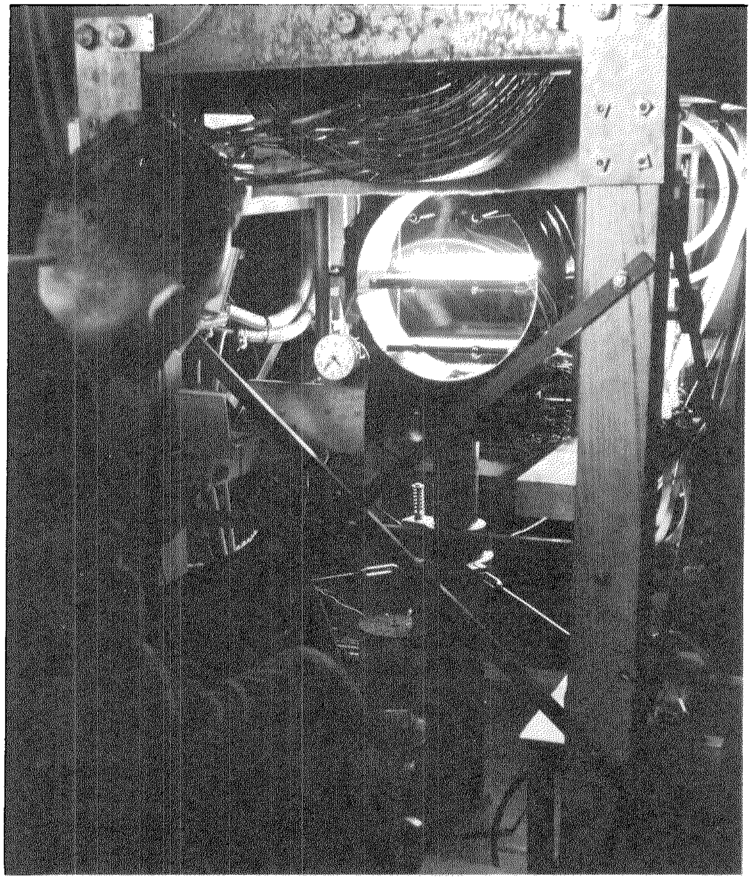
Cosmic Rays A Scientific Cornucopia

by Robert B. Leighton



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.

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.

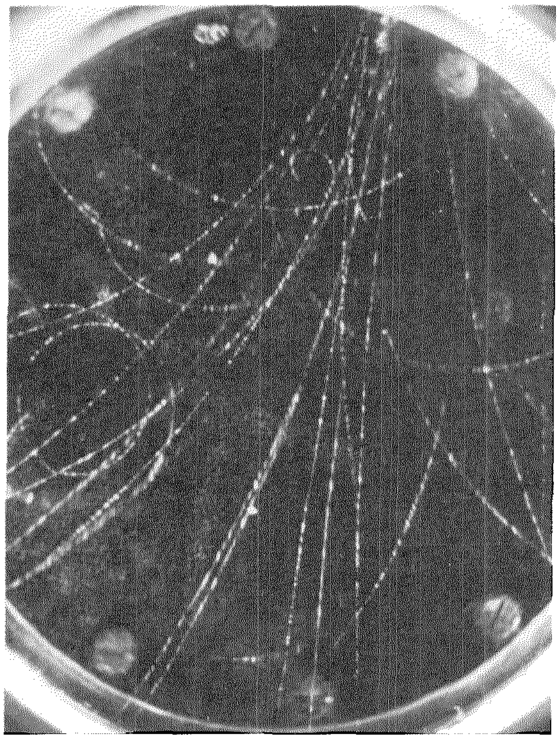
By the late 1920s, cosmic rays had developed into a very active field of research that had uncovered many intriguing and rather puzzling facts which resisted satisfactory explanation in terms of the particles, radiations, and physical interactions then recognized. The most characteristic property of 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.

