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California Institute of Technology

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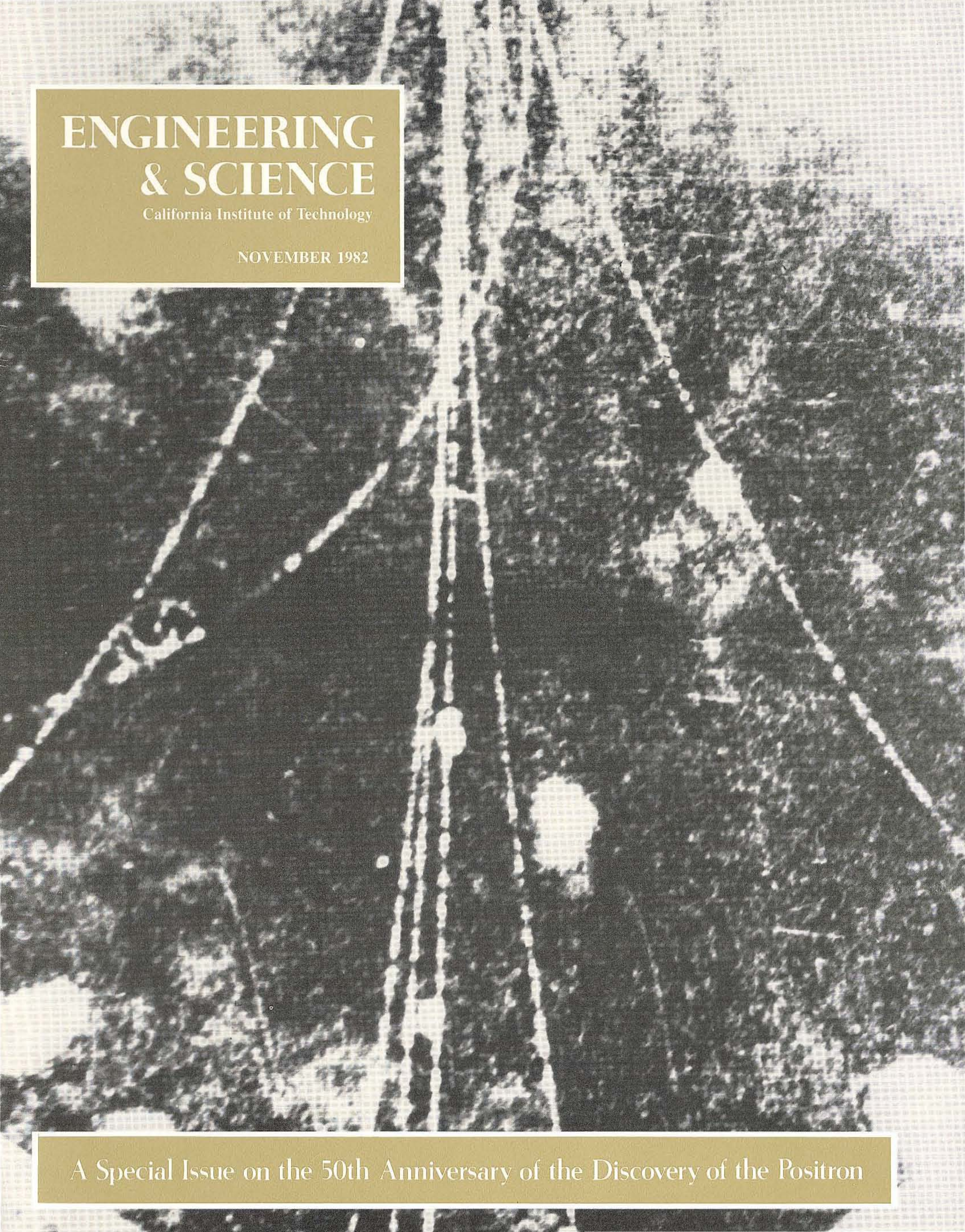
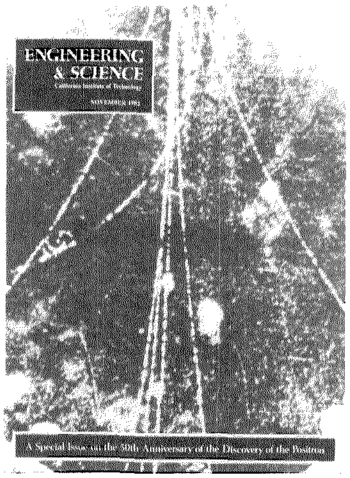


A Special Issue on the 50th Anniversary of the Discovery of the Positron

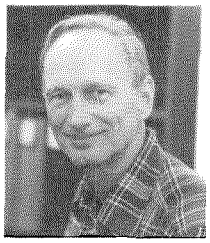
In This Issue



Happy Anniversary

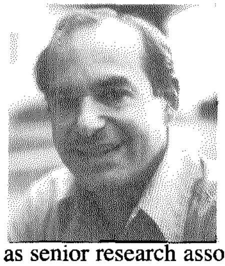
On the cover — a 50-year-old photograph that unexpectedly showed not only the tracks of electrons but also of positrons. Both appeared in the cloud chamber being observed by a young Caltech research fellow in physics, Carl Anderson. The 1932 discovery of the positron earned the Nobel Prize for Anderson, who is now Board of Trustees Professor of Physics Emeritus at the Institute. It also opened up a new era of particle physics, which is discussed in this special anniversary issue of *E&S*.

Contributors

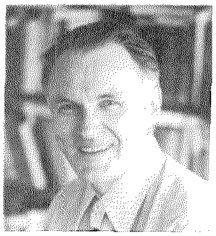


The author of "The Picture That Was Not Reversed," which begins on page 6, is Eugene Cowan, who came to Caltech in 1945 as a graduate student. He received his PhD in 1948, having done his work under Carl Anderson. For the next several years he made investigations of high-energy interactions in cosmic rays, proceeding, meanwhile, up the academic ladder from research fellow to full professor of physics in 1961. He is currently occupied with geophysical research into the dynamics of the mechanism that generates the earth's magnetic field.

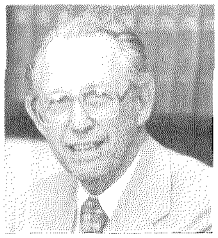
Before Robert Bacher retired in 1976, he had spent 27 years at Caltech in such positions as professor of physics, vice president, provost, and chairman of the Division of Physics, Mathematics and Astronomy. A distinguished scientist, he is the author of the introduction to this anniversary issue of *E&S* that appears on page 4.



John Schwarz, who writes about "Fifty Years of Antimatter" on page 24, has been at Caltech for ten years, first as a research associate in theoretical high-energy physics, and as senior research associate since 1981. His current work is in the area of supersymmetry and supergravity, which may lead to a unified description of interactions among elementary particles. Schwarz holds an AB from Harvard (1962) and a PhD from UC Berkeley (1966). He taught at Princeton before coming to Caltech.



Robert Leighton, a Caltech alumnus (BS '41, MS '44, PhD '47), became a research fellow in 1947. He worked with Carl Anderson on cosmic ray studies until 1960, by which time he was a full professor. Since then he has done research in both solar and planetary physics, and he served for five years as chairman of the Division of Physics, Mathematics and Astronomy. Leighton has designed and built many of the instruments used in his research, most recently several millimeter-wave radio telescopes that have extremely high surface accuracy. In this issue he returns to the world of cosmic rays with "Cosmic Rays — A Scientific Cornucopia," which begins on page 19.



Milton Plesset, professor of engineering science emeritus, was a National Research Fellow at Caltech in 1932-33, and he returned to the Institute as an associate professor of applied mechanics in 1948. He is considered an authority on the problems and progress of nuclear power. "Recollections of 1932-33" on page 15 is an excerpt of an interview with him about that year.

Among the younger generation of Caltech particle physicists is Robert McKeown, who came here from Argonne National Laboratory as assistant professor in 1980. He received his BS from the State University of New York — Stony Brook in 1974 and his PhD from Princeton in 1979. In addition to his experimental work on quarks, which he writes about in "The Search for Fractional Charges" beginning on page 26, McKeown's research also includes experiments on neutrino oscillations and pion interactions with nuclei.

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A SPECIAL ISSUE ON THE 50TH ANNIVERSARY OF THE DISCOVERY OF THE POSITRON

SCIENCE/SCOPE

For his pioneering contributions to geostationary communications satellites, Dr. Harold Rosen of Hughes has been given the prestigious Alexander Graham Bell Medal by the Institute of Electrical and Electronic Engineers. Rosen is credited with conceiving the first practical geostationary communications satellite, which orbits 22,300 miles high and covers over a third of the globe. Early satellites orbited lower and would have required a large fleet and complicated tracking procedures if continuous communications were to be provided.

Computers are being called upon to help create the "super chips" that will give military electronics systems a tenfold increase in data processing capability. Hughes is using computer-aided design programs to develop Very High Speed Integrated Circuits (VHSIC) and the systems in which these chips will be used. Computer help is essential because VHSIC chips are as complex as 100 Los Angeles street maps printed on a thumb tack, and they themselves are mere components of larger, more complex systems. Computer programs will help engineers design, lay out, and test a chip. They describe an entire system at many levels of detail simultaneously to predict performance under various operating conditions.

Landsat 4, the new second-generation Earth-watching satellite, is studying crops and other resources in greater detail than ever before possible. The spacecraft carries two primary instruments. One is a multispectral scanner like the ones on previous Landsat missions. The other is a thematic mapper, whose remote-sensing capabilities are a considerable improvement over the scanner's. The new mapper gathers different kinds of data and has a spatial resolution of 30 meters versus 80 meters of earlier scanners. Hughes and its Santa Barbara Research Center subsidiary built both instruments for NASA.

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Scientists have tracked the ash plume from the Mexican volcano El Cinchon using a weather satellite. Daylight and infrared pictures from GOES-5 (Geostationary Operational Environmental Satellite) clearly showed the April 4 eruptions even from 22,300 miles in space. Subsequent images revealed the plume rising high into the stratosphere and across the Yucatan peninsula. GOES-5 was built by Hughes and is operated by the National Oceanic and Atmospheric Administration.

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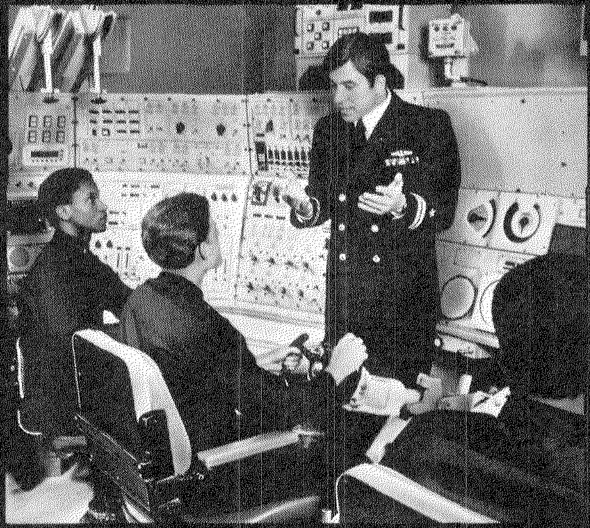

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THE POSITRON — ITS DISCOVERY

This photograph of Carl Anderson is one of a series of faculty portraits taken by physics staff member Tom Harvey.

AND IMPACT ON PARTICLE PHYSICS

An Introduction by Robert F. Bacher

THE YEAR 1982 marks the 50th anniversary of the discovery of the positron by Carl Anderson. This was the first antiparticle to be discovered, and it marked the beginning of a new era in particle physics. Robert Millikan, whose penetrating insight in physics was well known, suggested to Anderson that he use a cloud chamber in a magnetic field to study the nature of cosmic ray particles. Anderson's work produced many advances in techniques and led to the unambiguous identification of a positive particle with roughly electron mass on August 2, 1932.

During that same year, Chadwick announced the discovery of the neutron, which was to lead to major advances in nuclear physics and the whole field of nuclear energy. Also in 1932, Cockroft and Walton produced the first radioactivity initiated by protons accelerated in a machine. Moreover, it was the year in which Harold Urey discovered deuterium, which has played such an important role in nuclear physics. That year 1932, now 50 years ago, was indeed an outstanding one in the progress of science. The discoveries in those 12 months changed many of our concepts and led to great advances in our understanding of atomic nuclei. They also led to developments that had a major impact on our society.

This issue of *Engineering & Science* is devoted to a recall of Anderson's historic work and some of the findings that have followed. The introductory article by Eugene Cowan, who worked with Carl Anderson for many years, gives a careful account of the discovery of the positron and the events that led up to it. The discovery was so unexpected by most physicists that acceptance of the result, especially from Cambridge, came slowly.

Next is an excerpt from a paper by Anderson, prepared in 1980 to review the work that led to the discovery of the positron and later with Seth Neddermeyer to the discovery of the meson, now called the mu meson or muon.

Milton Plesset, who came to Caltech about the time of the first clear positron evidence, recounts his recollections of that time and his work with Robert Oppenheimer on this subject. Jacquelyn Bonner's biographical account of Anderson contains many interesting sidelights on his life not known to many because, as she points out, modesty is one of his strong characteristics.

Robert Leighton, who worked in cosmic rays with Anderson, has written a summary of the extensive cosmic ray work carried on that was not part of the early positron work. This includes the painstaking work with Seth Neddermeyer leading to the mu meson discovery. He also covers the period after 1945 in which, for about two decades until high-energy accelerators were developed and built, information about particle physics came predominantly from cosmic ray studies. Anderson and his colleagues played an important part in those studies.

John Schwarz has written a brief history of antimatter, which started with the positron discovery 50 years ago. He carries this along to the present when "positrons and antiprotons are the bread-and-butter tools of high-energy experimental physics." In the last article Robert McKeown discusses the current concept introduced by Murray Gell-Mann and George Zweig from Caltech of sub-proton and -neutron particles called quarks, which have fractional electronic charge ⅓ or ⅔ both plus and minus and which seem to be extremely reluctant to exist except in a group of three with charge ±e. Experiments are now being carried out in several laboratories to determine whether fractionally charged particles really exist. So far the evidence is positive but not definitive, but the next 50 years will bring much that is new. □

The Picture That Was Not Reversed

by Eugene Cowan

A three-part article that begins with the discovery of the positron, is followed by a commentary by physicist Richard Feynman and quotations from the scientific literature of the early 1930s, and ends with a few not-so-scientific items.

ON THE 2ND OF AUGUST 1932, a half-century ago, Carl Anderson peered through the small rectangle of a photographic film and caught the first glimpse of a new world, the world of antimatter. He saw what appeared to be a photographic negative reversed, a film viewed from the wrong side, and upside down as well. The picture showed the thin white trail left in a cloud chamber by a cosmic ray particle. Seen reversed, the trail could have been the track left by an ordinary fast moving negatively charged electron. This is the story of how that picture, which was *not* reversed, became the first clear view of particle-antiparticle symmetry — a symmetry that has since been extended to all known particles.

The story starts in the spring of 1930 when Carl was called to Dr. Robert Millikan's office to discuss a new apparatus to measure the energy of cosmic rays. In 1927, physicist Dmitrii Skobeltsyn had seen the tracks of cosmic rays appearing mysteriously in a cloud chamber used to study radioactivity. Millikan suggested that the cloud chamber could be placed in the field of a powerful electromagnet to measure the energy of individual cosmic rays. With this direction, Carl planned and built a unique apparatus.

The magnet coils consisted of lengths of copper tubing welded together to carry cooling water as well as electric current. An insulating braid was pulled on from the ends, inched forward, each advance more difficult than the last. After weeks of work and a basket full of worn-out cotton gloves, the tubing was wound into two coils around iron pole pieces. Additional iron to complete the framework brought the weight to nearly 2 tons. The heart of the apparatus was the cloud chamber, buried in the center of a small gap between the two coils and viewed through a hole in one of the pole pieces.

The cloud chamber was, and is, a temperamental tool, an instrument of amazing sensitivity that can make visible the path of a single moving electron. Delicate adjustments and unpredictable results make its use both art and science, and Carl did much to advance both. His method of adding alcohol to the water vapor in the chamber changed the previously faint trails to bright tracks that could be photographed. Even so, this required the momentary light of a powerful arc. A cloud chamber operates when a sudden expansion in volume cools a gas saturated with moisture. If conditions are precisely right, condensing droplets of fog form along the ion trail created by the motion of an invisible electron or other charged particle, leaving a visible track much as a distant unseen airplane leaves a visible vapor trail. In Carl's chamber the sudden expansion came when a movable piston forming the back of the chamber was released by a complicated mechanism, barely visible at the left side of the magnet in the picture at right. It was important to release the pressure quickly, and Carl designed a special system that permitted the piston to move suddenly into a vacuum, terminating with an explosive "bang." The loud "bangs" of this chamber's successors echoed through the cosmic ray laboratories at Caltech for the next 40 years, but none surpassed the speed of the original design.

