Theoretical particle physics

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CONTENTS

I. PRELUDES

"Gentlemen and Fellow Physicists of America: We meet today on an occasion which marks an epoch in the history of physics in America; may the future show that it also marks an epoch in the history of the science which this Society is organized to cultivate!" (Rowland, 1899).[1] These are the opening words of the address by Henry Rowland, the first president of the American Physical Society, at the Society's first meeting, held in New York on October 28, 1899. I do not believe that Rowland would have been disappointed by what the next few generations of physicists have cultivated so far.

It is the purpose of these brief preludes to give a few glimpses of developments in the years just before and just after the founding of our Society.

First, events just before: Invention of the typewriter in 1873, of the telephone in 1876, of the internal combustion engine and the phonograph in 1877, of the zipper in 1891, of the radio in 1895. The *Physical Review* began publication in 1893. The twilight of the 19th century was driven by oil and steel technologies.

Next, a few comments on "high-energy" physics in the first years of the twentieth century:

Pierre Curie in his 1903 Nobel lecture: "It can even be thought that radium could become very dangerous in criminal hands, and here the question can be raised whether mankind benefits from the secrets of Nature." [1]

From a preview of the 1904 International Electrical Congress in St. Louis, found in the *St. Louis Post Dispatch* of October 4, 1903: "Priceless mysterious radium will be exhibited in St. Louis. A grain of this most wonderful and mysterious metal will be shown." At that Exposition a transformer was shown which generated about half a million volts (Pais, 1986).

In March 1905, Ernest Rutherford began the first of his Silliman lectures, given at Yale, as follows:

> The last decade has been a very fruitful period in physical science, and discoveries of the most striking interest and importance have followed one another in rapid succession . . . . The march of discovery has been so rapid that it has been difficult even for those directly engaged in the investigations to grasp at once the full significance of the facts that have been brought to light . . . . The rapidity of this advance has seldom, if ever, been equalled in the history of science (Rutherford, 1905, quoted in Pais, 1986).

The text of Rutherford's lectures makes clear which main facts he had in mind: X rays, cathode rays, the Zeeman effect, α, β, and γ radioactivity, the reality as well as the destructibility of atoms, in particular the radioactive families ordered by his and Soddy's transformation theory, and results on the variation of the mass of β particles with their velocity. There is no mention, however, of the puzzle posed by Rutherford's own introduction of a characteristic lifetime for each radioactive substance. Nor did he touch upon Planck's discovery of the quantum theory in 1900. He could not, of course, refer to Einstein's article on the light-quantum hypothesis, because that paper was completed on the seventeenth of the very month he was lecturing in New Haven. Nor could he include Einstein's special theory of relativity among the advances of the decade he was reviewing, since that work was completed another three months later. It seems to me that Rutherford's remark about the rarely equaled rapidity of significant advances driving the decade 1895–1905 remains true to this day, especially since one must include the beginnings of quantum and relativity theory.

Why did so much experimental progress occur when it did? Largely because of important advances in instru-

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[1] Quoted in Pais, 1986. Individual references not given in what follows are given in this book, along with many more details.

mentation during the second half of the nineteenth century. This was the period of ever improving vacuum techniques (by 1880, vacua of 10^{-6} torr had been reached), of better induction coils, of an early type of transformer, which, before 1900, was capable of producing energies of 100 000 eV, and of new tools such as the parallel-plate ionization chamber and the cloud chamber.

All of the above still remain at the roots of high-energy physics. Bear in mind that what was high energy then ($\sim$1 MeV) is low energy now. What was high energy later became medium energy, 400 MeV in the late 1940s. What we now call high-energy physics did not begin until after the Second World War. At this writing, we have reached the regime of 1 TeV$=10^{12}$ eV$=1.6$ erg.

To do justice to our ancestors, however, I should first give a sketch of the field as it developed in the first half of this century.

II. THE YEARS 1900–1945

A. The early mysteries of radioactivity

High-energy physics is the physics of small distances, the size of nuclei and atomic particles. As the curtain rises, the electron, the first elementary particle, has been discovered, but the reality of atoms is still the subject of some debate, the structure of atoms is still a matter of conjecture, the atomic nucleus has not yet been discovered, and practical applications of atomic energy, for good or evil, are not even visible on the far horizon.

On the scale of lengths, high-energy physics has moved from the domain of atoms to that of nuclei to that of particles (the adjective "elementary" is long gone). The historical progression has not always followed that path, as can be seen particularly clearly when following the development of our knowledge of radioactive processes, which may be considered as the earliest high-energy phenomena.

