



TWENTY YEARS OF PHYSICS

PARTICLES

By ABRAHAM PAIS

PROLOG

HOT VERSUS COLD; dry versus wet. Such were the two values of the pair of attributes that in antique and medieval speculation characterized "the" four elements, the substances from which all bodies are made or derived: hot, dry fire; hot, wet air; cold, wet water; cold, dry earth.

Electrons, photons, protons and neutrons: Such were the four principal elements of matter and radiation, the "early" particles, as experimentally certified in the early 1930's, that is, before the onset of particle physics proper. The neutrino had been postulated as a fifth essence. Mass, spin and electric charge had been recognized as principal attributes. Gravitational, electromagnetic, nuclear and beta-decay forces had emerged; there was speculation whether the last two were one and the same. And some main ills of relativistic quantum field theory had been diagnosed—ills for which only a partial cure has been found since.

Particle physics is the next chapter in the exploration of the structure of matter. Typical of the youth and vi-

talidity of this new field, the main struggle is towards the right concepts. There is of course no sharp answer to the question: How old is particle physics? Still, if I had to single out one event to mark its beginnings, I would choose the discovery of the μ meson in 1947 because of its superfluity in the scheme of things at that time.

The early particles are by and large sufficient for the description of molecular, atomic and, to a considerable extent, nuclear structure, and of radioactivity. Thus there was a sense of imminent closure, one could well imagine that we had all the basic building blocks of matter. The μ meson gave a first jolt to this view. We are now certain that the early particles represent but a small fraction of the ingredients necessary to understand the structure of matter and the nature of the prime forces. Many new particles have entered the scene. New particle attributes, or what we now call quantum numbers, have been found necessary. New attributes of forces, in particular their transformation properties and symmetries, have been uncovered.

These developments during the last two decades have been predominantly experimental. The impressive body of information about particles has been due principally to the advent not only of new accelerators, but also to important new techniques of detection and data handling. We should not forget, however, the great debt we owe to cosmic-ray studies that gave the first impetus to this development. In the mid-1930's, cosmic rays gave us first the positron, then charged mesons, largely μ mesons. That these were not the nuclear-force π mesons hypothesized in 1935 was the content of the cosmic-ray discovery of $\pi^+ \rightarrow \mu^+ + \nu$ decay in 1947. This fact and the cosmic-ray finding of "V particles," hyperons and K mesons, in the late 1940's, set the stage for particle physics. It is quite probable that cosmic-

ray experiments will have another round of fundamental contributions.

FOUR FORCES, TWO NEUTRINOS

Prime forces

As we see it at the present, there are essentially four kinds of prime forces. The oldest one is the gravitational force, about which particle physics as such so far has had nothing to say. Although gravitational forces play an overriding role in the interaction between matter in bulk, they appear to be swamped by other particle forces, in the energy and distance region we have so far explored. For this reason I shall not come back to gravitation in what follows. Next there are electromagnetic forces; then strong forces, which include nuclear forces. Finally come weak forces that are responsible for nuclear beta-decay, $\pi-\mu$ decay and for many more decay processes.

Once there was a time when Coulomb's law, Ampère's law, Biot and Savart's law and other laws were known but not yet dynamically integrated. It is a stirring hope that the four forces will eventually be part of a more unified theory. But there is presently no clear road to that goal.

Electromagnetic and nuclear forces are associated with fields and their quanta. It is still a matter of speculation whether there is something similar for weak forces. The existence of a "weak field," the W field, has been proposed, and its quanta, W mesons, have been looked for, so far without success. If there are W mesons they are most probably heavier than $2\text{GeV}/c^2$. Unlike the π -meson situation, where the nuclear-force range provided a guide, there is no a priori clue to how heavy the W's should be. In any event experimental studies of weak interactions at high energies and especially the search for W quanta constitute some of the most important future problems. High-energy neutrino beams are a principal



Abraham Pais, a professor at Rockefeller University since 1963, received his PhD from the University of Utrecht in 1941. He worked with Leon Rosenfeld there and with Niels Bohr at the Institute of Theoretical Physics in Copenhagen. He joined the Institute for Advanced Study in Princeton in 1946 and was professor there from 1950 to 1963.

