Introductory Session

CURRENT TOPICS IN PARTICLE PHYSICS

Murray Gell-Mann

It's a great pleasure and a great honor to be here and to address such a distinguished audience and so many old friends, but I'm not at all clear about what the subject should be. It was implied that I had chosen the task of summarizing the Conference in advance; that is hardly the case. I've had lots of advice from many people about what to do. Some people have said, "I hope that you can tell us everything that's going to be important so we don't have to go to the sessions." Others have insisted that it would be absurd to try to summarize the Conference in advance and what I should do is to give some general philosophical statements about the progress of high energy physics and the meaning of high energy physics. Other people have told me that I am far too young and far too involved in the subject to be able to give any general philosophical pronouncements and that I should concentrate on some discussion of what's going on in the field. I think the last is probably the most reasonable. I'll try to say something about my personal prejudices about the field. The theme, let us say, is what I am eager to hear about at the Conference in the next few days on the basis of all the rumors since the preceding Conference. Now, if I don't mention something that you have done that's not at all because I don't consider it important or because I'm not anxious to hear about it but only because there isn't time to talk about everything here. And if I mention very few names, it will be simply because I don't want to make the mistake of leaving out any. I may mention some for purposes of identification or to quote those people who modestly left themselves off the invitation list.

Now, what sorts of things can we really expect to hear? We've been told by Professor McMillan about some of the profound changes that have taken place in the field since the first Rochester Conference. What has happened to theory in all the time since then? Then we were making unreliable calculations of the deuteron structure based on the exchange of one pion. Now we have gone to the stage where we make unreliable calculations of 50 or 60 bound states on the basis of exchanging 50 or 60 particles, and the progress is amazing. At that time, the experimental people were still debating about whether strange particles existed, and now we know they exist but not why.

In some respects, it's rather humbling to think about how little progress we've made in the last 15 years; but if we actually look at the data accumulated and the theoretical analysis, it's clear that we are much further on our way toward understanding the particles. It's rare that, at a meeting like this, one sees the synthesis actually forming before one's eyes, but what I think happens more often is that going home afterwards one has a lot of ideas that have seeped in during the meeting and that form a coherent picture in the mind.

What can we look forward to hearing? Something which we can certainly look forward to hearing, although not necessarily with pleasure, is a lot of discussion among the different kinds of theorists about whether one should work with "S-matrix theory" or "field theory" or "Lagrangian field theory" or "abstract field theory," and I would like to suggest, as a way of settling this once and for all, that we recognize how remarkable it is that field theory works at all, that so far we have not had to abandon our basic theoretical tool for understanding particles, namely relativistic quantum mechanics. It comes equipped with all its attendant details, which some people want to refer to as microcausality in space-time and other people as analyticity in momentum-space, but as far as anyone knows, these are very similar. It would be better if all the efforts that we expend on the discussions on which form of field theory one should use were devoted to arguing for a higher-energy accelerator so that we can do more experiments over the next generation and really learn more about the basic structure of matter.

The experiments at the highest energies now available at CERN and Brookhaven are certainly exciting. A number of quite refined experiments are now available on high-energy scattering. It's true that you can do experiments with large momentum transfer and experiments with the production of a great many particles, but those have not proved terribly easy to analyze so far; they present a challenge to theory. (If I seem to emphasize theory a great deal in this discussion, it is only because that is the way I make my living.) The experiments at high energies with small momentum transfer seem to be susceptible of rather detailed analysis, and I expect what we hear on the subject to be quite interesting. Some analysis has been carried out using optical model methods and some analysis using Regge poles.

Regge poles, as you recall, were very popular at the last-Conference-but-one for this purpose, and at the most recent Conference they were somewhat muted. To some extent, they seem to work again.

Now, the difficulties that have accumulated with them have been both theoretical and experimental. The experimental one was simply a failure of one or two trajectories to explain the data at high energies, but we now know that there are many mesons and it's not unreasonable that there should be about an equal number of trajectories, and so an analysis with several trajectories is by no means absurd. The theoretical difficulties were more serious; it was discovered that poles apparently implied other kinds of singularity in the complex plane of angular momentum. Some sort of horrible essential singularity seemed to develop which could move up to rather high J and therefore up to great prominence in high energy reactions. Imagine a hole in the wall that we cover with an ugly picture; when we want to take down the ugly picture we remember that we put it up in order to cover the hole in the plaster. So we have cuts in the angular momentum plane which were introduced in order to paper over the essential singularity; their existence is strongly suggested by theory, although not rigorously proved, and they are a real nuisance, as we shall see in a moment. It is still possible that further study may render them more innocuous.

If only poles are used, one finds the famous expression for their contributions to a high-energy scattering amplitude for a particle a going into b and c going into d, as a function of the invariant energy variable s and momentum transfer variable t:

$$\sum_n \frac{\beta_{abn}(t)\beta_{cdn}(t)}{\sin \pi(\alpha_n(t)-v)} \left\{1 \pm e^{-i\pi[\alpha_n(t)-v]}\right\} s^{\alpha_n(t)-\Delta}, \quad (1)$$

where the index n labels the trajectory, Δ is the number of units of helicity flip, and v is zero for meson trajectories and 1/2 for baryon trajectories. The angular momentum J of the Regge pole is $\alpha_n(t)$. The number ± 1 is called the signature of the trajectory; a meson trajectory of positive signature may have along it, for $t > 0$, meson states of even spin, while a negative-signature trajectory may have states of odd spin. Likewise a baryon trajectory of even signature can have particles of spin 3/2, 7/2, etc., along it, while a negative-signature baryon trajectory can have particles of spin 1/2, 5/2, etc., along it for $t > 0$. These particles correspond to poles in t of Expression 1. In high-energy scattering, however, we are concerned with the region $t < 0$, and we have no poles for particles of negative mass squared!

