40s nuclear forces became the frontier of research. To study them, physicists built accelerators: machines that would hurl particles at a nucleus fast enough to overcome the electromagnetic forces and get within nuclear force range.

At the same time, theorists tried to extend their successful electromagnetic theory to nuclear forces. Electromagnetic forces are carried by photons: one charged particle emits a photon and another absorbs it. Nuclear forces might also be carried by particles.

By postulating the right kind of energy-carrying particle—the nucleus' equivalent of a photon but having mass—theorists could explain the forces and why they extend only a short distance.

Two rules are involved: conservation of energy and the uncertainty principle.

According to the law of conservation of energy, any event must end up with the same amount of energy—including mass, a form of energy—as it started with.

The uncertainty principle qualifies that. It derives from the wave nature of matter, which sets a limit on the precision with which events can be measured. In one form, this uncertainty principle says that the energy of a particle can be known precisely over a fairly long time, as high energy time goes, but if the time period is shortened, the energy measurement becomes more indeterminate.

If a neutron or proton is to exert nuclear force by giving off a particle, energy conservation gets in the way: Where is the mass of the particle to come from? But suppose the particle—called a meson—exists for only a very short time. Then uncertainty enters, the energy of the system can't be measured as precisely, and energy conservation could be violated to the extent of that imprecision.

Theorists computed how much energy would be needed to create a meson, and how much time they can permit to elapse before they lose the energy uncertainty which the theory allows. In that time a meson could travel only a limited distance—and the distance a meson is able to carry energy is the distance over which a nuclear force could operate, they theorized.

It would be impossible to detect such a meson. But if enough energy were added to the system, by accelerating a proton and aiming it at another, then some of that energy could go to create the mass of a meson legitimately, without violating the energy conservation rule. In that case, it might exist long enough to be detected.

Accelerator experimenters did find a particle that would fit the role of the meson, in 1948. But with it, they discovered a Pandora's box of other particles whose function could not be explained.

At the same time the strong nuclear forces holding the nucleus together were being described, another force was found necessary to explain the behavior of some of the new particles being discovered. These weak forces—stronger than gravity but weaker than electromagnetic forces—were found to cause particles to decay or split into other particles. They were first identified as differing from strong forces in the explanation of a common phenomenon—the fact that some radioactive atoms give off electrons when they decay. The electron, goes the explanation, comes from the splitting up of a neutron within the nucleus of the atom. A proton and another particle called an anti-neutrino are also formed from the reaction. But the force that causes the neutron to split is much weaker than the strong forces holding the nucleus together.

Since the explanation of neutron decay, many particles have been found to be subject to weak forces, or undergo weak interactions, as the process is usually described. They constitute another field of inquiry in which physicists can hope to find answers to their questions.

High energy physics in recent decades has been concerned with identifying the particles created in collisions, defining their characteristics such as mass, charge, and spin, and trying to find rules which will predict how they will be created and destroyed, and how they act during their short lifetimes. Theorists have managed to group particles with similar intrinsic properties into groups of eight or 10, called symmetries. But the number of particles—upward of 200—and the complications involved make the explanations unsatisfactory to physicists who believe that simple explanations must exist.

One simple theory is that all the particles discovered are made up of even more basic particles, called quarks, a name assigned by Dr. Gell-Mann. By assuming three kinds of quarks, with charges of one-third or two-thirds the unit charge, along with three "antiquarks" with opposite charges, all the known particles and their properties could be explained by supposing that they were composed of either two or three quarks and antiquarks.

This attractively simple idea has been stymied by the fact that no quarks have ever been detected. There is an additional problem that no particle has ever been found to have a charge less than the electron's—which a quark must have. But since physicists don't know why charge always comes in unit size, it would not upset them to find that it didn't.

Physicists say that if quarks do exist, they will have a very large mass. Present estimates range between five and 10 Bev, three to six million times the mass of a proton.

The argument goes like this: a proton is supposedly made up of three quarks. Since the proton has much less mass, the excess mass of the quarks when they combine must go into energy which holds the proton together. It would take an equivalent amount of energy at the center of the proton to break it into quarks again.

The world's largest accelerator, the 33 Bev AGS at Brookhaven, can put eight Bev energy at the center of a proton: less than three Bev per quark. Since no quarks have been detected in such experiments at Brookhaven, quarks must have at least 2.67 Bev mass, and a beam stronger than Brookhaven's would be necessary to spring them loose.

Other experiments have been carried out using cosmic rays, another source of high energy particles. If quarks are created in outer space, they should be detectable on earth at a certain rate, depending on how hard they are to create, which again depends on how much mass they have.

A recent experiment by Dr. George Zweig and other scientists at the California Institute of Technology tried to detect quarks with very sensitive spark chamber equipment. Out of 150 million cosmic ray particles detected, not one was a quark. As a result of this and other experiments both here and abroad, the probable mass of the quark, if it exists, was pushed up to between five and 10 Bev.

The search for quarks in accelerators, where experimental conditions are much easier to control, will have to wait for higher energies—one of the major reasons physicists are interested in planned 200 and 300 Bev machines.

Another reason is that nuclear forces are explained by the meson-exchange theory at energies now available, but that theory also predicts certain results at higher energies. If these predictions are supported by experiment, it will reinforce the theory; if something unexpected happens, then the theory would again have to be revised.

A third intriguing prospect is the study of the elusive neutrinos and antineutrinos—having no mass and no charge—which result from weak interactions and can be found more readily at the higher energies.

All these experiments will be interesting. But "the most interesting will be the ones we can't think of now," says Dr. Charles A. Snow of the University of Maryland. "It's always that way." ◆

FROM SCANDINAVIA

The hope for small nations—

Nordic physicists see regional cooperation as their only hope as costs spiral and backwaters become permanent.

A decade ago Swedish high energy physicists planned a 1.2 Bev electron synchrotron at Lund University. National aspirations were still alive. This accelerator, had it been completed on time, would have led the world.

Today the Swedish high energy physicists and their colleagues in the other Nordic countries have no illusions. The Lund accelerator, dogged by administrative and development delays, has long ago been outclassed elsewhere. Its future, probably, is as a useful piece of training equipment.

The future of experimental work lies in international cooperation, both in Europe and within Scandinavia. "We have been able to work on a university scale up to now," says Prof. J. K. Bøggild of the Niels Bohr Institute in Copenhagen, "but it is a necessity to work together now."

For the experimentalists this is a simple matter of survival. For the theorists it is slightly less crucial—wherever two or three physicists are gathered together there is the possibility of the fruitful fusion of ideas—but in the small Nordic countries (Sweden, population 7.6 million, is the biggest) a flourishing person-to-person international exchange of ideas is more and more being seen as a condition of producing top class work.

International cooperation as such is nothing new, of course. The Bohr Institute has always been dedicated to facilitating research across national frontiers and there are today scientists from Red China working in the same building in Copenhagen with researchers from the United States. But at the moment high energy physics in Scandinavia is going through a period of adjustment to a more intense kind of cooperation. Bohr's moral idealism has been supplemented by practical necessity, but cooperation comes hard.

For experimentalists, especially, things are uncertain. The prospects are inviting. Like their colleagues in the rest of Europe they are dreaming of getting to work with the CERN storage rings and the projected 300 Bev accelerator. Meanwhile they are groping their way forward to more efficient cooperation among themselves, and the path is not always straightforward.

At the Bohr Institute work proceeds on the analysis of bubble chamber pictures. The pictures were taken at CERN in Geneva as part of a joint Nordic experiment involving 30 scientists. Part of the significance of working together can be judged from the fact that this was the first time that the