HIGH ENERGY PHYSICS

An informal report of the Rochester Conference

By Michael J. Moravcsik

FUTURE historians of science will find excellent material for a case study in the development of the so-called "Rochester" conferences on high-energy physics, the tenth of which took place at the end of August of this year.

To be sure, high-energy phenomena are among the most popular ones in present-day physics. It is nevertheless quite impressive to consider the amount of effort directed toward the understanding of these phenomena and the total material expenditure laid out to this end.

Compared to a decade ago, the available energies have been multiplied by a factor of 100, and the number of workers in the field also has shown a spectacular gain. (The number of participants at the conference increased by a factor of three despite attempts to keep the meeting to a manageable size.) High-energy physics has become a concern to governments, and its direction is part of the national policy.

Whether the results are commensurate with this grandiose attack is, I suppose, a matter of personal opinion. One thing is clear, however, and has been underlined again by this year's conference: The efforts to penetrate into higher and higher energy regions do not stem from the understanding of phenomena at lower energies. In this sense, perhaps, high-energy physics is moving too fast. Many of the problems concerning, for instance, low-energy pion physics, which confronted the high-energy conference five or ten years ago, are still with us, although perhaps in a somewhat modified form. These unsolved problems at 200 Mev do not discourage, however, investigations of phenomena at 20 Bev. In view of the complexity of the phenomena in elementary particle physics it is hard to tell whether such a development helps toward a unified understanding of processes at all energies or whether it will result in a superficiality of our knowledge for some time to come.

As it follows from the previous remarks, a well-integrated summary of this year's conference is impossible almost by definition. I will therefore divide the field into five rather arbitrary parts. The discussion of these should be construed as personal impressions, although certain attempts have been made toward objectivity. Following previous practice[1] no references are made to individuals and no claim is made with regard to completeness or balance.

THE first part of high-energy physics we will discuss covers phenomena up to an energy between 500 and 1000 Mev. It might be characterized by the following features:

a. It deals only with the "classical", or strangeness-zero elementary particles (nucleons, pions, electrons, and photons). We will exclude weak coupling phenomena so that muons and neutrinos will not be considered.
b. Multiple production channels are unimportant.
c. The energy is low enough so that decomposition into angular momentum states is a useful concept.

Historically this is, of course, the oldest energy range and hence our understanding of it is, relatively speaking, the best developed.

On the experimental side, the progress has been considerable indeed. All basic properties of the pi meson are now well known as a result of recent addition in terms of measurements of the neutral pion lifetime. Previously only a lower and an upper limit were known, which differed from each other by several powers of ten. Now we know that the lifetime is not more than a factor of three different from 1.5×10^{-16} sec.

Recent experiments have also shed additional light on the interaction between pions and nucleons. In the lowest energy region, new and more accurate experiments, in excellent agreement with each other, have fixed the previously somewhat oscillating value of the Panofsky

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[1] Michael J. Moravcsik, Physics Today 12, 10, 38 (Oct. 1959).

G. Salvini (Frascati).

ratio at something like 1.55 with an error of 0.02 or so. Relatively high-precision experiments were reported on the differential cross section of neutral pion photoproduction near threshold about which next to nothing was previously known. At somewhat higher energies new high-precision experiments are available on the total cross section of pion-nucleon scattering in the region of the second and third resonances, and angular distributions of single pion photoproduction in this energy range have also been carried out.

