

### Theory Falls Behind Experiments in High-Energy Physics

The 1968 "Rochester" conference on high-energy physics took place in Vienna from 26 Aug. to 5 Sept. It was held in the conference center of the Hofburg, in halls with marble walls, gorgeous decorations, and abominable acoustics. Some 1000 people attended it, about one quarter from the US, and most of them worked seven hours a day for seven days to review high-energy physics. Even so, a number of areas had to be left out, and even those areas included received a rather superficial treatment.

In summarizing the experimental situation I must start on an optimistic note. Five years ago the combined effort of some 30 people over two years might have resulted in perhaps 40 events of a reaction, which, arranged into four fat angular bins, was presented as a differential cross-section angular distribution. In sharp contrast a present-day set of differential cross sections typically consists of 10% measurements at ten or twenty different angles. Even more important, measurements of experimental observables other than differential cross section are beginning to be commonplace. Final-state polarization, experiments with linearly polarized photons and polarized targets are some examples. All in all, the quality of high-energy experiments is beginning to ap-

proach the level we have been used to in low-energy nuclear physics for years. The change is due to a combination of improved beams, improved detection equipment, and, perhaps most important, improved data-analysis methods and equipment. The impact of this qualitative improvement on the testing of theoretical ideas has been striking, and it probably contributes also to an improvement of morale in high-energy experimental physics. For the moment it appears that high-energy physics will not come to a halt because of the increasingly insurmountable difficulties of the experiments.

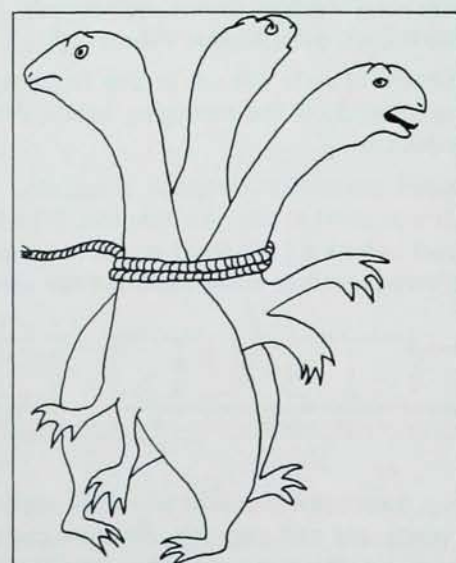
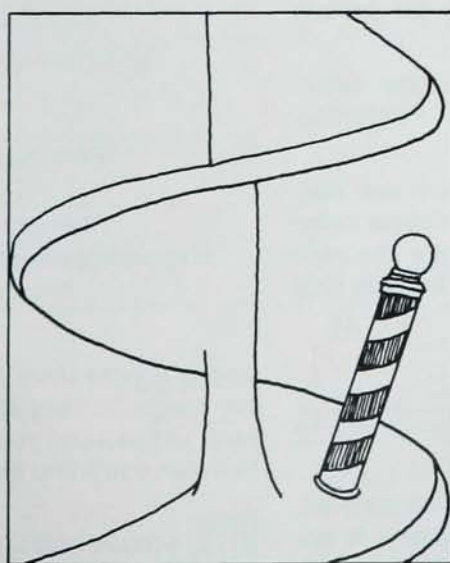
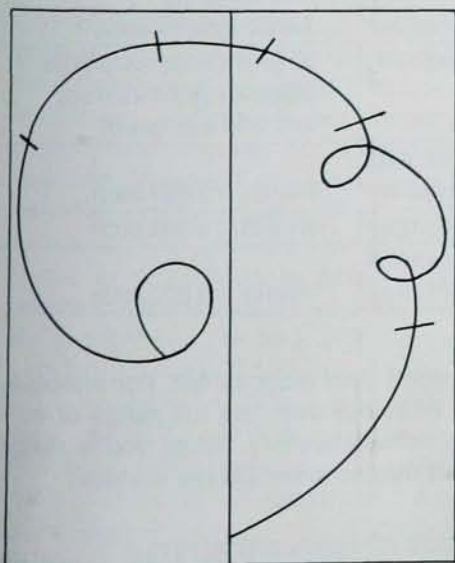
Now let us turn to the experimental results in more detail. Let us classify them into four rough categories, not according to the experimental technique used but according to their purpose. These categories are: discovery of new particles, determination of intrinsic properties of particles, study of particle decays, and determination of particle dynamics in reactions.

