HIGH-ENERGY PHYSICS

an account of the 1962 International Conference Geneva, July 4-11

By Michael J. Moravcsik

IF the history of physics is to be classified according to the relationship between our accumulation of information on nature and our understanding of this information, one can distinguish three kinds of periods. In the first, these two aspects of science are even, and the new information is fairly promptly digested in terms of existing theoretical schemes. In the second type of situation, the information obtained is basically new in terms of the theory which becomes inadequate to explain it: a crisis develops. Finally, in the third kind of period, a theoretical "break-through" is achieved, which then quickly makes sense of all the previously accumulated information, and even beyond that makes a multitude of predictions which keeps experimental physics busy for some time.

That high-energy (or, more properly, elementary-particle) physics is in the second of these alternatives today was well demonstrated by the eleventh so-called "Rochester" conference which took place in Geneva in early July. That a crisis exists is, I believe, generally conceded, although there is a strong difference of opinion as to the magnitude and seriousness of this crisis.

In general, physics is talked about in terms of experiment and theory. At the time of such a crisis, however, it is perhaps useful to add to this a third class also, consisting of phenomenology, or the classification of experimental information in terms of a plausible model or in terms of very general theoretical concepts whose validity is well established. Such a description of experiments serves as a common meeting place for theory and experiment, more accessible to the theorists than raw data and at the same time more instructive to experimentalists concerning future experiments than no analysis at all.

In this report, therefore, the conference will be discussed in terms of this trichotomy. At the conclusion of the report, a few remarks will also be made on the organizational aspects of the meeting.

It is perhaps needless to add that a meeting of this magnitude, with its parallel sessions and private discussions, can hardly be covered adequately by one person.

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I want to apologize, therefore, for any incompleteness or lack of balance in my report. At the same time, it is perhaps not completely useless to compare this account with that of the 1960 conference,[1] since presumably the two reports have been normalized to the same prejudices and shortcomings.

Let us then start with a review of the experimental situation. Fortunately for elementary-particle physics, no new higher-energy machines have been built in the past two years, and so work in the field, having previously skimmed the cream off the existing energy region, turned to more solid, more precise, although perhaps less-exciting experiments. The results, however, have been both impressive and exciting, well rewarding the prodigious number of man-hours and dollars (pounds, francs, rubles, etc.) spent on them.

In pion physics the lowest energy range (up to, say, 400 MeV) is still actively pursued, and experiments are refined to measure recoil nucleon polarization, and to use polarized gamma rays for photoproduction. Some previous apparent discrepancies have been resolved in the differential cross section of photoproduction, and more detailed work is being done in the region of the second and third resonances (between, say, 400 and 1000 MeV). The purpose here is to accumulate a sufficient amount of accurate data to be able to determine the contributions of all angular-momentum states in spite of the large number of states that might contribute significantly by the time the third resonance is reached.

One of the most spectacular experimental developments in the past two years has been the discovery of the various resonant states of the pion-pion interaction. There are three definitely established states of this kind, named ω, η, and ρ, respectively. The first two are three-pion resonances, while the last one is a two-pion resonance. They can be studied best in production or annihilation processes with two or three pions in the final state, in which case the momentum distribution of these pions shows a marked deviation from what is predicted by a uniform distribution in phase space. In addition, the existence of another two-pion state, the so-called ABC particle, is also well documented, and there is also some evidence for a ξ particle. In addition, there are some other suspicious "peaks", showing up in one ex-

[1] Michael J. Moravcsik, *Physics Today*, December 1960, page 20.

The main building at CERN, where the conference was held

periment and not in another. It is clear that additional work will have to be done before it is clear that we have the complete spectrum of these pionic states.

At the high-energy end of the pion-nucleon interaction (in the 5–25-BeV region) further information has been obtained on the total and differential cross section for pion-nucleon scattering, as well as on the inelastic cross sections. The importance of these data will be discussed later.

Further information has also been accumulated on the two-nucleon interaction. At low energies (in the elastic region) the main development has been the double- and triple-scattering experiments on the n-p system, either using neutron beams on hydrogen, or proton beams on deuteron. Such experiments will soon permit a unique phenomenological description of the isosinglet part of the two-nucleon interaction just as similar p-p experiments have pinned down the isotriplet part. In the high-energy region, similar to the pion-nucleon interaction, experiments measured the elastic and inelastic total and differential cross sections. It is possible to detect, for instance, the influence of the second and third pion-nucleon resonances on the inelastic nucleon-nucleon cross section. The precision of these experiments is being increased for reasons which will be evident from later discussions.