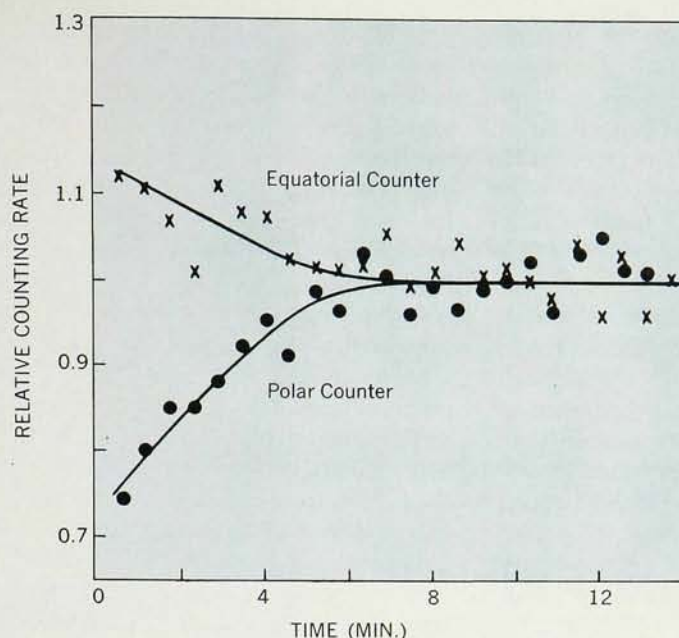
tool in this search, because neutrinos do not do anything but interact weakly. This fact raises some stupendous problems. A slow neutrino will make one interaction per light year's thickness of lead. For a 1-GeV neutrino one gains a factor of 10^5 , but still life is difficult. One needs a large flux and one needs tremendous shielding to filter out with very high precision other neutral particles that could confuse the issue. In the first neutrino-beam experiment at Brookhaven, for which the steel of the battleship *Missouri* was the filter, the principal finding was that there are two kinds of neutrinos, ν_e and ν_μ .

Early and new neutrinos

Before we come to that, the discovery of "the first neutrino" should be recalled. This particle was postulated to save the energy, momentum and angular-momentum conservation laws in beta decay. Conservation laws are currently not as inviolate as was thought earlier, but the three laws just mentioned are still believed to be rigorous. At the time the neutrino was proposed, some doubts were expressed about conservation in beta decay, however, doubts which could only be stilled if one could see the hypothetical emitted neutrino do something. This was done in 1956 with the intense $\bar{\nu}_e$ flux from nuclear reactors. One observed the reaction $\bar{\nu}_e + \text{proton} \rightarrow \text{neutron} + e^+$. Also, ν_e absorption has been detected, on heavier nuclei.

Now to the two-neutrino experiment. In μ^+ decay, $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$, a neutrino pair is formed. But such a pair can be annihilated. Somewhere along the way a photon can be created with a net result of $\mu^+ \rightarrow e^+ + \gamma$. But this decay was never seen, even though it does not involve more weak interaction than the $e^+ + \nu + \bar{\nu}$ decay. A way out, the correct way, was to say that in this decay ν and $\bar{\nu}$ are not each other's antiparticle. We now write the decay as $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$.