**New particles.** The first category, methods of discovering new particles, goes generally along two directions. We can study the correlations among particles in a many-particle final state of a reaction, by looking at the deviations from the distribution of kinematic variables as given by phase space

alone. Or we can make a complete angular-momentum decomposition of the reaction amplitudes and look for a resonance-type behavior in a certain angular-momentum state. The second method can so far be applied only to the nucleon-nucleon, pion-nucleon and kaon-nucleon systems, and only at relatively low energies. The list of "elementary" particles has again changed in the past two years, by the addition of some new particles, by the disappearance of the evidence for some particles previously thought to exist, and by improved knowledge of the intrinsic quantum numbers of the particles.

The difficulty of establishing new particles is increased because almost all of them are very unstable and hence have large widths that overlap with each other. Furthermore, in extreme cases, even the concept of a particle or resonance becomes hazy. A particular example is the so-called " $A_2$ " meson, which can show itself as two very close peaks in one correlation distribution, but only as one peak in another distribution.

The major improvement in the data on the pion-nucleon system is information on two-body inelastic channels, such as  $\pi + N \rightarrow K + Y$ ,  $\pi + N \rightarrow \rho + N$ , and  $\pi + N \rightarrow \pi + N^*$ , although this information has not been well in-



"... it is not clear whether what we mean by resonance is a counterclockwise loop in the Argand diagram, a pole on the second Riemann sheet, a bound state of quarks, or ...



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egrated into the analysis of the elastic pion-nucleon channel. Qualitatively, however, most resonances seen in the elastic channel are also observed in these inelastic reactions, as well as in the photoproduction process  $\gamma + N \rightarrow \pi + N$ .

A cosmic-ray experiment is exciting much interest. The original purpose was to measure cosmic-ray neutrinos, and the huge detection equipment is in a deep mine in Utah. A preliminary experiment was a measurement of the azimuthal distribution of high-energy muons from cosmic rays. If one assumes that these muons come from the decay of high-energy pions that, in turn, are produced by the high-energy primary particles impinging on the Earth's atmosphere, one finds, using quite model-independent assumptions, that many more muons should come from near zenith than from near the horizon. The experiment in Utah, however, appears to give almost no dependence on the azimuthal angle. One possible explanation of isotropy would be the existence of a very heavy meson, produced by cosmic-ray primaries through strong interaction and then decaying into muons. The imagination of a number of theorists has run wild in this direction, but was somewhat damped at the conference by the report that a group working in India with similar equipment could find no evidence for the Utah isotropy. Now these two groups, as well as others working at sea level, will repeat the experiments.

