The birth of elementary-particle physics

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In the 1930s and 1940s physicists significantly revised their views on the elementary constituents of matter, which during the 1920s they had assumed to be only the electron and the proton.

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By 1930, relativity and quantum mechanics were established, yet the excitement of the new physics was far from over. Indeed, the next half-century was characterized by startling experimental and theoretical discoveries and by new puzzles that appeared wherever one looked.

In the late 1920s all matter was thought to be made up of protons and electrons. There were, of course, many difficulties with this view, and the effort to revise it led to new problems—and to the birth of the field of modern elementary-particle physics. Three currents flowed together to make particle physics: nuclear physics, cosmic rays and quantum field theory. By the mid-1930s, there was conflict and apparent paradox where these fields overlapped, and although some of the conflict was resolved by the end of the 1940s, the resolution raised new and urgent problems.

Today there is increasing interest in this historical process. An international symposium was held recently at Fermilab to study the history of particle physics through lectures by important participants and through discussions among physicists and historians. An earlier symposium, at the University of Minnesota,[1] considered the role of nuclear physics in the origins of particle physics. This article is an outgrowth of the Fermilab meeting, which concentrated mainly on the parts played by cosmic rays and quantum field theory in the emergence of the new field. In the discussion of the origins of particle physics with which we begin this article, we retain that emphasis: We will mention the role of the atomic nucleus, but we shall concentrate on the roles of cosmic rays and theory.

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The nucleus and cosmic rays

There were many problems in treating the nucleus as a quantum mechanical system of protons and electrons.

▶ The nucleus was supposed to contain A protons and $A-Z$ electrons. But when the latter number is odd, as for lithium-6 or nitrogen-14, the spin and statistics are incorrect.

▶ Moreover, unpaired electron spins in the nucleus implied a hyperfine splitting of atomic spectral lines on a scale about a thousand-fold larger than is observed.

▶ In the relativistic quantum theory of the electron it was impossible to confine the light electron within the small nucleus.

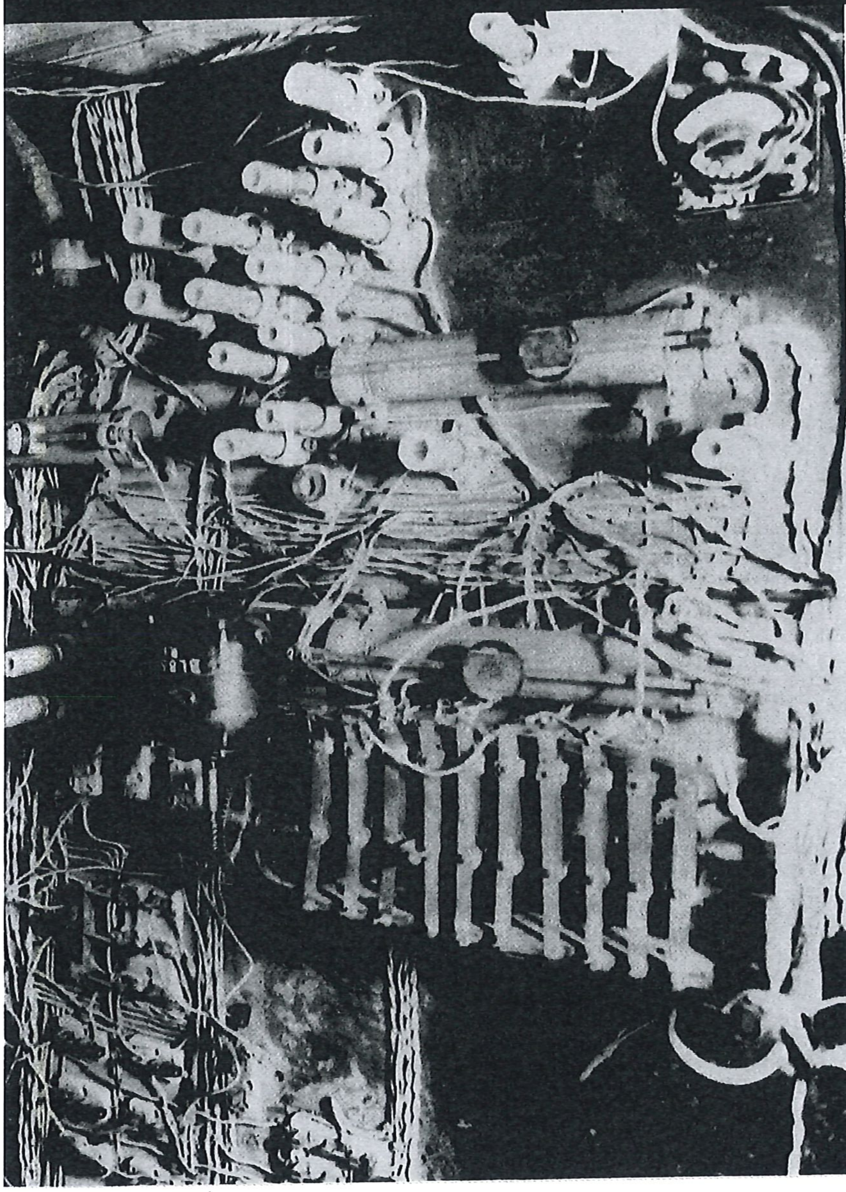
▶ Finally, there was the continuous spectrum of β-decay electron energies, which called into question even the conservation of energy.

