THE THEORY OF WEAK INTERACTION

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The topic of this report is the present state of the theory of universal weak interaction. This topic has been discussed in about 300 papers that have appeared since January 1, 1961, or that have been submitted to the conference in the form of preprints.

It is obviously impossible to speak about these papers in one hour. Neither does it appear proper to deal with some of them and entirely disregard the others. To resolve this dilemma, I have appended a detailed bibliography. This will permit me, in this report, to confine myself to a consideration of separate problems.

I. WHAT IS A UNIVERSAL INTERACTION?

A universal interaction is the gravitational interaction, which is the same for all particles. Electromagnetic interaction is apparently universal. At any rate, the electric charges of all charged particles are equal. But already in electrodynamics we encounter a deviation from universality in the form of the anomalous magnetic moments of baryons.

Everything that we know about weak interaction indicates, without doubt, that it is universal in character. The various processes due to this interaction are C and P non-invariant, but conserve combined parity. All leptons participate in weak interaction as two-component particles. Various slow processes are characterized by comparable—and in a number of cases even identical (up to within a good accuracy)—constants.

However, the universality of the weak interaction is expressed in a less clear-cut fashion than that of electrodynamics. To prove the universality of weak interaction, it is necessary to get over the impassable swamp of strong interaction. So far, not a single theoretician has been able to do this.

Notwithstanding the fact that this report deals with weak interactions, we shall frequently have to speak of strongly interacting particles. These particles pose not only numerous scientific problems, but also a terminological problem. The point is that " strongly interacting particles " is a very clumsy term which does not yield itself to the formation of an adjective. For this reason, to take but one instance, decays into strongly interacting particles are called non-leptonic. This definition is not exact because " non-leptonic " may also signify " photonic ". In this report, I shall call strongly interacting particles *hadrons*, and the corresponding decays *hadronic* (the Greek ἀδρός signifies " large ", " massive ", in contrast to λεπτός which means " small ", " light "). I hope that this terminology will prove to be convenient.

When reasoning about the universality of the weak interaction, one usually says: " Let us presume that the strong interaction is switched off... ". The first step in this direction was apparently taken by Gell-Mann when he postulated that if the strong interaction is " switched off ", the electromagnetic interaction of the particles will be completely described by their charges (principle of minimal electromagnetic interaction).

Since that time, the switching on and off of the interactions has become a very common occupation. Any theoretician can switch off any strong interaction of whatever strength or, at the worst, several undesirable mesons, all the while paying no attention whatsoever to nature. Nature, naturally, responds in the same fashion. It is quite obvious that we all realize how unsatisfactory these manipulations are and we are convinced that there is in nature a profound relationship between all known interactions. However, as long as this relationship remains unestablished, and as long as we are unable to calculate such quantities as the electric charge e or the constant of weak interaction G, and introduce them into the theory from outside, we shall apparently not be able to dispense with " switching on and off " and with minimal principles.

It is ordinarily taken for granted that when switching off strong interaction, all known hadrons (such as, for instance, the π meson or the Σ hyperon) do not cease to exist. However, especially now, when we have such a large number of resonances, it is obvious that there are no grounds for such a presumption.

The minimal principle, the formulation of which I shall now take up, is based on the assumption that if the strong interaction is switched off, then we will have only three fields in place of a multiplicity of hadrons. These fields may, for instance, be visualized as p, n, Λ—the fundamental particles of the Sakata model. The selection of three baryon fields is minimal if we require that, having switched on the strong interaction, all the quantum numbers describing the hadrons are, in principle, obtained.

The principle of the minimal electromagnetic interaction may now be formulated as follows: all electromagnetic interactions of hadrons are due to the interaction of the proton charge with the photon field.

Similarly, we can formulate the principle of the minimal weak interaction: all weak interactions of hadrons are due to the weak interaction of three initial fields.

In accordance with this principle and with the theory of universal V-A interaction, we write the Lagrangian of weak interaction as

$$\mathscr{L} = \frac{G}{\sqrt{2}} j j^{+}$$

where the current j is the sum of four currents: electronic $j_e = \bar{e}Ov$, muonic $j_\mu = \bar{\mu}Ov$, nucleonic $j_n = \bar{n}Op$ and strange $j_\Lambda = \bar{\Lambda}Op$. The operator $O = \gamma_\alpha(1+\gamma_5)$.

We shall not at present dwell on the question of the possibility of this Lagrangian being non-local. We shall simply note that if there exist intermediate vector bosons W, the interaction of the currents may be represented by the following scheme:

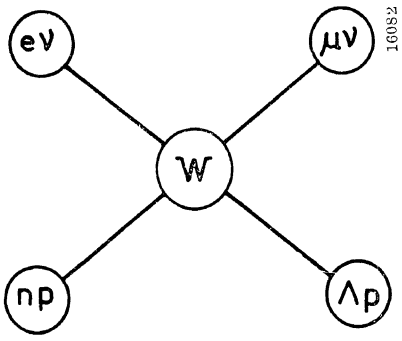

Fig. 1

Such weak interaction is universal since it has the same constant and is of the same form for different particles.

We have thus formulated the universality of the weak interaction. We did it in the old way, in terms of the Lagrangian. To do this at the present time is almost indecent. However, to speak seriously, it has not been proved that the four-fermion Lagrangian is indeed hopelessly bad. And so far no one has succeeded in formulating the universality of the weak interaction differently. (It may be noted that without the hypothesis about a universal bare Lagrangian, it is even impossible to formulate the problem of radiative corrections to the rate of muon decay.)

The universal theory about which I am speaking and which I shall from now on call " minimal model ", is in no way connected with the idea that certain elementary particles are more fundamental than others. As for the fundamental fields in this model they can be, not the Sakata particles p, n, Λ, but three other baryonic fields, for instance Ξ^-, Ξ^0, Λ, or three fields to which there corresponds no physical baryons: an isodoublet A and B and an isosinglet C (provided that the charges of B and C are the same).

All the corollaries of the theory remain in this case unaltered.

It is necessary to stress this because very frequently the question of the very existence of fundamental fields is confused with the question of which of the physical particles are more fundamental. Feynman recently postulated a principle according to which the latter question can never be answered. I do not think that we shall soon find out whether this principle is correct, but it is obvious that the minimal model does not contradict it.

But then maybe the minimal model is altogether without content? Maybe we would obtain the same results if we assumed that there exist not 3 but 5 fundamental fields, for example, p, n, Σ^+, Σ^0, Σ^-. It is easy to see that this is not so. If we considered all five fields *on an equal basis*, without imposing, *ad hoc*, additional symmetries and selection rules, we would straight away obtain, for instance, such a weak current as $\overline{\Sigma^+}n$, for which $\Delta Q = -\Delta S$ and which is forbidden in the minimal model. The list of such instances can be readily extended.

To summarize: the minimal model may be verified by experiments and rejected if experiments do not

corroborate its predictions. Conversely, confirmation of all corollaries of the model will indicate the correctness of the formulation of the universality given above. The minimal model scheme of the weak interaction will serve me as a basis for presenting and discussing the variety of papers dealing with the weak interaction theory. I shall try not to turn it into a Procrustean bed.

II. LEPTONIC CURRENTS

Conversion of the pair $\bar{\mu}\nu$ into the pair $(\bar{\nu}e)$ yields (in accordance with the scheme of Fig. 1) the decay $\mu\to e+\nu+\bar{\nu}$. But this normal process has long since ceased to interest the theoreticians. What they were interested in is the question of why the neutrino and the antineutrino produced in this process cannot annihilate virtually and lead to processes that are forbidden by experiment:

1. $\mu\to e+\gamma$
2. $\mu\to 3e$
3. $\mu\to e+2\gamma$
4. $\mu^+ + e^-\to 2\gamma$
5. $\mu^- + Z\to e^- + Z$.

The calculations of such processes, both in the model with W-mesons and with the four-fermion interaction in higher order approximations, were—on the whole—completed as early as in 1960 and were submitted at the last Rochester Conference. Subsequent theoretical investigation of these questions did not alter the basic conclusion: the absence of neutrinoless μ-e transitions appears very strange if the electronic and the muonic neutrinos are identical. Now the Brookhaven experiment (Danby *et al*) has confirmed this conclusion.