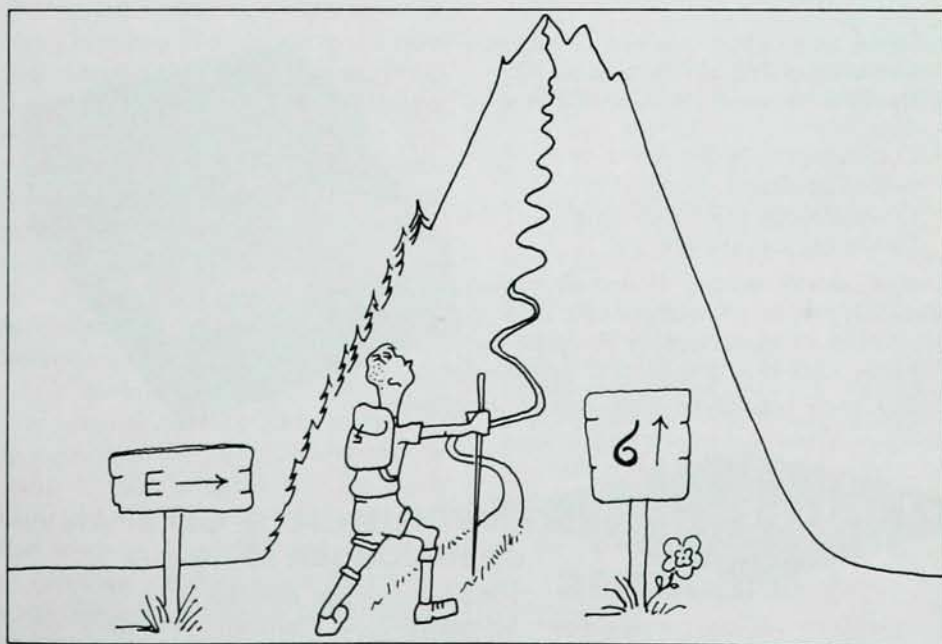
**Properties.** Determination of the intrinsic properties of particles has also progressed. Spins, parities, and other intrinsic quantum numbers of unstable particles, are generally determined from their decay distribution and polarizations. Some interesting developments have occurred in connection with some "ancient" characteristics of some "ancient" particles: The  $g - 2$  factors of both the electron and the muon, as determined experimentally, are now in disagreement with theory, the gap between the ends of the error bars being 2.5 and 0.5 standard deviations, respectively. The experimental value of the Lamb shift in hydrogen now also differs from its theoretical value by 3-4 standard deviations. Another intrinsic property that is studied with ever increasing accuracy is the form factor, or "charge" distribution, of various particles. For the electro-

magnetic form factors of nucleons no deviation from the functional form predicted by quantum electrodynamics has yet been found in electron-nucleon or muon-nucleon scattering, or in other reactions such as wide-angle pair production, wide-angle bremsstrahlung and muon tridents. There is also no evidence for a difference between the behavior of the electron and the muon; hence the mystery of why the muon exists at all persists. There is some evidence that, at high momentum transfers, the so-called "dipole fit" to nucleon form factors is not sufficient any longer. There is some problem with the form factor of the neutron. It is measured in electron-deuteron scattering, and thus a correction for the deuteron structure must be made. Such deuteron corrections also appear in other reactions such as neutron-proton scattering, which can be measured either directly as neutron-proton or indirectly as proton-deuteron scattering. The comparison of the two methods shows a possible discrepancy, so the question of such structure corrections has leaped into the foreground again. Attempts are also made to measure the pion electromagnetic form factor in electroproduction of pions and the form factors of some resonant states. The first result of colliding-beam electron-electron scattering experiments fails to show any deviation from relativistic predictions based on two pointlike charges.

**Particle decays** are studied with several aims in mind. As well as the determination of some intrinsic prop-

erties of the decaying particle, already mentioned, one might be interested in testing conservation laws, determining branching ratios, formulating a phenomenology of weak interactions or checking some dynamical predictions. For the conservation laws the main problem remains the possibility of CP violation ( $C$  = charge conjugation,  $P$  = space reflection). Kaon decays show fairly firm evidence of features that, in terms of our present ideas, are generally interpreted as coming from CP violation. In addition the  $\pi^+ - \pi^-$  asymmetry in the  $\eta \rightarrow \pi^+ \pi^- \pi^0$  decay suggests a possible nonzero effect that could be interpreted in terms of  $C$  violation. On the other hand, if CP were violated in general, one would also expect an electric dipole moment for the neutron, at least if CP violation has an electromagnetic origin. The experimental upper limit, however, for the electric dipole moment of the neutron has now been pushed down to  $4 \times 10^{-23}$  cm times the electronic charge, which is an extremely small quantity indeed. Attempts to test  $C$ ,  $CP$  and  $T$  (time reversal) in weak, electromagnetic, and strong interactions continue, as well as attempts to test the CPT theorem, which links  $T$  violation with CP violation. All of these conservation laws have withstood all tests so far in other electromagnetic and strong interactions.