Physicists seriously considered radical suggestions for modifying the mechanics, the electrodynamics and even the conservation laws. But the resolution was to hinge on new particles: the neutron, discovered by James Chadwick in 1932, and the neutrino, proposed by Wolfgang Pauli in 1930 and incorporated in a theory of β decay by Enrico Fermi in 1934. These two neutral particles permitted the banishment of electrons from nuclear models. Soon after Carl David Anderson's 1932 discovery of the positron in cosmic rays, Irene Curie and Frederic Joliot produced artifically radioactive light elements that decayed by positron emission, and the picture of nuclear β decay was complete.

Cosmic rays were discovered as a result of post-1900 investigations of fine-weather "atmospheric electricity," that is, ionization in the absence of an electrical thunderstorm. After one had accounted for all known sources of ionization, there remained a "residual" conductivity, even in closed vessels that were heavily shielded. This phenomenon implied the existence of a penetrating radiation of unknown origin.

Researchers—notably Victor F. Hess in Austria—conducted balloon flights, mainly in central Europe, to investigate altitude dependence of atmospheric conductivity. The manned balloons carried sealed electrometers whose rates of discharge first decreased with altitude, but then (above 2 km) began a marked increase. This pattern of ionization suggested the existence of an extraterrestrial source for the penetrating radiation, so that by the late 1920s one spoke of the *cosmic rays* (see box on page 39, *Discovery*). Until 1930, their specific ionization (ions per cm^3 per sec) was the only property systematically observed.

The focus changed at the end of the 1920s when researchers used two methods, coincidence counting and the cloud



Carl Anderson and control panel for cloud chamber in trailer on Pike's Peak, 1935. (Courtesy of Carl Anderson.)

chamber with magnetic field, to study the individual behavior of the charged particles produced by collisions of primary cosmic rays with air molecules. They adapted both methods from techniques used to study x rays and radioactivity. The two methods were flexible, permitting a variety of experiments to be performed; and they could be combined. Their descendants are the principal tools used today to study the interactions of elementary particles, whether the source be cosmic rays or accelerators. The pioneers in this enterprise were Walter Bothe and Werner Kolhörster in Berlin and Dmitry Skobeltzyn in Leningrad.

Improved detectors. Kolhörster, a colleague of Bothe at the Physikalisch–Technische Reichsanstalt in Charlottenburg, outside Berlin, and an experienced cosmic-ray worker, pointed out in 1928 that by aligning two point-counters in a vertical array, one could use Bothe's counting technique of coincidence to make a γ-ray telescope for cosmic rays. Bothe and Kolhörster then implemented a similar scheme, using the far-more-efficient Geiger–Müller tube counter. By mid-1929 they established that a 4.1-cm-thick gold block placed between the counters reduced the coincidence rate by only 24%, and they concluded from this that the primary rays had a "corpuscular nature."[2] Until then the rays had been thought to be high-energy photons and had been called (by Hess, for example) "ultra γ rays."

Bruno Rossi, at the physics laboratory of the University of Florence in Arcetri, Italy, soon found a way to improve the technique. By using a vacuum-tube circuit to detect the coincident discharges of the tube counters, he achieved greater flexibility and time resolution. With three out-of-line counters, he discovered that there was a great abundance of secondary radiation—later identified as "cascade showers."

Meanwhile in Leningrad, Skobeltzyn, who had been studying γ radiation from radioactive materials, began using the Wilson cloud chamber to observe the trajectories of cosmic-ray particles in a magnetic field. In such a field a charged particle's track is curved, with a radius of curvature directly proportional to the particle's momentum and inversely proportional to the magnetic field. Skobeltzyn noted that the tracks appeared to be associated with each other, to a degree difficult to account for by the scattering processes known at that time.[3] His was the first method for studying the interactions of particles of energies higher than those available from radioactive sources.

Skobeltzyn's counterpart in California was Carl David Anderson, who had been using a cloud chamber to study photoelectrons produced by x rays. Anderson wanted to move on to study Compton collisions of nuclear γ rays, but in 1930, at the urging of his boss, Robert A. Millikan, he began tooling up a cloud chamber and a strong magnetic field to observe cosmic-ray interactions. Anderson was to discover two new particles in cosmic rays: the positron and the muon.[4]

The other major step forward was Patrick M. S. Blackett and Giuseppe P. S. Occhialini's invention and use in 1932 of the counter-controlled cloud chamber.[5] In such a chamber, both the expansion and camera are activated by an electronic pulse from a counter array that selects a class of events, so that the incident particle "takes its own picture." Soon after Anderson had discovered what he referred to as "easily deflectable positives," Blackett and Occhialini used their new instrument to observe electron pair production and cascade showers. By 1930, therefore, the technical framework had been established for two decades of spectacular cosmic-ray and new-particle discoveries, made using counter and cloud-chamber techniques.

