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# WEAK INTERACTIONS
## ( Theoretical )

Rapporteur: S.B. Treiman

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S.M. Bilenky
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This publication is of a preliminary character. To facilitate the rapid appearance of Reports, they are printed in the form as presented by Rapporteurs.

This report was to have been given by Professor A. Pais, who however found himself at the last moment unable to attend the conference. He informed me of this circumstance essentially as I was boarding the airplane in New York 10 days ago; and he told me to do my duty, as he saw it. He provided me with a timely review manuscript which he had prepared, based on a comprehensive survey of the literature, including the latest preprints and even rumors. The still newer developments reported at this conference I shall transmit to him, for incorporation into his final report for the Conference Proceedings. Since I did not myself have the chance to do the necessary preparatory homework, my role will have to be that of rapporteur to the rapporteur; and here I shall touch only on a limited range of topics.

Insofar as the weak interactions are concerned, it is clearly so that the most striking new development we've heard about was contained in the report by the Princeton group, Christenson, Cronin, Fitch, and Turley. They announced the discovery of a two-pion mode of decay of the $K^o_2$ meson, a reaction which on the face of it implies the breakdown of CP invariance. Some further experimental confirmation was reported by Wattenberg, on behalf of the Illinois group of Abashian, Abrams, Carpenter, Fisher, Nepkens, and Smith.

One has already heard, especially over the clinking sound of Vodka glasses, a great deal of agitated discussion about the experiments and their implications. Luckily for me, however, no theoretical paper on the matter was formally presented to the conference; and I am therefore not obligated to provide you with a full theoretical framework for the understanding of this exciting new development. It is safe to predict, however, that a growing volume of theoretical papers on CP will shortly begin to appear. We can only hope that the experimentalists, who carry the real burden, will continue to lead the way.

The implication of the experiments is that the long-lived neutral K meson can decay, in complete isolation, into two pi-mesons. In the actual set-up of the Princeton group, the events in fact took place in helium gas; and some people have worried about this. Cronin, however, presented convincing evidence to the effect that our conventional understanding of regeneration is sufficiently correct to rule out the possibility that the events seen came from regenerated $K^{o}{}_{1}$ mesons. Moreover, in the set-up of the Illinois group, the decay events took place in vacuum. No doubt, however, it still remains an important task for the future to check these claims in a variety of ways, and to go on to a search for further evidence of CP violation in other weak interactions. Also, through the CPT theorem, which itself may not be immune, the overthrow of CP invariance of course implies a corresponding fate for the principle of time reversal invariance, and tests for this too are very much in order.

A number of schemes for preserving CP invariance in the face of the raw experimental results have been put forth informally at this conference, especially at the Vodka sessions.

Some people have raised the question whether the neutral $K^0$ beam still contains some $K^0_1$ component at the apparatus, even though it is many nominal $K^0_1$ lifetimes from its source. In effect the question is whether unstable particles, in particular the $K^0_1$ really decay exponentially in the way we learned as children, even over very long intervals of time. Perhaps what is initially a fast, essentially exponential decay curve, turns after a time into a slowly varying curve. The exact way in which an unstable system decay with time has been a fitful subject of theoretical discussion for many years. Although there is little experimental doubt about the exponential nature of decay for early times, there is surprisingly little experimental confirmation, as Fitch has pointed out to me, for times much longer than a few mean lives — especially where sub nuclear decay is concerned.

After all of this has been said, however, it seems best to interpret the $K^0_2$ decay results at face value as evidence for the violation of CP invariance. And via the deeply rooted CPT theorem we may also regard time reversal invariance as being itself suspected. According to the Princeton group, the amplitude for $K^0_2 \rightarrow 2\pi$ decay is approximately $2 \times 10^{-3}$ times smaller in magnitude than that for $K^0_1 \rightarrow 2\pi$ decay. This appears to represent a very small degree of CP violations – annoyingly small. It contrasts with our earlier experience of the overthrow of parity and charge conjugation invariance in the weak interactions. What is now exercising these people who accept the experiment at their face value is this: is there some theoretical sense in which we can regard this degfee of CP violation as being in fact large?

The notion is not a very precise one as stated. But the question is, are we allowed to imagine that CP violations might be large elsewhere in some weak reactions, in such a way however that this would be consistent with the small effect seen for $K^o{}_2$ decay into two pions?

According to our customary views, we ordinarily see weak interactions effects only to lowest order. So, for example, CP violation for, say, nucleon $\beta$-decay would not necessarily imply CP violation for say $\Lambda$ $\beta$ decay, even apart from the possibility of accidental dynamic cancellations. The one process is determined by a strangeness conserving current, the other by a strangeness changing one; and they do not communicate with each other insofar as first order effects are concerned. Similarly the parity violating non leptonic weak coupling which determine, say, $K^+$ decay into 2 pions do not communicate with the parity conserving counplings that determine $K^+$ – decay into 3 pions. But the neutral complex of $K^o{}_1$ and $K^o{}_2$ mesons is unique in this regard. The very linear combinations of $K^o$ and $\bar{K}^o$ which constitute the $K^o{}_1$ and $K^o{}_2$ mesons states are determined by second order effedts involving virtual two-step transitions between $K^o$ and $\bar{K}^o$.

