region of 300 Mc/sec[8] indicate a value of γ of about 2.6. The frequency distribution of the 18 showers as a function of the total effective number of sparks in the shower is shown in Fig. 3. In order to ascertain if this distribution is compatible with that to be expected for primary electrons with a geomagnetic cutoff at 4.5 BV, spectra of the type $kE^{-\gamma}$, with values of γ between 2 and 3.5, have been converted to shower-size distributions, using the mean value and spread of the distributions obtained during calibration measurements on 3, 4.5, 6, and 8 BeV/c electrons.[6] The experimental distribution is found to be compatible with the assumption that all but one [event A of Fig. 3(a)] of the electrons have momenta above the geomagnetic cutoff value and follow roughly the type of spectrum assumed. It is clear, however, that, with the present statistics, this distribution cannot be used to obtain a precise value of γ. A reliable determination of the energy spectrum requires much larger statistics and, as is planned, measurements of intensity at various latitudes during quite sun conditions.

The electron intensity measured here (which includes particles of both signs) would correspond, on the assumption of an energy spectrum of the type $kE^{-2.5}$ and of a magnetic field of 3×10^{-6} gauss, to a power of synchrotron emission of $(1.7\pm0.5)\times10^{-40}$ erg cm^{-3} Hz^{-1} sec^{-1} at a frequency of 10^9 cps, the critical frequency corresponding to 4.5 BeV/c.

We wish to thank, for their generous assistance, Professor Blamont, Mr. Regipa, and Dr. Lambert in the balloon flight; the groups from College de France, Saclay, and CERN in the calibration measurements; and Professor Labeyrie and Professor Occhialini throughout the work. The Italian group is indebted to the Consiglio Nazionale delle Ricerche for financial support.

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PHENOMENOLOGICAL ANALYSIS OF VIOLATION OF CP INVARIANCE IN DECAY OF K^0 AND $\bar{K}^0$†

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1. It was recently discovered[1] that the long-lived component K_L^0 of K^0-$\bar{K}^0$ decays into the $\pi^+\pi^-$ mode. Now if CP invariance holds, the $CP=+1$ and $CP=-1$ components of K^0-$\bar{K}^0$ decay independently. The $\pi^+\pi^-$ mode in the S-wave state has $CP=1$. Hence either the short-lived component K_S^0, or K_L^0, does not decay into $\pi^++\pi^-$, in contradiction to the new discovery.

Accepting the experimental result of reference 1, one is thus forced to the conclusion that CP invariance is violated in K^0-$\bar{K}^0$ decay, as explicitly stated in reference 1. Notice that this conclusion is independent of the details of the Weisskopf-Wigner formulation[2] of decay amplitudes, as applied to the K_0-$\bar{K}_0$ case by Lee, Oehme, and Yang,[3] whose notation we shall follow.[4] (In particular, small corrections to the exponential decay rule of the formalism cannot alter the conclusion that CP invariance is violated.)

In the present note we shall analyze the decay properties of K^0-$\bar{K}^0$, mostly from the phenomenological viewpoint. Possible further experiments will be discussed for their theoretical significance.

We shall assume CPT invariance, the validity of the Weisskopf-Wigner formulation,[2,3] and that for the strong and electromagnetic interactions, separate C, P, and T invariance hold.

In the next five sections, we shall also assume that electromagnetic interactions can be neglected, and that isotopic spin is conserved for the strong interactions. We shall come back to the electromagnetic effects in Sec. 7.

2. The experimental decay rates are tabulated in Table I. (We thank P. Franzini, J. Steinberger, and W. Willis for supplying the entries.)