A more-or-less independent experimental topic is the measurement of nucleon structure through electron scattering. It is a healthy development that three laboratories are now engaged in such measurements, thus permitting variety and cross checks. Further checks are possible on the neutron structure by comparing the elastic and inelastic scattering results of electrons on deuterons.

In the field of strange particles, again the most spectacular development is the discovery of resonances. If one counts only those which are well established, there are six such states known: one excited state of the K meson, three excited states of the Λ, and one each of the Σ and Ξ. The mass values of these states and in many cases their widths have been measured. In addition, in some instances enough information has been accumulated to try to guess at the spin and parity also. Again, there is no assurance that we have reached the end of the spectrum here, and various indecisive additional peaks will have to be confirmed or erased by future experiments.

Of the other experiments in strange-particle physics two of the particularly noteworthy ones measure the anomalous magnetic moment of the Λ by letting it travel through a long magnetic field and observing the rotation. The two results are -1.5 and 0.0 magnetons, both with a 0.5 error. Other experiments have further confirmed that parity is conserved in strong interactions, thus dispelling previous rumors to the contrary. Charge symmetry and charge independence has also been confirmed for the Σ-K production in pion-nucleon collisions. Finally, various antihyperons have been observed and an order of magnitude estimate for their production cross section in proton-antiproton collisions has been given. Further solid progress has also been made in the study of the low-energy K-nucleon interaction.

Perhaps the most significant, and at the same time also the most difficult experiment of the past two years has been the demonstration that the neutrinos associated with muons and those associated with electrons are different particles. The point of the experiment was to show that muon-type neutrinos, when interacting with nucleons, will produce only muons, but not electrons. This was found to be the case. In the same experiment it was also found that the production cross section agreed with theory. Evidence for or against the existence of an intermediate boson (negotiating weak interactions) was also sought, but results up to the time of the conference could only show that there was no evidence against the existence of such a particle.

Several experiments on the cross section of muon capture by He^3 into a di-proton mu-molecule, as well as by complex nuclei, were reported.

In weak interactions involving strange particles, a

Part of the US contingent: Wick and Goldhaber (Brookhaven) and Low (MIT) very useful experiment is to measure spin correlations between parent and daughter particles in a decay process. These can be used to test the validity of some invariance principles such as time reversal, as well as to deduce the spin of the parent particle. Such experiments have been carried out for the Λ and the Ξ. Some of the results will be discussed later.

The experiment which has been under way for at least two years to measure the anomalous part of the muon magnetic moment has been completed. Very high precision in the experimental parameters was a necessary prerequisite for this measurement. As was pointed out by the rapporteur, the results are "unfortunately" as expected (the moment agrees with that of the theoretical prediction, at least to order α) and hence the experiment will receive less attention than it really deserves.

There were also other measurements concerning the electromagnetic properties of muons. Muon pair production has been confirmed to take place, and the muon-hyperfine structure was shown to agree with theoretical anticipation. In all these measurements only the terms of the order α have been detected, as that field is still open to ambitious experimentalists.

Now let us turn to the theoretical developments. Efforts here can be roughly classed into three categories: group theory, S-matrix theory, and conventional field theory.

The first category includes those investigations which attempt to derive the spectrum of elementary particles from some group symmetry. Since it is known that isotopic spin and strangeness are conserved in strong interactions, one demands invariance under these and preferably only these transformations. This severely limits the number of groups one has to consider. Each group has several representations, and every particle is thought to belong to one of these representations. There are two models based on groups that are particularly favored by workers in the field: the octet model and the so-called G_2. The most verifiable predictions of these models are for branching ratios of certain reactions, or for the equality of certain reaction cross sections. No definite experimental test has been carried out so far. In addition, of course, some of these schemes seem to predict "naturally" the number and kind of particles we know of, and sometimes also those we have not discovered.

One of the shortcomings of such efforts is that they are not a substitute for a dynamical theory. In other words, they will, at best, be able to predict relative masses, but not interaction coupling strengths. Thus they exhibit only one aspect of elementary particles which should also follow from a fundamental dynamic theory of these particles if and when we construct it. They might, however, serve as a guide toward finding such a theory.