Radioactivity was discovered in 1896, the atomic nucleus in 1911. Thus even the simplest qualitative statement—radioactivity is a nuclear phenomenon—could not be made until fifteen years after radioactivity was first observed. The connection between nuclear binding energy and nuclear stability was not made until 1920. Thus some twenty-five years would pass before one could understand why some, and only some, elements are radioactive. The concept of decay probability was not properly formulated until 1927. Until that time, it remained a mystery why radioactive substances have a characteristic lifetime. Clearly, then, radioactive phenomena had to be a cause of considerable bafflement during the early decades following their first detection. Here are some of the questions that were the concerns of the fairly modest-sized but elite club of experimental radioactivists: What is the source of energy that continues to be released by radioactive materials? Does the energy reside inside the atom or outside? What is the significance of the characteristic half-life for such transformations? (The first determination of a lifetime for radioactive decay was made in 1900.) If, in a given radioactive transformation, all parent atoms are identical, and if the same is true for all daughter products, then why does one radioactive parent atom live longer than another, and what determines when a specific parent atom disintegrates? Is it really true that some atomic species are radioactive, others not? Or are perhaps all atoms radioactive, but many of them with extremely long lifetimes?

One final item concerning the earliest acquaintance with radioactivity: In 1903 Pierre Curie and Albert Laborde measured the amount of energy released by a known quantity of radium. They found that 1 g of radium could heat approximately 1.3 g of water from the melting point to the boiling point in 1 hour. This result was largely responsible for the worldwide arousal of interest in radium.

It is my charge to give an account of the developments of high-energy theory, but so far I have mainly discussed experiments. I did this to make clear that theorists did not play any role of consequence in the earliest stages, both because they were not particularly needed for its descriptive aspects and because the deeper questions were too difficult for their time.

As is well known, both relativity theory and quantum theory are indispensable tools for understanding high-energy phenomena. The first glimpses of them could be seen in the earliest years of our century.

Re relativity: In the second of his 1905 papers on relativity Einstein stated that

> if a body gives off the energy L in the form of radiation, its mass diminishes by L/c^2 . . . . The mass of a body is a measure of its energy . . . . It is not impossible that with bodies whose energy content is variable to a high degree (e.g., with radium salts) the theory may be successfully put to the test (Einstein 1905, reprinted in Pais, 1986).

The enormous importance of the relation $E=mc^2$ was not recognized until the 1930s. See what Pauli wrote in 1921: "Perhaps the law of the inertia of energy will be tested *at some future time* on the stability of nuclei" (Pauli, 1921, italics added).

Re quantum theory: In May 1911, Rutherford announced his discovery of the atomic nucleus and at once concluded that α decay is due to nuclear instability, but that β decay is due to instability of the peripheral electron distribution.

It is not well known that it was Niels Bohr who set that last matter straight. In his seminal papers of 1913, Bohr laid the quantum dynamical foundation for understanding atomic structure. The second of these papers contains a section on "Radioactive phenomena," in which he states: "On the present theory it seems also necessary that the nucleus is the seat of the expulsion of the high-speed β-particles" (Bohr, 1913). His main argument was that he knew enough by then about orders of magnitude of peripheral electron energies to see that the energy release in β decay simply could not fit with a peripheral origin of that process.

In teaching a nuclear physics course, it may be edifying to tell students that it took 17 years of creative confusion, involving the best of the past masters, between the discovery of radioactive processes and the realization that these processes are all of nuclear origin—time spans not rare in the history of high-energy physics, as we shall see in what follows.

One last discovery, the most important of the lot, completes the list of basic theoretical advances in the pre-World-War-I period. In 1905 Einstein proposed that, under certain circumstances, light behaves like a stream of particles, or light quanta. This idea initially met with very strong resistance, arriving as it did when the wave picture of light was universally accepted. The resistance continued until 1923, when Arthur Compton's experiment on the scattering of light by electrons showed that, in that case, light does behave like particles—which must be why their current name, photons, was not introduced until 1926 (Lewis, 1926).

Thus by 1911 three fundamental particles had been recognized: the electron, the photon, and the proton [so named only in 1920 (Author unnamed, 1920)], the nucleus of the hydrogen atom.