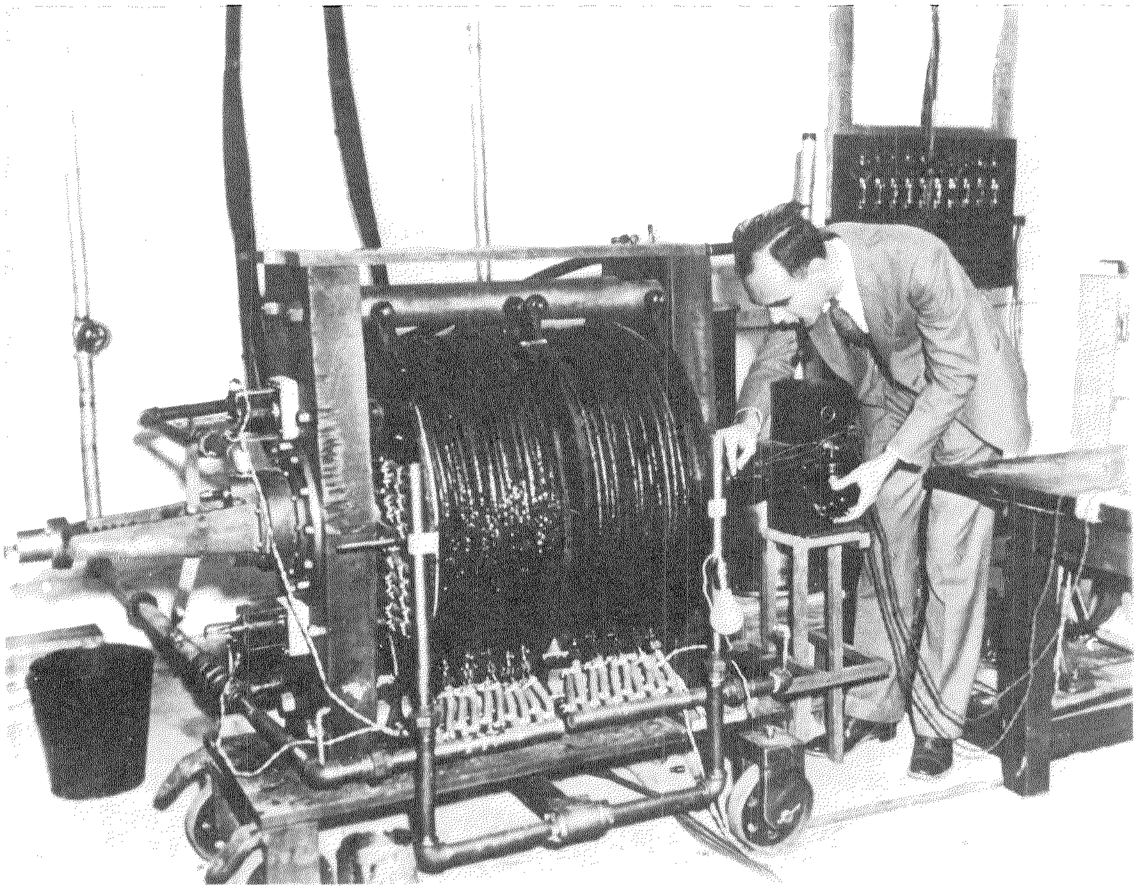
A glass window in the cloud chamber, opposite the piston, permitted photographs to be taken through a hole in the magnet pole piece (on the right in the picture). Two angles of view were needed for stereoscopic pictures, but there was room for only one camera lens to see the cloud chamber through the narrow hole. Carl's elegant solution — line the sides of the hole with mirrors. Effectively, the single lens became three.

The great power dissipated by the magnet coils was carried away by water circulated through the tubing that also carried the electric current. Part of the extensive water connection system appears at the bottom of the magnet in the picture. The magnet was designed to be powered by direct current from a large motor-generator with a rating of 425 kw — about 1/10 of the power used by the entire Caltech campus in the 1980s and many times the usual power needs of that day. The strength of the magnet field, which revealed the momentum of a cosmic ray by bending its path, was an important factor. Carl's magnet could sustain a continuous field of 17,000 gauss, which was greater than any of the later systems at Caltech patterned after it. At such levels the magnetic fields were no longer confined by the iron and could whisk a forgotten wrench from the floor and slam it into the magnet with a very large amount of force.

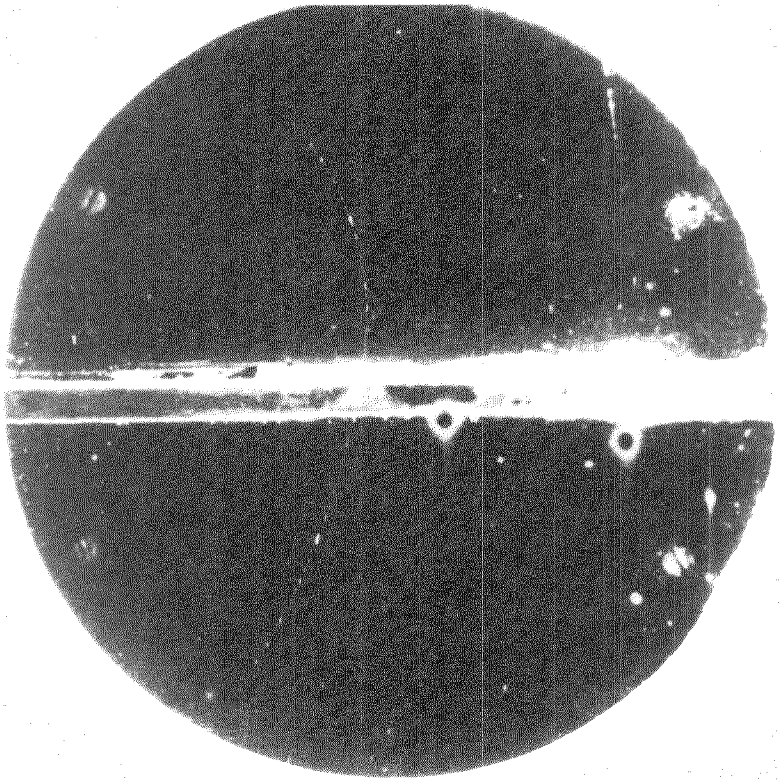
From the motor-generator set, which filled a small room in the depths of the aeronautics building (now Guggenheim Laboratory), heavy cables carried the power up to the roof, where the cloud chamber could be exposed to cosmic rays. The great penetrating power of these rays was not then known. Carl pushed the 425-kw generator to the limit and beyond, for brief periods as high as 600 kw, producing tremendous fields of over 25,000 gauss. Steaming water gushed from the magnet, bringing anxious reports of a vaporous liquid streaming from the campus across California Boulevard and down Arden Road.

Operation was often at night, when the power needs of the rest of the campus were small. The magnet was turned on, the cloud chamber compressed and made ready, but there was no way of knowing when a cosmic ray would arrive. To be visible it had to pass through the chamber in the brief fraction of a second it was sensitive after an expansion. A ''trigger'' was later devised by Blackett and Occhialini, but for these early operations Carl had to rely on chance. Over and over the cycle of the chamber was repeated — the blue-white flash of the arc light, the explosive ''crack'' of the chamber, and a tedious wait as the film was advanced and the chamber brought back to equilibrium. Night after night the cycle continued as the generator whirred and the brilliant flashes of the arc lit up the night sky over the campus. Thousands of pictures were taken, only a small fraction of which contained clear cosmic ray tracks. By the summer of 1931 the measured energy of cosmic rays had been pushed from 15 million electron-volts to 5 billion electron-volts.

In addition to the energy, the sign of charge,



The final apparatus of the magnetic cloud chamber appears in this photograph of December 1931 (released by the Associated Press under the confused headline ''The Atom Cracking Machine''). Carl Anderson adjusts the handmade camera that records the tracks in the cloud chamber on 35 mm film. The entire design was simple and cleanly executed; note the cut leg on the camera stool. Above all, it worked.



This photograph shows the track of the first clearly identified positive electron. The particle was moving upward, determined by the greater curvature of the top half of the track compared to the bottom half, which corresponds to the decrease in energy as the particle passed through the lead plate. The direction of motion and curvature clearly require a positive charge, and the possibility of a proton is ruled out both by the density and length of the track, which correspond to a mass near that of an electron.

plus or minus, could be determined by whether the path curved to the left or to the right in the magnetic field, that is, *if* the direction of motion of the particle was known. That seemed to present no problem since almost all cosmic ray particles come downward from above with only a small chance of being deflected upward. Particles of positive and negative charge occurred with about equal frequency, the natural assumption being that they were protons and electrons, the only known charged particles. One important factor remained. "Slow" particles, traveling at less than 95 percent of the speed of light, made dense tracks if they were heavy. Information about both the velocity and energy of the particle revealed the mass. Many of the slow particles that curved to the right, indicating a positive particle (if going downward), were too light to be protons, and therefore were taken to be electrons going upward. Carl said to Millikan, "You wouldn't expect it, but there must be electrons that are going up." Millikan said that that was ridiculous; they couldn't be moving up — any appreciable number of them anyhow; they must be protons.

To settle the argument, Carl placed a lead plate inside the cloud chamber so that a track would be visible as it entered and left the plate. Since the curvature after leaving would be greater than before entering the plate, because the particle must lose energy in going through, there could be no question about the direction of motion. It was a straightforward solution that then became the obvious solution.

The day arrived, August 2, 1932. A graduate student, Everett Cox, climbed the steps to the darkroom in the penthouse atop East Bridge and developed the film. Carl peered through the viewer as he slowly rolled the film, frame-by-frame, to the picture. A lone cosmic ray track in the center of the picture passed through the lead plate and emerged, the direction clearly indicated by the increase in curvature. And it was going upward! By some quirk of cosmic fate, completely unrelated to its historic role, it was the rare exception — a cosmic ray going up. The important thing was that the direction of motion combined with the sense of the curvature determined the sign of the charged particle, and the smoothly curved path left no doubt that the charge was positive. The large curvature and light density clearly revealed a mass near that of an electron.

As Victor Neher [now professor of physics emeritus] recently recalled, Everett was really worried. Did the film somehow get reversed? Did it get turned upside down? Carl Anderson knew the picture was not reversed and that it could not be ignored. It was a positive electron!

The course of science veered, from that flip of the film, to a chain of antiparticle discoveries that in 50 years now finds every particle with an antiparticle, a complete symmetry. We now see the possibility that our universe of matter could as well be replaced by a similar universe of antimatter, where perhaps the discovery of the negatron would be announced, presumably to meet the same disbelief.

As Oppenheimer related later, "Pauli thought it was nonsense; you find that in the relativistic part of his handbook article. Bohr not only thought it was nonsense, but was completely incredulous when he came to Pasadena." Rutherford remained unconvinced until Blackett and Occhialini had published similar work in February 1933. R. H. Fowler then wrote the following letter to Millikan:

> Dear Millikan,
>
> I have just had a letter from Rutherford which contains some of Blackett's work which may interest you and Anderson. It is that they have capitulated on the question of positive electrons and agree with Anderson that *there are present* in large numbers among the tertiary or quartinary (or whatever they are) ionizing particles seen in a Wilson photograph of the Cosmic ray effects *particles of positive charge and electronic mass.* I have few details. But I take it that Blackett has collected so many photographs of such

tracks as those earlier ones of Anderson that he can no longer resist this devastatingly interesting conclusion. Blackett's photos will come out in P.R.S. in March.

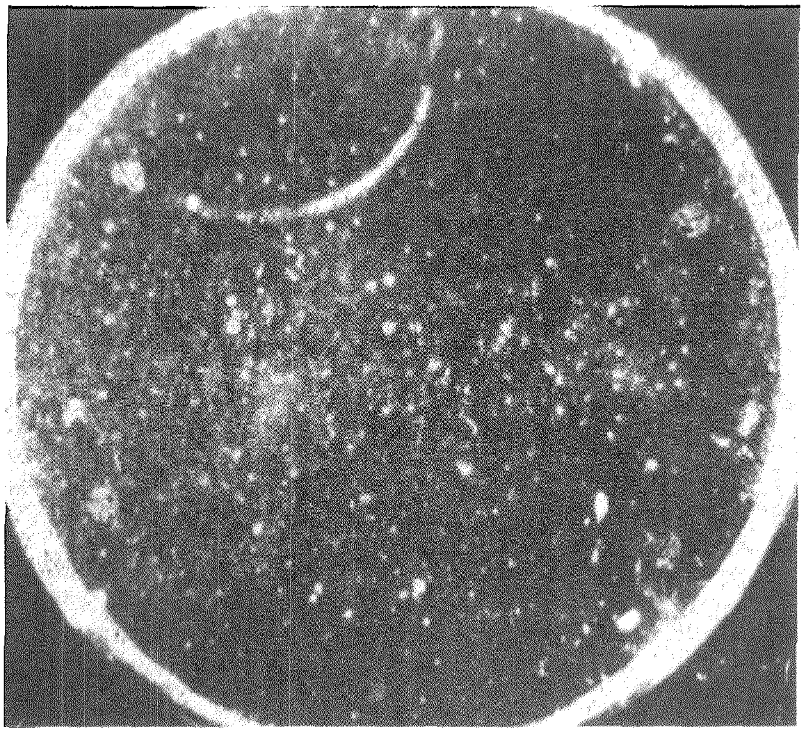
I have a lecture to deliver

Yours sincerely,
R. H. Fowler

Viva CalTech and Cav. Lab.

The relation between the discovery of the positron and Dirac's relativistic theory of 1929, by which it might have been predicted, can be traced through the direct quotes from the formal scientific literature that begin on page 11. The Dirac theory foresaw the possibility of a positive electron, but it played no part in the actual discovery. Although the discovery was unexpected, it was not a chance upturning of a gold nugget. Careful planning and skillful work had found a path to the whole lode. The picture at right shows the heavy curved blob of a cosmic ray track, not greatly different from thousands. In the eye of an acute observer it can have been made neither by an electron nor by a proton — only by a particle of intermediate mass. That particle left its track in Carl Anderson's cloud chamber in 1931. In the world of that time, made only of electrons and protons, there was no room for another particle. This picture was published later, in 1939, by Seth Neddermeyer and Carl Anderson with the caption that it was consistent with a mass between 150 and 200 times that of an electron. Seth was Carl's first graduate student. He arrived at about the time the magnet cloud chamber was completed and stayed after graduation through the exciting experiments on Pikes Peak, when they found room in the world for another particle, the μ meson whose track is pictured above.

By 1936, the year the Nobel Prize was awarded for the discovery of the positron, the growing list of elementary particles read e^-, p, n, e^+, μ^+, and μ^-, half of them discovered in Carl Anderson's cloud chamber. The neutron was discovered by Chadwick shortly before the discovery of the positron in the same year, 1932. That was the year of the beginning, the beginning of particle physics. There comes a time in the affairs of science to mark beginnings, a time to look backward, back half a century to the day when the evidence for antimatter hung by a slender trail of vapor, and the world's knowledge of antiparticles lay in the thoughts of Carl Anderson as he stared at the picture that was not reversed.



A particle of mass intermediate between an electron and proton left this heavy, curved track in Anderson's cloud chamber in 1931, a time when the existence of such particles was still unsuspected. This was later established to be the particle now called the mu meson.

RICHARD P. FEYNMAN, the Richard Chace Tolman Professor of Theoretical Physics and Nobel Laureate, was tracked down in Mexico and asked to comment for this article on the history of the relationship of Dirac's 1929 theory to the discovery of the positron. Quotes (chronologically by submission date) from the scientific literature that he refers to, along with other relevant citations, follow Feynman's remarks.

Let me summarize what I think the history of the thing is from looking at the papers. In December 1929 Dirac got a theory of his negative energy states; that they were filled and that there would be, then, holes (unfilled states) in them; that the holes would act like positive charges; and that they would be, perhaps, protons.

I think, judging the times, that there must have been an immediate tendency to suggest that they were protons; there was, of course, a strong conservatism and desire to avoid inventing new particles. Nowadays, when we have so many particles, we don't see why they resisted it. But I can appreciate the times, I think, and they didn't want to make the world complicated — it was supposed to be *simple*, with protons and electrons. So he thought they were protons. The fact that the mass was different was slightly disturbing, but there was an asymmetry which he *thought* existed. That was because of the interaction between the electrons. All the electrons in a negative energy state, he thought, would be interacting, and the interactions were a big complication that he couldn't see through and that, presumably, in some way gave the extra mass.

Two months later, in February 1930, Oppenheimer questions the idea that they're protons, and suggests that if the masses *were* different, due to interaction or something, there would be a lot of difficulties produced in the theory (the theory wouldn't give the right formulas for scattering of light by electrons, and so on), and he suggests that all the negative energy states are full and that there are two kinds of particles — electrons and protons — and they're not related to each other. As far as I can tell by reading it, he does not clearly or explicitly predict positrons. He says *all* the negative energy states are full; he does not discuss the possibility of the Dirac holes actually being produced or existing. It's not explicitly stated that there *should be*, definitely, a new particle of mass equal to that of the electron. He states only that the holes of Dirac could not be protons.

In March 1930, Dirac calculated quite accurately the annihilation rate of electrons and protons and therefore, presumably, the rate of production if they could be made. His calculations showed that it would be very, very high, and he was, of course, bothered by this. This demonstrated again, more directly, that protons couldn't be the holes. But the formulas were available for these things ahead of time, before Anderson's experiment, even though these calculations were not actually used until after the positron was discovered.