To analyze the decay of K^0-$\bar{K}^0$ we consider the decay matrix

$$\Gamma = \Gamma_0 + \Gamma_2 + \Gamma_l + \Gamma_{3\pi}, \tag{1}$$

and the mass matrix

$$M = M_0 + M_2 + M_l + M_{3\pi} + \cdots, \tag{2}$$

as sums of contributions from the $\pi\pi(I=0)$, $\pi\pi(I=2)$, leptonic, and 3π modes. One has, in the notation of reference 3,

$$\Gamma_0 = \begin{pmatrix} A_0^2 & A_0^2 \\ A_0^2 & A_0^2 \end{pmatrix}, \tag{3}$$

$$\Gamma_2 = \begin{pmatrix} A_2A_2^* & A_2^2 \\ A_2^{*2} & A_2A_2^* \end{pmatrix}, \tag{4}$$

$$\Gamma_l = \begin{pmatrix} \alpha_l & x_l + iy_l \\ x_l - iy_l & \alpha_l \end{pmatrix}, \tag{5}$$

and

$$\Gamma_{3\pi} = \begin{pmatrix} \alpha_{3\pi} & x_{3\pi} + iy_{3\pi} \\ x_{3\pi} - iy_{3\pi} & \alpha_{3\pi} \end{pmatrix}, \tag{6}$$

Table I. Experimental decay rates in 10^6 sec^{-1}.

Mode	K_S^0	K_L^0
$\pi^+ + \pi^-$	$\frac{2}{3} \times 1.1 \times 10^4$	2.6×10^{-2}
$\pi^0 + \pi^0$	$\frac{1}{3} \times 1.1 \times 10^4$	Not known
Leptons	~ 11	~ 11
$\pi^+ + \pi^- + \pi^0$	$\lesssim 2$	~ 2
$3\pi^0$	$\lesssim 4$[a]	~ 4
All modes	1.1×10^4	~ 18

[a]No available experimental information; the number given is based on the assumption that the $|\Delta| = \frac{1}{2}$ rule is approximately valid.

where A_0 and A_2 are the decay amplitudes of

$$K^0 \to \pi + \pi \;\; (I=0 \text{ standing wave})$$

and

$$K^0 \to \pi + \pi \;\; (I=2 \text{ standing wave}),$$

respectively. We have chosen the phase of K^0 so that

$$A_0 = \text{real} > 0. \tag{7}$$

We emphasize that this choice, which is always possible, serves to define the phase of K and $\bar{K}$. The quantities p and q are given by

$$p^2 = A_0^2 + A_2^2 + x_l + iy_l + x_{3\pi} + iy_{3\pi} + iM_r - M_i,$$

and

$$q^2 = A_0^2 + A_2^{*2} + x_l - iy_l + x_{3\pi} - iy_{3\pi} + iM_r + M_i, \tag{8}$$

with the real parts of p and q chosen ≥ 0. In Eq. (8) $M_r + iM_i = M_{12}$ is an off-diagonal element of M. The eigenstates and the eigenvalues of $\Gamma + iM$ were given by Eqs. (28) and (29) of reference 3. The decay amplitudes of K_S and K_L into π-π states are easily constructed, and are tabulated in Table II. The quantity F is

$$F = \exp[i(\delta_2 - \delta_0)], \tag{9}$$

where δ_2 and δ_0 are the π-π S-wave scattering phase shifts for the $I=2$ and $I=0$ states at the energy of the rest mass of K^0. Obviously,

$$R[K_S^0 \to \pi + \pi] + R[K_L^0 \to \pi + \pi] = 2A_0^2 + 2A_2A_2^* \sim 1.1 \times 10^4,$$

$$R[K_S^0 \to \text{lep}] + R[K_L^0 \to \text{lep}] = 2\alpha_l \sim 22,$$

and

$$R[K_S^0 \to 3\pi] + R[K_L^0 \to 3\pi] = 2\alpha_{3\pi} \sim 12. \tag{10}$$

The following quantities are of intrinsic experimental interest:

$$\eta_{+-} = a_{+-}^L / a_{+-}^S, \quad \eta_{00} = a_{00}^L / a_{00}^S. \tag{11}$$

We shall also use

$$\epsilon = (p-q)/p. \tag{12}$$

These quantities are useful because they are small parameters, as we shall see later.