Theory

Relativistic electron theory, which led to the "prediction" of the positron, and the quantum theory of fields were both on the agenda of theoretical physics after Werner Heisenberg and Erwin Schrödinger invented quantum mechanics in 1925 and 1926. Both theories emerged from the fertile brain of Paul A. M. Dirac. In a pioneering work of February 1927 on quantum electrodynamics (QED), Dirac proposed a solution to the problem of the wave–particle duality, which had puzzled physicists since Albert Einstein hypothesized the light-quantum in 1905.[6] At the end of his paper, Dirac summarized its contents as follows:

> The problem is treated of an assembly of similar systems satisfying the Einstein–Bose statistical

mechanics, which interact with another different system, a Hamiltonian function being obtained to describe the motion. The theory is applied to the interaction of an assembly of light-quanta with an ordinary atom, and it is shown that it gives Einstein's laws for the emission and absorption of radiation.

The interaction of an atom with electromagnetic waves is then considered, and it is shown that if one takes the energies and phases of the waves to be q-numbers satisfying the proper quantum conditions instead of c-numbers, the Hamiltonian function takes the same form as in the light-quantum treatment. The theory leads to the correct expressions for Einstein's *A*s and *B*s.

(The *A*s and *B*s are light-quantum emission and absorption probability amplitudes.) From this we can see that Dirac treated the electromagnetic field as a Bose–Einstein gas of light-quanta. The following year, Pascual Jordan and Eugene Wigner gave the analogous treatment for a Fermi–Dirac gas, applicable to electrons.[7] The Jordan–Wigner type of quantization, designed to prohibit more than one electron from occupying a given state, was just what Dirac needed to formulate the theory of holes and the notion of antimatter.

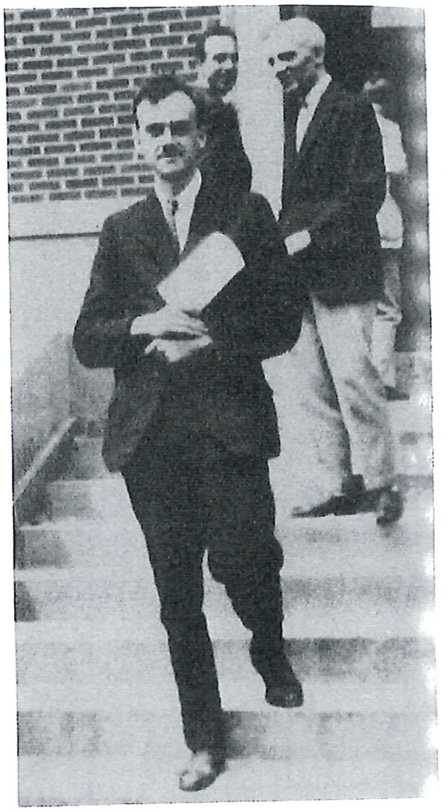
In his 1927 papers on the quantum theory of the electromagnetic field, Dirac quantized only the radiation part of the field, consisting of transverse waves. The Coulomb interaction was considered a part of the energy of the "matter" system, that is, the charged particles. This separation is convenient and often is a calculational necessity. However, as Gregor Wentzel has remarked, it "not only appears contrary to the spirit of Maxwell's theory, but also raises questions from the viewpoint of relativity theory... the splitting is not [relativistically] invariant."[8] Thus, in 1929, Heisenberg and Pauli took up a task whose completion would require the best theoretical efforts of the next two decades:

> ... to connect, in a contradiction-free manner, mechanical and electrodynamic quantities, electro–magneto-static interaction, on the one hand, and radiation-induced interactions on the other, and to treat them from a unified viewpoint. Especially [to take] into account in a correct manner the finite propagation velocity of electromagnetic forces.[9]

In the course of this work they discovered that the self-mass of the point electron was infinite, just as in the classical theory. (See box on page 42.) It was not until the postwar period that a more self-consistent QED was achieved. Nevertheless, the admittedly imperfect QED could still be fashioned into an effective tool for analyzing the high-energy cosmic rays.