At present, a large number of possible schemes are under discussion, in which neutrinoless μ-e transitions are forbidden. I believe the most attractive scheme is the one proposed in 1959 by Lipmanov. In this scheme, e^-, μ^+, ν are leptons, while e^+, μ^-, $\bar{\nu}$ are anti-leptons and neutrinoless μ-e transitions are forbidden by conservation of the leptonic charge. In this scheme the ordinary decay of a muon occurs with the emission of two ν's (and not ν and $\bar{\nu}$). According to Lipmanov, the neutrino, like the other fermions, is a four-component particle. Two of its components (the left-handed ones) enter into the electronic bracket, and the two right-handed ones in the muonic bracket; the leptonic current has the form

$$\bar{\nu}\gamma_\alpha(1+\gamma_5)e^- + \overline{\mu^+}\gamma_\alpha(1-\gamma_5)\nu$$

The attractive feature of this scheme is its economy: a separate muonic charge is not introduced, and use is made of all four components of the neutrino wave function.

If the neutrino mass is different from zero, this scheme should exhibit a transition of electronic components of the neutrino into muonic ones so that e.g. the neutrinos produced in the decay $\pi^-\to\mu^-+\nu$ could give rise to the reaction $\nu+n\to e^-+p$. Another example: the decay $K^+\to\pi^-+e^++\mu^+$ which would be possible in higher order approximations of the weak interactions. But due to the small neutrino mass (we know that $m_{\nu_e} < 200$ eV), these effects would be exceedingly small.

Unfortunately, for a massless neutrino one cannot contemplate experiments that would be capable of distinguishing the Lipmanov scheme from the ordinary one in which a muon and muonic neutrino have a conserved " muonic charge ", while the leptonic charge $+1$ is possessed by e^-, ν_e, μ^-, ν_μ, and both ν_μ and ν_e are left-polarized. But I think that Lipmanov's scheme may be of heuristic value. I hope that, in due time, we will know regarding the leptonic charge, not only that it is conserved, but also something else, something more dynamic; and then the question as to which particles are leptons and which are anti-leptons will in no way be immaterial.

As early as at the Kiev Conference, Marshak noted that the Lipmanov scheme contradicts the Kiev symmetry ($\Lambda\leftrightarrow\mu^-$, $p\leftrightarrow\nu$, $n\leftrightarrow e^-$). There are several attempts to preserve a sort of lepton-baryon symmetry (Nakamura and Sato, Maki, Iso). Iso, particularly, attempted to bring this scheme into agreement with a symmetry of the form $\Lambda\leftrightarrow\mu^+$, $n\leftrightarrow e^-$, $p\leftrightarrow\nu$. Unfortunately, the current

$$\bar{p}\gamma_\alpha(1+\gamma_5)n + \bar{p}\gamma_\alpha(1-\gamma_5)\Lambda$$

does not satisfy this new symmetry, while the following

$$\bar{p}\gamma_\alpha(1+\gamma_5)n + \bar{\Lambda}\gamma_\alpha(1-\gamma_5)p$$

leads to non-conservation of the electric charge. But are such simple symmetries between leptons and baryons necessary?

Let us now take another point of view, according to which there is such a conserved quantity as the muonic charge, which is equal to $+1$ for μ and ν_μ and is equal to zero for other particles. In this case it is natural to expect that the muonic neutrino will possess properties quite unlike those of the electronic neutrino. Thus, for example, it can possess mass. (The present upper limit for the mass of a muonic neutrino is ≈ 3 MeV.) Furthermore, the muonic neutrino can possess some kind of anomalous interaction. This possibility is particularly probable if it turns out that the muon has an anomalous interaction, which is absent in the case of the electron. The anomalous interaction of the muon could lead to a violation of the universality of weak interaction, due to the " anomalous " renormalization of the wave function of the muon. But universality is practically not violated if not only the muon, but also the muonic neutrino possess an anomalous interaction. In this case, renormalization of the wave functions of the muon and neutrino is nearly compensated for by renormalization of the vertex part of the weak interaction. This result has a simple physical interpretation. In the former case, the muon, having emitted a virtual quantum of the " anomalous " field, cannot decay because there is no body to absorb this quantum. This leads to a reduction in the probability of muon decay. In the latter case, decay can occur because the " anomalous " quantum can be absorbed by the muonic neutrino.

The limit for the magnitude and radius of the anomalous interaction of the muon (which limit follows from experiments on $g-2$, and the scattering of muons by nuclei) yields an upper bound for the cross-section of the anomalous scattering of a neutrino of energy of the order of GeV by a nucleon of roughly 10^{-31} cm^2. A special experiment performed at Dubna (Vasilevsky *et al.*) yielded roughly 10^{-32} cm^2 for the upper bound of this cross-section. As Pontecorvo and Chudakov have noted, the data obtained recently by Miyaka *et al.*, studying penetrating radiation at great depths, give an upper bound of approximately 10^{-34} cm^2 for this cross-section. According to Schwartz, the neutrino experiment at Brookhaven gives an upper limit for a possible anomalous interaction of neutrinos with nucleons of the order of 10^{-38} cm^2. So it seems that the muonic neutrino does not possess an anomalous interaction with nucleons. This may be a serious argument in favour of the absence of an anomalous nucleon-muon interaction. It is worthwhile to mention that the upper limit for the anomalous $(\nu\mu)(\nu\mu)$-interaction is much weaker now and that the corresponding experiments are of great interest. I shall not dwell upon other ideas connected with the question of two neutrinos, such as the multiplicative muonic quantum number (Feinberg and Weinberg), or the neutrino flip (Feinberg, Gürsey and Pais), or the hypothesis by von Dardel and Ghani that there exist four (or even six) different types of neutrinos.

In addition to the problem of two neutrinos, leptonic currents confront us with at least two other extremely important problems. Firstly, the question of the existence of neutrino scattering on electron (and muon). Secondly, the question of the existence of neutral leptonic currents.

The existence of weak $(\bar{\nu}e)(\bar{e}\nu)$ or $(\nu\mu)(\nu\mu)$ interactions is a direct consequence of the hypothesis of the product of currents. The observation of νe (or $\nu\mu$) scattering (due to this interaction) in laboratory conditions is a problem of extraordinary difficulty. An experiment on the production of e^+e^- or $\mu^+\mu^-$ pairs in the scattering of energetic neutrinos on the nuclear Coulomb field, may prove simpler:

$$\nu+Z\rightarrow\nu+e^+ +e^- +Z$$

$$\nu+Z\rightarrow\nu+\mu^+ +\mu^- +Z\,.$$

In stars, the $(\bar{\nu}e)(\bar{e}\nu)$ interaction could make the neutrino radiation of stars become more essential than their photon radiation. A large number of processes of neutrino radiation in stars have been considered theoretically:

1. $e^- +Z \rightarrow e^- +Z+\nu+\bar{\nu}$
2. $e^- +e^+ \rightarrow \nu+\bar{\nu}$
3. $\gamma+e^- \rightarrow e^- +\nu+\bar{\nu}$
4. $\gamma+\gamma \rightarrow \nu+\bar{\nu}$
5. $\gamma+Z \rightarrow \nu+\bar{\nu}+Z$
6. $\gamma+\gamma \rightarrow \gamma+\nu+\bar{\nu}\,.$

However, from astrophysical data, it has not been possible to find out whether these reactions actually occur in stars.

The scheme of Fig. 1 contains only charged currents. However, experiment does not exclude the existence of neutral leptonic currents like $\bar{e}e$, $\bar{\mu}\mu$, $\bar{\nu}\nu$. On the basis of the experimental evidence $(K^+\rightarrow\pi^+ +e^+ +e^-)$,

it may be taken that the interaction of neutral leptonic currents with a neutral strange current of the same strength as the ordinary weak interaction, is excluded. However, their weak interaction with one another and with a neutral nucleonic current, if it exists, is either masked by the considerably more intense electromagnetic interaction, or leads to processes which are very difficult to observe: i.e., of the type of weak scattering of neutrinos on nuclei. The search for neutral leptonic currents is of very great interest. Various aspects associated with these currents are mentioned in the papers by Bludman, Pontecorvo and King.

