The Omega-Minus Experiment

An account of the experiment, performed with Brookhaven National Laboratory's 33-billion-electron-volt accelerator, that confirmed the existence of a new particle predicted by the "eightfold way"

by William B. Fowler and Nicholas P. Samios

Among the landmarks of physics in the 20th century are the successful predictions of theoretical physics. The Davisson-Germer experiment showing that electrons behave like waves (predicted by Louis de Broglie), the discovery of the massless neutrino (predicted by Wolfgang Pauli), the discoveries of the positron and other antiparticles (predicted by P. A. M. Dirac)—these are some of the successes of hypotheses that to many seemed hardly more than speculations when they were first proposed. Each was a concept invented by abstract, mathematical reasoning based on earlier experimental results, and each was eventually verified by physical detection of the predicted phenomenon. The latest in this series of remarkable "inventions" is the omega-minus particle, whose existence was predicted only two years ago and has now been confirmed by actual production of the particle.

There are special reasons why the discovery of this particle has aroused the interest of physicists. It supports a theory that shows promise of introducing some kind of order into the puzzling assortment of particles that physicists have detected in their dissection of the atomic nucleus. The theory was proposed in 1961 by Murray Gell-Mann of the California Institute of Technology and independently by Yuval Ne'eman of Tel Aviv University in Israel [see "Strongly Interacting Particles," by Geoffrey F. Chew, Murray Gell-Mann and Arthur H. Rosenfeld; SCIENTIFIC AMERICAN, February]. It groups the particles into families according to their quantum properties. Gell-Mann noted that one of the families apparently was incomplete. Nine members of the family were known; the theory indicated there should be a tenth, and it specified the properties the missing particle must possess.

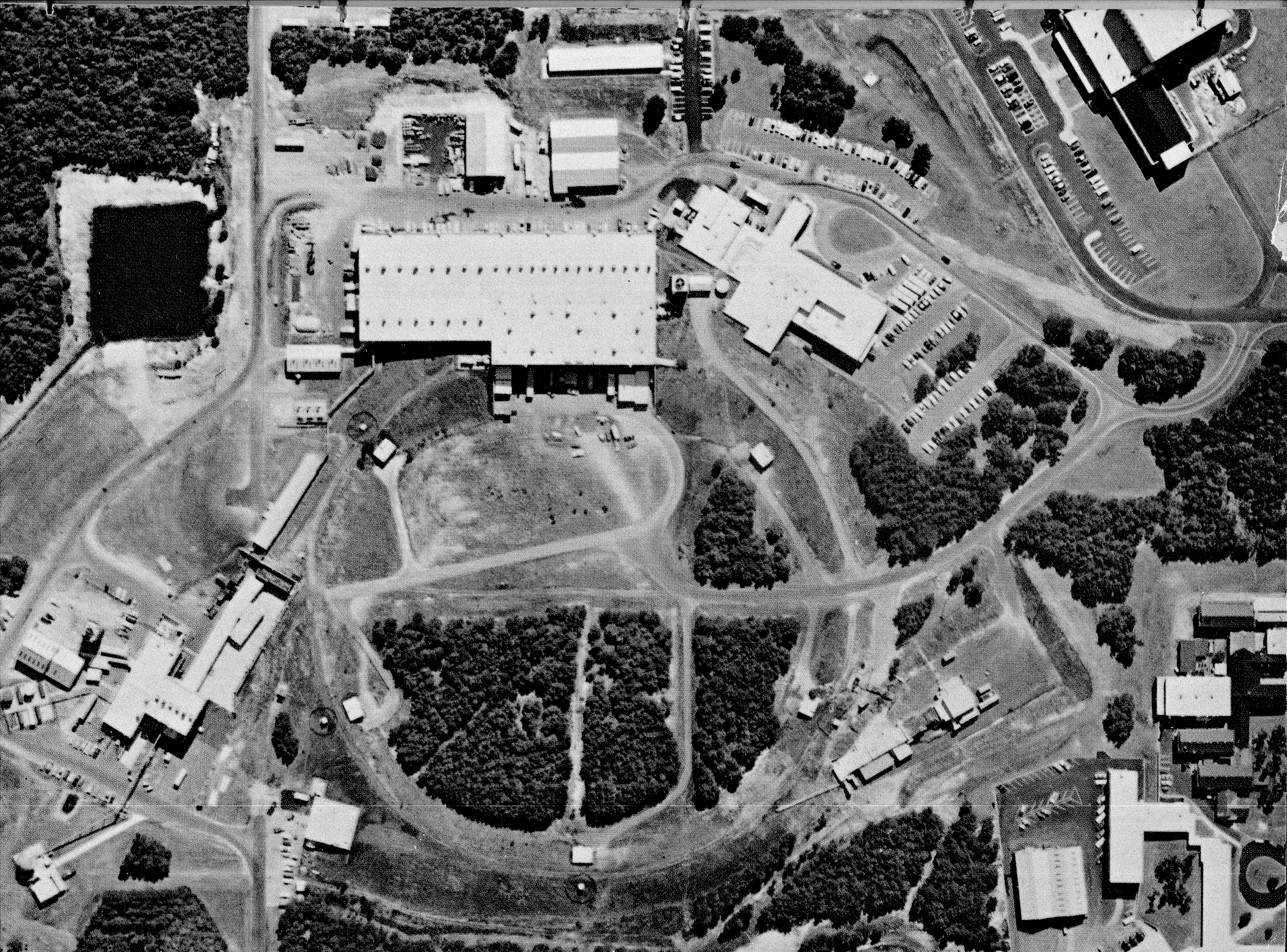
The situation was somewhat like the one presented by Dmitri Mendeleev when he devised the periodic table of the elements in 1869. Mendeleev saw that there were three vacancies at certain positions in his table, and he insisted that elements corresponding to those vacancies, whose properties he described, must exist and would someday be found. They were discovered not long afterward. Similarly, the missing particle described by Gell-Mann, which he named omega-minus, was found when it was searched for, and it proved to have exactly the properties specified by the theory.