If we were to consider such transitions only on the mass shell, then, insofar as the 2 pion mode of $K^o$ and $\bar{K}^o$ decay dominates all other modes of decay, the linear combination of $K^o$ and $\bar{K}^o$ which constitutes the long-lived $K^o{}_2$ could not have a very large amplitude for decay into two pions, no matter how badly CP invariance were violated. This was noted some time ago by Weinberg. But when off-mass virtual transitions are taken into account, the conclusion no longer follows if the parity violating non-leptonic Hamiltonian also violates CP invariance. It becomes then a hard and quantitative question whether $K^o_2$ decay would still be suppressed appreciably. On the other hand, if this part of the Hamiltonian- the part which converts K and $\bar{K}$ into 2 pions — is CP conserving, then CP violation elsewhere would more surely have only a small effect in causing a departure of the $K^o_2$ state from one which is purely odd under CP.

Along these lines, in a recent preprint Sachs has proposed the following possibility. Suppose, contrary to most current belief, that the strangeness changing hadron currents involve a $\Delta S=\Delta Q$ part as well as a $\Delta S \neq \Delta Q$ part. Then the transition from $K^o$ to $\bar{K}^o$ could be effected, among other ways, by a two step combination of $\Delta S = \Delta Q$ and $\Delta S = -\Delta Q$ transitions. If the CP violation occurs as between these two pieces, even though the non-leptonic interactions were perfectly CP conserving, this would alter the combinations of $K^o$ and $\bar{K}^o$ that constitute the $K^o_1$ and $K^o_2$ states and some $K^o_2$ decays into 2 pions could take place. With roughly equal amounts of $\Delta S=\Delta Q$ and $\Delta S=\bar{\Delta} Q$, and with maximal CP violating phase between them, Sachs finds that he can account roughly for the magnitude of the $K^o_2 \rightarrow 2\pi$ effect which is seen.

Of course, experimental evidence for appreciable $\Delta S = -\Delta Q$ currents is not very compelling these days. Fry has pointed out however, that if the $\Delta S \neq \Delta Q$ current is mainly vector, one could understand the experimental absence of $K^+ \rightarrow 2\pi^+ + e^- + \nu$ decay (the axial current dominates kinematically here over the vector), and also perhaps the absence of $\Sigma^+ \beta$ decay (the axial current contribution roughly three times as much as a vector current of equal intrinsic strength). Of course $K^0_{e3}$ and $K^0_{\mu 3}$ decays are purely vectorial, so here any $\Delta S = -\Delta Q$ contributions have a good chance to show up. But as Sachs and Fry have argued, in analyzing the experimental data, one should re-examine matters in the light of possible large violations of CP univariance. Hitherto, the analyses have been based on the assumption that CP invariance holds true.

I have singled out in the above only one of the possible ways to account for the small amplitude for $K^0_2 \to 2\pi$ decay on a scheme involving somewhere a large violation of CP invariance. One can of course put the blame directly on the non-leptonic Hamiltonian itself, and perhaps elsewhere too. The game then is to do this in some elegant way and to avoid the creation of a too large amplitude for $K^0_2 \to 2\pi$ decay. On the current- current model of the weak interactions, Cabbibo, for example, has suggested that perhaps the so-called second class currents, hitherto generally thought to be absent, are in fact present and CP violating. There is no obvious reason why the division should occur in this way, although it has a certain aesthetic appeal. But one must make sure that not too much $K^0_2$ is thereby introduced. The second class currents, to be sure, would in any case be suppressed in $\beta$-decay, but for purely kinematic reasons not applicable to the problem under discussion. We can expect in the near future to hear many other proposals, but improved understanding will probably have to await further experimental leads.

Let me now turn to some other topics in the weak interactions.

