Session 5

OTHER ASPECTS OF WEAK INTERACTIONS: HIGH ENERGY NEUTRINO PHYSICS AND QUESTIONS OF C, P, T NONINVARIANCE

T. D. Lee, Rapporteur

I. High Energy Neutrino Physics

There has been no new discovery made during the last two years by using the high energy neutrinos from the accelerators. For the elastic cross section, all results are still consistent with the crude approximation that the axial-vector form factor is approximately the same as the vector form factor. The lower limit of the mass of the intermediate boson, which has still not been observed, is $m_w > 2$ BeV. The μ neutrino remains different from the e neutrino.

There are two contributions given at the Conference on the cosmic ray neutrino reactions. The first is the Kolar gold field experiment[1] reported by Dr. Menon. There are 11 possible cosmic-ray neutrino events of which 4 are sure. The rate is $\approx 8 \times 10^{-13}$ events per cm^2 per second per steradian. The second is the Case-Witwatersrand experiment[2] reported by Dr. Reines. There are 17 sure events and the rate is $\lesssim 5 \times 10^{-13}$ events per cm^2 per second per steradian.

Both results are consistent with the hypothesis that these neutrinos are generated from the cosmic rays in the atmosphere. There is no evidence of any anomalous neutrino source or any anomalous high energy neutrino cross section, nor any evidence of the intermediate boson with $m_w \lesssim 2$ to 3 BeV.

II. Phenomenological Analysis of CP-Nonconserving Interactions

Next, we discuss the present theoretical status of CP nonconservation. The experimental situation was beautifully summarized by Professor Fitch yesterday; after two years, there remains only the $K_2^0 \to \pi^+\pi^-$ decay[3] that shows CP nonconservation. In other reactions, such as η^0 decay, the experimental situation on CP violation is unclear and confused. I am happy to say that it is quite the opposite on the theoretical side. Two years ago there was almost no theory predicting CP nonconservation; now, there are far too many different kinds of CP-violating theories.

We may write for the total Hamiltonian

$$H = H_+ + H_- ,$$

where $$(CP)H_\pm(CP)^{-1} = \pm H_\pm .$$

From $K_2^0 \to \pi^+\pi^-$, we know only that the CP = -1 interaction H_- exists, but of its other properties, very little is known. The different types of CP-nonconserving interaction H_- can be classified[4] according to its selection rule with respect to the strangeness S. (See the table.)

Now, the K_1^0 and K_2^0 states are related to the K^0 and $\bar{K}^0$ states (provided CPT theorem holds) by

$$K_1^0 = [(1+\epsilon)K^0 + (1-\epsilon)\bar{K}^0] \times 1/\sqrt{2}(1+|\epsilon|^2)$$

	Coupling constant of H_-	Selection rule of H_-
Superweak (Ref. 5)	$\approx 10^{-9}\ G_{wk}$	$\Delta S = \pm 2$ allowed
Weak (Ref. 6)	$10^{-1} - 10^{-3}\ G_{wk}$	$\Delta S = \pm 1$ allowed $\Delta S \neq \pm 2$
Nonweak (Ref. 7, 8)	e (electromagnetic) $10^3\ G_{wk}$	$\Delta S = 0$ only P conserved C nonconserved

and

$$K_2^0 = [(1+\epsilon)K^0 - (1-\epsilon)\bar{K}^0] \times 1/\sqrt{2}(1+|\epsilon|^2) ,$$

where $\bar{K}^0 = (CPT)K^0$.

If H_- is Wolfenstein's superweak interaction, then neglecting effects $O(F/G_{wk}) \sim O(10^{-9})$, only in the decays of K_1^0 and K_2^0 can one detect any CP violations; furthermore, all such CP violations are characterized by the single parameter ϵ, which, in this case, has already been measured:

$$|\epsilon| = |\eta_{+-}| = (1.83 \pm .12) \times 10^{-3}$$

and $$\arg \epsilon = \tan^{-1} 2(m_2 - m_1)/\gamma_1 \approx 42° .$$

It should, however, be emphasized that in any case, from the various known decay amplitudes of K_1^0 and K_2^0, one can establish[9] that $\arg \epsilon = 42° \pm (\lesssim 15°)$, independent of the underlying mechanism of H_-, whether it is weak or nonweak. In general, the parameter η_{+-} is given by $\eta_{+-} = \epsilon + \epsilon'$, where ϵ' is due to the CP-violating amplitude in the I = 2 two-pion state. Although $\eta_{+-} = \epsilon$ in the superweak case, a great variety of other possibilities would also lead to $\eta_{+-} \approx \epsilon$; for example, if one assumes that only $\Delta I = 1/2$ transitions violate CP. Thus, it is difficult to use measurements on, say, $\arg \eta_{+-}$ to establish the validity of the superweak case, unless such a phase is measured to an accuracy of within $\approx 1°$.