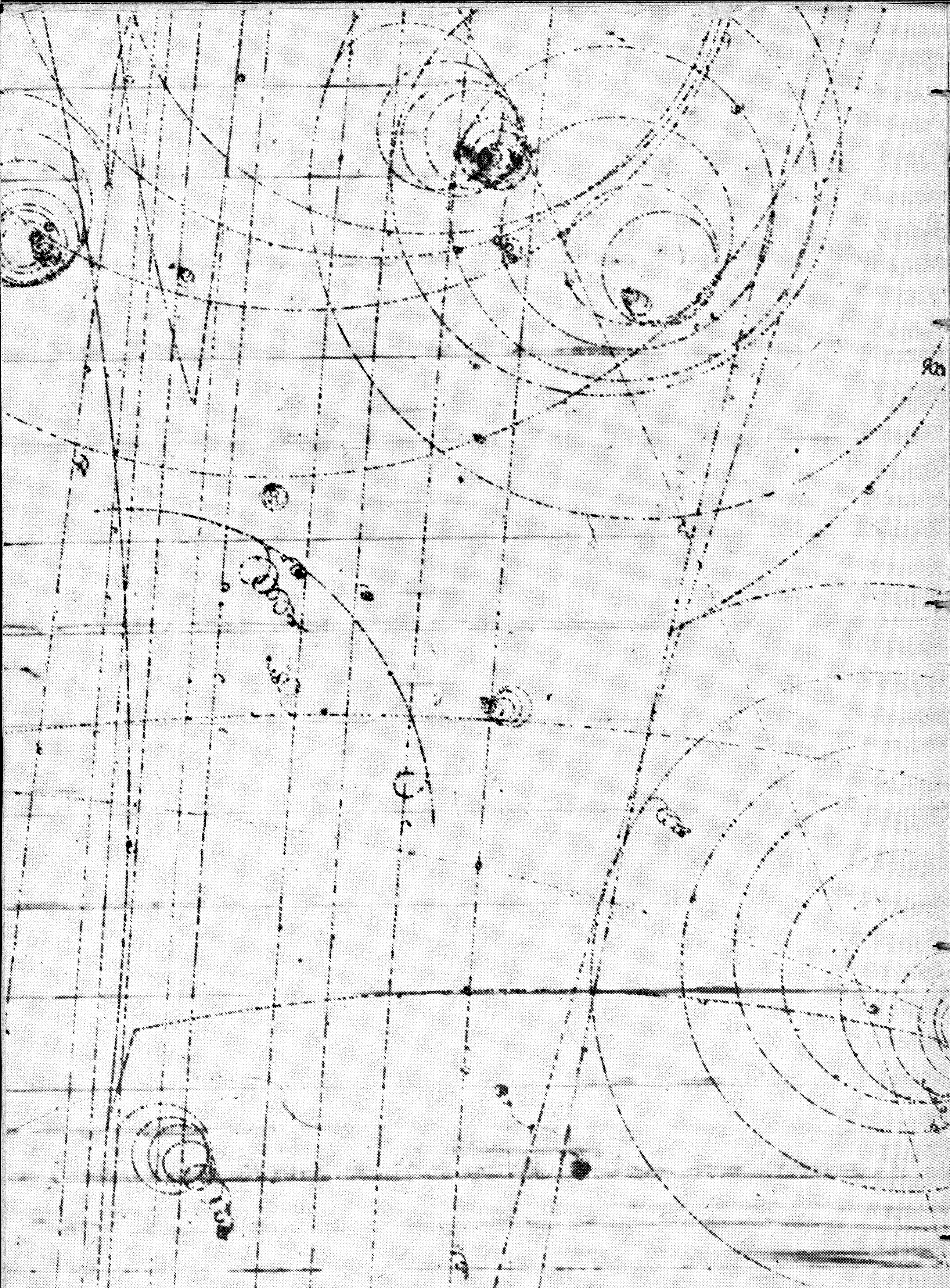
This article will relate how the omega-minus was produced and identified. The details of the theory need not concern us here; they were thoroughly discussed in the February issue by Gell-Mann and his coauthors. It classifies nuclear particles (baryons and mesons) by a system based on the branch of mathematics called group theory. The system is known as SU(3) symmetry and has also been named the "eightfold way," because it involves eight mathematical operators related to the quantum numbers of particles.

According to this scheme the particles constituting a family must all have the same spin angular momentum (speed of intrinsic spin) and the same parity (left-handedness or right-handedness). They may differ in mass, electric charge and the properties known as "strangeness" and "isotopic spin," but in these quantities they must be related to one another by certain rules.

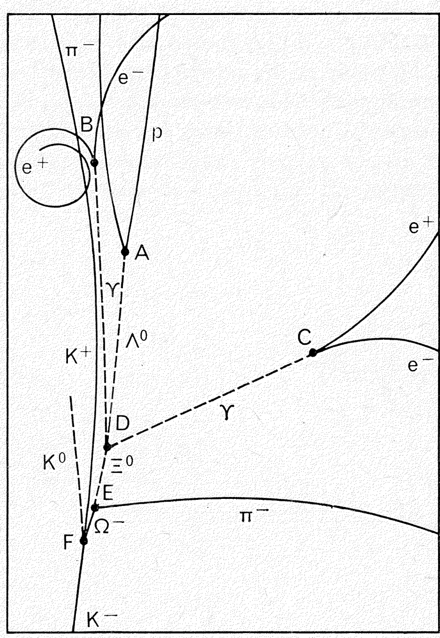
The family with which we are concerned starts with the baryons called delta particles—delta-minus, delta-zero, delta-plus and delta-double-plus (with two units of positive charge). The members of this quartet have a spin angular momentum of 3/2 units, positive parity and an effective mass of 1,238 million electron volts. (In particle physics mass is now commonly expressed in terms of energy.) Now, if one looks around for other known baryons that may belong to the same family, the sigma particle of mass 1,385 mev (million electron volts) immediately appears to be a likely relative. Like the deltas, the three charge versions of the sigma particle (sigma-minus, sigma-zero and sigma-plus) have a spin angular momentum of 3/2 and positive parity. The quantum number describing the strangeness of the delta particles is zero; that of the sigmas is minus one. The deltas have an isotopic spin of 3/2; the sigmas, an isotopic spin of 1—a half-unit difference. Thus the sigma triplet, at a higher mass level than the delta quartet, begins to form a symmetrical pyramid [*see illustration on page 42*].

BROOKHAVEN ACCELERATOR with which the omega-minus experiment was performed appears in the aerial photograph on the opposite page. The ring-shaped configuration of ground to the right of the large building at left center is a mound covering the tunnel that houses the magnet ring in which protons are accelerated to 33 billion electron volts. The beam of protons is injected into the ring by a linear accelerator that is housed in the small building at lower right center. The main target area is in the building at left center. The accelerating ring is some 800 feet in diameter. The accelerator, known as an alternating gradient synchrotron, has been in operation since 1960.





