250 keV. The estimate of this matrix element with a simple model yields a value which is just 50% larger than this experimentally determined value, whereas a similar comparison in ^{208}Pb showed a factor of ~5 difference. There is, therefore, no *a priori* need to introduce the isovector mode in the ^{208}Po case. It is, however, not clear what the effect of the isovector mode would be in this case, since the coupling is between protons and neutron holes, whereas in ^{208}Pb the coupling is between neutrons and neutron holes. It will be important to determine whether the introduction of the isovector quadrupole mode can explain simultaneously the large deviation from the simple model in ^{208}Pb and the near agreement in ^{208}Po.

We would like to thank R. A. Sorenson for useful discussions, the accelerator operators for their cooperation, the scanning groups at Carnegie-Mellon University and the University of Pittsburgh for their excellent scanning, and the Health Physics group for their help and advice in the fabrication of the radioactive target.

†Work supported by the National Science Foundation and the U. S. Atomic Energy Commission.

*Permanent address: Physics Department, Punjab University, Chandigarh, India.

‡Present address: Sloan-Kettering Research Institute, New York, N. Y. 10021.

§Permanent address: The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark.

‖Present address: University of Minnesota, Minneapolis, Minn. 55455.

[1]L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

[2]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, to be published), Vol. II.

[3]C. Ellegaard, P. D. Barnes, R. Eisenstein, E. Romberg, T. S. Bhatia, and T. R. Canada, "Inelastic Scattering of Deuterons, Protons and Tritons on ^{210}Po" (to be published).

[4]K. Erb, T. S. Bhatia, and T. R. Canada, private communication (to be published).

[5]G. J. Igo, P. D. Barnes, and E. R. Flynn, Phys. Rev. Lett. 24, 470 (1970), and Ann. Phys. (New York) 66, 60 (1971).

[6]R. A. Broglia, V. Paar, and D. R. Bes, Phys. Lett. 37B, 257 (1971).

[7]C. D. Siegal, thesis, Carnegie-Mellon University, 1972 (unpublished).

[8]C. Ellegaard, P. D. Barnes, E. R. Flynn, and G. J. Igo, Nucl. Phys. A162, 1 (1971).

Test of *CP* Noninvariance in the Decay $K^{\pm}\to\pi^{\pm}\pi^0\gamma$†

R. J. Abrams,* A. S. Carroll, T. F. Kycia, K. K. Li, J. Menes,‡ D. N. Michael, P. M. Mockett,§ and R. Rubinstein
Brookhaven National Laboratory, Upton, New York 11973
(Received 17 January 1973)

A careful search has been made for possible CP-nonconserving differences between $K^+\to\pi^+\pi^0\gamma$ and $K^-\to\pi^-\pi^0\gamma$ decays. In a sample of over 4000 completely reconstructed decays in the charged-pion kinetic-energy interval of 51 to 100 MeV, the asymmetry is 0.005 ± 0.020, with a systematic uncertainty of ±0.022, indicating no evidence for a CP-invariance violation. This result, combined with that obtained from the sum spectrum, suggests that the direct emission is largely magnetic dipole.

In a previous paper,[5] we presented evidence for direct emission in this decay which confirmed the possibility that a CP-invariance violation could be observed. In particular, if the direct emission of the magnitude observed were largely due to a CP-nonconserving electric-dipole transition, we could expect an asymmetry $(R^+-R^-)/(R^++R^-)$ in the decay rates $R^{\pm}$ up to approximately 0.06 in the charged-pion kinetic-energy interval of 51 to 1000 MeV. Furthermore, in some region of the Dalitz plot an asymmetry as large as approximately 0.2 could be observed. In the present paper we compare $K^+\to\pi^+\pi^0\gamma$ with $K^-\to\pi^-\pi^0\gamma$ decays and set limits on the asymmetry.