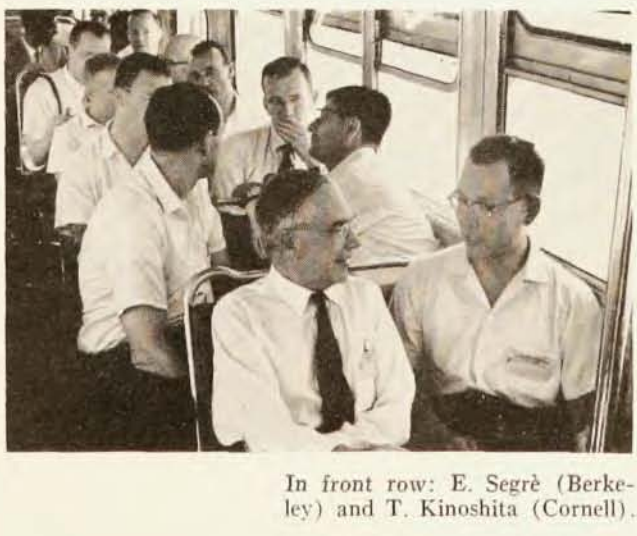
Another class of experiments dealt with the nucleon-nucleon interaction. Triple proton-proton scattering data have become quite extensive, and the first neutron-proton triple scattering experiment has been reported. Strangely enough, the least complete energy region in this field is the lowest one, between 5 and 50 Mev, but this gap is to be closed in the next few years by experiments now in the planning stage.

A new phenomenon to be attacked experimentally in this "classical" energy region is pion-pion interaction. It was the theoretical developments in the last two or three years that directed attention to this process. In particular, the double dispersion relation approach to elementary particle physics considers this process the most basic one, without which others, such as pion-nucleon and nucleon-nucleon interactions, cannot be understood. Unfortunately, since we do not have free pion targets, the experiments exhibiting the pion-pion interaction are either difficult to perform or hard to interpret theoretically. Those already completed fall into the latter category, and measure the final-state interaction of two pions in proton-deuteron or pion-proton collisions. The method of analysis is either the approximate calculation of other final-state effects over and above which the pion-pion interaction is supposed to exhibit itself, or the extrapolation to a point in the unphysical region where only the pion-pion interaction contributes. Both these procedures entail large uncertainties and thus the evidence for pion-pion interaction, while suggestive, is far from being clean cut. It will be several years before the really unambiguous experiments, such as electron-positron annihilation into two pions, can be performed.

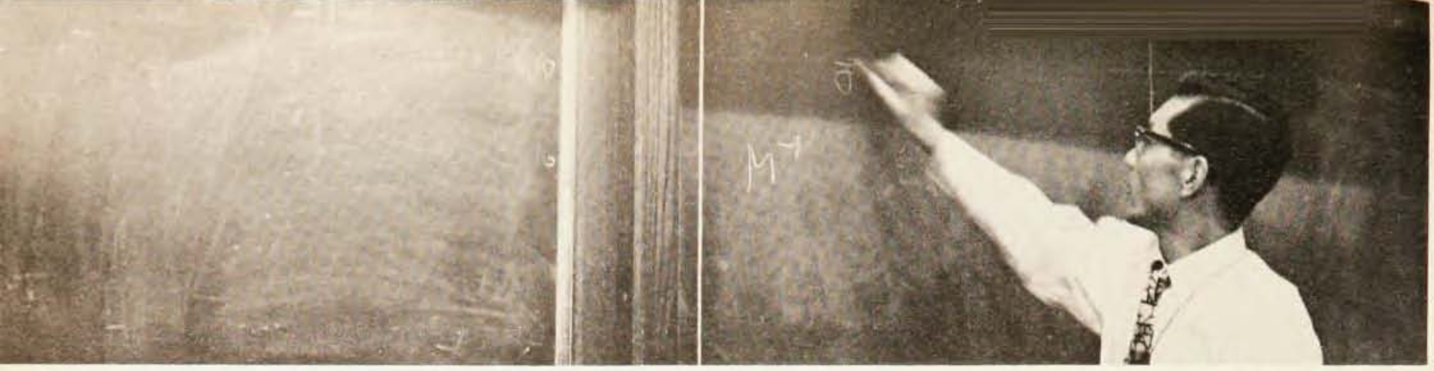
Yet another group of experiments were concerned with the electromagnetic structure of the nucleon. It was reported that the upper limit for the electric dipole moment of the proton is now 3×10^{-15} cm times the electronic charge, almost two magnitudes smaller than the previous limit. It was also demonstrated that the difference between the electronic and the protonic charges is less than one part in 4×10^{19}. As far as the electric and magnetic charge distributions in the nucleons are concerned, experiments measuring the form factors describing these distributions have been pushed to higher energies and are carried out now by two different groups in good agreement with each other. Some of the newer findings at higher energies are somewhat confusing, however. In particular, using the assumption that the magnetic form factors of the neutron and the proton are the same, one finds an electric form factor for the neutron which is different from zero, whereas previously it was thought to be zero. Also, at these energies the electric and the magnetic form factors of the proton seem to begin to deviate from each other. A new and improved analysis of all existing data is, however, in order before definite conclusions can be drawn.