What doublet might constitute the next level of the pyramid? The difference in mass between the delta and the sigma particles, 147 mev, suggested that the mass of the next pair of particles should be about 1,532 mev, 147 mev higher than that of the sigmas. No such particle, bearing the right quantum numbers, had been detected. At the biennial International Conference on High Energy Physics in Geneva in July, 1962, however, experimenters reported the discovery of a pair of xi particles (xi-minus and xi-zero) of mass 1,530 mev. Gell-Mann, who was present at the conference, immediately saw the connection between this almost routine announcement and the eightfold way.



BUBBLE-CHAMBER PHOTOGRAPH on the opposite page was the first to show the existence of the omega-minus particle. The sequence of events in the production of the particle is given in the map above. The track of a K-minus meson (K^-) is seen at bottom of the photograph. The K^- collides with a proton at vertex *F* to yield a K-zero meson (K^0), a K-plus meson (K^+) and an omega-minus particle (Ω^-). The K^+ makes an identifiable track. The Ω^- disintegrates at vertex *E* to a pi-minus (π^-) and a xi-zero (Ξ^0) particle. The Ξ^0 is identified by its decay products, seen emerging from decay vertex *D:* two gamma rays that give rise to positron-electron pairs (e^+ and e^-) at *C* and *B*, and a lambda zero (Λ^0) that yields a π^- and a proton (p) at vertex *A*. Knowledge of the masses and momenta of charged decay products of neutral particles that leave no tracks (*broken lines*) enable physicists to identify them. Thus the third particle branching from vertex *F* is known to be a K^0.

The new xi particles qualified for membership in the family with the delta and sigma particles by their mass (very close to the predicted 1,532 mev). What was more, their strangeness was minus two, further confirming their position in the pyramid, because the strangeness quantum numbers now ran: delta quartet, zero; sigma triplet, minus one; xi doublet, minus two.

It was now possible to predict with reasonable confidence that the pyramid must be crowned by a singlet at the apex—a particle of strangeness minus three, spin 3/2, positive parity, negative charge and mass about 1,676 mev (146 mev higher than that of the xi particles). A determined, full-scale search for this particle, already named omega-minus, was therefore launched almost immediately.

Many of the nearly 100 known nuclear particles had already been placed in families (consisting of eight members each) on the basis of the new theory of classification. They seemed to fit into the theoretical system of organization very satisfactorily. It is one thing, however, to devise a scheme describing a set of known facts and quite another to create a generalization that will bring to light new phenomena previously undreamed of. The test of any grand-scale theory is its ability to predict what was previously unpredictable and to lead to new knowledge. If the eightfold way could produce, out of pure theory, the exact properties of a new particle, it might be an important step toward unraveling the obscurities surrounding the fundamental nature of matter and energy. The quest for this particle was worth a large effort.

It required, first of all, powerful and sophisticated tools, and fortunately tools adequate for the job were already at hand. The very large machines that have been built for nuclear physics in recent years were designed for just such crucial and difficult experiments as this one. The Brookhaven National Laboratory, with its 33-bev (33-billion-electron-volt) accelerator and a new 80-inch liquid-hydrogen bubble chamber, was prepared for the opportunity and welcomed the task of searching for the omega-minus. The situation was an experimentalist's dream: an important theory to be tested, a specific and crucial prediction on which the theory could stand or fall and equipment fully capable of producing and detecting the predicted particle if it existed. In November, 1963, Brookhaven undertook a large-scale omega-minus experiment that was to engage a large number of physicists (including the authors of this article), engineers and technicians.

What interaction might produce the omega particle? There was available a beam of high-energy K mesons, generated as secondary products by the 33-bev alternating-gradient synchrotron. Calculations suggested that sufficiently energetic K-minus particles, on interacting with target protons, would produce the omega-minus baryon and K-plus and K-zero mesons by the following reaction: $K^- + p \rightarrow \Omega^- + K^+ + K^0$. How much energy would the K-minus projectiles need to generate this reaction? The masses of the products (omega-minus, K-plus and K-zero) respectively represented energies of 1,676 mev, 494 mev and 498 mev, or a total of 2,668 mev. Because part of the energy of the projectiles in such a reaction goes into the energy of motion, or momentum, of the products emerging from the reaction, it was calculated that the K-minus mesons would need to hit the target protons with an energy of at least 3,200 mev. To heighten the probability of producing the reaction, it would be desirable to use a K-minus beam with substantially more energy than that minimum. Fortunately the accelerating and beam-separating system was capable of creating such beams with energies up to 5,000 mev.

The experiment was therefore designed as follows. A 5,000-mev beam of K-minus mesons would be shot into the bubble chamber. To avoid producing a confusion of tracks in the chamber the K-minus injections would be limited to bursts of 10 to 20 particles during the exposure time of each picture. It was hoped that an occasional K-minus meson would interact with a proton in the liquid hydrogen and produce an omega-minus particle. The omega-minus would be identified by the products into which it decayed.

