7

The Neutral Kaon System

From the discovery of the K_L^0 to CP violation, 1956–1964, and beyond

The development of the concept of strangeness created something of a puzzle: What is the nature of the K^0 and $\overline{K}^0$? They differ only in their strangeness, a quantity not conserved by the weak interactions, through which they decay. Thus, for example, they both can decay into $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$. The explanation was given by Gell-Mann and Pais before parity violation was discovered. We present their proposal modified to incorporate parity violation, but assuming at first that the combination, CP, of charge conjugation and parity inversion is a good symmetry of both the weak and strong interactions.

The K^0 is an eigenstate of the strong interactions, as is the $\overline{K}^0$. They are antiparticles of each other so they can be transformed into each other by charge conjugation and thus have opposite strangeness. If there were no weak interactions, the K^0 and $\overline{K}^0$ would be stable and equal in mass. The weak interactions break the degeneracy and make the neutral kaons unstable. The particles with well-defined masses and lifetimes are the physical states. These states are linear combinations of K^0 and $\overline{K}^0$, the strong interaction eigenstates.

Since the action of CP on a K^0 produces a $\overline{K}^0$ we can establish a phase convention by

$$CP|K^0\rangle = |\overline{K}^0\rangle. \tag{7.1}$$

If CP is conserved, the physical eigenstates are the eigenstates of CP. These are simply

$$|K_1^0\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle + |\overline{K}^0\rangle\right], \tag{7.2}$$

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}\left[|K^0\rangle - |\overline{K}^0\rangle\right], \tag{7.3}$$

where K_1^0 has $CP = +1$ and K_2^0 has $CP = -1$. The decays $K^0 \to \pi^+\pi^-$ and $\overline{K}^0 \to \pi^+\pi^-$ are both allowed by the weak-interaction selection rules. The $\pi^+\pi^-$ state with angular momentum zero necessarily has $P = (-1)^L = +1$, $C = (-1)^L = +1$ since both C and P interchange the two pions, which are in an s-wave, and thus $CP = +1$. It follows

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that the K_2^0 cannot decay into $\pi^+\pi^-$ if CP is conserved. On the other hand, a $\pi^+\pi^-\pi^0$ state that is entirely s-wave must have $CP = -1$ because the $\pi^+\pi^-$ part has $CP = +1$ by the above reasoning, while the remaining π^0 has $CP = -1$. Since the important decay channel $\pi\pi$ is closed to it, the K_2^0 has a longer lifetime than the K_1^0.

Because K^0 and $\overline{K}^0$ have well-defined strangeness and strangeness is conserved in hadronic collisions it is these states that are directly produced. Gell-Mann and Pais noted that basic quantum mechanics tells us to regard a produced K^0 as a superposition of the CP-even K_1^0 and the CP-odd K_2^0. The K_1^0 portion of the state dies much more rapidly than the K_2^0 portion, so that after a period of time only the latter is present if the particle has not yet decayed. While decays into $\pi\pi$ or $\pi\pi\pi$ are possible from either K^0 or $\overline{K}^0$, by the $\Delta S = \Delta Q$ rule, a decay to $e^+\nu\pi^-$ is possible only from K^0, while a decay to $e^-\overline{\nu}\pi^+$ must come from $\overline{K}^0$.

The K_2^0 was observed in 1956 by Lande *et al.* using a 3-GeV beam from the Brookhaven Cosmotron (**Ref. 7.1**). A cloud chamber filled 90% with helium and 10% with argon was placed six meters from the interaction point. All K_1^0s and Λs would have decayed by the time of their arrival at the cloud chamber. In the cloud chamber, forked tracks were observed that were kinematically unlike $\theta^0 \rightarrow \pi^+\pi^-$. It was concluded that they represented $\pi^\pm e^\mp \nu$, possibly $\pi^\pm \mu^\mp \nu$, and occasionally $\pi^+\pi^-\pi^0$. The lifetime was judged to be in the range 10^{-9} s $< \tau < 10^{-6}$ s, whereas the short-lived $K^0\,(\theta)$ had a lifetime around 10^{-10} s. Additional evidence for a long-lived neutral K was obtained by W. F. Fry and co-workers using a K^- beam from the Bevatron with an emulsion target (**Ref. 7.2**).

These results were followed by a more complete report by Lande, Lederman, and Chinowsky showing clearly the $\mu\pi\nu$, $e\pi\nu$, and 3π modes (Ref. 7.3). They obtained further confirmation of the Gell-Mann–Pais prediction by noting a neutral K that interacted with a helium nucleus to produce $\Sigma^- ppn\pi^+$, a state with negative strangeness. The neutral K beam was overwhelmingly of positive strangeness initially since the threshold for $pn \rightarrow p\Lambda K^0$ is much lower than that for, say, $pn \rightarrow pnK^0\overline{K}^0$. Thus there was strong evidence for the transformation $K^0 \rightarrow \overline{K}^0$.

In vacuum, the time development of the K_1^0 and K_2^0 is

$$|K_1^0(\tau)\rangle = e^{-im_1\tau-\Gamma_1\tau/2}\frac{1}{\sqrt{2}}\left[|K^0(0)\rangle + |\overline{K}^0(0)\rangle\right], \tag{7.4}$$

$$|K_2^0(\tau)\rangle = e^{-im_2\tau-\Gamma_2\tau/2}\frac{1}{\sqrt{2}}\left[|K^0(0)\rangle - |\overline{K}^0(0)\rangle\right], \tag{7.5}$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and decay rates of the K_1^0 and K_2^0. Here τ is the proper time, $\tau = t/\gamma$, t is the time measured in the laboratory, and $\gamma = (1-\beta^2)^{-1/2}$, where $\beta = v/c$. Because of virtual weak transitions between the K^0 and $\overline{K}^0$, the masses m_1 and m_2 differ slightly. If a state, $|\Psi\rangle$, that is purely K^0 is produced at $\tau = 0$, it will oscillate

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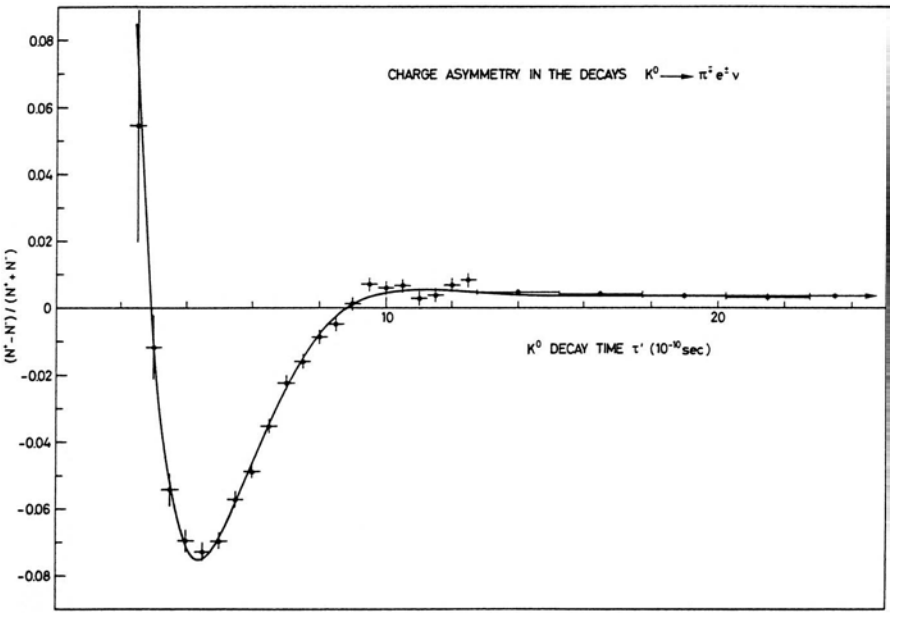


Figure 7.1. The charge asymmetry observed for $K^0 \to \pi^- e^+ \nu$ and $\overline{K}^0 \to \pi^+ e^- \overline{\nu}$ as a function of the proper time, starting from a predominantly K^0 beam. The number of observed positrons is N^+ and the number of observed electrons is N^-. The interference effect seen is sensitive to the $K_L - K_S$ mass difference. For large values of the proper time, the non-zero asymmetry is a CP violating effect and determines $\mathrm{Re}\,\epsilon$ [S. Gjesdal *et al.*, *Phys. Lett.* **52B**, 113 (1974)]. This CP violating effect was first observed in Refs. 7.6 and 7.7.

between K^0 and $\overline{K}^0$ with amplitudes

$$\langle K^0|\Psi(\tau)\rangle = \frac{1}{2}(e^{-im_1\tau-\Gamma_1\tau/2} + e^{-im_2\tau-\Gamma_2\tau/2}), \tag{7.6}$$

$$\langle \overline{K}^0|\Psi(\tau)\rangle = \frac{1}{2}(e^{-im_1\tau-\Gamma_1\tau/2} - e^{-im_2\tau-\Gamma_2\tau/2}). \tag{7.7}$$

These oscillations can be observed through semileptonic decays since the semileptonic decays are $K^0 \to \pi^- e^+ \nu$ and $\overline{K}^0 \to \pi^+ e^- \overline{\nu}$. An example is shown in Fig. 7.1. There the charge asymmetry in the decay of K^0 is shown as a function of the proper time. The ratio of "wrong sign" leptons (e^-) to "right sign" leptons (e^+) from a state that is initially a K^0, integrated over all time, is

$$\frac{\text{wrong sign}}{\text{right sign}} = \frac{(\Gamma_1 - \Gamma_2)^2 + 4(\Delta m)^2}{2(\Gamma_1 + \Gamma_2)^2 - (\Gamma_1 - \Gamma_2)^2 + 4(\Delta m)^2}, \tag{7.8}$$

where $\Delta m = m_1 - m_2$. Since the decay rate of the K_1^0, Γ_1, is much greater than the K_2^0 decay rate, Γ_2, this ratio is nearly unity.