In a paper on magnetic poles the next year Dirac says some very explicit things. In the first place, the fact that the holes had to have the same mass as the electron had been demonstrated in a formal way by Weyl, who apparently thought the idea so obvious that he didn't bother to publish it except in his book about quantum mechanics in 1931. (Early in 1929 Weyl had also already suggested that the negative energy states of the Dirac theory were somehow related to protons. Dirac then modified Weyl's idea in his 1929 paper inventing the hole theory — that the negative energy states that were not occupied were protons.) Oppenheimer, as well as Weyl, had pointed out that if there *were* holes, they would have to have the same mass. I suspect that both Oppenheimer and Weyl were simply saying at this time that the holes couldn't be protons — not that the holes *were* some other particle. They just felt that there was still a difficulty, that they didn't know what the holes were.

But in this paper in May 1931, Dirac explicitly discusses the reality of holes. Of these papers it's the earliest one in which he really *believes* that holes are going to be there, that they can be made experimentally, and he discusses an experiment that he says is very, very difficult. (He wanted to hit two gamma rays together.) But he talks about the reality and the possibility of producing them. Of course, by that time he knew that they would have the same mass as an electron.

Over a year later, in September 1932, Anderson finds them experimentally, which, of course, clears up a lot of difficulty. I think that it's during that year between May 1931 and September 1932 that Dirac proposed the reality of the holes — that is, the positrons, or "anti-electrons," as he called them — but that many other people, including Pauli and Bohr, thought it was nonsense. Oppenheimer, in his later recollections, says that he doesn't think he thought of mechanisms to produce pairs before Anderson and that he had no opinion as to whether the holes really could be made. But I think Dirac really *believed* that they could be made.

As to the influence that discovering the positron had on theoretical physics, it's pretty obvious that the idea of the holes as positrons — the mass the same as the electron — was considered a possibility by Dirac and a great difficulty by other people, because there weren't any positrons. It's always wonderful how experiment throws away the cobwebs and straightens everything out and decides it all very nicely. Where many people were worrying, now they're all satisfied.

Dirac did say (in the 1931 paper) that the idea that there would be antiparticles for particles was much more general than just for the electron and the positron and comes from the problem of wedding together relativity and quantum mechanics. One of the reasons is that there was no way to avoid the two solutions of a square root. The formula for the energy of a particle is the square root of the momentum squared plus the mass squared, and that square root has two signs. So there would be negative energies. He was very clever in filling those negative energy states and inventing the hole theory to get rid of them. But he saw that there would be a general problem, that there's no way around that plus and minus sign for *any* particles. In classical physics the sign didn't give any difficulty, because once you started with a positive sign, its continuity didn't permit you to jump to the negative sign. But the quantum mechanics has discontinuous transitions with the emission of photons possible, and therefore you couldn't get rid of the minus sign. So I guess that very early everybody knew (after Anderson, of course, made it easy for everybody to believe it) that relativity and quantum mechanics went together to produce the need for antiparticles. I think, on the part of Dirac, who was one of the few who really believed his own theory, this was a rather brilliant prediction in the face of the conservatism with which he originally started — that there shouldn't be too many new particles. I think it is quite dramatic to invent or to discover the need for another particle by theoretical argument and then have experiment demonstrate its reality for all to see.

The main effect of the discovery was, of course, to clear the air, to make it wonderfully dramatic that this theory of Dirac's (which was fitting all the numbers so well in spite of the apparent difficulties of those holes) was a true prediction. That was what the experimental discovery said. But most people didn't have the guts to go along with it as Dirac had. So I would say that Dirac really predicted the positron.

Dirac and Oppenheimer, 1935.

December 6, 1929, P. A. M. Dirac, *Proceedings of the Royal Society,* A126 (1929-30), pp. 360-365, "A Theory of Electrons and Protons."

"We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons.*"

"In this way we can get over the three difficulties mentioned at the end of the preceding section. We require to postulate only one fundamental kind of particle, instead of the two, electron and proton, that were previously necessary."

February 14, 1930, J. R. Oppenheimer, *Physical Review,* 35 (March 1, 1930), pp. 562, 563, "On the Theory of Electrons and Protons."

"If we return to the assumption of two independent elementary particles of opposite charge and dissimilar mass, we can resolve all the difficulties raised in this note, and retain the hypothesis that the reason why no transitions to states of negative energy occur, either for electrons or protons, is that all such states are filled."

March 26, 1930, P. A. M. Dirac, *Proceedings of the Cambridge Philosophical Society,* 26 (1930), pp. 361-375, "On the Annihilation of Electrons and Protons."

"According to these ideas, when an electron of positive energy makes a transition into one of the unoccupied negative-energy states, we have an electron and proton disappearing simultaneously, their energy being emitted in the form of electromagnetic radiation."

1931, H. Weyl, *Gruppentheorie und Quantenmechanik,* 2nd ed. (English translation), p. 263.

"The quantum jump of an electron between positive and negative energy levels, which was so undesirable in the Dirac theory as formulated in the previous section, now appears as a process in which an electron and a proton are simultaneously destroyed and as the inverse process. The assumption of such an occurrence, for which our terrestrial experiments offer no justification, has long been entertained in astrophysics, as it seems otherwise extremely difficult to explain the source of the energy emitted by stars.

"However attractive this idea may seem at first it is certainly impossible to hold without introducing other profound modifications to square our theory with the observed facts. Indeed, according to it the mass of a proton should be the same as the mass of an electron (so long as it is invariant under interchange of right and left); this hypothesis leads to the *essential equivalence of positive and negative electricity under all circumstances — even* on taking the interaction between matter and radiation rigorously into account."

May 29, 1931, P. A. M. Dirac, *Proceedings of the Royal Society,* A133 (1931), pp. 60-72, "Quantised Singularities in the Electromagnetic Field."

"It was shown that one of these holes would appear to us as a particle with a positive energy and a positive charge and it was suggested that this particle be identified with a proton. Subsequent investigations, however, have shown that this particle necessarily has the same mass as an electron and also that, if it collides with an electron, the two will have a chance of *annihilating one another much too great to be consistent with the known* stability of matter.

"It thus appears that we must abandon the identification of the holes with protons and must find some other interpretation for them. Following Oppenheimer, we can assume that in the world as we know it, *all*, and not merely nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of them in nature, on account of their rapid rate of recombination with electrons, but if they could be produced experimentally in high vacuum they would be quite stable and amenable to observation. An encounter between two hard γ-rays (or energy at least half a million volts) could lead to the creation simultaneously of an electron and anti-electron, the probability of occurrence of this process being of the same order of magnitude as that of the collision of the two γ-rays on the assumption that they are spheres of the same size as classical electrons. This probability is negligible, however, with the intensities of γ-rays at present available.

The protons on the above view are quite unconnected with electrons. Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton. Theory at present is quite unable to suggest a reason why there should be any differences between electrons and protons."

September 1, 1932, C. D. Anderson, *Science,* 76 (September 9, 1932), pp. 238, 239, "The Existence of Easily Deflectable Positives."

"The interpretation of these tracks as due to protons, or other heavier nuclei, is ruled out on the basis of range and curvature.

"*The specific ionization is close to that* for an electron of the same curvature, hence indicating a positively charged particle, comparable in mass and magnitude of charge with an electron."

September 10, 1932, R. M. Langer, *Science,* 76 (September 30, 1932), pp. 294, 295, "The Fundamental Particles."

"The present theory of the electron seems to lead inevitably to an electron with negative energy and — with the help of the assumption due to Dirac that the negative energy states are almost filled — to a positive electron of the same mass."

". . . the electron and the Dirac magnetic pole are the fundamental particles."

February 7, 1933, P. M. S. Blackett and G. P. S. Occhialini, *Proceedings of the Royal Society,* A139 (1933), pp. 699-727, "Some Photographs of the Tracks of Penetrating Radiation."

". . . it is necessary to come to the same remarkable conclusion that has already been drawn by Anderson from similar photographs. This is that some of the tracks must be due to particles with a positive charge but whose mass is much less than that of a proton.

"The existence of positive electrons in these showers raises immediately the question of why they have hitherto eluded observation. It is clear that they can have only a limited life as free particles since they do not appear to be associated with matter under normal conditions. It is conceivable that they can enter into combination with other elementary particles to form stable nuclei and so cease to be free, but it seems more likely that they disappear by reacting with a negative electron to form two or more quanta. This latter mechanism is given immediately by Dirac's theory of electrons."

February 28, 1933, C. D. Anderson, *Physical Review,* 43 (1933), pp. 491-494, "The Positive Electron."

"It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally then be called a negatron."

June 9, 1933, J. R. Oppenheimer and M. S. Plesset, *Physical Review,* 44 (1933), pp. 53-55, "On the Production of the Positive Electron."

"This is what we should expect from the pairs, which should lose practically all of their kinetic energy in passing through matter, and in which the anti-electron near the end of its range should combine with an electron with the radiation of two quanta of about a half-million volts."

November 20, 1963, oral interview (unpublished) of J. R. Oppenheimer by Thomas S. Kuhn, Archive for the History of Quantum Physics.

Oppenheimer: I must have seen Dirac's note on electrons and protons shortly after it came out. I think that year (1929-30) I went first to Berkeley and came at Christmas time to Pasadena. My recollection is that I saw this in Pasadena. I guess the following note, or actually paper, on radiative transitions had something about the annihilation. You could then ask "what did I think?" Well, obviously I thought that the proton system and the electron system were separate and in normal experience one had only the one sign of charge. I don't think that I thought about mechanisms which would produce pairs until the Anderson thing. I think that I had no opinion as to whether this conclusion of the theory would be borne out. This may seem odd because if they could be annihilated they certainly could be produced, but it isn't the first time and it wasn't the last that one wondered really whether detailed balancing was right. This happened with the strange particles too, of course, and with the new meson and so on. It's always been right, and I think it's probably one of the few things that will continue to be, but I would just say that puzzlement was it. I talked to Anderson about it —

Kuhn: Before the positron?

Oppenheimer: Sure, and he talked to me, but I didn't encourage him to think that this was a good experiment, and he didn't look for positrons because there might be a place for them in a theory of whose general rightness no one was at all sure. Pauli thought it was nonsense; you find that in the relativistic part of his handbook article. Bohr not only thought it was nonsense but was completely incredulous when he came to Pasadena. It wasn't until — not that he'd seen the picture — that helped — I could explain to him how naturally the pair production would have to come out if this was a correct view at all that he became convinced. He left Pasadena convinced that it was a consequence of the hole theory and that this was genuine progress. I think there was a World's Fair in Chicago, and he went there, and when he talked about it he talked about having become convinced of this. That I think went on in Pasadena not least because there was a beautiful photograph but primarily because he hadn't thought about relativistic theory and changing particle numbers and all such things, and it was reassuring to him that the framework was there and that if there were troubles with it they were no worse than the troubles with light quanta in the hydrogen atom. They were the same kind of pushing a theory beyond what the traffic was good for.

February 2, 1934, P. A. M. Dirac, *Proceedings of the Cambridge Philosophical Society,* 30 (1933-34), pp. 150-163, "Discussion of the infinite distribution of electrons in the theory of the positron."

Footnote: "As this theory was first put forward, *Proc. Roy. Soc.,* A126, p. 360 (1930) and *Proc. Camb. Phil. Soc.* 26, p. 361 (1930), the holes were assumed to be protons, but this assumption was afterwards seen to be untenable, since it was found that the holes must correspond to particles with the same rest mass as electrons. See *Proc. Roy. Soc.,* A133, p. 61 (1931)."

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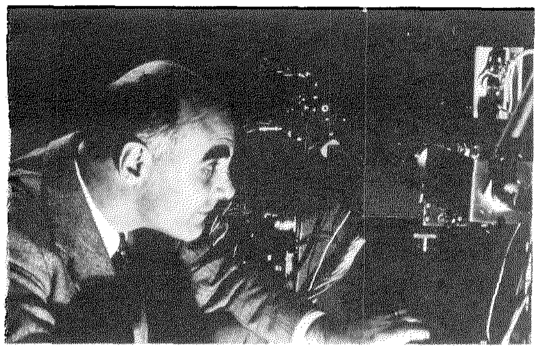


Unraveling the Particle Content of Cosmic Rays

by Carl D. Anderson

Most of the articles in this special issue of E&S *were written by colleagues of Carl Anderson. Each in its own way pays tribute to the 50th anniversary of the discovery of the positron and the later discovery of the mu meson. The most authoritative source of information about how it all happened, however, is Anderson himself. Below is an excerpt from a paper he prepared for an international conference of historians of science held at Fermilab in the fall of 1980. This paper, entitled "Unraveling the Particle Content of Cosmic Rays," will appear in its entirety in* The Birth of Particle Physics *by Brown and Hoddeson, to be published by Cambridge University Press.*

AT ABOUT THE END of 1929, when it became clear to me that I was likely to receive my PhD degree at Caltech in June 1930, I made an appointment to see Dr. Millikan. The purpose of my visit was to see if it were at all possible for me to spend one more year at Caltech as a postdoctoral research fellow. My reason for doing so was twofold: to carry out an experiment I had in mind and to learn something about quantum mechanics.

After a brief discussion with Dr. Millikan, in which I described the experiment and my desire to study quantum mechanics, he informed me that this would not be possible. The gist of his remarks was that, having had both my undergraduate and graduate training at Caltech, I was very provincial and should plan to continue my work at some other institution under a National Research Council fellowship, about the only fellowship available at that time for postdoctoral studies. Thus, I had no choice but to apply for the fellowship, and I wrote to Arthur H. Compton at the University of Chicago. I received a cordial reply and began planning for my sojourn at Chicago, an idea that appealed to me more and more as time went on.

One day I received a call from Dr. Millikan asking me to see him in his office. The gist of his comments on this occasion was that he wanted me to spend one more year at Caltech and build an instrument to measure the energies of the electrons present in the cosmic radiation. By this time, Chicago was clearly my first choice, and I used all the arguments that he had previously presented for not staying at Caltech. He replied that all these arguments were valid and cogent, but that my chances of receiving an NRC fellowship would be better after one more year at Caltech. He was a member of the NRC fellowship selection committee at the time.

Again, I seemed to have no choice in the matter. Without further ado I began work on the design of the instrument he had proposed for the cosmic ray studies. It was to consist of a cloud chamber operated in a magnetic field. This equipment, however, would require a very powerful magnetic field, for the cosmic ray electrons were expected to have energies in the range of at least several hundred million electron volts.

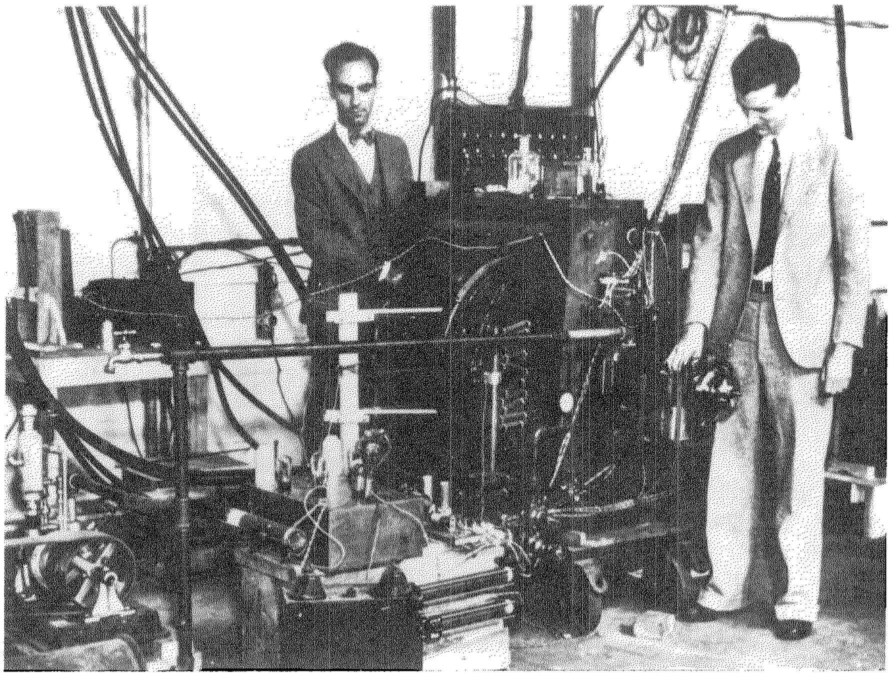
The first results from the magnet cloud chamber were dramatic and completely unexpected. There were approximately equal numbers of particles of positive and negative charges, in sharp contrast to the Compton electrons expected from simply the absorption of high-energy photons.

It was, of course, important to provide unambiguous identification of the unexpected particles of positive charge, and this could best be done by gathering whatever information was possible on the mass of the particles, inasmuch as the photographs clearly showed that in all cases these particles carried a single unit of electric charge. Experimental conditions were such that no information as to a particle's mass could be ascertained except in those cases in which the particle's velocity was appreciably lower than the velocity of light, which was true for only a small fraction of the events. Only a few of the low-velocity particles were clearly identified as protons.