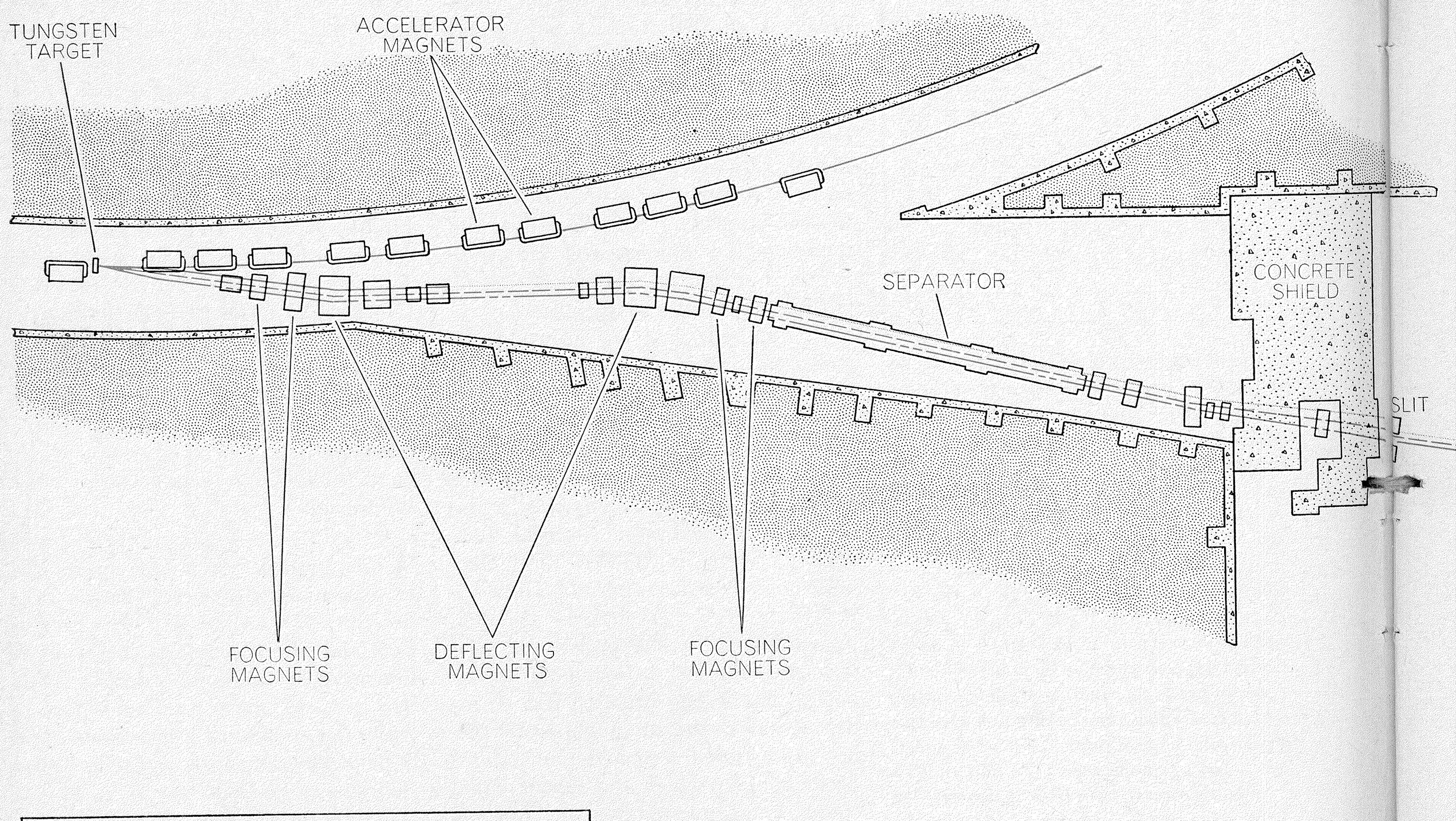
The physical system set up for the experiment deserves at least a brief description. If a beam of 33-bev protons from the alternating-gradient synchrotron were directed into a bubble chamber, it would produce such a deluge of tracks that individual events could hardly be picked out of the scramble. When Brookhaven decided to build its 80-inch bubble chamber, one of its staff physicists, Medford S. Webster, undertook to develop a means of producing a pure beam of secondary particles that could be used with the chamber. The proton beam from the accelerator produces a veritable blizzard of secondary particles—pi mesons, K mesons and many others—when it hits a metal target. Webster devised a system for separating out the K mesons scattered from such a target and focusing them into a beam. His system, using electrostatic beam separators and deflecting and focusing magnets, is 450 feet long and produces a fine beam only six hundredths of an inch high when it emerges from the final transmitting slit. This beam, as we have mentioned, has an energy of 5,000 mev, or five bev.

Brookhaven's large new bubble chamber, 80 inches long and containing 900 liters of liquid hydrogen, is monitored by three cameras, so that the particle tracks within it can be located in three-dimensional space. Like all such instruments, it is equipped with a large electromagnet and other devices for identifying the charge and other properties of the particles that have formed the tracks. It can make photographs at the rate of one every second, allowing for recompression of the chamber after each recording of tracks.

Now came the critical question: What kind of photograph would identify the omega-minus particle? That is to say, into what products might the omega-minus decay? Consideration of the various conservation rules narrowed down the ways in which the omega-minus might decay into three most likely possibilities: it might break down into (1) a xi-minus particle and a neutral pi meson, (2) a xi-zero particle and a pi-minus meson or (3) a lambda-zero particle and a K-minus meson. These, then, were the results watched for in analyzing the photographs.

After six weeks of arduous labor in perfecting the operation of the beam equipment to obtain a sufficiently pure and intense beam of K-minus mesons, photography of the bombardment of the bubble chamber by the beam began on December 14, 1963. In the ensuing months the entire system—the accelerator, the beam equipment, the bubble chamber and the cameras—was operated on an around-the-clock basis. By January 30, 50,000 good photographs had been obtained. As the photographs were made the tracks were scanned and analyzed closely. This entailed making very accurate measurements and calculations of the precise locations within the chamber where interactions or decays took place and of the angles and curvatures of the tracks that were made by the new particles emerging from these reactions.

On January 31 there turned up a photograph with a set of tracks that seemed to signal the production of an omega-minus particle. The sequence of tracks indicated that the omega-minus had decayed into a xi-zero particle and a pi-minus meson, and both products had gone on to further decays. According to the predicted process for the creation of the omega-minus, the interaction of the K-minus projectile and the proton was expected to produce K-plus and K-zero mesons along with the omega-minus. The photograph showed the track of a K-plus meson emerging from the point of the interaction. There was no sign of the formation of a K-zero, but this was not surprising, because the uncharged particle itself would make no track and it might well have left the



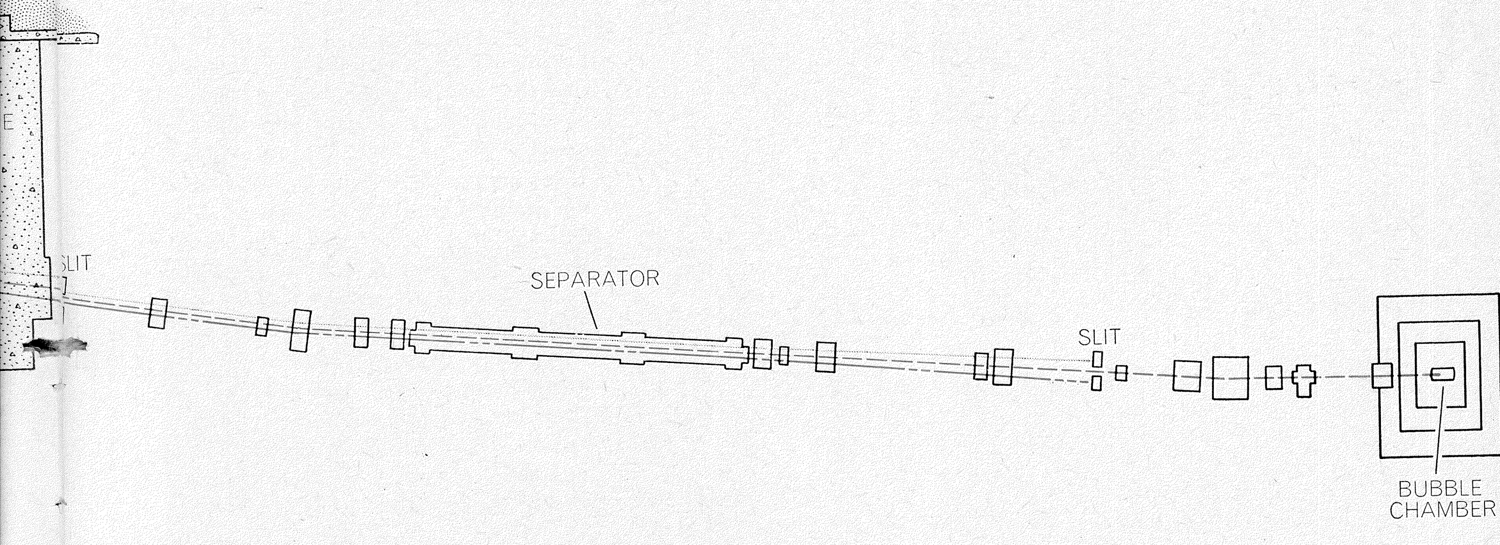
EXPERIMENTAL ARRANGEMENT shows the tungsten target (*left*) into which the accelerated proton beam is deflected after acceleration. Focusing magnets gather secondary particles from the target; deflecting magnets select, on the basis of momenta, which particles are to pass on to the electrostatic beam separator. This separator then deflects the particles to an extent dependent on their