Even more dramatic predictions had been made for the neutral-K system. Pais and Piccioni in 1955 predicted that K_2^0 s passing through matter would regenerate a coherent

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K_1^0 component. In matter, the time development is altered because the K^0 and $\overline{K}^0$ interact differently with nucleons. For example, $\overline{K}^0 p \to \pi^+\Lambda$ is allowed while $K^0 p \to \pi^+\Lambda$ is not. In fact, the elastic-scattering amplitudes, f and $\overline{f}$, for $K^0 p$ and $\overline{K}^0 p$ differ, just as those for $K^+ p \to K^+ p$ and $K^- p \to K^- p$ do. Forward-moving neutral kaons accumulate an extra phase from elastic scattering. As in ordinary electromagnetic interactions, this scattering can be translated into an index of refraction

$$n = 1 + \frac{2\pi N}{k^2} f(0), \tag{7.9}$$

where N is the number density of scatterers, k is the wave number of the incident particles, and $f(0)$ is the (complex) elastic-scattering amplitude in the forward direction, which is related to the total cross section by the optical theorem

$$\sigma_{tot} = \frac{4\pi}{k} \mathrm{Im} f(0). \tag{7.10}$$

Since K^0 and $\overline{K}^0$ have different total cross sections, they have different (complex) indices of refraction. In going a distance l, a particle picks up an extra phase $k(n-1)l$. The distance l is related to the proper time interval by $l = \tau\beta\gamma$.

To incorporate this effect, we write first the Schrödinger equation for propagation in free space. It is easy to guess what this is since we already have the solutions in the form of $|K_1^0(\tau)\rangle$ and $|K_2^0(\tau)\rangle$. If we let ψ be a column matrix whose upper entry gives the K^0 component and whose lower entry gives the $\overline{K}^0$ component, then in terms of the proper time

$$i\frac{\partial\psi}{\partial\tau} = \begin{pmatrix} M - i\dfrac{\Gamma}{2} & M_{12} - i\dfrac{\Gamma_{12}}{2} \\ M_{12} - i\dfrac{\Gamma_{12}}{2} & M - i\dfrac{\Gamma}{2} \end{pmatrix} \psi \equiv \mathcal{H}\psi, \tag{7.11}$$

where $M = (m_1 + m_2)/2$, $\Gamma = (\Gamma_1 + \Gamma_2)/2$, $M_{12} = (m_1 - m_2)/2 = \Delta m/2$, and $\Gamma_{12} = (\Gamma_1 - \Gamma_2)/2 = \Delta\Gamma/2$. We indicate the elastic K^0-nucleus forward scattering amplitude by f_0 and that for $\overline{K}^0$ by $\overline{f}_0$. The effective Hamiltonian $\mathcal{H}$ includes the effects of weak decays and the interactions that are second order in weak interactions responsible for Δm and $\Delta\Gamma$. With the inclusion of the effects of the medium we have

$$i\frac{\partial\psi}{\partial\tau} = \begin{pmatrix} M - i\dfrac{\Gamma}{2} - \dfrac{2\pi N\beta\gamma f_0}{k} & M_{12} - i\dfrac{\Gamma_{12}}{2} \\ M_{12} - i\dfrac{\Gamma_{12}}{2} & M - i\dfrac{\Gamma}{2} - \dfrac{2\pi N\beta\gamma \overline{f}_0}{k} \end{pmatrix} \psi. \tag{7.12}$$

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This is a slight modification of the Hamiltonian $\mathcal{H}$, so the eigenstates – the states that propagate without turning into each other – are only slightly different from the eigenstates in vacuum, that is, K_1^0 and K_2^0. A bit of algebra reveals that these states may be written

$$|K_1^{0\prime}\rangle = |K_1^0\rangle + r|K_2^0\rangle, \tag{7.13}$$

$$|K_2^{0\prime}\rangle = |K_2^0\rangle - r|K_1^0\rangle, \tag{7.14}$$

where the regeneration parameter is a small number, typically of order 10^{-3},

$$r = -\frac{\pi N \beta\gamma}{k} \cdot \frac{f_0 - \overline{f}_0}{m_1 - m_2 - \frac{i}{2}\Gamma_1}. \tag{7.15}$$

The expression has been simplified by noting that since the K_1^0 decays much faster than the K_2^0 , $\Gamma_1 \gg \Gamma_2$.

If a neutral kaon beam travels a long distance, only K_2^0 s are left. If the K_2^0 s traverse a medium, quantum mechanics tells us to analyze their propagation in terms of the eigenstates in that medium. The K_2^0 is mostly $K_2^{0\prime}$, but with a small component of $K_1^{0\prime}$. These two pieces will acquire slightly different phases passing through the medium. When they exit, the states must be reanalyzed in terms of K_1^0 and K_2^0. This will reintroduce a component of K_1^0 of order r. The result is that an amplitude for K_1^0 will be generated proportional to

$$r\left[1 - e^{(i\Delta m + \Delta\Gamma/2)L}\right], \tag{7.16}$$

where $L = l/\beta\gamma$. We see then, that the amount of K_1^0 regenerated depends on the difference of the masses. It is thus possible to measure this difference which is extremely small compared to mass splittings like those between isospin partners.

An early measurement of the mass difference was made by F. Muller *et al.* at the Bevatron using regeneration techniques (**Ref. 7.4**). In addition to K_1^0 s produced coherently in exactly the forward direction, K_1^0 s are produced through the ordinary scattering process $K_2^0 p \to K_1^0 p$. This "diffractive" process produces particles mostly in the forward direction also, but not with such pronounced forward peaking as the coherent regeneration. Through the reaction $\pi^- p \to K^0\Lambda$, Muller *et al.* generated a 670-MeV/c neutral kaon beam. A 30-inch propane bubble chamber was placed downstream where the surviving beam was purely K_2^0. The K_1^0s produced by the K_2^0 beam were detected by looking for charged pion pairs that reconstructed to the proper mass. By measuring the angular distribution of these K_1^0 s it was possible to demonstrate the existence of the coherently regenerated beam. A first measurement of the mass difference was obtained:

$$|m_2 - m_1|/\Gamma_1 = 0.85\ {}^{+0.3}_{-0.25}. \tag{7.17}$$

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The current values are $1/\Gamma_1 = 0.8953 \pm 0.0005 \times 10^{-10}$ s and $m_2 - m_1 = 0.5292 \pm 0.0009 \times 10^{10}\ \mathrm{s}^{-1}$, giving $(m_2 - m_1)/\Gamma_1 = 0.474$. The determination that the mass of the K_2^0 is greater than the mass of the K_1^0 required measuring interference with an additional phase known a priori. In practice this meant observing the scattering of neutral kaons with nucleons and looking at the interference between the K^0 and $\overline{K}^0$ contributions.

After the fall of parity invariance, it appeared that the combination of charge conjugation plus parity, CP, was still a good symmetry, as we assumed in the above analysis. There were (and are) solid theoretical reasons for believing that the combination of time reversal invariance, T, together with C and P gives a good symmetry, CPT. Thus if CP is a good symmetry, so is T.

If CP is a good symmetry, the longer-lived neutral kaon is strictly forbidden to decay into two pions. Nonetheless, in 1964 Christenson, Cronin, Fitch, and Turlay observed its decay to $\pi^+\pi^-$(**Ref. 7.5**). Another supposed symmetry had fallen. The experiment, carried out at the Alternating Gradient Synchrotron (AGS) at Brookhaven found that the CP-violating decay had a branching ratio of about 2×10^{-3}. Since most of the prominent decays of the longer-lived neutral kaon (which we henceforth refer to as K_L^0) have two charged particles in the final state, just as in the decay being sought, careful momentum measurements and particle identification were essential to separating $K_L^0 \to \pi^+\pi^-$ from the background.

The apparatus was a two-armed spectrometer, each arm of which had a magnet for momentum determination, scintillator for triggering on charged particles, a Cherenkov counter for discriminating against $e^\pm$ simulating $\pi^\pm$, and spark chambers for tracking the charged particles. A small but convincing signal was obtained for the CP-violating decay. The experiment was soon repeated and confirmed at several laboratories.

If CP is conserved, with the convention $CP|K^0\rangle = |\overline{K}^0\rangle$ the off-diagonal matrix elements of $\mathcal{H}$ are $(M_{12} - i\Gamma_{12}/2) = \frac{1}{2}(\Delta m - i\Delta\Gamma/2)$. If we chose a new phase convention for the states, $|K^0\rangle \to e^{i\chi}|K^0\rangle$ and $|\overline{K}^0\rangle \to e^{-i\chi}|\overline{K}^0\rangle$, one off-diagonal matrix element would become $M'_{12} - i\Gamma'_{12}/2 = e^{-2i\chi}\frac{1}{2}(\Delta m - i\Delta\Gamma/2)$ and the other $M''_{12} - i\Gamma''_{12}/2 = e^{2i\chi}\frac{1}{2}(\Delta m - i\Delta\Gamma/2)$. The conservation of CP, which we have assumed to this point would be manifested by M'_{12} and Γ'_{12} being relatively real, and similarly for M''_{12} and Γ''_{12}. In addition, we would find $M'_{12} = M''^*_{12}$ and $\Gamma'_{12} = \Gamma''^*_{12}$.

When CP is violated, the equation for time development takes the more general form

$$i\frac{\partial\psi}{\partial\tau} = \begin{pmatrix} M - i\dfrac{\Gamma}{2} & M_{12} - i\dfrac{\Gamma_{12}}{2} \\ M^*_{12} - i\dfrac{\Gamma^*_{12}}{2} & M - i\dfrac{\Gamma}{2} \end{pmatrix}\psi, \tag{7.18}$$

where M and Γ are still real, but M_{12} and Γ_{12} are complex. If M_{12} and Γ_{12} are not relatively real, CP is violated in the mass matrix. The off-diagonal M_{12} corresponds to virtual K^0-$\overline{K}^0$transitions while Γ_{12} is due to real transitions, which are dominated by the $I = 0\ \pi\pi$ state, as explained below.