As more data were accumulated, however, a situation began to develop that had its awkward aspects, in that practically all of the low-velocity cases involved particles whose masses seemed to be too small to permit their interpretation as protons. The alternative interpretations in these cases were that these particles were either electrons (of negative charge) moving upward or some unknown lightweight particles of positive charge moving downward. In the spirit of scientific conservatism, I tended at first toward the former interpretation (i.e., that these particles were upward-moving negative electrons). This led to frequent, and at times somewhat heated, discussions between Professor Millikan and myself, in which he repeatedly pointed out that everyone knows that cosmic ray particles travel downward, not upward, except in extremely rare instances, and that therefore these particles must be downward-moving protons. This point of view was very difficult to accept, however, because in nearly all cases the specific ionization of these particles was too low for particles of proton mass.

To resolve this apparent paradox, a lead plate was inserted across the center of the chamber in order to ascertain the direction in which these low-velocity particles were traveling and to distinguish between upward-moving negatives and downward-moving positives. It was not long after the insertion of the plate that a fine example was obtained in which a low-energy lightweight particle of positive charge was observed to traverse the plate, entering the chamber from below and moving upward through the lead plate. Ionization and

Robert A. Millikan (right above) visited Anderson at Pikes Peak in the summer of 1935. The cogwheel railway car and engine in the background transported tourists up the mountain. Below, Anderson and Seth Neddermeyer with the magnet cloud chamber in which the tracks of both positrons and muons were discovered.



curvature measurements clearly showed this particle to have a mass much smaller than that of a proton and, indeed, a mass entirely consistent with an electron mass. Curiously enough, despite the strong admonitions of Dr. Millikan that upward-moving cosmic ray particles were rare, this indeed was an example of one of them.

Soon additional instances of lightweight positive particles traversing the plate were observed; in addition, events in which several particles were simultaneously emitted from a common source were observed. Clearly, in both types of cases the direction of motion was known, and it was therefore possible to identify the presence of several more lightweight positive particles whose mass was consistent with that of an electron but not with that of a proton — in short, the positron.

It has often been stated in the literature that the discovery of the positron was a consequence of its theoretical prediction by Paul A. M. Dirac, but this is not true. The discovery of the positron was wholly accidental. Despite the fact that Dirac's relativistic theory of the electron was an excellent theory of the positron, and despite the fact that the existence of this theory was well known to nearly all physicists, including myself, it played no part whatsoever in the discovery of the positron.

During the months that followed the discovery of the positron, my graduate student, Seth Neddermeyer, and I accumulated much more data and at least for a while believed the bulk of the high-energy particles to be electrons about equally divided between positive and negative charges. But doubts soon began to develop, and it was only through the discovery of the meson that these doubts were finally resolved.

The discovery of the meson, unlike that of the positron, was not sudden and unexpected. Its discovery resulted from a series of careful, systematic investigations all arranged to follow certain clues and to resolve some prominent paradoxes that were present in the cosmic rays. A principal aim of our experiments was to identify the penetrating cosmic ray particles. They had unit electric charge and were therefore presumably either positive or negative electrons or protons, the only singly charged particles known at that time.

There were difficulties, however, with any interpretation in terms of known particles. These particles seemed, in fact, to be neither electrons nor protons. We tended, however, to lean toward their interpretation as electrons, and we "resolved" the paradox in our informal discussions by speaking of "green" electrons and "red" electrons — the green electrons being the penetrating type, and the red the absorbable type that lost large amounts of energy through the production of radiation.

In the summer of 1936 Neddermeyer and I were quite firmly convinced that all the data on cosmic rays as known at that time nearly forced on us the conclusion that the penetrating sea-level particles could be neither electrons nor protons and must therefore consist of particles of a new type.

Evidence for the existence of new particles of intermediate mass was first presented in a colloquium at Caltech on November 12, 1936; but perhaps the first reference in the "literature" to the new particles was the last sentence in my Nobel lecture on the positron delivered in Stockholm on December 12, 1936. In the more than 40 years since the delivery of that address I have received no reaction at all from it; so I will quote that sentence here: "These highly penetrating particles, although not free positive and negative electrons, will provide interesting material for future study." □

Recollections of 1932-33

MILTON PLESSET, now professor of engineering science emeritus at Caltech, first came to the Institute in 1932-33 as a National Research Fellow. He brought with him a PhD from Yale, where he had done a part of his thesis on a solution to Paul Dirac's relativistic theory. This theory opened up the now-verified idea that every particle in nature has its antiparticle. Plesset spent most of his time that year working with Paul Epstein on another aspect of theoretical physics, but he also encountered Carl Anderson, who had just discovered and identified the positron, the antiparticle for the electron.

''I remember,'' said Plesset in a recent interview, ''walking from my office in Bridge to the Athenaeum in the evenings and being impressed by the flashes of light from the windows of the lab on the top floor of Guggenheim, where Anderson was operating his cloud chamber and making photographs of cosmic rays, in which he found tracks of electrons (as expected) and also of positively charged particles. That was totally unexpected. He used the aeronautics building because it had the only source of power large enough for his magnet, and he had to work at night because that was the only time the power was available to him.

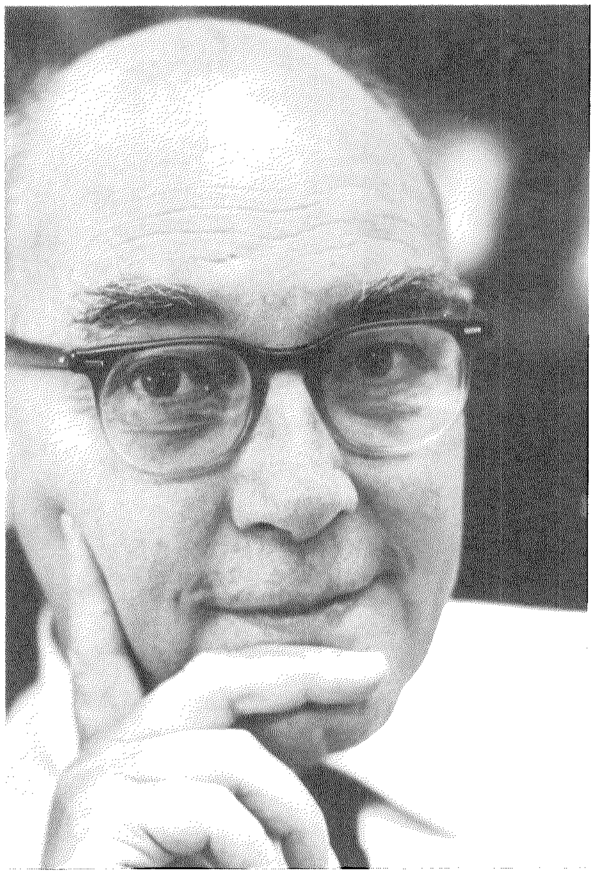
''Both Dirac's theory and Carl's growing belief that the positive particles showing tracks in his photos couldn't be protons but had to be anti-electrons or positrons, as he called them, were radical concepts for those days. They were hard for physicists to accept or account for. But I was entranced with the possibility that what Carl was claiming resolved some of the problems in Dirac's theory, and I persuaded Robert Oppenheimer that we should try to explain the production of the pairs — electron and anti-electron — theoretically. I don't know whether we were the first to use the word ''pairs'' for particles and antiparticles, but it's come to be the accepted term.

''Oppenheimer wasn't wildly enthusiastic about the Dirac theory, but I think he was kind of at loose ends right then. Work on the quantum theory of the atom was pretty well finished, and he may have been looking for what he was going to concentrate on next. He was one of the most erudite physicists I ever met, full of ideas and insights. When he came down to Caltech from Berkeley each spring, it was rather like a comet coming across the sky. It was very exciting for me to work with him, and our paper — ''On the Production of the Positive Electron'' — did come up with some reasonable quantitative explanations.

''It had a lot of significance for experimental work, particularly some that was being done at Caltech. Charles Lauritsen's group was working on the interaction of gamma rays and matter, and Robert Millikan was deeply involved with cosmic rays and their origin. If the calculations Oppenheimer and I had done meant anything — and if Dirac's theory could be extended to high energies — it would be difficult to continue to accept photons as a significant component of the primary radiation. About a year later it was proved in Copenhagen that the theory was valid for very high energies.

''Millikan was very concerned about all this. I remember one hot day in the spring of 1933 he nabbed me just as I had gotten into my fiancée's car to go out. He put his foot on the running board and kept us there in the hot sun for an hour while he pursued the question of whether Dirac — and Anderson — were right. You know, he really didn't care much for theoretical physics. He had a lot of respect for the old school of theoretical physicists — Sommerfeld and Ehrenfest, for example — but he was suspicious of those who were active in quantum mechanics, like Dirac and Oppenheimer. We all have our blind sides, and this was one of Millikan's.

''Someone once told me that Dirac originally came up with his theory while taking a train trip from Moscow to Vladivostok. He didn't have anything to do for eight days but think, and what he thought helped him get a Nobel Prize in 1933. Carl's discovery, which won the Nobel Prize in 1936, established Dirac's theory as one of the most stimulating in all of physics, and it opened up a whole new world of research.'' ☐



A Man Who Speaks Swedish

STANDING on the Stockholm docks on a summer day in 1926, a 21-year-old American college student was surprised to find himself speaking Swedish with a local fisherman. He didn't know he could speak the language. Just over ten years later, that latent ability once more stood him in good stead. He received the Nobel Prize in physics from King Gustav and was able to converse with the king in his native tongue.

The young man was Carl Anderson and, of course, he didn't acquire such linguistic capability completely out of the blue. Both of his parents came to the United States in their late teens, and though they spoke English in their home, Swedish was always part of the background.

Carl was born in New York in 1905, and when he was about seven, the Andersons moved to Los Angeles. He attended grade school and then Los Angeles Polytechnic High School, from which he graduated in 1923. His chief extracurricular interest in those years was electrical engineering, and he was able to get material for a lot of experimenting by making the rounds of nearby garage repair shops where he picked up discarded but still serviceable batteries.

With hope for an electrical engineering career motivating him, Carl applied for admission to Caltech. This step was against the advice of almost everyone he talked to except his physics teacher, but he went ahead anyway and stayed firmly committed to his engineering goals — until the third term of his sophomore year. He was then among the select few students whose grades warranted their being put in "Section A," where sophomore physics was covered in the first two terms, and Ira Bowen's course in modern physics was offered in the third term. That course converted engineer Anderson to physicist Anderson.

After Carl received his BS in 1927, he stayed on as a graduate student working on X-ray photoelectrons under the supervision of Robert Millikan — at least officially. For several months, actually, he didn't have a research adviser, but when he mentioned this to Millikan, Millikan volunteered his own services. Anderson does not recall that the Nobel Prizewinning physicist and head of the Institute ever entered his laboratory or discussed his research with him. Nevertheless, there must have been considerable interaction and mutual respect because after Carl received his PhD, *magna cum laude*, he became a research fellow at the Institute, working with Millikan on cosmic ray studies.

Millikan was a pioneer in cosmic ray research, and he had already measured their enormous penetrating power. What he wanted Anderson to do was to measure the energy of the electrons they produced, and the best way to do that at the time was in a cloud chamber. After conferring with Millikan, Anderson designed and built an apparatus consisting of a giant electromagnet wrapped around a cloud chamber. An arc lighted camera was focused on the window of the chamber to record the visible vapor trail of electrons or other charged particles passing though the chamber.

This was in the early 1930s, a time when scientists had identified two elementary particles of matter — the electron, with its negative charge, and the positively charged nucleus of the hydrogen atom, the proton. Anderson realized that he had found something new when his photographs showed what appeared to be a positively charged electron. This particle was eventually named the positron, and its discovery brought Anderson the 1936 Nobel Prize in physics.

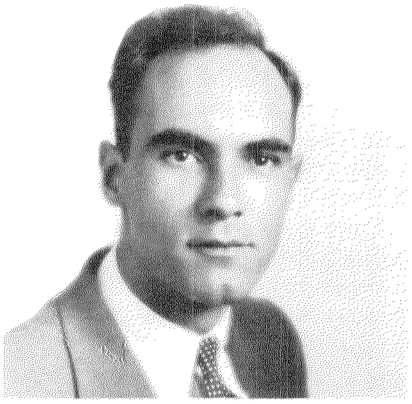
Acceptance of the reality of the positron did not come easily to Anderson or to Millikan — or to physicists in general. But when it became clear that no other explanation of the observed phenomenon made sense, the concept of matter and antimatter enunciated by Dirac was confirmed. Since then research in this field has led to the discovery of so many elementary particles, each with its antiparticle, that physicist Enrico Fermi is said to have remarked that if he could remember all of their names he would have been a botanist.

By the time Anderson received his Nobel Prize — at the age of 31 — he and his first graduate student, Seth Neddermeyer (now professor of physics emeritus at the University of Washington), had identified two more of the fundamental particles of matter, the positive and negative meson, or muon. Nothing of that discovery came about by chance; it was the result of four years of careful, systematic investigation. Part of it was done at the summit of Pikes Peak in Colorado because the intensity of cosmic radiation is greater at high elevations than it is at sea level. Later, Anderson also conducted research in Panama, in the White Mountains of California and in a B-29 airplane that operated at altitudes up to 40,000 feet.

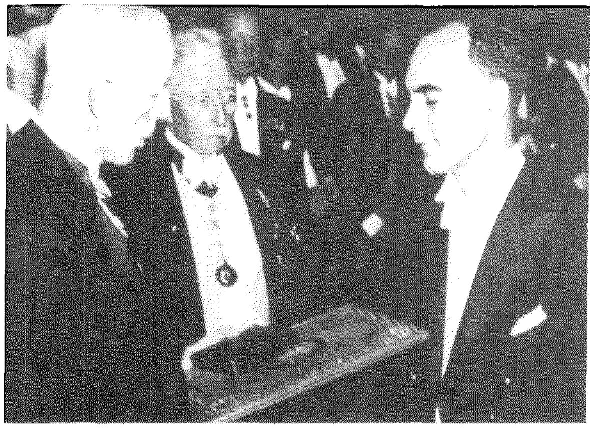
In 1933 Anderson was promoted from research fellow to assistant professor, a step that improved both his academic standing and his financial situation. The award of the Nobel Prize had similar beneficial effects, though Carl had to borrow $500 from Millikan to pay for his ticket to Stockholm to receive the award. In 1937 he was promoted to associate professor, and in 1939 he became professor.

The outbreak of World War II changed the activities of both Caltech and Anderson. Teaching and peacetime research had to take a back seat to war-related efforts. Arthur Compton of the University of Chicago offered Carl the directorship of the bomb-development laboratory, and Anderson visited Chicago in early 1942 to look the situation over. He turned the job down because, in the first place, he felt he did not have the necessary administrative skills and, in the second, he did not have the resources to support himself in Chicago and his semi-invalid mother in Califor-

Carl Anderson's 1926 Junior Travel Prize of $900 gave him nearly six months in Europe during which he climbed its second highest peak, Monte Rosa. At the left above is the Swiss guide for the climb.

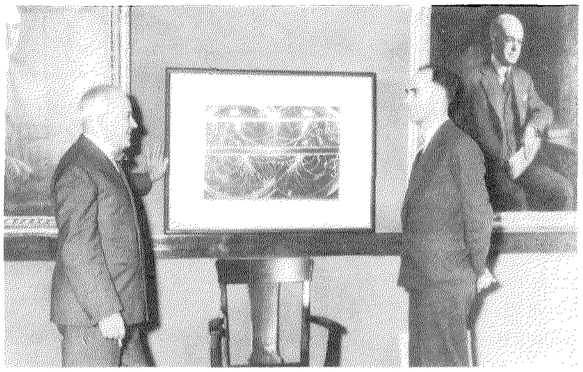


Graduating in 1927, Anderson was a member of both the campus scholastic honor societies, Tau Beta Pi and Sigma Xi.

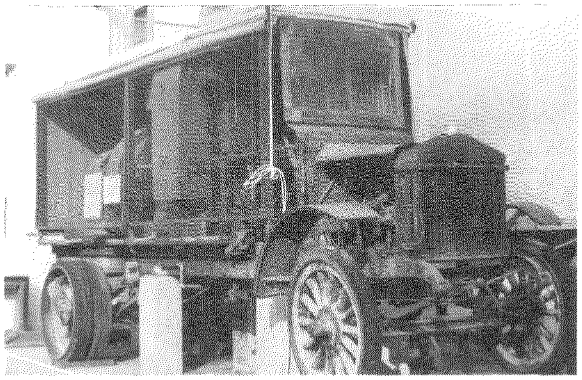


In 1936 King Gustav of Sweden presents Anderson with the Nobel Prize in physics in recognition of his discovery of the positron.