3. The following remarks serve to orient further analysis:

(a) If $\text{Im}A_2 = 0$, $y_l = 0$, $y_{3\pi} = 0$, and $M_i = 0$, then $p = q$, and Table II shows that $K_L \not\to \pi + \pi$, in con-

Table II. Decay amplitudes of K_S and K_L into π-π states.

State	Amplitudes[a]
$I=0$ (standing wave)	$a_0 = A_0(pp^* + qq^*)^{-1/2}(p \pm q)$
$I=2$ (standing wave)	$a_2 = (pp^* + qq^*)^{-1/2}(A_2 p \pm A_2^* q)$
$\pi^+ + \pi^-$ (outgoing wave)	$a_{+-} = (pp^* + qq^*)^{-1/2}\{[(\frac{2}{3})^{1/2}A_0 + (\frac{1}{3})^{1/2}A_2F]p \pm [(\frac{2}{3})^{1/2}A_0 + (\frac{1}{3})^{1/2}A_2^*F]q\}$
$\pi^0 + \pi^0$ (outgoing wave)	$a_{00} = (pp^* + qq^*)^{-1/2}\{[(\frac{1}{3})^{1/2}A_0 - (\frac{2}{3})^{1/2}A_2F]p \pm [(\frac{1}{3})^{1/2}A_0 - (\frac{2}{3})^{1/2}A_2^*F]q\}$

[a]Upper sign for K_S, lower sign for K_L.

tradiction with the experimental result of reference 1.

(b) If $\Delta Q = \Delta S$ for the leptonic decay modes of K^0-$\bar{K}^0$, then Γ_l and M_l of Eqs. (1) and (2) are both multiples of the unit matrix. Therefore, $y_l = 0$. The leptonic mode does not in this case contribute to CP violation as observed in reference 1, even though the lepton mode itself could violate CP invariance. We shall, however, not make the assumption that $\Delta Q = \Delta S$ in this paper.

(c) Phenomenologically, it is not possible to distinguish between the four M's on the right-hand side of Eq. (2). In other words, measurable quantities can only depend on M, but not on M_0, M_2, M_l, or $M_{3\pi}$ separately.

(d) If $\mathrm{Im}A_2 = 0$, then Table II gives directly

$$a_{+-}{}^{\mathrm{L}}/a_{+-}{}^{\mathrm{S}} = a_{00}{}^{\mathrm{L}}/a_{00}{}^{\mathrm{S}}. \qquad (13)$$

(e) If $M_i = 0$, and $y_l + y_{3\pi} = 0$, then $p^2 - q^2 = A_2^2 - A_2^{*2}$. It will be clear in Sec. 4 that

$$|a_0{}^{\mathrm{L}}/a_2{}^{\mathrm{L}}| = O(\mathrm{Re}A_2/A_0), \qquad (14)$$

provided that $|A_2|/A_0$ is small.

(f) If $\mathrm{Im}A_2 = 0$ and $M_i = 0$, then, given the experimental decay rates of K^0-$\bar{K}^0 \to$ leptons and 3π, and of $K_S \to \pi + \pi$, the rate $K_L \to \pi^+ + \pi^-$ is at most $1.75[1 + (M_\gamma/A_0{}^2)^2]^{-1} \times 10^{-2}$. This is too low to account for the experimental result of reference 1. We shall discuss this in more detail in Sec. 5.

Accordingly, roughly there are four ways to violate CP invariance in the decay of K^0-$\bar{K}^0$, namely, $\mathrm{Im}A_2 \neq 0$, $y_l \neq 0$, $y_{3\pi} \neq 0$, and/or $M_i \neq 0$. They correspond to CP (or T) noninvariance due to the interference between the dominant $\pi\pi(I=0)$ mode and (α) the $\pi\pi(I=2)$ mode ($\mathrm{Im}A_2/A_0 \neq 0$); ($\beta$) the lepton mode ($y_l \neq 0$), ($\gamma$) the 3π mode ($y_{3\pi} \neq 0$), and/or (δ) the off-energy shell contributions to the $K \leftrightarrow \bar{K}$ elements of the mass operator $M(M_i \neq 0)$. This possibility has been discussed by Sachs and Treiman.[5]

According to (f) above, (β) and (γ) together by themselves are too small to account for the magnitude of the observed effect. Thus the more important contribution to the observed CP violation has to come from (α) and/or (δ). [Theoretically it is, of course, to be expected that if any interference of the type (α), (β), or (γ) is present, then an interference of type (δ) is also present, in general.]