There were also experiments reported which were aimed at proving the validity of isotopic spin conservation. It was shown, for instance, that the cross section for the process $d + d \rightarrow He^4 + \pi^0$, which is forbidden by isotopic spin conservation, is less than 0.02 microbarn.

The theoretical understanding of all these experiments is far from complete. Work is going on along phenomenological lines as well as in terms of basic concepts. The first has been fairly successful. The assignment of the second and third pion-nucleon resonances as being in the $T = 1/2$, $J = 3/2$, D state and in the $T = 1/2$, $J = 5/2$, F state, respectively, is now fairly certain, and a complete (although not necessarily unique) semiphenomenological description of the proton-proton interaction has been given up to 400 Mev in terms of phase shifts and the one-pion exchange contribution. The basic theory, using nowadays mostly dispersion theoretical techniques, also showed some progress. A very accurate determination of the pion-nucleon coupling constant has been made using a clever variant of the pion-nucleon dispersion relations. Another calculation of the pion-nucleon interaction, utilizing semi-phenomenological information on the pion-pion interaction, managed to give a fair prediction of the "small"



In front row: E. Segrè (Berkeley) and T. Kinoshita (Cornell).



S. Machida (Tokyo).

pion-nucleon phase shifts for the first time. It has also been shown that dispersion relations applied to pion-nucleon scattering show the same features as the old static theory which in turn was well supported by experiments. Some progress has been reported in the solution of the equations for the pion-pion interaction, and dispersion relations applied to nucleon-nucleon scattering are also under investigation. On the other hand, some rather large apparent discrepancies have been discovered between the predictions of dispersion relations as they had been used for pion photoproduction and the corresponding new experimental data, particularly for neutral pions. The agreement here was previously thought to be good to within ten percent. The discrepancy is apparently caused by contributions from the unphysical region. In the restricted angular region where this contribution is small the agreement is good. This might mean that even for a qualitative understanding of phenomena, even at the lowest energies, rather complex approximations to the dispersion relations are needed and care must be exercised in defining the region of validity.

There is of course also the question of whether the present-day dispersion techniques are valid at all. Again, some progress has been recorded in the form, for instance, of the proof of the Mandelstam formulation of double dispersion relations for four-particle processes in the absence of anomalous thresholds, to all orders in perturbation theory. But the much more fundamental problem, that of extending the double dispersion relations to multiparticle processes, is at the present completely unsolved, and is also an appreciable obstacle in practical calculations. It seems clear that a really basic and sweeping insight into elementary particle theory, comparable to that of the formulation of quantum theory in the atomic and nuclear phenomena, is yet to come if it will come at all.