What distinguishes ν_e from ν_μ ? Whenever a μ^+ is created it is accompanied by a ν_μ as in $\pi^+ \rightarrow \mu^+ + \nu_\mu$. A ν_e always goes with an e^+ as in β^+ decay. This is checked by verifying that a ν_μ beam can only regenerate μ^- , not e^- . That, in brief, is the two-neutrino experiment, and for all we presently know it is the only distinc-



ASYMMETRY IN COBALT-60 DECAY found by C. S. Wu and collaborators showed that parity is not conserved in weak interactions. Experiment measured angular distribution of electrons and gammas emitted in decay. Graph gives gamma count as a function of time for equatorial and polar counters.

tion between ν_e and ν_μ . It appears to be one of nature's extravaganzas to have such doubling. It corresponds to a pair of conservation laws: one for μ number ($=1$ for μ^- , ν_μ ; -1 for μ^+ , $\bar{\nu}_\mu$; 0 otherwise) and one for e number ($=1$ for e^- , ν_e ; -1 for e^+ , $\bar{\nu}_e$; 0 otherwise). Conservation of μ number + e number = lepton number was known for a somewhat longer time.

This whole "lepton family" of μ , e , ν_e , and ν_μ is very strange. They fall outside any symmetry scheme we have for the strongly interacting particles, or hadrons, as they are called since 1962. But nature must have its reasons that reason has not yet fathomed. That is why high-energy weak-interaction studies are one of our great hopes for progress.

HADRON SYMMETRIES

Isospin

This development started with isospin. We like to think that proton and neutron would be a degenerate doublet, the nucleon (N), if electromagnetic effects are neglected. Similarly the $\pi^\pm$ form a triplet together with the π^0 , the first particle discovered with accelerators, in 1950. As we know from many instances in quantum

physics, degeneracy is naturally associated with invariance; and invariance is associated with conservation laws. In this case a new conservation principle emerged, that of isospin, T . For the nucleon $T = 1/2$ and "quantizing along a preferred direction," we let $T_3 = 1/2, -1/2$ correspond to proton, neutron respectively. Likewise the π has $T = 1$ with $T_3 = 1, 0, -1$ for π^+, π^0, π^- . The preferred direction comes from the fact that particles are distinguishable of course by their charge $Q = T_3 + N/2$, where N is the nucleon number. This form of Q applies to both nucleon and π . We have learned that the total T and T_3 are conserved in strong interactions—while electromagnetism violates T , conserves T_3 . Is this a "preferred 3-direction in some space?" For the present we do not know better than to say that T "behaves as" an angular momentum, in an abstract sense, made mathematically precise by saying that we deal with the T components as generators of an invariance group $SU(2)$.

General awareness of how isospin arguments may provide rapid insights dates from the time of the 1952 Rochester Conference. The first π -nucleon resonance (the 3,3-resonance) had been discovered. In the resonance

region, the cross-section ratio for $(\pi^+ + p \rightarrow \pi^+ + p)$: $(\pi^- + p \rightarrow \pi^- + p)$: $(\pi^- + p \rightarrow \pi^0 + n)$ is about as 9: 1: 2. This would correspond to the production of N^* particles, with appropriate charge, by way of $\pi + N \rightarrow N^*$, provided that N^* has $T = 3/2$. The N^* decays rapidly into $N + \pi$ again.

We consider this wide N^* -scattering maximum as much of a particle as the N . By the same token we could call an excited state of atomic hydrogen as much of a particle as its ground state. We know so much more about hydrogen in terms of structure, however, that we are not helped there by that language. Perhaps in some future time we will think differently about particles too.

Since the N^* days many more higher nucleon resonances have been identified. Much work is still in progress here, particularly because inelastic processes complicate the isolation and the identification of resonances. Yet all these resonances represent but one facet of the richness of structure that has been uncovered these past 20 years.

A new spectroscopy

The mentioned resonances have a characteristic lifetime of 10^{-23} sec. However, since the late 1940's and early 1950's we have learned that in π -nucleon collisions, for example, other particles can also be created that are akin to the nucleons but that, relatively speaking, live astronomically long, more like 10^{-10} sec. These are hyperons, such as the Λ .