The phenomenology of weak interactions continues to be successful. The characteristics of weak decays may be described in terms of one angle parameter only, although this angle is



... an experimental peak." (Another concept of resonance.)

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## MEETINGS

slightly different for the vector and axial-vector parts, and for mesonic and baryonic decays. Much new information has been accumulated on the branching ratios of kaon decays, which can serve to check such rules as the  $|\Delta I| = 1/2$  rule ( $I$  being the isospin).

**Dynamics.** The last group of experiments is perhaps the largest one, and consists of data on reaction cross sections. Apart from the extremely preliminary data from the Serpukhov accelerator on proton-proton scattering at 70 GeV, data are restricted to below 30 GeV, and most of the interesting data appear to come below 10 GeV. Much effort has centered around differential cross sections of various reactions at very small or very large angles, because the theoretical Regge-pole predictions apply mainly to those cases. In the low-energy region pion-nucleon scattering has now been sufficiently studied in terms of differential cross sections and polarizations, up to about 2 GeV, to allow a definite and perhaps even unique partial-wave analysis. The nucleon-nucleon system is known in these terms only up to 0.8 GeV, and even there not very well. The kaon-nucleon system also has some partial-wave descriptions at low energies. Other data are not complete enough yet to determine reaction amplitudes, so comparison with theory is possible only through features of some of the simplest experimental observables. Differential cross sections at various energies and angular ranges have been measured for:  $\pi + N \rightarrow \pi + N$ ,  $\pi + N \rightarrow K + Y$ ,  $\pi + N \rightarrow \pi + \pi + N$ ,  $\gamma + N \rightarrow \pi + N$ ,  $\gamma + N \rightarrow \pi + N^*$ ,  $\gamma + N \rightarrow K + Y$ ,  $\gamma + N \rightarrow \rho + N$ ,  $\gamma + N \rightarrow \omega + N$ ,  $\gamma + N \rightarrow \phi + N$ ,  $p + p \rightarrow p + p$ ,  $n + p \rightarrow n + p$ ,  $\bar{p} + p \rightarrow \bar{p} + p$ ,  $K + N \rightarrow K + N$  and some others. Polarization information for the reactions  $\pi + N \rightarrow \pi + N$ ,  $\pi + N \rightarrow K + Y$ ,  $p + p \rightarrow p + p$  and  $\bar{p} + p \rightarrow \bar{p} + p$  exists, and the photoproduction reaction  $\gamma + N \rightarrow \pi + N$  has been studied with linearly polarized photons. There is also cross-section and multiplicity information on reactions resulting in many final-state particles, such as  $\pi + N \rightarrow n \pi + N$ , where  $n$  is some not-too-high integer. A surprising result came from kaon-photoproduction data, which showed that  $SU_3$  symmetry fails for that reaction at small momentum transfers, even

at the highest energies where data exist.

In other dynamical experiments electron and positron scatterings appear to be equal within experimental error: thus they show no effects of two-photon exchange processes. We have a particularly accurate and complete set of measurements of proton-proton scattering including scattering at large angles, as a function of energy. An interesting and promising area is high-energy reactions from nuclei, such as coherent photoproduction from nuclei.

**High-energy theory.** Not many years ago the theoretical trends in high-energy physics were concentrated on efforts that had very little to do with experiments. The Mandelstam representation, bootstrap theory, and even most of ordinary dispersion theory, were perhaps esthetically attractive, but seldom did they result in numerical predictions or even in a qualitative guide as to what experiments should be performed. More recent trends in high-energy theory might well turn out to be just as unsuccessful in solving the problem of elementary-particle dynamics, but at least they have a much closer relationship to experimental high-energy physics. It is impossible to overestimate the importance of this relationship for the morale of experimentalists, and for keeping theoretical physics from becoming only a mathematical exercise.

