CERN Sets Intermediate Vector Boson Hunt

To find this key particle of unified quantum field theories, the laboratory first had to learn how to produce and store intense beams of antiprotons

Geneva. The Super Proton Synchrotron (SPS) is the flagship accelerator among several machines of the European Organization for Nuclear Research (CERN). It stretches nearly 7 kilometers in forming an almost circular hexagon that crosses from Switzerland into France and back again in the countryside near here. Unlike a very similar machine at the Fermi National Accelerator Laboratory that is plainly visible to an air traveler flying west out of Chicago, the SPS would never be noticed by the casual visitor because it lies some 40 meters underground and is covered by woodland and, in spring, by bright yellow fields of mustard.

Near the eastern edge of one such clump of woods next to one of the accelerator's six straight sections (at about the 4 o'clock position if the SPS were a clock face) lie two giant circular shafts 20 meters in diameter descending to an underground experimental hall. Peering over the edge of one of the shafts, an observer halfway expects to meet the nose cone of a waiting missile. Instead, workers far below are busily preparing an elementary particle detector that will weigh over 2000 tons and will cost in the neighborhood of 40 million Swiss francs ($20 million) when completed this fall.

The detector is part of a 200-million-Swiss-franc undertaking to convert the SPS into the world's first proton-antiproton colliding-beam storage ring and in the process make it also the most energetic machine ever. Protons at 270-billion electron volts (GeV) will collide head on with antiprotons of the same energy, thereby providing a collision energy (540 GeV) as great as that extractable from a conventional fixed-target proton synchrotron of 155,000 GeV, a machine that would be inconceivable to build.

Last June the SPS was shut down to begin the conversion process from a synchrotron to a storage ring and to allow digging the underground experimental hall and another similar one to house a second large detector. In April, CERN scientists successfully obtained collisions between protons and antiprotons in a smaller machine, the Intersecting Storage Rings (ISR), that was built a decade ago to study proton-proton collisions. The SPS itself has just reopened for initial testing as a colliding-beam machine. And by this fall, physicists expect to commence hunting the intermediate vector boson, the one particle that they must find if current hopes for a unified theory of all the forces that affect elementary particles are not to be dashed.

The search for the intermediate vector boson dates back to the 1930's when the Japanese physicist Hideki Yukawa proposed a similar particle. At the time, the quantum field theory of the electromagnetic force (quantum electrodynamics or QED), although yet to be fully worked out, was nonetheless well established. The massless photon carried the electromagnetic force between electrically charged particles, according to QED. Yukawa postulated that analogous particles should exist in properly developed quantum field theories of the other two forces that are active in the world of elementary particles: the strong nuclear force that binds nuclei together and the weak force that governs many decay processes. Because both of these forces operate only over distances comparable to the size of nuclei, Yukawa further suggested that, unlike the photon, these particles should have rest masses. A mass would limit the distance they could travel before decaying and would thus determine the range of the force being transmitted. In quantum field theories, all of the particles that carry forces belong to the vector boson category, which is defined by certain properties that vary from one class of particles to the next.

In the modern conception, the strong nuclear force binds quarks together to form elementary particles such as protons and neutrons. A massless vector boson called the gluon (actually there are eight of these) carries this force, which has an infinite range. The most persuasive evidence for gluons was accumulated over the last 2 years by several groups working at the Deutsches Elektronen-Synchrotron laboratory in Hamburg, West Germany (*Science*, 26 June, p. 1488). The "old" strong nuclear force that holds the nucleus together is, in effect, a remnant of the quark binding force, although there is as yet no satisfactory theory for how it is that pions (discovered in 1947) with a mass of 0.14 GeV become the vector bosons that carry this remnant force, which extends only over 10^{-13} centimeter.

But it is the weak force that is the center of all the commotion at CERN these days, because the vector boson that transmits this interaction has never been found. In the late 1960's and early 1970's, several theorists made significant contributions to the construction of the now "standard" model of the weak force. The theory makes fairly specific predictions for the masses of *three* vector bosons involved in the weak force. A neutral particle (the Z^0) has a mass of about 90 GeV, while two positive and negative electrically charged bosons (the W^+ and W^-) are just under 80 GeV, giving a range of about 10^{-15} centimeter for the weak force. The revamped SPS proton-antiproton collider will be the first accelerator with enough energy to produce these particles.