S-matrix theory has undergone a minor crisis of its own during the past two years. It will be recalled that the 1960 conference voiced high hopes for the future of elementary-particle theory in terms of the double-

Dzelepov (Dubna), Bethe (Cornell), and Heisenberg (Munich)

dispersion-relation approach. That this was undue optimism became evident this year. Only a very few double-dispersion calculations have been brought to any conclusion at all, and the results are rather modest. Further work on the solution of the pion-pion equation (basic to all dispersion theoretical calculations) was reported, but the fundamental problem of divergences has yet to be conquered. Perhaps the most complete dispersion calculation was on the two-nucleon interaction, although this also utilized some semiempirical information. The results are in good agreement with the D and F phases observed from experiment, showing that the two-pion exchange region has been well calculated. The S and P phases, however, have not been attempted yet. Since some old-fashioned potential calculations might also be able to give the D and F phases correctly, and because of the semiempirical elements underlying the results, it is difficult to say whether this calculation should be chalked up as a triumph for dispersion relations.

Part of the reason for the decline in the attention devoted to the double dispersion relations in their original form is that a new idea has found its converts in the theoretical ranks. The innovation is to look at the reaction amplitudes as a function of energy and *angular momentum*, the latter being treated as a continuous (and, in fact, complex) variable also. The contribution to the amplitudes then comes from the singularities in the angular momentum plane, and these singularities travel around in this plane as one changes the energy. In particular, one can plot the real part of the angular momentum as a function of the energy variable along the real axis. The result is a trajectory in this picture. There is some restriction as to where these trajectories can lie without causing physically observable absurdities. Beyond that, however, essentially nothing is known about whether these trajectories are straight lines (as it is now assumed for the sake of simplicity), and what their slope is if they are. The hope is that these

Baldin (Moscow)

trajectories can group the particles that lie among them into families, but so far hardly any trajectory has been found to have more than two particles. In the extreme philosophical end of this approach there would be no really elementary particles, as opposed to composite particles, but only angular-momentum trajectories which, whenever the angular momentum reached a physical value, would give a physical particle.

The existence of such trajectories for elementary-particle physics is at the present only a conjecture, although investigations on the Schrödinger equation or on the Bethe-Salpeter equation in the ladder approximation make such a conjecture not completely implausible. Thus one naturally turns to the experimental predictions of such a scheme.

It turns out that it is only at high energies that the angular-momentum trajectories can yield easy theoretical predictions. In the low-energy region, too many singularities contribute for us to be able to arrive at any qualitative conclusions. At high energies there are two main features of this theory: prediction of the behavior of the total cross section prior to its entering the asymptotic limit, and the narrowing of the small angle or diffraction peak with rising energy.

For the first of these, it may be recalled that in the asymptotic limit (at very large energies) very general assumptions require the equality of cross sections for a reaction involving a certain particle and the corresponding reaction involving its antiparticle. Before this limit is reached, however, the two cross sections are in general different, and the new theory gives a prediction for the difference of the two cross sections in this region. The particular example explored so far has been the cross sections of pp, np, $p\bar{p}$, and $\bar{p}n$ reactions. The new theory was able to get the experimentally observed relationship only if, in addition to the ω, ρ, and ABC particles it also took into account another, as yet undetected, particle.

The narrowing of the diffraction peak is perhaps the strongest piece of support for the new theory. It has been found experimentally that the width of the diffraction peak in the high-energy differential cross sections decreases as the energy rises. Classically, this would mean that the nucleon gets larger as the energy increases. At the same time, the total cross section remains constant with energy, which gives rise to a contradiction. In the new theory there is room for interpretation of such a phenomenon. Whether conventional arguments can also explain this behavior is not quite clear; at least one claim has been made that this is so.

The new theory has another advantage in supplying a "natural" cut-off for various divergent quantities that plague elementary-particle physics. Thus, for instance, vector particles can now be dealt with consistently. This qualitative feature of the theory might also have practical consequences at low energies.

Although this is partly a matter of taste, the new form of the S-matrix theory also offers an esthetic advantage. Strong-interaction physics has always been handicapped by our predilection for doing theoretical physics in terms of expansions, that is, in terms of successive approximations which converge. Such an approach does not seem to work very well for strong interactions. In the new S-matrix approach the calculation is more like a self-consistent scheme: one can start anywhere, and successive iterations are only to ensure self-consistency. In actuality, however, even S-matrix calculations are done in terms of the distance of singularities from the physical region in question, so that the practical significance of the above remark is not clear.