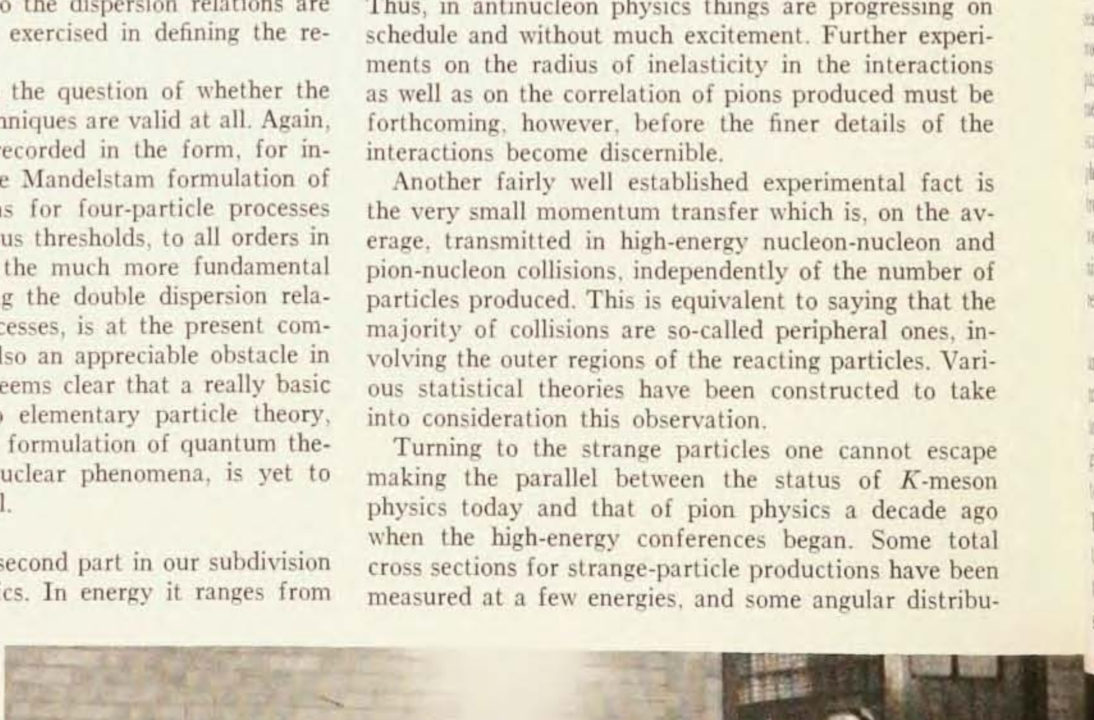
LET us now turn to the second part in our subdivision of high-energy physics. In energy it ranges from about 1 Bev to about 6 Bev, and includes strange-particle processes in the lowest energy range, as well as antinucleon and multipion processes. It is in fact characterized by the multiplicity of channels which makes angular momentum decomposition of doubtful utility. Even in cases where low-energy phenomena are involved, like in the K-meson-nucleon scattering, the scattering matrix has to take into account inelastic processes.

Let us first discuss the strangeness zero phenomena. Continued experiments on antiproton-proton scattering resulted in the discovery of a quite large polarization. The first rudimentary measurements of the anomalous magnetic moment of the antiproton do not disagree with expectations. The antiproton-proton modes of annihilation into two pions or two K mesons have been found to have an upper limit of 0.4 and 0.1%, respectively. Antiproton-proton and antiproton-neutron cross sections have been shown to be approximately equal. Thus, in antinucleon physics things are progressing on schedule and without much excitement. Further experiments on the radius of inelasticity in the interactions as well as on the correlation of pions produced must be forthcoming, however, before the finer details of the interactions become discernible.

Another fairly well established experimental fact is the very small momentum transfer which is, on the average, transmitted in high-energy nucleon-nucleon and pion-nucleon collisions, independently of the number of particles produced. This is equivalent to saying that the majority of collisions are so-called peripheral ones, involving the outer regions of the reacting particles. Various statistical theories have been constructed to take into consideration this observation.

Turning to the strange particles one cannot escape making the parallel between the status of K-meson physics today and that of pion physics a decade ago when the high-energy conferences began. Some total cross sections for strange-particle productions have been measured at a few energies, and some angular distribu-

B. Rose (Harwell), J. Cassels (Cornell), M. Levy (Orsay), G. Breit (Yale), and V. P. Dzhelepov (Dubna).



tions have also been investigated. One of the interesting possibilities in these reactions is the conjectured appearance of cusps in the cross section at energies where new channels enter. So far there is essentially no evidence for these cusps, except for possible irregularities in some angular distributions, but if they exist they might furnish information on relative parities. Experimental evidence on the asymmetry in lambda decay (an indication of parity nonconservation in strong interactions) is inconclusive. No experimental evidence has been obtained so far for the existence of a bound sigma-neutron system. More data has been gathered on hyperfragments such as more accurate lifetimes, and a resonance for the lambda-pion system is suggested by the data at 1370 Mev. This latter finding, if confirmed, would be the first example of a resonance in hyperon interactions.