B. Weak and strong interactions: Beginnings

In the early decades following the discovery of radioactivity it was not yet known that quantum mechanics would be required to understand it nor that distinct forces are dominantly responsible for each of the three radioactive decay types:

Process	Dominant interaction
α decay	strong
β decay	weak
γ decay	electromagnetic

The story of α and γ decay will not be pursued further here, since they are not primary sources for our understanding of interactions. By sharpest contrast, until 1947—the year μ-meson decay was discovered—β decay was the *only* manifestation, rather than one among many, of a specific type of force. Because of this unique position, conjectures about the nature of this process led to a series of pitfalls. Analogies with better-known phenomena were doomed to failure. Indeed, β decay provides a splendid example of how good physics is arrived at after much trial and many errors—which explains why it took twenty years to establish that the *primary* β process yields a continuous β spectrum. I list some of the false steps—no disrespect intended, but good to tell your students.

(1) It had been known since 1904 that α rays from a pure α emitter are monochromatic. It is conjectured (1906) that the same is true for β emitters.

(2) It is conjectured (1907) that the absorption of monoenergetic electrons by metal forces satisfies a simple exponential law as a function of foil thickness.

(3) Using this as a diagnostic, absorption experiments are believed to show that β emitters produce homogeneous energy electrons.

(4) In 1911 it is found that the absorption law is incorrect.

(5) Photographic experiments seem to claim that a multiline discrete β spectrum is present (1912–1913).

(6) Finally, in 1914, James Chadwick performs one of the earliest experiments with counters, which shows that β rays from RaB (Pb^{214}) and RaC (Bi^{214}) consist of a continuous spectrum, and that there is an additional line spectrum. In 1921 it is understood that the latter is due to an internal conversion process. In 1922 the first nuclear energy-level diagram is sketched.

Nothing memorable relevant to our subject happened between 1914 and 1921. There was a war going on. There were physicists who served behind the lines and those who did battle. In his obituary to Henry Moseley, the brilliant physicist who at age 28 had been killed by a bullet in the head at Suvla Bay, Rutherford (1915) remarked: "His services would have been far more useful to his country in one of the numerous fields of scientific inquiry rendered necessary by the war than by the exposure to the chances of a Turkish bullet," an issue that will be debated as long as the folly of resolving conflict by war endures.

Continuous β spectra had been detected in 1914, as said. The next question, much discussed, was: are these primary or due to secondary effects? This issue was settled in 1927 by Ellis and Wooster's difficult experiment, which showed that the continuous β spectrum of RaE (Bi^{210}) was primary in origin. "We may safely generalize this result for radium E to all β-ray bodies and the long controversy about the origin of the continuous spectrum appears to be settled" (Ellis and Wooster, 1927).

Another three years passed before Pauli, in December 1930, gave the correct explanation of this effect: β decay is a three-body process in which the liberated energy is shared by the electron and a hypothetical neutral particle of very small mass, soon to be named the neutrino. Three years after that, Fermi put this qualitative idea into theoretical shape. His theory of β decay, the first in which quantized spin-$\frac{1}{2}$ fields appear in particle physics, is the first quantitative theory of weak interactions.

As for the first glimpses of strong-interaction theory, we can see them some years earlier.

In 1911 Rutherford had theoretically deduced the existence of the nucleus on the assumption that α-particle scattering off atoms is due to the $1/r^2$ Coulomb force between a pointlike α and a pointlike nucleus. It was his incredible luck to have used α particles of moderate energy and nuclei with a charge high enough so that his α's could not come very close to the target nuclei. In 1919 his experiments on α-hydrogen scattering revealed large deviations from his earlier predictions. Further experiments by Chadwick and Etienne Bieler (1921) led them to conclude,

> The present experiments do not seem to throw any

> light on the nature of the law of variation of the forces at the seat of an electric charge, but merely show that the forces are of very great intensity . . . . It is our task to find some field of force which will reproduce these effects" (Chadwick and Bieler, 1921).

I consider this statement, made in 1921, as marking the birth of strong-interaction physics.

C. The early years of quantum field theory

Apart from the work on β decay, all the work we have discussed up to this point was carried out before late 1926, in a time when relativity and quantum mechanics had not yet begun to have an impact upon the theory of particles and fields. That impact began with the arrival of quantum field theory, when particle physics acquired, one might say, its own unique language. From then on particle theory became much more focused. A new central theme emerged: how good are the predictions of quantum field theory? Confusion and insight continued to alternate unabated, but these ups and downs mainly occurred within a tight theoretical framework, the quantum theory of fields. Is this theory the ultimate framework for understanding the structure of matter and the description of elementary processes? Perhaps, perhaps not.

