Nobel prize to Rubbia and van der Meer for finding W and Z

Carlo Rubbia and Simon van der Meer of CERN share the 1984 Nobel prize in physics for "their decisive contributions to the large project which led to the discovery of the field particles W and Z, communicators of weak interaction." In 1976 Rubbia and his collaborators had the idea of converting the Super Proton Synchrotron at CERN into a proton–antiproton collider, where the W and Z particles could be created. In 1968 van der Meer had invented the method of stochastic cooling, which allowed the dense packing and storage of enough antiprotons to make the W and Z in $p\bar{p}$ collisions. The CERN $p\bar{p}$ collider project, the largest ever to appear in the context of the Nobel prize, yielded its first collisions in 1981. Two year later, in 1983, both the W and Z were observed by the UA1 detector group led by Rubbia and by the UA2 detector group. The Royal Swedish Academy of Sciences, in announcing the award, said, "Two persons in the CERN project are outstanding—Carlo Rubbia, who had and developed the idea, and Simon van der Meer, whose invention made it feasible." This year's prize, which is worth about $193 000, is the first to honor work done at CERN.

The electroweak theory, which unifies the weak and electromagnetic interactions, requires the existence of the $W^\pm$ and Z as mediators of the electroweak interaction, along with the photon. In 1979 Sheldon Glashow, Abdus Salam and Steven Weinberg shared the Nobel prize "for their contribution to the theory of the unified weak and electromagnetic interaction between elementary particles, including *inter alia* the prediction of the weak current." Glashow, in 1961, developed a gauge theory with four gauge bosons—the W^+ and W^- to mediate charged-current weak interactions such as beta decay, the photon, and a particle now known as the Z^0 to mediate what were then hypothetical neutral-current weak interactions. In a neutral-current interaction, a Z^0 is exchanged and the particles keep the same electric charge they had before the interaction.

In 1967 Weinberg and independently in 1968 Salam developed an electroweak gauge theory based on the same four gauge bosons; the theory has exact symmetry between weak and electromagnetic interactions but it is spontaneously broken by the so-called Higgs mechanism (after Peter Higgs). Five years ago, in his Nobel lecture, Glashow said, "All gauge mesons must be massless, yet the photon is the only massless meson. How do the other gauge bosons get their masses? There was no good answer to this question until the work of Weinberg and Salam as proven by 't Hooft [in 1971] for spontaneously broken gauge theories. Until this work was done, gauge meson masses had simply to be put in *ad hoc*." The Higgs mechanism allows one to obtain a relation between the $W^\pm$ mass and the Z mass and an angle θ_W, which can be experimentally determined from neutrino experiments or the scattering of polarized electrons from deuterons, for example. From this calculation the mass of the W was predicted to be roughly 80 GeV, and the Z roughly 90 GeV.

Neutral currents. Once 't Hooft showed that the theory of Weinberg and Salam was renormalizable, the work attracted wide attention. In particular, experimenters started looking for the existence of neutral currents. Two groups, succeeded in 1973—first the Gargamelle group at CERN, then the Harvard–Pennsylvania–Wisconsin–Fermilab group working at Fermilab. (The Gargamelle collaboration had groups from Oxford, Orsay, Aachen, Milan, London, École Polytechnique, Brussels and CERN.) Both groups originally had set out to look for the W, before the Weinberg–Salam theory was taken seriously. But neither the Super Proton Synchrotron at CERN nor the Fermilab synchrotron had enough energy to produce an intermediate vector meson, according to the mass predictions of the Weinberg–Salam theory. The leaders of the original Harvard–Pennsylvania–Wisconsin collaboration, begun in 1969, were Carlo Rubbia of Harvard (whose wave function usually has had as much amplitude at CERN as in the United States), Alfred Mann of Pennsylvania and David Cline of Wisconsin.