This long lifetime posed a new puzzle: Like $\pi + N \rightarrow N^*$, these particles come forth in strong reactions. They also are heavy enough, like the N^* , to decay back into nucleon + π ; and they do. But apparently this decay is tremendously inhibited, entirely unlike N^* decay. This process was explained by the associated production mechanism: The production of Λ , for instance, goes by way of the strong interaction $\pi + N \rightarrow \Lambda + K$ where the K is a new meson, and one could show that in this way strong production and weak decay $\Lambda \rightarrow N + \pi$ were decoupled.

The kinship between hyperons and nucleons is that all hyperons eventually decay into nucleons. So nucleon conservation became (nucleon + hyperon) conservation or baryon con-

servation, as we have been saying since 1953. This conservation law we believe to be absolute: All of the prime forces obey this law. There are less universal conservation principles too. For example, associated production was interpreted in terms of a new conservation, of strangeness or of hypercharge Y . T^2 , T_3 and Y are conserved strongly; only T_3 and Y are conserved electromagnetically; T_3 and Y are nonconserved weakly. But the electric charge $Q = T_3 + Y/2$ is conserved absolutely. This Q formula now extends the earlier formula $Q = T_3 + N/2$ to include the new hypercharge degree of freedom.

The full array of baryon spectroscopy can now be characterized as follows. For each value of Y many resonances have been found that have various T and other quantum numbers. They decay strongly, conserving Y , towards their " Y ground state," then weakly on to the baryon ground state, the nucleon. And it is very much the same story with mesons. This new spectroscopy, one of the important experimental contributions to this period, has been made possible by ingenious techniques for analyzing many-particle reactions. More of it is to come, but already we have gained from it some substantial insights.

Conservation and violation rules

First, it was found that even if a force does not respect a conservation law, there may be some systematics to the way the violation occurs. These are the violation laws. Thus the weak force that violates Y does this such that the jump ΔY of Y equals ± 1 only. This same force violates T but such that $\Delta T = 1/2$. It would lead too far afield to explain that these are in turn only approximate statements. But they are good approximations.

Next a search started for higher symmetries. It was tempting to find more intimate connections between Y and T , with its $SU(2)$ group. Eventually it was found that an embedding of Y and T in the group $SU(3)$ leads to a very useful further ordering of the hadrons. Such a bigger symmetry would lead to larger degeneracies if it were exact. But it is assumed that the group is approximate and that along with it again come specific violation laws, as expressed for example in the way $SU(3)$ multiplets split up. In this way sets of isospin multiplets

could be seen to be connected as broken-up $SU(3)$ multiplets. The discovery of the Ω^- , a particle predicted in order to fill an otherwise complete $SU(3)$ multiplet, was a beautiful confirmation of the usefulness of $SU(3)$.

No connection is known between these hadron symmetries and space-time symmetries. In this respect these new symmetries differ from some approximate symmetries in other parts of physics. For example, Russell-Saunders coupling in atoms is an approximate "static" symmetry, good only for states that have low average momentum. Such "dynamical symmetries" have also made their appearance in particle physics. Notably $SU(6)$ is of this static variety. It has enabled us to recognize connections between $SU(3)$ multiplets of different spin. One of its interesting predictions is the value $-3/2$ for the magnetic-moment ratio of proton and neutron.