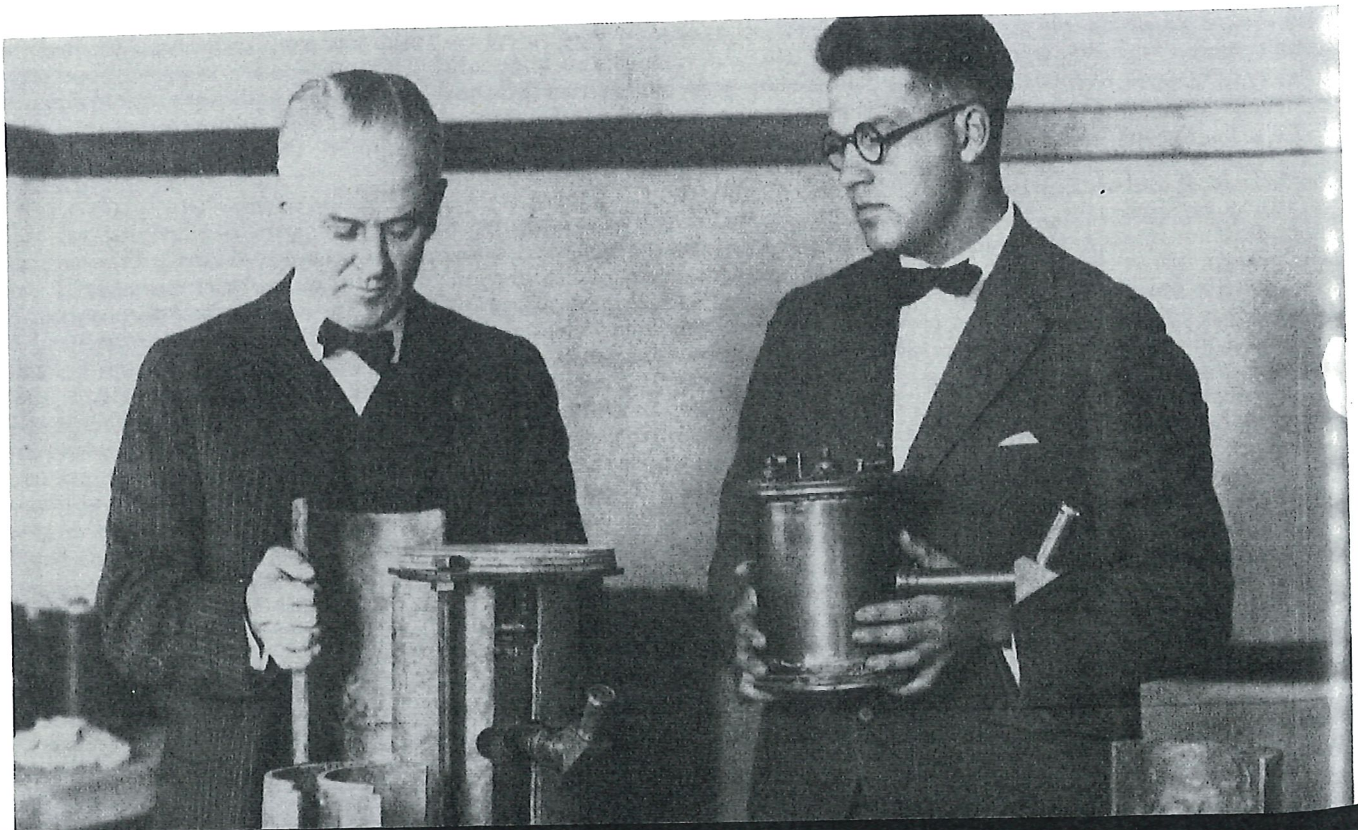
QED and cosmic rays

Some disturbing experiments at moderate energies—energies somewhat larger than twice the rest mass energy of the electron—showed a much greater energy degradation and scattering of high-energy γ rays than was predicted by a Compton-effect calculation based on Dirac's relativistic electron theory.[10] By 1933, the excess absorption was found to be due to the production of electron–positron pairs, and the excess "scattering" was traced to photons produced by pair annihilation. This resolved the "doubts at $2mc^2$,"



Paul A. M. Dirac (at right) in Ann Arbor, Michigan, in 1929. Leon Brillouin is in the background.

Robert A. Millikan and G. Harvey Cameron (below) with early cosmic-ray electroscopes. In this photo, taken about 1925, Millikan (left) is holding some lead shielding and Cameron an electroscope. (Photos courtesy AIP Niels Bohr Library.)



which, however, moved then to $137mc^2$.

The existence of doubts about the validity of QED at energies of the order of $137mc^2$ is corroborated by Anderson, who says that in 1934 members of the Caltech group spoke among themselves of "'green' electrons and 'red' electrons—the green electrons being the penetrating type, and the red the absorbable type." But the green electrons did not behave like electrons. Although the formulas giving the ionization energy loss for very fast charged particles were considered to be accurate, there seemed to be a problem with the radiation formulas, even in 1934. Referring to Anderson's analysis of cloud chamber photographs, Hans Bethe and Walter Heitler said that "*the theoretical energy loss by radiation is far too large to be in any way reconcilable with the experiments of Anderson.*"[11] For the particles of energy 300 MeV (the assumed green electrons), Anderson found an energy loss of 35 MeV per centimeter of lead, whereas Bethe and Heitler concluded that "it seems impossible that the theoretical energy loss can be smaller than about 150 million volts per centimetre lead for Anderson's electrons."

Instead of suggesting that these strangely behaving electrons might be some other particles, Bethe and Heitler proposed a possible explanation that reveals the spirit of the time:

> This can perhaps be understood for electrons of so high an energy. The de Broglie wave-length of an electron having an energy greater than $137mc^2$ is smaller than the classical radius of the electron $r_0 = e^2/mc^2$. One should not expect that ordinary quantum mechanics which treats the electron as a point-charge could hold under these conditions. It is very interesting that the energy loss of the fast electrons really proves this view and thus provides the *first instance in which quantum mechanics apparently breaks down for a phenomenon outside the nucleus.* We believe that the *radiation of fast electrons will be one of the most direct tests for any quantum-electrodynamics to be constructed.*[11]

QED proves indispensable. The problem was not with QED but with the assumption that Anderson's penetrating high-energy "green" electrons were electrons. They were, in fact, mesotrons (now called muons), about 200 times as massive. But about three years had to pass before anyone had the courage, or the faith in QED, to ascribe the discrepancy to new particles.