We can, in various reactions involving the exchange of particular quantum numbers, try to analyze the scattering amplitudes in terms of one or more leading trajectories (with the largest α_n) having those quantum numbers, using Eq. 1. Unfortunately, the most obnoxious cuts that are thought to exist in the angular momentum plane give contributions that, at $t = 0$, are smaller than the leading pole contributions only by a factor of ln s at large s, and for $t < 0$, are larger than the leading pole contributions. These dominant cuts can be roughly described as giving terms that go as $s^{\alpha(0)}/\ln s$, where α is the leading trajectory. Nevertheless, a description in terms of poles alone usually gives a good description of the data. Are the dominant cuts absent because of some hole in the theoretical arguments for them? Or are they present, but with small numerical coefficients? If the latter is true, then for $t < 0$ the higher we go in energy the more the waters will be muddied by the dominant cuts, a most unpleasant situation. With these remarks, let me forget cuts and go on with an account of the description of high-energy two-body reactions in terms of poles.

In any reaction in which strangeness, isotopic spin, or baryon number is exchanged, the analysis in terms of one or two leading trajectories works beautifully. Thus we find trajectories on which the nucleon and $\Delta(1240)$ could lie, meson trajectories on which the ρ and "A_2" could lie, and so forth.

From forward amplitudes or total cross sections, we find rather precise values for $\alpha(0)$. Also, there are many interesting theoretical properties of trajectories at $t = 0$, some of which will undoubtedly be discussed at this meeting. Trajectories with different signatures and different parities and different charge-conjugation behavior can be connected at $t = 0$ and have α's that are equal or that differ by integers. The reason is that if we solve a bound-state problem at $t = 0$, we can describe the system as having energy and momentum equal to zero, so that there is four-dimensional angular invariance, much higher symmetry than usual.

Another kind of place where interesting information is available, both theoretically and experimentally, is where a trajectory passes through certain half-integral or integral values of α. The contribution of the trajectory to particular scattering amplitudes or to all amplitudes may have to vanish at such a point. The various kinds of zeroes give dips in the angular distributions of scattering processes at characteristic values of t, and a number of such dips seem to have been identified in the data. For the "ρ trajectory," for example, we now have good evidence that $\alpha = 0$ at $t \approx -0.6$ (BeV)^2, as well as that $\alpha(0) \approx 0.5$ at $t = 0$. For the "N trajectory," we have fair evidence that $\alpha = -1/2$ at $t \approx -0.2$ (BeV)^2, as well as that $\alpha(0) \approx -0.3$ at $t = 0$.

In this way a set of provisional trajectories has been plotted, using information from scattering at $t \leq 0$ and information from the existence of known particles at certain values of $t > 0$. These trajectories are all nearly linear in t over a considerable range and with roughly the same slope, around 1 (BeV)$^{-2}$. For example, the $t \leq 0$ portion of the nucleon trajectory just mentioned connects smoothly with the points corresponding to Re $\alpha = 1/2$ at (0.94 BeV)^2, Re $\alpha = 5/2$ at (1.68 BeV)^2, and with suspected $9/2^+$ and $13/2^+$ resonances lying higher. The Δ trajectory has $\alpha(0) \approx -0.1$, passes through $\alpha = 3/2$ at (1.24 BeV)^2, 7/2 at (1.92 BeV)^2, and may pass through higher suspected resonances with $11/2^+$ and $15/2^+$.

Now let us look at meson trajectories. The ρ trajectory is rather straight, and suggests that states with $J = 3^-, 5^-$, etc., should show up at rather well-defined masses; there is even some slight experimental evidence that this is so, as we shall no doubt hear. The "A_2" trajectory with opposite parity and signature appears to lie very close by, passing through the 2^+ meson at about (1.31 BeV)^2 and suggesting the existence of $J = 4^+$, etc., lying higher. The rough coincidence of trajectories and residues of opposite signature and parity has been called "exchange degeneracy" because it is exact in two-body systems with no exchange forces.

A very simple picture of the 1^- and 2^+ nonets of mesons then emerges, in which they lie on roughly straight, parallel, and exchange-degenerate trajectories, but we must then rearrange somewhat our ideas about elastic scattering amplitudes in which no quantum numbers are exchanged, like the sum of pp and $\bar{p}p$ amplitudes, or the sum of π^-p and π^+p amplitudes. Here the main effect experimentally is diffraction scattering, dominated by the exchange of the "Pomeranchuk pole" with $\alpha(0) = 1$ or nearly so, and it was thought that this pole had a trajectory passing through the 2^+ meson f^0 at (1.25 BeV)^2. It is now much more natural to say that the next highest trajectory, with $\alpha(0) \approx 0.4$, passes through this meson, while a still lower trajectory passes through the 2^+ meson $f^{0\prime}$ at (1.5 BeV)^2. The Pomeranchuk pole is left high and dry, with no known mesons on its trajectory, which is also rather flat, since the diffraction scattering peak does not show much shrinking in t as s gets larger. It may be that the Pomeranchuk pole is a fixed one, with $\alpha(t) = 1$. If that is so, then describing the leading term in diffraction scattering by means of the coupling to this pole is the same as describing it by an "optical model," and may be capable of describing not only the diffraction data at small negative values of t but also the data up to very high values. The leading term has, of course, the form $s\, f_{ab}(t)\, f_{cd}(t)$, where, for elastic scattering, a = b and c = d.