4. The $|\Delta I| = \frac{1}{2}$ rule is well verified in general, and for the $K \to \pi + \pi$ decay in particular. Thus, $|A_2/A_0| \ll 1$. Dropping A_2/A_0 in Table II, we obtain

$$\eta_{+-} \sim (p-q)/(p+q) = \epsilon/(2+\epsilon). \qquad (15)$$

Thus the experimental small value of $|\eta_{+-}|$ shows that $|\epsilon| \ll 1$.

We proceed to expand various quantities to the lowest nonvanishing order of ϵ and A_2/A_0:

$$\eta_{+-} = \tfrac{1}{2}[\epsilon + (2)^{1/2} iF\, \mathrm{Im}A_2/A_0], \qquad (16)$$

$$\eta_{00} = \tfrac{1}{2}[\epsilon - 2(2)^{1/2} iF\, \mathrm{Im}A_2/A_0], \qquad (17)$$

and

$$R[K_S{}^0 \to \pi^+ + \pi^-] - 2R[K_S{}^0 \to \pi^0 + \pi^0] = 2\sqrt{2}[\mathrm{Re}A_2/A_0]\cos(\delta_2 - \delta_0) \times R[K_S{}^0 \to \pi + \pi(I=0)]. \qquad (18)$$

Furthermore, since Γ_l is positive definite, $\alpha_l \geq |x_l|$, $\alpha_l \geq |y_l|$; or by Eq. (10),

$$|x_l| \lesssim 11, \quad |y_l| \lesssim 11. \qquad (19)$$

Similarly,

$$|x_{3\pi}| \lesssim 6, \quad |y_{3\pi}| \lesssim 6. \qquad (20)$$

Thus these elements are negligible compared with $A_0{}^2$. {In more general cases, we can establish a somewhat better bound for y. For any mode C,

$$y_C^2 \leq R[K_S^0 \to C]R[K_L^0 \to C].\}$$

Using Eq. (8) one sees that $|\epsilon| \ll 1$ implies $M_i \ll A_0^2$. Thus one has an approximate expression for the difference of the two eigenvalues of $\Gamma + iM$:

$$\lambda_+ - \lambda_- = 2A_0^2 + 2iM_r. \tag{21}$$

Therefore,

$$M_r = m_S - m_L. \tag{22}$$

Using these one obtains from Eq. (8)

$$\epsilon = \frac{-M_i + i(y_l + y_{3\pi})}{A_0^2 + i(m_S - m_L)}. \tag{23}$$

Equations (16)–(23) form the basis of a phenomenological analysis.

5. If $\mathrm{Im}A_2 = 0$ and $M_i = 0$, then it follows from Eqs. (16) and (23) that

$$R[K_L^0 \to \pi^+ + \pi^-] = 6(y_l + y_{3\pi})^2 \times 10^{-5}[1 + (M_r/A_0^2)^2]^{-1}. \tag{24}$$

Statement 3(f) then follows from Eqs. (19) and (20). This is too small by a factor of 3 or 15 for[6] $|m_S - m_L| = 1/2\tau_1$ or $3/2\tau_1$. {If, moreover, we believe that the $\Delta Q = -\Delta S$ matrix element is at most 50% of that for $\Delta Q = \Delta S$ as a result of the Paris experiment,[7] then $(x_l^2 + y_l^2)^{1/2}/\alpha_l < 2(\frac{1}{2})/[1 + (\frac{1}{2})^2] = \frac{4}{5}$. Hence, $|y_l| < 9$. Thus we can strengthen the argument by about 20%.}