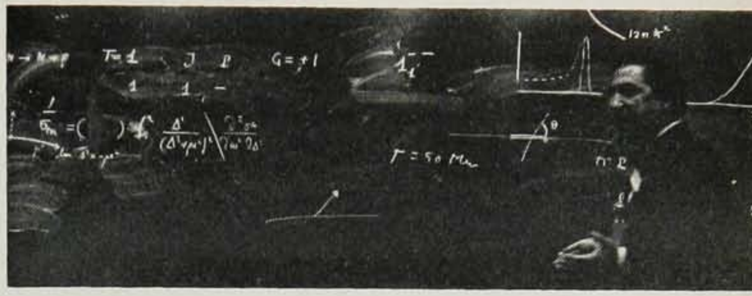
The third domain of activity in elementary-particle-physics theory is in conventional field theory. Beside some formal progress concerning the basic structure of field theory, the most significant line here is the nonlinear theory. Calculational techniques in this theory are still too rudimentary to be able to say much about the comparison with experiments, but it can be said that so far no blatant contradiction has been found between the predictions and known facts.

The picture would hardly be complete without saying something about the theory of weak interactions. The

Italian delegates Amaldi and Cini (Rome), and Castagnoli (Turin) previous discussion dealt mainly with methods in strong-interaction physics, although some of the techniques were also carried over to weak processes. The ideal goal, of course, would be to find a theory to fit both strong and weak interactions, but progress toward this goal has been essentially nil, and some in fact doubt whether the goal can be attained at all. Thus, weak-interaction theory has remained basically unchanged since the 1930's, when the four-fermion interaction was proposed. Some dispersion calculations have been made recently of various weak processes, always with drastic approximations, which sometimes work, and then effort is directed toward the understanding of why such approximations do work. One new element in the picture has been the intermediate boson theory, in which the weak interactions are negotiated by the exchange of such a boson, usually called W. At the present, however, there is no experimental evidence for the existence of such a particle. There are even some very fundamental questions, such as the precise definition of what we mean by a universal weak interaction, that remain topics of discussion.

Now let us turn to the third general class of activities in high-energy physics, that is, to phenomenology. One of the general concerns here is to determine the quantum numbers of elementary particles. Although such quantum numbers, like strangeness, spin, parity, isotopic spin, or G-parity (behavior under the combined operation of particle conjugation and isotopic spin rotation) do not give us information on the specific nature of the interactions, they account for selection rules, branching ratios, and to some extent even for some angular distributions. Perhaps the oldest and most important of these determinations concerns the relative parity of the K meson and hyperons. The problem has still not been solved with absolute assurance, although the evidence continues to point toward a K-Λ odd relative parity. The most widely used method for this determination involves K capture by helium to form a hyperfragment, but the spin of such a hyperfragment and the question of whether it has excited states is still not quite settled. The K-Σ parity is much more open to question. Investigation of K-nucleon collisions producing a pion and a Σ so far tend to support a negative parity, but there is evidence from other reactions to the contrary. It is of interest to note that five years after the discovery of the pion its parity was definitely known, while K mesons have been around for over a decade and their parity is still in doubt.

Attempts have been made to determine the spin of the newly discovered K^* resonant state, and angular distributions of its decay suggest zero. Present evidence also suggests that the ω, ρ, and η all have negative parity, with the first two having spin one, and the last one zero spin. In doubt also are the angular momentum



Pupi (Bologna)

and parity quantum numbers of the excited hyperon states.

Several rather successful attempts were reported at the conference to obtain salient features of certain interactions more or less directly from experimental data. Thus, for instance, the pion-pion interaction in pion-nucleon scattering has been exhibited by calculating the conventional terms in the pion-nucleon interaction and ascribing the long-range part of the remainder to the pion-pion interaction. The existence of the newly discovered heavy mesons has been utilized by several groups in describing the nucleon-nucleon interaction in terms of single-particle exchanges involving the pion and some of these heavier bosons. Excellent agreement is thus achieved with experimental phase shifts using only a handful of parameters. This success means new hope in the two-nucleon problem that the small-range part of the interaction could be calculated after all from meson theory by manageable mathematical techniques.

Much attention has been directed toward the higher pion-nucleon resonances also, not only in terms of trying to determine their spin and parity, but also to give some kind of "explanation" for their existence. One rather attractive scheme, for instance, describes them as resulting from the appearance of inelastic processes

Clockwise, from left: Schwinger (Harvard), Nambu (Chicago), Marshak (Rochester), Heisenberg (Munich), and two backs (unidentified). *Photos by Moravcsik* which react back at the elastic pion-nucleon scattering and photoproduction.