From a phenomenological point of view, the superweak interaction gives definite predictions about all CP-violating amplitudes, namely, zero for all processes except the decays of the neutral K mesons. If this is the case, then for all practical purposes, we have already determined all that could be measured concerning CP-violating parameters, and it will take a very long time for us to learn anything more about the CP-violating interaction. The superweak interaction has a certain appeal, because, then, we do not have to think any more.

If the CP-violating interaction belongs to the "weak" case, then there should be other weak processes besides K_1^0, K_2^0 decays that exhibit some small CP violations; if the CP-violating interaction belongs to the "nonweak" case, then in addition, there should be some strong processes that exhibit small C or T violations; if the CP-nonconserving interaction is the electromagnetic case, then, in addition, there should be some electromagnetic processes that have sizable C, T noninvariant amplitudes. To be sure, none of these effects can be detected easily, and this accounts for the present remarkable lack of new experimental information.

From the theoretical side, the difficulty is the other way around. It is too easy to add a small C- or CP-violating term to the present strong or weak interaction. The difficulty is to develop some principles which might enable one to make selections among this multitude of such possibilities. In case the CP-violating interaction is the electromagnetic interaction, some relatively exact statements can be made, because of charge conservation and the possibility of a minimal interaction principle.

III. Some Properties of Q_K and η^0 Decay

Let us discuss the case in which the strong interaction is assumed to be invariant under a particle-antiparticle conjugation operator $C \equiv C_{st}$,

$$[C_{st}, H_{st}] = 0,$$

but

$$[C_{st}, H_\gamma] \neq 0.$$

Let

$$\mathcal{J}_\mu = \text{hadronic electromagnetic current,}$$

$$\mathcal{J}_\mu = J_\mu + K_\mu,$$

$$C_{st} = -1 : \; J_\mu = \tfrac{1}{2}(\mathcal{J}_\mu - C_{st}\mathcal{J}_\mu C_{st}^{-1}),$$

$$+1 : \; K_\mu = \tfrac{1}{2}(\mathcal{J}_\mu + C_{st}\mathcal{J}_\mu C_{st}^{-1})$$

Since $\mathcal{J}_\mu$ is absolutely conserved, and C_{st} is conserved under H_{st}, it follows that, under H_{st}, J_μ and K_μ are separately conserved. Thus, the charges

$$Q_J = -i \int J_4 d^3 r$$

and

$$Q_K = -i \int K_4 d^3 r$$

must be separately conserved quantities under H_{st};

$$[Q_J, C_{st}] = 0$$

and

$$\{Q_K, C_{st}\} = 0.$$

The total charge is $Q = Q_J + Q_K$.

It is easy to show[10] that $Q_K \mid \text{known particle}\rangle = 0$. This follows simply from the fact that all known particles change the sign of their charges under C_{st}. Thus, particles with $Q_K \neq 0$ must be some unknown particles called $a^\pm$:

$$Q_K \mid a^\pm\rangle \neq 0.$$

Under fairly general conditions, it can also be shown that as operators[11] Q_K = isoscalar, $Q_J = I_z + Y/2$, even though the isospin of the $a^\pm$ particles is not zero; i.e., the commutation relations between Q_K and the isospin vector $\underset{\sim}{I}$ are just like that between the usual hypercharge $\tilde{Y}$ and $\underset{\sim}{I}$.

If we assume that K_μ and J_μ transform under $\underset{\sim}{I}$ like Q_K and Q_J, then we find K_μ = isoscalar, and J_μ = isoscalar + isovector.

We list the various consequences if K_μ is isoscalar:

1. To the lowest order in α, because of isospin conservation, $\eta^0 \not\to \pi^0 + e^+ + e^-$.

2. To the lowest order in α, there is no time-reversal violation effect in $\Sigma^0 \to \Lambda^0 + e^+ + e^-$.

3. In $\eta^0 \to \pi^+ + \pi^- + \pi^0$, the final $C_{st} = -1$ three-pion state must be of I = 0, the $\pi^\pm$ asymmetry parameter is given by $A \approx (kR)^6 \sin(\delta_1 - \delta_0)$, where δ_1, δ_0 are the strong-interaction 3π eigen phase shifts in the I = 1 and I = 0 states, respectively. Furthermore, this asymmetry would change sign between the neighboring sextants in the Dalitz plot.

The interaction radius R is, of course, not known. If we take $R \sim 1/m_\eta$, then we find $|A| < 10^{-3}$. Because of the factor $(kR)^6$, this upper limit is very sensitive to the value of R asssumed.

4. In $\eta^0 \to \pi^+ + \pi^- + \gamma$, the $\pi^\pm$ asymmetry has an upper limit $|A| < [\sim 1.5\,\%]$ if $R \sim 1/m_\eta$.

Thus, none of these is particularly sensitive to the isoscalar current K_μ. More sensitive tests can be made by studying the inelastic collision of e^- on polarized targets,[12] the reciprocity relation[13] on $\gamma N \rightleftarrows \pi N$, and[14] $\gamma d \rightleftarrows np$. If there exists a strangeness-conserving nonleptonic weak interaction, then one may try to measure the magnitude of the electric dipole moment of the neutron, and use it as a test[15] of T invariance of the electromagnetic interaction.