The $\pi^{\pm}\pi^0\gamma$ decay mode was studied from kaon decays in flight in an experiment performed in a 1.8-GeV/c partially separated beam at the Brookhaven National Laboratory alternating gradient synchrotron. The incident kaon and its charged decay pion were recorded with a core read-out wire-spark-chamber spectrometer. The conversion points of the three γ's were recorded in a γ detector[6] which consisted of eight layers of lead, an optical spark chamber, and

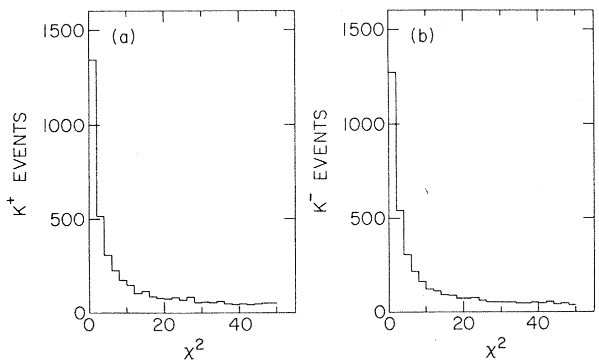

FIG. 1. χ^2 distributions for the fitted events obtained from (a) 8.39×10^9 incident K^+'s, and (b) 8.46×10^9 incident K^-'s.

a 32-element scintillator hodoscope. The trigger required an incident kaon, three or more γ's in the γ detector, and a charged particle in a hodoscope at the end of the spectrometer. Approximately equal numbers of K^+ and K^- events were recorded. The recorded information was used to make a two-constraint fit with the $\pi^\pm\pi^0\gamma$ hypothesis. Some 4000 events above background were obtained in the charged-pion c.m. kinetic-energy (T_c) interval of 51 to 100 MeV. Further details of the experiment are given in Ref. 5.

Great care was taken to keep the experimental detector symmetric for K^+ and K^-. The detection apparatus was left-right symmetric and the magnetic field was frequently reversed to avoid differences in geometric detection efficiency. Also, the beam was frequently switched from K^+ to K^- and the kaon flux equalized to keep running conditions and spark-chamber performance the same for each sign. The average wire-chamber reconstruction efficiency for the K^+ runs was equal to within 0.1% of that for the K^- runs.

In Figs. 1(a) and 1(b) we show the χ^2 distributions for the fitted K^+ and K^- events. The equality of their shapes indicates that there are no observed asymmetries in the measurement errors. A comparison of the backgrounds from $15<\chi^2<50$ gives a confidence level for equality of 75% and an asymmetry of 0.025 ± 0.022. Before comparing the K^+ and K^- distributions, the backgrounds under the $\chi^2<10$ peak were subtracted by a linear extrapolation from the region $15<\chi^2<50$. The interval of T_c used for these distributions is the full range scanned (51 to 100 MeV) rather than the more limited range (55 to 90 MeV) used in Ref. 5, because there are no end-effect problems that are not charge symmetric.

Several checks were made to see that there were no systematic biases between the observed $K^+\to\pi^+\pi^0\gamma$ and $K^-\to\pi^-\pi^0\gamma$ decays so that the kaon flux could be used for normalization. During the scanning and measuring of the $K^\pm\to\pi^\pm\pi^0\gamma$ events, a 1-in-20 sample of events within the τ' region ($T_c<45$ MeV) was also included in the scanning lists. Over 60% of these events showed three or four γ's in the correct counter groups of the γ hodoscope. Because these events had very nearly the same scanning and measuring difficulty as the $\pi^\pm\pi^0\gamma$ events, they are an excellent check on the relative normalization of K^+ and K^- for almost the entire analysis procedure. The asymmetry for these events was 0.012 ± 0.013 using incident kaons for normalization. A previous experiment[7] has shown that 3γ and 4γ events in the τ' region have an asymmetry of 0.0017 ± 0.0020. Sets of $K_{\pi2}$ runs (requiring two or more γ's in the trigger) interspersed between the $\pi\pi\gamma$ runs were scanned, measured, and fitted with three constraints using the $K_{\pi2}$ hypothesis. These runs had an asymmetry of -0.003 ± 0.026. A 1-in-5 rescan of the $\pi\pi\gamma$ events yielded a scanning and measuring efficiency of 0.746 ± 0.020; the efficiences had an asymmetry of 0.024 ± 0.035. The inner-bremsstrahlung component of the fits to the K^+ and K^- spectra gave an asymmetry of -0.056 ± 0.032. To check that the small differences in beam distributions for K^+ and K^- had no significant effect, actual samples of beam tracks of each kind were used in the Monte Carlo detection program. Identical detection efficiencies were found for K^+ and K^- decays and for both magnet polarities. The average beam momenta for K^+ and K^- were determined to be the same to within $\frac{1}{4}$%.