Another use of phenomenological considerations is the description of the elastic and inelastic electron scattering off nucleons and nuclei in terms of form factors. They give the deviation from point-charge scattering, due to the electric charge and magnetic momentum distribution of the scatterer. There are two form factors for both the proton and the neutron, but there is some arbitrariness in how to define them, and it seems to be advantageous now to use the "electric" and "magnetic" definitions instead of the formerly popular "Dirac" and "Pauli" form factors. The neutron form factors can be obtained by both elastic and inelastic electron scattering off a deuteron, and there is some disagreement between the two results. It seems, nevertheless, that the neutron electric form factor is consistent with zero at all momentum transfers.

Considerable phenomenological work has also been carried out on low-energy pion photoproduction, a veritably classical topic in elementary-particle physics. The improved data indicate that it might be difficult to fit both neutral and charged pion photoproduction in terms of the first few multipole states, especially if the relationship between scattering phase shifts and photoproduction amplitudes is taken into account. There is also conflicting evidence on the importance of the pion-pion interaction in pion photoproduction processes, although in general it appears to be small. A method has also been suggested to measure the form factor of the pion in pion photoproduction experiments near threshold.

Much of the theoretical work on the low-energy K-nucleon interaction is also phenomenological in nature, describing the scattering in terms of reaction matrices allowing for the inelastic channel of pion plus hyperon. Effective-range-type expansions have been found to be useful. The description of hypernuclei in terms of potentials, is also progressing, aided by the increasing amount of information available on the binding energies of these objects.

In weak-interaction theory, one of the matters of concern is whether certain currents are conserved in the interactions or not. For instance, the question of whether vector currents are conserved in strangeness-conserving interactions is still up in the air because a check of the consistency between the muon lifetime and the O^{14} data is hampered by our lack of knowledge of the radiative corrections and isotopic purity of the O^{14}. The evidence for a conserved axial current appears to be declining. More seriously, the $\Delta I = \frac{1}{2}$ rule, previously in agreement with experimental evidence, appears now to be in jeopardy, and the $\Delta Q = \Delta S$ rule also appears not to hold.

Finally, let us turn to the nonphysical aspects of the conference. As was the case two years ago, the first three days of the conference featured parallel sessions with ten-minute, contributed papers. Then, after a week-end of rest, three days were devoted to rapporteurs giving survey talks. I personally liked this arrangement, but many others would have laid more stress on the reviews at the cost of the short talks. The lack of room in CERN's main lecture hall (which holds only 300) dictated the invitation of some 150 participants only on the basis of an "observer" status, which permitted them to listen to the rapporteur talks only by television in an adjoining room. There was much to be desired, however, in the technical aspects of this arrangement. In general, the method of organization of the conference as well as the way in which invitations have been extended have again come under increasing discussion this year, and it is expected that the organizing committee might do some further experimentation to see if improvements can be made. This was also the first time that two years elapsed between two successive conferences. This biennial system appeared to work out satisfactorily, with scores of specialized conferences organized by various institutions filling in the gap.

The gigantic job of recording the talks and discussions at the various sessions was handled by an unprecedentedly large battery of very efficient scientific secretaries. A very welcome new feature was the advanced handing out of copies of all of the 323 abstracts submitted to the conference, which served not only as a means of orientation but also as an interim record until the proceedings of the conference appear sometime in October.

The tone of the present report is somewhat pessimistic concerning the present status of high-energy physics. Such pessimism might be construed to imply that conferences of this sort are therefore a waste of money and energy. I would like to hasten to emphasize that this is not at all the case, and that a meeting of this kind is a very important ingredient in progress in a field. From the point of view of a run-of-the-mill worker in elementary-particle physics, the main benefits of the conference are educational. It is becoming increasingly difficult to keep up with developments in the whole of elementary-particle physics, and the rapporteurs' reports at least give an indication of what the main problems and the promising avenues of attack are, and also give further references to the literature. Secondly, the talks and discussions at the conference often supply and stimulate ideas for further research. There is no systematic way of obtaining such stimulation, and often just one small remark by a contributor is sufficient to inspire a new idea. There is simply no substitute for such a person-to-person interchange which tends to be less formal and hence bolder and often more speculative than written communications in journals. Finally, personal acquaintance with colleagues known previously only from journal headings can often lead to much closer cooperation in research. This is particularly important in a fast-moving branch of physics where much of the information is exchanged through preprints and private communication. Elementary-particle physics is a complex enough field of human inquiry to warrant team-type attack in the most general sense, and the conference symbolizes well the nature of such an attack, which can only lead to an eventual "break-through" in this field.