If, on the other hand, one finds experimentally that the final 3π in the $\eta^0 \to \pi^+\pi^-\pi^0$ can be in an I = 2 (which has $C_{st} = -1$) state, the $\pi^\pm$ asymmetry is given approximately by $A \sim (kR)^2 \sin(\delta_1 - \delta_2)$, which can be much larger ($\lesssim$ 5 %) than the previous $I_{3\pi} = 0$ case, even if $R \approx 1/m_\eta$. This then would lead to the interesting conclusion not only that C violation is not weak, but if it is due to the electromagnetic interaction, then the isospin transformation property of K_μ is not proportional to its charge Q_K. In the same connection, it has been suggested by Dr. Okun[16] and discussed by Dr. Kabir in this Conference that one may also ask whether the isospin property of J_μ is, or is not, proportional to Q_J; i.e., whether the well-known selection rule $\Delta I = 0, 1$ of the electromagnetic interaction is really a valid one.

Independent of the result of 3π asymmetry in η^0 decay, any proposal in which $K_\mu \neq 0$ has to encounter the question: Why is the particle-antiparticle conjugation determined by the strong interaction different from the usual charge-conjugation operation? This leads us to discuss a simple model of all interactions.

IV. A Simple Model

At present, we know that

$$H_{wk} = G_{wk}\Sigma(V_\lambda^{wk} + A_\lambda^{wk})^\dagger \cdot (V_\lambda^{wk} + A_\lambda^{wk}),$$

$$H_\lambda = e V_\lambda^\gamma \cdot A_\lambda,$$

where A_λ denotes the electromagnetic field, and V_λ^γ the electromagnetic current. In general, there are various particles with different spins; V_λ^γ can be written as

$$V_\lambda^\gamma = V_\lambda^\gamma(\text{spin } 0) + V_\lambda^\gamma(\text{spin } 1/2) + V_\lambda^\gamma(\text{spin } 1) + \cdots .$$

We observe that, at least for the free particle and at the zero mass limit for spin 1/2 particles, these currents obey the following two properties:

(a) they are all bilinear functions of field operators with the minimum number of derivatives,

(b) $\partial V_\lambda^i/\partial X_\lambda = \partial A_\lambda^i/\partial X_\lambda = 0$. For V_λ^γ, (a) is identical with the minimal principle of electromagnetic interaction; (b) holds for the leptonic part of $(V_\lambda + A_\lambda)^{wk}$ only at the zero mass limit; the same applies to the hadronic part of A_λ^{wk}.

In this model, let us propose that

$$H_{st} = G_{st}(A_\lambda^{st})_j^i \cdot (A_\lambda^{st})_i^j,$$

where i and j vary from 1 to 3, and all repeated indices are summed over. The V_λ^γ is related to V_λ^{wk} and A_λ^{st} is related to A_λ^{wk}.

What we will show is that if A_λ^{st} consists of some charged spin-1 field,

$$A_\lambda^{st} = A_\lambda^{st}(\text{spin } 1/2) + A_\lambda^{st}(\text{spin } 1),$$

then $C_{st} \neq C_\gamma$. To show this, let us recall that the currents which satisfy the above conditions (a) and (b) for different spin fields are

spin 0, $$V_\lambda = i\left(\frac{\partial\phi^\dagger}{\partial X_\lambda}\phi - \phi^\dagger\frac{\partial\phi}{\partial X_\lambda}\right),$$

spin 1/2, $$V_\lambda = i\psi^\dagger\gamma_4\gamma_\lambda\psi,$$

$$A_\lambda = i\psi^\dagger\gamma_4\gamma_\lambda\gamma_5\psi,$$

spin 1, $$V_\lambda = i\left(\frac{\partial\phi_\mu^\dagger}{\partial X_\lambda}\phi_\mu - \phi_\mu^\dagger\frac{\partial\phi_\mu}{\partial X_\lambda}\right) + \cdots,$$

$$A_\lambda = \epsilon_{\lambda\rho\mu\nu}\frac{\partial}{\partial X_\rho}(\phi_\mu^\dagger\phi_\nu).$$

If one defines the charge-conjugation operator as

$$C_\gamma\phi C_\gamma^{-1} = \phi^\dagger,$$

$$C_\gamma\psi C_\gamma^{-1} = \psi^\dagger \quad (\text{Majorana representation}),$$

$$C_\gamma\phi_\mu C_\gamma^{-1} = \phi_\mu^\dagger,$$

then one finds

	spin 0	spin 1/2	spin 1
$C_\gamma V_\lambda C_\gamma^{-1}$	$-V_\lambda$	$-V_\lambda$	$-V_\lambda$
$C_\gamma A_\lambda C_\gamma^{-1}$	---	$+A_\lambda$	$-A_\lambda$