**Reggeism.** Perhaps the most densely populated theoretical trend is the Regge-pole scheme. It has been with us for some years now, but some important additions have been made during the past two years. It is a subject surrounded with an unusual amount of controversy, sometimes with emotional overtones, so that a "balanced" evaluation might not only be almost impossible, but would also miss the flavor of excitement in the field. I will try therefore to give two extreme views on Regge theory, one by a great enthusiast and one by a bitter opponent.

To an ardent fan, Regge theory is a fundamental theory of strong interactions that is well on its way to give a unified account of all experimental data in the field. He will point out the various correct predictions of Regge theory for some shrinking diffraction peaks, for dips in angular distributions, for particle trajectories in the mass-versus-spin plots, and, in its multi-Regge form, for multiplicities in multiparticle final states. He will rave about the way Regge theory can auto-

matically eliminate divergencies previously encountered in high-spin particle exchanges. He will point at the finite energy-sum rules, which are essentially dispersion relations written for the difference of asymptotic and non-asymptotic amplitudes, and demonstrate their power of relating high-energy Regge contributions to low-energy resonances, thus giving a natural explanation of the latter. He will demonstrate with great excitement how a Regge pole, when decomposed into partial waves, gives counterclockwise loops in the Argand diagram that can be interpreted as resonances. He will marvel at the brilliant way Regge theory has discovered new sets of particles (so-called "conspirators") that have not been seen directly but become evident through a comparison of Regge theory and experiment. He will emphasize the way in which finite energy-sum rules, in Regge theory, make possible the formulation of a new bootstrap theory, thus enabling the calculation of all strong-interaction dynamics from the principle of self-consistency. Finally, he will explain how the multi-Regge exchange theory, together with the assumption of the existence of only "local" correlations between particles in complicated diagrams, allows the formulation of theories of multiparticle processes without ever leaving the physical region of the reaction amplitudes, thus circumventing one of the difficulties of previous S-matrix theories.

To a severe critic, the Regge-pole scheme is *ad hoc* phenomenology that has gone sour. He will point out that, originally, the Regge-pole scheme started from the hope that the relatively simple pole structure in the complex angular-momentum plane, found for the nonrelativistic Schrödinger equation with some harmless potentials, will carry over to general, relativistic reaction amplitudes. The original attraction was the expectation that, perhaps, dynamics can be formulated entirely in terms of poles with contributions that can be calculated; so no bothersome cuts of the usual type would have to be reckoned with. In this original scheme each such pole trajectory could be characterized in terms of three parameters: the intercept and slope of the trajectory, and the residue. He will point out that, as experimental data began to accumulate, this simple scheme certainly had to be abandoned, as it disagreed with the data. In fact, he will add, when-



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ever substantial new experimental information was obtained (and, in particular, every time a new type of experimental observable was measured), the theory had to be made more complicated to accommodate the data. By now, he would assert, the scheme involves extra particle trajectories (so-called "conspirators") that represent particles nobody has ever seen, arranged in such a way as to get rid of various obvious inconsistencies in the very small- and very large-angle region. Even so, evidence, both experimentally and through model calculations, is accumulating to indicate the importance of cuts in the angular-momentum plane; thus we run into the same road block, painted a different color, that has plagued high-energy theory for the past 30 years. As to the bootstrapping properties of Regge poles, he will point out that comparison with experiments tends to indicate that the asymptotically high-energy behavior of reactions is not of the Regge type at all, or, in terms of the Regge language, the so-called "Pomeranchuk trajectory" is an extremely peculiar object. Thus, hybrid theories, in which some Regge features are shotgun mated to phenomenological elements of a quite different type, are more successful in explaining data than any pure Regge scheme, even if these Regge schemes make use of additional parameters through conspirators, daughter trajectories, nonlinear trajectories, and residues that depend on the momentum transfer. He will claim that Regge-pole phenomenology undoubtedly has some successes but then, given a certain set of parameters optimized against experimental data, it is very difficult to construct a theory that is all wrong. Altogether, however, he will say that the Regge scheme has become too cumbersome and too arbitrary to be credible as representing the optimal way of understanding high-energy reactions.

