25, 1167 (1967)]; M. Ya. Azbel', Zh. Eksperim. i Teor. Fiz. 53, 1751 (1967) [translation: Soviet Phys.-JETP 26, 1003 (1968)]. H. J. Lee, Phys. Rev. 166, 459 (1968).

[8]V. Canuto, H.-Y. Chiu, C. Chiuderi, and H. J. Lee (to be published).

[9]L. D. Landau and E. M. Lifshitz, Statistical Physics (Addison-Wesley Publishing Company, Inc., Reading, Mass., 1958).

BRANCHING RATIO AND POSSIBLE CP NONCONSERVATION IN RADIATIVE $K_{\pi 2}$ DECAY

J. McL. Emmerson and T. W. Quirk
Nuclear Physics Laboratory, Oxford, England
(Received 5 May 1969)

We have determined with 90% confidence an upper limit of 1.90×10^{-4} for the branching ratio of the decay mode $K^+\to\pi^+ +\pi^0+\gamma$ in the range of T_{π^+} from 55 to 80 MeV. We discuss the implications of this result for a possible CP nonconservation in radiative $K_{\pi 2}$ decay.

In this Letter we report an upper limit to the branching ratio of the decay mode $K^+\to\pi^+ +\pi^0+\gamma$. Interest in this mode has been aroused by the possibility[1,2] that a comparison of $K^\pm\to\pi^\pm+\pi^0+\gamma$ might reveal asymmetries which violate CP invariance while still satisfying TCP. The several phenomenological analyses[3,4] have been based on the work of Good.[5] They assume that the decay matrix element contains a direct-emission term which is of the same order as the inner-bremsstrahlung term. The contribution made to the decay by interference between these terms could show a CP-nonconserving asymmetry.

If one assumes further[2-5] that the dominant direct-emission terms are $E1$ and $M1$ and sums over the photon polarization, then interference occurs only between the inner-bremsstrahlung and $E1$ terms. The branching ratio may then be written as

$$R^\pm = B^2[1+\gamma C_1\cos(\delta_{11}-\delta_{20}\pm\varphi)+C_2(\gamma^2+\beta^2)], \quad (1)$$

where B^2 is the branching ratio for pure inner bremsstrahlung and the second and third terms represent the contributions to the branching ratio from the direct-emission terms.[3] γ and β are real positive numbers which give, respectively, the amplitudes for $E1$ and $M1$ direct emission relative to inner bremsstrahlung. In the terminology of Good,[5] $\gamma = gA\mu^4/GM^4$ and $\beta = 2gB\mu^4/M^4$. The δ_{IJ} are $\pi\pi$ phase shifts taken at the appropriate energies and φ is a CP-nonconserving phase. B^2, C_1, and C_2 are functions of the kinematic limits for the decay. For T_{π^+} between 55 and 80 MeV and all allowed π^0 energies, $B^2=1.36\times 10^{-4}$, $C_1=1.80$, and $C_2=2.00$.[6]

For a comparison of the K^+ and K^- decay modes, the branching-ratio asymmetry is given by

$$A=\frac{R^+-R^-}{R^++R^-}=\frac{\gamma C_1\sin(\delta_{11}-\delta_{20})\sin\varphi}{1+\gamma C_1\cos(\delta_{11}-\delta_{20})\cos\varphi+C_2(\gamma^2+\beta^2)}. \quad (2)$$

Clearly, in order to produce a CP-nonconserving effect it is necessary that γ be nonzero, and it is of considerable interest to know the limits which can be placed on it.

The present experiment is part of a series of stopping-K^+ experiments performed at Nimrod. The apparatus (Fig. 1) has been described elsewhere.[7] Kaons were brought to rest in the beryllium-plate spark chamber. The momentum of the outgoing π^+ was measured by a magnetic spectrometer. Pions were separated from muons by their range-momentum correlation. Electrons were identified by the Cherenkov counter. The three outgoing gamma rays were detected in the spark chambers $B1$-$B4$, which formed four sides of a cube centered at the beryllium chamber. Each chamber contained 35 brass plates 0.12 radiation lengths thick.

614 π^+ were identified with a spectrometer momentum between 105 and 170 MeV/c. After double scanning 41 were found to have three or four gamma rays. These events were measured and the gamma-ray energies estimated from spark counting. The events were least-squares fitted. No events satisfied the hypothesis of $K^+\to\pi^+ +\pi^0+\gamma$ at the 1% probability level with T_{π^+} between 55 and 80 MeV.[8] The rate for three- or four-gamma-ray events could be entirely accounted for by assuming that they were due to background gamma rays in the spark chambers accompanying a $K_{\pi 2}$ decay in which the π^+ interacted in the beryllium chamber before entering the spectrom-