6. The amplitude ratios η_{+-} and η_{00} are experimentally measurable quantities. The experiment of reference 1 gives

$$|\eta_{+-}| = 2.1 \times 10^{-3}(1 \pm 0.1). \tag{25}$$

A measurement[8] of $R[K_L^0 \to \pi^0 + \pi^0]$ would yield $|\eta_{00}|$. If one introduces further assumptions, this rate can be predicted. For example, according to Sec. 3, (d) and (e),

if $\mathrm{Im}A_2 = 0$, then $R[K_L^0 \to \pi^0 + \pi^0] = 1.3 \times 10^{-2}$;

if $M_i = y_l + y_{3\pi} = 0$, then

$$R[K_L^0 \to \pi^0 + \pi^0] = 5.2 \times 10^{-2}. \tag{26}$$

Existing experiments yield only a rough upper bound:

$$R[K_L^0 \to \pi^0 + \pi^0] < (\sim 1), \quad |\eta_{00}| < (\sim 2 \times 10^{-2}).$$

Without additional assumptions, there are no theoretical arguments that $R[K_L^0 \to \pi^0 + \pi^0]$ cannot be as large as this experimental upper bound.

It is clear that in order to measure the phases of the amplitude ratios η_{+-} and η_{00}, interference between K_L and K_S decays into these modes must be studied. To obtain greater sensitivity, the intensity ratio of K_L and K_S must be such that their decay amplitudes into these modes are about comparable.[9] The relative phase θ between the K_L and K_S beams must also be known in order to determine the phase of η_{+-} (or of η_{00}). But to determine the difference of the phases of η_{+-} and η_{00} it is not necessary to know θ.

It is convenient to construct a diagram of the complex numbers η_{+-}, η_{00}, ϵ, and iF related through Eqs. (16) and (17), as shown in Fig. 1.

(a) If η_{+-} and η_{00} are completely measured, the quantities ϵ and $F\,\mathrm{Im}A_2/A_0$ are known. Thus $\delta_2 - \delta_0$ is measured up to $\pm n\pi$, and $\mathrm{Im}A_2/A_0$ is known up to a sign. If further $m_S - m_L$ is known, then through (23), M_i and $y_l + y_{3\pi}$ are determined.

(b) If $|\eta_{+-}|$, $|\eta_{00}|$, and the phase difference

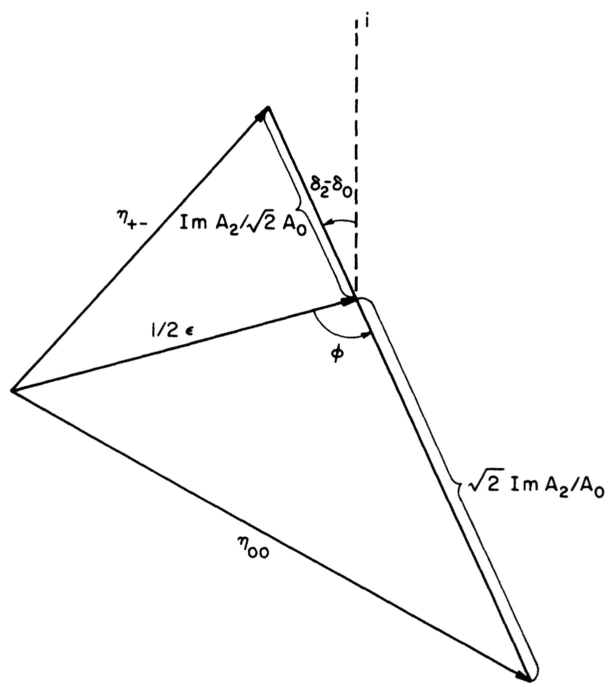

FIG. 1. Geometrical relation between η_{+-}, η_{00}, and other quantities.

of η_{+-} and η_{00} are known, then the triangle of Fig. 1 can be constructed, but its orientation relative to the real axis is known only if $\delta_2-\delta_0$ is independently obtained.