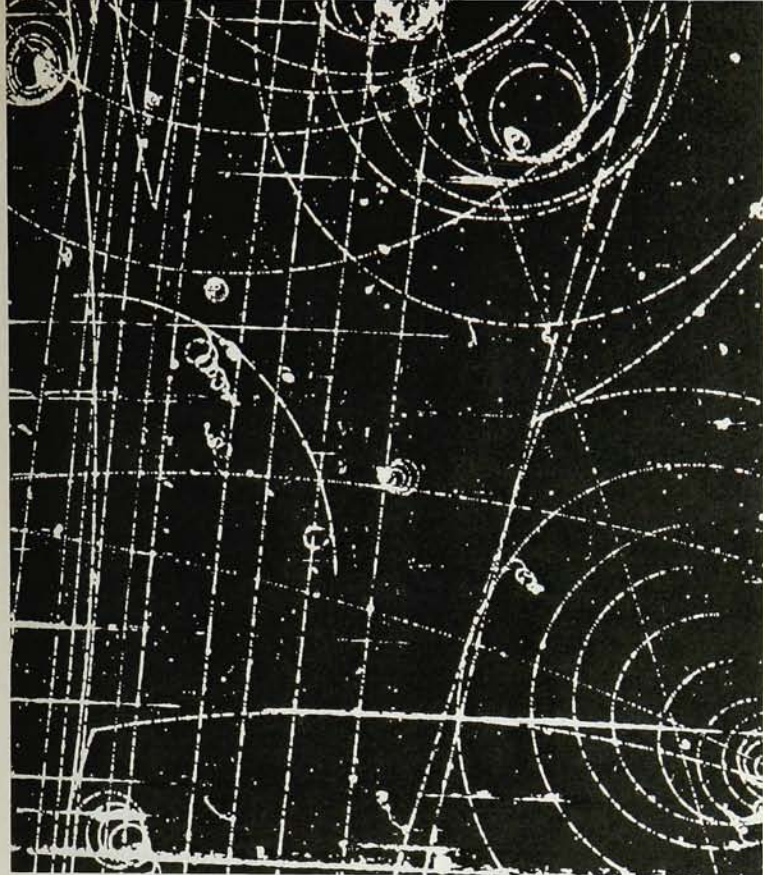
Dynamical symmetries may yield important clues to particle dynamics. Thus one may wonder, as in the so-called "bootstrap approach," whether symmetries like isospin could, after all, be dynamical in origin. These and other studies, which go by names such as "collinear," "coplanar symmetry" and "noncompact group symmetry," may have their role to play in future developments.

Hadron physics is not at all a study of resonances only. The resonance region is now known to go beyond 2 GeV/c^2 . But there is a transresonance region that is less bumpy. There, new and important regularities have been found about energy- and momentum-transfer dependence. Another and major source of information on strong forces comes from the use of electromagnetic and leptonic probes of hadrons, from which we have learned so much about form factors. The discovery of the antinucleons in the 1950's (and of other antibaryons later on) has added much information.

An issue under debate is whether current hadron physics is a chemistry in terms of a more fundamental triplet of particles, as yet unseen. The future will decide.

HADRODYNAMICS

We do not know whether there is any analog in hadrodynamics to the Max-



OMEGA-MINUS DISCOVERY through bubble-chamber photographs completed an SU(3) multiplet and proved the usefulness of the theory.

well-Lorentz equations in electrodynamics. In electrodynamics we have a small parameter, the fine-structure constant α , in terms of which one can expand. All concrete knowledge about quantum electrodynamics is tied to the smallness of α . To our knowledge hadrodynamics has no equivalent of the small α . So while one can postulate field equations for strong phenomena, we do not know of any reliable approximate solutions; thus we cannot certify the correctness of these equations.

Thus hadrodynamics is not as advanced as electrodynamics, in which the greatest dynamical progress in the last 20 years has been made. In spite of the infamous infinities of field theory, a new technique called "renormalization" has led to the extraction of meaningful finite answers to higher orders in α than had been thought possible by most. Small feedback effects of strong forces on electromagnetic phenomena will soon be in experimental reach. There may perhaps be other limitations on "pure" electromagnetism. High-precision measurements such as the mu-meson $g-2$ experiment are of crucial importance for such questions. This $g-2$ was known

to 30% in 1958 and is presently known to 1 part in 10^{-3} .

Hadrodynamics has moved forward, too. First, studies are in progress of the content of general axioms for field theory. It is a difficult field, no less vital because its application is still rather remote from concrete physics, though it is getting closer. Second, vast efforts have been made to see how far one can proceed with quite general postulates, such as causality and unitarity, that do not necessarily presuppose the existence of an underlying field theory.