It was tempting at the time to explain away discrepancies between observed high-energy phenomena and theoretical expectations by appealing to a breakdown of QED at small distances, at a "fundamental length" or at the corresponding large momenta. But this became impossible by 1937; by that time, through a complex series of steps, QED showed itself to be not only useful after all, in spite of its menacing infinities, but also the indispensable means for understanding the nature of the cosmic rays. Although the electrodynamics of such energetic particles were questioned, Evans James Williams showed in 1933 that the important momentum transfers involved are small and that in a suitably chosen reference frame the collisions are gentle ones that do not involve high energies or small distances.[12]

In another step, taken in 1934, Bethe and Heitler calculated the relativistic formulas for bremsstrahlung (x-ray production) and electron pair creation. As noted earlier, they found significant disagreement with Anderson's results when they assumed Anderson was looking at electrons. Also, Williams and Carl-Friedrich von Weizsäcker showed that no disagreement with theory was to be expected, *even if QED were to break down at* $137mc^2$. Again, the argument was based upon looking at the collisions in a suitable rest frame.[12] As Williams said in his 1935 article, "We find that the quantum mechanics which enter into the existing treatments really concerns energies of the order of mc^2 however big the energy of the electron or photon."

By 1937 QED had also demonstrated its usefulness by explaining the behavior of the "soft component" of the cosmic rays, the cascade showers. Many physicists contributed to the solution of this problem; the first successes were by Homi J. Bhabha and Heitler, and by J. F. Carlson and J. Robert Oppenheimer.[13] However, the infinities of QED remained, and to obtain useful results they had to be ignored or thought of as corrections that would be "small," were they calculable in finite terms.

Particles envisioned, particles seen

The particle discoveries of the early 1930s (if we can call the neutrino proposal a discovery) permitted the banishment of electrons from the nucleus. On the heels of the discovery of the neutron, Heisenberg made a model of the nucleus as a non-relativistic quantum-mechanical system of neutrons and protons in which the neutron was to some extent treated as an elementary particle, the neutral counterpart of the proton. However, within this scheme Heisenberg tried to model the neutron as a tightly bound compound of proton and electron, in which the electron loses most of its properties—notably its spin, magnetic moment, and fermion character. The dominant nuclear force was to consist of the ex-

Development of cosmic-ray physics

In successive periods there was always at least one change that was so significant that it required a totally new interpretation of the previous observations.

Prehistory (to 1911, especially from 1900):
- ▶ "Atmospheric electricity" during calm weather
- ▶ Conductivity of air measured by electrometers
- ▶ Connection with radioactivity of earth and atmosphere
- ▶ Geophysical and meteorological interest

Discovery (1911–1914) **and exploration** (1922–1930):
- ▶ Observers with electrometers ascend in balloons and measure the altitude dependence of ionization, showing that there is an ionizing radiation that comes from above
- ▶ Such measurements begin in 1909 and continue (at interval) to about 1930, in the atmosphere, under water, underground
- ▶ The primaries are assumed to be high enough photons from outer space
- ▶ Search for diurnal and annual intensity variations
- ▶ Study of energy homogeneity

Early particle physics (1930–1947):
- ▶ Direct observation of the primaries is not yet possible, but the "latitude effect" shows they are charged particles
- ▶ Trajectories of secondary charged particles are observed with cloud chambers and counter telescope arrays, and momentum is measured by curvature of trajectory in a magnetic field
- ▶ Discoveries of positron and pair production
- ▶ Soft and penetrating components
- ▶ Radiation processes and electromagnetic cascades
- ▶ Meson theory of nuclear forces
- ▶ Discovery of mesotron (present day muon)
- ▶ Properties of the muon, including mass, lifetime and penetrability
- ▶ Two-meson theory and the meson "paradox"

Later particle physics (1947–1953):
- ▶ Particle tracks observed in photographic emulsion
- ▶ Discovery of pion and π–μ–e decay chain
- ▶ Nuclear capture of negative pions
- ▶ Observation of primary cosmic-ray protons and fast nuclei
- ▶ Extensive air showers
- ▶ Discovery of the strange particles
- ▶ The strangeness quantum number

Astrophysics (1954 and later):
- ▶ Even now the highest energy particles are in cosmic rays, but such particles are rare
- ▶ Studies made with rockets and earth satellites
- ▶ Primary energy spectrum, isotopic composition
- ▶ X-ray and γ-ray astronomy
- ▶ Galactic and extragalactic magnetic fields

change of this much abused electron.

After Fermi's successful theory of β-decay gave the neutrino a more legitimate status than it had previously enjoyed, there were attempts (although not by Fermi) to incorporate electron–neutrino pair exchange into the Heisenberg nuclear picture—the so-called Fermi-field model. However, it was shown to be impossible to fit simultaneously the range and strength of nuclear forces together with nuclear β decay. In an attempt to resolve this conflict, Hideki Yukawa, in Japan, made a bold imaginative stroke by introducing a new theory of nuclear forces that required the existence of a new type of particle, a fundamental massive boson.[14] The particle was to carry either the positive or negative electronic unit charge, and its exchange was to be the agent of Heisenberg's charge-exchange nuclear force. From the range of nuclear forces its mass was determined to be about 200 electron masses. Furthermore, Yukawa's meson (as it later became known) was to be capable of decaying into an electron and neutrino, in accord with Yukawa's proposed mechanism for nuclear β decay. Finally, it was predicted to be a part of the cosmic-ray flux.