Thus, if there exists a sum of such spin 1/2 and spin 1 currents in the strong-interaction current A_λ, then the strong interaction cannot be invariant under the charge-conjugation operator (provided that the spin 1 field is charged). To be specific, let us assume the existence of a spin 1/2 unitary triplet field ψ_i and a charged unitary singlet spin 1 field ϕ_μ:

$$(A_\lambda^{st})_j^i = i\psi_i^\dagger\gamma_4\gamma_\lambda\gamma_5\psi_j + \delta_j^i\,\epsilon_{\lambda\rho\mu\nu}\frac{\partial}{\partial X_\rho}(\phi_\mu^\dagger\phi_\nu)$$

$$H_{st} = G_{st}(A_\lambda^{st})_j^i(A_\lambda^{st})_i^j.$$

Define

$$C_{st}\psi_i C_{st}^{-1} = \psi_i^\dagger, \qquad C_{st}\phi_\mu C_{st}^{-1} = \phi_\mu.$$

Then, we have

$$C_{st}(A_\lambda^{st})_j^i C_{st}^{-1} = (A_\lambda^{st})_i^j$$

and $$C_{st}H_{st}C_{st}^{-1} = H_{st}.$$

In this model, the usual octet part of the $(A_\lambda^{st})_j^i$ current is related to the hadronic part of A_λ^{wk}, and it is easy to verify that H_i is invariant under C_i, P_i, T_i, where i = st, γ or wk, and $C_i P_i T_i$ = same. The C_i operator is defined by

$$C_{st}(A_\lambda^{st})_j^i C_{st}^{-1} = (A_\lambda^{st})_i^j,$$

$$C_\gamma(V_\lambda^\gamma)C_\gamma^{-1} = -V_\lambda^\gamma,$$

$$C^{wk}(V_\lambda + A_\lambda)^{wk}C_{wk}^{-1} = (V_\lambda + A_\lambda)^{wk\dagger}.$$

Because of the difference between these currents we find

$$C_{st} \neq C_\gamma \neq C_{wk} \neq C_{st},$$

and because $C_i P_i T_i$ = same, we find the various nonconservations of P_i and T_i. This model is only a simple illustration of how C_{st} can be different from C_γ.

In this model, the C_{st}-violating current is simply the minimal vector current of the spin 1 field, and it is an isoscalar.

Let $|a^\pm\rangle$ denote the particle state associated with such a spin 1 field ϕ_μ. It is clear that $a^\pm$ does not correspond to any known particle. If one is in the spirit of Gell-Mann's "chimeron," one may say that $a^\pm$ is also the intermediate boson of the weak interaction, although I will not assume it to be also a magnetic monopole.

V. Some General Remarks

In conclusion, I would like to make some general remarks about the question of C, P, T nonconservation. Our views of such discrete symmetries have undergone great changes in recent years. Although P and C symmetries have been well established since 1957 as only approximately valid, until the recent discovery of the 2π decay of the long-lived K_2^0 meson it was still possible to believe the essential symmetry of right and left by using CP, instead of P. From a fundamental point of view, therefore, the discovery of CP violation in K_2^0 decay and the indirect conclusion of time-reversal asymmetry are a more decisive blow to our notions on geometric symmetry principles than earlier results.

Indeed, the fact that P, CP, and T symmetries are violated means that these operators are not defined. To see this, let us recall that the space-inversion operator P (or, CP) in the Hilbert space should represent the coordinate transformation P (or CP): $\vec{r} \to -\vec{r}$, $t \to +t$. Now, the time translation operator is $e^{-iH\tau}$: $\vec{r} \to +\vec{r}$, $t \to t + \tau$. From a geometrical point of view, it is obvious that the space inversion $\vec{r} \to -\vec{r}$ must commute with the time translation $t \to t + \tau$. On the other hand, $[H, P] \neq 0$ (or $[H, CP] \neq 0$) implies that the alleged space-inversion operator P (or CP) fails to satisfy the multiplication law of the coordinate transformations that it is supposed to represent; thus, the fact that the space-inversion symmetry is being violated shows that the operator P (or CP) cannot be exactly defined. The same arguments can be applied equally well to the time-reversal operator.

We may, however, give an approximate definition of P, C, and T by replacing the total interaction H by a certain part H_i, such that within this approximation H_i is invariant under C_i, P_i, and T_i. It is clear that operators C_i, P_i, T_i thus defined depend on the approximation $H \approx H_i$. We know that if $H \approx H_{st}$, then there exists a C_{st}, P_{st}, and T_{st} operator. The (C_{st} P_{st}) and T_{st} symmetries thus defined must be violated by some other interactions. But at present it is not clear by what part of the interaction, whether it is electromagnetic or whether it is by some other interactions.

The evolution of our views on these discrete symmetry operators has been one of the most remarkable ones in physics. Apart from its physical information and philosophical implications, it certainly has demonstrated to us in a most forceful way the necessity of keeping an open-minded approach in physics. The search for the origin of CP violation is certainly a difficult one; yet, this difficulty is precisely its challenge. Let me hope that in the next Conference, we may have not one but many solid pieces of experimental information on CP violation to discuss, instead of merely theoretical speculations, as I have given you today.