This approach is commonly known as dispersion theory. It started around 1955 with the forward π -nucleon dispersion relations, which, from the combined views of rigor and usefulness, are still the best in this business. Next, nonforward relations were conjectured and partially proven. Double dispersion relations, both in energy and momentum transfer, were also conjectured.

The essential contents of such relations are analyticity properties of amplitudes. Studies in this field fall roughly in two connected domains: One tries to prove sufficient analyticity; or one assumes it and asks for

consequences. Thus the analytic property called "crossing symmetry" connects the amplitudes for $a + b \rightarrow c + d$ (s channel), $a + \bar{c} \rightarrow \bar{b} + d$ (t channel), $a + \bar{d} \rightarrow \bar{b} + c$ (u channel), where $\bar{b}$ is the anti- b . Perturbation expansions, one of the strong guides in this field, led one to believe that the analytic continuations needed for crossing are feasible. When no general proof yet existed, the property was nevertheless used, and to advantage. This is a typical instance of how one tries to forge forward on several fronts simultaneously.

One important example is the Regge-pole hypothesis, according to which families of resonances with the same internal quantum numbers but different spin are dynamically linked. By crossing, the high-energy behavior in the s channel comes out, in the simplest instance, as a power law, with the exponent being related to the occurrence of such resonance families in the t and u channels.

It is often asked how much of the dynamics can be pinned down in terms of these various analyticity properties and conjectures. Opinions vary strongly, but some interesting general results have been obtained this way.

C, P, T: WEAK DYNAMICS

Discrete symmetries

It can fairly be said that in this period the insight into the structure of weak interactions has undergone a major development. Foremost is the discovery of their behavior with respect to space reflection (P invariance), time reversal (T invariance) and charge conjugation (C invariance). Crudely speaking, C invariance states that the physical laws should be unchanged if all signs of intrinsic multipole moments (electric charge, magnetic moments, etc.) are reversed. Weak interactions turned out to violate P . The incentive to this development came from the " $\theta-\tau$ puzzle," which boils down to the statement: A spinless particle cannot decay into two and, alternatively, into three pseudoscalar particles unless P is violated. The actual discovery of P violation came in 1956 from beta-decay studies, immediately followed by the discovery of a similar effect in $\pi-\mu$ decay. It was found, moreover, that these interactions also violate C . However, some

degree of order was restored by the realization of the invariance, to considerable accuracy, under the combined inversion CP.

At first sight this development may seem to presage new views on space-time description. Whether this is so remains to be seen, however. Actually these invariances imply delicate quantum-mechanical phase relations. What happens is that the forces can be divided into parts that separately satisfy P invariance, for example. But these parts do not congeal into overall P invariance; a mismatch or clash occurs. One invariance of great importance, the closest to pure space-time properties, is CPT invariance, which we believe to be true rigorously. Delicate checks on this are not far off. If CPT invariance were to fail, then I would say all hell will break loose.

Related to CP invariance, and to so-called " γ_5 invariance," is the two-component theory of the neutrino, which states that neutrinos couple with only one of their two possible helicity states. Also, CP yields much information about the properties of perhaps the most subtle system in particle physics, the (K^0 , $\bar{K}^0$) system. This is a pair of particles with a mass difference that is $\sim 10^{-13}$ its mean mass, a difference that has actually been observed as a result of delicate interference phenomena, which this system richly provides.

Then in 1964 came the next blow. CP invariance also turned out effectively to be inexact, as was shown from a small violation in the neutral K system. This time no new kind of order has as yet been reestablished. It is perhaps the biggest challenge today to find out, even phenomenologically, what goes on. This effect violates our sense of elegance and simplicity. Its interpretation may well be profound.

Currents currents everywhere

Other information on weak dynamics has been gathered. It has been found for most weak interactions (and may be true for all) that they are effectively four-vector currents of hadrons and leptons coupled to other such currents. The hadron currents have a vector part V_λ and an axial-vector part A_λ . This V-A theory settled a structure question dating from the 1930's.