In 1937 Anderson and others discovered in cosmic rays both positive and negative charged particles with masses about 200 times that of the electron. Some researchers greeted this as a fulfillment of Yukawa's prediction.[15] A number of properties of these particles, including mass, charge and lifetime, were determined before or during World War II; properties such as spin and parity, and the characteristics of interactions, were not determined unambiguously until the large accelerators came into use at the turn of the 1950s.[18] The fact that the known properties, other than the charge, did not provide a satisfactory match between the meson observed in cosmic rays and Yukawa's postulated meson of nuclear force stimulated new field theories that went beyond QED.

Because these new field theories had even worse divergence difficulties than QED, and because their strong interactions made perturbation methods far more questionable, there again arose practical as well as esthetic demands for curing or circumventing "the infinities" of field theory. The theoretical struggle was double-pronged: One effort was to find a version of meson theory that agreed with the cosmic-ray meson's behavior; another was to find a meson theory to fit the nuclear forces, whose complicated behavior came to be better known. An important success of the second approach was Nicholas Kemmer's symmetric meson theory of nuclear forces, which established the utility of the concept of isospin and called for the existence of a charged triplet of positive, negative and netural mesons.[16] The neutral meson, whose two-photon decay initiates the majority of cascade showers in the cosmic rays, was not observed until it was artificially produced in 1950.

Admitting a new particle. The cosmic-ray meson (muon) is the main component of the hard or penetrating cosmic rays. The penetrating rays were seen as early as 1929 in the first absorption measurements made on individual cosmic-ray particles, and perhaps were suggested by even earlier measurements. But it was not until 1937 that Seth Henry Neddermeyer and Anderson claimed these cosmic-ray mesons to be new charged particles—neither electrons nor protons—on the basis of their ability to penetrate a 1-cm thickness of platinum.[4] Even though scientists elsewhere, in England and France for example, were making similar observations, the preferred interpretation was that QED breaks down at high energies. That was the view of Blackett, who called the particles electrons and considered that a modification of the radiation formulas was in order.[17] Two French cloud-chamber groups emphasized that there were "two species of corpuscular rays" (like Anderson's red and green electrons) differing in their penetrating power; however, they did not insist on any *new* particles.[18] Two observations of mesons stopping in the gas of a cloud chamber permitted a determination of their masses sufficient to show them to be roughly 200 times the electron mass, or about one-tenth of the proton mass.[19]

The next step was to deal with the problem posed by the false identification of the muon with Yukawa's nuclear meson: If the cosmic-ray meson were Yukawa's strongly interacting particle, why did it not seem to interact at all? The remaining story of the muon—the determination of its mass, lifetime and interaction properties, and the growing sense of bewilderment and paradox in the confrontation between experiment and theory—was climaxed when an Italian group proved that negative muons stopping in carbon decay before they can be captured by the nucleus.[20]

The grand finale came when a group at Bristol University in England used a new nuclear photographic emulsion technique to reveal the pion, Yukawa's nuclear meson, and its decay into the muon, the cosmic-ray meson.[21] However, the solution of the π–μ paradox produced a new one, the "muon puzzle": making sense of the evidence that the muon was a heavy version of the electron—in modern terms, a second-generation lepton. The observation of the complete decay chain, pion→muon →electron, together with the long muon lifetime, strongly suggested this similarity. Today this is known as the puzzle of the "generations" of quarks and leptons.

Unification and diversification

Many physicists today believe that we are approaching a new synthesis in our view of matter, in which the world will be seen as made up of a few types of elementary particles that interact by means of a small number of forces, with both particles and forces being aspects of a few or perhaps even a single quantum field. An important reason for this confidence in unification is the apparent success of the theory of the unified electroweak field. The 1979 Nobel lectures in physics deal with this subject and with speculative theories of a more advanced type, having names such as "electronuclear grand unification" and "extended supergravity."

The mood of those lectures is one of barely qualified optimism.[22] Sheldon Glashow, for example, while cautioning against the adoption of a "premature orthodoxy," contrasts the present with 1965, when he began theoretical physics and when "the study of elementary particles was like a patchwork quilt." He continues:

> Things have changed. Today we have what has been called a "standard theory" of elementary particle physics in which strong, weak, and electromagnetic interactions all arise from a local symmetry principle. It is, in a sense, a complete and apparently correct theory, offering a qualitative description of all particle phenomena and precise quantitative predictions in many instances. There are no experimental data that contradict the theory. In principle, if not yet in practice, all experimental data can be expressed in terms of a small number of "fundamental" masses and coupling constants. The theory we now have is an integral work of art: The patchwork quilt has become a tapestry.

These remarks are reminiscent of other far-reaching syntheses: not only the "mechanical philosophy" of the eighteenth century and the "electromagnetic synthesis" at the end of the nineteenth century, but also physics as it appeared about 50 years ago. Then it was believed that there were only two fundamental material particles (electron and proton), only two fundamental forces (gravitation and electromagnetism), and that the fundamental laws were known (relativity and quantum mechanics). Accordingly, as Stephen Hawking reports, shortly after Dirac published his relativistic wave equation for the electron, Max Born said that "Physics, as we know it, will be

Lunches at the Niels Bohr Institute in Copenhagen. These photos, taken in 1934, show (at right) Walter Heitler with Leon Rosenfeld and (below) Werner Heisenberg and Niels Bohr. (Photos courtesy Paul Ehrenfest Jr)

over in six months.[23]