Although the 1973 Gargamelle and HPWF experiments had shown evidence for neutral currents (and obtained a value for θ_W), the existence of neutral currents was then called into question by the so-called high-*y* anomaly and some atomic-physics experiments that did not show the nonconservation of parity predicted by the electroweak theory. But an experiment at SLAC in 1978 convincingly showed parity nonconservation by an amount consistent with the theory in the scattering of polarized electrons off deuterons.

With neutral currents being confirmed, the electroweak theory became widely accepted. But two keystones of the theory remained hypothetical—the W and the Z. Although many groups had looked for the W and Z as accelerator energies increased, by the mid 1970s, with the Glashow–Salam–Weinberg theory looking so good, it became clear that no existing accelerator could produce particles with the predicted mass values—about 80 GeV for the W and about 90 GeV for the Z.

Cooling antiprotons. In 1976 Rubbia, Peter McIntyre (then at Harvard with Rubbia) and Cline proposed converting the existing synchrotrons at Fermilab and at CERN to proton–antiproton colliders, with the specific purpose of finding and measuring the properties of the W and Z. A paper on the proposal was submitted by the three men to *Phys. Rev. Letters* and was rejected as inappropriate to the journal. Rubbia, McIntyre and Cline had been encouraged to make their proposal by two schemes for reducing the momentum spread of an antiproton beam—electron cooling, proposed by Gersh I. Budker in 1966, and stochastic cooling, invented by Simon van der Meer in 1968 but not published until 1972. Because a typical particle beam has significant spread in momentum, individual particles travel slightly different radii and thus contribute to the finite size of the particle beam. If the beam is "cooled," so that the momentum spread is reduced, the beam size

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will shrink and the particle density increase, thus helping to increase the luminosity.

Budker, who was before his death head of the Institute of Nuclear Physics in Novosibirsk, first described his electron-cooling scheme at a conference on colliding beams in Saclay. To cool a proton or antiproton beam, he proposed allowing an electron beam to travel in the same direction at almost the same velocity. The protons or antiprotons will tend to lose their transverse momentum to the electrons by Coulomb scattering, and the entire system would tend toward equipartition of energies. Over a large number of turns the oscillation amplitudes and momentum spread of the protons or antiprotons would be reduced gradually while the electron oscillations would grow. The net effect would be to reduce drastically the volume of phase space occupied by the protons or antiprotons. Budker at the time hoped to build a p$\bar{p}$ collider with 25 GeV in each beam. By the mid 1970s Budker, Alexander Skrinsky and their collaborators had demonstrated the effectiveness of electron cooling (PHYSICS TODAY, April 1977, page 17).

Van der Meer's first report on stochastic cooling,[1] dated August 1972, considers how to damp betatron (or orbital) oscillations in the Intersecting Storage Rings at CERN, to produce a kind of Maxwell's demon. In his introduction, he wrote, "As is well known, Liouville's theorem predicts that betatron oscillations cannot be damped by the use of electromagnetic fields deflecting the particles. However, this theorem is based on statistics and is only strictly valid either for an infinite number of particles, or for a finite number if no information is available about the position in phase plane of the individual particles. Clearly, if each particle could be separately observed and a correction applied to its orbit, the oscillations could be suppressed." He argued that the statistical fluctuations of the average beam position caused by the finite number of particles could be detected with pickup electrodes and then a corresponding correction could be applied. For efficient damping, he said, the feedback system would need a large bandwidth, that is a short response time. Van der Meer concluded his 1972 report, "This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect."

The stochastic cooling method uses the pickup electrodes to sense the deviation of the instantaneous center of charge of the beam. This signal is amplified and then takes a short-cut across a chord of the ring to a corrector with the appropriate phase further along the orbit; this correction reduces deviation of the center of charge. One can think of stochastic cooling as feedback action of individual particles upon themselves disturbed by other particles. The disturbance varies with the square of the feedback gain because of its random nature. On the other hand, the single-particle or cooling effect varies linearly with the gain. So it is always possible to find a gain value low enough to make cooling predominate, to reduce the amplitude of oscillation for more particles than for those whose amplitude is increased.