There is more. The theory is not simply a model of the weak force; it also describes how to unify the electromagnetic and weak forces. In our world, the two forces are clearly distinct. But in a more "symmetrical" world, such as that conjectured to have existed in the early moments of the universe just after the Big Bang, the two were alike both in strength and in character. There were four massless bosons to carry this undifferentiated force. As the universe expanded and cooled, a "symmetry-breaking" mechanism came into play that caused the two forces to appear as separate interactions, and the four bosons split into the three particles that carry the weak force and the photon.

The electro-weak theory purports to explain how all this came about. And the symmetry-breaking mechanism invoked in the theory has also been incorporated into so-called grand unified theories that include the strong nuclear force as well. When the early evidence for gluons emerged two summers ago, an ecstatic Leon Lederman, the director of Fermilab, exclaimed to the press, "Now we're beginning to see how it's all put together." If physicists at CERN do not see the three vector bosons at the predicted energies, Lederman's statement will be,

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in the once-popular jargon, inoperative.

It is not the whole edifice of elementary particle theory that would fall by the wayside. Quantum field theory as the correct way to describe particles and forces would survive. And other symmetry-breaking mechanisms are possible besides the one developed by Steven Weinberg of Harvard University and by Abdus Salam of Imperial College London that is incorporated in the electroweak theory. But the emotional investment in the currently favored scheme is immense. Unification—all of nature described by a single force—is like the Holy Grail to particle physicists, and they would be deeply disappointed to have to start their quest again from the beginning after seeming to come so close.

CERN's role in the soon-to-begin hunt for the three weak force vector bosons had its origin in 1976 when Carlo Rubbia, who divides his time between Harvard and CERN, David Cline, who does the same for the University of Wisconsin and Fermilab, and Peter McIntyre, who is now at Texas A & M, proposed a proton-antiproton collider. In separate interviews, Cline and Rubbia recalled for *Science* what the thinking was at the time. By the mid-1970's several important experimental results from accelerator centers in both the United States and Europe caused high energy physicists to take the unified electro-weak theory more seriously than they had before. But the most crucial tests would require the production of the intermediate vector bosons themselves, and these were predicted to be too massive to be produced in any existing machine. Rubbia says that several alternatives were considered that involved accelerators then in the planning or even preplanning stage, such as ISABELLE (a magnified version of CERN's ISR, now under construction at Brookhaven National Laboratory, which will smash two 400-GeV beams of protons into one another) and LEP (an electron-positron colliding-beam storage ring with a total collision energy expanding from 100 GeV at first to about 260 GeV later, for which CERN is only now close to getting approval). But at that time it would be 10 to 15 years before these machines would be operating, too long to wait in view of the intense excitement building up over the unified electro-weak theory.

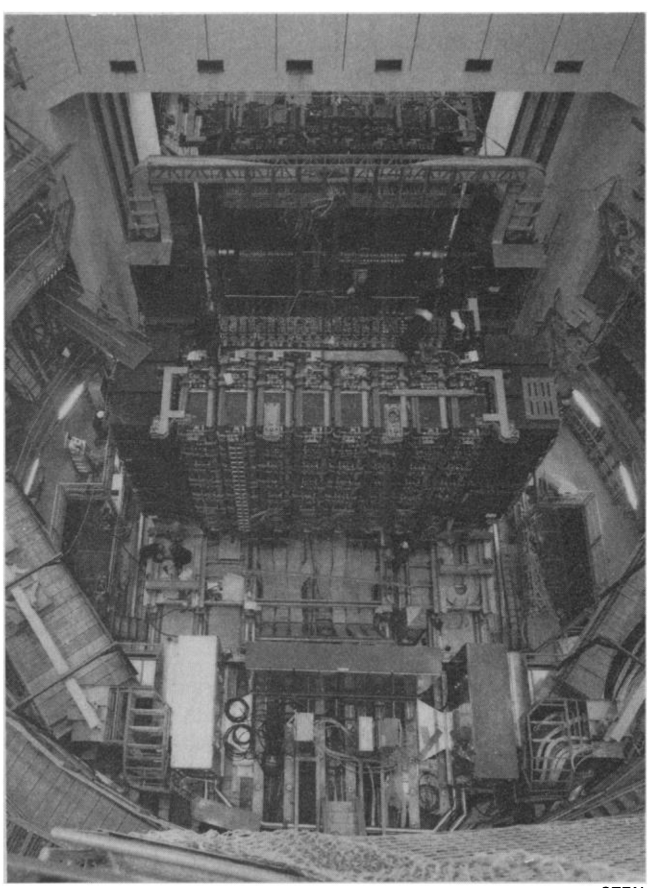
So attention turned to the possibility of modifying an existing accelerator, the most logical candidates being the proton synchrotrons at Fermilab (500 GeV) and CERN (450 GeV). As fixed-target machines, the effective collision energy extractable (and thus the most massive particle producible) was a bit over 30 GeV. But if a second beam of particles, antiprotons, were circulated in the same ring in the opposite direction, the collision energy would be twice the energy of each beam. And it would not be necessary to build an entirely new accelerator.