**Current algebras.** Leaving the Regge dilemma up in the air, I turn to current algebras as the second of three major dynamical schemes now in vogue. Current algebras grew out of an analogy with electromagnetic (and perhaps weak-interaction) dynamics, formulated in terms of currents, and they assume that strong-interaction dynamics is also determined by currents having certain commutation relations. From these commutators, with essen-

tially no further assumptions except perhaps partial conservation of axial currents, one can get so-called "soft-pion theorems," which relate the amplitudes of a reaction to those of the same reaction with an extra very low-energy pion emitted in addition. In principle the theorem holds for zero-mass pions, and so some disagreement with experiments can be expected. In practice these theorems work fairly well, except for some reactions like eta decay.

To get more out of current algebra one needs additional model-dependent assumptions. For example some recent work assumes an algebra for fields instead of only currents, and obtains some spectral-function sum rules that are saturated with one-particle states. This technique allows us to carry predictions to higher energies and also deal with "hard" processes. For example some partial widths for the decay  $\rho \rightarrow 2\pi$  and  $A_1 \rightarrow \rho + \pi$  have been calculated this way, in fair agreement with experiment. An application of the soft-pion technique has been the calculation of the S-wave pion-pion scattering length, although the comparison with this number, not directly accessible experimentally, has not been definitive. Work has also been done to provide some fundamental justification for the current commutators being as they are. Current algebra, an approach very different from Reggeism, has had some experimental success; it has the esthetic asset of trying to unify electromagnetic, weak, gravitational and strong interactions through the idea of currents. For the present, however, it appears to be only of limited applicability, and even within the limited area it is not completely free of apparent failures. Also, as with other theories, one is sometimes not certain whether a given result is a unique prediction of that particular theory, or is something that can be obtained just as easily from other theories.

**Quark model.** The original idea of quarks grew out of the success of the  $SU_3$  group in explaining the classification of many particles and their intrinsic quantum numbers. Among the irreducible representations of that group, the 8- and 10-dimensional ones found immediate use in the classification, but the even lower three-dimensional representation did not seem to represent any known particle. It is natural, therefore, to assume that such particles, called quarks, might never-