1. As a result of new, precision calculations for the wave functions of $\mu$-mesic hydrogen molecules, a highly quantitative basis has now become available for the analysis of the fundamental capture reaction $\mu^- + p \rightarrow n + \nu$. The present situation was reviewed for us by Ericson. As we already knew before, from capture experiments in hydrogen and in complex nuclei, the dominant form factors, vector and axial vector, are very nearly identical to those which appear in $\beta$ decay. This accords with the principle of electron, $\mu$-meson universality. In capture, which involves the larger momentum transfer, velocity dependent terms also have a chance of showing up, so that other form factors of the nucleon-lepton interaction can also be studied - in particular, the weak magnetism and induced pseudoscalar terms. Since there is independent evidence in support of the conserved vector current theory, the tendency is to accept from the theory the implication for the weak magnetism term and also to accept electron $\mu$-meson universality. This leaves then the induced pseudoscalar term as an object of inquiry, together with the possibility of detecting the presence of the second class current terms. If one for the time being omits the latter, then, according to Ericson, the molecular theory and corresponding hydrogen capture experiments are now sufficiently good so that, solely from hydrogen capture, one can determine the induced pseudoscalar coupling constant $g_p$ to a pretty fair accuracy. He reports that the ratio $g_p/g_A$ can be said to be in the range + 4 to +12 the best value being about 6.5. This agrees well enough with a theoretical estimate obtained some time ago: $g_p/g_A \simeq 7$. On the other hand, for capture by complex nuclei, there is some evidence which suggests considerably larger values of $g_p$. For complex

nuclei, there are of course the usual complications involved in getting nuclear matrix elements. But as Ericson has emphasized, there arises the deeper question for velocity dependent terms such as the pseudoscalar one: how reliable is our conventional treatment of the nucleus as being a bag of nucleons insofar as the analysis of velocity dependent effects in $\mu$-capture is **concerned?** Should the effective value of $g_p$ for example, be the same in a complex nucleus as it is in $\mu$-capture by hydrogen? There is a Ph.D. degree in this question.

2. One of the dominant themes in present-day **discussions** of weak interactions has to do with the introduction of SU(3) notion into the theories of these processes. Cabbibo has introduced a model in which the strangeness conserving ($\Delta S=0$) and strangeness changing ($\Delta S=1$) charged currents are taken to be members of a common unitary octet. The vector and axial currents are written

$$V_\lambda = \cos\theta_V\, V_\lambda(\Delta S=0) + \sin\theta_V\, V_\lambda(\Delta S=1)$$

$$A_\lambda = \cos\theta_A\, A_\lambda(\Delta S=0) + \sin\theta_A\, A_\lambda(\Delta S=1)$$

Cabbibo accepts the CVC hypothesis for $V_\lambda(\Delta S=0)$ and he supposes, further, that $\theta_A=\theta_V$.

Neglecting violations of SU(3) symmetry in the strong interactions, one can compute $|\theta_A|$ from a comparison of $K_{\mu2}$ and $\pi_{\mu2}$ decays; $|\theta_V|$ from a comparison of $K_{e3}$ and $\pi_{e3}$ decays. According to Brene, Hellesen and Roos, one finds $|\theta_A| = 0.264 \pm 0.004$, $|\theta_V| = 0.218 \pm 0.015$, the near equality being rather impressive. From an analysis of hyperon decays, Brene et al., find a consistent fit, on the assumption $\theta_A = \theta_V = \theta$, with $=0.240 \pm 0.014$ and with d to f ratio of axial vector matrix elements similar to that of pseudoscalar meson coupling to baryons in the strong interactions. The overall consistency is quite remarkable.

3. Concerning the $\Delta I = \frac{1}{2}$ rule for nonleptonic decays, the experimental confirmation is presently in a very good condition. On the current-current hypothesis, it can be understood rigorously only if one adds to the usual charged lepton currents some additional ones. An elegant scheme along this line was reported by D'Espagnat. In terms of intermediate bosons it involves a unitary triplet of bosons and a corresponding antitriplet. On the other hand, Dashen, Frautschi, Gell-Mann and Hara have considered the possibility that only the ordinary charged currents are involved but that there is operative a general enhancement of the resulting octet non-leptonic coupling by virtue of strong interaction effects. How this dynamical effect is to come about is not yet fully explained, but these authors go on to discuss ways in which the two possibilities can be distinguished. The current-current model in general implies that weak, hence parity-violating, contributions must occur for non-leptonic, strangeness conserving reactions, i.e., for reactions dominated by strong couplings. On the octet enhancement model, as they show, these contributions must transform mainly like an isotopic scalar; whereas with extra currents, a la D'Espagnat, there should appear also important terms which transform like an isotopic vector.

4. Marshak, Okubo, and Ryan have raised an interesting possibility with respect to unitary triplet intermediate bosons, namely, that they could interact strongly with ordinary particles without jeopardizing the weakness of normal weak interactions. The bosons would possess unit triality, hence would be stable against strong decay into ordinary particles if interactions stronger than the weak ones possess triality invariance. Of course this means the

bosons would have to couple strongly to other particles only in pairs. This opens up the possibility of strong contributions to boson pair production. On **earlier** views pair production would be only electromagnetic in strength.