Quantum electrodynamics (QED), the earliest quantum field theory, originated on the heels of the discoveries of matrix mechanics (1925) and wave mechanics (1926). At that time, electromagnetism appeared to be the only field relevant to the treatment of matter in the small. (The gravitational field was also known by then but was not considered pertinent until decades later.) Until QED came along, matter was treated like a game of marbles, of tiny spheres that collide, link, or disconnect. Quantum field theory abandoned this description; the new language also explained how particles are made and how they disappear.

It may fairly be said that the theoretical basis of high-energy theory began its age of maturity with Dirac's two 1927 papers on QED. By present standards the new theoretical framework, as it was developed in the late twenties, looks somewhat primitive. Nevertheless, the principal foundations had been laid by then for much that has happened since in particle theory. From that time on, the theory becomes much more technical. As Heisenberg (1963) said: "Somehow when you touched [quantum mechanics] . . . at the end you said 'Well, was it that simple?' Here in electrodynamics, it didn't become simple. You could do the theory, but still it never became that simple" (Heisenberg, 1963). So it is now in all of quantum field theory, and it will never be otherwise. Given limitations of space, the present account must become even more simple-minded than it has been hitherto.

In 1928 Dirac produced his relativistic wave equation of the electron, one of the highest achievements of twentieth-century science. Learning the beauty and power of that little equation was a thrill I shall never forget. Spin, discovered in 1925, now became integrated into a real theory, including its ramifications. Entirely novel was its consequence: a new kind of particle, as yet unknown experimentally, having the same mass and opposite charge as the electron. This "antiparticle," now named a positron, was discovered in 1931.

At about that time new concepts entered quantum physics, especially quantum field theory: groups, symmetries, invariances—many-splendored themes that have dominated high-energy theory ever since. Some of these have no place in classical physics, such as permutation symmetries, which hold the key to the exclusion principle and to quantum statistics; a quantum number, parity, associated with space reflections; charge conjugation; and, to some extent, time-reversal invariance. In spite of some initial resistance, the novel group-theoretical methods rapidly took hold.

A final remark on physics in the late 1920s: "In the winter of 1926," K. T. Compton (1937) has recalled, "I found more than twenty Americans in Goettingen at this fount of quantum wisdom." Many of these young men contributed vitally to the rise of American physics. "By 1930 or so, the relative standings of *The Physical Review* and *Philosophical Magazine* were interchanged" (Van Vleck, 1964). Bethe (1968) has written: "J. Robert Oppenheimer was, more than any other man, responsible for raising American theoretical physics from a provincial adjunct of Europe to world leadership . . . . It was in Berkeley that he created his great School of Theoretical Physics." It was Oppenheimer who brought quantum field theory to America.

D. The 1930s

Two main themes dominate high-energy theory in the 1930s: struggles with QED and advances in nuclear physics.

1. QED

All we know about QED, from its beginnings to the present, is based on perturbation theory, expansions in powers of the small number $\alpha = e^2/\hbar c$. The nature of the struggle was this: To lowest order in α, QED's predictions were invariably successful; to higher order, they were invariably disastrous, always producing infinite answers. The tools were those still in use: quantum field theory and Dirac's positron theory.

Infinities had marred the theory since its classical days: The self-energy of the point electron was infinite even then. QED showed (1933) that its charge is also infinite—the vacuum polarization effect. The same is true for higher-order contributions to scattering or annihilation processes or what have you.

Today we are still battling the infinities, but the nature of the attack has changed. All efforts at improvement in the 1930s—mathematical tricks such as nonlinear modifications of the Maxwell equation—have led nowhere. As we shall see, the standard theory is very much better than was thought in the 1930s. That decade came to an end with a sense of real crisis in QED.

Meanwhile, however, quantum field theory had scored an enormous success when Fermi's theory of β decay made clear that electrons are not constituents of nuclei—as was believed earlier—but are *created* in the decay process. This effect, so characteristic of quantum field theory, brings us to the second theme of the thirties.

2. Nuclear physics

It was only after quantum mechanics had arrived that theorists could play an important role in nuclear physics, beginning in 1928, when α decay was understood to be a quantum-mechanical tunneling effect. Even more important was the theoretical insight that the standard model of that time (1926–1931), a tightly bound system of protons and electrons, led to serious paradoxes. Nuclear magnetic moments, spins, statistics—all came out wrong, leading grown men to despair.

By contrast, experimental advances in these years were numerous and fundamental: The first evidence of cosmic-ray showers (1929) and of billion-eV energies of individual cosmic-ray particles (1932–1933), the discoveries of the deuteron and the positron (both in 1931) and, most trail-blazing, of the neutron (1932), which ended the aggravations of the proton-electron nuclear model, replacing it with the proton-neutron model of the nucleus. Which meant that quite new forces, only glimpsed before, were needed to understand what holds the nucleus together—the strong interactions.