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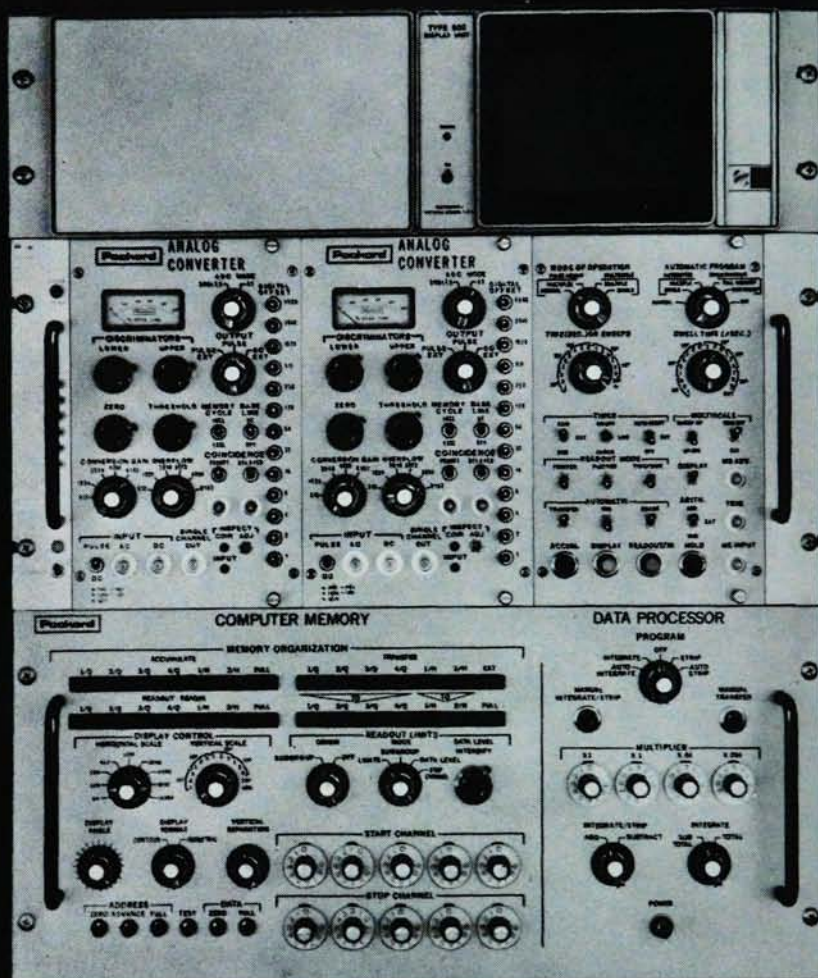
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theless exist, and that other particles can therefore be thought of as being bound states of quarks. To obtain some of the predictions from such a theory, one must assume some specific interaction between quarks—for instance, that the total wave function is symmetric. The quark model has had many successes. Among the static properties, it predicts the ratio of magnetic moments of proton and neutron to be  $-1.50$ ; experimentally the ratio is  $-1.46$ . This number, however, has been predicted before, though perhaps on a more phenomenological basis. The model naturally gives many selection rules for decays, many decay rates of hyperons to an accuracy of about 10%, and it correctly predicts the scaling law for the electric and magnetic form factors of the proton. The model classifies almost all the known particles correctly, including their spin and parity. It fails to give, even approximately, the correct branching ratio of  $\lambda$  zero to  $\sigma$  zero in kaon-plus photoproduction, but gives many other branching ratios well. There are also some defects of the model. First, although there are three quarks, we find saturation in most cases by two quarks. Second, and more important, nobody has ever seen a quark, although a number of ingenious experiments have been devised to see them. The experiments are generally based on the facts that the quarks should have charges with absolute values  $e/3$  and  $2e/3$  ( $e$  being the electronic charge), and that some of them have a negative charge. No quark has ever been seen, and so one can place a lower limit on their mass (assuming interaction cross sections roughly consistent with their presumed role in strong interactions); this limit is now many GeV. The third objection stems from the second: The picture of particles with masses of 2 GeV or less, as bound states of two or more particles with multi-GeV masses, is esthetically unsatisfactory. It is therefore possible that quarks really do not exist, but some unknown dynamical principle results in particles that look as if they were made up of quarks. Only further study will solve this problem.

As to the relationship of the quark model to, say, Regge poles, an imaginative attempt made recently to construct a generalization of the quark model appears to yield, fairly naturally, some Regge features. No experi-

mental test has been undertaken yet.

**Other models.** A number of other theoretical ideas under consideration have been important to varying degrees. One is the vector-dominance idea, according to which a photoproduction process, for instance, is closely related to a process in which the photon is replaced by a vector meson. Many calculations of reaction cross sections, electromagnetic mass differences and other experimental observables have been made, using this model, with considerable, although not unblemished, success. In a number of cases where Regge models failed vector dominance came through. Some discrepancies exist, however, in hadronic decays; values for the photon-rho-meson coupling constant (or vertex function) derived with this model, from photoproduction on the one hand and leptonic decay on the other, do not agree. This discrepancy, however, may simply result from the different value of the vertex function at different energy values. The conceptual importance of the vector-dominance model is in its insistence that the photon is in many respects quite similar to the (strongly interacting) vector mesons; the prevailing view a few years back was that the electromagnetic interaction is qualitatively different from strong interactions and hence should not be considered in the S-matrix framework.

Another type of high-energy model uses semiclassical ideas to describe reaction amplitudes. A number of groups have worked on such schemes, which are extensions and variations of models developed some time ago in nuclear-reaction theory and general quantum-mechanical scattering theory. They use basically the eikonal approximation, in which angular momentum is replaced by a continuous variable, the impact parameter; some integrations can then be carried out explicitly.