In conclusion, we shall dwell upon the role of the neutrino in cosmology. A number of papers are devoted to discussions of the possible neutrino fluxes in the universe: Pontecorvo and Smorodinsky, Zel'dovich and Smorodinsky, Kharitonov, and Weinberg. The latter paper, for instance, points to the fact that there should be a degenerate neutrino sea in the universe. The Fermi energy E_F of this sea (its depth) differs for different models of the universe. However, this sea is so shallow in all cases, that the effects due to it (such as distortion of the β spectrum) are very difficult to observe. The foregoing authors note that the gravitational action of neutrinos (if their fluxes are sufficiently great) could play a significant role in the evolution of the universe.

It is interesting to note that the gravitational field, if its interaction with neutrinos conserves parity, should generate also right-handed neutrinos and left-handed antineutrinos, in addition to left neutrinos and right antineutrinos. These anomalous particles will not be able to participate in weak interactions and will be absolutely " sterile ". It may be noted that if the Lipmanov scheme, mentioned above, held, then the " anomalous " components would be muonic neutrinos and antineutrinos, and, consequently, would not be " sterile ".

III. IS NUCLEONIC VECTOR CURRENT CONSERVED ?

At the last Rochester Conference, Feynman stressed the fact that the constants of vector interaction determined from O^{14} decay and μ decay differ by about 1 % and that when account is taken of electromagnetic corrections, this difference is doubled. This difference of constants contradicts the conservation of vector current, which in the minimal model is obligatory.

Our faith in the conservation of vector current has now substantially risen mainly due to experimental studies viz. the measurement of the decay constants $\pi^+ \to \pi^0 + e^+ + \nu$ (Dunaitsev *et al.*; Depommier *et al.*; Larsen *et al.*) and the measurement of weak magnetism (Mayer-Kuckuck) in the decays of N^{12} and B^{12}, the results of which are in good agreement with theory. But in what state is the theoretical analysis of radiative corrections to β decay and of deviations from isotopic invariance in the O^{14} nucleus? It is well known that a rigorous calculation of radiative corrections to β decay cannot be carried out consistently in modern theory due to the virtual strong interactions and to the logarithmic divergence. Nevertheless Feynman had argued that the main part of these corrections caused by relatively soft virtual photons is quite reliable.

Geshkenbein and Popov and also Berman have considered earlier disregarded diagrams in which a virtual photon emerges from a four-fermion vertex. These diagrams are due to virtual strong interaction, and their exact calculation is impossible. The estimates depend very strongly upon what is assumed about virtual strong interaction. Geshkenbein and Popov conclude that the contribution of these diagrams may compensate the contribution of the " ordinary " ones. Berman's conclusion is that these diagrams are unimportant and that perhaps electromagnetic correction of virtual W mesons is responsible for the existing μ-β discrepancy.

The isotopic non-invariant corrections in O^{14} were discussed by Blin-Stoyle and Tourneaux. They consider that these corrections can diminish the matrix element by roughly 1 % and consequently, can be responsible for the above mentioned discrepancy. Yesterday I was told by Berman that, according to recent calculations of MacDonald and Altman, these corrections are smaller by three orders of magnitude. It would be very interesting to know what the truth is.

Spector and Blin-Stoyle, and also Fujita have analyzed the RaE decay and on this basis they have adduced some additional arguments in favour of the conservation of vector current.

I think that we have no serious grounds for doubting the conservation of vector current. Nevertheless, it would be very good to increase by an order of magnitude the accuracy of the measurement for the decay $\pi^+ \to \pi^0 + e^+ + \nu$.

IV. " ALMOST " CONSERVED AXIAL CURRENT ?

In the minimal model, the form of the axial current $\bar{p}\gamma_\alpha\gamma_5 n$ is defined uniquely. This current, in conjunction with virtual strong interactions, yields all the known axial matrix elements, such as

$$M_\alpha^\pi = Gf\phi q_\alpha$$

in the decays $\pi \to l+\nu$ where ϕ is the wave function of the π meson and f is the constant to be used in the Goldberger-Treiman formula (see below)

$$M_\alpha^N = Gu_p\{a(q^2)\gamma_\alpha\gamma_5 + b(q^2)q_\alpha\gamma_5\}u_n$$

in neutron β decay or in μ capture.

$$M_\alpha^\Sigma = G\bar{u}_\Lambda\{A(q^2)\gamma_\alpha + B(q^2)q_\alpha + C(q^2)\sigma_{\alpha\beta}q_\beta\}(1 \text{ or } \gamma_5)u_\Sigma$$

in the decays $\Sigma \to \Lambda + e + \nu$.

At present we are not able to calculate the scalar functions of q^2 in these matrix elements. Particularly, we cannot explain why the quantity $a(0)$ is so close to unity. At the 10th Rochester Conference attempts to establish a relationship between the above mentioned functions were considered in very great detail. Underlying these attempts was the hypothesis that axial current is " almost " conserved:

$$\sigma_\alpha j_\alpha^A \approx \pi$$

where π means the π meson field. For the matrix element M^Σ, this hypothesis is actually equivalent to the presumption that both the quantity $B(q^2)$ and the divergence $q^\alpha M_\alpha^\Sigma = GD(q^2)\bar{u}_\Lambda\gamma_5 u_\Sigma$ must (for small q^2) be determined by the π meson pole.

Assuming

$$D(q^2) = \frac{d(q^2)}{q^2-\mu^2}, \quad B(q^2) = \frac{b(q^2)}{q^2-\mu^2}$$

where $d(q^2)$ and $b(q^2)$ for small q^2 are almost constant and taking into account that

$$D(q^2) = (M_\Sigma \pm M_\Lambda)A(q^2) + q^2 B(q^2)$$

we have for $q^2 \approx \mu^2$

$$d \approx b\mu^2,$$

for $q^2 = 0$

$$\frac{d}{-\mu^2} = (M_\Sigma \pm M_\Lambda)A$$

whence $A = -\dfrac{b}{M_\Sigma \pm M_\Lambda}$. If we now take it that $B = g_{\Sigma\Lambda\pi}f$ (pole approximation), the following relation results:

$$A = -\frac{g_{\Sigma\Lambda\pi}f}{M_\Sigma \pm M_\Lambda}$$

in which the plus sign corresponds to the same parity of Σ and Λ ($P_{\Sigma\Lambda} = +1$), and the minus sign to opposite ($P_{\Sigma\Lambda} = -1$). In the first case, we have a result similar to the well known Goldberger-Treiman formula:

$$a = \frac{\sqrt{2}\, g_{N\pi\pi}f}{2M_N}$$

As we shall now see, the result for the case $P_{\Sigma\Lambda} = -1$ is very strange and indicates that the initial hypothesis concerning the almost conserved axial current is doubtful. The case of $P_{\Sigma\Lambda} = -1$ has been considered in detail by Bernstein and Oehme. They substituted into the expression for A the quantity $g_{\Sigma\Lambda\pi}$, which is obtained on the basis of the " deuteron " model of the Σ hyperon. According to this model, most of the time the Σ hyperon exists in the form of $\Lambda+\pi$, which are in the S state. In this case, the binding energy of the π meson is not very great

$$(\Delta = M_\Lambda - M_\Sigma + \mu \approx 70 \text{ MeV})$$

and the $\Lambda+\pi$ system has rather large dimensions. This permits the determination of $g_{\Sigma\Lambda\pi}$ in a way similar to that in which $g_{\alpha NN}$ is determined for the deuteron. To the quantity $\Delta \approx 70$ MeV corresponds $\dfrac{g^2_{\Sigma\Lambda\pi}}{4\pi} \approx 1.5$, which in turn gives $A \approx 7$. (Let it be recalled that experiment yields $f \approx \mu$). Such a large magnitude of A gives for the decay rate of $\Sigma \to \Lambda + e + \nu$ a value which is roughly 0.5% of the probability of hadronic decays.