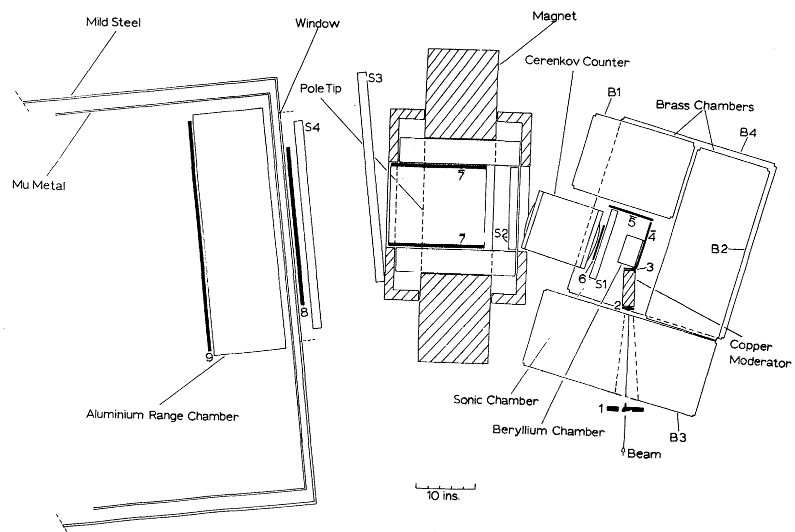

FIG. 1. Diagram of apparatus.

eter.

Gamma rays from the $K_{\pi 2}$ mode were used to determine the response of the spark chambers. The gamma-ray energy resolution from spark counting was found to be 30%. The detection efficiency of the chambers was checked by comparing real and Monte Carlo $K_{\pi 2}$ gamma-ray distributions. Similar checks were made using gamma rays from the K_{e3} mode.

For the $\pi\pi\gamma$ mode, we have calculated by Monte Carlo methods the efficiency for detecting three gamma rays in the spark chambers. We find for the inner-bremsstrahlung term of Eq. (1) that our sensitivity is such that one event (π^+ with three gamma rays) is equivalent to a branching ratio of 0.94×10^{-4} for T_{π^+} from 55 to 80 MeV, after allowing for π^+ interaction and decays in flight. The branching ratio is obtained by normalizing to K_{e3} events.[7] The ratios of the efficiencies, relative to inner bremsstrahlung, for the direct-emission and interference terms of Eq. (1) are

$$R_{\text{de}}=1.67$$

and

$$R_{\text{int}}=1.43.$$

Thus at the 90% confidence level the branching ratio limits obtained from Eq. (1) give the relation

$$1>3.04R_{\text{int}}\gamma\cos(\delta_{11}-\delta_{20}+\varphi)+3.38R_{\text{de}}(\gamma^2+\beta^2). \tag{3}$$

The 90% limit for β, assuming that $\gamma=0$, is $\beta<0.42$ corresponding to a branching ratio of 1.9×10^{-4}. The 90% limit for γ, assuming that $\beta=0$, is $\gamma<0.19$ for $\delta_{11}-\delta_{20}+\varphi=0$ and $\gamma<0.96$ for $\delta_{11}-\delta_{20}+\varphi=\pi$ with branching ratios of 1.9×10^{-4} and 1.5×10^{-4}, respectively.

We have calculated the expected asymmetry from Eq. (2), assuming that $\delta_{11}-\delta_{20}=10°$[9] and $\beta=0$. These results are shown in Fig. 2 for small φ together with our limits for γ. φ is expected to be close to 0 or π if CP nonconservation is a purely weak-interaction phenomenon[4]; however

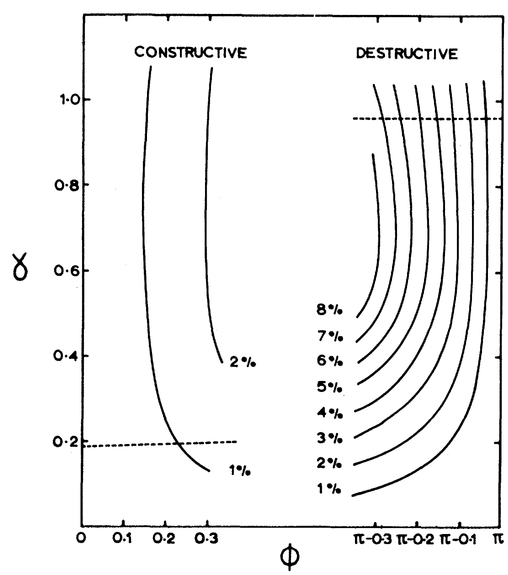

FIG. 2. CP-nonconserving asymmetry A for $\delta_{11}-\delta_{20}=10°$ and $\beta=0$. Lines of constant asymmetry are shown as a function of γ and φ for constructive and destructive interference. The two broken lines show the outer limits for γ set at the 90% confidence level by this experiment.

it has been suggested[10] that CP nonconservation might be due to interference between weak and electromagnetic interactions. In this case φ could approach $\frac{1}{2}\pi$. In this case Eq. (3) gives $\gamma < 0.4$. An upper limit to the asymmetry for large φ is 14%.