The approximate equality of the number of p and n in nuclei implied that short-range nn and pp forces could not be very different. In 1936 it became clear from scattering experiments that pp and pn forces in $1s$ states are equal within the experimental errors, suggesting that they, as well as nn forces, are also equal in other states. From this, the concept of charge independence was born. From that year dates the introduction of isospin for nucleons (p and n), p being isospin "up," neutron "down," the realization that charge independence implies that nuclear forces are invariant under isospin rotations, which form the symmetry group SU(2).

With this symmetry a new lasting element enters physics, that of a *broken symmetry*: SU(2) holds for strong interactions only, not for electromagnetic and weak interactions.

Meanwhile, in late 1934, Hideki Yukawa had made the first attack on describing nuclear forces by a quantum field theory, a one-component complex field with charged massive quanta: mesons, with mass estimated to be approximately $200m$ (where m=electron mass). When, in 1937, a particle with that order of mass was discovered in cosmic rays, it seemed clear that this was Yukawa's particle, an idea both plausible and incorrect. In 1938 a neutral partner to the meson was introduced, in order to save charge independence. It was the first particle proposed on theoretical grounds, and it was discovered in 1950.

To conclude this quick glance at the 1930s, I note that this was also the decade of the birth of accelerators. In 1932 the first nuclear process produced by these new machines was reported: $p+\mathrm{Li}^7 \to 2\alpha$, first by Cockroft and Walton at the Cavendish, with their voltage multiplier device, a few months later by Lawrence and coworkers with their first, four-inch cyclotron. By 1939 the 60-inch version was completed, producing 6-MeV protons. As the 1930s drew to a close, theoretical high-energy physics scored another major success: the insight that the energy emitted by stars is generated by nuclear processes.

Then came the Second World War.

III. MODERN TIMES

As we all know, the last major prewar discovery in high-energy physics—fission—caused physicists to play a prominent role in the war effort. After the war this brought them access to major funding and prepared them for large-scale cooperative ventures. Higher-energy regimes opened up, beginning in November 1946, when the first synchrocyclotron started producing 380-MeV α particles.

A. QED triumphant

High-energy theory took a grand turn at the Shelter Island Conference (June 2–4, 1947), which many attendees (including this writer) consider the most important meeting of their career. There we first heard reports on the Lamb shift and on precision measurements of hyperfine structure in hydrogen, both showing small but most significant deviations from the Dirac theory. It was at once accepted that these new effects demanded interpretation in terms of radiative corrections to the leading-order predictions in QED. So was that theory's great leap forward set in motion. The first "clean" result was the evaluation of the electron's anomalous magnetic moment (1947).

The much more complicated calculation of the Lamb shift was not successfully completed until 1948. Here one meets for the first time a new bookkeeping in which all higher-order infinities are shown to be due to contributions to mass and charge (and the norm of wave functions). Whereupon mass and charge are *renormalized*, one absorbs these infinities into these quantities, which become *phenomenological parameters*, not theoretically predictable to this day—after which corrections to all physical processes are finite.

By the 1980s calculations of corrections had been pushed to order α^4, yielding, for example, agreement with experiment for the electron's magnetic moment to ten significant figures, the highest accuracy attained anywhere in physics. QED, maligned in the 1930s, has become theory's jewel.

B. Leptons

In late 1946 it was found that the absorption of negative cosmic-ray mesons was ten to twelve orders of magnitude weaker than that of Yukawa's meson. At Shelter Island a way out was proposed: the Yukawa meson, soon to be called a pion (π), decays into another weakly absorbable meson, the muon (μ). It was not known at that time that a Japanese group had made that same proposal before, nor was it known that evidence for the two-meson idea had already been reported a month earlier (Lattes *et al.*, 1947).

The μ is much like an electron, only ~200 times heavier. It decays into $e+2\nu$. In 1975 a still heavier brother of the electron was discovered and christened τ (mass ~1800 MeV). Each of these three, e, μ, τ, has a distinct, probably massless neutrino partner, ν_e, ν_μ, ν_τ. The lot of them form a *particle family*, the leptons (name introduced by Møller and Pais, 1947), subject to weak and electromagnetic but not to strong interactions. In the period 1947–1949 it was found that β decay, μ decay, and μ absorption had essentially equal coupling strength. Thus was born the *universal* Fermi interaction, followed in 1953 by the law of lepton conservation.

So far we have seen how refreshing and new high-energy physics became after the war. And still greater surprises were in store.