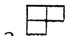
Let us assume that the high-energy data are correctly described in terms of Regge poles (plus perhaps a fixed pole and whatever associated cuts and other singularities in the complex plane are required). Now consider the bulk of the experimental results at lower energies, described in terms of the formation and production of resonances and, to some extent, in terms of the exchange of bound states and resonances (the peripheral model). An immense amount of information is now being gathered about hundreds of bound and resonant states of the meson and baryon systems. We are learning from the data first of all their masses and quantum numbers. We are learning about the baryon-baryon-meson and meson-meson-meson coupling constants among all the states; these govern the strong decays of resonances and the exchanges of meson and baryon states. We are also learning from electromagnetic production and decays some of the matrix elements of the electromagnetic current between states; in some cases, electron scattering experiments tell us form factors. The much more difficult neutrino experiments are beginning to tell us a little bit about the matrix elements of the weak current and their form factors. All of this information, together with the high-energy work on Regge trajectories, is beginning to fit into a coherent picture of the mesons and baryons.

We discuss first the masses and quantum numbers of the meson and baryon states and the strong coupling constants among them. These can be incorporated, along with our knowledge of trajectories, into a unified systematics of hadron states. We have seen that the trajectories $\alpha(t)$ are studied for $t \leq 0$ in high-energy experiments, and that when $t > 0$ the same trajectories give us the hadron states. For example, any meson of mass μ and spin J corresponds to a situation in which a trajectory n with the right quantum numbers and with signature $(-1)^J$ has $\mathrm{Re}\,\alpha = J$ at $t = \mu^2$ and $\mathrm{Im}\,\alpha$ proportional to the width of the meson state, while the coupling parameter $\beta_{abn}(t)$ of the trajectory to two hadron states a and b gives, at $t = \mu^2$, the coupling constant of the meson state to a and b. The same kind of thing is true of baryon states and baryon trajectories. The rough linearity in t of trajectories suggests not only that we will have long series of rotational levels, as in nuclear physics, but also that these will be rather narrow, since the widths are proportional to $\mathrm{Im}\,\alpha$ and a "real analytic function" that is nearly linear does not have much of an imaginary part.

Now it is not only in the relation between mass M and angular momentum J that we have such simplicity in the systematics. We know that if we think of M as a function of I, Y, J, and so forth, we can define families of particles or trajectories for which the variation of M in all these variables is very smooth. That brings us to the subject of approximate symmetries of the hadrons and their strong interaction. The main features of what we now know about the approximate symmetries of the hadron spectrum are most simply described by the "quark model."

We consider three hypothetical and probably fictitious spin 1/2 quarks, falling into an isotopic doublet, u and d (for "up" and "down"), with charges +2/3 and -1/3 respectively, and an isotopic singlet s with charge -1/3. Corresponding to these quarks q we take the three kinds of antiquarks $\bar{q}$. We make the known bound and resonant states of the mesons formally out of $\bar{q}q$ and the known bound and resonant baryon states out of qqq.

For the mesons, we obtain roughly degenerate nonets, including the ^1S nonet that gives pseudoscalar mesons and the ^3S nonet that gives vector mesons. The series $^3S_1$, $^3P_2$, $^3D_3$, $^3F_4$, etc., gives the two trajectories on which the known vector and tensor mesons lie. We expect to find, near the tensor mesons, also the $^3P_1$ nonet (ordinary axial vector mesons) and the $^3P_0$ nonet (scalar mesons). The singlet configuration should give trajectories including not only the pseudoscalar nonet and its expected rotational excitations (^1S, ^1D, ^1G, etc.), but also the ^1P, ^1F, ··· nonets, where ^1P corresponds to axial vector mesons with opposite charge conjugation, that should lie in the region just above 1 BeV as do the other P states. We shall hear, I am sure, how well the theoretical $^1P_1$, $^3P_0$, and $^3P_1$ nonets fit in with the observed bumps in this region of mass. I understand that the evidence is consistent with the theoretical picture, but not conclusive.

For the baryons, we start with the lowest configurations of qqq, corresponding to the $J = 1/2^+$ octet and the $J = 3/2^+$ decimet. These correspond to $^2S_{1/2}$ and $^4S_{3/2}$, where the spin-unitary-spin wave function is symmetrical. The simplest assumption is that the quarks have a totally symmetric wave function altogether (unlike real fermions) and that the ground state is an overall s state, as in a problem with mostly ordinary forces. (It is also possible, of course, that the ground state is a complicated S state made of two internal p waves and that the quarks act like fermions, but I shall not pursue that further.) The next likely configurations include only one with negative parity, namely a P state that transforms, as do the internal coordinates $\mathbf{x}_1 - \mathbf{x}_2$, $(\mathbf{x}_1 + \mathbf{x}_2)/2 - \mathbf{x}_3$, according to the Young diagram , and gives $^2P_{1/2}(\mathbf{1})$, $^2P_{3/2}(\mathbf{1})$, $^2P_{1/2}(\mathbf{8})$, $^2P_{3/2}(\mathbf{8})$, $^2P_{1/2}(\mathbf{10})$, $^2P_{3/2}(\mathbf{10})$, $^4P_{1/2}(\mathbf{8})$, $^4P_{3/2}(\mathbf{8})$, and $^4P_{5/2}(\mathbf{8})$. In the language of "SU(6)," we have for the ground state a $\mathbf{56}$ with $L = 0^+$, and for the first negative parity family a $\mathbf{70}$ with $L = 1^-$. The observational evidence is, I understand, in reasonable agreement with this picture, but there is also evidence for low-lying excited configurations of positive parity, which may be $\mathbf{56}$, $L = 0^+$, $\mathbf{56}$, $L = 2^+$, and perhaps some others.