Our branching-ratio limit is compatible with the result $(2.2 \pm 0.7) \times 10^{-4}$ of Cline and Fry.[11] Clearly our limit allows a large value of γ for interference as favored by Cline[12] but this would be in conflict with the results of Wolff and Aubert.[13] However, like all present measurements, our result remains consistent with $\gamma = 0$ and $\beta = 0$.

We should like to thank Dr. P. K. Kabir for several useful discussions.

[1]V. V. Solov'ev and M. V. Terent'ev, Zh. Eksperim. i Teor. Fiz. 2, 336 (1965) [translation: JETP Letters 2, 213 (1965)]. T. D. Lee and C. S. Wu, Ann Rev. Nucl. Sci. 16, 471 (1966).

[2]S. Barshay, Phys. Rev. Letters 18, 515 (1967).

[3]G. Costa and P. K. Kabir, Phys. Rev. Letters 18, 429, 526 (1967), and Rutherford Laboratory Report No. 6 K/LR (revised) (unpublished).

[4]N. Christ, Phys. Rev. 159, 1292 (1967).

[5]D. Good, Phys. Rev. 113, 352 (1959).

[6]Inner bremsstrahlung rate calculated with $K_{\pi 2}$ branching ratio of 20.94% and $m_K = 493.83$ MeV.

[7]D. R. Botterill, R. M. Brown, A. B. Clegg, I. F. Corbett, G. Culligan, J. McL. Emmerson, R. C. Field, J. Garvey, P. B. Jones, N. Middlemas, D. Newton, T. W. Quirk, G. L. Salmon, P. H. Steinberg, and W. S. C. Williams, Phys. Rev. Letters 21, 766 (1968), and Phys. Rev. 171, 1402 (1968).

[8]Three events fitted the $\pi\pi\gamma$ hypothesis if the gamma-ray energy measurements were not included in the fit.

[9]$\delta_{11} - \delta_{20} = 10°$. This implies that for $\gamma = 0$, $\beta < 0.43$, while for $\beta = 0$, $\gamma < 0.19$ for constructive interference and $\gamma < 0.96$ for destructive interference.

[10]J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev. 139, B1650 (1965).

[11]D. Cline and W. F. Fry, Phys. Rev. Letters 13, 101 (1964).

[12]D. Cline, Phys. Rev. Letters 16, 367 (1966).

[13]B. Wolff and B. Aubert, Phys. Letters 25B, 624 (1967).

STUDY OF HYPERON-NUCLEON INTERACTION IN THE REACTION $K^- d \to \pi^- p \Lambda$ AT REST*

Tai Ho Tan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 30 June 1969)

A Λp system with high statistics and mass resolution was studied in detail. The broad bump in the low-mass region can be attributed to contribution from both the impulse and final-state–interaction mechanisms. The low-energy Λp scattering parameters are deduced to be $a_0 = -2.0 \pm 0.5$ and $r_0 = 3.0 \pm 1.0$ F. The higher mass spectrum can be fitted to two Breit-Wigner resonant structures with $M_1 = 2128.7 \pm 0.2$, $\Gamma_1 = 7.0 \pm 0.6$, and $M_2 = 2138.8 \pm 0.7$, $\Gamma_2 = 9.1 \pm 2.4$ MeV. Attempts were carried out to understand these peaks via a ΣN final-state–interaction model.

An experiment to investigate hyperon-nucleon production in $K^- d$ interactions at rest was carried out by exposing the Columbia–Brookhaven National Laboratory 30-in. deuterium bubble chamber to a low-energy separated K^- beam at the alternating-gradient synchroton. We present here results from the study of reaction $K^- d \to \pi^- p \Lambda$. A detailed analysis on a precisely measured Λp mass spectrum was carried out with the aid of a final-state hyperon-nucleon–interaction model as is schematically represented by the diagram in Fig. 1. In particular, we have attempted to determine the nature of the observed enhancement near the 2129-MeV region[1-3] and to extract information on Λp and $\Sigma^+ n$ scatterings.

Our data include 2470 events from sample (a) where all particles were measured and 2431 events from sample (b) where Λ was missing. All events from (a) satisfied a two-vertex seven-constraint (7C) fit while events from (b) satisfied a 1C fit. No ambiguity in the fit between Λ and Σ^0 production was found. To minimize the measurement errors a fiducial volume was imposed to ensure that at least 10 cm of measurable track length is available for all nonstopping charged tracks. Events with a stopping proton track

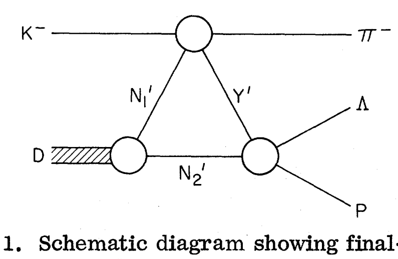

FIG. 1. Schematic diagram showing final-state hyperon-nucleon interaction.