We have learned a good deal more about V_λ and A_λ . First, V_λ has been found to be related, essentially by a

simple proportionality, to part of the electromagnetic current. As a result some weak effects can be expressed in terms of electromagnetic parameters (weak magnetism). Second (skipping even more technicalities), we have learned that the divergence of A_λ is proportional to the π field. In this way one can give a fair prediction of the $\pi\text{-}\mu$ decay rate in terms of other known parameters. Third, V_λ and A_λ are current operators in the quantum-mechanical sense. Of late, intensive studies have been made of the commutation relations of these and other current operators, a subject known as current algebra. Although much here remains problematic, there has been some degree of success. In particular it has been possible to evaluate the absolute ratio of the Gamow-Teller and the Fermi constants of beta decay in terms of, essentially, π -nucleon scattering information. Moreover a number of interesting "soft pion" results have been obtained that relate reactions involving n π mesons to reactions involving one π less.

EPILOG

These few pages constitute an attempt to leave the nonspecialist with a sense of the state of particle physics. It is a state not unlike the one in a symphony hall a while before the start of the concert. On the podium one will see some but not yet all of the musicians. They are tuning up. Short brilliant passages are heard on some instruments; improvisations elsewhere; some wrong notes too. There is a sense of anticipation for the moment when the symphony starts.

The briefest of summaries of the period could well read: Our hats off to the experimentalists. As World War II ended, the highest proton energy available was 20 MeV—now we can wish Serpukhov good luck with its 75 GeV. In between lies the story of the 400–600-MeV synchrocyclotrons, of the 3-GeV Brookhaven Cosmotron, already mothballed meanwhile, of the Berkeley Bevatron, of the linacs, of Dubna, Saclay, DESY and Rutherford, of the Brookhaven and CERN 30-GeV machines, to give an incomplete list.

At the first Rochester meeting (Rochester, byword in particle physics) we spent a whole afternoon discussing three τ -meson decays—now we

are about to have beams with 10^5 K's per pulse. In 1957 the world production of K_{e3} was some 50 events. Now, a single experiment has produced millions. In 1957 the K_2 was discovered in a 5000-picture bubble-chamber experiment. In 1966 10^7 bubble-chamber pictures were taken in the US. The present marks the transition of a 10^5 to a 10^6 picture average per experiment. New track chambers dominate the scene: the bubble chambers, from a few cc volume, in 1953, to the coming 4-meter monsters; the spark chambers; and others. New counter techniques have been developed, and on-line computers aid in the data evaluation. Rapid-scanning devices and elaborate computer programs make possible data handling on a new yet happily forever insufficient scale; such is the push toward higher statistics and rarer events.

Gone are the days of a Faraday and his Anderson, of a Rutherford and his Kay. This is the time of team effort. To bewail this is to bewail the second law of thermodynamics. Nor does it signify the end of the highly individualist scientist. It has changed the nature but not the value of the contribution of the separate university to the development of physics's frontiers. It has emphasized the need for national and international collaboration. The leading role of the CERN in particle physics is in fact one of the most striking manifestations of the revitalization of postwar Europe. The Trieste Institute, largely devoted to particle theory, helps to draw the developing nations together.

The harvest in these lively years has been rich. New particles, a new spectroscopy; the new symmetry structure from force to force, the overturn of hallowed notions about C, P and T; the beginnings of a new dynamics: Those were the 20 years that were.

As to what is next—who can say? More spectral and form-factor information, to be sure. What we badly need is a greater synthesis. Perhaps there will be paradoxes that will lead us to revise very basic concepts. Perhaps we will realize that paradoxes are already with us. Imperfect as our knowledge is, we have learned so much, found so many novel questions. In these 20 years we have had the fun of living through the beginnings of a great new adventure. There is more to come. $\square$