Footnotes and References

1. C. V. Achar, M. G. K. Menon, V. S. Narasimham, P. V. Ramana Murthy, B. V. Sreekantan, K. Hinotani, S. Miyake, D. R. Creed, J. L. Osborne, J. M. B. Pattison, and A. W. Wolfendale, Detection of Muons Produced by Cosmic Ray Neutrinos Deep Underground, Paper 5b.1.

2. F. Reines, M. F. Crouch, T. L. Jenkins, W. R. Kropp, H. S. Gurr, and G. R. Smith, Phys. Rev. Letters 15, 429 (1965).

3. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

4. T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965).

5. The possibility of a superweak interaction was first pointed out by L. Wolfenstein, Phys. Rev. Letters 13, 562 (1964). The general implication of the superweak interaction was discussed by Lee and Wolfenstein (Ref. 4).

6. The possibility that the CP violation is due to the weak interaction is an obvious one after the experimental discovery of $K_2^0 \to \pi^+\pi^-$. The precise mechanism of such a weak CP violation has been the subject of many theoretical papers. We give only an incomplete list of these papers: R. G. Sachs, Phys. Rev. Letters 13, 286 (1964); T. N. Truong, Phys. Rev. Letters 13, 358a (1964); 17, 153 (1966); S. L. Glashow, Phys. Rev. Letters 14, 35 (1965); E. P. Shabalin, J. E. T. P. Letters 2, 276 (1965); N. Cabibbo, Phys. Letters 12, 137 (1964); L. Wolfenstein, Phys. Letters 15, 196 (1965); Okun and Zeldovic, Phys. Letters 16, 319 (1965). See also F. Salzmann and G. Salzmann, Phys. Letters 15, 91 (1965), and B. A. Arbuzov and A. T. Filippov, Phys. Letters 20, 537 (1966).

7. J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 138, B1650 (1965); see also S. Barshay, Phys. Letters 17, 78 (1965).

8. T. D. Lee and L. Wolfenstein (Ref. 4); L. B. Okun, Soviet J. Nucl. Phys. 1, 670 (1965); J. Prentki and M. Veltman, Phys. Letters 15, 88 (1965).

9. See, especially, L. Wolfenstein, Nuovo Cimento 62A, 17 (1966).

10. T. D. Lee, Phys. Rev. 140, B959 (1965).

11. For a brief discussion, see footnote 20 of Ref. 10. A general proof is given elsewhere.

12. N. Christ and T. D. Lee, Phys. Rev. 143, 1310 (1966); see also C. A. Piketty, Nuovo Cimento 44A, 39 (1966); B. Desplanques and G. Karpman, Nuovo Cimento 38, 627 (1965).

13. N. Christ and T. D. Lee, Phys. Rev. 148, 1520 (1966).

14. S. Barshay, Phys. Rev. Letters 17, 49 (1966).

15. G. Feinberg, Phys. Rev. 140, B1402 (1965).

16. A. D. Dolgov, A. B. Kaidalov, I. Yu. Kobzarev, L. B. Okun, and V. I. Zakharov, On Possible Violation of the $\Delta T = 0$, 1 Rule for Electromagnetic Current, Paper 5a.5.

Discussion

Barshay (Rutgers): Professor Lee, could you comment on the possible decay modes of this new particle, should it exist? Could it have also strong or electromagnetic decays?

Lee: I do not know if it exists. If the hypothetical spin 1 particle is also the weak intermediate vector boson, it will decay just like the usual one. It could not decay by a strong or electromagnetic decay. K_μ is conserved in the strong interactions and also in the electromagnetic interactions in the model.

Truong (Brown): I would like to ask what average P-wave $\pi\pi$ phase shift do you use to estimate the asymmetry in $\eta^0 \to \pi^+\pi^-\gamma$ decay?

Lee: What I use is an upper limit, not an estimation, which is 30°. This is as large as I think you can have. Therefore, if it's much smaller you can scale accordingly.

Truong: I think that the value of 30° is too large if one extrapolates the $\pi\pi$ P-wave phase shift from the ρ resonance. The asymmetry should be much smaller, as you estimated. There is another process where the $\pi\pi$ interaction is large and has much larger asymmetry. Barrett and I have calculated the asymmetry in $\eta' \to \pi^+\pi^-\gamma$ decay and found that it is large.

Lee: In the η' there is one difficulty. There is probably another neutral particle, the X', which has the same mass as the η' but a different isospin value.

Truong: There is another way of testing C violation in electromagnetic interactions, namely trying to detect an effect in weak interactions other than $K_L \to 2\pi$. One should try to find asymmetry in spectra and partial rate of τ^+ vs τ^-, τ'^+ vs τ'^- and also $\pi^+\pi^-$ asymmetry in $K_L^0 \to \pi^+\pi^-\pi^0$.