In general, the spectrum looks like the solution of a wave equation with a rather simple "potential." For example, for the mesons, the situation for M^2 resembles that of the energy in a three-dimensional harmonic oscillator with perturbations giving spin-orbit splitting, octet-singlet splitting for the spin singlet, and simple SU(3) breaking. The harmonic oscillator would give trajectories with J exactly linear in M^2.

Now what is going on? What are these quarks? It is possible that real quarks exist, but if so they have a high threshold for copious production, many BeV; if this threshold comes from their rest mass, they must be very heavy and it is hard to see how deeply bound states of such heavy real quarks could look like $q\bar{q}$, say, rather than a terrible mixture of $q\bar{q}$, $qq\bar{q}\bar{q}$, and so on. Even if there are light real quarks, and the threshold comes from a very high barrier, the idea that mesons and baryons are made primarily of quarks is difficult to believe, since we know that, in the sense of dispersion theory, they are mostly, if not entirely, made up out of one another. The probability that a meson consists of a real quark pair rather than two mesons or a baryon and antibaryon must be quite small. Thus it seems to me that whether or not real quarks exist, the q and $\bar{q}$ we have been talking about are mathematical; in particular, I would guess that they are mathematical entities that arise when we construct representations of current algebra, which we shall discuss later on. Their effective masses, to the extent that these have meaning, seem to be of the order of one-third the nucleon mass. One may think of mathematical quarks as the limit of real light quarks confined by a barrier, as the barrier goes to an infinitely high one.

If the mesons and baryons are made of mathematical quarks, then the quark model may perfectly well be compatible with the bootstrap hypothesis, that hadrons are made up out of one another.

Experimentally, it is a very interesting question whether all reasonably well-defined excited meson and baryon states fit in with the $\bar{q}q$ and qqq assignments, which allow only nonets for the mesons and only 1, 8, and 10 representations of SU(3) for the baryons, or whether there are resonances that must be assigned to higher configurations, like $\bar{q}q\bar{q}q$ or $qqqq\bar{q}$. If the latter is the case, then we must find resonances with exotic I and Y values. It will be interesting to find out how the evidence for such states stands at present. This matter, although important, is, of course, not absolutely fundamental, since we know that continua with such quantum numbers exist, and it is a dynamical question whether or not well-defined resonances are found.

The quark model, if correctly interpreted, should give information not only about the hadron spectrum, but also about the strong coupling constants or, more generally, the couplings of pairs of particles to trajectories. Some successes have been achieved by the so-called $[U(6)]_W$ symmetry, and it is to be hoped that the relation of this approximate symmetry to the quark model and to current algebra will soon be much better understood. A striking success in interpreting high-energy scattering data comes from a very simple assumption of symmetry and universality of meson and baryon couplings to the highest meson Regge poles, including the "Pomeranchuk pole" that governs diffraction scattering. This assumption amounts merely to "quark counting," and in its most primitive form says that total meson-baryon and baryon-baryon cross sections are in the ratio 2:3, since the meson is made of two quarks and the baryon of three. It will be fascinating to see how well the various relations work that have come out of "quark counting." I should say that one can apply this method to the high energy data even if the Regge pole hypothesis should collapse.

Now we have spoken of the relations of current algebra and I should like to go on now to discuss them, as well as other sets of presumably exact relations (to all orders in the strong interaction) that we use as theoretical tools in describing the hadrons. Let us start with the new superconvergence relations, which I hope will be presented to the Conference, the work of Fubini and collaborators. These pertain to hadron scattering amplitudes without currents.

Consider a hadron scattering amplitude $A(s,t)$, without kinematic singularities and involving Δ units of helicity flip. We have seen in Eq. 1 and the discussion following that the asymptotic behavior of $A(s,t)$ is (at $t = 0$ and, in the worst case of cuts, for $t \leq 0$) $s^{\alpha(0)-\Delta}$, where α is the leading exchanged trajectory. (Even if not derived theoretically, such power laws can be simply taken from experiment.) Take, for convenience, an amplitude for which $\mathrm{Re}\,A(\nu)$ is odd in $\nu \equiv s-u$. If $\alpha(0) - \Delta < 1$ (and it is always ≤ 1), then such an amplitude obeys an unsubtracted dispersion relation in ν for fixed t:

$$A(\nu) = \frac{2\nu}{\pi} \int d\nu' \frac{\mathrm{Im}\,A(\nu')}{\nu'^2 - \nu^2 - i\epsilon} . \qquad (2)$$

Now suppose $\alpha(0) - \Delta < -1$; we get an additional sum rule or "superconvergence relation",

$$\int d\nu' \, \mathrm{Im}\,A(\nu') = 0. \qquad (3)$$

To take a concrete example, consider nucleon-antinucleon exchange scattering, so that objects like the deuteron are exchanged. In these two-baryon channels, the trajectories must lie very low; moreover, in the nucleon-antinucleon system we can get Δ as high as 2. Thus there are numerous superconvergence rules like Eq. 2. They express exactly the kind of physics that one attempted to express 25 years ago by saying that there must be several mesons, giving nucleon-nucleon forces with cancelling singularities, so that the deuteron would have a binding energy that is finite and even small. Approximating all the $A = 0$ states by discrete mesons M, Eq. 3 describes such a cancellation,

$$\sum_M g^2_{NNM} f(m_N^2, m_M^2) = 0, \qquad (4)$$

where f is a kinematic function.