C. Baryons, more mesons, quarks

In December 1947, a Manchester group reported two strange cloud-chamber events, one showing a fork, another a kink. Not much happened until 1950, when a CalTech group found thirty more such events. These were the early observations of new mesons, now known as K^0 and $K^{\pm}$. Also in 1950 the first hyperon (Λ) was discovered, decaying into $p+\pi^-$. In 1954 the name "baryon" was proposed to denote nucleons (p and n) and hyperons collectively (Pais, 1955).

Thus began baryon spectroscopy, to which, in 1952, a new dimension was added with the discovery of the "33-resonance," the first of many nucleon excited states. In 1960 the first hyperon resonance was found. In 1961 meson spectroscopy started, when the ρ, ω, η, and K^* were discovered.

Thus a new, deeper level of submicroscopic physics was born, which had not been anticipated by anyone. It demanded the introduction of new theoretical ideas. The key to these was the fact that hyperons and K's were very long-lived, typically $\sim 10^{-10}$ sec, ten orders of magnitude larger than the guess from known theory. An understanding of this paradox began with the concept of associated production (1952, first observed in 1953), which says, roughly, that the production of a hyperon is always associated with that of a K, thereby decoupling strong production from weak decay. In 1953 we find the first reference to a hierarchy of interactions in which strength and symmetry are correlated and to the need for enlarging isospin symmetry to a bigger group. The first step in that direction was the introduction (1953) of a phenomenological new quantum number, strangeness (s), conserved in strong and electromagnetic, but not in weak, interactions.

The search for the bigger group could only succeed after more hyperons had been discovered. After the Λ, a singlet came, Σ, a triplet, and Ξ, a doublet. In 1961 it was noted that these six, plus the nucleon, fitted into the octet representation of SU(3), the ϱ, ω, and K^* into another 8. The lowest baryon resonances, the quartet "33" plus the first excited Σ's and Ξ's, nine states in all, would fit into a decuplet representation of SU(3) if only one had one more hyperon to include. Since one also had a mass formula for these *badly broken* multiplets, one could predict the mass of the "tenth hyperon," the Ω^-, which was found where expected in 1964. SU(3) worked.

Nature appears to keep things simple, but had bypassed the fundamental 3-representation of SU(3). Or had it? In 1964 it was remarked that one could imagine baryons to be made up of three particles, named quarks (Gell-Mann, 1964), and mesons to be made up of one quark (q) and one antiquark ($\overline{q}$). This required the q's to have fractional charges (in units of e) of 2/3 (u), $-1/3$ (d), and $-1/3$ (s), respectively. The idea of a new deeper level of fundamental particles with fractional charge initially seemed a bit rich, but today it is an accepted ingredient for the description of matter, including an explanation of why these quarks have never been seen. More about that shortly.

D. *K* mesons, a laboratory of their own

In 1928 it was observed that in quantum mechanics there exists a two-valued quantum number, parity (P), associated with spatial reflections. It was noted in 1932 that no quantum number was associated with time-reversal (T) invariance. In 1937, a third discrete symmetry, two-valued again, was introduced, charge conjugation (C), which interchanges particles and antiparticles.

K particles have opened quite new vistas regarding these symmetries.

1. Particle mixing

In strong production reactions one can create $K^0(S=1)$ or $\overline{K^0}(S=-1)$. Both decay into the same state $\pi^+ + \pi^-$. How can charge conjugation transform the final but not the initial state into itself? It cannot do so as long as S is conserved (strong interactions) but it can, and does, when S is not conserved (weak interactions). Introduce $K^1=(K^0+\overline{K^0})/\sqrt{2}$ and $K^2=(K^0-\overline{K^0})/\sqrt{2}$. We find that K^1 can and K^2 cannot decay into $\pi^+ + \pi^-$. These states have different lifetimes: K^2 should live much longer (unstable only via non-2π modes). Since a particle is an object with a unique lifetime, K^1 and K^2 are particles and K^0 and $\overline{K^0}$ are *particle mixtures*, a situation never seen before (and, so far, not since) in physics. This gives rise to bizarre effects such as regeneration: One can create a pure K^0 beam, follow it downstream until it consists of K^2 only, interpose an absorber that by strong interactions absorbs the $\overline{K^0}$ but not the K^0 component of K^2, and thereby regenerate K^1: 2π decays reappear.