Feinberg (Columbia): A measurement of the electric dipole moment of the neutron to an accuracy of 10^{-24} e·cm would be very useful in distinguishing between the different alternatives for explaining the CP violation. In the hypothesis of superweak interactions, one expects an electric dipole moment of less than 10^{-28} e·cm. In the hypothesis of 10^{-2} violation in weak interactions, one expects a dipole moment of about 10^{-23} e·cm. In the hypothesis of a large electromagnetic T violation, one expects a dipole moment of about 10^{-20} e·cm, so these alternatives can be easily distinguished by the prospective measurements to be done at Brookhaven and Oak Ridge.

Lee: Yes, so the future looks very bright. [It is important to note that these estimations depend sensitively on the additional assumption that there exists a $\Delta S = 0$, nonleptonic weak interaction which has a coupling constant comparable in magnitude to that of β decay. If such an interaction does not exist, then the expected value of the neutron electric dipole moment would be $\approx 10^{-26}$ e·cm if the T violation is due to the electromagnetic interaction, and $\approx 10^{-28}$ to 10^{-29} e·cm if the T violation is due to the weak interaction.]

Nauenberg (Santa Cruz): Have you looked into the effect of the $\pi^{\pm}\pi^{0}$ mass difference on the $\pi^{+}\pi^{-}$ asymmetry in η decay under the assumption that the C-violating transition is $\Delta I = 0$?

Lee: I believe there was one discussion during the Conference by Dr. Shaw. The idea is that the pions have a mass difference, so that even if the C violation is $\Delta I = 0$ you can mix in some $\Delta I = 2$ through this mass difference. To begin with, let us ask what will be the asymmetry even if you have pure $\Delta I = 1$ for K_{μ} and $\Delta I = 0, 1$ for J_{μ}. In this case, the final 3π can be in an $I = 2$, $C = -1$ state, and the $\pi^{\pm}$ asymmetry parameter can be estimated to be $A \approx (kR)^2 \sin(\delta_1 - \delta_2)$, where δ_1 and δ_2 are the 3π eigen phase shifts for the $I = 1$ and $I = 2$ final states. If K_{μ} is pure $\Delta I = 0$, then $A \approx (kR)^6 \sin(\delta_1 - \delta_0)$. What Dr. Nauenberg wants to point out, which has been discussed by Dr. Shaw, is that through the pion mass difference there can be an $I = 2$ three-pion final state even if K_{μ} satisfies the $\Delta I = 0$ rule; this will give a $\pi^{\pm}$ asymmetry $A \approx (\Delta m/m)(kR)^2 \sin(\delta_1 - \delta_2)$, which is the order of 10^{-3} if we take the interaction radius to be of the order of m_{η}^{-1}. Now, one can push this a little, but it seems extremely hard to get something of the order of a few percent.

Frazer (San Diego): I would like to comment on the sensitivity of time-reversal tests in photo- or electroproduction of pions in the region of the $N^*(1238)$. Here we are in the unusual situation of having a quite successful dynamical theory—the Chew-Goldberger-Low-Nambu theory. If one examines this theory, he finds that T invariance is not a necessary assumption. The weaker assumption of Hermitian analyticity (which is about as well-founded as crossing) suffices. Therefore, any T violation must fit into the discrepancy between the CGLN theory and experiment. Perhaps the situation would be more favorable at the higher-energy resonances.

Lee: I think this remark is a relevant one. On the other hand, one can also look apart from the theoretical point of view and examine the experimental situation—the question of measuring, say, the relative phase in the M1(3/2) and the E1(1/2). Now, we may ask: Independent of theory, can we measure the relative phase? The answer is yes. If you measure, to the order of 10% accuracy at the right energy and the right angle, the reciprocity, then you would measure this relative phase angle to the order of 10° accuracy. Dr. Frazer stressed that by using the Chew-Goldberger-Low-Nambu theory, one can get a relatively small deviation for this phase angle at the first resonance even if there is a basic large T violation.

Barshay: I comment on Professor Frazer's remark. I think reciprocity should be tested experimentally, not theoretically—in $\gamma + d \rightleftarrows \eta + p$ and $\gamma + p \rightleftarrows \pi^{+} + \eta$, wherever it is possible, at energies about 150 MeV.

Todorov (Dubna): I would like to hear Professor Lee's opinion about the possibility of explaining CP violation by an interaction with strength $e \cdot G_{wk}$. I guess you are classifying this possibility in the group of weak-type interactions. I am referring to the paper by Arbuzov and Filippov (Paper 5a.1, submitted to Physics Letters), in which such a theory is proposed on a geometrical ground.

Lee: I think this is one of the many possible theories. I should mention in this connection that Salzmann and Salzmann have proposed a similar theory by allowing the weak vector boson to have an electric dipole moment. One cannot rule out such theories on the basis of the present experimental data. The situation reminds me of a cosmology; we have only one experiment but many theories. I regard this situation as unhealthy.