Disregarding the relation that this result has to the experiment, let us examine more carefully the physics behind it. This physics is very strange. Indeed, let us consider the imaginary Σ hyperon for which $\Delta \ll \mu$. Taking into account that in this limiting case $g^2_{\Sigma\Lambda\pi} \approx \sqrt{\Delta}$, it is easy to find that A will become of the order of unity when $\Delta \ll 1$ MeV. We thus find that a system $\Lambda+\pi$ of very large dimensions has a matrix element of the same magnitude as the neutron. Since this system can undergo β decay only when the Λ and the π that form a Σ hyperon approach each other

at small distances, it follows that the cross-section for the reaction $\Lambda+\pi\to e+\nu+\Lambda$ must be very large so as to compensate for the small frequency of $\Lambda\pi$ collisions. The objection may be raised that for such small Λ an appreciable role will be played by structure singularities, not taken into account in these arguments. Another limiting case, when $M_\Sigma\to M_\Lambda$ ($\Delta\to\mu$), also appears strange, for if the quantity $g_{\Sigma\Lambda\pi}$ is bounded, then A increases indefinitely for $\Delta\to\mu$. But physically this is absolutely improbable. The foregoing reasoning, which is due to Kobzarev, Pomeranchuk and myself, shows that the hypothesis of the pole-like character of the divergence and the equivalent hypothesis about the almost conserved axial current are in no way obvious or even likely.

Even if the parities of Σ and Λ are indeed the same, these arguments may be applied to the β decay of some appropriate resonance. Similar reasoning may be applied also to transitions between a pair of nuclear levels of opposite parity. For example

$$C^6_{13}(1/2+)\to N^7_{13}(1/2-).$$

In this case Δm is very small and the axial constant would come out as a number of tremendous magnitude. But the entire picture will be distorted here by anomalous singularities and it is natural to expect that the one-pion pole is negligible in this case.

The principal argument supporting the hypothesis of the almost conserved current is the agreement of the Goldberger-Treiman formula with experiment. However, it may be that this agreement is accidental.

I will not give the contents of the other papers devoted to the hypothesis of the almost conserved axial current and will pass on to a consideration of the strange current.

V. STRANGE CURRENT AND UNIVERSALITY

All the recently obtained experimental data either confirm the hypothesis that strange current consists of two components, V and A, or do not contradict it. It is remarkable that all leptonic decays of the hadrons with change of strangeness are suppressed by roughly an order of magnitude as compared with similar decays in which the strangeness is conserved. This suppression may be an expression either of the non-universality of weak interaction (the bare constant of the β decay of the Λ hyperon G_Λ is about three to four times less than G), or of the renormalization effects of strong interaction, or of both together. The latter possibility is so depressing that we shall not consider it and only dwell on the first two.

In a large number of papers (Ikeda, Ogawa and Miyachi; Cabibbo and Gatto; Gell-Mann; Kobzarev and Okun; Shekhter) it was presumed on the basis of a unitary symmetry of strong interaction that $G_\Lambda/G\approx 1/4$ and the renormalization effects are small. According to this picture the leptonic decays with change of strangeness should be similar to decays in which strangeness is conserved up to numerical coefficients of the type $\sqrt{2}$. In particular, in the β decay of the Λ hyperon the matrix element (like the neutron matrix element) must be close to the form V-A.

Exceedingly clear-cut predictions arise also for K_{e_3} and K_{μ_3} decays. Generally speaking, the matrix elements of these decays are of the form

$$[f_+(q^2)p_\alpha+f_-(q^2)q_\alpha]$$

where $p=k_K+k_\pi$, $q=k_K-k_\pi$. If the unitary symmetry in K_{e_3} decays is not greatly violated, the matrix element of these decays must be similar to the matrix element of the decay of $\pi^+\to\pi^0+e+\nu$ and, consequently, the condition $\xi=f_-/f_+\ll 1$ must be fulfilled. From experiments on the K_{e_3} decays of K^+ mesons (Brown *et al.*) and K^0_2 mesons (Luers *et al.*; also see an analysis of this experiment in a paper by Valuev) it follows that $f_+(q^2)$ is but weakly dependent on q^2. Assuming that f_+ and f_- are constants, it is easy to calculate the ratio R of the probabilities of K_{μ_3} and K_{e_3} decays:

$$R=0.65+0.13\xi+0.019\xi^2.$$

When $\xi\ll 1$, we get $R=0.65$. Several experiments give the following limits: $0.57\leqq R\leqq 2.30$, the most recent data being $R=0.95\pm 0.15$. In this connection, an accurate (within 5%) measurement of the magnitude of R is of considerable interest. The muon spectrum in K_{μ_3} decay was measured in two experiments. The first of them (Dobbs *et al.*) gives $\xi\approx -9$, the second (Brown *et al.*) gives $\xi\approx 1$. Very important for verifying the magnitude of ξ is an experiment measuring the polarization of muons in K_{μ_3} decay. If ξ is small, it must be right-handed; if ξ is large, left-handed.

If it turns out that $|\xi|\gg 1$, then this will mean that the leptonic decays of hadrons are not the object where

the unitary symmetry of strong interaction is most vividly manifested. The large magnitude of ξ would strike a blow not only at the above-mentioned "unitary" schemes, but also at a variety of other hypotheses, such as the almost-conserved strange current advanced by Gandelman, and the "polological" hypothesis of Bernstein and Weinberg (in this connection, see a paper by Chew). Neither do the form factors considered by Acioli and MacDowell agree with $|\xi| \gg 1$.

In bringing to a close this survey of papers on K_{e_3} decays, I should like to mention a paper by Brene *et al.*, in which very detailed calculations (with numerous graphs) are made of the spectra and polarizations of particles in these decays; a study by Bolsteri and Geffen, and a paper by MacDowell, in which methods are proposed for treating experimental spectra and angular distributions. These methods can help to solve the problem of a possible admixture of S and T interactions and to find the dependence of f_+ and f_- upon q^2.

If we now return to the problem of the universality of weak interactions, it may be thought, apparently, that the suppression of leptonic decays of strange particles is due to "non unitary" strong interactions and does not represent a challenge to the idea of universality, at least not in the form in which the latter is embodied in the minimal model.

VI. DOES THE $\Delta Q = \Delta S$ RULE HOLD?

Crawford has discussed experimental results which indicate the existence of decays

$$K^0 \to e^-(\mu^-) + \nu + \pi^+$$

$$\Sigma^+ \to n + \mu^+ + \nu\,.$$

These decays violate the $\Delta Q = \Delta S$ rule, which follows from the minimal model, and their existence would mean a serious, possibly fatal, blow to this model. The confirmation of the violation of the $\Delta Q = \Delta S$ rule would drastically change the simple model of weak interaction and would give rise to a whole series of very important consequences.

(1) The current×current hypothesis would be excluded because the product of currents with $\Delta Q = \Delta S$ and with $\Delta Q = -\Delta S$ will yield transitions with $\Delta S = 2$. Thus the existence of $K^0 \to \pi^+$ and $\bar{K}^0 \to \pi^+$ transitions yield in the first order with respect to the weak interaction a frequency of transition $K^0 \to \bar{K}^0$, and consequently also a mass difference Δm of the order of 10^7, which contradicts experiment (see Fig. 2).

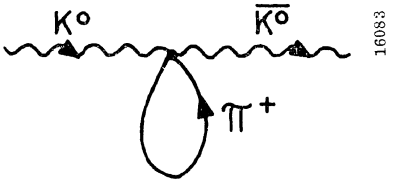

Fig. 2

Another interesting remark connected with Δm is given by Ioffe. He pointed out that virtual $K^0_{e_3}$ and $\bar{K}^0_{e_3}$ transitions would give large Δm, if the $\Delta Q = \Delta S$ rule is violated, provided the weak interaction of virtual leptons has a large cut-off.

I shall explain this in more detail. Consider a diagram of the type shown in Fig. 3.