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Because CP violation in the neutral K system is a small effect, M_{12}/Γ_{12} is nearly real and we write

$$M_{12} = R\Gamma_{12}(1 + i\kappa), \tag{7.19}$$

where R and κ are independent of the phase convention for the states and $|\kappa| \ll 1$. The small imaginary part has an insignificant effect on the masses and lifetimes and we can write

$$\Gamma_{12} = e^{-2i\phi}(\Gamma_S - \Gamma_L)/2 \equiv e^{-2i\phi}\Delta\Gamma/2, \tag{7.20}$$

$$2R|\Gamma_{12}| = m_S - m_L = \Delta m. \tag{7.21}$$

where the (convention-dependent) phase of Γ_{12} is displayed explicitly. In fact we already know that $R = \Delta m/\Delta\Gamma \approx -0.47$.

The physical states are

$$|K_S^0\rangle = \frac{1}{\sqrt{2}}\left[e^{-i\phi}(1+\epsilon)|K^0\rangle + e^{+i\phi}(1-\epsilon)|\overline{K}^0\rangle\right],$$
$$|K_L^0\rangle = \frac{1}{\sqrt{2}}\left[e^{-i\phi}(1+\epsilon)|K^0\rangle - e^{+i\phi}(1-\epsilon)|\overline{K}^0\rangle\right], \tag{7.22}$$

where

$$\epsilon = \frac{i\kappa R}{2R - i}. \tag{7.23}$$

This determines the phase of ϵ to be

$$\arg\epsilon = \tan^{-1}\frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L} = 43.5^\circ, \tag{7.24}$$

once we use $\kappa > 0$, which follows from the determination that $\Re\epsilon > 0$, described below.

Let us look at some of the details of the $K_L^0 \to \pi\pi$ decay. The 2π states can be decomposed into $I = 0$ and $I = 2$ components, since an $I = 1$ $\pi\pi$ state cannot have $J = 0$. Each decay amplitude has a strong phase and a weak phase. The strong phase is due to the interaction of the pions in the final state and is thus the same for the decays of K_S^0 and K_L^0. Roughly speaking, since the interaction is only in the final state, its effect is to introduce a factor $e^{i\delta}$, half that of the full scattering, $e^{2i\delta}$, where δ is the $\pi\pi$ phase shift at a center-of-mass energy equal to m_K.

The weak phase is intrinsic to the decay itself and arises from the weak interaction Hamiltonian. The Hamiltonian must be Hermitian so the weak amplitude for a $\overline{K}^0$ decay must be the complex conjugate of that for a K^0 decay. In terms of the real quantities $\mathcal{A}_I$ and the weak phases λ_I we have

$$\langle(2\pi)_I|H_{\rm wk}|K^0\rangle = \mathcal{A}_I e^{i\lambda_I} e^{i\delta_I} \tag{7.25}$$

$$\langle(2\pi)_I|H_{\rm wk}|\overline{K}^0\rangle = \mathcal{A}_I e^{-i\lambda_I} e^{i\delta_I}. \tag{7.26}$$

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These results can be simplified by observing the following. First, the much faster decay of the K_S^0 compared to $K^+ \to \pi^+\pi^0$ shows that $|\mathcal{A}_0| \gg |\mathcal{A}_2|$. This is known as the $\Delta I = 1/2$ rule since the $\Delta I = 3/2$ interaction responsible for $K^+ \to \pi^+\pi^0$ (which has $I = 2$ in the final state) is weaker than the $\Delta I = 1/2$ operator responsible for $K_S^0 \to \pi^+\pi^-$. Now just as the hypothetical decay rate of a K^0 to a $\pi\pi$ state with isospin I would be proportional to $(\mathcal{A}_I e^{i\lambda_I} e^{i\delta_I})^*(\mathcal{A}_I e^{i\lambda_I} e^{i\delta_I})$, the transition matrix element Γ_{12} is proportional to $(\mathcal{A}_I e^{i\lambda_I} e^{i\delta_I})^*(\mathcal{A}_I e^{-i\lambda_I} e^{i\delta_I})$ and thus has the phase $e^{-2i\lambda_I}$. Since the $I = 0$ amplitude dominates, we have from Eq. (7.20), to a very good approximation, $\phi = \lambda_0$.

Violation of CP in the neutral K system arises from the small numbers ϵ and $\lambda_2 - \lambda_0$. Keeping terms of first order in these parameters

$$\langle(2\pi)_{I=0}|H_{\rm wk}|K_S\rangle = \sqrt{2}\mathcal{A}_0 e^{i\delta_0}, \tag{7.27}$$

$$\langle(2\pi)_{I=2}|H_{\rm wk}|K_S\rangle = \sqrt{2}\mathcal{A}_2 e^{i\delta_2}, \tag{7.28}$$

$$\langle(2\pi)_{I=0}|H_{\rm wk}|K_L^0\rangle = \sqrt{2}\epsilon\mathcal{A}_0 e^{i\delta_0}, \tag{7.29}$$

$$\langle(2\pi)_{I=2}|H_{\rm wk}|K_L^0\rangle = \sqrt{2}(\epsilon + i\lambda_2 - i\lambda_0)\mathcal{A}_2 e^{i\delta_2}. \tag{7.30}$$

Note that both ϵ and $\lambda_2 - \lambda_0$ are independent of the phase convention chosen for the neutral kaon states. The traditional CP-violation parameters for the neutral K system are defined by

$$\eta_{+-} = \frac{\langle\pi^+\pi^-|H_{\rm wk}|K_L^0\rangle}{\langle\pi^+\pi^-|H_{\rm wk}|K_S^0\rangle} = \epsilon + \epsilon', \tag{7.31}$$

$$\eta_{00} = \frac{\langle\pi^0\pi^0|H_{\rm wk}|K_L^0\rangle}{\langle\pi^0\pi^0|H_{\rm wk}|K_S^0\rangle} = \epsilon - 2\epsilon'. \tag{7.32}$$

Expanding in the small quantity $\mathcal{A}_2/\mathcal{A}_0$, we find

$$\epsilon' = \frac{i}{\sqrt{2}} e^{i(\delta_2-\delta_0)}(\lambda_2 - \lambda_0)\frac{\mathcal{A}_2}{\mathcal{A}_0} = \frac{i}{\sqrt{2}} e^{i(\delta_2-\delta_0)}{\rm Im}\frac{\mathcal{A}_2 e^{i\lambda_2}}{\mathcal{A}_0 e^{i\lambda_0}}. \tag{7.33}$$

The mass-mixing matrix determines ϵ while ϵ' is due to CP violation in the decays. From its definition, the magnitude of $\eta_\pm$ can be rewritten in terms of the branching ratio for the CP-violating decay $K_L \to \pi^+\pi^-$ and three other well measured quantities:

$$|\eta_{+-}|^2 = \frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_S^0 \to \pi^+\pi^-)} = \frac{B(K_L^0 \to \pi^+\pi^-)\Gamma(K_L^0 \to \text{all})}{B(K_S^0 \to \pi^+\pi^-)\Gamma(K_S^0 \to \text{all})} \approx (2.3\times10^{-3})^2. \tag{7.34}$$

The analogous measurement for the decay into neutral pions is of course more difficult.

To measure the phases of η_{+-} and η_{00} requires observing the interference between $K_L^0 \to \pi\pi$ and $K_S^0 \to \pi\pi$. This can be accomplished using a K_L^0 beam and regenerating a

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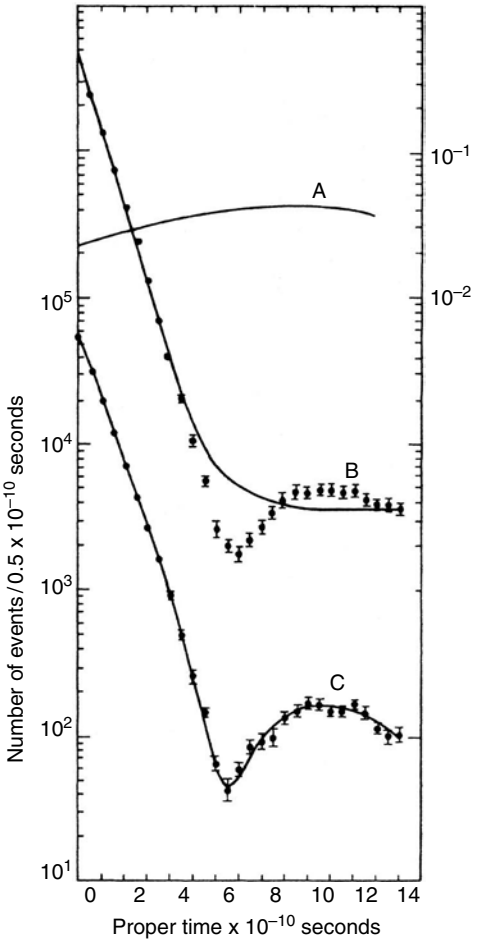


Figure 7.2. Data for $K_{L,S} \to \pi^+\pi^-$ as a function of the proper time after a K_L^0 beam has passed through a carbon regenerator. Curve A shows the detection efficiency as indicated on the right-hand scale. Curve B shows data for all values of the K momentum. The solid curve shows the shape expected in the absence of K_L^0–K_S^0 interference. The interference is apparent and can be used to determine ϕ_{+-}. Curve C shows the data for a restricted interval of K momenta. The solid curve shows a fit including interference. [W. C. Carithers *et al.*, *Phys. Rev. Lett.* **34**, 1244 (1975)]

small amount of K_S^0, or by using a K^0 beam. In the latter case, one first sees the quickly decaying K_S^0 component. At the end, one sees only the CP-violating K_L^0 decay (if care is taken to observe only the $\pi\pi$ final state!). In between, there is an interval when the contributions from K_S^0 and K_L^0 are comparable, and the interference can be measured. In Fig. 7.2 data obtained using the regenerator method are shown.