Now this approximation of integration over complicated continua by summation over resonant states is our most powerful method of approximation in hadron physics. Very difficult problems in analytic functions of several variables are replaced by algebraic problems. It is a challenge at present to algebraize, in a systematic way, all the superconvergence relations for hadrons and then to try to find representations of the resulting algebraic system in terms of discrete meson and baryon states.

Meanwhile, one adopts the temporary expedient of a much more drastic approximation, which involves not only converting the integrals into sums, but also making these finite sums with a small number of terms. In this way one gets interesting but less reliable formulae; for example, in π-ρ scattering there is a superconvergence relation that can be drastically approximated as

$$g^2_{\pi\rho\omega}(m_\omega^2 - m_\rho^2 - m_\pi^2) + g^2_{\pi\rho\phi}(m_\phi^2 - m_\rho^2 - m_\pi^2) + \cdots = 0. \qquad (5)$$

This is amusing, because experimentally $m_\omega^2 - m_\rho^2 - m_\pi^2$ is nearly zero in the first term, while $g^2_{\pi\rho\phi}$ is nearly zero in the second.

Many of the approximate relations among the hadron couplings and masses that have been found in investigations of the bootstrap hypothesis come directly out of this kind of truncation applied to the superconvergence relations.

For the other kinds of relations, we need the weak and electromagnetic currents, local operators that are sandwiched between states of hadrons on the mass shell to give matrix elements for photon emission and absorption and form factors for weak or electromagnetic interaction with lepton pairs.

We can obtain a direct analog of the superconvergence relations by replacing one of the incoming or outgoing particles in a two-body scattering amplitude by a current. The resulting relations can be approximated much as in Eq. 4, giving us, for example,

$$\sum_M g_{\gamma\pi M}\, g_{\pi\pi M}\, \phi(m_\pi^2, m_M^2) = 0 \qquad (6)$$

for the photopion effect on pions.

Now let us go further and replace two of the four vertices by currents. Then we no longer have superconvergent dispersion relations, and the right-hand side of our equation is no longer zero. Instead, we pick up, on the right-hand side, a matrix element of the equal-time commutator of the two currents. Now we are talking about the relations of current algebra.

The assumptions of current algebra can be arranged in a hierarchy of credibility. We start with the most believable one and then add further assumptions. The charge operators $F_i = \int \mathcal{F}_{i0}\, d^3x$ of the vector currents $\mathcal{F}_{i\alpha}$ $(i = 0, 1, \cdots 8)$ of hadrons occurring in the electromagnetic and weak interactions are assumed to obey the equal-time commutation rules of the algebra of U(3):

$$[F_i, F_j] = i f_{ijk} F_k. \quad (7)$$

Here, F_0 is proportional to the baryon number; F_1, F_2, and F_3 are the components of the isotopic spin; F_8 is proportional to the hypercharge Y, related to strangeness; and F_4, F_5, F_6, and F_7 have $|\Delta Y| = 1$ and $|\Delta I| = 1/2$ and are not conserved by the strong interaction, hence time-dependent. We may then treat also the axial vector currents $\mathcal{F}_{i\alpha}^5$ ($i = 0, 1, \cdots 8$) of hadrons occurring in the weak interaction and suppose that they form an octet and singlet under the algebra of the F_i, so that their charges $F_i^5 = \int \mathcal{F}_{i0}^5 d^3x$ satisfy

$$[F_i, F_j^5] = i f_{ijk} F_k^5. \quad (8)$$

Then we can assume that the algebra of the F_i and F_i^5 closes in the simplest possible way to form the algebra of U(3)×U(3):

$$[F_i^5, F_j^5] = i f_{ijk} F_k. \quad (9)$$

Finally, we know from microcausality that the charge densities $\mathcal{F}_{i0}(\underset{\sim}{x})$, $\mathcal{F}_{i0}^5(\underset{\sim}{x})$ must commute with each other at nonvanishing spatial separations, so that we have such relations as

$$[\mathcal{F}_{i0}(\underset{\sim}{x}), \mathcal{F}_{j0}(\underset{\sim}{x}')] = i f_{ijk} \mathcal{F}_{k0}(\underset{\sim}{x})\, \delta(\underset{\sim}{x} - \underset{\sim}{x}') + \text{gradient terms},$$

where the gradient terms involve a finite number of derivatives of δ functions and integrate to zero. We may assume that these gradient terms vanish and obtain the "local current algebra" at equal times:

$$\begin{aligned}
[\mathcal{F}_{i0}(\underset{\sim}{x}), \mathcal{F}_{j0}(\underset{\sim}{x}')] &= i f_{ijk} \mathcal{F}_{k0}\, \delta(\underset{\sim}{x} - \underset{\sim}{x}'), \\
[\mathcal{F}_{i0}(\underset{\sim}{x}), \mathcal{F}_{j0}^5(\underset{\sim}{x}')] &= i f_{ijk} \mathcal{F}_{k0}^5\, \delta(\underset{\sim}{x} - \underset{\sim}{x}'), \qquad (10) \\
[\mathcal{F}_{i0}^5(\underset{\sim}{x}), \mathcal{F}_{j0}^5(\underset{\sim}{x}')] &= i f_{ijk} \mathcal{F}_{k0}\, \delta(\underset{\sim}{x} - \underset{\sim}{x}').
\end{aligned}$$

That these equal-time relations do not contradict the principles of relativistic quantum mechanics, no matter how badly approximate symmetries are broken, we can see by constructing a formal mathematical Lagrangian field theory with coupled "quark fields" q (or u, d, and s) and seeing that these relations are true in such a theory; the theory may then be thrown away and the commutation relations retained. Such a formal quark-field approach can be used also to exhibit the universality of strength and form of the weak interaction.