These are for the most part semiqualitative results. Somewhat more quantitative is the status of K mesons, and it is here that the analogy with pions is suggestive. Much effort is directed toward the determination of the K-meson parity. The method currently in the lead is the negative K absorption in helium, producing a lambda hyperfragment and a pion. It has become more and more certain that the capture is predominantly in the ground state, and it is also probable that the ground state of the resulting hyperfragment has zero spin. If all these assumptions are correct, the existence of the reaction, which has been conclusively demonstrated, would indicate a negative lambda-K-meson relative parity. Similar indications of a negative hyperon-K-meson parity are also available from K-meson-nucleon scattering (using dispersion relations), from K-meson photoproduction (using extrapolation techniques), and from other hyperfragment data. Since a number of weak pieces of evidence do not quite add up to a definite proof, more experiments are in order before the result can be quoted in freshman physics textbooks.

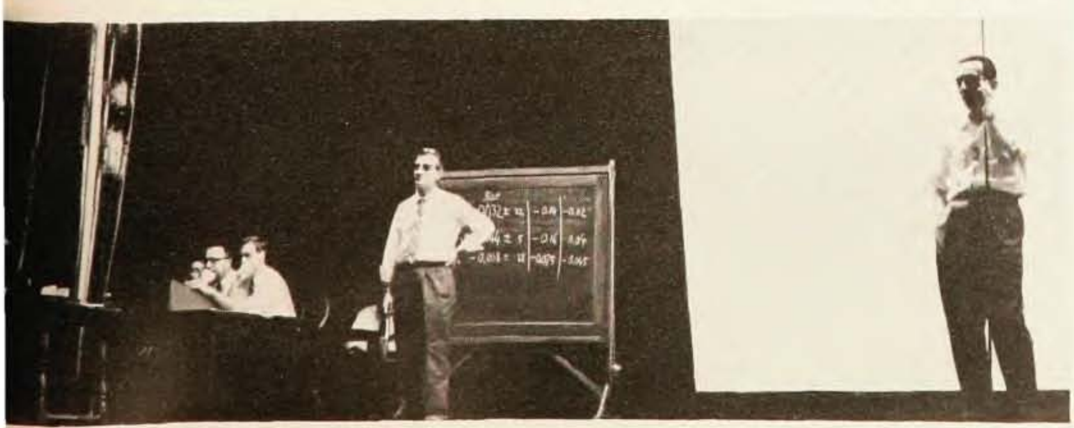
As in the case of early pion physics, a considerable amount of work is done on the most basic process, meson-nucleon scattering. For negative K mesons the angular distribution seems to be isotropic at low energies. At higher energies the P-wave contribution seems to set in very fast. Charge-exchange scattering is small. There is some evidence for a constructive Coulomb interference. At momenta as high as 2 Bev/c the scattering is all diffraction, corresponding to an opaque sphere with a radius of 0.8 fermi. The positive K meson scatters isotropically and its cross section is energy-independent up to 500 Mev.

Measurements of K scattering on deuterons have also been carried out, but they are complicated by apparently strong final-state interactions.

The theoretical interpretation of K-meson-nucleon scattering has been first made in terms of the scattering-length approximation, which is complicated here by the inelastic processes. This interpretation agreed with some experimental facts but appears to disagree with some new ones. More recently a very rough application of dispersion relations has been made using some phenomenological information on the pion-pion interaction. Whether it will agree with the experiments is not known.

All in all, one can say that the experimental side of K-meson physics is struggling through its first, semiquantitative phases, and theory is trying a few plausible schemes while waiting for more data as well as theoretical developments concerning related elementary-particle reactions.