CP violation has been observed in $K_L^0 \to \mu\pi\nu$ and $K_L^0 \to e\pi\nu$. Aside from phase space considerations, these decays should be similar. From the $\Delta S = \Delta Q$ rule, one anticipates that the allowed decays to $\pi\mu\nu$ should be $K^0 \to \pi^-\mu^+\nu$ and $\overline{K}^0 \to \pi^+\mu^-\nu$. It follows

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directly that

$$A_L = \frac{\Gamma(K_L^0 \to \pi^- \mu^+ \nu) - \Gamma(K_L^0 \to \pi^+ \mu^- \nu)}{\Gamma(K_L^0 \to \pi^+ \mu^- \nu) + \Gamma(K_L^0 \to \pi^- \mu^+ \nu)} = 2\Re\,\epsilon. \tag{7.35}$$

Unlike the $K_L^0 \to \pi\pi$ decay, the decay process here is allowed even without CP violation. It is the small difference between two allowed rates that is due to CP violation. Thus very high statistics are required. The result can be compared to the measurement of the real part of ϵ obtained in the $K_L^0 \to \pi\pi$ decays. An early measurement of $K \to \pi e \nu$ was obtained by a group headed by Steinberger (Ref. 7.6). The analogous process, $K \to \pi \mu \nu$ was measured by a team led by M. Schwartz (Ref. 7.7). Data from a later experiment are shown in Fig. 7.1.

In 1999, CP violation was observed in an additional decay, $K_L^0 \to \pi^+\pi^- e^+ e^-$ (Ref. 7.8). The relevant observable is the distribution of the angle ϕ between the plane containing the e^+ and the e^- and the plane containing the π^+ and the π^- in the rest frame of the decaying K_L^0. The distribution contains pieces that vary as $\sin^2\phi$, $\cos^2\phi$, and $\sin\phi\cos\phi$, the last of which is CP violating. One mechanism that yields this final state is the CP-violating decay $K_L^0 \to \pi^+\pi^-$ followed by emission of a virtual photon that materializes as an electron–positron pair. To see CP violation requires interference and the dominant interfering process is the CP-conserving direct decay $K_L^0 \to \pi^+\pi^-\gamma$, with M1 photon emission. The asymmetry

$$A = \frac{N_{\sin\phi\cos\phi>0} - N_{\sin\phi\cos\phi<0}}{N_{\sin\phi\cos\phi>0} + N_{\sin\phi\cos\phi<0}} \tag{7.36}$$

is impressively large, 13.6%.

Because CP violation seems such a fundamental aspect of particle interactions, enormous efforts have been expended to measure the parameters η_{+-} and η_{00}. The values for the CP-violation parameters cited in the 2008 *Review of Particle Physics* are

$$|\eta_{+-}| = (2.233 \pm 0.012) \times 10^{-3}, \tag{7.37}$$

$$\phi_{+-} = \arg\,\eta_{+-} = 43.51^\circ \pm 0.05^\circ, \tag{7.38}$$

$$|\eta_{00}| = (2.222 \pm 0.012) \times 10^{-3}, \tag{7.39}$$

$$\phi_{00} = \arg\,\eta_{00} = 43.52^\circ \pm 0.05^\circ, \tag{7.40}$$

$$A_L = (3.32 \pm 0.06) \times 10^{-3}$$

The results indicate that η_{+-} and η_{00} are very nearly equal, or, equivalently, ϵ' is nearly zero. This could be explained if all the CP violation were due entirely to an interaction that changed strangeness by two units. All the CP violation then is in the K mass matrix and $\epsilon' = 0$. This is called the superweak model. Violation of CP in the decay of a neutral K, a $\Delta S = 1$ process, is called direct CP violation. The Standard Model of electroweak interactions, discussed in Chapter 12, predicts that ϵ'/ϵ is non-zero but small primarily because $|A_2/A_0| \approx 1/20$, a reflection of $\Delta I = 1/2$ rule. Any definitively non-zero result

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for ϵ'/ϵ suffices to rule out the superweak model. This can be accomplished by measuring $|\eta_{00}|^2$ and $|\eta_{+-}|^2$. Some uncertainties are reduced by taking the ratio

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \approx 1 - 6\mathrm{Re}\frac{\epsilon'}{\epsilon}, \tag{7.41}$$

In fact, ϵ'/ϵ is known to be nearly real because the phases of ϵ' and ϵ are quite similar. Data from a 1988 experiment NA31 at CERN (Ref. 7.9) indicated a small, non-zero value, $\epsilon'/\epsilon = 0.0033 \pm 0.0011$, disfavoring the superweak model. Early results from experiment E731 at Fermilab did not confirm this non-zero value. Continued improvements in experiments at CERN (NA48, Ref. 7.10) and Fermilab (KTeV, Ref. 7.11) ultimately converged on small but distinctly non-zero values, with the average $\mathrm{Re}(\epsilon'/\epsilon) = (1.67 \pm 0.23) \times 10^{-3}$. The superweak model was more a straw man than a theory, but knocking it down took three decades.

Exercises

7.1 Derive the relation between the forward-scattering amplitude and the index of refraction by considering a plane wave of matter or light incident on a thin slab of material. Determine the shift in the phase of the wave passing through the material.

7.2 Show that the decay $\phi(1020) \rightarrow K_S^0 K_L^0$ is allowed but $\phi(1020) \rightarrow K_S^0 K_S^0$ and $\phi(1020) \rightarrow K_L^0 K_L^0$ are forbidden.

7.3 Verify the expression for the eigenstates of the neutral K system in matter. Estimate the size of the regeneration parameter in beryllium for a momentum of 1100 MeV, the conditions of the original CP-violation experiment. Estimate f_0 and $\overline{f}_0$ using the optical theorem and data for the K^+p and K^-p total cross sections.

7.4 A beam of K^0 is created at $t = 0$. Assuming CP conservation, what is the intensity of $\overline{K}^0$ in the beam as a function of the proper time? Plot the results for $|\Delta m|\tau_1 = 0, 1, 2, \infty$. See Camerini *et al.*, *Phys. Rev.* **128**, 362 (1962).

7.5 Consider a neutral kaon beam that is purely K^0 at $t = 0$. Show that the rate of decay into $\pi^+\pi^-$ as a function of the proper time, τ, is proportional to

$$e^{-\Gamma_S\tau} + 2|\eta_{+-}|e^{-(\Gamma_S+\Gamma_L)/\tau/2}\cos\left[\phi_{+-} - (m_L - m_S)\tau\right] + e^{-\Gamma_L\tau}|\eta_{+-}|^2.$$

Further Reading

The standard reference for the formalism is T. D. Lee and C. S. Wu *Ann. Rev. Nucl. Sci.*, **16**, 511 (1966).

A nice treatment of this material is given in *Weak Interactions of Leptons and Quarks*, by E. D. Commins and P. H. Bucksbaum, Cambridge University Press, Cambridge, 1983.

A comprehensive review is given in B. Winstein and L. Wolfenstein, *Rev. Mod. Phys.* **65**, 1113 (1993).

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References

7.1 K. Lande *et al.*, "Observation of Long Lived Neutral V Particles." *Phys. Rev.*, **103**, 1901 (1956).

7.2 W. F. Fry, J. Schneps, and M. S. Swami, "Evidence for Long-lived Neutral Unstable Particle." *Phys. Rev.*, **103**, 1904 (1956).

7.3 K. Lande, L. M. Lederman, and W. Chinowsky, "Report on Long Lived K^0 Mesons." *Phys. Rev.*, **104**, 1925 (1957).

7.4 F. Muller *et al.*, "Regeneration and Mass Difference of Neutral K Mesons." *Phys. Rev. Lett.*, **4**, 418 (1960).

7.5 J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, "Evidence for the 2π Decay of the K_2^0 Meson." *Phys. Rev. Lett.*, **13**, 138 (1964).

7.6 S. Bennett *et al.*, "Measurement of the Charge Asymmetry in the Decay $K_L^0 \to \pi^{\pm} + e^{\mp} + \nu$." *Phys. Rev. Lett.*, **19**, 993 (1967).

7.7 D. Dorfan *et al.*, "Charge Asymmetry in the Muonic Decay of the K_2^0." *Phys. Rev. Lett.*, **19**, 987 (1967).

7.8 A. Alavi-Harati *et al.*, KTeV Collaboration, "Observation of CP Violation in $K_L \to \pi^+\pi^- e^+ e^-$ Decays ." *Phys. Rev. Lett.*, **84**, 408 (2000).

7.9 CERN–Dortmund–Edinburgh–Mainz–Orsay–Pisa–Siegen Collaboration, "First Evidence for Direct CP Violation." *Phys. Lett.*, **206B**, 169 (1988).

7.10 J. R. Batley *et al.*, NA48 Collaboration, "A Precision Measurement of Direct CP Violation in the Decay of Neutral Kaons into Two Pions." *Phys. Lett.*, **544B**, 97 (2002).

7.11 A. Alavi-Harati *et al.*, KTeV Collaboration, "Measurements of Direct CP Violation, CPT Symmetry, and Other Parameters in the Neutral Kaon System." *Phys. Rev.*, **D67**, 012005 (2003).

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Observation of Long-Lived Neutral *V* Particles*

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THE application of rigorous charge conjugation invariance to strange particle interactions has led to the prediction of rather startling properties for the θ^0-meson state.[1] Some of these are: (I) the existence of a second neutral particle, θ_2^0, for which two-pion decay is prohibited; (II) the consequent existence of a second

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TABLE I. Data on V^0 events.