Omnes (Strasbourg): Since the intermediate boson is not observed, the rather remote possibility for its being a Regge pole is worth mentioning. It could have spin 1 for zero mass, zero residue, and would respect the locality of weak interactions. It would also explain the seemingly constant neutrino total cross section at high energy. It would never be produced as an observable particle. Analogous considerations can be made in conventional field theory with vanishing form factors at zero momentum transfers. You will never find it.

Michel (Bures-sur-Yvette): I would like to defend the usefulness of P and T even if they are not conserved. For free particles, or in a given reaction, P can be defined kinematically. P and T are elements of the Poincaré group and we know their action on space, time, energy, momentum, and polarization. (T exchanges, of course, initial and final particles in a reaction.)

The confusion you spoke about when considering invariance of Lagrangians can be avoided if one remembers that the discrete operations are defined up to a phase. As is well known to theorists who have worked on it, to prove that a Lagrangian is CPT-invariant and CP-violating, you have to prove that you can find an involutive transformation which has the action-defined CPT and, whatever choice of phase no CP involution can be performed. A likely possibility considered by you and many is that the full Lagrangian is CP-violating and any subpart of it is not, so you cannot blame CP violation for particular interactions, but the coexistence of all of them.

Lee: Kinematically you can, of course, have the coordinate transformations: space inversion and time inversion, but when you have a Lagrangian which is not invariant under any definition of C, P, T then in the Hilbert space, the unitary and the antiunitary operators C, P, T are also not defined (except their product CPT, which is well defined). [For the free particles, P (or CP) and T can indeed be defined. This is because the usual free-particle Lagrangian is invariant under P (or CP) and T. This cannot be (exactly) true for any physical reaction. Of course, one may select, among the infinite variety of possibilities, a specific ad hoc operator "P" in the Hilbert space (applicable to all states) and insist that it correspond to the geometrical transformation $\vec{r} \to -\vec{r}$, $t \to +t$. The fact that this operator "P" does not commute with the time translation operator $e^{-iH\tau}$ shows that the identification of "P" with the space-inversion transformation is an artificial one, except as an approximation.]

Telegdi (Chicago): I have two questions. I am somewhat embarrassed about the first one. I understand so little, so that's why I'm asking you. There was a recent letter by Rolnick which roughly makes the following statement: If one combines your ideas of C violation and some form or other of SU(6) (I have to make that statement carefully since I don't know what's meant by it), if one embraces these ideas one reaches the conclusion that particles of fractional charge are unavoidable— like quarks. Would you like to comment on that?

Lee: No comment.

Gottfried (Cornell): The content of Rolnick's letter is as follows. Let us adopt Professor Lee's suggestion that a nonzero Q_K exists, and amend the Gell-Mann—Nishijima formula accordingly. It is then rather natural to look for a strong-interaction symmetry group that has one generator, Q_K, even under C, as well as the two commuting SU(3) generators T_3 and Y, which are odd under C. However, because C must be an automorphism of this group, one can show that none of the rank-three Lie groups has the properties just delineated. In view of this, there does not seem to be any reason to worry about the question of particles with noninteger charge mentioned by Telegdi.

Telegdi: Second question. After Kabir presented some of his own work and Okun's remarks about this part of the current with isospin 2, there was a small discussion among several people who attended this talk. The quintessence of this talk was that known information on the selection rules in nuclear physics already rules out such currents. Perhaps Professor Radicati could comment on this.

Radicati (Pisa): What do you want me to comment about? I agree with what Telegdi said. There is evidence in nuclear physics coming from the validity of the E1 isotopic spin selection rule that there is no $\Delta I = 2$ component in the electromagnetic current.

Lee: That, I think, is very important. It shows, perhaps, that the idea that the isospin transformation properties of the current and the charge are the same is a useful one.

Kabir (Rutherford): Whatever support the assumed $\Delta I = 0$, 1 selection rule for electromagnetic interaction may receive from selection rules for nuclear γ transitions, this may not be very relevant to the question of possible terms in the electromagnetic current transforming as $|\Delta I| > 1$ objects, because (a) individual nucleons can only have $|\Delta I| \leq 1$ interactions, so that to the extent that the electromagnetic interaction of nuclei is well described by the sum of the interactions of individual nucleons, nuclear interactions are not sensitive tests, and (b) if the $|\Delta I| > 1$ parts of the electromagnetic interaction correspond to vanishing charge, their effects are more likely to appear at momentum transfers greater than those commonly occurring in nucleon transitions.

Low (MIT): In connection with $|\Delta I| = 2$ electromagnetic currents, it is of interest to ask whether $|\Delta I| = 2$ β-decay currents exist. One can examine this by comparing transitions from the two ends of an I = 2 multiplet to an I = 1 multiplet underneath. The data at present appear to show a 1-standard-deviation discrepancy. Also here we must remember that single nucleons can't produce a $\Delta I = 2$ transition, so that many nucleon effects are needed so that the amplitude can be quite suppressed.