In the limit of zero range for the weak interaction (and we have not yet detected a finite range) it appears to have the form

$$\frac{G}{\sqrt{2}} (J_\alpha^{tot})^+ J_\alpha^{tot},$$

where G is the universal Fermi constant and

$$J_\alpha^{tot} = \bar{\nu}_e \gamma_\alpha (1 + \gamma_5) e + \bar{\nu}_\mu \gamma_\alpha (1 + \gamma_5) \mu^- + J_\alpha. \quad (11)$$

Here, J_α is the hadronic part of the weak current and, in the formal quark field picture, corresponds to a term just like the first two terms above,

$$\bar{u} \gamma_\alpha (1 + \gamma_5)(d \cos\theta + s \sin\theta), \quad (12)$$

where θ is the curious angle between the strangeness-preserving and strangeness-changing weak couplings of hadrons, and has a value around 15°. The currents $\mathcal{F}_{i\alpha}$ and $\mathcal{F}_{i\alpha}^5$ correspond formally to $\bar{q}(\lambda_i/2)\gamma_\alpha q$ and $\bar{q}(\lambda_i/2)\gamma_\alpha\gamma_5 q$ respectively, where the λ_i are 3×3 isotopic matrices such that $\lambda_i/2$ represents the algebra of U(3).

Now let us return to the applications of current algebra, as exhibited in Eq. 10. Serious applications have been delayed from 1961, when the relations were proposed, until 1965, when the trick was suggested of sandwiching the relations between hadron states of infinite momentum (say, P_z equal to a fixed value that goes to infinity, with P_x and P_y finite). The state of motion of the hadron states on both sides of the operator relations is relativistically meaningful, since we have already fixed a Lorentz frame by talking about equal-time commutation relations as a way of presenting relations between operators at points spacelike to each other. Thus, equal-time commutators between states with $P_z = \infty$ are a covariant notion, and can be made "manifestly covariant" if we wish. As a general technique, working at $P_z = \infty$ is very useful. Thus the method of doing relativistic calculations prevalent before the Rochester Conferences were started (taken from Heitler's book, for example) becomes very similar to the method of Feynman diagrams. Running by a system at velocity c, we can no longer tell the difference between Heitler and Feynman. Likewise, we cannot distinguish Low from Goldberger, since the Low equations at $P_z = \infty$ are essentially the dispersion relations.

From local current algebra at $P_z = \infty$, we get, as we said earlier, sum rules that can be written in a manner resembling Eqs. 3, 4, 5, and 6, but with two vertices of the four-legged diagram corresponding to currents and with a right-hand side given by the matrix element of the equal-time commutator. We get equations such as

$$\int d\nu' [\operatorname{Im} A_{ij}(\nu', t, k_1^2, k_2^2) - \operatorname{Im} A_{ji}(\nu', t, k_1^2, k_2^2)] = i f_{ijk} F_k(t), \quad (13)$$

where ν' is, as before, a relativistic energy variable, t is the invariant momentum transfer variable between the initial and final currents, and k_1^2 and k_2^2 are the invariant momentum transfers squared for the initial and final currents respectively. On the right-hand side, we have a form factor for the current that appears on the right-hand side of the equal-time commutator.

Suppose that in Eq. 13 we are dealing with a commutator between vector charge densities. Then the left-hand side will have poles at $k_1^2 = -\mu^2$ and $k_2^2 = -\mu^2$, where μ is the mass of a vector meson. The right-hand side has no such poles. Thus if we look at the coefficient of the compound pole at $k_1^2 = -\mu^2$ and $k_2^2 = -\mu^2$, we recover a superconvergence relation like Eq. 3 for the scattering of a vector meson. If we look at the coefficient of a single pole, say at $k_1^2 = -\mu^2$, we recover a relation like Eq. 6 describing the superconvergence of an amplitude in which an electromagnetic current produces a vector meson.

The new predictions of current algebra are those in which the right-hand side plays a role. For example, we may take the first moment in t of a relation of the type Eq. 13 obtained by sandwiching the commutators between nucleon states and obtain, for $k_1^2 = k_2^2 = 0$, the formula

$$(\mu_A^V)^2 + 1/2\pi^2\alpha \int ds'/(s' - m_N^2) \times [2\sigma_{1/2}^V(s') - \sigma_{3/2}^V(s')] = \langle r^2 \rangle_1^V/3, \quad (14)$$

where μ_A^V is the isovector anomalous moment of the nucleon, σ_I^V is the total photonucleon cross section for isovector photons going into hadrons with isotopic spin I, and $\langle r^2 \rangle_1^V$ is the mean-square radius corresponding to the isovector Dirac form factor F_1^V of the nucleon. The comparison of this relation with experiment suggests fair agreement, but much more information is needed on the amplitudes for the photoeffect above $s = (1.5 \text{ BeV})^2$.