Event number	P_+ Mev/c	I_+[a]	P_- Mev/c	I_-[a]	θ[b]	$Q^*_{\pi\tau^0}$ Mev	Comment
1	360±10	<2	206±37	<2	52°	96±17	Not τ^0[d]
2	···		117±50	<2	151°	···	(→) track short
3	>100	<2	>100	<2	140°	···	Both tracks short
4	224±5	<2	58.5±4	<2	91.5°	66±2	Not τ^0; probable e^-
5	147±23	<2	197±6	<2	113.6°	121±12	Not τ^0
6	83±5	<2	137±3	<2	81.0°	40±2	$I_->I_+$, probable $\pi^-\mu^+$, π^-e^+, or μ^-e^+
7	142±13	<2	255±5	<2	124°	163±10	Not τ^0
8	197±25	<2	234±9	<2	97°	147±14	Not τ^0
9	241±33	<2	67±20	<2	142°	109±18	Not τ^0, probable e^-
10	194±8	<2	223±4	<2	140°	140±5	Not τ^0
11	111±4	<2	114±5	<2	77.5°	34±1.4	$I_->I_+$, like No. 6
12	249±5	<2	89±1	2–3	42.0°	38±1.2	Probable π^-
13	290±25	<2	86±25	<2	92°	103±12	μ^- or e^-, ∴ not τ^0
14	183±5	<2	44±5	3–4	102.7	52±2	π^- or μ^-
15	>150	<2	62±7	<2	99°	···	3° deflection in +. P_{sec}=287 ±30. Possible $\pi-\mu$ decay. Probable e^-
16	508±18	<2	150±2	<2	65.9°	160±7	Not τ^0, $I_->I_+$
17	136±8	1.5–2	164±5	<2	118.6°	101±5	$I_+>I_-$. Probable π^+, not τ^0
18	251±15	<2	201±50	<2	65.9°	93±15	Not τ^0
19	327±15	<2	112±10	<2	38.3°	51±4	$\pi^+\to\mu^+$, P_μ^*=20±10 Mev
20	167±3	<2	114±3	<2	65.5°	40±2	
21	152±5	<2	120±24	<2	112.5°	79±8	
22	283±10	<2	222±10	<2	50.1°	72±6	Coplanar, $P_\perp$=59±30 Mev/c
23	89±1	<2	272±9	<3	128.5°	134±10	Not τ^0

[a] This is a visual estimate of the ionization, in units of minimum ionization as determined from nearby light tracks of P <50 Mev/c.
[b] Angle errors have not been computed. An average error of 3° has been used.
[c] $Q^*_{\pi\pi}$ for a normal θ^0 is 214 Mev.
[d] τ^0 is defined as $\to\pi^++\pi^-+\pi^0$ and is excluded by Q value or transverse momentum.

lifetime, considerably longer than that for two-pion decay of the $\theta_1^0(\sim 1\times 10^{-10}$ sec); (III) a complicated time dependence for the nuclear interaction properties.[2] The only additional assumption in this "particle mixture" theory is the nonidentity of θ^0 and its antiparticle.

These theoretical considerations have stimulated us to undertake a search for long-lived neutral particles. To this end, the Columbia 36-in. magnet cloud chamber was exposed to the neutral radiation emitted from a copper target at an angle of 68° to the 3-Bev external proton beam of the Brookhaven Cosmotron.[3] Charged particles are eliminated by the combination of a 4-ft long Pb collimator and a 4×10^5 gauss-inch sweeping magnet. The 6-meter flight path from target to chamber represents ~100 mean lives for the well-known Λ^0 and θ^0 particles which are produced at this energy.[4] To date twenty-six V^0 events have been observed. All of these events have anomalous Q values for two-pion decay, all but one are noncoplanar with the line of flight, and all but one demand at least one neutral secondary to balance transverse momentum.

The cloud chamber operates at a pressure of 0.91 atmos of He and 0.10 atmos of argon. The only additional matter in the direct path of the neutral radiation is the 1-cm thick Lucite chamber wall. A 1.5-in. thick lead filter was placed at the entrance to the collimator to reduce the γ-ray flux reaching the chamber. The aperture (5 in.×1.5 in.) defined a solid angle of 0.002 steradian at 68° to the incident protons. The arrangement yielded readable photographs at a beam intensity of $\sim 10^8$ protons per pulse, although the flux through the chamber was estimated to be $\sim 10^4$ neutrons. The latter fact points up the virtue of the technique employed.

The relevant primary data on 23 measured V^0 events, found in a run of 1200 pictures, are listed in Table I. We have considered various background effects which could possibly simulate V^0 events:

(1) Production of meson pairs in the gas by neutrons or photons, the nuclear recoil track being too short to observe. However, the number of neutrons above meson production threshold energy at 68° was expected to be quite small. This was verified experimentally by the fact that no negative prongs (i.e., π^- mesons) were observed to emerge from 1218 neutron-induced stars in the gas.

(2) Decay of π^0 mesons, produced in the gas without recoil, into the alternate mode $e^+e^-\gamma$. This is ruled out kinematically for 16 of the events. The argument in (1) also applies.

(3) Production of large-angle electron pairs in the gas by photons.

(4) Bremsstrahlung or scattering of backward-moving particles with consequent large-angle deflections.

These possibilities lead to the prediction of thousands of smaller angle events and to the necessity for large fluxes of backward-moving particles. Neither of these is observed. These arguments will be detailed in a more complete report. They lead to the conclusion that

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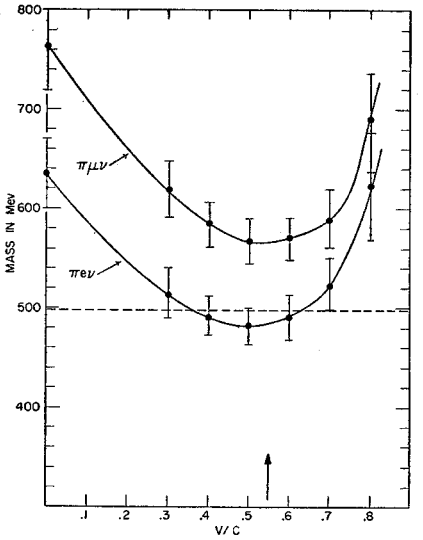


FIG. 1. Average calculated primary mass *vs* velocity of primary particle for assumed decay schemes $\pi^+e^-\nu^0$ and $\pi^+\mu^-\nu^0$. The arrow indicates the peak of the phase space spectra (reference 5). The vertical bars are average deviations of the mean.

the events listed in Table I are indeed examples of the disintegration of a long-lived neutral particle.

A preliminary analysis of the data yields some information on the properties of the new particle.

(1) All but three of the forty-six secondaries are determined to be lighter in mass than the K meson. None can be protons. We have assumed that all are pions, muons, or electrons. The identification of several of the decay products as pions or electrons is indicated in the table.

(2) We have considered various three-body decay schemes, motivated by the observed charged K-meson modes. In Fig. 1, we plot for assumed decay products $\pi^{\pm}e^{\mp}\nu^0$ and for $\pi^{\pm}\mu^{\mp}\nu^0$, the variation of the average computed mass (15 events were available) of the incoming primary as a function of its assumed velocity. Permutations of the relevant combinations of π's, μ's, e's, and ν's yield similar results. For example $\pi^+\mu^-\nu^0$, $\mu^+\pi^-\nu^0$, $\mu^+e^-\pi^0$, and $\pi^+e^-\pi^0$ are almost coincident. These graphs emphasize the conclusion that the resultant incoming velocity distribution is kinematically sensible only for primary masses near the K mass of 500 Mev.[5] One may also infer that, for a K mass primary, $\pi e\nu$ secondaries are more frequent than $\pi\mu\nu$ or, say, $\mu e\pi$.

(3) All but two of the events are kinematically inconsistent with a Λ^0-mass particle decaying into $\mu^{\pm}e^{\mp}N$ or $e^{\pm}e^{\mp}N$.[6]

(4) Figure 2 illustrates the detection sensitivity as a function of lifetime for a K-mass particle. Although

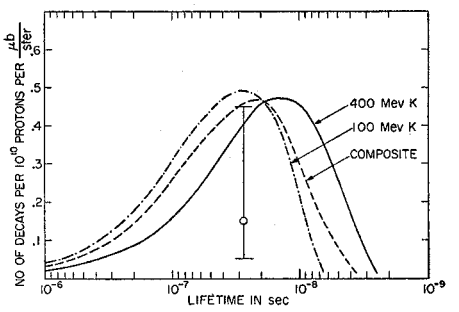


FIG. 2. Detection sensitivity for K mesons as function of lifetime. The composite curve is obtained with the spectra of reference 5. The point indicates the observed yield with a production cross section of ~ 20 μb/sterad.

the production cross section for K^0 mesons[7] has a large uncertainty, comparison with the observed yield serves to limit the lifetime to the range 10^{-6} sec$>\tau>3\times10^{-9}$ sec. The observed uniform distribution of events in the chamber, together with Fig. 1 also sets a lower limit: $\tau>1\times10^{-9}$ sec. If the lifetime is on the short side of the above interval, then it is likely that many of the anomalous V^0's observed in cosmic rays are examples of this particle, and not alternate decay modes of the θ_1^0.[8]

At the present stage of the investigation one may only conclude that Table I, Fig. 2, and Q^* plots are consistent with a K^0-type particle undergoing three-body decay. In this case the mode $\pi e\nu$ is probably prominent,[9] the mode $\pi\mu\nu$ and perhaps other combinations may exist but are more difficult to establish, and $\pi^+\pi^-\pi^0$ is relatively rare. Although the Gell-Mann-Pais predictions (I) and (II) have been confirmed, long lifetime and "anomalous" decay mode are not sufficient to identify the observed particle with θ_2^0. In particular, a neutral τ meson, if three-pion decay has a small branching ratio, may have these properties. A much stronger test of particle mixtures must await the observation of nuclear interactions or of the striking interference effects which are also predicted by Pais and Piccioni,[2] Treiman and Sachs,[2] and Serber.[10]

The authors are indebted to Professor A. Pais whose elucidation of the theory directly stimulated this research. The effectiveness of Cosmotron staff collaboration is evidenced by the successful coincident operation of six magnets and the Cosmotron with the cloud chamber.

* Supported by the U. S. Atomic Energy Commission and the U. S. Atomic Energy Commission-Office of Naval Research Joint Program.

[1] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955).

[2] Further discussion of particle mixtures have been given by A. Pais and O. Piccioni, Phys. Rev. **100**, 932 (1955); G. Snow, Phys. Rev. **103**, 1111 (1956); S. Treiman and R. G. Sachs, Phys. Rev. **103**, 1545 (1956); K. Case, Phys. Rev. **103**, 1449 (1956).