THE division of our third part from the second one is somewhat tenuous, inasmuch as it is dictated by historical development of particle accelerators and not by basic physics. It includes phenomena involving mostly strangeness zero particles, from 6 to 8 Bev on up. The information in this region is fragmentary and theory, apart from general statistical considerations, is essentially nonexistent. The one object in this energy range which is theoretically of immediate interest is the comparison of data with the Pomeranchuk theorem. This theorem states that under quite general assumptions the cross section of a process involving a certain particle and the cross section of the same process involving the corresponding antiparticle go asymptotically to the same constant as the energy goes to infinity. This has been investigated for proton-proton and proton-antiproton scattering. The former sits on a plateau in the 10–25-Bev range, while the latter drops with energy but even at the highest energy investigated so far is still 30% higher than the former. Presumably the Pomeranchuk theorem does not hold for these processes at these energies yet, because the reaction that distinguishes the two processes (proton-antiproton annihilation) has still a substantial cross section compared to the multipion processes in which the two processes are similar. On the other hand, the Pomeranchuk theorem seems to hold already at this energy for positive and negative pion-proton scattering.



G. Bernardini (CERN) and G. C. Wick (Brookhaven) served respectively as chairman and rapporteur for one of the sessions.

Various experiments have been carried out in the 10–25 Bev region concerning the multiplicity of secondaries, and the results agree only roughly with statistical calculations. In particular, D, He^3, and H^3 have been observed in such high-energy collisions and the mechanism which produces such "heavy" fragments is not completely understood.

Very useful and accurate measurements have been made of the pion-nucleon scattering total cross sections, showing a plateau for negative pion-proton scattering. The new data connect smoothly to data at low energies.

In summary, one might say that the results in this energy range so far are more distinguished by what they do not show than what they do. No new particles have been seen, the measured cross sections are smooth functions of energy, and the statistical theory appears to work, at least approximately. The experiments have just begun, however, and soon reactions involving strange particles, mu mesons, and neutrinos will also be investigated.

There is one more theoretical development concerning very-high-energy phenomena which merits attention. It has been emphasized by several people that in the high-energy processes producing many particles, due to the diagram on which one pion only is exchanged and the momentum transfer is small, the cross section can be very large. In particular, it was shown that a high-energy photon beam can in this way produce a very intense and well collimated high-energy pion beam. Thus some of the experimental difficulties anticipated for very-high-energy accelerators might be less serious than thought previously.

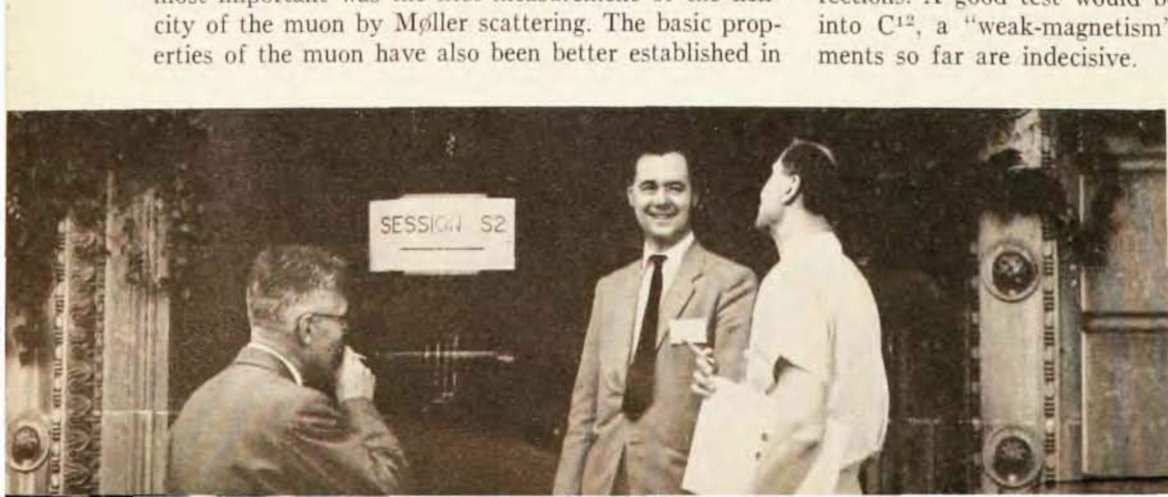
THE fourth part of our discussion deals with weak interactions which, at least at the present, constitute a subject almost completely independent of the strong interactions we discussed in the first three sections, although it is becoming more and more evident that this division is not a natural one. The particles under investigation are muons, electrons, and neutrinos, in addition to the decay properties of strongly interacting particles.