Because there's a limit to the smallest time interval one can resolve with the electronics, in a given time slice the beam has a changing population of particles. This mixing leads to samples that evolve, and the cooling process can be progressive. Van der Meer uses an analogy: Imagine a box that has weights suspended from springs; the weights oscillate vertically with different frequencies and amplitudes. If one shakes the box up and down in exactly the appropriate way (stochastic cooling), one can bring all the weights to a standstill.

Despite van der Meer's modestly phrased report in 1972, by 1974 electronics had become sufficiently fast (in the gigahertz range) to make a test of stochastic cooling feasible on the Intersecting Storage Rings. During a seven-hour test, a cooling rate of 2% per hour was obtained, but only the vertical spread was reduced. Similar results on the horizontal spread were obtained in the ISR in 1976.

Proton–antiproton colliders. That year Rubbia and his colleagues started pushing the conversion of the Fermilab and CERN synchrotrons into p$\bar{p}$ colliders. In January 1977 in an interview, Rubbia described his thinking to us: The W could be observed in an e^+e^- collider with 100 GeV in the center of mass, but such an experiment would not occur until 1992. Or the W could be found with Isabelle, the proton–proton collider then under construction at Brookhaven (which at that time was to have 400 GeV in the center of mass); that experiment would not occur until 1985. Actually, in large part because of the success achieved at the CERN p$\bar{p}$ collider, Isabelle was cancelled in the middle of 1983, long before it was completed. In that 1977 interview Rubbia explained, "We want to make an exploratory search three years from now," at low cost, using the single ring of an existing synchrotron to make a p$\bar{p}$ collider. Fermilab's conversion would allow 300 GeV in each beam and CERN's conversion would allow 270 GeV in each beam, or 540 GeV in the center of mass. Although the W was expected to have a mass of only about 80 GeV, the full 540 GeV is not available; the 270-GeV proton (antiproton) momentum is shared almost equally among some number of gluons and three quarks (antiquarks). The reaction is quark + antiquark $\rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$.

In that January 1977 interview Rubbia further explained that Fermilab was already building the Tevatron, to do fixed-target experiments at 1000 GeV. CERN, on the other hand, had no such plans. "The only chance they have is to collide protons with antiprotons." Fermilab *did* decide to do a p$\bar{p}$ collider conversion, using the Tevatron instead of the 400-GeV Main Ring, and on a much slower time scale than CERN.

The Royal Swedish Academy of Sciences, in its press announcement, explains Rubbia's role: "Rubbia brought the idea to CERN. Committing himself intensely, exploiting his deep knowledge in broad areas and with catching enthusiasm he succeeded in convincing the CERN management that the project might well be feasible." Rubbia estimated that to produce about 10 W particles, and one Z particle, about 10^9 collisions had to occur.

CERN set up a study group for the p$\bar{p}$ project headed by van der Meer. Both electron and stochastic cooling were to be studied. The $g-2$ ring previously used for measuring the muon magnetic moment was converted and became ICE, the Initial Cooling Experiment. By the middle of 1978 stochastic cooling had been demonstrated in three dimensions. The experimenters had cooled an antiproton beam in 15 seconds while the momentum density had increased by a factor of 20. Further theoretical work and, most importantly, says Roy Billinge of the CERN accelerator group, Lars Thorndahl's development of a faster and more efficient method of momentum cooling, showed that one could use a single dc-operated accumulator ring based entirely on stochastic cooling and stacking. So a detailed proposal was prepared, to convert the SPS into a machine that could either be used for fixed-target experiments (as before) or as a p$\bar{p}$ collider, at a cost of 200 million Swiss francs. The Council approved the project in June.