2. Violations of *P* and *C*

A K^+ can decay into π^+ and π^0, the "θ mode," or into $2\pi^+ + \pi^-$, the "τ mode." Given the spin (zero) and parity (odd) of pions, a τ (spin zero) must have odd parity but a θ even parity! How can that be? Either θ and τ are distinct particles rather than alternative decay modes of the same particle, or there is only one K but parity is not conserved in these weak decays. This was known as the θ-τ puzzle.

In 1956, a brilliant analysis of all other weak processes (β decay, μ decay) showed that P conservation had never been established in any of them (Lee and Yang, 1956). In 1957 it was experimentally shown that in these processes both parity and charge conjugation were violated! (Wu *et al.*, 1957; Friedman and Telegdi, 1957). Up until then these invariances had been thought to be universal. They were not, a discovery that deeply startled the pros.

This discovery caused an explosion in the literature. Between 1950 and 1972, 1000 experimental and 3500 theoretical articles (in round numbers) appeared on weak interactions. New theoretical concepts appeared: two-component neutrino theory; the V-A (vector minus axial-vector) theory of weak interactions, the remarkable link between its A-part and strong interactions, which in turn led to the concept of a partially conserved axial current; the insight that, while C and P were violated, their product CP still held—which sufficed to save the concept of particle mixture.

3. Violations of *CP* and *T*

In 1964, a delicate experiment showed that, after all, K^2 *does* decay into π^+ and π^-, at a rate of ~0.2 percent of all decay modes, a rate weaker than weak. CP invariance had fallen by the wayside; its incredibly weak violation made the news even harder to digest. (Particle mixing remained substantially intact.) The following thirty years of hard experimental labor have failed so far to find any other CP-violating effect—but has shown that T is also violated!

That, in a way, is a blessing. In the years 1950–1957 the "CPT theorem" was developed, which says that, under very general conditions, any relativistic quantum field theory is necessarily invariant under the product operation CPT—which means that, if CP is gone, T separately must also be gone.

E. Downs and ups in mid-century

The postwar years as described so far were a period of great progress. It was not all a bed of roses, however.

1. Troubles with mesons

It seemed reasonable to apply the methods so successful in *QED* to the meson field theory of nuclear forces, but that led to nothing but trouble. Some meson theories (vector, axial-vector) turned out to be unrenormalizable. For those that were not (scalar, pseudoscalar), the analog of the small number $e^2/\hbar c$ was a number larger than 10—so that perturbation expansions made no sense.

2. *S*-matrix methods

Attention now focused on the general properties of the scattering matrix, the S matrix, beginning with the successful derivation of dispersion relations for π-nucleon scatterings (1955). This marked the beginning of studies of analytic properties of the S matrix, combined with causality, unitarity, and crossing, and culminating in the bootstrap vision which says that these properties (later supplemented by Regge poles) should suffice to give a self-consistent theory of the strong interactions. This road has led to interesting mathematics but not to much physics.

3. Current algebra

More fertile was another alternative to quantum field theory but closer to it: current algebra, starting in the mid-sixties, stimulated by the insights that weak interactions have a current structure and that quarks are basic to strong interactions. Out of this grew the proposal that electromagnetic and weak vector currents were members of an SU(3) octet, axial currents of another one, both taken as quark currents. Current algebra, the commutator algebra of these currents, has led to quite important sum rules.

4. New lepton physics

In the early sixties design began of high-energy neutrino beams. In the late sixties, experiments at SLAC revealed that high-energy "deep"-inelastic electron-nucleon scattering satisfied scaling laws, implying that in this régime nucleons behaved like boxes filled with hard nuggets. This led to an incredibly simple-minded but successful model for inelastic electron scattering as well as neutrino scattering, as the incoherent sum of elastic lepton scatterings off the nuggets, which were called partons.

F. Quantum field theory redux

1. Quantum chromodynamics (QCD)

In 1954 two short brilliant papers appeared marking the start of non-Abelian gauge theory (Yang and Mills, 1954a, 1954b). They dealt with a brand new version of strong interactions, mediated by vector mesons of zero mass. The work was received with considerable interest, but what to do with these recondite ideas was another matter. At that time there were no vector mesons, much less vector mesons with zero mass. There the matter rested until the 1970s.

To understand what happened then, we must first go back to 1964, when a new symmetry, static SU(6), entered the theory of strong interactions. Under this symmetry SU(3) and spin were linked, a generalization of Russell-Saunders coupling in atoms, where spin is conserved in the absence of spin-orbit coupling. The baryon octet and decouplet together formed one SU(6) representation, the "56," which was totally symmetric in all three-quark variables. This, however, violated the exclusion principle. To save that, the u, d, and s quarks were assigned a new additional three-valued degree of freedom, called *color*, with respect to which the 56 states were totally antisymmetric. The corresponding new group was denoted $SU(3)_c$, and the "old" SU(3) became flavor SU(3), $SU(3)_f$.