Although there may be up to a trillion or so particles in the packets that constitute a beam in a storage ring, the particle density is not large, about 10^{15} per cubic centimeter. In short, the particles do not collide nearly as often as in fixed-target accelerators where there is a solid or liquid target. However, if the beams are circulated for several hours, then eventually a significant fraction of the particles will be used up. But this mode of operation imposes stringent requirements on the vacuum in the beam pipe and on the magnets that guide and confine the particles in the storage ring that fixed-target machines, where there is just one beam that lives only a few seconds, do not have to meet. CERN's SPS was so well designed (Rubbia says "overdesigned") as a synchrotron that it would serve nicely as a storage ring. Fermilab's accelerator, which was built rapidly and under severe budget constraints, would require extensive modifications to have storage ring capability.

Rubbia notes that the CERN proton-antiproton collider is expected to produce about one intermediate vector boson every few hours. Even at this rate, the price tag of 200 million Swiss francs could buy several years of interesting physics. Perhaps it was for this reason that CERN's co-Directors General at the time, John Adams of Great Britain and Leon van Hove of Belgium, got behind the project immediately and energetically supported it. Rubbia gives them credit for "taking a hell of a chance" because many physicists were skeptical at first and said so.

In the meantime, under former director Robert Wilson, Fermilab opted to build a new ring to fit in the same tunnel as its proton synchrotron. The use of high field superconducting magnets would enable a proton beam to reach 1000 GeV without an increase in the size of the ring, which would also be of high enough quality to serve as a storage ring for protons and antiprotons to collide at this energy. The colliding-beam part of the project could be operational in 1984.

Actually, there was a second reason for CERN's being able to get the jump on Fermilab. The Geneva laboratory was able to build its machine within its existing budget, thus obviating the need for a lengthy review process, whereas Fermilab had to enter into competition with other U.S. laboratories for funds.


CERN

UA-1 detector

Detectors at CERN are jointly financed by the laboratory and by the institutions from which the members of the research teams come. Carlo Rubbia's UA-1 magnetic detector, shown here in an underground experimental hall, is the only one of the proton-antiproton experiments built with American participation. There are 100 members in the collaboration, coming from the universities of Aachen, Birmingham, Rome, and Vienna, from Queen Mary College (London) and the Collège de France (Paris), from the Annecy Particle Physics Laboratory, CERN, the Rutherford Laboratory, and the Saclay Nuclear Research Center, and from the University of California at Riverside.

In addition to the prospect of getting a jump on Fermilab, one development that undoubtedly helped make up the minds of the CERN directors was a series of successful 1976 tests, in CERN's ISR, of stochastic cooling, a technique for producing compact beams of antiprotons with each particle having nearly the same energy and momentum. Up to that time, no one was confident of being able to make such antiproton beams.