Let us first talk about weak interactions involving strangeness zero particles. It appears from the talks and discussions at the conference that in the interaction triangle having as vertexes neutrons and protons, electrons and neutrinos, and muons and neutrinos, respectively, by far the weakest side is that connecting the nucleons with the muon. Of the other results the most important was the first measurement of the helicity of the muon by Møller scattering. The basic properties of the muon have also been better established in other respects. The mass of the muon is now known to one part in 10 000 and its charge is that of the electronic charge to within one part in 20 000. Furthermore, it has been demonstrated by improved measurements that the muon-nucleon scattering at large angles is not anomalous, as it was believed on the basis of some older cosmic-ray experiments. Most of the discussion was spent, however, on the weak link in the interaction triangle, that is, on muon capture. One of the difficulties here is that the process of interest is masked by complicated nuclear effects. In this connection hyperfine structure effects were extensively discussed. Recently it has been suggested that the capture experiment might be cleaner if done on protons directly, but no experiment has been carried out to date.

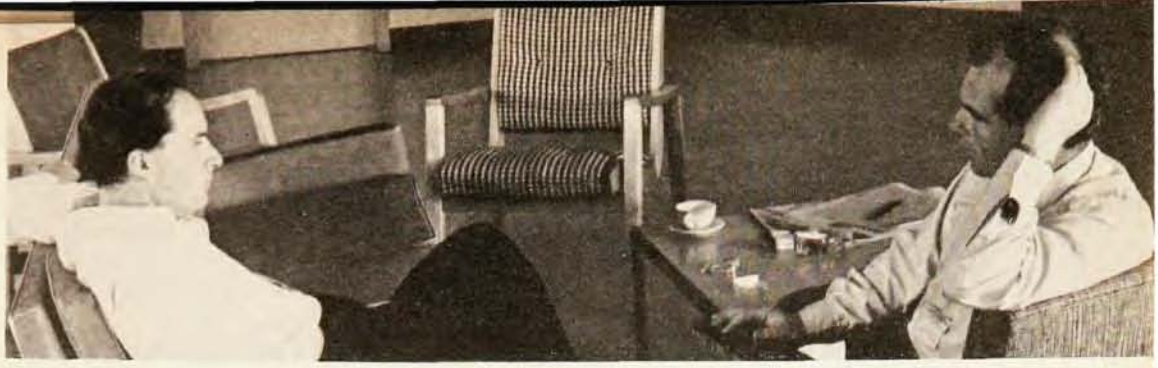
The discussion on weak interactions involving strange particles centered around the mounting evidence for the validity of the $\Delta I = 1/2$ rule. This rule demands, for instance, that the ratio of the probabilities of the lambda decaying into a negative pion and of the lambda decaying at all be 2/3. Four recent experiments give something like 0.65 ± 0.04. Similar evidence comes from the sigma decay, although there some uncertainty is introduced by the unknown value of the polarization. For K mesons the probability of decay into two neutral pions should be a third of the total, and experiments give 0.30 ± 0.04. Similarly, in the leptonic decay of the K meson a ratio which is supposed to be 1/2 has been measured to be 0.42 ± 0.12. Also, the lambda and sigma decay asymmetry parameters agree very well with the predicted values. Granting that in principle it is impossible to "prove" a theory, the case for the $\Delta I = 1/2$ rule appears very strong indeed.

Two experiments were reported also testing the validity of CP invariance, both with positive results. Finally, two other elegant experiments utilized the interference and regeneration properties of the K_1^0 and K_2^0 mesons.

In the theory of the weak interactions one of the outstanding puzzles is still why the original calculation of the pion decay, which used some appalling approximations, agrees so well with experiments. The answer is unknown, but the guesses are numerous. Other, similarly bold dispersion calculations have been carried out on the K-meson decay, and on muon capture. One subject of great interest is whether vector current conservation holds. Its prediction for the muon lifetime checks within 2–3%, and some believe that the discrepancy might be ascribed to electromagnetic or other corrections. A good test would be the beta decay of B^{12} into C^{12}, a "weak-magnetism" effect, but the experiments so far are indecisive.