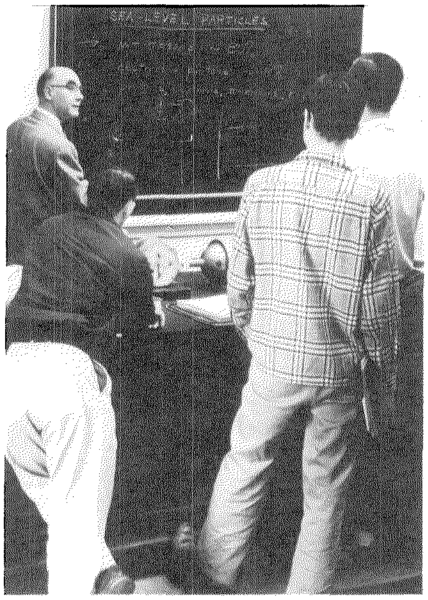
Four cheers instead of three is an old Swedish custom, and in 1965 Anderson was proud to lead them in honor of Richard Feynman, whose Nobel Prize award had just been announced. Unfortunately, Feynman himself is mostly hidden in the crowd.



Robert Millikan and Carl Anderson with cloud chamber photographs of the positron.



This motor generator mounted on a 1911 Pierce Arrow was given to Anderson by film director and Caltech alumnus Frank Capra. Towed to Caltech and parked in the alley beside the aeronautics building, it provided power for the cloud chamber magnet.



Teaching is a part of the life of most professors, including Nobel Laureates. Here Anderson is explaining something about the particle content of the cosmic radiation to a group of students.

A Nobel Prizewinning teacher-to-student cycle began with Robert Millikan in 1923 . . .

. . . proceeded to Carl Anderson in 1936 . . .

. . . and went on to Donald Glaser in 1960.

nia. Instead, he spent a good deal of time during the war years working on the solid-propellant rocket project headed by Caltech physicist Charles Lauritsen. Specifically, his work dealt with how to fire these rockets from aircraft, and this effort was successful enough that he was flown to Europe in 1944 to supervise the installation of the first aircraft rockets on Allied fighter planes.

One of the first things that happened to Anderson after the war was giving up being a bachelor. After an eight-month-long engagement, he and Lorraine Bergman drove off to Santa Barbara one Sunday in 1946 to find an open church and get married. That turned out to be more difficult than expected, but a few telephone calls located a Seventh Day Adventist minister who was willing to perform the ceremony. Entirely coincidentally, the bride and groom encountered James Page, chairman of the Caltech Board of Trustees, with his wife and a friend, and invited them to the wedding. The Pages reciprocated by taking the newlyweds to their home in Montecito for a champagne wedding reception. For most of the ensuing 36 years the Andersons have lived in San Marino, California. They have two sons — Marshall, who is a mathematician and computer analyst, and David, a physicist.

After the war Anderson returned to studies of cosmic radiation. His research group included Robert Leighton and Eugene Cowan, both now professors of physics at Caltech. It also included Donald Glaser, who received the 1950 Nobel Prize in physics for his invention of the bubble chamber, another device for detecting atomic particles. Anderson still hopes that Glaser will have a Nobel Prizewinning student to continue the professor-to-student cycle that began with Millikan.

In the course of their research Anderson and his group took literally tens of thousands of pictures, each of which was methodically examined in the hope of seeing interesting particle tracks. More than a little tedium was involved in this process, but it paid off for Anderson's research group as they accumulated photographic evidence of many examples of new fundamental particles that came to be known as "strange particles."

By the late 1950s Anderson's kind of cosmic ray studies was beginning to be replaced by work done on huge high-energy accelerators, and he was willing to take on administrative work in addition to the committee service he was accustomed to giving to the Caltech community. He became chairman of the Division of Physics, Mathematics and Astronomy in January 1962, and he held the job until 1970. While he was in office, two physicists at the Institute received Nobel Prizes — Richard Feynman in 1965 and Murray Gell-Mann in 1969 — two events in which Anderson took great pleasure but for which he claims absolutely no credit. Carl Anderson is, in fact, a modest man. When Caltech feted him with an Athenaeum dinner after he had received the Nobel Prize, he responded to the highly laudatory speeches by recalling the first medal he ever won.

"I won it for improvement in physical achievement when I was a Caltech freshman," he explained. "To begin with, I was among the poorer runners, broad-jumpers, and high-jumpers, but at the end of the term I finished ahead of several of them, so they gave me second prize — a silver medal."

He then went on to admit that the reason for the improvement was simple — he changed his shoes. Originally he had thought that the test had something to do with ROTC, so he wore his heavy Army shoes. For the later test he wore sneakers.

Neither that prize nor the Nobel Prize was the last of his honors. He has, for example, been awarded three honorary doctorates, and he has received the Gold Medal of the American Institute of the City of New York, the Presidential Certificate of Merit, the Elliott Cresson Medal of the Franklin Institute, and the John Erickson Medal of the American Society of Swedish Engineers.

In retirement now (he has been Board of Trustees Professor Emeritus since 1976) Anderson has been doing quite a lot of writing, and in 1979 he recorded an oral history for the Caltech Archives, in which the interviewer asked him if he felt that society should spend huge sums on scientific projects. Carl Anderson replied: "If you ask how many millions or billions of dollars a fundamental particle is worth, the answer is that I don't know. Doing science is a matter of faith. You just have to explore the physical world. Curiosity is a part of human nature, and there will always be science for the sake of science — for the sake of pure understanding."

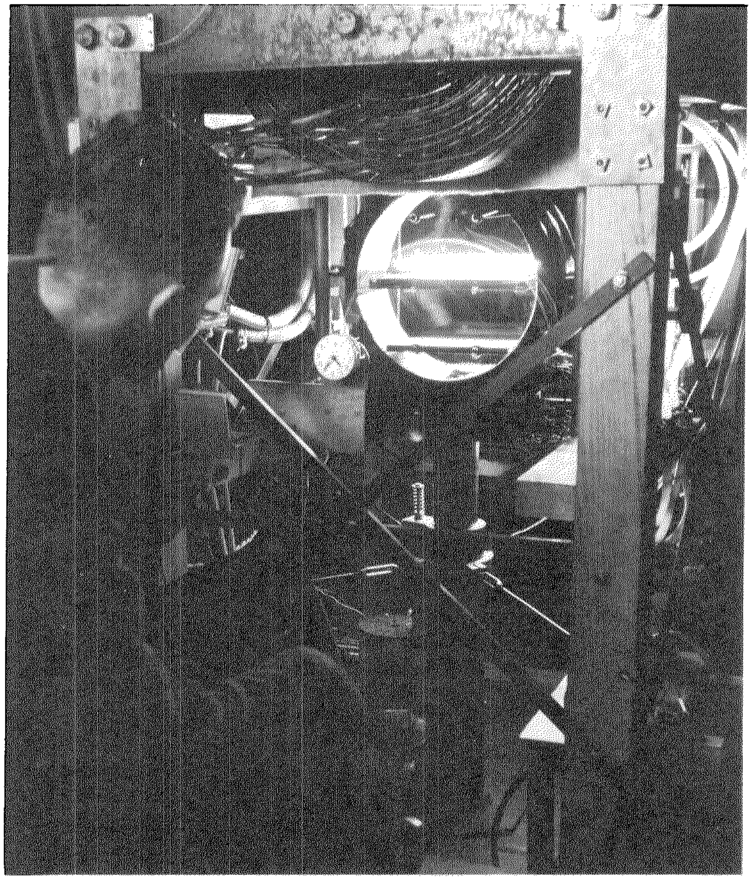
The young man who was able to speak Swedish to a fisherman and to converse with a king, is also obviously a competent spokesman in English in behalf of science. ☐ *-JB*

Cosmic Rays
A Scientific Cornucopia

by Robert B. Leighton

CARL ANDERSON once remarked to me that, if we can find how to measure something that couldn't be measured before, or how to measure it much more accurately, we are almost sure to find something interesting. The story of the positron and of the ensuing stream of amazing discoveries that followed is an illustration of those rare, happy instances in which several essential factors came together under just the right circumstances to bear great fruit.

By the late 1920s, cosmic rays had developed into a very active field of research that had uncovered many intriguing and rather puzzling facts which resisted satisfactory explanation in terms of the particles, radiations, and physical interactions then recognized. The most characteristic property of the rays near sea level was their great penetrating power. By analogy with X rays, whose penetrating power was known to increase as the voltage across the X-ray tube is increased, the sea-level cosmic rays would appear to correspond to X-ray tube voltages of hundreds of millions of volts. Yet, above a few thousand feet altitude, the intensity of cosmic radiation, as measured by the rate of production of ions in the air, increased rapidly with height, indicating the presence at high altitiudes of a highly absorbable (lower "voltage") component. Both of the above features showed a regular variation with latitude (specifically with geomagnetic latitude) that signaled the presence of charged particles among the primary rays outside the earth's atmosphere. The problem of untangling all the known effects and placing them into a coherent pattern, in terms of incoming primary rays interacting with the atmosphere to produce various secondary effects, was difficult because of the complexity of the phenomena and the relative coarseness of the observing tools of the time. These were mainly ionization chambers, which measured only the total ionization produced, irrespective of the nature or energies of the particles or radiations present.



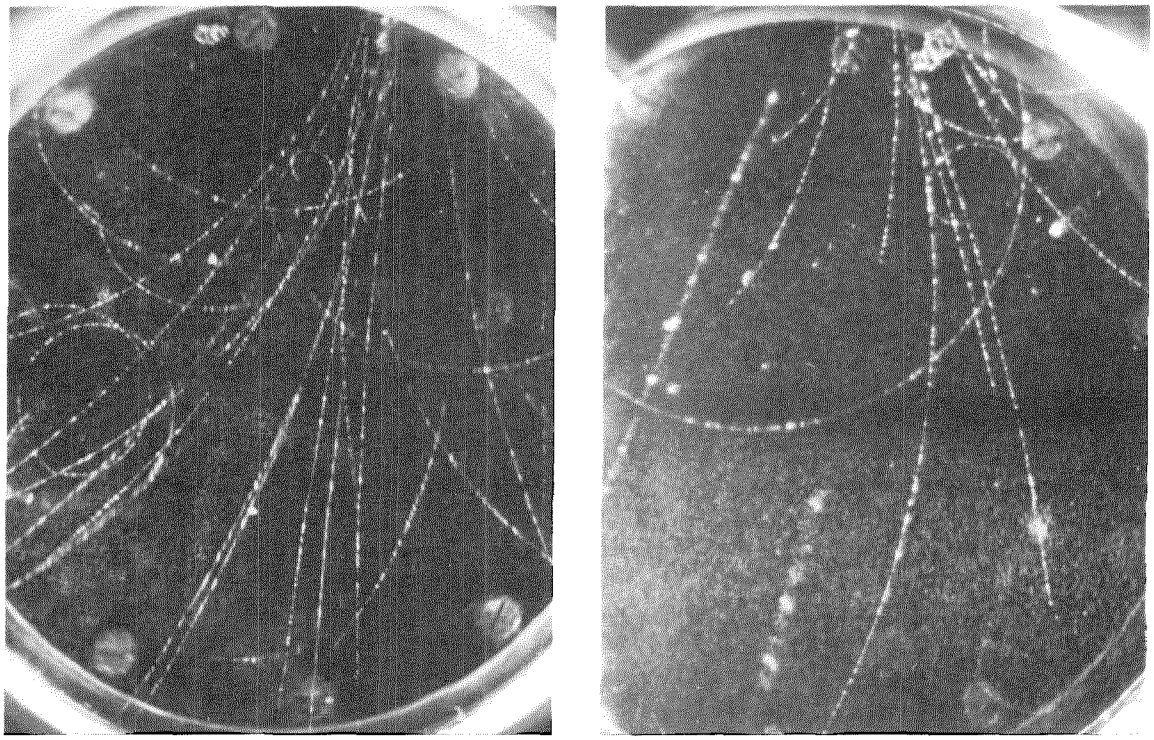
In this 1949 photograph Robert Leighton looks for tracks in a "falling cloud chamber," designed to take full advantage of the magnetic field. While the particles passed through, the chamber remained enclosed by the magnet, and then dropped into view during the fraction of a second that it took the droplets to form tracks. The instrument was used to study the disintegration products of the muon.

At about the same time, the right basic tool for the problem became ripe for exploitation: the cloud chamber within a strong magnetic field (the "magnet cloud chamber"). The cloud chamber itself is a well-known device that renders visible the tracks of charged particles moving through it (by condensation of a supersaturated vapor into droplets upon the ion trails left by the particles along their paths). It had long been a valuable tool in the study of the alpha, beta, and gamma rays of radioactivity and the nuclear disintegrations these rays sometimes induce in their passage through matter.

The addition of a magnetic field by Skobeltsyn in 1929, in his study of gamma rays emitted by radioactive substances, provided the means for measuring the sign of charge and the momentum of charged particles. Anderson at Caltech, and others elsewhere, soon adopted this technique. (The product of the magnetic field strength B, and the radius of curvature R of the particle's path, is proportional to the momentum mv of the particle.)

To this point, cloud chambers were triggered on a preset time cycle that was unrelated to the possible passage of particles through the chamber; the events appearing in the chamber were effectively selected at random. The use of Geiger Müller counters in so-called coincidence arrays, which had been introduced by Bothe and Kolhörster in the late twenties, permitted one to distinguish between, say, single, unaccompanied particles and two, three, or more time-coincident particles; this technique was first combined with a magnetic cloud chamber at Cambridge in 1933. This selectivity provided a powerful means of enriching cloud chamber pictures in whatever kind of event was of interest, and greatly speeded up the collection of data. That technique, too, was rapidly adopted by others.

Finally, the right combination of people to apply the right tools to the problem existed at Caltech in the late twenties and early thirties. Robert A. Millikan had long recognized the scientific importance of cosmic rays and had himself led an energetic group of researchers including Ira S. Bowen, H. Victor Neher, and (later) William H. Pickering in a worldwide, sea-level to mountaintop (and airplane) series of measurements. Millikan had data, he had questions to be answered, and, as chief executive of Caltech and world-recognized scientific leader, he had the necessary influence and financial sources to embark upon any new research direction he saw fit in order to further his scientific interests.



Photographed in the cloud chamber in the 1930s, both pictures show small showers of electrons and positrons, the electrons curving to the left, the positrons to the right.

In 1930 Anderson had just finished his PhD research, using a cloud chamber to study the properties of photoelectrons produced by X rays. He appealed to Millikan for permission and support to stay at Caltech for one postdoctoral year to study the scattering and absorption properties of the radiation from Thorium C″, which emitted 2.6 million-volt gamma rays. At first, Millikan turned down his request, citing the importance of gaining a broad viewpoint that going elsewhere would help to foster. Later, perhaps seeing the magnet cloud chamber as the key to revealing the detailed composition of the cosmic radiation, he reversed himself and argued Anderson *out* of going elsewhere, persuading him to stay at Caltech to design and build a new, super-powerful magnet cloud chamber and use it to study the composition of the cosmic radiation. By not supporting the proposed study of Th C″, Millikan may have delayed by a year or more Anderson's discovery of the positron, which almost certainly would have resulted from that study; on the other hand, shifting Anderson's attention to the cosmic rays may also have accelerated the discovery of the mu meson. In any case, it was most fortunate for Anderson, for Millikan, and for science that things happened as they did.

The steps that led to the discovery of the positron in 1932 are detailed earlier in this issue. Those steps were of course but a part of the whole Caltech effort, which aimed toward a general investigation of the composition of the cosmic radiation. As far as the sea-level (Pasadena) radiation was concerned, Anderson's randomly triggered pictures up to 1933 showed that:

1. Nearly all of the cosmic ray particles produced a density of ionization corresponding to singly charged particles moving at close to the speed of light. (The ion density produced by a rapidly moving charged particle varies directly as the square of its charge, and inversely as the square of its speed.)
2. The curvatures of the tracks in the magnetic field corresponded to particle energies up to at least 5000 MeV.
3. Positive and negative single particles occurred in roughly equal numbers, and accounted for by far the greatest part of the ionization.
4. No appreciable fraction of particles whose curvature corresponded to electron-energies of less than 500 MeV could be as heavy as protons.
5. Occasionally, groups or *showers* of time-associated tracks occurred in which roughly equal numbers of positive and negative particles were present.

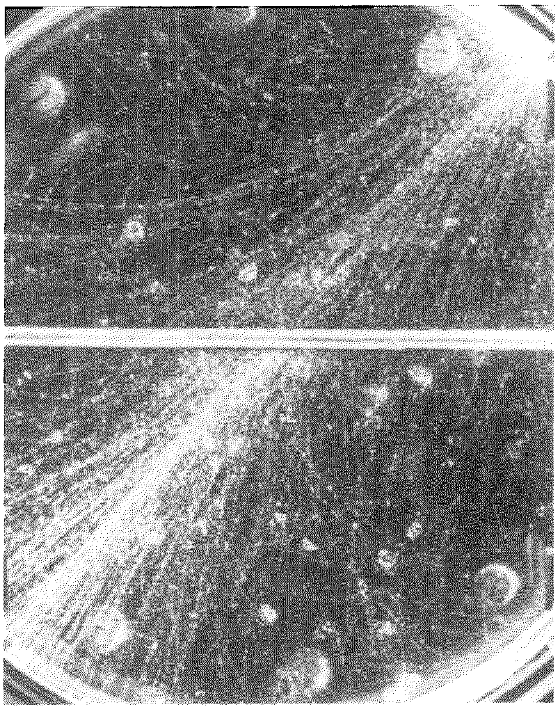
When these results were interpreted in terms of particles then known (including, of course, the positron), the conclusion was that essentially *all* of the particles involved must be electrons and positrons, but it was recognized that the penetrating power of the highest energy component was much greater than the somewhat crude theoretical ideas of the time would have predicted. That is, the absorptive interaction of these ''electrons'' with matter (the earth's atmosphere, the cloud chamber gas, or lead or carbon plates placed inside the chamber) was anomalously weak. At the same time, the mechanisms and circumstances involved in the formation and decay of the electron-positron showers were completely obscure.