bubble chamber before decaying into other particles.

These interpretations of the photograph rested simply on visual inspection. They now had to be verified in quantitative terms. In any reading of such an event in particle physics the burden of proof lies heavily on the experimenter. He must show, by precise measurements and calculations of the density, length, angles and curvatures of the tracks, that they actually identify the particles and reactions they seem to depict. The group proceeded to several days of feverish activity to check the photograph.

The photograph of this event and a diagram picking out the significant tracks appear on pages 38 and 39. To reconstruct what happened one starts with the final decays recorded and works backward to the main event. Let us start with the event signalized by the fork (called a "vertex") labeled *A* in the diagram. The right-hand track emerging from this vertex is clearly heavier than nearby parallel tracks that represent K-minus particles in the beam coursing through the chamber. Measurements identify this track as that of a proton. Similarly, the left-hand track from the same vertex identifies that particle as a pi-minus meson. On the basis of the measured momenta and masses of these particles, equations for the conservation of energy and of momentum allow one to calculate that the proton and pi-minus meson emerged from the decay of a lambda-zero particle with a mass of 1,115 mev. Now, the lambda-zero particle, having no electric charge, made no track in the chamber, but the direction of its path (indicated by a broken line in the diagram) can be calculated from the properties of the two tracks branching from vertex *A*. This path must lead to a point where the lambda-zero particle originated. There are no visible tracks indicating the location of that vertex, but two events shown in the photograph evidently stem from it. These events are the creation of electron-positron pairs at the points labeled *B* and *C* in the diagram. The two pairs of antiparticles must have been produced by energetic gamma rays. Although the gamma rays left no tracks in the chamber, their paths and point of intersection can be calculated from the measured momenta (including, of course, direction) of the electron-positron pairs. This point (*D*) also lies on the calculated path of the lambda-zero particle. Thus it is clear that the lambda-zero particle and the two gamma rays were generated by the decay of another particle at *D;* calculations show that this particle must have been a xi-zero baryon with a mass of 1,316 mev, and that it decayed into the lambda-zero particle and a pi-zero meson, which promptly decayed into the two gamma rays that proceeded to form electron-positron pairs.

The xi-zero, like the lambda-zero, left no track, but again the direction of its path can be calculated. Projecting this backward, we come at last to a visible vertex at point *E*, where the xi-zero originated; a track going off sharply to the right is consistent with a pi-minus meson that was produced at the same time. Adding up the momenta of the xi-zero and the pi-minus, we obtain the momentum of the parent particle from which they sprang. One can calculate



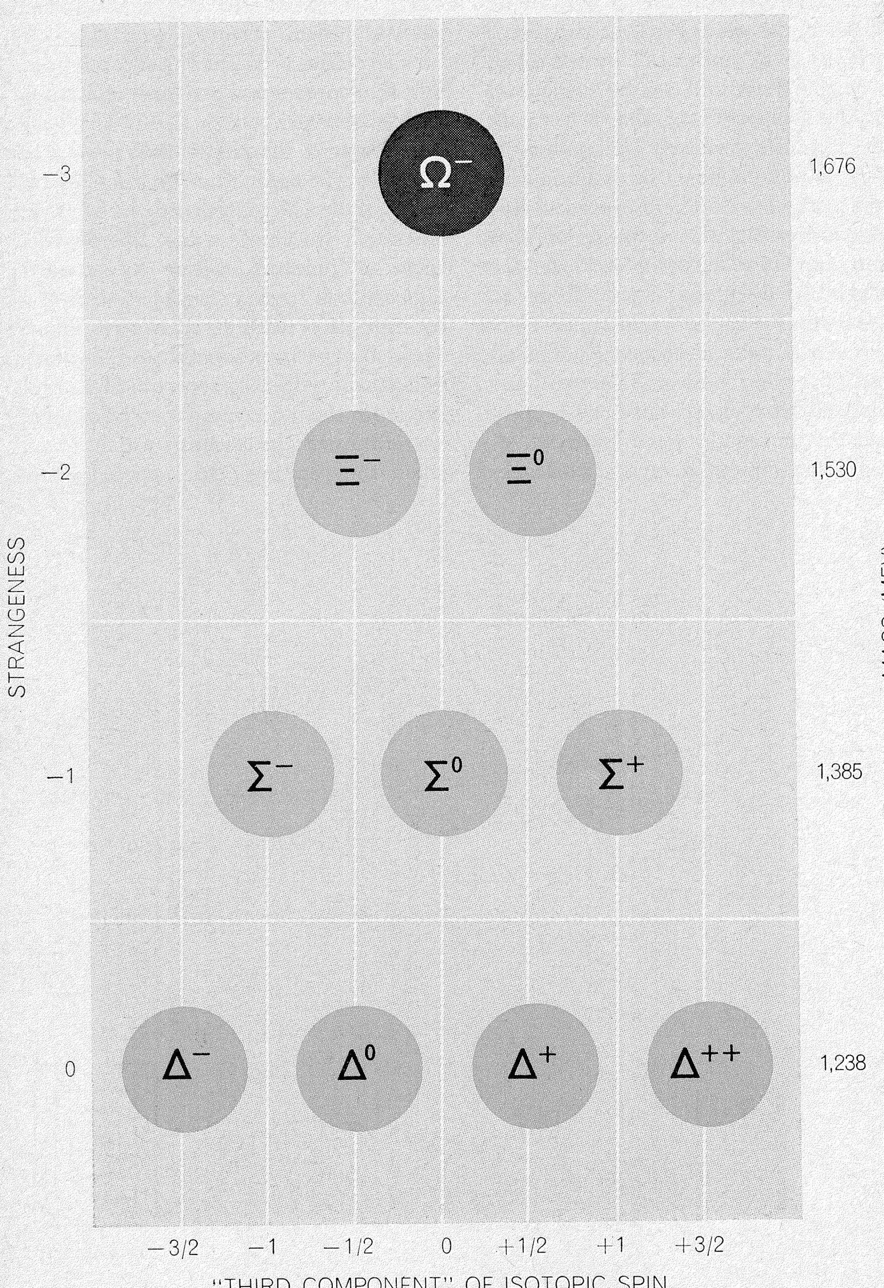
mass and focuses them on a slit (one inch by .05 inch) that blocks most pi mesons (*light-colored line at top of the beam*) and most antiprotons (*colored line at bottom*). Before the slit the ratio of K-minus mesons (*line in middle of the beam*) to pi-minus mesons to antiprotons is 10 to 800 to 10. As the beam enters the bubble chamber, after another separator stage, the ratio is 10 to 1 to 0.