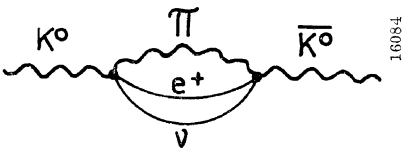

Fig. 3

Its contribution will be of the order

$$\Delta m \approx G^2 \Lambda^2 M^3\,,$$

where Λ is the cut-off energy for weak interactions of leptons, and M has the same meaning for hadrons. If we assume that M is of the order of magnitude of the nucleon mass and take the Δm from experiment, then we get $\Lambda \approx M$. Another possible solution of this problem which Ioffe proposes is that the leptonic loop does not contain the quadratic divergence, like corresponding loops in quantum electrodynamics.

(2) A strange current with $\Delta Q = -\Delta S$ does not satisfy the condition $\Delta T = 1/2$. Indeed, from the very definition of strangeness ($Q = T_3 + B/2 + S/2$) it follows that if $\Delta Q = -\Delta S = 1$, then $\Delta T_3 = 3/2$, and consequently $\Delta T \geqq 3/2$. Thus, the strange current ought to contain components not only with $\Delta T = 1/2$, but also with $\Delta T = 3/2$. In support of the point that the strange current satisfies the $\Delta T = 1/2$ was the fact that, in experiments by Neagu *et al.* and Luers *et al.*, the probabilities of decays $K^0_2 \to e^+ + \nu + \pi^-$ and $K^+ \to e^+ + \nu + \pi^0$ were roughly equal. But recent

results by Alexander *et al.* do not confirm this equality which, predicted on the basis of the $\Delta T = 1/2$ rule, appears purely accidental when $\Delta T = 3/2$ is present.

(3) Other decays must exist with $\Delta Q = -\Delta S$, such as

$$\Xi^0 \to \Sigma^- + e^+ + \nu$$

$$K^+ \to e^- + \nu + 2\pi^+ .$$

In connection with the possible violation of the $\Delta Q = \Delta S$ rule, the search for these decays becomes exceedingly interesting.

I shall not dwell on other corollaries of violation of the $\Delta S = \Delta Q$ rule. They have been considered in detail in the papers by Behrends and Sirlin, Takeda, Pais, Sachs and Treiman. I shall only mention the fact that the number of intermediate W mesons, if they exist, becomes very large; in some schemes it reaches 16!

I should like once again to stress the importance of the problem of the $\Delta Q = \Delta S$ rule and to call on experimentalists to investigate this matter whatever the effort involved. Experimental clarification of this problem will greatly stimulate progress of the weak interaction theory.

VII. NEUTRAL K-MESONS

The question of which is heavier, K_1^0 or K_2^0, is considered in a number of papers. Barger and Kazes, and also Nilsson have tried to give an answer to this question. I should like to make a few remarks in this connection.

If the world were organized so that the mass of the π meson were greater than that of the K meson, and if there were no leptons and photons at all, then the K mesons would be stable. We could then apply to the consideration of the question of Δm the Lehman theorem, according to which any interaction reduces the mass of a stable boson:

$$\delta m^2 = \frac{\int_{\kappa_0^2}^{\infty} (m^2 - \kappa^2)\rho(\kappa^2)d\kappa^2}{\int_{\kappa_0^2}^{\infty} \rho(\kappa^2)d\kappa^2}$$

and consequently, $\delta m^2 < 0$, if $\kappa_0^2 > m^2$. If we now assume that the $K_1^0 - K_2^0$ mass difference is due mainly to states with minimal mass and if we take into account the transitions $K_1^0 \to 2\pi$ and $K_2^0 \to 3\pi$, we could obtain $|\delta m_1^2| > |\delta m_2^2|$, and, consequently, $\Delta m = m_1 - m_2 < 0$.

Unfortunately, even within the framework of the above mentioned extreme simplifications we would not be completely consistent, for the lightest intermediate state for K_2^0 is not the three-pion state but a one-pion state and its contribution can be decisive. It is clear that if we now return to our real world, where the mass of π mesons is equal to m_π, and the K mesons are non-stable ($\kappa_0^2 < m^2$), then δm^2 can have any sign and it is difficult to say anything definite about the sign of Δm. Barger and Kazes took into account the contribution of two-pion decay to the mass of K_1^0 and found that the sign of Δm depends upon the phase of $\pi\pi$ scattering. Nilsson considered virtual baryonic loops and obtained $\Delta m < 0$. These authors did not take into consideration the one-pion diagram. I think that everyone will agree with me that we do not as yet know which of the mesons K_1^0, or K_2^0 will be heavier in experiment. Experiments that could give an answer to this question are discussed by Good and Pauli, and also by Matinyan. They are, apparently, quite realistic.

A beam of neutral K mesons with its fanciful properties has become the favourite toy of physicists, who are devising all manner of *Gedanken* experiments with it. I shall mention only two examples. Various authors, a.o. Lee and Yang (unpublished), Day, Inglis, Ogievetsky, consider interference effects in a system of two neutral K mesons, which are a magnificent illustration of quantum-mechanical paradoxes, associated with reduction of the wave packet.

Another example, as Good has noted, the existence of long-lived K_2^0 mesons indicates the absence of antigravitation in the case of neutral K mesons, for if (in contrast to K^0 mesons) $\bar{K}^0$ mesons were repulsed from the earth, then the gravitational interaction would rather quickly transform K_2^0 into K_1^0, just as nuclear interaction does. A note by Okonov *et al.* is devoted to this same idea.

VIII. τ-DECAY

The available data on π meson spectra in various τ decays are well described by a linear distribution of the form

$$W(\varepsilon) = 1 + \alpha(\varepsilon - \tfrac{1}{2})$$

where ε is the energy of an odd π meson divided by its maximal value ($0 \leqq \varepsilon \leqq 1$). According to Ferro-Luzzi *et al.* 1347 τ^- and 899 τ^+ decays yield $\alpha_\pm = 0.53 \pm 0.07$, while 119 τ' decays yield $\alpha' = -1.0 \pm 0.4$. According to Luers *et al.* the π^0 meson spectrum in 52 decays of $\tau^0 \to \pi^+ + \pi^- + \pi^0$ is characterized by $\alpha = -1.5 \pm 0.6$. These data do not contradict the $\Delta T = 1/2$ rule, from which it follows that

$$\alpha_0 = \alpha' = -2\alpha_\pm$$

These data are usually compared with the Khuri-Treiman formula, in accordance with which $\alpha \pm \approx 0.1 a_c$, where a_c is the S-wave amplitude of charge exchange of π mesons in units of the π meson Compton wavelength.

A large number of papers published recently indicate that there are not enough grounds for such a comparison. In the works of Barton and Kacser, Baqi Bég and De Celles, Riazuddin and Fayyazuddin, there is an indication that the linear dependence with ε may be partly due to P-wave effects. In particular, in the latter two papers there is a discussion of the contribution of resonance vector states (ρ meson and K^* meson). I should like to mention that the *A.B.C.* resonance, if it exists, would give an important contribution to τ decay.

In a paper by Gribov, the effect of $\pi\pi$ interaction on the distribution of π mesons in τ decay is considered in an approximation $ka \ll 1$, $kr_0 \ll 1$, $a \approx r_0$, where k is the maximum momentum of the π meson in τ decay, a is the amplitude of $\pi\pi$ interaction, and γ_0 is the radius of strong interaction. Gribov takes into account the contribution of all diagrams of the type shown in Fig. 4. He proceeds from the fact that the only source of information concerning the π-π interaction are terms proportional to $\sqrt{\varepsilon - 1}$, and not to $(\varepsilon - 1)$, because the latter arise not only due to expansion with respect to the parameter ka (π-π interaction) but also due to expansion with respect to the parameter kr_0 (structural effects of the P wave type).