Using the commutator of two axial-vector charge densities at $k_1^2 = 0$, $k_2^2 = 0$, and $t = 0$, we have the Adler-Weisberger relation

$$\left(\frac{G_A}{G_V}\right)^2 + \int ds' \phi(s')[\sigma(\nu \to e^-, s') - \sigma(\bar{\nu} \to e^+, s')] = 1 , \quad (15)$$

where G_A is the axial vector coupling constant of the nucleon and G_V the vector coupling constant, $\phi(s')$ is a known kinematical function, and the cross sections are for the sum of all processes in which the lepton comes out with zero momentum transfer when a neutrino or antineutrino strikes a proton.

This relation cannot be tested by observation until we have much better data on neutrino-induced reactions,but a trick can be used to obtain still another kind of sum rule, this time an approximate one. We make the so-called "PCAC approximation," that the matrix elements of the divergence of the isovector axial vector current at $k^2 = 0$ are given roughly by the contribution of the one-pion pole at $k^2 = m_\pi^2$. Combining PCAC with the sum rule Eq. 15 we get a rule that is verifiable by experiment:

$$\left(\frac{G_A}{G_V}\right)^2 + \int ds' \psi(s')[\sigma_{\pi^- p}(s') - \sigma_{\pi^+ p}(s')] = 1, \quad (16)$$

where ψ is another known kinematic function inversely proportional to the pion decay rate into leptons and the σ's are total π-N cross sections. This rule works well; an optimist would say it verifies the algebra and the PCAC approximation, while a pessimist could say that both principles are in error but the errors cancel.

Current algebra and PCAC have been applied with some success also to leptonic weak decays, for example relating $K \to \pi$ + leptons to $K \to 2\pi$ + leptons. The method is also capable of giving some information about strong amplitudes such as π-π scattering lengths, as we shall probably hear at this meeting.

Still another twist has been given to current algebra sum rules in a contribution to the Conference that discusses matrix elements of commutators between vacuum and two-particle states, rather than between one-particle states. Sum rules emerge that resemble Eq. 13, but with the integration in the left-hand side performed (for example) on $k_1^2 + k_2^2$, with $k_1^2 - k_2^2$, ν, and t fixed. From the assumed convergence of such rules one can, by looking at the coefficients of particle poles, extract superconvergence relations for form factors. Now, high-energy electron scattering experiments have suggested that certain electromagnetic form factors, like $F_2^V(t)$ for the nucleon isovector anomalous magnetic moment, tend to zero faster than $1/t$, so that in the unsubtracted dispersion relation

$$F_2^V(t) = \frac{1}{\pi} \int \frac{dt'}{t' - t - i\epsilon} \, \text{Im} \, F_2^V(t') \quad (17)$$

we have

$$\int dt' \, \text{Im} \, F_2^V(t') = 0. \quad (18)$$

Now we have some theoretical support for such a form factor superconvergence relation. By the way, this Conference should tell us some new experimental results on the nucleon form factors at very large t.

Before leaving the subject of current algebra, let me say that it is tempting to try two theoretical constructions based on such an algebra. One is to write down a set of densities, including the vector and axial vector charge densities, with known equal-time commutation rules and to try to express the total hadronic stress-energy-momentum tensor $\theta_{\mu\nu}$ (the lowest order coupling to gravity) in terms of such currents. Since the integrals $P_\mu = \int \theta_{\mu 0} d^3x$ give the space and time displacement operators (momentum and energy), such a formulation would give "equations of motion" that would completely describe the hadron system. Such a program might possibly be successful, with a relatively simple form for $\theta_{\mu\nu}$, and might even be equivalent to the bootstrap theory.

A less ambitious but more immediate objective is to try to approximate the systems of well-defined baryon and meson levels (idealized to an infinite set of sharp levels going up to infinite energy) as small relativistic representations of the algebra of V and A charge densities at $P_z = \infty$, small in the sense that the huge number of variables of relativistic quantum mechanics would be replaced approximately by a few, for example two spins, a relative coordinate, and two isotopic spins to describe the meson levels. In this way it might be possible to arrive at a relativistic quark model, with a mathematical $\bar{q}q$ description of the meson levels. Now we have lingered long enough on current algebra.

The most exciting topic, of course, is the chapter that was opened two years ago at the Conference in Dubna with the report by Fitch, Cronin, Christensen, and Turlay of CP violation. That chapter is one that is only begun, no doubt. More experiments have confirmed the original result; more investigations have taken place to study the same effect, which is K_2^0 decay into two pions. There are only two more parameters really to be gotten out of that, the phase and the ratio of the $2\pi^0$ to the $\pi^+ + \pi^-$ mode. Some progress has been made with each of those but they're not finished yet. In the meantime, the possible implications for all other kinds of experiments are discussed in some very interesting work; the three hypotheses that are most popular are the following.

One is the "super-weak coupling," that is, a new CP-violating interaction with $|\Delta Y| = 2$, very, very weak (like weak interactions squared), and exploiting the tiny mass difference between K_1^0 and K_2^0 to give the Fitch-Cronin effect. That's my favorite hypothesis because it predicts no new observable effects at all, given present technology. In the Fitch-Cronin effect, it does predict the phase of the K_2^0 into 2π and the charge ratio, but it means that in other processes one is extremely unlikely, for a long time, to see any effects because it's hard to find another process with such a tiny energy denominator of 10^{-5} electron volt, that could show up the super-weak interaction.