The asymmetry in the K^+ and K^- rates that we obtain for the total data sample between the T_c limits of 51 to 100 MeV is

$$(R^+-R^-)/(R^++R^-)=0.005\pm0.020.$$

From a study of various methods of event selection and background subtraction it is estimated that the limits of the systematic uncertainty are ±0.022. This asymmetry can be compared with the values of -0.055 ± 0.05 and 0.03 ± 0.12 from other experiments[7,8] for slightly narrower T_c ranges.

Since we can fully reconstruct our events on the Dalitz plot, a more sensitive comparison is to fit the difference spectrum of the K^+ and K^- decay rates, as projected on the variable W, with the expression

$$d(R^+ - R^-)/dW = 2f\epsilon(W)I(W)[2\mathcal{E}\sin(\delta_1{}^1 - \delta_0{}^2)\sin\varphi(\mu^2/m^2)W^2]. \quad (1)$$

This is the spectrum due to interference between direct emission and inner bremsstrahlung. The variable W is defined in terms of the kaon mass (m), the pion mass (μ), the γ energy (E_γ), and the π^0 energy (E_0) as $[E_\gamma(\frac{1}{2}m - E_0)/\mu^2]^{1/2}$. Contours of constant asymmetry on the Dalitz plot are given by fixed values of W in the lowest multipole approximation. $I(W)$ is the inner-bremsstrahlung branching ratio as a function of W, $\mathcal{E}$ is the electric-dipole amplitude, $\delta_1{}^1 - \delta_0{}^2$ is the $\pi\pi$ phase-shift difference ($\approx 10°$),[9] φ is the CP-nonconserving phase which would have a value of 90° for maximum CP nonconservation, $\epsilon(W)$ is the detection efficiency as determined by Monte Carlo means, and f is the fraction (0.053) of incident kaons decaying in our fiducial volume.

The W projection of the difference between the K^+ and K^- rates is shown in Fig. 2. The best fit of Eq. (1) to the data gives

$$\mathcal{E}\sin(\delta_1{}^1 - \delta_0{}^2)\sin\varphi = 3.1 \pm 2.4,$$

with a χ^2 of 18.0 for nineteen degrees of freedom. The error shown above is statistical only. From a study of various methods of event selection and background subtraction it is estimated that the limits of the systematic uncertainty are ± 2.1.

The sum spectrum of the two decay rates is given by

$$\frac{d(R^+ + R^-)}{dW} = 2f\epsilon(W)I(W)\left[1 + 2\mathcal{E}\cos(\delta_1{}^1 - \delta_0{}^2)\cos\varphi\frac{\mu^2}{m^2}W^2 + (\mathcal{E}^2 + \mathfrak{M}^2)\frac{\mu^4}{m^4}W^4\right], \quad (2)$$

where in addition to the electric dipole amplitude $\mathcal{E}$ in the direct-emission term, there is a noninterfering magnetic-dipole amplitude $\mathfrak{M}$. Using our result from Ref. 5 for the fit to the sum spectrum, and the present fit to the difference spectrum, we obtain the total asymmetry by integrating Eqs. (1) and (2) for the T_c range 51 to 100 MeV of $(R^+ - R^-)/(R^+ + R^-) = 0.025 \pm 0.019$.

A fit has also been carried out to the difference spectrum of K^+ and K^- decay rates as projected on the variable T_c. This fit gives

$$\mathcal{E}\sin(\delta_1{}^1 - \delta_0{}^2)\sin\varphi = 0.8 \pm 2.5.$$

The value we obtain from the difference spectrum for $\mathcal{E}\sin(\delta_1{}^1 - \delta_0{}^2)\sin\varphi$ is small (and consistent with zero), which eliminates some of the earlier estimates for large CP-nonconserving differences in $K^\pm \to \pi^\pm\pi^0\gamma$ decays.[2,3] Since we have previously found from the sum spectrum that $\mathcal{E}\cos(\delta_1{}^1 - \delta_0{}^2)\cos\varphi$ is also small and consistent with zero,[5] the most probable interpretation is one in which the magnetic-dipole transition dominates the direct emission. In addition, the CP-nonconserving phase φ must be indeterminate. However, the hypothesis that the direct emission is pure electric dipole with $\varphi = 90°$ is less than 2 standard deviations from our most probable value.