Gribov's results show that to find terms of the type $\sqrt{\varepsilon - 1}$ experimentally is a very difficult task. In the π^- meson spectrum in the decay $\tau^+ \to 2\pi^+ + \pi^-$, they are practically absent. They can yield an effect of several tens of percent in the π^+ meson spectrum in the decay $\tau^+ \to 2\pi^0 + \pi^+$ if the charge-exchange

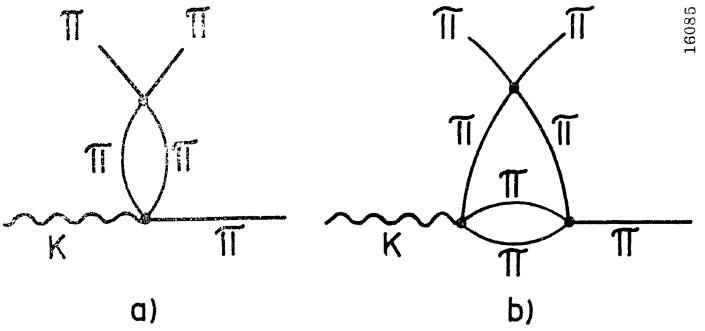

Fig. 4

cross-section $\pi^+ + \pi^- \to 2\pi^0$, to which these terms are proportional, is sufficiently large. In addition they yield a certain rather small asymmetry of angular distribution of π mesons in τ decay, for the observation of which 10^4-10^5 events are necessary. The search for these effects is a very interesting and important task. But what are we to do with the already experimentally available linear dependence upon ε? I think that there is sense in continuing Gribov's calculation, making the additional assumption that $r_0 \ll a$, and (on the basis of diagrams (a) and (b)) calculating also the terms that are linear with respect to ε. This would permit determining what magnitude of π-π interaction is necessary to obtain the experimentally observed values of α and further, knowing the π-π scattering from independent experiments, it would be possible to isolate the contribution of structural effects.

A step in this direction has been made by Lomon *et al.*; however, they took into consideration only a few of the terms arising on the basis of diagrams of type (b).

IX. CONCLUDING REMARKS

In spite of the 300 papers which I mentioned at the beginning of my talk there was almost no marked progress in the weak interaction theory during the two years since the 1960 Rochester Conference. I think this was mainly due to experimental uncertainty concerning a large number of very important points, such as the two neutrino problem, or the $\Delta Q = \Delta S$ rule, or the $\Delta T = 1/2$ rule.

Due to lack of experimental facts it was impossible either to disprove the simplest weak interaction theory, such as the minimal model, or to confirm it. Now, when the experimental situation is changing radically, we may expect that during the next two years important progress in the weak interaction theory will be made.

I would like to express my gratitude to I. Kobzarev for numerous discussions of the situation in weak interactions. In preparing this report I have used widely the arguments which we both published in a number of our papers.

I am very grateful to Dr. Rollnik for his help in preparing this report.

I am indebted to a number of the participants of this conference for reading the preliminary version of this report and making valuable remarks.

DISCUSSION

FAISSNER: I have a remark pertaining to the question of a possible anomalous scattering of muon-neutrinos from nucleons. I do not think that the neutrino experiment done by Schwartz and co-workers does exclude an anomalous ν_μ scattering with a cross-section much higher than that of the conventional lepton "scattering" $\nu_\mu + N \to \mu + N'$. The reason is that the recoil proton in a hypothetical $\nu_\mu p$-scattering would have, depending on the form factor, a momentum of the order of some 100 MeV/c at most which in terms of energy is only a few tens MeV. Such a recoil proton would have been ascribed invariably to the neutron background which was present in the Brookhaven-Columbia neutrino experiment. Looking for the anomalous muon-neutrino scattering would require a quite different neutrino experiment, sensitive to low-energy protons, with a very good shielding against slow and medium-fast neutrons.

You quoted an upper limit of $\approx 10^{-38}$ cm^2 for the cross-section. My statement is that, taking the Brookhaven-Columbia results by themselves, this limit could easily be 10^{-37} or even 10^{-36} cm^2.

OKUN: The limit of 10^{-38} cm^2 was quoted yesterday by Schwartz.

SCHWARTZ: I pointed out yesterday that in our experiment we would be insensitive to neutrino-proton elastic scattering, because of the triggering difficulty and because of the neutron background. If single π^0's were produced in neutrino collisions, without the production of a lepton, we should have observed them if they had energies of the order of several hundred MeV. We have observed none. We have observed two events which do not show an obvious lepton. These can be explained by having a muon produced at an angle such that it would not be observed in the spark chamber.

TREIMAN: I did not understand your discussion of $Ke3$ decay. Why is there expected to be any relation between $Ke3$ and $\pi^+ \to \pi^0 + e + \nu$ decays in your model? Who said the couplings *should* be the same? Your bare couplings did not involve K mesons at all.

OKUN: What I was referring to is the so-called "unitary symmetry"; in the Sakata model this is the symmetry between p, n and Λ. When referring to the discrepancy between G_A and G_n, it is usually tacitly assumed that the effects of the strong "non unitary" interactions are negligible. Now, let us do this in a consistent way, and assume that they are small also in the decay of a K^+ into π^0, with emission of leptons. In the limit of unitary symmetry, the mass of K^+ is equal to the mass of π^0, and only the sum of the momentum four-vectors will appear in the matrix element. If now the unitary symmetry violating interaction is turned on, this form of the matrix element will be spoilt, but if unitary symmetry makes any sense, it will not be spoilt entirely. This was expressed by the relation $\xi < 1$. If experiment will tell that $\xi \geqslant 1$ then this would mean that "non-unitary" interaction is important and may be responsible for the suppression of the leptonic decays of strange particles.

G. MORPURGO: With which confidence do the present results of the B_{12} experiments discriminate between the conserved vector current and a theory with bare nucleons?

OKUN: As for the B_{12} experiment, I know only that the authors claim to have proved weak magnetism, but Wolfenstein, in his talk, expressed some doubts on this.

WOLFENSTEIN: The experiment on the N_{12} and B_{12} β decay showed agreement with the conserved vector current theory in the difference between the N_{12} and B_{12} spectra. However, each spectrum alone differed from the theoretical expectations (as investigated by Morita), and this is the reason for the doubts I expressed.

VAN DE WALLE: I have a comment pertinent to the question of the conserved strange current. In Berkeley we have looked at the energy dependence in the $K^+_{\mu 3}$ form factors implied by the conserved vector current theory for strangeness non-conserving currents and we were able to exclude such an energy dependence with a χ^2 probability of 98%. Our data are compatible with the less drastic energy dependences required by the theory of the partially conserved current.

FEINBERG: I would like to ask a question regarding the model that you suggested, where both the muon-neutrino and the muon interact with some new field. You said that in that case you would get no renormalization of the μ decay coupling constant. Is that true only if you neglect the mass of the μ meson?

OKUN: Yes, that is only true if you neglect the mass of the muon in comparison with the mass of that intermediate particle, X say.

FAISSNER: Is the existence of such a field not already excluded by the precision measurements on the electromagnetic properties of the muon, in particular by g-2?

OKUN: Estimates of the possible anomalous interaction of the neutrino were made on the basis of the g-2 experiment. If we suppose that there is some anomalous interaction we can calculate, in addition to a g-2 value, the cross-section for a possible anomalous neutrino interaction and this comes out to be of the order of 10^{-31} cm^2.

MANDELSTAM: With regard to the discrepancy between the vector coupling constants in β and μ decay, I should like to point out that we do not really know how to define universality to an accuracy of 1%, i.e., to an accuracy where electromagnetic corrections are not negligible. The reason is that the definition of universality depends on a conserved vector current, and the vector current is no longer conserved when electromagnetic

interactions are included. The usual treatment in such cases is based on the assumption that the bare coupling constants in the Lagrangian are equal. When one tries to deduce observable consequences of such an assumption, one arrives at infinite results. It may be that if we were clever enough to calculate without perturbation theory, the results would be finite, but it may also be that it is meaningless to talk about unrenormalized coupling constants and that we do not know how to define universality when the appropriate conservation laws are not satisfied.

MORPURGO: The Blin-Stoyle and Tourneux calculation takes into account the effect of the $\pi^0-\pi^\pm$ mass difference in destroying charge independence, if I am correct. Does the paper by MacDonald, which you mentioned, also treat the $\pi^\pm-\pi^0$ mass difference or simply the effect of the Coulomb potential?

OKUN: I hope so.