A. P. Rudik (Moscow), J. C. Polkinghorne (Cambridge), and N. Kemmer (Edinburgh).



A. W. Merrison (CERN) and J. Cassels (Cornell).

There are also several general theories of weak interactions, some conjecturing the existence of new particles, others based on the existence of an intermediate boson. In some of these prescriptions like the $\Delta I = 1/2$ rule arise naturally, but it is difficult to design feasible experiments which could demonstrate the existence of these conjectured particles.

THE last part of our discussion briefly deals with general theories presented at the conference. In a sense these theories transcend and include all the previous topics. In practice, however, none of them is sufficiently well established or developed to be of much help in the day-to-day theoretical calculations which are made to check specific experiments.

One of these general theories mentioned at the conference is called the composite model of elementary particles in which three basic fields are postulated pertaining to the proton, neutron, and the lambda. From these the other particles can be constructed. The theory predicts the existence of an isotropic singlet neutral pion in addition to the conventional neutral pion. The pion-nucleon resonances also arise from the theory, as well as some K-meson-nucleon resonances hitherto unobserved.

Considerable attention was given at the meeting to the results of the nonlinear spinor theory. Some of this work helped to dispel previous doubts concerning the compatibility of the theory with well-established features of modern physics such as the probability interpretation, parity conservation in strong interactions, the appearance of strange particles, etc. It is claimed that the nonconservation of parity in weak interactions seems to arise naturally. Other attempts have been in the direction of exploring the mathematical properties of the nonlinear theory.

These considerations, together with several others not mentioned here, leave one with some optimism regarding the future of elementary-particle physics. It is nice to know, in any case, that some attempts are made at a really basic understanding of these phenomena. Otherwise, however, the feeling one gets in reviewing the past decade is that, while the small-scale progress has been impressive, for the solution of the over-all problem, even in principle, the effort and ingenuity applied so far have been insufficient. But then, looking back at past history of science, perhaps it is unreasonable to demand that a new realm of physics be comprehended in as short a time as a decade.

AND now about the nonphysical aspects of the conference. The gargantuan task of the organization has been done very well. Several delegates, hitherto barred by the McCarran act, attended the conference. On the other hand, several top Soviet delegates, specifically invited by the organizing committee, cancelled their trip at the last minute for reasons unknown. Their absence was sincerely regretted. Most of the delegates were housed in the new dormitories of the University, and convenient and quite high-quality cafeteria food was available, as well as a swimming pool in the basement. Cocktail parties, a concert, and several trips added to the program. The main speaker at the conference banquet was AEC chairman McCone who emphasized to the international audience that the federal government is happy to aid high-energy physics as long as it does not cost too much.

As far as the structure of the sessions is concerned, a rather happy compromise has been struck between the perpetually fighting two points-of-view of using either many contributed papers or a few rapporteur lectures. The first two days of the conference featured four parallel sessions, with contributed and invited papers. After this most of the delegates took off for weekend excursions, but the few rapporteurs worked feverishly through Saturday and Sunday to prepare for the next three and a half days consisting of summarizing talks. I found this basically a very sound scheme, but certain minor modifications might perhaps be useful. Firstly, this year the plenary sessions featuring the rapporteurs also included some additional invited papers and even some rather ad hoc contributed talks. It might be good to make sure that the invited papers presented in plenary sessions are of sufficient generality and importance to be of interest to the whole conference, and contributed papers should be strictly confined to the specialized sessions. Secondly, it would immensely facilitate the work of the rapporteurs as well as of the secretariat if a strict deadline could be established for contributions to the conference. Such a deadline, perhaps three weeks before the opening of the conference, would also prevent the presentation of half-ready and undigested results arrived at during a day-and-night marathon a few days before the opening. Thirdly, the organizing committee, when selecting rapporteurs, might take into account the fact that scientific excellence is not always correlated with clarity of thought and oratorical ability.

It has been decided that from now on these high-energy conferences will be held every second year instead of annually. There are many arguments supporting this course, and it is probably a wise decision. Nevertheless many of us will regret having to wait for two years now to attend a conference as pleasant and instructive, both on a scientific and human level, as this one was.