[3] See Piccioni, Clark, Cool, Friedlander, and Kassner, Rev. Sci. Instr. **26**, 232 (1955). The ejected beam is focused by a quadrupole magnet pair to a 3-in. diameter circle. Two bending magnets

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were used to steer the beam onto the 1.5 in.×4 in.×5 in. long target.

[4] Blumenfeld, Booth, Lederman, and Chinowsky, Phys. Rev. **102**, 1184 (1956).

[5] We are grateful to R. Sternheimer for computing the energy spectrum of K mesons emitted at 68° under various assumptions as to the collision mechanism. These calculations yield similar spectra, all of which peak near 100 Mev. See Block, Harth, and Sternheimer, Phys. Rev. **100**, 324 (1956).

[6] For example, one member of a Λ^0 parity doublet may have a long lifetime. See T. D. Lee and C. N. Yang, Phys. Rev. **102**, 290 (1956).

[7] Collins, Fitch, and Sternheimer (private communication).

[8] Kadyk, Trilling, Leighton, and Anderson, Bull. Am. Phys. Soc. Ser. II, **1**, 251 (1956). For a recent summary see Ballam, Grisaru, and Treiman, Phys. Rev. **101**, 1438 (1956).

[9] Examples of this decay mode have been reported by Slaughter, Block, and Harth, Bull. Am. Phys. Soc. Ser. II, **1**, 186 (1956). A particularly clear event has been observed by the Ecole Polytechnique group. We are indebted to J. Tinlot and B. Gregory for this data and for helpful discussions on anomalous V^0's.

[10] R. Serber (private communication).

Evidence for a Long-Lived Neutral Unstable Particle*

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(Received July 19, 1956)

During a systematic search for K^- mesons in a pellicle stack exposed to a channel of negative particles from the Berkeley Bevatron, four unusual events of the following nature were found: an unstable particle originated in the emulsion from a small star which was produced by a neutral particle. The channel was at 90° to a target bombarded by 6-Bev protons and defined a momentum of 280 Mev/c.

Since the events were of an unusual nature, each one will be described separately.

Event 1.—A $_\Lambda He^4$ hyperfragment originated from a star which also consisted of a π meson of 42±12 Mev, two short recoil tracks, and a proton of 16.6 Mev. The star was produced by a neutral particle. The hyperfragment decayed from rest into a π^- meson, a proton, and a He^3 recoil. The binding of the Λ^0 particle was found to be 1.8±0.6 Mev.[1] A drawing is shown in *A* of Fig. 1.

Event 2.—A negative K meson of 14 Mev was produced in a star which in addition had a low-energy electron and a nucleonic particle of 115 Mev. The K^- meson produced a star from rest consisting of a π meson, a hyperfragment which decayed nonmesonically, and nucleons. The nucleonic particle from the primary star left the stack and therefore the direction of its motion could not be established. However, the kinetic energy of this particle was not sufficient to produce a K^- meson if it were an incident Σ^- or Ξ^- hyperon; therefore we assume that it was an outgoing particle. This event is shown in *B* of Fig. 1.

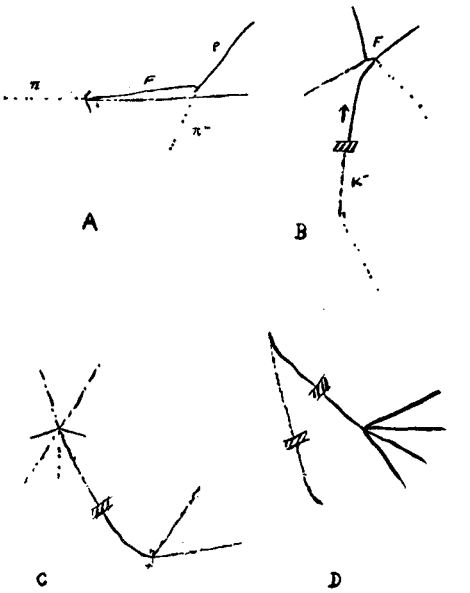


Fig. 1. Drawings of four events which were found in a pellicle stack as shown. A $_\Lambda He$ hyperfragment was produced in *A*, a K^- meson in *B*, probably a Σ^- hyperon in *C*, and a hyperfragment or a Σ^- hyperon in *D*.

Event 3.—A track, 730 microns long, from a seven-pronged star, has a two-pronged star associated with its ending. The primary star was produced by a neutral particle and has a visible kinetic energy of 160 Mev. The connecting particle had a charge of one and appeared to have stopped. The two nuclear particles from the secondary star had a total charge of two or three. In addition there are two tracks of low-energy electrons indicating that the connecting particle was captured. A mass measurement along the connecting track gave $(2200\pm750)m_e$. These facts indicate that the secondary star was produced by a Σ^- hyperon or possibly a Ξ^- hyperon or a K^- meson. A drawing of this event is shown in *C* of Fig. 1.

Event 4.—One particle from a small five-pronged star, which had no incoming particle, appears to have stopped and produced a one-prong star. The prong was most likely due to a proton of 9 Mev. The range of the connecting track is 230 microns. Gap counting showed that the secondary star was not the result of a scattering. Also it is possible to exclude the absorption of a slow π^- meson as its cause. The event is interpreted as a nonmesonic hydrogen hyperfragment decay or the capture of a negative hyperon or K meson. The event is shown in *D* of Fig. 1.

It is very improbable that these four events were produced by fast neutrons since the ratio of these

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events to energetic neutron stars in the stack is large ($\sim 1/10$). Also the flux of energetic neutrons at 90° to the target is expected to be small. They cannot be cosmic-ray events because their tracks can be followed through the stack, which was in a disassembled state both shortly before and after the machine exposure. These events can be interpreted as the nuclear interaction of a neutral unstable particle of the same "strangeness" as that of the K^- meson and the Λ and Σ hyperons.

The total energy in event 2 is too high to have been due to a neutral K from the charge exchange of a K^- meson in the beam. Furthermore, the expected number of such events, if due to charge exchange, is less than one per 20 cc of emulsion, whereas the density of these unusual events is probably greater than one per cc of emulsion.

Also it seems unlikely that the events could have been due to neutral θ's which were produced in the deflecting magnet because they would have had to have lived about 20 mean lifetimes.

These events can be explained by assuming that long-lived neutral K mesons were produced at the target with about the same frequency as the K^+ mesons. A small fraction of these neutral K mesons could have penetrated the shielding (about two feet of brass) between the plates and the target and then interacted in the pellicle stack. The lifetime of these particles must have been at least 10^{-8} sec. The existence of a long-lived neutral K meson was predicted by Gell-Mann and Pais.[2]

The authors are indebted to Dr. E. J. Lofgren for making possible the exposures to the Bevatron. Discussions with Dr. George Snow were stimulating and helpful.

* Supported in part by the U. S. Atomic Energy Commission and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

[1] This hyperfragment has been described in detail (event 90) by Fry, Schneps, and Swami, Phys. Rev. **101**, 1526 (1956).

[2] M. Gell-Mann and A. Pais, Phys. Rev. **97**, 1387 (1955). Dr. G. A. Snow has pointed out the possibility of a long-lived τ^0 meson [Phys. Rev. **103**, 1111 (1956)].

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VOLUME 4, NUMBER 8 PHYSICAL REVIEW LETTERS APRIL 15, 1960

REGENERATION AND MASS DIFFERENCE OF NEUTRAL K MESONS*

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A very significant feature of the Gell-Mann–Pais particle mixture theory[1,2] is the regeneration of the $K1$ from the $K2$ neutral meson. We examine the three possible types of regeneration and give the results of an experiment that exhibits the expected transformations as demanded by the theory. The experiment also allows an estimate of the difference between the masses of $K1$ and $K2$.

One of the three types of regeneration has been described previously[3]: A plate inserted into a parallel beam of $K2$ particles produces a parallel beam of $K1$ particles. This phenomenon, which we will henceforth call transmission-regeneration, is in striking contrast with other known processes whereby a particle transforms into another one: a parallel beam of charged pions obviously cannot produce a parallel beam of neutral pions by interacting with a plate.

Here we point out another process that typically follows from the theory, namely the regeneration by diffraction. Because the $\overline{K}^0$ and the K^0 waves are diffracted by a nucleus with different amplitudes, the diffracted wave contains $K1$ as well as $K2$ particles. Thus $K1$ mesons are regenerated by a nucleus with a typical diffraction angular distribution.

Regeneration of $K1$ can also occur by interaction of $K2$ with single nucleons. The angular distribution of this nucleon-regeneration is broad, not essentially different from that obtained in K-nucleon scattering, and therefore it is not a crucial consequence of the particle mixture theory.

All three of these components will emerge from a plate traversed by a parallel beam of $K2$'s. The angular distribution should permit one to recognize each component separately.

Case[4] and Good[5] have shown that the intensity of the transmitted component is a very sensitive function of the mean life τ_1 of the $K1$ and of the difference δm between the masses of $K1$ and $K2$. The mass difference appears in the final expression because of the phase difference it introduces between the $K1$ and the $K2$ waves, an effect which was first noted by Serber[6] in connection with K^0 production. Moreover, Good pointed out that the intensities of both the transmitted and "scattered" component (in the forward direction) are proportional to $|f_{21}{}^0|^2$, $f_{21}{}^0$ being the amplitude of the regenerated $K1$, at zero angle, in a $K2$-nucleus collision. Good's "scattered" component must be identified with the diffracted component described above. Thus the intensity ratio of the transmitted wave to diffracted wave is a function only of δm and τ_1. We derive here in a more concise way the expression for this ratio.