that its mass must have been between 1,668 and 1,686 mev (allowing for the uncertainties in the calculations). This is precisely on the mark for the predicted mass of the omega-minus particle—1,676 mev.

If the decay at point E (into the xi-zero and pi-minus particles) was indeed that of an omega-minus particle, then the track between E and F in the diagram was that of the omega-minus itself, and the particle was born at F. At F we have a vertex with the visible track of the omega-minus going off to the right and a track identified as that of a K-plus meson curving off to the left. There is a deficit of about 498 mev from the interaction that gave rise to these visible products; that deficit represents the K-zero particle that left no track.

To reconstruct the events from the beginning now instead of from the end: At F an energetic K-minus meson colliding with a proton produced an omega-minus particle and K-plus and K-zero mesons; the omega-minus traveled on to E and there decayed into a pi-minus and a xi-zero particle; the xi-zero decayed at D into two gamma rays (which materialized into electron-positron pairs at B and C) and a lambda-zero particle; at A the lambda-zero in turn decayed into a proton and a pi-minus meson.

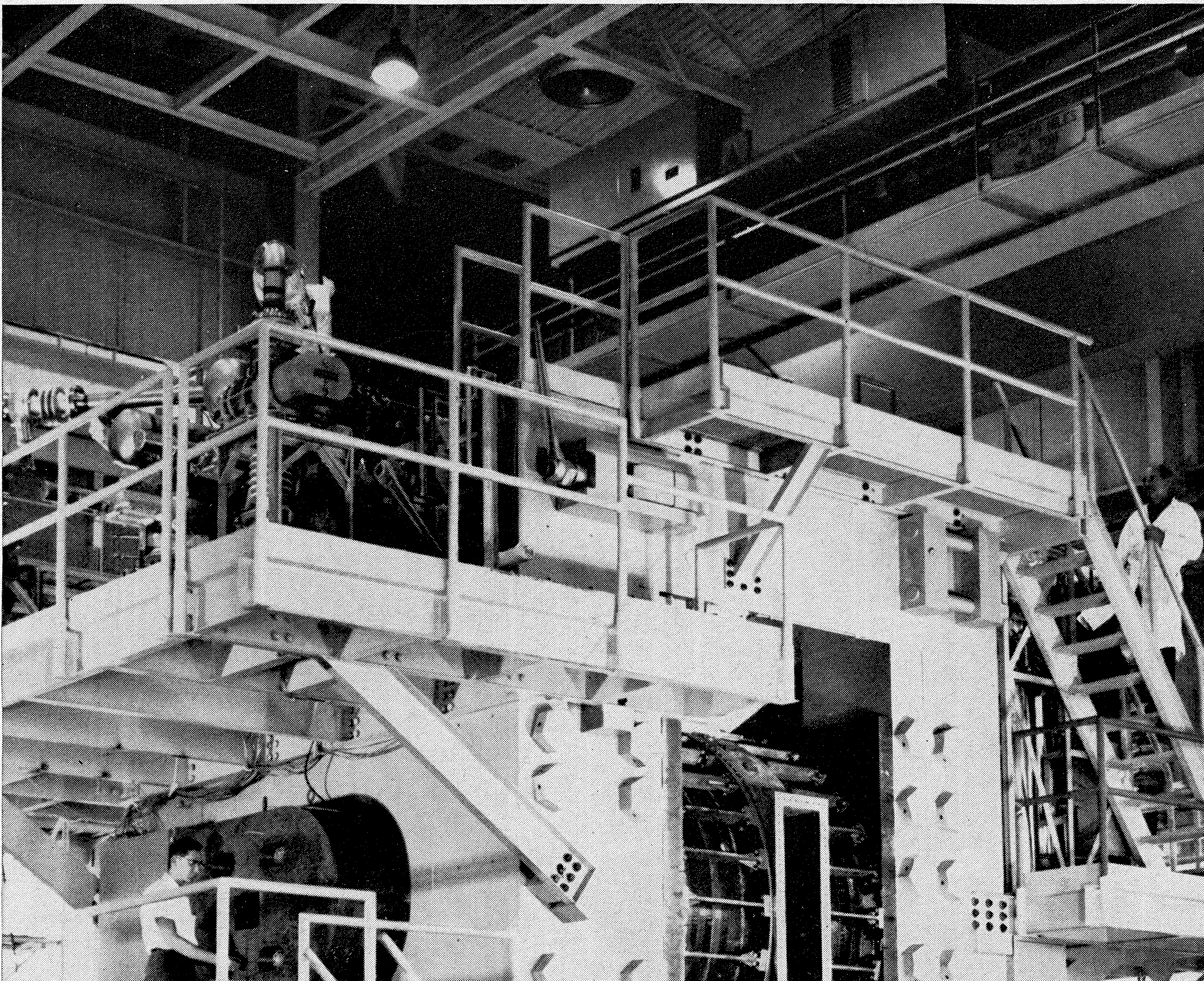
The length of the track made by the omega-minus particle in the bubble chamber (one inch) shows that its lifetime was almost a ten-billionth of a second, the typical lifetime of a strange particle. The decay of a strange particle is a "weak" interaction in which strangeness is not conserved but is changed by one unit. This rule provided confirmation that the particle caught in the photograph was the predicted omega-minus particle. The theory predicted that it should have a strangeness of minus three; its decay should therefore result in products with a total strangeness quantum number of minus two. That was, in fact, the observed result: the strangeness of the xi-zero particle is minus two and that of the pi-minus meson is zero.