MORPURGO: Which is the more likely estimate of the rate of the $\pi^+\to\pi_0+e^++\nu$ if the conserved vector current theory were not true? I know, of course, that there are divergences. Do you know about any other calculation of the $\pi^+\to\pi^0+e^++\nu$ decay without conserved vector current?

OKUN: There was a very old calculation of this type which was done by Zel'dovich in the Middle Ages. Then I was told by Dr. Rollnik just two days ago, that some students of his have calculated these things.

ROLLNIK: The result of a simple perturbation calculation depends strongly on a cut-off and if you take this cut-off at the energy of a nucleon mass, you get approximately the same decay rate as in the conserved vector theory. But, if you increase the cut-off to 2 nucleon masses, the result is four times larger or so.

YAMAGUCHI: I would like to add one remark on the reference. The hypothesis of minimal electromagnetic interaction has been introduced by Wick in his paper published in the middle of the thirties (*).

MARSHAK: I know that it was implicit in your talk, but I would like to emphasise again the difference between the breakdown of the $\Delta Q = \Delta S$ and the $|\Delta T| = {}^1/_2$ selection rules. Within the framework of your Λnp model one likes very much a $T = {}^1/_2$ strangeness non-conserving current which, combined with the nucleon current gives both $|\Delta T| = {}^1/_2$ and $|\Delta T| = {}^3/_2$. Hence the new evidence which is appearing now against the $\Delta T| = {}^1/_2$ rule should be considered independently of the evidence for $\Delta S = -\Delta Q$. For example, difficulty of the K_1^0—K_2^0 mass difference would not arise if the $|\Delta T| = {}^1/_2$ selection rule is incorrect, as long as the $T = {}^1/_2$ current suffices.

THIRRING: You gave a Goldberger-Treiman-like relation for the $\Sigma\to\Lambda+e+\nu$ decay. Then you showed that it contradicts common sense. Does it also contradict the meagre experimental information we have on this decay?

OKUN: We do not know what the relative $\Sigma\Lambda$ parity is. If it is negative then there is a contradiction.

NAMBU: I would like to comment on the argument of Dr. Okun against the partially conserved axial vector current. I think that is a very interesting example. However, in order to establish a strict conservation, you have to switch off the mass of the pion, or at least one has to neglect the mass of the pion in comparison to the nucleon mass. Now, in the case of an odd $\Sigma\Lambda$ parity in the formula you wrote down, there appeared the difference of the Σ, Λ masses, which is small compared to the baryon mass itself. Nobody knows what this difference in the masses is due to. It could be that this mass difference is also related to the violation of the conservation law of the axial current, that is, related to the pion mass. In such a case one must be careful because it may be that one cannot apply the conservation idea in a simple way. I must also say that if we take the view that the axial vector conservation is O.K., then we can derive not only consequences for the weak interactions, but also for the strong ones, namely one can relate in any process where soft pions are emitted, the soft pion emission amplitude to the non-pion emission amplitude and this could give you another test of the underlying idea of the conserved axial vector current.

OEHME (added after the session): I would like to add a remark to Okun's discussion of dispersion relations for the axial current in the decay $\Sigma\to\Lambda+e+\nu$. There are two essential assumptions: (1) that one can write an unsubtracted dispersion relation for the matrix element of the divergence of the current, and (2) that the contribution of the pion pole is dominant. If one takes assumption (1) as a postulate, then the validity of the approximation (2) depends very much upon the actual mass ratios in the $\Sigma\Lambda\pi$ system, and I do not think that one can simply extrapolate our results to the limits $m_\Sigma\to m_\Lambda+m_\pi$ and $m_\Sigma\to m_\Lambda$. In the case of weak binding, structure singularities become relevant. Concerning the limit of tight binding, it may even be quite satisfactory that, within this framework, one cannot make the mass difference $m_\Sigma-m_\Lambda$ arbitrarily small without drastically changing other parameters like the pion mass or the coupling constant $f_{\Sigma\Lambda\pi}$.

(*) G. C. Wick, Accad. Lincei, Atti *21*, 170, (1935).

BIBLIOGRAPHY ON WEAK INTERACTIONS

Period January 1961 to May 1962

The actual references will be found on p. 860 in alphabetic order of authors

LEPTONIC CURRENTS

1. $\mu \to e + \gamma$ and $\mu \to 3e$ decays

Experiment: Alikhanov *et al.* ($R_{e\gamma} < 5 \cdot 10^{-7}$); Bartlett *et al.* ($R_{e\gamma} < 6 \cdot 10^{-8}$); Grittenden *et al.* ($R_{e\gamma} < 2.5 \cdot 10^{-5}$; $R_{3e} < 4 \cdot 10^{-6}$); Frankel *et al.* ($R_{e\gamma} < 1.9 \cdot 10^{-7}$); Parker *et al.* ($R_{3e} < 5 \cdot 10^{-7}$); Babaev *et al.* ($R_{3e} < 2 \cdot 10^{-7}$).

Theory: Berman; Nilsson and Marshak; Nilsson; Lee; Dreitlein and Primakoff ($\mu \to e + 2\gamma$); Okun; Cabibbo and Gatto; Bialynicki-Birula.

2. $\mu^- + Z \to e^- + Z$ reaction

Experiment: Sard *et al.* ($R < 4 \cdot 10^{-6}$); Conversi *et al.* ($R < 2.4 \cdot 10^{-7}$).

Theory: See 1.

3. Leptonic interactions at very high energies

Experiment: Danby *et al.*; Schwartz.

Theory: Markov and Zheleznykh; Kozhushner and Shabalin; Nilsson; Van Zhun *et al.*; Feinberg and Gürsey (high energy neutrino reactions); Albright, Blankenbecler and Goldberger; Markov; Nguyen Van-hieu (virtual weak interactions at very small distances); Pais; Lee and Yang.

4. Muonium—antimuonium

Theory: Feinberg and Weinberg; Glashow; Okun and Pontecorvo; Cabibbo and Gatto.

5. Classification of leptons

Theory: Ryan; Ouchi and Senba; Renson; Okabayashi *et al.*; Holladay and Roos; Lipmanov, Ramakrishnan *et al.*; Feinberg and Gürsey.

6. Possible properties of the muonic neutrino

Experiment: Bernardini (project); Vasilevsky *et al*; Danby *et al.*

Theory: Iso (polarization); Bahcal and Curtis (Mass); Kobzarev and Okun; Mandeltsveig (anomalous interaction); Krolikowsky; Feinberg, Gürsey and Pais (neutrino flip); Feinberg; von Dardel and Ghani (more than two neutrinos?).

7. Neutrino reactions in stars

Theory: Chiu and Stabler; Ritus ($\gamma + e^- \to e^- + \nu + \bar{\nu}$); Chiu; Gell-Mann; Matinyan and Tsilosani ($\gamma + \gamma \to \nu + \bar{\nu}$, $\nu + Z \to \nu + \bar{\nu} + Z$).

8. Neutrino and cosmology

Pontecorvo and Smorodinsky; Kharitonov (possible neutrino flux). Zel'dovich and Smorodinsky; Weinberg; Kobzarev and Okun (neutrino and gravitation).

9. Neutral leptonic current

Bludman; Pontecorvo; King.

10. $\mu \to e + \nu + \bar{\nu}$ decay

Experiment: Lundy; Block *et al.*; Lathrop *et al.*; Allaby *et al.*

Theory: Huff; Johnson *et al.*; Chilton.

NUCLEONIC CURRENT

11. Conservation of the vector current

Experiment: P. Depommier *et al.*; R. R. Larsen *et al.*; Dunaitsev *et al.* ($\pi^+ \to \pi^0 + e^+ + \nu$); Mayer-Kuckuck and Michel (B^{12}, N^{12}); Lundy ($\mu \to e + \nu + \bar{\nu}$); Butler and Bondelid; Bardin (O^{14});

Theory: Fujita (RaE); Spector and Blin-Stoyle (RaE); Blin-Stoyle and Le Tourneux (O^{14}); MacDonald and Altman: see also next item.

12. Radiative corrections

Theory: Geshkenbein and Popov; Ginzburg and Serebryakov; Vymazal (β-decay); Da Prato and Putzolu ($\pi^+ \to \pi^0 + e^+ + \nu$). Smorodinsky and Hu Shi-ke ($\pi \to l + \nu$); Berman and Sirlin.