The computation of the expected transmitted and diffracted intensities can be greatly simplified by neglecting, from the start, the regeneration of $K2$ from $K1$. As the number of $K1$'s is always less than one thousandth of the number of $K2$'s, this approximation is very good. We consider then a plane wave of $K2$ particles, of wavelength λ, crossing our plate, which contains N nuclei per cubic centimeter. If each nucleus produces $K1$'s with a forward amplitude $f_{21}{}^0$, an infinitesimal thickness dx of the plate at depth x

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(x in the direction of the incoming $K2$ beam; $x=0$ and $x=L$ denote the limits of the plate) produces a $K1$ wave amplitude $iN\lambda f_{21}{}^0 dx$ which arrives at the end of the plate with the amplitude

$$da_1 = iN\lambda f_{21}{}^0 dx \exp\left(-ik_2 x - ik_1(L-x) - \frac{L-x}{2v\gamma\tau_1} - \frac{L}{2u}\right).$$

Notice that the $K2$ wave has traveled to depth x before producing the $K1$ wave, which then travels from x to L; u is the collision mean free path, which is the same for $K1$ and $K2$, because both particles are a half-and-half mixture of K^0 and $\bar{K}^0$; v is the velocity of the particles; γ is the Lorentz factor; $\hbar k_1$ and $\hbar k_2$ are the momenta. Let us call $\Lambda = v\gamma\tau_1$ the decay mean free path of the $K1$'s and introduce the dimensionless quantities $l = L/\Lambda$ and $\delta = (m_2 - m_1)c^2/(\hbar/c_1)$. By integration with respect to x we obtain, for the transmitted intensity,

$$|a|^2 = \frac{4|f_{21}{}^0|^2 N^2\Lambda^2\lambda^2}{1+4\delta^2}\,|e^{-i\delta l} - e^{-l/2}|^2 e^{-L/u}. \quad (1)$$

On the other hand, the nuclei, incoherently from each other, regenerate $K1$'s by diffraction with a differential cross section $d\sigma_{21}/d\omega = |f_{21}|^2$. The number of diffraction-regenerated $K1$'s in the infinitesimal thickness dx at x, in the forward direction, surviving through the thickness $L-x$ is

$$d\left(\frac{dn_1}{d\omega}\right)^0 = |f_{21}{}^0|^2 N \exp\left(-\frac{L-x}{v\gamma\tau_1} - \frac{L}{u}\right)dx,$$

which is integrated to give

$$\left(\frac{dn_1}{d\omega}\right)^0 = |f_{21}{}^0|^2 N\Lambda(1-e^{-l})e^{-L/u}. \quad (2)$$

The ratio between (1) and (2) is

$$R = 4N\Lambda\lambda^2\,|e^{-i\delta l} - e^{-l/2}|^2/[(1-e^{-l})(1+4\delta^2)]. \quad (3)$$

To observe these regeneration processes, we have inserted a plate in the Berkeley 30-inch propane chamber. The chamber was placed in a beam of $K3$ particles which traversed the instrument lengthwise and perpendicular to the plate. The experimental setup will be described in more detail in a later article. Here we give only a brief description.

A beam of 1.1-Bev/c negative pions impinged on a five-foot hydrogen target. The 670-Mev/c K^0 produced in the target travelled a distance of 22.5 feet before arriving at the 30-inch propane chamber, so that approximately one $K2$ crossed the chamber per 10^{11} protons in the Bevatron beam. About 200 000 pictures were taken, half of them with a 1.5-inch iron plate to enhance the diffracted wave relative to the transmitted wave, and the other half with a 6-inch iron plate which yields an intense transmitted wave.

We limited the analysis to those two-prong events in which the positive prong could be recognized to be a meson on the basis of ionization and momentum. We also required that the decay occur within two mean lives from the plate and that the primary momentum be equal, within the errors, to the beam momentum. The $Q(\pi,\pi)$ distribution of these selected events shows a marked peak around the expected value of 220 Mev, which fact proves the regeneration of $K1$. As a further selection, we keep only those events for which Q differs by no more than 1.4 standard deviations from the peak value.

By measuring the vector momenta of the two prongs, we determine the angle θ between the $K1$ and the incident $K2$ beams, within an error of about 2 degrees.

The angular distributions are shown in Fig. 1. The diffraction curve has been computed with an optical model method[7] using the known cross sections for K^+ and K^- with protons and nuclei.[8] The curve is quite close to the black-sphere distribution. Figure 1 clearly shows a diffraction component and a superimposed transmission peak. Most of the transmission peak is confined to angles smaller than 2.5 degrees ($\cos\theta > 0.999$), which is just what we expect from an infinitely narrow peak measured with our errors. The mere presence of such a large transmission peak is a proof that the mass difference is smaller than, say, $5\hbar/\tau_1$.

Referring to the data for the 6-inch plate, 29 events occur in the interval for $\cos\theta$ between 0.998 (3.5°) and 1, which should contain the total number T of the transmitted $K1$'s and a part D of the diffracted ones. Knowing the diffraction angular distribution we can compute D from the 31 particles in the 0.980 to 0.998 interval, assuming that that region contains only diffracted $K1$'s. A nucleonic background will actually be present in this interval, which we ignore for the moment. We thus obtain $D=12$, which gives $T=17$. For comparison with formula (3), we note that $(dn_1/d\omega) = 1.18(D/\omega)$, where the factor 1.18 is equal to the ratio of the intensity at zero degrees to the average intensity within ω, ω being the solid angle in the peak interval, that is, $2\pi \times 0.002$. It is convenient to compare $T/1.18D$

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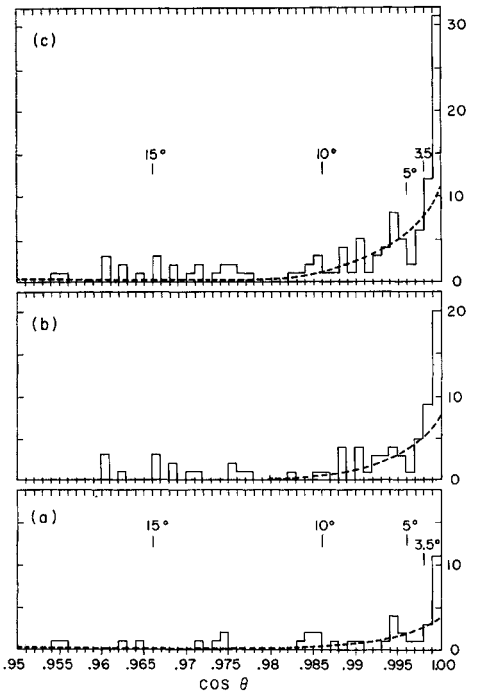


FIG. 1. Histograms of number of $K1$ decay events per 0.001 interval of $\cos\theta$ (θ is the angle between the direction of the primary $K2$ beam and the regenerated $K1$). (a) Data for the 1.5-inch plate; (b) data for the 6-inch plate; (c) combined data for the two plates. The curves are diffraction angular distributions normalized in the 0.980 to 0.998 interval for $\cos\theta$.

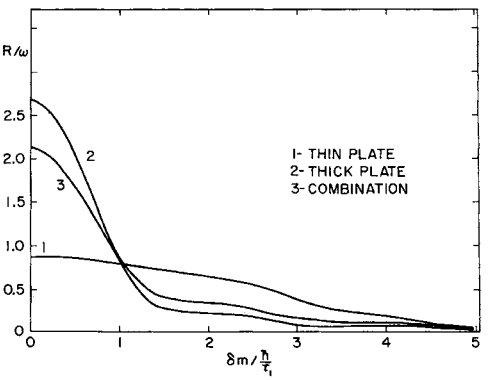


FIG. 2. Calculated intensity of the forward regenerated $K1$'s versus the $K1$-$K2$ mass difference. The ordinate R/ω is the ratio of the transmission-regenerated $K1$'s to the diffraction-regenerated $K1$'s in the interval $\cos\theta > 0.998$.

with R/ω, which is plotted in Fig. 2 versus the mass difference, in units of $\hbar/\tau_1$. We obtain $T/1.18D = 1.2 \pm 0.53$, which gives $\delta m = 0.85^{+0.4}_{-0.25}$. With a probability of 95%, $\delta m < 1.4$.

In the same way, we find from the thin plate alone $\delta m = 0$ ($\delta m < 4.5$ with 95% probability) and from the combination of thin and thick plate $\delta m = 0.85^{+0.3}_{-0.25}$ ($\delta m < 1.5$ with 95% probability).

If we correct for nucleonic or any other background, we would obtain a larger value for R, hence a smaller value for δm. For instance, assuming a uniform background from $\cos\theta = 0.96$ to $\cos\theta = 1$, the compounded data for both plates yield $\delta m = 0$ ($\delta m < 1.1$ with 95% probability). In view of a remark by Okun' and Pontecorvo,[9] this result indicates that decay rates for $\Delta S = 2$ are 10^5 times slower than for $\Delta S = 1$.

We are grateful to many people who generously contributed to this experiment, particularly Edward J. Lofgren, Myron L. Good, Richard L. Lander, Robert E. Lanou, Marian N. Whitehead, Roy Kerth, and Frank T. Solmitz. The pictures have been scanned by J. Peter Berge, Karl Brunstein, Layton Linch, Mrs. Glennette Anneson, Mrs. Rokalana Gamow, and Mrs. Ottilie Oldenbusch.

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† On leave of absence from Ecole Polytechnique, Paris and Marine Nationale Francaise.

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[1] M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955).

[2] T. D. Lee, R. Oehme, and C. N. Yang, Phys. Rev. 106, 340 (1957).

[3] A. Pais and O. Piccioni, Phys. Rev. 100, 1487 (1955).

[4] K. M. Case, Phys. Rev. 103, 1449 (1956).

[5] M. L. Good, Phys. Rev. 106, 591 (1957); Phys. Rev. 110, 550 (1958).

[6] R. Serber (private communication), quoted in 3.

[7] S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. 75, 1352 (1949).

[8] Total cross sections measured by H. C. Burrowes, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, and R. A. Schluter, Phys. Rev. Letters 2, 117 (1959). See also report by L. W. Alvarez at the

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Ninth Annual International Conference on High-Energy Physics, Kiev, 1959 (unpublished). For K^+ we used the optical model potential of 28 Mev-i 19 Mev. We are indebted to B. Sechi Zorn and G. T. Zorn for communication of their unpublished results, and to L. S. Rodberg and R. M. Thaler for showing to us their unpublished article on K^+ scattering in emulsions.

[9]L. Okun' and B. Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 1587 (1957) [translation: Soviet Phys. - JETP 5, 1297 (1957)].