A. Goldhaber (Berkeley): What is the basis for the choice of radius in the η decay? This is crucial to the upper limit on C-violating effects.

Lee: There is no real basis. It is only an estimate. If it is much larger than m_η^{-1}, say m_π^{-1}, then kR can be of order unity and the magnitude of the effect can be quite large. However, there is a way to distinguish experimentally $\Delta I = 0$ from $\Delta I = 2$ from the asymmetry of the spectrum. If it is $\Delta I = 0$, the asymmetry must change sign from sextant to sextant, since the C = -1 three-pion state must be a completely antisymmetric one. If it is $\Delta I = 2$, then it will not. By looking at the experimental spectrum, one can then work backwards and see which it is. I believe at present the experimental situation is quite unclear.

Ne'eman (Tel Aviv): Since you haven't sketched your proof of the nonexistence of the isovector possibility, does your proof, in fact, also exclude the possibility of a complete octet multiplet, and: does it also mean that it has to be a unitary singlet in the limit of SU(3)?

Lee: Right, the operator Q_K is also a unitary singlet.

Källen (Lund): I should like to comment about the definition of C, P, and T. It appears to me that the point made by Michel is that there is no difficulty in defining these symmetry operations at a given time. Your statement is that if you perform these operations at different times you get different results. This is certainly correct, but it appears to me that the statement that you cannot define C, P, or T as a consequence of this is a bit extreme. If you only state at which time you perform the symmetry operations, these concepts are perfectly well defined.

Lee: When you have, at every different time, a different definition, that means you have an infinite number of definitions. When anything has an infinite number of definitions, that's as good as being undefined.

Källen: Well, then you define the P operation at a given time; then you know what you're doing.

Lee: You may.

Amaldi (Istituto di Sanità,Rome): Would you comment about the use of the $\phi \to \omega + \gamma$ decay as a measure of CP nonconservation in the hypothesis that K_μ is an isoscalar?

Lee: The $\phi \to \omega + \gamma$ decay is consistent with the $\Delta I = 0$ rule; therefore it is possible in principle. However, the question is the rate. It is not, at this moment, clear what the rate might be. [The $\phi \to \omega + \gamma$ is, however, forbidden by SU(3) symmetry if K_μ transforms like a unitary singlet.]

Weisskopf (MIT): I have a simple question. You said that your new particle, which you called ϕ, might be the W meson, or decay like the W; but if it does so, where does the new kind of charge Q_K go then? It should be conserved, you said.

Lee: Yes, it is conserved by the strong and electromagnetic interactions, but it is not conserved by the weak interaction. You see, in a strict sense, there is only one conservation law for the electromagnetic current; that's the conservation of the total charge. Only because the strong interactions are invariant under C_{st} which is not equal to C_γ do we have two conservation laws. But these separate conservation laws are only approximate.

Nauenberg: It has been repeatedly stated at this Conference that the superweak theory of C violation and most other theories predict the phase of ϵ to be $\approx 42°$. Isn't it true, however, that the sign of ϵ is not predicted?

Lee: To begin with, there is an ambiguity in the sign of ϵ, but it can be determined, since $\eta_{+-} = \epsilon$.

Yang (Stony Brook): In answer to Nauenberg, the sign is not theoretically determined.

Wolfenstein (Carnegie Tech): There is a sign ambiguity. If we write $\epsilon = \epsilon_0 e^{i\delta}$ with δ between +90° and -90°, then the superweak interaction predicts δ but ϵ_0 may be positive or negative and theory cannot tell the sign. This sign determines whether the interference is constructive or destructive, and has now been determined by experiment.

Lee: From the superweak interaction, one determines only the tangent of the phase of ϵ, and there are always two solutions which differ by π. In the same theory, $\epsilon = \eta_{+-}$, and the phase of η_{+-} has now been determined experimentally in the interference experiments.

M. Goldhaber (Brookhaven): What can $2\pi^0$ relative to $\pi^+\pi^-$ decays of K_2^0 teach us to decide among the various models?

Lee: Thank you very much. I meant to mention this point. For the K_2 decay, there are two parameters. One is η_{00}, the amplitude for $K_2 \rightarrow 2\pi^0$ divided by the amplitude for $K_1 \rightarrow 2\pi^0$. If the superweak theory is right, then $\eta_{00} = \eta_{+-} = \epsilon$. However, in many other models, this can also be true, or approximately true. I think only in one specific model is this absolutely not true; that is the model in which the violation is $\Delta I = 3/2$ only. Also, many models do not give you an exact prediction, but only a range of values. The $\Delta I = 3/2$ model is, however, definite, and it gives a factor-of-2 difference; i.e., $\eta_{00} = -2\,\eta_{+-}$.

Sachs (Argonne): I just want to repeat something I said in the discussion. And that is that this equation $\eta_{00} = \eta_{+-} = \epsilon$ is valid for a very wide class of models, not just the superweak model. The only cases in which it's not valid are the cases in which there is a violation in $\Delta I = 3/2$.