An Antiproton Accumulator needed to be built (see the article by Cline and Rubbia in PHYSICS TODAY, August 1980, page 44) to cool and stack antiprotons, until the desired quantity was collected. By the summer of 1980, only two years after the project was approved, the AA (under the joint leadership of Billinge and van der Meer) was completed. The antiprotons that are even-


CERN

Carlo Rubbia (left) and Simon van der Meer toast each other at a CERN celebration. The two shared the 1984 Nobel prize for contributions to the project that led to discovery of the W and Z.

tually accelerated to 270 GeV in the SPS are created by bombarding a fixed target (located in front of the AA) with 26-GeV protons from the old Proton Synchrotron. Every 2.4 sec a pulse of 10^{13} protons yields about 10^7 antiprotons with 3.5 GeV.

Antiproton accumulation occurs in the following way: The first pulse is injected into the ring by "kicker" magnets. This pulse is precooled, reducing the momentum spread of the particles by a factor of ten, and then the antiprotons are moved into the main part of the vacuum chamber, into the stack position. The second pulse is injected 2.2 sec later; then the second pulse is precooled and stacked. After 150 pulses, the stack contains 10^9 antiprotons. After three hours of this procedure, a dense core has begun to form in the stack. After 120 hours, the AA has 10^{12} antiprotons orbiting in the stack, and 6×10^{11} are concentrated in a core. Radiofrequency fields are used to extract the $\bar{p}$ core for injection into the PS, while the residue of antiprotons is used to start the next core. The $\bar{p}$ beam circulates in one direction of the PS while a p beam circulates in the other direction. While in the PS the antiprotons are accelerated from 3.5 GeV to 26 GeV, then transferred in bunches to the SPS. Within the SPS beams of p and $\bar{p}$ circulate in opposite directions, bunch by bunch. Both beams are accelerated simultaneously to 270 GeV with two separate rf systems and then the beams are stored. Then so-called low-beta insertions are used to squeeze the beams to small dimensions in the two collision regions of the $p\bar{p}$ collider.

The Swedish Academy's announcement notes that van der Meer's "ingenious method for the dense packing of protons . . . guided by magnetic fields . . . is rather sophisticated. Even experts found it hard to believe in the possibility. The method was successfully tested at CERN. It was finetuned for use on the current of antiprotons. Van der Meer and his coworkers finally succeeded in increasing the current of antiprotons several hundred thousand times using a facility specially built for production, storage and dense packing. The first collisions in SPS were made in the summer of 1981. The hunt for expected and unexpected phenomena was on, and still continues."

Detectors. While Rubbia was convincing the CERN management to build the $p\bar{p}$ project, he was also assembling a large term of collaborators to build a huge, sophisticated, general-purpose detector to be placed in one of the two interaction regions planned for the collider. Their proposal for the UA1 detector (where UA is short for the Underground Area that had to be excavated to house the detector) was accepted by the CERN Research Board at the end of June 1978, just at the time when the project itself was getting the green light. The UA1 group, led by Rubbia, eventually involved 130 physicists from 13 labs—Aachen, Annecy, Birmingham, CERN, Helsinki, Queen Mary College, London, Collège de France, Riverside, Rome, Rutherford, Saclay, Vienna and Wisconsin.

In December 1978 a second big experiment was approved, employing a second detector, UA2. The UA2 group eventually involved 50 physicists from six labs—Bern, CERN, Niels Bohr Institute, Orsay, Pavia, and Saclay. Its spokeman is Pierre Darriulat (CERN).

The UA1 detector, Rubbia explains, is "a huge beast [weighing in at 2000 tons], essentially a concentric set of boxes," something like the Russian toy with dolls within dolls. A dipole magnet produces a 7-kG field over an 85-m^3 volume. The iron return yoke of the magnet acts as a hadron calorimeter, inside which is an electromagnetic calorimeter. Within the electromagnetic calorimeter is the central tracking detector that surrounds the collision region. Outside the hadron calorimeter (or magnet) is a muon detector.

The UA2 detector (weighing 200 tons) is of a simpler conception and doesn't have a large magnet surrounding the central drift chambers. Particles produced from collisions are picked up in an inner vertex detector containing interleaved proportional chambers and drift chambers. Surrounding the vertex detector are the central electromagnetic and hadronic calorimeters.