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VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

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(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$ 48-in. collimator at an average distance of 14.5 ft. from the internal target. This collimator was followed by a sweeping magnet of 512 kG-in. at ~20 ft. and a 6-in.$\times$ 6-in.$\times$ 48-in. collimator at 55 ft. A $1\frac{1}{2}$-in. thickness of Pb was placed in front of the first collimator to attenuate the gamma rays in the beam.

The experimental layout is shown in relation to the beam in Fig. 1. The detector for the decay products consisted of two spectrometers each composed of two spark chambers for track delineation separated by a magnetic field of 178 kG-in. The axis of each spectrometer was in the horizontal plane and each subtended an average solid angle of 0.7×10^{-2} steradians. The spark chambers were triggered on a coincidence between water Cherenkov and scintillation counters positioned immediately behind the spectrometers. When coherent K_1^0 regeneration in solid materials was being studied, an anticoincidence counter was placed immediately behind the regenerator. To minimize interactions K_2^0 decays were observed from a volume of He gas at nearly STP.

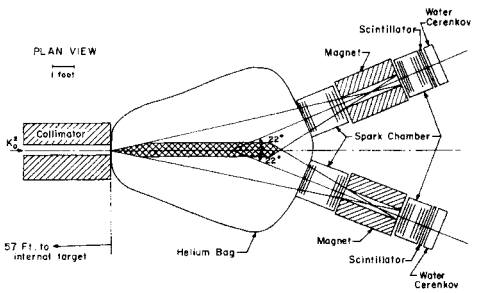


FIG. 1. Plan view of the detector arrangement.

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This angle should be zero for two-body decay and is, in general, different from zero for three-body decays.

An important calibration of the apparatus and data reduction system was afforded by observing the decays of K_1^0 mesons produced by coherent regeneration in 43 gm/cm^2 of tungsten. Since the K_1^0 mesons produced by coherent regeneration have the same momentum and direction as the K_2^0 beam, the K_1^0 decay simulates the direct decay of the K_2^0 into two pions. The regenerator was successively placed at intervals of 11 in. along the region of the beam sensed by the detector to approximate the spatial distribution of the K_2^0's. The K_1^0 vector momenta peaked about the forward direction with a standard deviation of 3.4 ± 0.3 milliradians. The mass distribution of these events was fitted to a Gaussian with an average mass 498.1 ± 0.4 MeV and standard deviation of 3.6 ± 0.2 MeV. The mean momentum of the K_1^0 decays was found to be 1100 MeV/c. At this momentum the beam region sensed by the detector was 300 K_1^0 decay lengths from the target.

For the K_2^0 decays in He gas, the experimental distribution in m^* is shown in Fig. 2(a). It is compared in the figure with the results of a Monte Carlo calculation which takes into account the nature of the interaction and the form factors involved in the decay, coupled with the detection efficiency of the apparatus. The computed curve shown in Fig. 2(a) is for a vector interaction, form-factor ratio $f^-/f^+=0.5$, and relative abundance 0.47, 0.37, and 0.16 for the K_{e3}, $K_{\mu 3}$, and $K_{\pi 3}$, respectively.[3] The scalar interaction has been computed as well as the vector interaction

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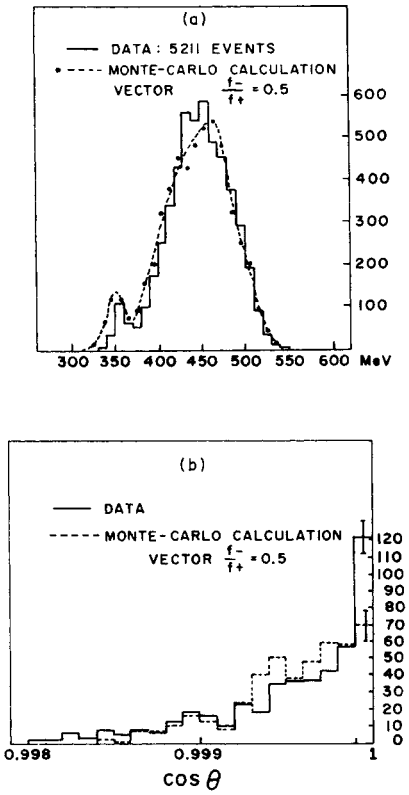


FIG. 2. (a) Experimental distribution in m^* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those events in the range $490 < m^* < 510$ MeV. The calculated curve is normalized to the number of events in the complete sample.

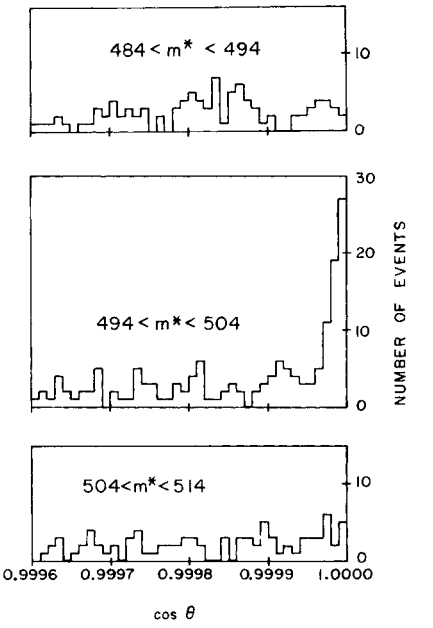


FIG. 3. Angular distribution in three mass ranges for events with $\cos\theta > 0.9995$.

with a form-factor ratio $f^-/f^+ = -6.6$. The data are not sensitive to the choice of form factors but do discriminate against the scalar interaction.

Figure 2(b) shows the distribution in $\cos\theta$ for those events which fall in the mass range from 490 to 510 MeV together with the corresponding result from the Monte Carlo calculation. Those events within a restricted angular range ($\cos\theta > 0.9995$) were remeasured on a somewhat more precise measuring machine and recomputed using an independent computer program. The results of these two analyses are the same within the respective resolutions. Figure 3 shows the results from the more accurate measuring machine. The angular distribution from three mass ranges are shown; one above, one below, and one encompassing the mass of the neutral K meson.

The average of the distribution of masses of those events in Fig. 3 with $\cos\theta > 0.999\,99$ is found to be 499.1 ± 0.8 MeV. A corresponding calculation has been made for the tungsten data resulting in a mean mass of 498.1 ± 0.4. The difference is 1.0 ± 0.9 MeV. Alternately we may take the mass of the K^0 to be known and compute the mass of the secondaries for two-body decay. Again restricting our attention to those events with $\cos\theta > 0.999\,99$ and assuming one of the secondaries to be a pion, the mass of the other particle is determined to be 137.4 ± 1.8. Fitted to a Gaussian shape the forward peak in Fig. 3 has a standard deviation of 4.0 ± 0.7 milliradians to be compared with 3.4 ± 0.3 milliradians for the tungsten. The events from the He gas appear identical with those from the coherent regeneration in tungsten in both mass and angular spread.

The relative efficiency for detection of the three-body K_2^0 decays compared to that for decay to two pions is 0.23. We obtain 45 ± 9 events in

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the forward peak after subtraction of background out of a total corrected sample of 22 700 K_2^0 decays.

Data taken with a hydrogen target in the beam also show evidence of a forward peak in the $\cos\theta$ distribution. After subtraction of background, 45 ± 10 events are observed in the forward peak at the K^0 mass. We estimate that ~10 events can be expected from coherent regeneration. The number of events remaining (35) is entirely consistent with the decay data when the relative target volumes and integrated beam intensities are taken into account. This number is substantially smaller (by more than a factor of 15) than one would expect on the basis of the data of Adair et al.[4]

We have examined many possibilities which might lead to a pronounced forward peak in the angular distribution at the K^0 mass. These include the following:

(i) K_1^0 coherent regeneration. In the He gas it is computed to be too small by a factor of $\sim 10^6$ to account for the effect observed, assuming reasonable scattering amplitudes. Anomalously large scattering amplitudes would presumably lead to exaggerated effects in liquid H_2 which are not observed. The walls of the He bag are outside the sensitive volume of the detector. The spatial distribution of the forward events is the same as that for the regular K_2^0 decays which eliminates the possibility of regeneration having occurred in the collimator.

(ii) $K_{\mu 3}$ or K_{e3} decay. A spectrum can be constructed to reproduce the observed data. It requires the preferential emission of the neutrino within a narrow band of energy, ±4 MeV, centered at 17 ± 2 MeV ($K_{\mu 3}$) or 39 ± 2 MeV (K_{e3}). This must be coupled with an appropriate angular correlation to produce the forward peak. There appears to be no reasonable mechanism which can produce such a spectrum.

(iii) Decay into $\pi^+\pi^-\gamma$. To produce the highly singular behavior shown in Fig. 3 it would be necessary for the γ ray to have an average energy of less than 1 MeV with the available energy extending to 209 MeV. We know of no physical process which would accomplish this.

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$ where τ_1 and τ_2 are the K_1^0 and K_2^0 mean lives and R_T is the branching ratio including decay to two π^0. Using $R_T = \frac{3}{2}R$ and the branching ratio quoted above, $|\epsilon| \cong 2.3 \times 10^{-3}$.

We are grateful for the full cooperation of the staff of the Brookhaven National Laboratory. We wish to thank Alan Clark for one of the computer analysis programs. R. Turlay wishes to thank the Elementary Particles Laboratory at Princeton University for its hospitality.

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‡A. P. Sloan Foundation Fellow.

§On leave from Laboratoire de Physique Corpusculaire à Haute Energie, Centre d'Etudes Nucléaires, Saclay, France.

[1]M. Bardon, K. Lande, L. M. Lederman, and W. Chinowsky, Ann. Phys. (N.Y.) 5, 156 (1958).

[2]D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov, Phys. Rev. Letters 6, 552 (1961).

[3]D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. 133, B1276 (1964).

[4]R. Adair, W. Chinowsky, R. Crittenden, L. Leipuner, B. Musgrave, and F. Shively, Phys. Rev. 132, 2285 (1963).

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