Although the positron discovery of August 1932 was a validation of Dirac's theory, that particle (and the neutron, neutrino and meson) totally destroyed the synthesis that appeared to be at hand in 1930. As Millikan said: "Prior to the night of 2 August 1932, the fundamental building-stones of the physical world had been universally supposed to be simply protons and negative-electrons."[24] Progress in the 1930s and the next few decades would lie not in unification of forces and reduction in the number of elements but rather in diversification—the discovery of new particles, the enlargement of the particle concept and the recognition of new nuclear forces, both strong and weak. During the 1930s and 1940s there were discovered the first antiparticle (the positron), the second baryon (the neutron), the second lepton (the muon), a neutral massless lepton (the neutrino, although actually first detected in 1953), the first massive field quanta, both charged and neutral (the pions), and the strange particles. By 1950, the modern idea of families of particles and the distinction between hadrons and leptons had already emerged. The idea of the universal weak interaction was also in the air. For hadrons there was the beginning of what Victor Weisskopf has called the "third spectroscopy" (that is, after those of atoms and nuclei), although all three cases involve not only spectroscopy but also structures. Thus the path toward unification, which looked attainable for a few years after resolution of the π–μ paradox, now seemed to twist through a minefield of the most diverse phenomena.

Particles and human attitudes

Because of their fundamental and universal character, elementary particles (and their unexpected properties such as indeterminacy, complementarity, strangeness and spin) both influence and are influenced by our general world outlook, from our primitive perceptions to our most advanced philosophical conceptions. Space limitations allow us only a glance at these issues, which we explore more fully in the symposium volume on which this article is based.

Some of the greatest battles occurred in the 1930s and 1940s over the enlargement of the concept of elementary particles far beyond the Newtonian mass point. Two of these battles involve the neutron and the neutrino and belong also to nuclear physics. At the Minnesota symposium, Maurice Goldhaber recalled:

> I remember being quite shocked when it dawned on me [in 1934] that the neutron, an "elementary particle" as I had by that time already learned to speak of it, might decay by β-emission with a half-life that I could roughly estimate . . . to be about half an hour or shorter . . .[1]

The battles over the positron and over the two mesons illustrate the psychological resistance of physicists to admit new particles to their cherished scheme. Dirac, in his first paper on the positron, and Anderson, in tune with what he called the "spirit of conservatism," both initially identified this new particle as a proton. Dirac even tried to make an argument for increasing the positron mass to the size of the proton mass; he realized that the new particles could not be protons only after Hermann Weyl proved mathematically that the holes had to have the same mass as electrons.

Yukawa had virtually no support outside Japan for his proposed nuclear meson until the mu meson was observed. Bohr's response to the proposal by the Kyoto group that there is a neutral meson in addition to the charged one was "Why do you want to create such a particle?" And the tantalizing π–μ paradox during 1937–1947 arose out of the reluctance to admit that there could be a second particle, having a mass similar to that of the Yukawa particle but in other respects behaving differently.

Researchers in the 1930s and 1940s were strongly affected by the overwhelming economic, social and political upheavals of that period. To list but a few:

- ▶ the economic depression, which took away jobs and financial security
- ▶ the rise of fascism in Europe, which displaced many physicists (including

Development of quantum field theory

Prehistory
Classical (19th century):
▶ Electromagnetism (Faraday, Maxwell, Hertz, Lorentz)
Quantum (1900–1927):
▶ Blackbody radiation (Planck, 1900)
▶ Photon hypothesis (Einstein, 1905)
▶ Stationary states of atom (Bohr, 1913)
▶ Atomic emission and absorption coefficients (Einstein, 1916)
▶ Bose and Fermi statistics (1924)
▶ Electron waves (de Broglie, 1924)
▶ Exclusion principle and spin (Pauli, Goudsmit, and Uhlenbeck, 1925)
▶ Quantum mechanics of atoms and molecules (Heisenberg, Schrödinger, Dirac, Born, 1925–1926)
▶ General transformation theory (Dirac, 1927)

Birth and early development (1927–1929):
▶ Quantum electrodynamics (QED) (Dirac, 1927)
▶ Second quantization (Jordan and Klein, 1927, and Jordan and Wigner, 1928)
▶ Relativistic electron theory (Dirac, 1928)
▶ Relativistic QED (Heisenberg and Pauli, 1929)
▶ Theory of holes (Dirac, 1929)

Developments, difficulties and doubts (1929–1934):
▶ Applications of QED and Dirac theory (Klein and Nishina, 1929; Oppenheimer *et al.*; Bethe and Heitler, 1934)
▶ Experimental tests (Meitner and Hupfeld, 1930, Tarrant, Gray, Chao)
▶ Specter of infinite energy shifts (Oppenheimer, 1930)
▶ Specter of infinite vacuum polarization (Dirac, 1932)

New fields (1934–1946):
▶ Scalar field theory (Pauli and Weisskopf, 1934)
▶ Beta decay theory (Fermi, 1934)
▶ Meson theory of nuclear forces (Yukawa, 1935)
▶ Relativistic spin-one theory (Proca, 1936)
▶ "Infrared" radiation (Bloch and Nordsieck, 1937)
▶ S-matrix (Wheeler, 1937, and Heisenberg, 1943)
▶ Developments of meson theory (Fröhlich, Heitler, Kemmer, Yukawa, Sakata, Taketani, Kobayasi, 1938)