Out of gauges and colors grew quantum chromodynamics (QCD), a quantum field theory with gauge group $SU(3)_c$, with respect to which the massless gauge fields, gluons, form an octet. In 1973 the marvelous discovery was made that QCD is *asymptotically free*: strong interactions diminish in strength with increasing energy—which explains the parton model for scaling. All the earlier difficulties with the strong interactions residing in the low-energy region ($\lesssim$ few GeV) were resolved.

A series of speculations followed: $SU(3)_c$ is an unbroken symmetry, i.e., the gluons are strictly massless. The attractive potential between quarks grows with increasing distance, so that quarks can never get away from each other, but are *confined*, as are single gluons. Confinement is a very plausible idea but to date its rigorous proof remains outstanding.

2. Electroweak unification

In mid-century the coupling between four spin-1/2 fields, the Fermi theory, had been very successful in organizing β-decay data, yet it had its difficulties: the theory was unrenormalizable, and it broke down at high energies ($\lesssim$300 GeV). In the late 1950s the first suggestions appeared that the Fermi theory was an approximation to a mediation of weak interactions by heavy charged vector mesons, called $W^{\pm}$. That would save the high-energy behavior, but not renormalizability.

There came a time (1967) when it was proposed to unify weak and electromagnetic interactions in terms of a SU(2)×U(1) gauge theory (Weinberg, 1967), with an added device, the Higgs phenomenon (1964), which generates masses for three of the four gauge fields—and which introduces one (perhaps more) new spinless boson(s), the Higgs particle(s). One vector field remains massless: the photon field; the massive fields are $W^{\pm}$, as conjectured earlier, plus a new neutral field for the "Z," coupled to a hypothesized neutral current.

During the next few years scant attention was paid to this scheme—until 1971, when it was shown that this theory is renormalizable, and with a small expansion parameter!

There now followed a decade in particle physics of a kind not witnessed earlier in the postwar era, characterized not only by a rapid sequence of spectacular experimental discoveries but also by intense and immediate interplay between experiment and fundamental theory. I give a telegraph-style account of the main events.

1972: A fourth quark, charm (c), is proposed to fill a loophole in the renormalizability of SU(2)×U(1).

1973: First sighting of the neutral current at CERN.

1974: Discovery of a new meson at SLAC and at Brookhaven, which is a bound $\overline{c}c$ state.

1975: Discovery at SLAC that hadrons produced in high-energy e^+e^- annihilations emerge more or less as back-to-back jets.

1977: Discovery at Fermilab of a fifth quark, bottom, to be followed, in the 1990s, by discovery of a sixth quark, top.

1983: Discovery at CERN of the W and the Z at mass values that had meanwhile been predicted from other weak-interaction data.

Thus was established the validity of unification, a piece of reality of Maxwellian stature.

IV. PROSPECTS

The theory as it stands leaves us with several desiderata.

$SU(3)_c$ and SU(2)×U(1) contain at least eighteen adjustable parameters, whence the very strong presumption that the present formalism contains too much arbitrariness. Yet to date SU(2)×U(1) works very well, including its radiative corrections.

Other queries. Why do P and C violation occur only in weak interactions? What is the small CP violation trying to tell us? Are neutrino masses strictly zero or not? What can ultrahigh-energy physics learn from astrophysics?

The search is on for the grand unified theory which will marry QCD with electroweak theory. We do not know which is the grand unified theory group, though there are favored candidates.

New options are being explored: global supersymmetry, in which fermions and bosons are joined within supermultiplets and known particles acquire "superpartners." In its local version gravitons appear with superpartners of their own. The most recent phase of this development is superstring theory, which brings us to the Planck length ($\sim 10^{-33}$ cm), the inwardmost scale of length yet contemplated in high-energy theory. All this has led to profound new mathematics but not as yet to any new physics.

High-energy physics, a creation of our century, has wrought revolutionary changes in science itself as well as in its impact on society. As we reach the twilight of 20th-century physics, now driven by silicon and software technologies, it is fitting to conclude with the final words of Rowlands's 1899 address with which I began this essay:

> Let us go forward, then, with confidence in the dignity of our pursuit. Let us hold our heads high with a pure conscience while we seek the truth, and may the American Physical Society do its share now and in generations yet to come in trying to unravel the great problem of the constitution and laws of the Universe (Rowland, 1899).

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