These experiments, however, do not yield any information on $\mathrm{Re}A_2/A_0$. It seems that the only experimental method of determining this ratio is to measure the rate difference on the left-hand side of Eq. (18). Existing experiment[10] gives

$$\mathrm{Re}A_2=(0\pm 1)\sec(\delta_2-\delta_0). \qquad (27)$$

7. In the above discussion, electromagnetic effects are completely neglected. Inclusion of these effects introduces (a) mass splits between $\pi^+\pi^-$ and $\pi^0\pi^0$ states (and related effects), and (b) additional channels like $\pi\pi\gamma$. To account for (a) one introduces two eigenstates of the S matrix for the strong and electromagnetic interactions of the $\pi\pi$ S-wave state at the K^0 mass. The resultant change comprises only small real corrections to the coefficients $(\frac{2}{3})^{1/2}$ and $(\frac{1}{3})^{1/2}$ and the phase shifts δ_2 and δ_0 in Table II.

As to (b), electromagnetic effects do not introduce CP noninvariance. Thus it is reasonable to expect additional channels, such as $\pi\pi\gamma$, not to introduce matrix elements which are imaginary in phase relative to A_0. In any case, experimentally the rates $K_{\mathrm{S,\,L}}\to\pi+\pi+\gamma$ are limited:

$$R[K_{\mathrm{S}}\to\pi^++\pi^-+\gamma]<(\sim 1)$$

(from Kirsch et al.[11]) and

$$R[K_{\mathrm{L}}\to\pi+\pi+\gamma]<(\sim 1)$$

(from total rate). It is reasonable to assume

$$R[K_{\mathrm{S}}\to\pi^0+\pi^0+\gamma]<(\sim 1).$$

By an argument similar to that leading to Eq. (19), we have then

$$|y_{\pi\pi\gamma}|<(\sim 1.5).$$

Thus electromagnetic effects are expected to be negligible in the discussion of CP noninvariances of the preceding sections.

8. We now make two supplementary remarks. One may raise the question of the evidence of T invariance in neutron[12] and Λ[13] decays and perhaps other decays. To reconcile this evidence with the CP noninvariance of reference 1, it may be that the weak interaction consists of two terms:

$$H=H_{\mathrm{strong}}+H_{\mathrm{el}}+H_{W1}+H_{W2},$$

where (a) $H_{\mathrm{strong}}+H_{\mathrm{el}}+H_{W1}$ satisfies CP invariance, (b) $H_{\mathrm{strong}}+H_{W1}$ obeys the $|\Delta I|=\frac{1}{2}$ rule, and (c) H_{W2} is weaker than H_{W1}, and violates the $|\Delta I|=\frac{1}{2}$ rule.

Another question concerns the $\pi\pi(I=2)$ decay rates of K^+ and of K^0. From Eqs. (16) and (17),

$$|\mathrm{Im}A_2|=\tfrac{1}{3}\sqrt{2}A_0|\eta_{+-}-\eta_{00}|<(\sim\tfrac{2}{3}). \qquad (28)$$

If the decay amplitude of $K^+\to\pi+\pi$ $(I=2)$ is A_2^+, the experimental rate of this process gives

$$|A_2^+|=3.9. \qquad (29)$$

Comparing Eqs. (27), (28), and (29) one concludes that more accurate measurements of $R[K_{\mathrm{S}}\to\pi^++\pi^-]-2[K_{\mathrm{S}}\to\pi^0+\pi^0]$, and information about $|\eta_{00}|$ and $\delta_2-\delta_0$ can be used to analyze the $K\to\pi+\pi$ $(I=2)$ amplitude into $|\Delta I|=\frac{3}{2}$ and $|\Delta I|=\frac{5}{2}$ components.

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For other recent discussions of CP noninvariance in K^0-$\bar{K}^0$ decay, see a recent article by Sachs.[14]

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AMPLIFICATION OF MICROWAVE PHONONS IN GERMANIUM. M. Pomerantz [Phys. Rev. Letters 13, 308 (1964)].

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In the third paragraph from the end, the word "amplification" is to be understood to mean amplification constant, α.