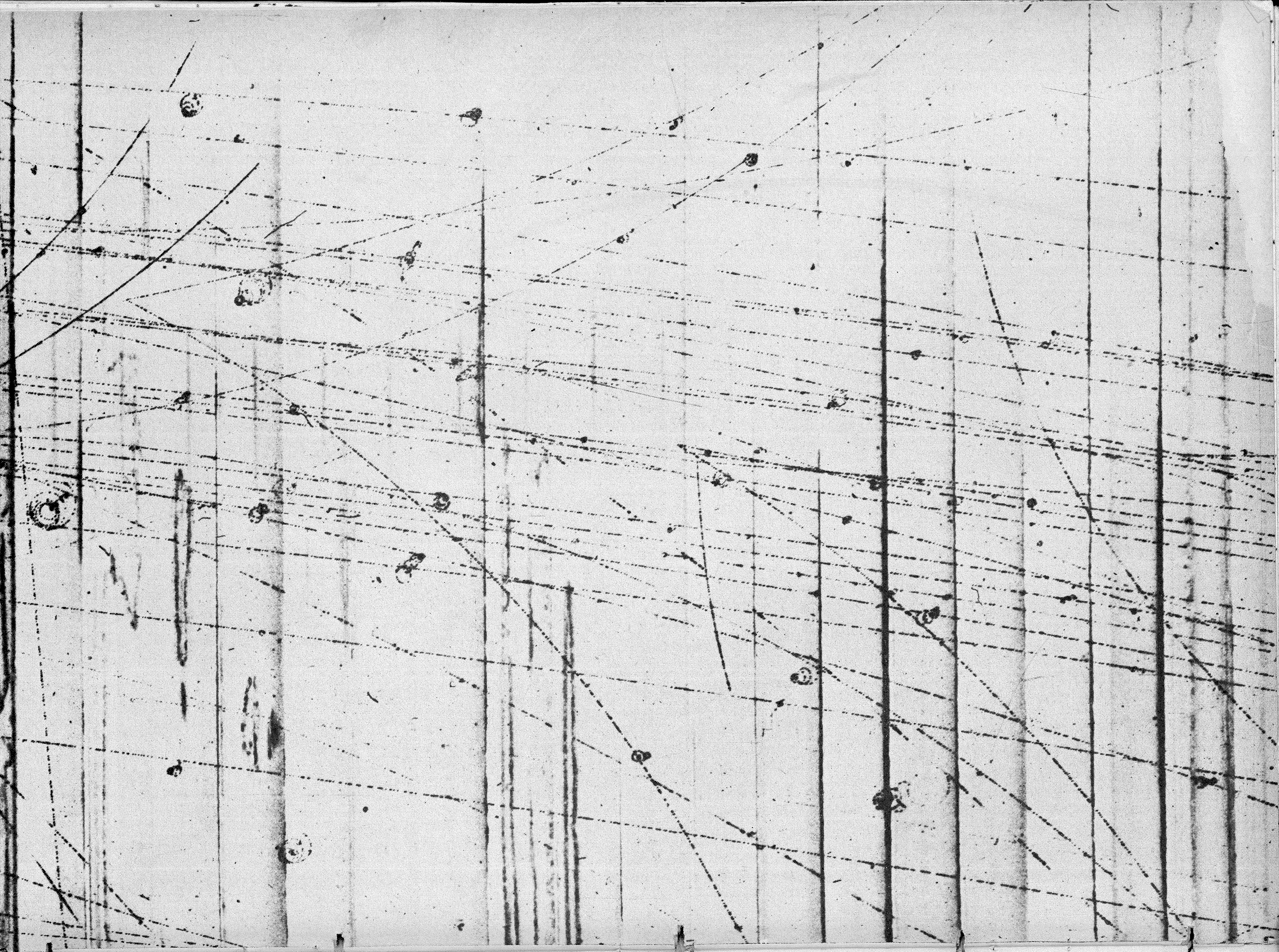
THE EIGHTFOLD WAY as represented here groups together particles with the same intrinsic spin and the same parity in a pyramid indicating how the particles are related by certain rules. The particles differ in mass (*column at right*), "strangeness" (*column at left*) and a "third component of isotopic spin" (*bottom*) related to electric charge. The four-member delta family (Δ^-, Δ^0, Δ^+ and Δ^{++}), the three-member sigma family (Σ^-, Σ^0 and Σ^+) and the two-member xi-family (Ξ^- and Ξ^0) suggested a single-member family with predictable properties to crown the pyramid. The omega-minus particle (Ω^-) was then discovered, verifying the scheme. The isotopic spin of the delta baryons is 3/2; that of the sigma baryons is 1; that of the xi baryons is 1/2; that of the omega-minus particle is 0.

A few weeks after the discovery of the first omega-minus particle a second one was produced in the bubble chamber. This time it decayed into a lambda-zero particle and a K-minus meson, one of the other predicted modes of decay for the omega-minus. The K-minus particle thereby produced then broke down by a rare decay process into three pi mesons—two negative and one positive. The photograph this time also showed the production of a K-zero meson along with the omega-minus, the K-zero being signaled by its prompt decay into a pi-minus meson and a pi-plus [*see illustration on page 44*]. Again the total strangeness of the products of the omega-minus decay was minus two. Moreover, the mass of the omega-minus particle was again as predicted, the measurements and calculations this time placing it between 1,671 and 1,677 mev. From the measurements of the particle's two appearances in the bubble chamber the average value derived for its mass was 1,675 mev, in astonishingly good agreement with the value of 1,676 mev predicted by the eightfold way.

The sequence of developments in this second materialization of the omega-minus, with the times involved, is illus-



LIQUID-HYDROGEN BUBBLE CHAMBER is located in the middle of this assembly at the Brookhaven National Laboratory. The 80-inch-long chamber is mounted behind the rectangular window, which is closed with a quarter-inch-thick metal cover during operations. Through a similar window the K-minus beam enters the chamber, which is surrounded by the copper coils and iron yoke of a 400-ton magnet. Above the staircase at left are openings through which three cameras photograph events in the chamber.