By July 1981 the $p\bar{p}$ project had stored 270-GeV antiprotons and the UA1 detector had seen its first $p\bar{p}$ collisions (PHYSICS TODAY, February 1982, page 17). A major experimental run for both UA1 and UA2 was scheduled for Spring 1982. However, while the UA1 detector was being set up, it became contaminated, and had to be dismantled for cleaning. The major experimental run was delayed until UA1 was back in shape, and the 30-day run that led to the W discovery began in October. By the following month the UA1 group had some early indications of two W particles; but these candidates were later discarded in the sample of five W events reported in January 1983.

By the end of the run, the $p\bar{p}$ collider had achieved a luminosity of 5×10^{28} cm^{-2} sec^{-1}, obtained from beams of 3×10^{11} protons and 4.8×10^{10} antiprotons. Both the UA1 and UA2 detector groups had examined 10^9 $p\bar{p}$ collisions during the run, out of which they recorded about 10^6.

W and Z are found. Both groups looked for the W decaying into a charged lepton and a neutrino. In mid-January at meetings in Rome, CERN and New York the UA1 group announced it had five W events, four with a W^- decaying to an electron and a neutrino and one with a W^+ decaying to a positron and a neutrino. The UA1 group looked for two kinds of candidate events: those with isolated electrons having large transverse momentum and those with a large fraction of the transverse energy missing (carried by neutrinos). The five candidate events (PHYSICS TODAY, April 1983, page 17) identified by each test were exactly the same five events. The W mass reported in the discovery paper[2] was (81 ± 5) GeV/c^2, in excellent agreement with the predictions of the electroweak theory. In mid-February UA2 submitted a paper reporting[3] four W events.

The discovery of the Z was almost inevitable and its announcement followed close on the heels of the W announcement. In fact, although Z production had been expected to be 1/10 as great as W production, its signature was expected to be much easier to identify, namely a pair of energetic charged leptons back to back. In the third running period of the $p\bar{p}$ collider, from early in April until early in July, 1983, integrated luminosity was six times greater than the run at the end of 1982. This time the Z turned up, and on 1 June the UA1 group announced[4] it had found five events. Four of them were $Z \to e^+e^-$ and one was $Z \to \mu^+\mu^-$. On 15 July the UA2 group also reported[5] finding the Z. The Z mass value reported by UA1 was 95.2 ± 2.5 GeV/c^2, and by UA2 was 91.2 ± 1.7 GeV/c^2. The electroweak theory with radiative correction predicted 94.0 ± 2.5 GeV/c^2.

Biographies. Rubbia, who is 50, earned his physics degrees at the Scuola Normala Superiore of Pisa and at the University of Pisa. He spent a couple of years at Columbia University as a postdoc and from there returned to Europe. He joined the staff of CERN in 1961, where he is a senior physicist. In addition, since 1970 he has been a professor in the Harvard University physics department.

Van der Meer, who is 59, attended the Technische Hogeschool in Delft, and received a Dutch diploma in physical engineering. He worked for N.V. Phillips in Eindhoven before joining CERN in 1956, where he has been ever since. He was leader of the power supply group for the ISR and for the SPS, and then was joint project leader for the Antiproton Accumulator. —GBL

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Briefings point out special, low-cost research opportunities

In an effort to highlight for government funding officials "areas in which incremental funding may lead to major advances," a research briefing panel headed by Hans Frauenfelder (University of Illinois) and APS president Mildred Dresselhaus (MIT) conducted a series of briefings in Washington last Fall on "Selected Opportunities in Physics." At the request of the President's Office of Science and Technology Policy and the NSF, the panel had selected emergent fields of physics research in which, they felt, modest additional funding would exert "high leverage toward rapid progress." Large facilities and well-established research programs were explicitly excluded from consideration.