The problem stems from the fact that the antiprotons, produced by bombarding a metal target with a high energy proton beam, tend to have a wide distribution of energies and momenta. With respect to the uniform motion of a beam in a circular accelerator, the particles dance about like molecules in a hot gas. The question is how to cool them down. One way was invented by the late Gersh Budker at the Soviet Union's Institute of Nuclear Physics at Novosibirsk. A "cool" beam of electrons (all with the same energy and momentum) passes in parallel with the antiproton beam for a short distance. As in mixing a hot and cold gas, some of the "heat" of the antiprotons gets transferred to the electrons. Repeating the process millions of times with fresh electron beams soon cools the antiprotons sufficiently, if their energy is not too high (about 0.2 GeV or less). Unfortunately, the process does not work well with high energy antiprotons (3.5 GeV) as produced at CERN.

CERN's solution was invented in 1968 by one of its own physicists, Simon van der Meer. Van der Meer's innovation, stochastic cooling, involves the use of a sensing device at one spot on a storage ring to generate an electrical signal proportional to the deviation of the particles from the ideal orbit. Since so many particles pass by at once, the signal consists of a portion that represents the average position or velocity of all the particles plus a part that looks like noise, which corresponds to various motions of the individual particles. The signal races across the ring, arriving before the particle beam that has to travel around the ring, to a second "kicker" device, which generates a voltage that is used to adjust the particle position or velocity. Some particles are knocked into a more ideal orbit and others bumped into a poorer one. But on the average, if the electronics are correctly adjusted, the beam is cooled. Although the idea sounds simple enough, stochastic cooling was a conceptual breakthrough. At first glance, van der Meer told *Science*, it appears to violate a fundamental principle of statistical mechanics (Liouville's theorem) that accelerator designers had construed as prohibiting cooling of a particle beam by an electric or magnetic field. The use of the sensing device in effect provides information about individual particles and thereby overcomes the limitations of Liouville's theorem, which applies to a continuous statistical ensemble only.

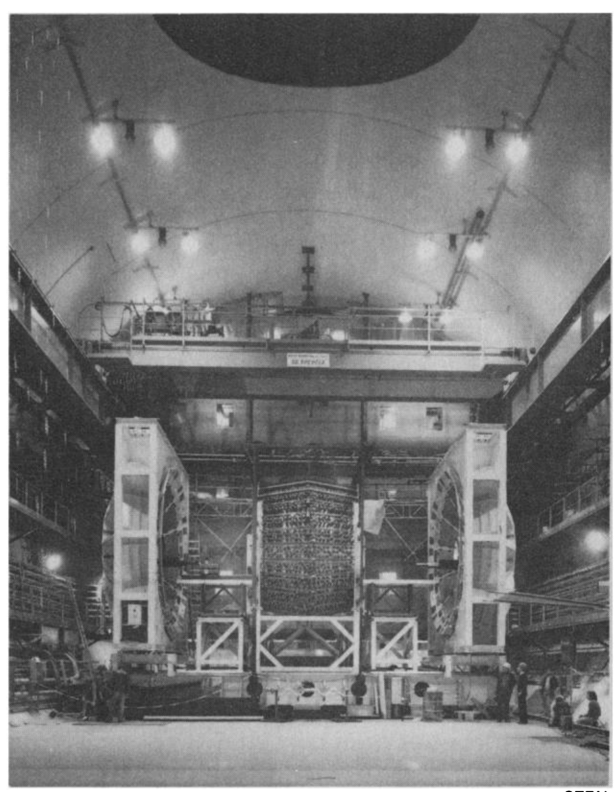
The first stochastic cooling experiments were in 1974 in the ISR and were aimed at better control of the proton beams in that machine. But the interest gradually shifted to antiprotons. After the 1976 experiments, which were done with protons, van der Meer, Rubbia, and Guido Petrucci of CERN modified an older and smaller machine for tests with antiprotons as well as protons. Among other accomplishments of this device, which was called the Initial Cooling Experiment or ICE, was the 1978 demonstration that it was simultaneously possible to bring together the velocities of particles moving with different speeds and to reduce the horizontal and vertical excursions of particles away from the ideal orbit. A similar test also established a new record for the antiproton lifetime of 86 hours (in theory the lifetime is the same as that of the proton—which is, for all intents and purposes, infinite—but antiprotons are annihilated immediately on touching ordinary matter, so that establishing the decay time is not trivial).