13. Axial current

Theory: Balachandran; Banerjee; Bernstein and Oehme; Marshak and Okubo; Dennery and Primakoff; Gell-Mann and Zachariasen (" almost conserved " current).

14. β decay, μ capture and $\pi \to l + \nu$ decays

Experiment: Clark and Robson (neutron β decay); Evseev *et al.*, Egorov *et al.*, Maier *et al.*, Lundy *et al.* (μ capture in various nuclei). Filippov *et al.*; Zaimidoroga *et al.* (μ capture in He^3). Hildebrand (μ capture in H); Bleser *et al.* (μ capture in H); Dzelepov *et al.*; Bardon ($\pi \to \mu + \nu$), Backenstoss *et al.* ($\pi \to \mu + \nu$).

Theory: Bietti; Blokhintsev and Dolinsky; Überall; Silbor and Überall; Singer; Telegdi; Lobov and Shapiro; Ericson and Sens.

15. Neutrino-nucleon interaction

Experiment: Bernardini (project); Vasilevsky *et al.*; Schwartz.

Theory: Azimov and Shekhter; Berman; Überall; Cabibbo, Lee; Belyaev, Nguyen Van-hieu. See also § 6. Yamaguchi.

STRANGE CURRENT

16. Leptonic decays of hyperons

Experiment: Bhowmik *et al.* ($1\Lambda_e$; $1\Sigma_e$); Franzini and Steinberger ($1\Sigma^-_e$); Quareni *et al.* (0); Humphrey *et al.* ($1\Sigma^-$); Eisler *et al.* ($1\Lambda_\mu$), Aubert *et al.* ($8\Lambda_e$); A. Galtieri *et al.*; L. Bertanza *et al.*

Theory: Fujimura *et al.*; Dreitlein and Primakoff; Bernstein and Oehme; Gandelman; Harrington; Singh and Udgaonkar.

17. K_{e3} and $K_{\mu 3}$ decays

Experiment: Luers *et al.* ($0.57 < R < 1.067$; K^0_{e3}-spectrum) (*); Dobbs *et al.* ($K^+_{\mu 3}$ spectrum); Brown *et al.* (K^+_{e3} spectrum); Roe *et al.* ($0.83 < R < 1.30$); Bøggild *et al.* ($0.76 < R < 1.85$). Astier *et al.* ($0.85 < R < 2.30$); Bhowmik; Neagu *et al.*; J. L. Brown *et al.*

Theory: Brene, Egardt and Qvist; Valuev; Bolsteri and Geffen; Achioli and MacDowell; Kobzarev and Okun; Chew; Bernstein and Weinberg; Hiraki; Hara and Takebe; Pais.

18. $\Delta Q = \Delta S$ selection rule

Experiment: Ely *et al.*; Baldo-Ceolin; A. Galtieri *et al.*; G. Alexander *et al.*

Theory: Behrends and Sirlin; Ioffe; Pais; Takeda; Sachs and Treiman.

HADRONIC (NON-LEPTONIC) INTERACTIONS

19.

Experiment: Beall *et al.* ($\alpha_{\Lambda \to p + \pi} < 0$, $\alpha_{\Sigma^+ \to p + \pi^0} = 0.75 \pm 0.17$); Fowler *et al.* ($\alpha_{\Sigma^- \to \Lambda + \pi} > 0$), Leitner *et al.* ($\alpha_\Lambda < 0$); Bowen *et al.*; Bhowmik.

Theory: Nakamura and Konuma; Nambu and Sakurai; Feldman, Matthews and Salam; Pais; Bose and Marshak; Rosen; Balachandran and Venkatesan; Barshay and Pendelton; Meyer, Prentki and Yamaguchi; Harrington; Maki and Ohnuki.

20. Hyperfragments

Theory: Dalitz and Ryasekharan; Iwao; Lulka; Pniewski and Danysz.

(*) R denotes the branching ratio $K_{\mu 3}/K_{e3}$.

21. τ decay

Experiment: Ferro-Luzzi *et al.* (τ^-); Luers *et al.* (τ^0).

Theory: Barton and Kacser; Baqi Bég and De Celles; Bonnevay; Gribov; Lomon, Morris, Irwin and Truong; Sawada, Ueda and Yonezawa; Riazuddin and Fayyazuddin; Danilov and Dyatlov; deltsveig and Solovyev.

22. Parity non-conservation in nuclear forces

Theory: Vladimirsky and Andreev; Blin-Stoyle and Spector; Flamm and Freund.

23. Neutral barryonic currents

Markov and Nguyen Van-hieu.

RADIATIVE DECAYS

24. $K\to 2\pi\gamma$ decay

Experiment: Monti *et al.*; Stern.

Theory: Chew; Barshai and Iso; Ivanter.

25. $K\to e\nu\gamma$ decay

Theory: Berman, Ghani and Salmeron; Kanazawa, Sugawara and Tanaka; Neville.

26. $\Sigma\to p\gamma$ and $\Sigma\to n\pi+\gamma$ decays

Experiment: Schneps and Kang ($p\gamma$); Glasser *et al.* (pγ); Quareni *et al.* ($n\pi^+\gamma$).

Theory: Calucci and Furlan ($p\gamma$); Sawamura ($p\gamma$); Iwao and Leitner ($n\pi^+\gamma$); Prakash and Zimerman ($p\gamma$); Lyaginanad, Ginzburg (pe^-e^+ and $p\mu^-\mu^+$).

27. Other radiative decays

Experiment: Binnie *et al.* ($\pi\to\mu\nu\gamma$); Depommier *et al.* ($\pi^+\to e^+\nu\gamma$); G. Conforto *et al.* ($\mu+Z\to Z'+\nu+\gamma$).

Theory: Lobov and Shapiro ($\mu^-+p\to n+\gamma+\nu$).

NEUTRAL *K*-MESONS

28. K_1^0-K_2^0 mass difference and lifetime

Experiment: Camerini *et al.* ($\Delta m = 1.5^{+0.3}_{-0.2}$); Fitch *et al.* ($\Delta m = 1.9\pm 0.3$); Good *et al.* ($\Delta m = 0.85^{+0.4}_{-0.25}$); Darmon *et al.* (lifetime of K_2^0). (See also § 18).

Theory: Good and Pauli; Matinyan; Barger and Kazes; Glashow; Ioffe; Nilsson; Kobzarev; Okun. (See also § 29 and 18.)

29. Interference effects

Theory: Good; Okonov, Podgoretsky and Khrustalev (gravitation); Day; Inglis; Ogievetsky, Okonov and Podgoretsky ($\overline{K}$, K); Dreitlein and Primakoff ($K\to 2\gamma$); Barshay and Iso ($K\to 2\pi\gamma$).

INTERMEDIATE MESONS

30. Production and decay of ω mesons

Theory: Lee, Markstein and Yang; Ebel and Walker; Lee; Solovyev and Tsukerman; Bernstein and Feinberg; Dombey; Fröhlich (classification); Lee and Yang.

31. Possible indirect evidence for ω mesons

Theory: Lee; Berman; Kanazawa *et al.* ($Ke\gamma\nu$); Nakamura and Itani; Matthews and Salam; Oneda, Pati and Sakita.

GENERAL SYMMETRIES

32. CP-conservation

Experiment: Anikina *et al.* (K_2^0); Charpak *et al.*

Theory: Sachs and Treiman; Shirokov; Ekstein; Bell.

OTHER SYMMETRIES

33.

Coleman and Glashow; d'Espagnat and Prentki; Pais; Gupta; Gell-Mann and Zachariasen; G. Gürsey; Behrends and Sirlin; Bludman; Fujii; Gell-Mann; Glashow; Ikeda, Mijachi, Ogawa; Itô and Fujii; Lipmanov; Okubo and Marshak; Salam and Ward.

REVIEW ARTICLES AND LECTURES

34.

Adair; Lee; Feynman; Garwin; Okun; Pais; Berman; Feinberg; Merrison.

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