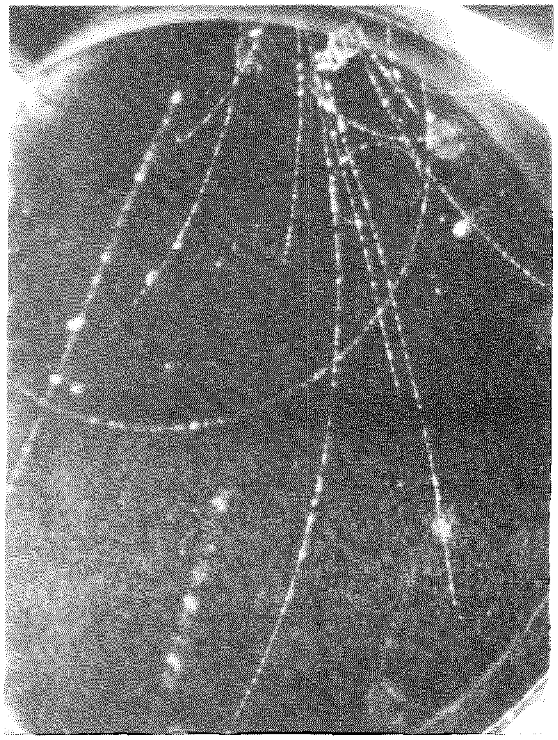
At about the same time, the right basic tool for the problem became ripe for exploitation: the cloud chamber within a strong magnetic field (the "magnet cloud chamber"). The cloud chamber itself is a well-known device that renders visible the tracks of charged particles moving through it (by condensation 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.

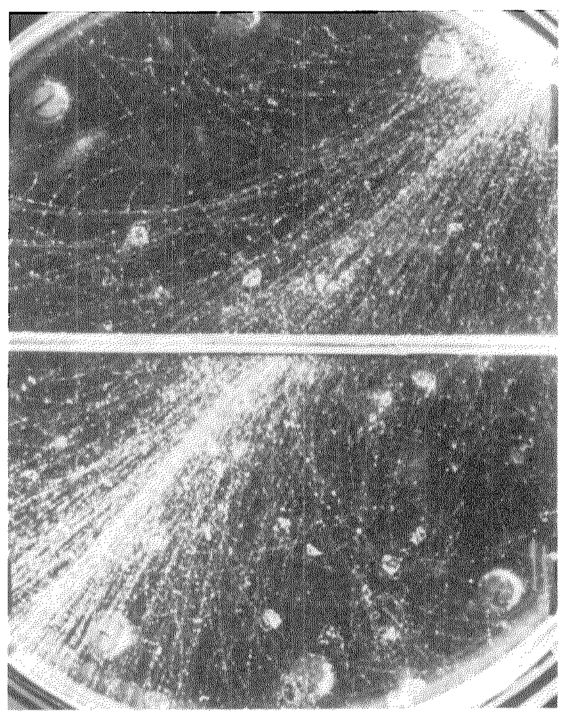
When these results were interpreted in terms of particles then known (including, of course, the positron), the conclusion was that essentially *all* of the particles involved must be electrons and positrons, but it was recognized that the penetrating power of the highest energy component was much greater 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.

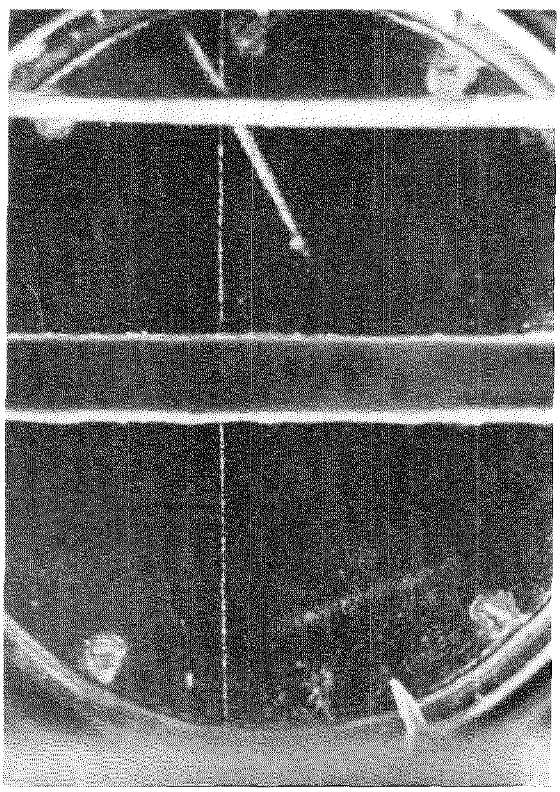


This relatively large electron shower was photographed in the late 1940s in a B-29 at 30,000 feet.

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." □