At about this time, Anderson's first graduate student, Seth H. Neddermeyer, assumed an important role in the cloud chamber studies, in a fruitful collaboration that extended for several years after Neddermeyer received his doctorate.

Anderson and Neddermeyer attacked the mystery of the absorptivity of high-energy ''electrons'' directly by measuring the energy losses of a number of these single particles, whose energies (if they *were* electrons) were less than about 250 MeV, as the particles traversed a lead plate inside the cloud chamber. These measurements showed definitely the existence of cases in which the energy loss was quite large, and entirely consistent with theoretical expectations for electrons. They also showed, equally definitely, the existence of cases where the loss was much smaller than expected.

Now, the mechanism of the energy losses in question — that is, by radiation or electromagnetic waves (photons) as the charged particle is deflected this way and that by its close encounters with charged atomic nuclei — is such that a lightweight charged particle like an electron, being relatively easily deflected, will radiate strongly. Similarly, a heavier, less easily deflected particle will radiate only weakly, namely, in inverse proportion to the square of its mass. Thus, the measurements could have been interpreted as indicating the presence of two groups of particles — one of electronic mass, and the other of much greater than electronic mass.

The latter group of particles, however, *could not be as massive as protons*, for protons having the same (or greater) track curvature as a 250 MeV electron would be moving much slower than the speed of light and therefore would have left a much denser trail of ions in the chamber. In the intellectual climate of the time, most people were not yet ready to resolve this ''two-electron'' paradox so simply — that is, by postulating the existence of intermediate-mass particles — but preferred to cling to the notion that, for some reason or other, under certain (unspecified) conditions, high-energy electrons and positrons did not lose significant amounts of energy by nuclear encounters.

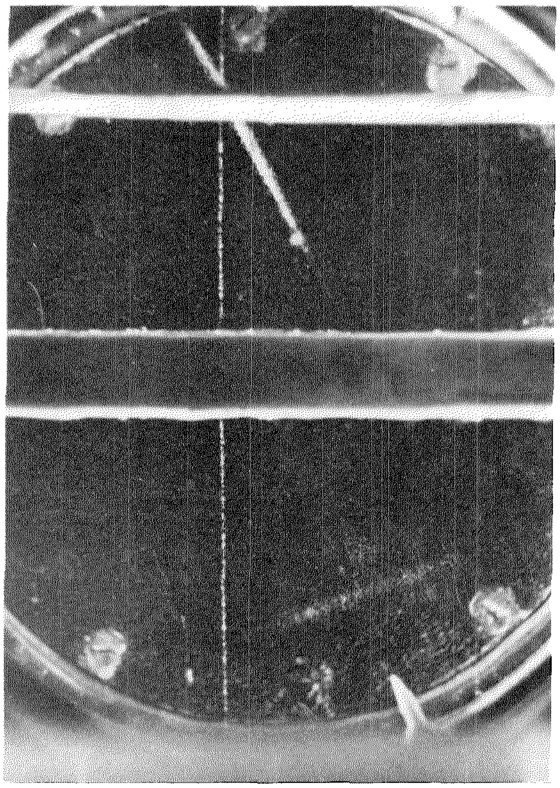


This relatively large electron shower was photographed in the late 1940s in a B-29 at 30,000 feet.

For reasons not directly related to these considerations, Millikan was anxious to have cloud chamber data on the composition of cosmic rays at higher altitude, and he suggested to Anderson that the apparatus be operated at the top (14,000 feet altitude) of Pikes Peak, Colorado. The interesting story of how this was carried through is related in an earlier issue of *E&S* (September 1981). It suffices to say here that some 10,000 photographs were obtained on Pikes Peak during the summer of 1935. These pictures revealed that the frequency of occurrence of electron showers, relative to that of single particles, was much greater at Pikes Peak than at Pasadena. Aside from the exact numbers involved, which were presumably of great interest to Millikan, what probably excited Anderson and Neddermeyer most was the fact that these photographs included hundreds of new examples of electron showers, and it now became possible to measure the energy loss in lead for electrons found in showers, up to energies as great as 400 MeV. The result was clear: *For electrons (+ or −) occurring in showers, the energy loss in the lead plate agreed within observational uncertainty with theoretical expectations.*

Two important conclusions could now be drawn:

1. The fact that high-energy (shower) electrons *do* radiate in accord with theory provides in itself a natural explanation of the electron showers, in terms of a chain of successive processes of radiative production of photons and their subsequent absorption to produce new electron pairs.
2. The enormously weaker radiative losses by the singly occurring "electrons" exists because of a *fundamental difference in the character of the particles*, not because of a difference in energy.



The single vertical track of an unaccompanied penetrating particle was most likely made by a muon. The broad slanting track near the top was made by a slow-moving particle that passed through the chamber shortly before the muon.

From late 1936 on, Anderson and Neddermeyer adopted the assumption of a mass intermediate between the electron and the proton as "the best working hypothesis" for understanding the behavior of the anomalously penetrating, singly occurring particles. This idea was not immediately widely accepted, however, until several individual cases, where the mass itself could be estimated by one of the several available methods, were found by Anderson and Neddermeyer, and by others. These mass estimates were generally consistent with a value near 200 electron masses. The new particles were called mesotrons.

Quite independent of the cosmic ray work was a striking suggestion by Yukawa in 1935 that nuclear forces might be mediated by a massive boson (a particle having integral spin) analogous to the mediation of the electric force by the massless boson, the electromagnetic photon. Yukawa's theory required a boson mass of about 200-300 electron masses. As might have been expected, this idea too was generally resisted, but soon some people came to regard the Anderson-Neddermeyer mesotron as a confirmation of Yukawa's ideas.

That *both* the mesotron and Yukawa's particle might have been more enthusiastically received is correct; that they were the *same particle*, unfortunately, was wrong. For Yukawa's particle to perform its role of carrying the nuclear force, it must certainly react strongly with nuclear matter; yet, the mesotron's main property was its manifest propensity for *not* interacting with matter other than through its electric charge. This problem was of course well recognized, and it was not resolved until several years later.

The Pikes Peak expedition drew attention to yet another important component of cosmic rays — the nuclear component. The picture showed a considerable number of cases in which a nucleus in the lead plate (or other nearby nucleus outside the chamber) was violently disrupted by a cosmic ray particle, the total energy of the fragments being at least several thousand million electron volts (GeV). These cases were remarked upon by Anderson and Neddermeyer in their 1936 paper describing the Pikes Peak results. If it were not already so, it must now have been obvious to all, that the cosmic radiation represented not only an important phenomenon in its own right, but also a significant, ubiquitous, useful, free source of energetic particles of every possible type, a source extending to incredibly high particle energies. (Indeed, even today's largest accelerators cannot match the energies present in some individual cosmic ray primaries.) This aspect of the cosmic rays became a major theme for Anderson's research program.

The five-year-long calamity of World War II soon intervened, and little progress in basic science was made during that time. Indirectly, of course, much progress was made in electronics and other technologies that were widely useful in science and elsewhere after the war. Moreover, the popular appreciation of several technical wartime developments such as radar, automatically controlled aircraft landings, nuclear weapons, and the like — which were (rightly or wrongly) associated in the public mind with basic science — led to an unprecedented availability of funds for basic research. This meant that the scientific enterprise grew rapidly once the war had ended.

Within two years after the war, two major advances in elementary particle physics were made, both in England. One was that the true Yukawa particle, called the pi meson or pion, was found by a group at Bristol, using a new technique that employed very thick, particle-sensitive photographic emulsions as a recording medium for cosmic ray particles. It turned out that the pion weighs about 275 times as much as an electron, and in the free state decays in a hundred-millionth of a second or so into Anderson and Neddermeyer's mesotron (now called a mu meson or muon) and a neutrino (postulated by Pauli in 1931).

The second major advance was the discovery of two more kinds of unstable particles in cosmic-ray-induced nuclear reactions. This was done by a group at Manchester, using a magnet cloud chamber. These particles, one neutral and one charged, were the first of a considerable number of so-called strange particles that were subsequently discovered, some in cosmic rays and some in high-energy accelerator experiments.

By this time there was a better "market" for new particles, and relatively little resistance to whatever new results or ideas came along. There was, however, a certain exasperation in some quarters at the unexpected, and seemingly unnecessary, proliferation of the experimenters' "zoo" of strange particles. I. I. Rabi is reported to have greeted the announcement of the muon with: "Who ordered *that*?" And, as I remember it, Arthur Roberts was prompted in the early or mid-fifties to ask, plaintively (to his own piano accompaniment):

> There was *one* meson, *two* mesons —
> Some people thought that was *too few*
> mesons —
> But what're ya gonna do with *twenty-two*
> mesons?
> Some people don't know when to stop!

The first particle to be discovered by use of a high-energy accelerator was the neutral pi meson, found by a group at Berkeley in 1950. For the next decade or so, cosmic ray experiments continued to provide significant data on the new particles but, predictably, the field was eventually taken over by the high-energy machines once their energy surpassed the threshold for strange-particle production.

For almost two postwar decades Anderson's research group contributed significantly to the study of the elementary particles using the cosmic radiation. Even as that activity gradually waned, the two experimental fields of high-energy particle physics and cosmic rays remained alive and well at Caltech. Caltech faculty and students have led or participated in many significant experiments at the major high-energy facilities, and other Caltech faculty have pursued cosmic ray research well above the atmosphere and into interplanetary space — and beyond. Detailed accounts of new results in these fields have often appeared in these pages and will doubtless continue to do so in the future. Thus, the amazing story of the composition of the cosmic rays is by no means finished, and the cornucopia's fruits still flow.

Even though we are not yet at the end of the story, in retrospect we see that the decade of the thirties reached an important climax. The discovery and acceptance of the neutrino, the neutron, the positron, and the mesotron, all in the span of a few years, marked the opening of a new era — or better, a reawakening — of elementary particle physics. These discoveries stimulated still others in a chain that has not been broken to this day.

The discovery of the positron may be called serendipitous, though it was far from accidental; of the muon, the discovery might also be termed serendipitous, in the sense that the sea-level cosmic radiation consisted of a practically pure beam of muons, simply waiting to be recognized. The tenacity and insight that Anderson and Neddermeyer showed in deducing and then proving the true nature of these penetrating cosmic rays is a model of scientific detective work. They did indeed "find something interesting." □

Fifty Years of Antimatter

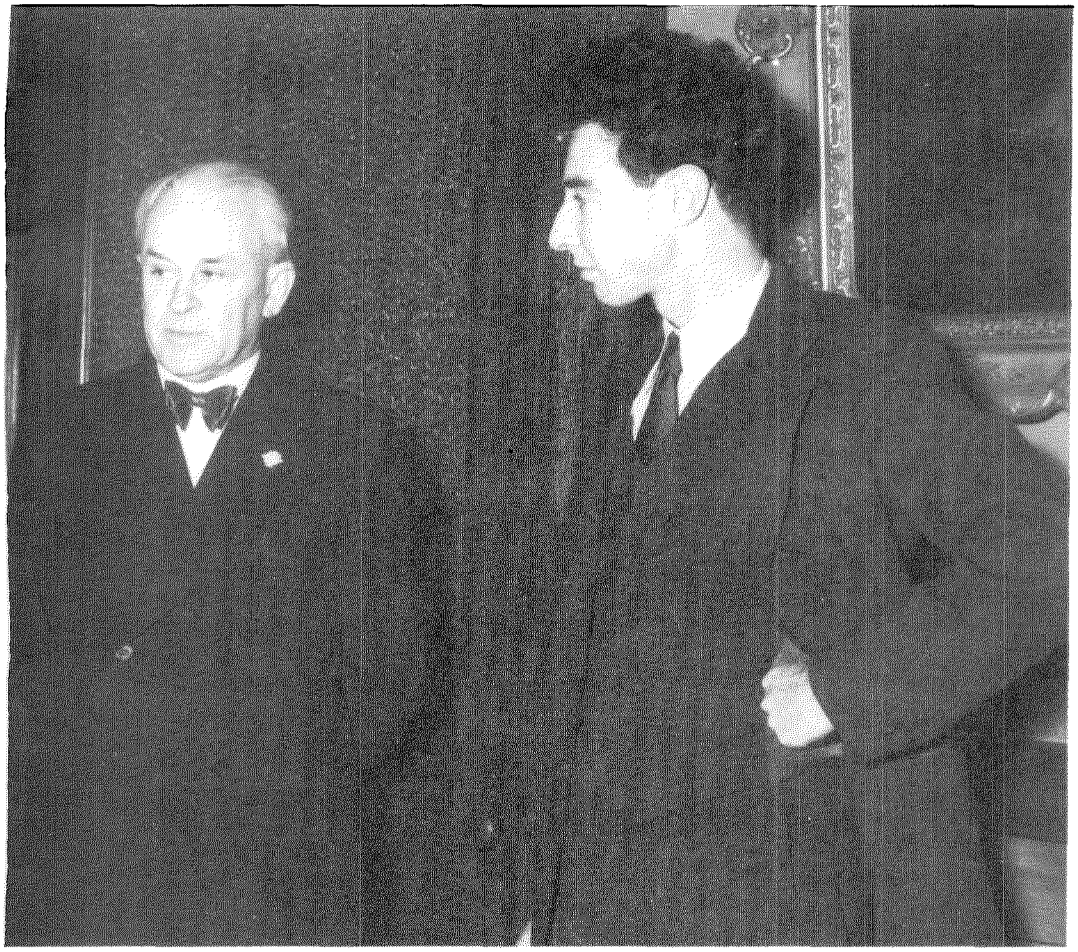
by John H. Schwarz

THE CONCEPT of antimatter arose with P. A. M. Dirac's pioneering work of 1928 — four years before Carl Anderson's discovery of the positron confirmed it. Dirac formulated an equation for the electron incorporating the requirements of quantum mechanics, electrodynamics, and special relativity. This equation not only successfully accounted for small relativistic effects in the energy levels of the hydrogen atom, but led to additional predictions that were completely new and unexpected.

Although negative energy has no meaning in classical physics, Dirac's equation seemed to say that an electron could have negative energy. He argued, however, that a consistent interpretation would be possible by supposing that the negative energy states are all occupied and therefore unobservable. Furthermore, by supplying suitable energy it would be possible to knock an electron out of the "infinite sea of negative-energy electrons," creating a real positive-energy electron and a "hole" in the sea. This hole would behave as a particle in its own right, with properties identical to those of the electron, except that its electric charge would be opposite (positive). At first Dirac suggested that the holes be identified as protons, but he soon rejected this interpretation, since the proton is some 2000 times heavier than an electron. Thus by 1931 Dirac was predicting the existence of an "anti-electron." Few people had any belief that an actual particle existed, and so no search was under way at the time the particle was discovered in the following year by Anderson, who called it the positron (a contraction of "positive electron"). In recent years the positron has been found experimentally to have the same mass as the electron with extremely high precision.

The positron was the first antiparticle to be discovered, but it was clear from Dirac's work that *all* elementary particles should have their own antiparticles. In particular, he predicted the existence of antiprotons. Since they are very rare in cosmic rays (and interact high in the atmosphere) and more difficult than positrons to produce with particle accelerators because of their greater mass, it was not possible to confirm the existence of antiprotons until the proton synchrotron called the "Bevatron" was completed in Berkeley in 1955. It was the first accelerator with sufficient energy to create antiprotons by converting kinetic energy into mass in accordance with the rules of relativity ($E=mc^2$). The pace of discovery has quickened since then, and by now many more species of particles and antiparticles have been observed.

In modern theoretical treatments, matter and antimatter are described in a completely symmetrical fashion without the need for reference to the Dirac sea. The existence of antimatter is understood as a consequence of a fundamental symmetry — called TCP — that is an inescapable consequence of any relativistic quantum theory. T refers to time reversal, C to particle-antiparticle conjugation, and P to spatial inversion (parity). This symmetry means that a movie of antimatter



A photography session at Caltech in May 1935 involved these three famous physicists: from left to right, Paul Dirac, Robert Millikan, and Robert Oppenheimer. Dirac first formulated the concept of antimatter, for which he received the Nobel Prize in physics in 1933 at the age of 32.

— run backwards in time and side-reversed — is described by the same equations as ordinary matter in real life.