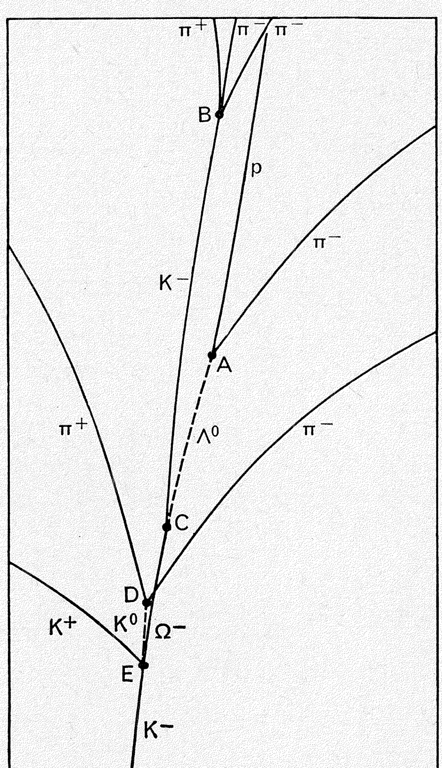


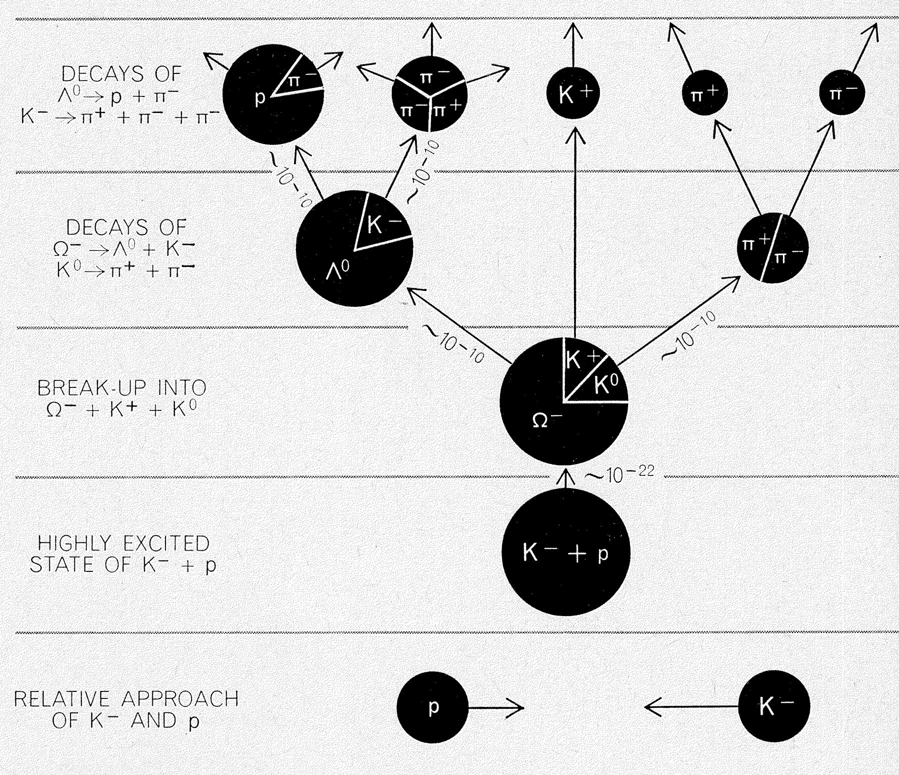
trated in the diagram on this page. A five-bev K-minus meson moving at close to the speed of light collides with a proton in the bubble chamber. The two particles form a very "hot," or highly excited, lump of nuclear matter that immediately breaks up into an omega-minus particle and K-zero and K-plus mesons, with the omega-minus carrying off most of the mass. The omega-minus decays into a lambda-zero particle and a K-minus meson, each of which decays further—the lambda-zero into a proton and a pi-minus meson, the K-minus into three pi mesons. Meanwhile the K-zero meson has decayed into two pi mesons. Thus from the original proton and energetic K-minus meson have come a proton, six pi mesons and a K-plus meson. Of these products only the proton is stable; all the mesons will eventually decay further.

To verify the predictions of the eightfold way and establish the identity of the omega-minus particle beyond any question, three more proofs are wanted. The two photographs showed two different modes of decay of the omega-minus; we would like to see the third one that was predicted as being likely, namely, its decay into a xi-minus particle and a pi-zero meson. Then we need determinations of the spin and parity of the supposed omega-minus particle. The two photographs establish its mass and strangeness quantum number satisfactorily, but for calculation of its spin and parity we shall need many more photographs of the event, because these properties can only be deduced from the statistical distributions of the angles involved in the various decays.

At the time of the writing of this article hundreds of thousands of photographs have been made at Brookhaven and thousands more at the European Organization for Nuclear Research (CERN) in Geneva, which has started a similarly intensive search for the omega-minus with its own alternating-gradient synchrotron. Although many hundreds of events that may represent omega-minus particles have been detected, so far the only photographs that give unambiguous evidence of the production of the particle are the two described in this article. The discovery of two such events within a month of each other was an extremely lucky coincidence; it is now calculated that the "cross section," or probability, for the production of an omega-minus particle by a collision between a five-bev K meson and a proton must be only a few microbarns. (A microbarn is 10^{-30} square centimeter.)

Needless to say, the production of the omega-minus has greatly intensified the interest in the eightfold way, or SU(3) symmetry, as an opening wedge toward understanding the interrelations of the nuclear particles and their behavior as agents of the forces within the nucleus. A great deal of theoretical work is now under way in a search for possibly smaller and more basic families of particles, consisting of not eight or 10 but only three members per family. And, just as the experimental discovery of the omega-minus has quickened the theoretical studies, so is it likely that further developments in the theory will suggest new experiments, calling for larger particle accelerators, more complex beam arrays and larger bubble chambers.





SECOND BUBBLE-CHAMBER PHOTOGRAPH in which an omega-minus particle appeared (Ω^-) helped to verify the existence of such a particle. It is shown at left, and the significant events are explained in the map at left above and presented in time sequence in the schematic chart at right. The collision of a K-minus beam and a proton (K^- and *p*) at speeds close to that of light yields a K-plus meson (K^+) branching to the left, a K-zero meson (K^0) that in about 10^{-10} second decays into positive and negative pi mesons (π^+ and π^-) and an omega-minus that soon decays into a lambda-zero (Λ^0) and a K^-. This K^- is seen (*top*) branching into three pi mesons. The lambda-zero gives way to a π^- and a *p*, the latter being the only stable product of the original reaction. The K and six pi mesons take about 100 times longer to decay (*time is in seconds*) than the particles shown decaying in chart at right.