Renormalization (1947 and later):
▶ Lamb shift (Lamb and Retherford, 1947)
▶ Calculation of Lamb shift (Bethe, 1947)
▶ Electron magnetic moment (Foley and Kusch, 1948)
▶ Renormalized relativistic QED (Tomonaga, Schwinger, Feynman, Dyson, 1948–1949)

Weisskopf, Bethe, Fermi, Rossi and Rudolf Peierls) from their homes in Germany and Italy, and at the same time dissolved much of the research establishments in those countries
▶ the political controls on philosophy (including physics) in certain countries
▶ the brutal war, with its diversion from research to defense work
▶ its bombings and destruction
▶ the death camps
▶ the economic shortages
▶ the breakdown of communications between countries
▶ the occupations.

Other authors have dealt with these developments, but their effects on physics have not yet been fully examined. Many vital social issues have not been considered. For example, the postwar occupations had a definite impact on physics. In Japan, the American occupation in 1945–1951 slowed nuclear-physics research by explicitly prohibiting experimental nuclear physics. Yet at the same time the occupation helped to establish the institutional basis for Japan's rapid progress in nuclear physics during the 1950s and 1960s.

In the postwar period, particle physics grew very rapidly, as did other subfields of physics. Many factors contributed to this postwar boom:
▶ the greater internationalism of science resulting from the war
▶ new experimental techniques developed as part of the weapons programs
▶ new funding mechanisms that emerged from the wartime support for research, resulting in, for example, the National Science Foundation and the Atomic Energy Commission
▶ the new widespread appreciation of the value of science for national security
▶ the sudden reentry into physics of graduate students and other researchers who, after about four years away, were anxious to make up for lost time
▶ the closer relationship between theory and experiment resulting from the experience of the large wartime projects such as building the bomb and developing radar for defense.

These and other influences need to be illuminated in detailed scholarly studies, for such larger issues are inseparable from the intellectual development of physics. Scholars will need to probe them deeply to understand fully the birth of particle physics.

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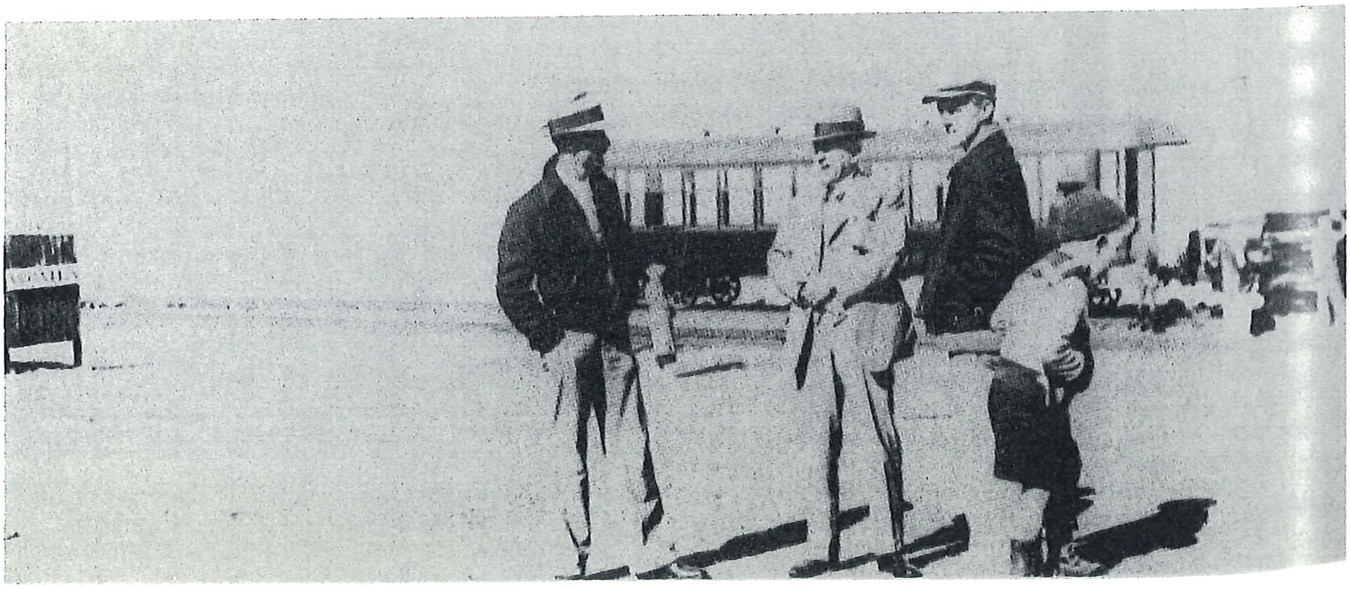
Robert Millikan (center) visits Seth Neddermeyer (right) and Carl Anderson on the summit of Pike's Peak, where Anderson set up his cloud-chamber experiment. The photograph was taken in 1935. (Courtesy of Carl Anderson.)



Hideki Yukawa and Richard Feynman during Feynman's visit to Kyoto, Japan, in the summer of 1955. Left to right: Mrs. Yukawa, Satio Hayakawa, Feynman, Yukawa, Koichi Mano, Minoru Kobayasi. (Courtesy of Satio Hayakawa.)

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