Nowadays positrons and antiprotons are the bread-and-butter tools of high-energy experimental physics, and such particles are produced by the trillions for use in colliding beam experiments. At SLAC (the Stanford Linear Accelerator Center) there are two "storage rings," called SPEAR and PEP, in which electrons and positrons circulate in opposite directions, guided by magnetic fields and accelerated by electric fields, making head-on collisions in several intersection regions that are observed by very sophisticated detector systems. Similar experiments are done at storage rings called DORIS and PETRA at DESY (the Electron Synchrotron Laboratory in Hamburg, Germany). Proton-antiproton colliding-beam experiments have recently begun at CERN (the large European high-energy physics laboratory) and will take place in a few years at Fermilab (its American counterpart in Batavia, Illinois). These are by far the highest-energy experiments of all and therefore of great current interest.

An interesting challenge that cuts across the disciplines of particle physics and cosmology is to reconcile the observed excess of matter over antimatter in the universe with the symmetry between them in the fundamental equations. There is some evidence that our galaxy is made entirely from matter, and it is generally believed that the same is true of all galaxies throughout the universe. Observations indicate that there is roughly one proton (and no antiproton) for every billion photons (the quanta of light) in the universe. In recent years a surprising amount of progress has been made toward deducing the relative numbers of photons, protons, and antiprotons from first principles within the context of a new type of quantum field theory that unifies the description of the strong nuclear forces with that of the electromagnetic and weak nuclear forces. These theories also predict the instability of protons with a lifetime of about 10^{31} years. Numerous large experimental efforts are currently under way searching for proton decay. The chain of events that has followed the first sighting of a positron 50 years ago is remarkable indeed! Now, particle physics and cosmology appear to be entering a new era that should be just as exciting and challenging. □

The Search for Fractional Charges

by Robert McKeown

CARL ANDERSON'S *discovery of the positive electron* — the positron — validated by the mid-1930s the Dirac theory that every particle in nature has its antiparticle. It also reinvigorated the interest of physicists in these smallest constituents of ordinary matter — neutrons and protons (which form atomic nuclei) and electrons. In the years since an almost endless series of pairs of elementary particles have been found, but in 1964 Caltech physicists Murray Gell-Mann and George Zweig introducted a new concept. They proposed that two of those particles — neutrons and protons — are composed of subunits called quarks.

Today this view is very well established experimentally and is the basis for our present theories of the fundamental particles, in spite of the fact that no one has ever isolated a quark nor found a free quark in nature. In fact, current theories maintain that quarks exist only in certain combinations that correspond to the observed particles and thus cannot be isolated. The proton is a combination of three quarks, while the neutron corresponds to a different configuration of three quarks. Of course, just as the electron has an antiparticle (the positron), the quarks have antiparticles called antiquarks. Various configurations of quarks and antiquarks have been observed, but they are not arbitrary — only the particular combinations allowed by theory are seen.

One property of the allowed combinations is that the particle that results will have "integral charge." It was first demonstrated by Millikan that particles possess electric charge in multiples of the fundamental unit, e. The proton has charge +e and the electron −e. Quarks, however, have the peculiar property that their charges are multiples of ⅓e, so that they have "fractional charge." Most experimental attempts to isolate quarks or find free quarks utilize this special property as a signature. Many searches for other fractional charges have been attempted, but most concentrate on looking for charges that are ± ⅓e or ± ⅔e. They include cosmic ray experiments, surveys of bulk matter (such as lunar rocks), and efforts to observe production of fractionally charged particles in high-energy accelerators. Until recently all these experiments yielded negative results. (The observation of a fractional charge, incidentally, does not necessarily imply that an isolated quark has been found. Other fractionally charged particles may exist in nature, and their discovery would be just as significant as the discovery of a free quark.)

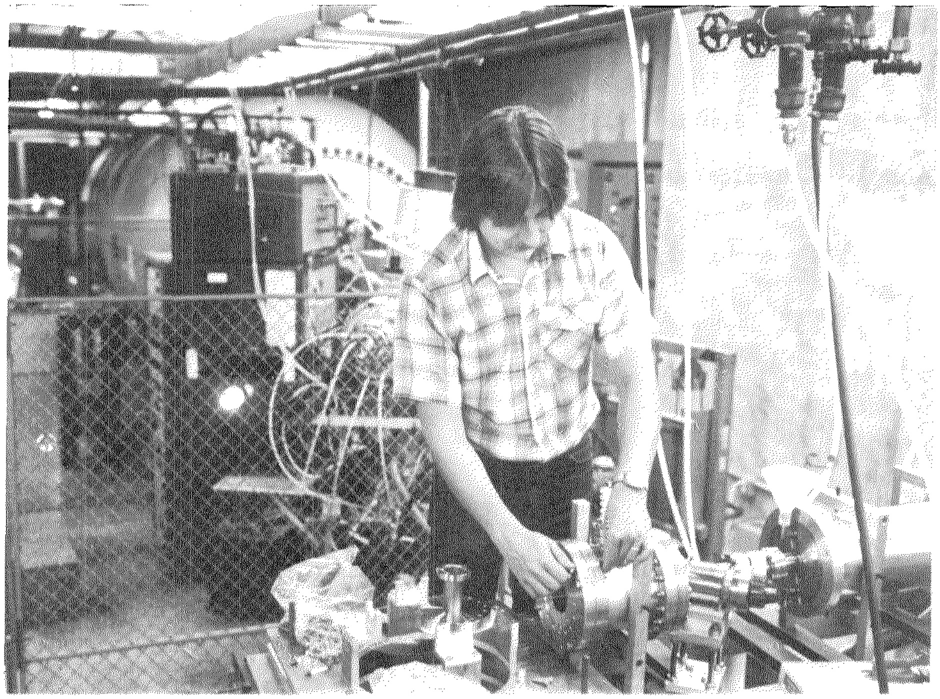
During the last few years, Stanford University Professor W. Fairbank and his collaborators have been running an experiment that consistently indicates the presence of fractional charges that are multiples of ⅓e. Their experiment is analogous to Millikan's famous oil-drop experiment to determine the charge of the electron, except that they use superconducting niobium spheres levitated by magnetic fields. (Millikan used charged oil droplets.) The charge on a niobium sphere is measured by observing the motion of the sphere under the influence of an applied electric field. Of course, all that can be measured is the total charge on the sphere; the fractional charge (or charges) may reside anywhere in or on the sphere.

No other experimental effort has reproduced or corroborated this result, although none has duplicated the experimental conditions of the Stanford experiment. Similar measurements on iron spheres by a group in Italy give null results. Zweig has pointed out, however, that the fractional charges may have unique chemical properties that cause them to concentrate only in certain materials. Nevertheless, the experimental results to date indicate that if free fractional charges exist in nature they are very rare. We could expect to find only one in about 10^{18} normal atoms of material. Several additional experiments are in progress that attempt to verify the result obtained by Fairbank.

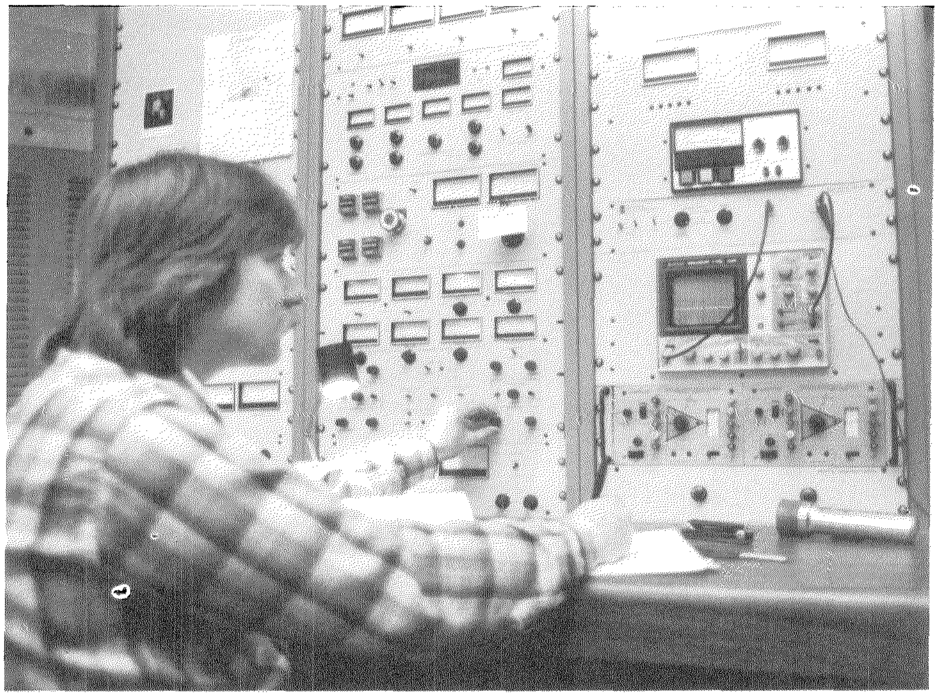
One of those experiments is being readied here at Caltech in the Kellogg Radiation Laboratory by a group that includes Charles Barnes, professor of physics, and me, plus research fellows B. H. Cooper and J. H. Thomas, and graduate students Richard Milner and Raymond Rau. The technique to be used in our search involves extracting the fractionally charged particles from the host material (niobium, for example) by eroding the material with an ion beam. The charged particles that are ejected in this process (including the fractional charges) will be injected into an electrostatic tandem accelerator and accelerated by several million volts. The energetic particles will then be electrostatically deflected into a particle detector where they will be counted and identified by their energy and amount of deflection. This technique allows determination of the charge of the detected particles without regard for their mass, which is unknown. The detection of fractional charges with this apparatus would also allow measurement of other properties, such as their mass, as well as collection and concentration of these particles for study or technological application.

A variety of materials can be searched with this method, although the initial effort will concentrate on niobium. In fact, it will be possible to search the actual niobium spheres used in the Stanford experiment. The Caltech experiment is designed to detect fractional charges at the concentration level indicated by the Stanford results, and a niobium sphere of the size used in the Stanford experiment can be searched in less than an hour using the accelerator techniques to be employed at Caltech. The apparatus for the Caltech experiment is now under construction, and measurements should begin in early 1983.

Perhaps, even as Robert Millikan determined the charge of the electron and Carl Anderson proved the existence of the positive electron, we will be able to find a fractional charge and thus take one more step in the understanding of the fundamental constituents of matter in our universe. ☐



Looking for charged particles in the 1980s involves considerably more sophisticated equipment than Carl Anderson's magnet cloud chamber of the 1930s, as these photographs indicate. Above, Robert McKeown assembles instruments being prepared for an experiment in search of free fractional charges. In the background is the high-current, high-resolution 3-MV tandem accelerator recently installed at Caltech that will be used in the experiment. The control panel for the accelerator is shown below.



The Picture That Was Not Reversed

by Eugene Cowan

. . . *continued from page 12*

The quotations on pages 11 and 12 from the scientific literature indicate the flavor as well as the facts of the era of the discovery of the positron. And at the end of this article are three short items — not from the scientific literature — that show another aspect of doing science.

I have put this story together as a scientist who spent 25 years listening to the whir of generators and the bang of cloud chambers in the laboratory started by Carl Anderson. With Robert Leighton, myself, and others the work continued after 1945 along Carl's path. The light of the arc became the blinding flash of Xenon tubes, and the "bang" of Carl's chamber deepened to the "boom" of a walk-in monster. The thousands of pictures multiplied a hundredfold, and the world of elementary particles came into closer view as the years fell behind. And we faced the path ahead. Now we turn to face about. Words from the Fowler/Rutherford letter echo across the 50 years. Viva Caltech! And we answer back. Viva Carl Anderson! ☐

Googly-Antigoogly

THE TASK of naming new particles has occasionally stimulated some flights of unexpected fancy in 20th-century physicists. Carl Anderson stuck to a rational approach, however, when, six months after its discovery, he suggested the name "positron" as a contraction of positive electron. He added that from symmetry considerations the electron should really be called the "negatron," but 40 years of usage was too much to overturn, and the electron remained to pair with the positron.

It might have been worse. A British physicist with a classical bent suggested that the positive electron be called the "oreston," since Orestes was the brother of Electra. Another sports-minded British physicist wanted the name "googly," from the peculiar hop of a cricket ball when it curved in the wrong direction. Physicists escaped, perhaps only by months, the fate of attending symposia on googly-antigoogly annihilation.

Practical Applications

NO ONE can possibly quantify the benefits to mankind of the great discoveries of science. Even when those benefits are direct, however, their application often awaits other discoveries. Hundreds of years lie between Gilbert's 16th-century discovery of magnetic forces and the electric power of the 20th century. Isaac Newton died in 1727, and his equations ride with every airplane that flies today.

Things may be speeding up, though. After less then 50 years, Carl Anderson's discovery of the positron made possible a new medical technique (called PET for positron emission tomography) that allows physicians to examine the brain and body in ways never before possible. They can now view metabolic changes in the activity of the organ under examination — seeing an actual picture of the changes in the brain when, for example, a loud noise becomes soft music. They can also watch blood flow and metabolism in the heart and blood vessels, which may lead to a better understanding of the mechanisms of heart attacks and strokes.

The PET scanner works because positrons consist of antimatter. In studies with this instrument, a subject is injected with some biochemical (glucose, for example) that is tagged with a short-lived radioactive substance that emits positively charged particles — positrons. Since the positron is an anti-electron, when it meets an electron (which is negatively charged) in the body's cells, the two particles completely annihilate each other. In the process, they produce two gamma rays moving in directly opposite directions with an energy corresponding to the mass of the destroyed particles (according to Einstein's equation $E = mc^2$). These gamma rays can be detected by a scanning device. Collected and translated into color-coded images, the resulting patterns indicate the intensity of metabolic activity — that is, the rate of consumption of tagged biochemical — in whatever organ is under scrutiny.

No Matter

BACK IN the 1950s the *San Francisco Chronicle* published an article about antimatter that evoked a response in the form of a poem from physicist Harold Furth. In January 1967 *E&S* reprinted an excerpt from the *Chronicle* story and the entire poem in an article written by Murray Gell-Mann, now Robert Andrews Millikan Professor of Theoretical Physics at Caltech and Nobel Laureate. With permission from both Furth and *The New Yorker* (in which the poem originally appeared), we once more offer these items as our final word on antimatter — at least for this special issue of Caltech's magazine.

PERILS OF MODERN LIVING

> A kind of matter directly opposed to the matter known on earth exists somewhere else in the universe, Dr. Edward Teller has said . . . He said there may be anti-stars and anti-galaxies entirely composed of such anti-matter. Teller did not describe the properties of anti-matter except to say there is none of it on earth, and that it would explode on contact with ordinary matter.
>
> *–San Francisco Chronicle*

Well up beyond the tropostrata
There is a region stark and stellar
Where, on a streak of anti-matter,
Lived Dr. Edward Anti-Teller.

Remote from Fusion's origin,
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from Earth.

Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.*

—Harold Furth

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DEGREES NOW HELD (OR EXPECTED)

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ALUMNI FLIGHTS ABROAD

This program of tours, originally planned for alumni of Harvard, Yale, Princeton, and M.I.T., is now open to alumni of California Institute of Technology as well as certain other distinguished colleges and universities. Begun in 1965 and now in its sixteenth year, it is designed for educated and intelligent travelers and planned for persons who might normally prefer to travel independently, visiting distant lands and regions where it is advantageous to travel as a group.

The program offers a wide choice of journeys to some of the most interesting and unusual parts of the world, including Japan and the Far East; Central Asia, from the Khyber Pass to the Taj Mahal and the Himalayas of Nepal; the surprising world of South India; the islands of the East, from Java and Sumatra to Borneo and Ceylon; the treasures of ancient Egypt, the world of antiquity in Greece and Asia Minor; East Africa and Islands of the Seychelles; New Guinea; the South Pacific; the Galapagos and South America; and more.

REALMS OF ANTIQUITY: A newly- expanded program of itineraries, ranging from 15 to 35 days, offers an even wider range of the archaeological treasures of classical antiquity in Greece, Asia Minor and the Aegean, as well as the ancient Greek cities on the island of Sicily, the ruins of Carthage and Roman cities of North Africa, and a comprehensive and authoritative survey of the civilization of ancient Egypt, along the Nile Valley from Cairo and Meidum as far as Abu Simbel near the border of the Sudan. This is one of the most complete and far-ranging programs ever offered to the civilizations and cities of the ancient world, including sites such as Aphrodisias, Didyma, Aspendos, Miletus and the Hittite citadel of Hattusas, as well as Athens, Troy, Mycenae, Pergamum, Crete and a host of other cities and islands of classical antiquity. The programs in Egypt offer an unusually comprehensive and perceptive view of the civilization of ancient Egypt and the antiquities of the Nile Valley, and include as well a visit to the collection of Egyptian antiquities in the British Museum in London, with the Rosetta Stone.

SOUTH AMERICA and THE GALAPAGOS: A choice of itineraries of from 12 to 29 days, including a cruise among the islands of the Galapagos, the jungle of the Amazon, the Nazca Lines and the desert of southern Peru, the ancient civilizations of the Andes from Machu Picchu to Tiahuanaco near Lake Titicaca, the great colonial cities of the conquistadores, the futuristic city of Brasilia, Iguassu Falls, the snow-capped peaks of the Andes and other sights of unusual interest.