5. I conclude, finally, with a remark on inelastic high energy neutrino-induced reactions. It is due to S.Adler and opens up some interesting experimental possibilities. Consider a strangeness conserving reaction

$$\nu + N \rightarrow \ell + \beta_1 + \beta_2 + \cdots$$

where N is a nucleon (or nucleus), l is a lepton, and $\beta_1 \beta_2$ .... are various other particles. Adler noticed the following thing. Consider the configuration in which the lepton emerges in the forward direction, so that its momentum is parallel with that of the incoming neutrino. Then insofar as the mass of the lepton can be neglected, the differential cross section for this configuration is proportional to

$$|\langle \beta_1 \beta_2 \ldots | \frac{\partial J_\lambda^V}{\partial x_\lambda} + \frac{\partial J_\lambda^A}{\partial x_\lambda} | N \rangle|^2$$

The proportionality factors are definite but I do not bother to write them down. The remarkable fact is that for this configuration the differential cross-section is determined solely by the divergence of the hadron current.

In particular, if the conserved vector current theory is correct, then the vector contribution disappears and it then follows that all parity violating effects must vanish for the forward lepton configuration. Two examples:

(i) Consider $\nu + N \rightarrow \ell + N + \pi$

In general one can expect to find that the outgoing nucleon is polarized, e.g. $\langle \vec{\sigma} \cdot \vec{q}_\ell \rangle \neq 0$ However, for forward leptons such an effect must disappear.

(ii) More usefully, from a practical viewpoint, consider

$$\nu + N \to \ell + N + \pi_a + \pi_b$$

Again, in general one can expect to find in the spectrum a parity violating term $(\vec{q}_a \times \vec{q}_b)\cdot\vec{q}_\nu$. The coefficient must however vanish for forward lepton configurations.

In actual experiments one of course cannot restrict himself to precisely forward lepton events. Presumably one would attempt to detect the parity violating terms for general configurations and then test whether the coefficients tend toward zero as the lepton approaches the forward direction.

A model calculation on the reaction $\nu + N \to \ell + N + \pi$ indicates that $\langle \vec{\sigma}\cdot\vec{q}_\ell \rangle$ drops off fast for lepton angles below 15° for neutrino energy $E_\nu \approx 1$ BeV. Adler has also attempted estimates of the effect of finite lepton mass, for the important case where it is a muon. The dominant effects came from peripherical diagrams and do not vitiate the conclusion that parity violating terms essentially vanish in the conserved vector current theory for forward lepton configurations.

The familiar test of the CVC hypothesis in "elastic" neutrino induced reactions $\nu + N \to \ell + N$ is of course well known, and involves a comparison of the vector and weak magnetism form factors with the corresponding electromagnetic form factors for the nucleon. Adler's remark opens the possibility of checking up on the CVC hypothesis for general inelastic reactions.

Moreover, if the CVC hypothesis is correct, then for forward lepton configurations the sole contribution to inelastic neutrino induced reactions comes from the divergence of the axial vector current. This object, as is known, has been the subject of a lot of theoretical discussion. There exists an experimentally successful theoretical formula which relates the pion decay amplitude to the axial vector coupling constant of decay and the strong coupling constant for pion-nucleon interactions. It was originally gotten from some **daring** manipulations of a dispersion theoretic nature. But later it was seen to emerge from another point of view which lends itself to generalization. According to this, the divergence $\frac{\partial J_\lambda^A}{\partial x_\lambda}$ is supposed to be such a gentle operator that for small momentum transfer the matrix element $\langle s_2 | \frac{\partial J_\lambda^A}{\partial x_\lambda} | s_1 \rangle$ **receives its main contribution from the one pion intermediate state.** On this basis, Adler has shown that for forward lepton configurations, the differential cross section for $\nu + N \to \ell + \beta_1 + \beta_2$ must be proportional to the corresponding cross section for $\pi + N \to \beta_1 + \beta_2 + \cdots$. In particular, the angular distributions of the particles $\beta_1, \beta_2, \ldots$ must be the same in the corresponding strong and weak interactions if these "partially conserved axial current (PCAC)" ideas are correct. It will certainly be of the highest importance to check these relations experimentally.

Still more remarkable, however, is this. In applying the above ideas to the reaction $\nu + N \to \ell + N + \pi + \pi$, Adler has noticed that one is led to a certain relation which connects the strong pion-nucleon coupling constant G and the pion-nucleon amplitude $A^+$ evaluated at a certain point in the unphysical region.

All weak coupling effects have cancelled out in this relations which therefore amounts to a consistency requirement on the strong interactions for the validity of the PCAC hypothesis. I will not write down the relation in question, but I do assert that it is a completely non-obvious equation. Adler has evaluated the amplitude

$A^+$ at the unphysical point involved by the use of dispersion relations; and he finds that the PCAC relation is remarkably well confirmed. The whole complicated business will be published in due time.

Despite, therefore, the disappointment one may feel at the failure of W meson searches in present high energy neutrino runs it is clear that these experiments have much information to yield. And we now have also to think about CP!

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