The briefing report on selected opportunities in physics is one of nine such briefings on various research topics in science and technology requested by OSTP director George Keyworth as input for the preparation of the FY1986 budget. The briefing panel reports were prepared under the auspices of COSEPUP (the Committee on Science, Engineering and Public Policy) and published in November by the National Academy Press. The only other physics topic among the nine chosen by Keyworth for the 1984 briefings was solar–terrestrial physics. That briefing was prepared by a panel headed by Charles Kennel (UCLA).

This is the third consecutive year that Keyworth has asked for such briefings. The selection of topics for FY1987 by OSTP, NSF and COSEPUP was to be completed last month, with briefings due for presentation next June, four months earlier in the budget cycle than has been the practice until now.

Selected Opportunities in Physics. In addition to the Keyworth briefing in October, Dresselhaus, Frauenfelder and panel member William Brinkman (Sandia) conducted additional briefings in Washington for agency representatives from DOE, DOD and NASA; NSF director Erich Bloch and his colleagues; and DOE Office of Energy Research director Alvin Trivelpiece. Brinkman is chairman of the National Academy of Sciences Physics Survey Committee. The Committee's much anticipated report, of which the briefing panel made extensive use, should be released early this year.

From among 20 suggested fields of physics research, the panel, with the aid of other experts, had chosen six "areas of special opportunity." As one panel member put it, "we were looking for embryonic, undernourished areas of special promise." The six areas chosen were:

- ▶ physics at the laser–atomic frontier
- ▶ relativistic plasma waves
- ▶ physical properties of deliberately structured materials
- ▶ biomolecular dynamics and intercellular cooperativity
- ▶ cosmology
- ▶ nuclear matter under extreme conditions

These six areas, the panel's report tells us, "promise to yield fundamental results of great interest. Many . . . are likely to advance technology . . . [and] all six cut across lines of narrow specialization." Cosmology, for example, has lately forged intriguing links between astronomy and particle physics.

The laser–atomic frontier generates research opportunities by applying advanced laser technology to fundamental problems in atomic and molecular physics. The briefing report stresses a number of such research opportunities and their possible applications:

▶ Trapped particles. Using laser light, one can trap ions and neutral atoms, and cool them to very low temperatures. This opens the way to ultra-high-precision measurements of frequencies, masses, the possible anisotropy of space, and collective motion in plasmas and gases.

▶ New spectroscopies. Femtosecond light-pulse generation (PHYSICS TODAY, December 1982, page 19) now make possible "snapshots" of atomic collisions, molecular reactions and fast surface phenomena. Femtosecond spectroscopy has applications in fast circuitry and instrumentation. Another new high-resolution spectroscopy of atoms, ions and molecules involves the use of relativistic particle beams to Doppler-shift highly stable visible laser output into the ultraviolet. One can thus investigate QED effects in highly charged ions and make new kinds of photoejection measurements.

▶ New and previously inaccessible species such as multiply excited atoms, molecular ions and clusters can be created by lasers. One can thus study correlated electron motion, catalysis, and the evolution from single atoms to condensed matter.

▶ Matter in intense fields produced by high-power lasers will permit the study of nonlinear phenomena and multiphoton processes (PHYSICS TODAY, November 1984, page 21), perhaps opening the way to novel photochemical processing and isotope separation techniques

▶ New light sources include excimer lasers and the generation of extreme ultraviolet and soft-x-ray light in supersonic atomic beams. Such techniques may provide small-scale alternatives to accelerator-based light sources.

Relativistic plasma waves involve electrons and ions at high velocities. Exploration of such waves could elucidate exotic astrophysical objects and the sources of cosmic rays. Understanding relativistic collective electromagnetic phenomena may lead to novel accelerators and radiation generators.

▶ Particle accelerators. The long-range future of high-energy physics may well depend on novel acceleration schemes such as plasma accelerators, grating accelerators and free-electron-laser accelerators (PHYSICS TODAY, February 1983, page 19). These schemes