For a number of "cross-disciplinary" problems in high-energy theory the concept of a resonance can serve as an example. I believe this is also an interesting case study for some aspects of the operation of the scientific method. It might happen that a certain concept becomes well defined and very useful in a certain context or within a limited field of physics. Its utility then motivates its generalization to other areas, into which it is introduced by intuitive analogy. As long as there is only one such generali-

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zation, and the extension of the concept has not gone far afield, there is no problem. When, however, several such generalizations meet, after having taken different, long detours from the original concept, we suddenly discover that we do not know any longer what we mean by that concept. This is what I believe has happened to the concept of resonance, originally taken from mechanics and electrodynamics and successfully used in nuclear physics. In particle physics, however, we have come to the point when it is not clear whether what we mean by resonance is a peak in a cross section, a counterclockwise loop in a partial-wave Argand diagram, a pole on the second Riemann sheet of the complex-reaction amplitude, a partial-wave projection of a Regge pole, a bound state of a multiquark system, or perhaps several or all of these. There is an apparent regress compared a few years ago, but it is only apparent as it will undoubtedly lead to a more sophisticated understanding of the general concept of a resonance.

**Weak-interaction theory.** My impression is that unlike, say, five years ago, weak interactions are now theoretically in better shape than strong interactions. Weak-interaction phenomenology has been quite successful, and more fundamental calculations in terms of an intermediate-boson model (in which it is assumed that the usual Fermi interaction is mediated by the exchange of one boson), or in terms of current-current interaction models, have done quite well. The inclusion of strong-interaction effects is still not settled, but the effects are generally small. A number of conceptual problems remain, notably the treatment of divergencies in such calculations. The problem here is that, although the lowest-order calculations give quite good results, the higher-order corrections are often, at least formally, divergent. One can take care of these divergencies by introducing *ad hoc* cut-offs at reasonable energies, but mathematically such a procedure is hardly tenable. There have been some attempts to eliminate such divergencies, and other attempts to modify the theory, so that the divergencies have a minimal effect on the experimental observables. One modified theory writes the Lagrangian in terms of not one current but a sum of several currents, and arranges, by assumption, the various

pieces to minimize the divergencies. According to this theory neutrino-electron scattering should behave qualitatively differently from other weak-interaction processes, but it is somewhat difficult to check this experimentally at present.

**In summary,** I have to confess that I was less than encouraged by the state of high-energy theory. The field continues to be in a flux, and it is fair to say that the majority of the people in the field do not believe that we have reached a basic understanding of particle physics, or that we necessarily are moving in the right direction. The picture presented in this report of high-energy physics is not altogether a rosy one. The definite experimental progress has been accomplished through almost superhuman effort by a large number of ingenious people and at the expenditure of large sums of money. In theory, progress has been less evident, and for some years a large number of competent people have been nibbling at a few imaginative but apparently not profound enough ideas. Conformity is rampant in high-energy theory, and so is the flight into pretty but apparently irrelevant mathematics. One naturally asks why so many talented people have chosen this as their way of life.

I believe that, among the factors contributing to the answer of this question, the central one has to do with the fact that high-energy phenomena form at present the only branch of physics, and one of the few branches of natural sciences in general, where our attention is directed toward learning the most basic laws of nature, to understand phenomena in a most fundamental way. It is, at the present, one of the very few truly pioneer fields of science. The feeling that one is contributing, however little, to overcome perhaps the greatest scientific challenge mankind has faced so far compensates for much frustration, hard work and impatience with apparent lack of progress.

\* \* \*

*This work was supported by the US Atomic Energy Commission. I am indebted to some of my colleagues for helping me with their notes in the collection of all the factual details of the conference. They shall remain nameless, however, lest the impression be given that they are also responsible for the opinions.*

*My wife drew the cartoons.*

*The conference proceedings will be published shortly by CERN.*

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