EAST AFRICA—KENYA, TANZANIA AND THE SEYCHELLES: A distinctive program of 5 outstanding safaris, ranging in length from 16 to 32 days, to the great wilderness areas of Kenya and Tanzania and to the beautiful islands of the Seychelles. The safari programs are carefully planned and comprehensive and are led by experts on East African wildlife, offering an exceptional opportunity to see and photograph the wildlife of Africa.

THE SOUTH PACIFIC and NEW GUINEA: A primitive and beautiful land unfolds in the 22-day EXPEDITION TO NEW GUINEA, a rare glimpse into a vanishing world of Stone Age tribes and customs. Includes the famous Highlands of New Guinea, with Sing Sings and tribal cultures and customs, and an exploration of the remote tribal villages of the Sepik and Karawari Rivers and the vast Sepik Plain, as well as the North Coast at Madang and Wewak and the beautiful volcanic island of New Britain with the Baining Fire Dancers. To the south, the island continent of Australia and the islands of New Zealand are covered by the SOUTH PACIFIC, 28 days, unfolding a world of Maori villages, boiling geysers, fiords and snow-capped mountains, ski plane flights over glacier snows, jet boat rides, sheep ranches, penguins, the Australian "outback," historic convict settlements from the days of Charles Dickens, and the Great Barrier Reef. Optional visits can also be made to other islands of the southern Pacific, such as Fiji and Tahiti.

CENTRAL ASIA and THE HIMALAYAS: An expanded program of three itineraries, from 24 to 29 days, explores north and central India and the romantic world of the Moghul Empire, the interesting and surprising world of south India, the remote mountain kingdom of Nepal, and the untamed Northwest Frontier at Peshawar and the Punjab in Pakistan. Includes the Khyber Pass, towering Moghul forts, intricately sculptured temples, lavish palaces, historic gardens, the teeming banks of the Ganges, holy cities and picturesque villages, and the splendor of the Taj Mahal, as well as tropical lagoons and canals, ancient Portuguese churches, the snow-capped peaks of the Himalayas along the roof of the world, and hotels which once were palaces of maharajas.

THE FAR EAST: Itineraries which offer a penetrating insight into the lands and islands of the East. THE ORIENT, 30 days, surveys the treasures of ancient and modern Japan, with Kyoto, Nara, Ise-Shima, Kamakura, Nikko, the Fuji-Hakone National Park, and Tokyo. Also included are the important cities of Southeast Asia, from Singapore and Hong Kong to the temples of Bangkok and the island of Bali. A different and unusual perspective is offered in BEYOND THE JAVA SEA, 34 days, a journey through the tropics of the Far East from Manila and the island fortress of Corregidor to headhunter villages in the jungle of Borneo, the ancient civilizations of Ceylon, Batak tribal villages in Sumatra, the tropical island of Penang, and ancient temples in Java and Bali.

Prices range from $2,350 to $4,500 from U.S. points of departure. Air travel is on regularly scheduled flights of major airlines, utilizing reduced fares which save up to $600.00 and more over normal fares. Fully descriptive brochures are available, giving itineraries in detail and listing departure dates, hotels, individual tour rates and other information. For full details contact:

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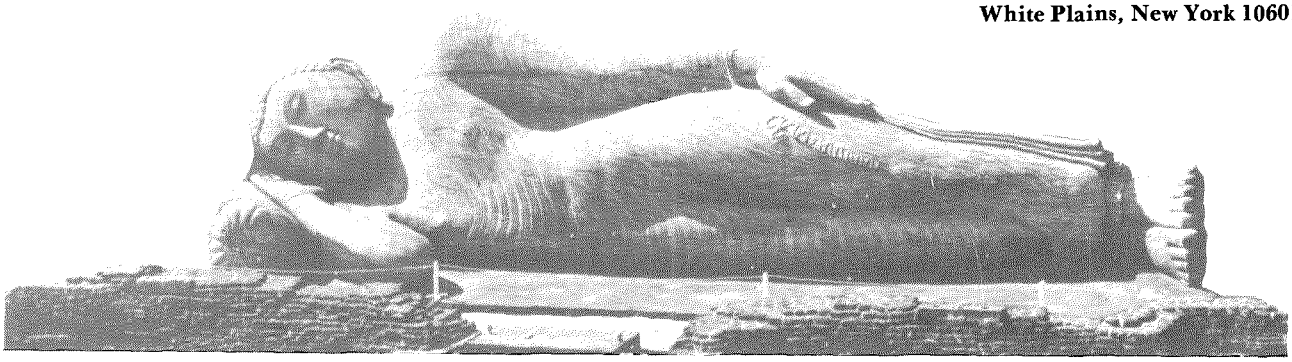
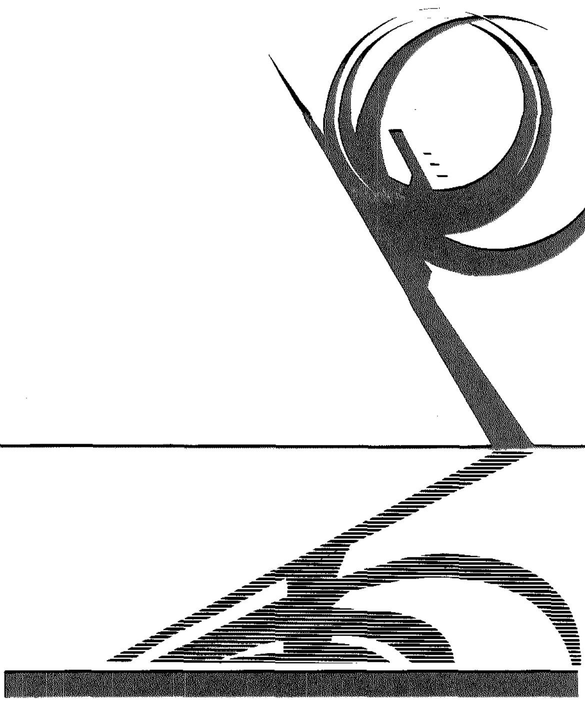




▶ The sculpture "**Aurora**" by artist Jerome Kirk symbolizes innovation and response... it was designed to commemorate Raychem's first 25 years and anticipates future success.

Random Walk

With Us This Year...

. . . at least two new students with unusual qualifications — youth and family ties. Graduate student Chi-Bin Chien was barely 16 years old when he registered at Caltech last year. He didn't actually arrive on the campus until this fall, however, because he was spending a year at Cambridge University in England on a Churchill scholarship. At 15, Chien was the youngest recipient of the bachelor's degree from Johns Hopkins University in the 106 years of the institution's existence, and he walked off with general and departmental honors plus the Donald E. Kerr Memorial Award in Physics. He will be continuing his work in physics at Caltech.

Another kind of rare case is that of Karl Clauser, the fifth member of his family and the first of the third generation of Clausers to register at the Institute. It all began when his grandfather, Milton U. Clauser, and his great-uncle, Francis, took three degrees apiece at Caltech in the 1930s. Francis is now Clark Blanchard Millikan Professor of Engineering Emeritus. Karl's father, Milton J., received a PhD in 1966 and is now a physicist with Sandia Labs in Albuquerque, New Mexico. His uncle, John Clauser, got a BS in 1964, and he is a physicist at Lawrence Livermore Laboratory.

In Memoriam

WILLIAM H. CORCORAN, Institute Professor of Chemical Engineering, died on August 21 while vacationing in Hawaii. Corcoran was an alumnus, with BS, MS, and PhD degrees from Caltech, and he was an active participant in the academic and administrative life of the community. He served for ten years as Caltech's first vice president for Institute Relations. He was a distinguished chemical engineer, educator, and industrial consultant, and the holder of many awards, including in 1980 the Engineer of the Year Award from the Institute for the Advancement of Engineering. He was also a member of the National Academy of Engineering.

A memorial service in Corcoran's honor was held in October, and *E&S* will report on it in a forthcoming issue.

Coming Up

WHEN Peter J. Wyllie (above) arrives at Caltech in July 1983, the man who shakes his hand most cordially is likely to be Barclay Kamb, professor of geology and geophysics. Wyllie, who comes as a professor of geology, will also be taking over as chairman of the Division of Geological and Planetary Sciences, and Kamb will be stepping down after holding that post for 11 years.

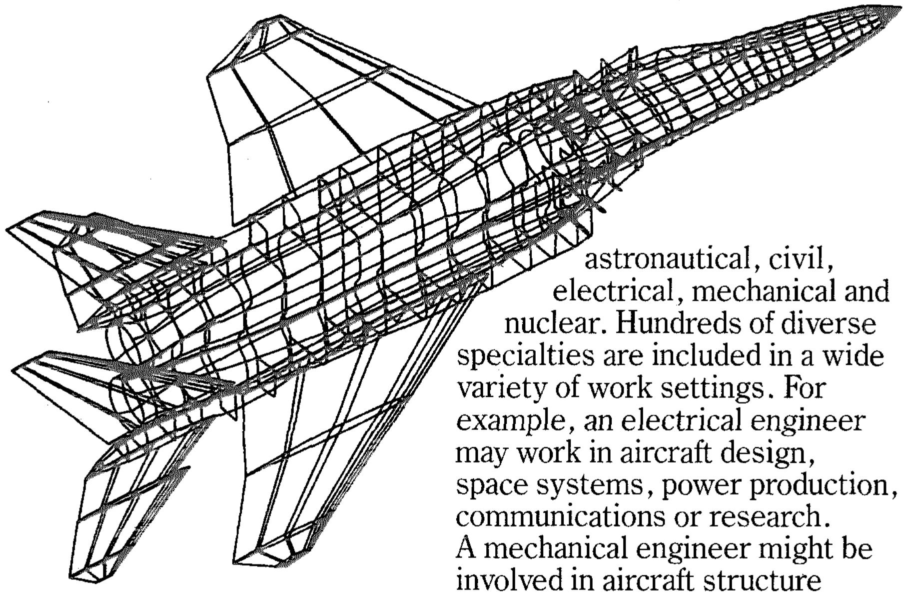
Wyllie, 52, is currently the Homer J. Livingston Professor and chairman of the Department of Geophysical Sciences at the University of Chicago. He went there in 1965 after being on the faculties of Leeds University in England, The Pennsylvania State University, and Scotland's University of St. Andrews, where he had received a BSc, a BSc with honors, and a PhD. He is an authority on the formation of igneous and metamorphic rocks, and he has over 200 scientific papers and three books to his credit, as well as a number of awards for teaching and research.

Counterpoint

IN THE May issue of *E&S*, Sue VandeWoude reported on the 1982 Student-Faculty conference, including the fact that a discussion of "the need to educate grad students and new faculty about the honor system" had taken place. That statement created some protest among graduate students who feel that though the discussion did indeed take place the assumption on which it was based was unwarranted. Here, for example, is a letter we recently received:

> Dear Editor:
>
> As the immediate past chairman of the Graduate Student Council, I feel it is necessary to express a counterpoint to Sue VandeWoude's "The 1982 Student-Faculty Conference."
>
> The undergraduate student body has no monopoly on the introduction, education, and enforcement of the honor code. The so-called "need to educate grad students . . . about the honor system" has been fulfilled for several years now by the G.S.C. and the Caltech administration. Even Caltech undergrads who continue as grad students are "educated." My contacts with alumni, faculty, administration, and individual undergraduates have never yielded any substantial allegations of graduate student misconduct. It appears that only in the collective anonymity of fora such as the conference are these doubts expressed. If the behavior of graduate students is of such concern, why are we never given a chance to express our views and concerns?
>
> Unsubstantiated charges by any sector of the Caltech community are harmful. These charges start as rumor and soon become accepted as fact. The maturity of the graduate student body prevents equally malicious countercharges from being levied against the undergrads.
>
> I hope that greater caution is exercised in the future before such potentially damaging statements are made or, worse, printed.
>
> Sincerely,
> Albert Lin, PhD '82

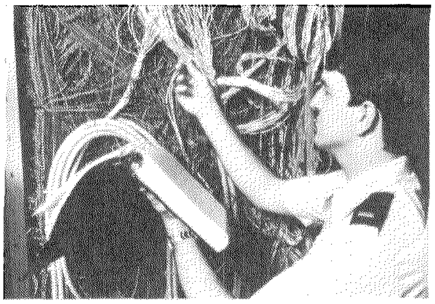
ENGINEERING TAKES ON EXCITING NEW DIMENSIONS IN THE AIR FORCE.



Computer-generated design for investigating structural strengths and weaknesses.

Developing and managing Air Force engineering projects could be the most important, exciting *challenge of your life*. The projects extend to virtually every engineering frontier.

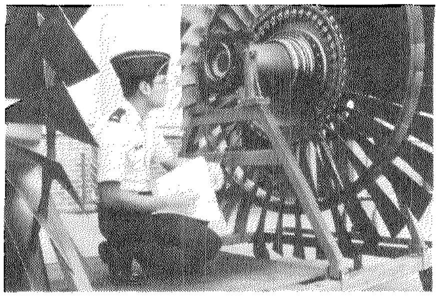
8 CAREER FIELDS FOR ENGINEERS



Air Force electrical engineer studying aircraft electrical power supply system.

Engineering opportunities in the Air Force include these eight career areas: aeronautical, aerospace, architectural, astronautical, civil, electrical, mechanical and nuclear. Hundreds of diverse specialties are included in a wide variety of work settings. For example, an electrical engineer may work in aircraft design, space systems, power production, communications or research. A mechanical engineer might be involved in aircraft structure design, space *vehicle launch pad* construction, or research.

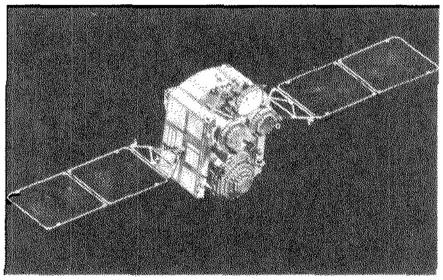
PROJECT RESPONSIBILITY COMES EARLY IN THE AIR FORCE



Air Force mechanical engineer inspecting aircraft jet engine turbine.

Most Air Force engineers have complete project responsibility early in their careers. For example, a first lieutenant directed work on a new airborne electronic system to pinpoint radiating targets. Another engineer tested the jet engines for advanced tanker and cargo aircraft.

OPPORTUNITIES IN THE NEW USAF SPACE COMMAND



Artist's concept of the DSCS III Defense Satellite Communications System satellite. (USAF photo.)

Recently, the Air Force formed a new Space Command. Its role is to pull together space operations and research and development efforts, focusing on the unique technological needs of space systems. This can be your opportunity to join the team that develops superior space systems *as the Air Force moves into the* twenty-first century.

To learn more about how you can be part of the team, see your Air Force recruiter or call our Engineer Hotline toll free *1-800-531-5826* (in Texas call 1-800-292-5366). There's no obligation.

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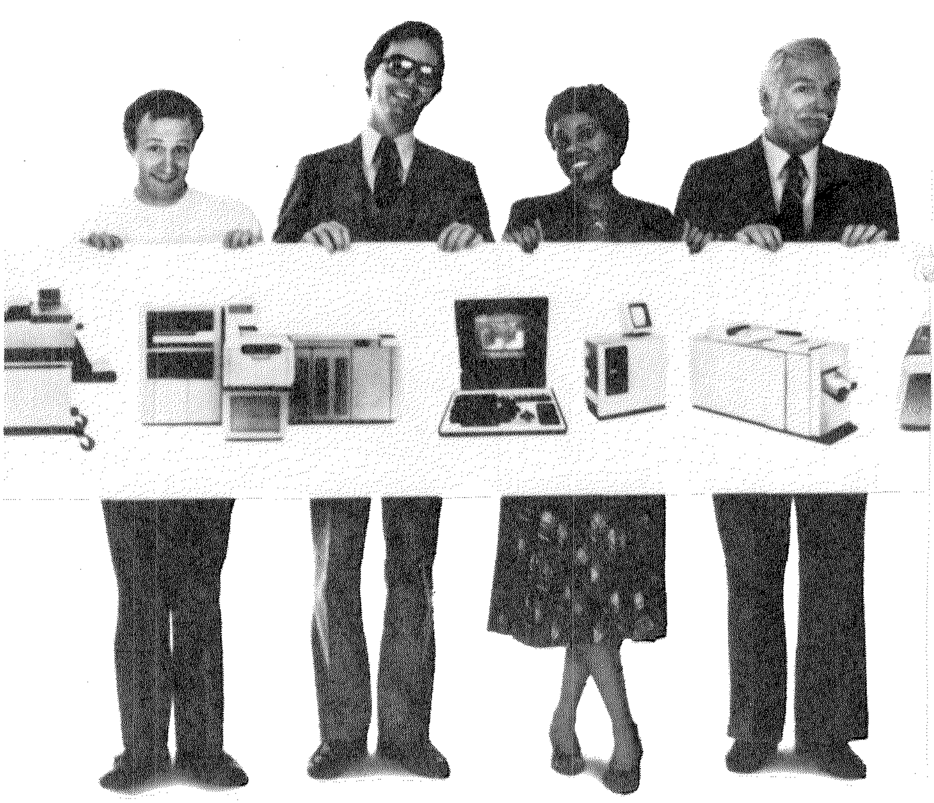

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