Next on the agenda was the construction of an all-new 50-million-Swiss-franc machine, the Antiproton Accumulator, the construction of which was headed by van der Meer and Roy Billinge of CERN. The purpose of this accelerator is the building up of a beam of nearly a trillion 3.5-GeV antiprotons. These particles are then injected into the SPS's predecessor synchrotron (the PS) where their energy is boosted to 26 GeV. From the PS the antiprotons go to the SPS. The accumulator is different from other machines in that it has a very wide beam pipe. A burst of some 10 million antiprotons from a tungsten metal target bombarded by a pulse of 10 trillion 26-GeV protons from the PS enters the accumulator, where the antiprotons are partially cooled. After the first cooling step, the antiprotons are nudged from a smaller radius orbit to a larger radius orbit where further cooling takes place. At the same time, the second antiproton pulse enters the accumulator and the process is repeated at intervals of 2.5 seconds. After each repetition, the number of antiprotons in the outer orbit grows until, after about 24 hours, the final count of 6×10^{11} antiprotons is reached.

The accumulator, which took about 2 years to construct, was put into operation last July. For reasons that are not yet fully understood, the maximum number of antiprotons that can be crammed into one beam has been limited to about 10^{11}, according to Michael Crowley-Milling of CERN. The main effect of this deficiency is that the number of proton-antiproton collisions in the SPS will be down by the same factor, and this will

UA-2 detector

Pierre Darriulat's UA-2 experiment was not in the original plans for CERN's proton-antiproton collider project and so it is in an earlier stage of construction than the UA-1. At the top of the photo, one can see the shaft through which all large pieces of equipment must be lowered to the exceptionally deep (63 meters) underground experimental hall. The 44 members of the UA-2 collaboration come from the universities of Bern, Copenhagen, and Pavia and from CERN, the Orsay Linear Accelerator Laboratory, and the Saclay Nuclear Research Center.



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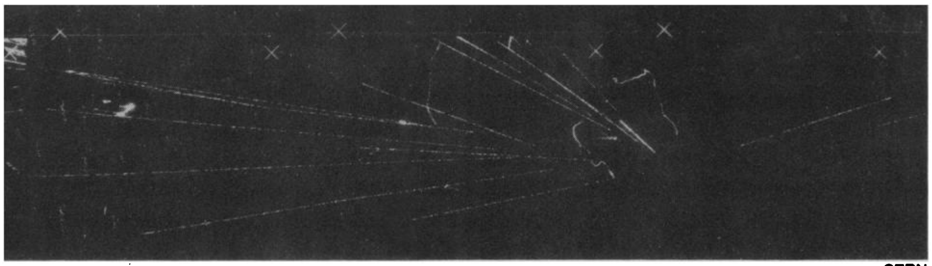

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Streamer chamber photograph of first proton-antiproton collisions in the ISR

limit the rate at which data can be collected at first.

Actually, the first test of proton-antiproton collisions has already taken place. CERN physicists guided 26-GeV proton and antiproton beams into the ISR, where for the first time in an accelerator, these particles smashed head on into one another on 4 April. The antiproton beam was a thousand times weaker than the proton beam, and no new physics is expected in the early runs. As performance improves, the plans are to have a full antiproton research program in the ISR in parallel with that in the SPS.

But CERN physicists are mostly looking forward to this autumn when proton-antiproton collisions in the SPS are scheduled to begin. Erwin Gabathuler, one of the laboratory's two research directors, told *Science* that the first collisions could come as early as August, but that there will be a period of machine testing until November. (At least one detector will be in place, however, to gather early data.) Following a 2-week shutdown, experiments will commence in earnest "whatever the luminosity," says Gabathuler. Luminosity is a critical machine characteristic because it describes the frequency of collisions. The collider is designed to reach a luminosity of 10^{30} cm^{-2} sec^{-1}. At present, the lower than hoped for number of particles in the beam constructed by the Antiproton Accumulator will reduce this value. But Gabathuler points out that the collision energy in the SPS will be ten times higher than that in the ISR and that therefore, "Even if the luminosity is only 10^{26}, we will go ahead." On the basis of the performance of the Antiproton Accumulator ring, he expects a luminosity of at least 10^{28} and hopes for 10^{29}.