Another possibility is that the CP-violating force is 10^{-2} or 10^{-3} of the weak interaction (or comparable to the weak interaction with some inefficiency factor) and gives the effect directly. With this kind of theory, one should certainly expect to see a number of other consequences. In particular, one should find a nonzero value of the neutron electric dipole moment, which has been measured down to the level of weak interactions already and is going to be measured, they say, far more accurately during the next few months or years, using walking neutrons from Oak Ridge or Brookhaven, or perhaps elsewhere.

The third kind of theory is of a totally different nature, saying that the interaction is 10^{-2} or 10^{-3} of the strong interaction, is just C-violating, and combines with the P-violating weak interaction to give the effect. Now,in this case, the experimental implications, of course, are tremendous. Since the strength is 10^{-2} or 10^{-3}, why, you can look for the new force anyplace; you can see it behind every shutter. In particular, when there is a process like η decay, which occurs only through electromagnetism, then competing decay through the new thing will be of a similar order of magnitude and you can look for considerable asymmetry. We can look forward to some enjoyable arguments during this meeting, over whether, in fact, an η-decay asymmetry has been found. I don't know if it will reach the height of comedy achieved in Siena two years ago, but it may be pretty good. Perhaps after a few months we will really know whether there is any asymmetry or not.

If the third explanation should be right, then one can think of the possibility, particularly emphasized by Lee and collaborators, that the new interaction is in fact simply electromagnetic and corresponds to the existence of an electromagnetic current with two terms in it, the ordinary term with C = -1 (where C is the strong charge conjugation) and another unusual term with C = +1. Now, such a theory poses a very difficult dilemma. If the new current has no charge--in other words, if the charge operator for the C = +1 part of the current is zero--then the current doesn't follow the charge in its quantum numbers. But we tend to expect that it should, from Ampère's law that the currents consist completely of the motion of charges. We would at least expect that quantum numbers of the currents should follow the quantum numbers of the charge, what I have sometimes called the idea of minimal electromagnetic interaction. Now, this would be completely wrong, if the new current exists and has a charge operator which is zero. An alternative possibility is that the C = +1 charge is not zero. Then there must exist some entirely new charged particle, for example something called $\kappa+$, which is taken into itself by C. Of course CPT still takes $\kappa+$ into $\kappa-$, so you do have a $\kappa-$ particle, but nevertheless C takes $\kappa+$ into itself. Well, that's also extremely interesting, if there exists an entirely new class of strongly interacting particles which are charged but are taken into themselves by strong charge conjugation. That would be as exciting as the violation of minimum electromagnetic interactions.

What I'm really looking forward to hearing at this meeting is the theoretical proposal of a new hypothetical particle that is a triplet with respect to SU(3) like the quark, is an intermediate boson for the weak interactions,is carried into itself by C although charged, obeys parastatistics and has a single magnetic pole. For this particle I suggest the name "chimeron," and I look forward not only to hearing it proposed but also to hearing its existence partially confirmed.

In the meantime the old questions are still with us. Is quantum electrodynamics violated a little bit before we get to the level of the hadron vacuum polarization which we know must be there? Some experimental evidence, I think, will be discussed here and we'll have to see whether there is any good evidence for violation at present or not. What about the weak interaction? The current-current picture for the weak interaction works extremely well. In fact, by combining that picture with current commutation rules and PCAC, theorists have made a lot of progress in relating the different weak decays to each other. This is true of the leptonic weak decays, where decays with no pions, one pion, two pions, and so on, have been related to each other. It is also true, even more strikingly, of the nonleptonic weak decays in which $K_1^0 \to 2\pi$ and $K \to 3\pi$ have been related to each other, and the baryon decays $\Lambda \to N + \pi$, $\Sigma \to N + \pi$, and $\Xi \to \Lambda + \pi$ have been related to each other. The latter is good only for S waves, I might say for the benefit of my theoretical friends; the P wave still resists explanation to some extent. Still, the current-current picture looks good. Another question that has been around for a long time, about 12 years, concerns the $\Delta I = 1/2$ rule or what may now be called octet dominance for the nonleptonic weak interaction. Is it really just a dynamical enhancement or does it come from some basic interaction which has to be added to the charged current times its Hermitian conjugate? In other words, is there an extra current peculiar to hadrons, that makes the $|\Delta I| = 1/2$ rule true by symmetry, or is it simply that the formula $J_\alpha^+ J_\alpha$ is right and that the $\Delta I = 1/2$ rule comes from a dynamical enhancement of the octet part of $J_\alpha^+ J_\alpha$? I would say that a lot of the recent theoretical work indicates that the dynamical enhancement idea may be right, but the issue is by no means settled.

How about the structure of the weak interaction itself, though? Assuming the current-current form is right, what's the range of the interaction? Is there an intermediate boson that's responsible for the exchange? Nobody knows. How do we do calculations in higher order in the weak interaction? Nobody really knows yet. And then there is a still deeper question to which nobody has any answer at all. Why are there hadrons and leptons, strongly interacting particles and particles with no strong interactions? Why are there the gravitational, electromagnetic, and weak interactions? Why is there this funny lepton spectrum with the e and the μ, and the symmetry between the two, and the two neutrinos? As Rabi once asked, "Who ordered that?" My colleague Feynman for many years had on his blackboard in a little box the question "Why does the muon weigh?" It's been erased. Why is there the funny angle that we spoke of before, the Cabibbo angle, between the strangeness-changing and the strangeness-preserving currents? Nobody knows. I think that it's not discouraging, but rather that it's marvelous not to know all of these fundamental things. We still have problems to work on. Thank you.