The vector bosons are created when a quark in a proton and an antiquark in an antiproton collide and annihilate, making a miniature fireball of pure energy in the process. The energy can rematerialize as any of several particles, subject to certain constraints, including the vector bosons. These entities live only the briefest of instants before decaying into more conventional particles. It is by the decay products that physicists will determine whether vector bosons were created and what their properties are. The nice thing about the vector bosons, says Cline, who is journeying to Geneva for a 6-month stay beginning this October so "I can be there when they find the vector bosons," is that they have rather distinctive decay products. Thus, although there is a very large background of extraneous events that will make accumulating good statistics a lengthy process, the few events needed to signal the presence of the vector bosons will come rather quickly, perhaps by Christmas.

Rubbia notes that the full 540-GeV collision energy will not be available to one annihilating quark-antiquark pair because this energy must be divided between the six particles and the gluons that hold them together in the colliding proton and antiproton. The result is that the effective collision energy will not be greatly in excess of that needed to produce an intermediate vector boson, and their production rate will be low, even with the full 10^{30} cm^{-2} sec^{-1} luminosity, compared to the rate in LEP, where the particles may come every 10 seconds or so. Gabathuler calls the proton-antiproton collider a poor man's LEP both for this reason and for the lower cost. The first (100 GeV) phase of LEP is estimated to cost 950 million Swiss francs.

The job description of accelerator center administrators apparently requires them to be optimists. If the luminosity of the collider should at first turn out to be significantly lower than 10^{29}, other experiments remain feasible, says Gabathuler. If the figure were 10^{28}, for example, it might be possible to measure the mass of the much sought top quark by the end of the year. Not finding this particle would not be as catastrophic as failing to see the intermediate vector bosons, because the unified theory can be modified to encompass its absence. Nonetheless, uncovering signs of the top quark would be a major discovery.

To look for vector bosons, top quarks, and whatever else may turn up in the proton-antiproton collider, five mainly European collaborations are building detectors to place in the two spots around the SPS ring where experimental halls are being completed. Two of the research teams have designed large, general-purpose detectors. Rubbia, who heads the UA-1 collaboration, says modestly that his instrument is rather conventional in design and follows the lead set in the 1970's by physicists working at Stanford's first electron-positron storage ring. The idea is that, since collisions are rare and the resulting event rate is much smaller than in fixed target machines, it is too expensive to have many specialized detectors. Instead, "We build the biggest magnet we can afford and try not to miss a thing," says Rubbia.

The second large detector is being built by the UA-2 collaboration headed by CERN's Pierre Darriulat. Like UA-1, this group primarily wants to find and study the vector bosons. But there is also considerable interest in a phenomenon called jets. Jets means that particles emanating from a collision do not come out uniformly in every direction. Instead they tend to come in a few groups, each containing several particles all going in about the same direction. This behavior is required by quantum chromodynamics, the theory of the strong nuclear force, and its study is a principal means of verifying the theory.

Alternating with the UA-2 detector will be the UA-5 streamer chamber. The experimental hall and the detectors are constructed in such a way that the smaller UA-5 can be lifted over the UA-2 instrument, which in turn can be moved on air cushions into place around the SPS beam pipe or wheeled away to make room for its partner. The UA-5 group is interested in exotic events of the type seen in several recent cosmic-ray experiments. The proton-antiproton collider is the first accelerator to give collision energies comparable to those occurring when cosmic rays smash into the nuclei of gas molecules in the upper atmosphere. It is the UA-5 instrument that will be in place when the first collider test runs start up in August or September.

UA-3 and UA-4 are smaller, more specialized experiments that can run at the same time as the larger ones.

Despite their eagerness to get on with the vector boson hunt, CERN scientists, as is the wont of all high energy physicists, are already thinking of the next machine. LEP, if it is built as expected, will be an immense accelerator, some 27 kilometers in circumference, of electrons and positrons. Rubbia says, "Some of us are thinking that we could copy Fermilab's superconducting magnets and put a proton storage ring in the LEP tunnel. Then we could have a proton-antiproton collider with many trillions of electron volts."—ARTHUR L. ROBINSON