It can be shown[10] that CPT invariance requires that

$$R(K^+ \to \pi^-\pi^0) + R(K^+ \to \pi^+\pi^0\gamma) = R(K^- \to \pi^-\pi^0) + R(K^- \to \pi^-\pi^0\gamma),$$

neglecting the final states with $\geq 2\gamma$'s. Our result on the difference of $K^\pm \to \pi^\pm\pi^0\gamma$ rates thus gives a 90%-confidence limit on the difference of the $K_{\pi 2}$ branching ratios of $< 7\times 10^{-5}$, assuming CPT invariance in the decay.

In conclusion, the values we have found for the asymmetry of $K^+ \to \pi^+\pi^0\gamma$ and $K^- \to \pi^-\pi^0\gamma$ are consistent with zero, and therefore the data show no evidence for CP nonconservation in the $K^\pm \to \pi^\pm\pi^0\gamma$ decay mode.

This experiment would have not been possible without the skilled assistance of C. Anderson, G. Munoz, H. Sauter, F. Seir, and O. Thomas. We wish to thank our very able scanners and the alternating gradient synchrotron staff. We are

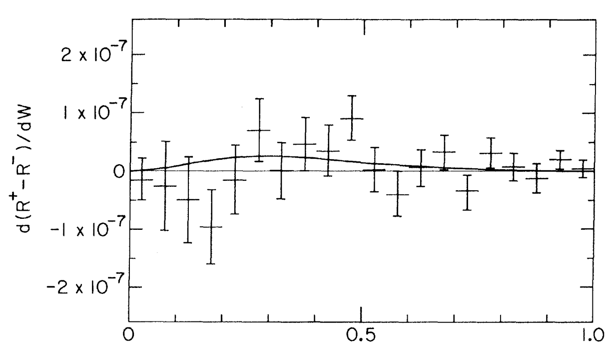

FIG. 2. Results for $d(R^+ - R^-)/dW$ [as defined in Eq. (1)] as a function of W. The curve is the best fit to the interference spectrum.

greatly indebted to J. Fuhrmann for his extensive contributions to the design and construction of equipment. The assistance of N. Samios and R. Shutt in providing additional scanning support is much appreciated.

†Work supported by the U. S. Atomic Energy Commission.

*Present address: University of Illinois, Chicago, Ill. 60680.

‡Present address: French Hill 118/3, Jerusalem, Israel.

§Present address: University of Washington, Seattle, Wash. 98195.

[1]T. D. Lee and C. S. Wu, Annu. Rev. Nucl. Sci. 16, 471 (1966).

[2]G. Costa and P. K. Kabir, Phys. Rev. Lett. 18, 429, 526 (1967).

[3]S. Barshay, Phys. Rev. Lett. 18, 515 (1967).

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

[5]R. J. Abrams, A. S. Carroll, T. F. Kycia, K. K. Li, J. Menes, D. N. Michael, P. M. Mockett, and R. Rubinstein, Phys. Rev. Lett. 29, 1118 (1972).

[6]R. J. Abrams, A. S. Carroll, T. F. Kycia, K. K. Li, J. Menes, D. N. Michael, P. M. Mockett, and R. Rubinstein, BNL Report No. 17365, 1972 (to be published).

[7]K. M. Smith, P. S. L. Booth, H. R. Renshall, P. B. Jones, G. L. Salmon, W. S. C. Williams, P. J. Duke, W. M. Evans, R. E. Hill, W. R. Holley, D. P. Jones, and J. J. Thresher, reported by K. Winter, in *Proceedings of the Amsterdam International Conference on Elementary Particles,* edited by A. G. Tenner (North-Holland, Amsterdam, 1971), p. 354.

[8]R. R. Edwards, E. W. Beier, W. K. Bertram, D. P. Herzo, L. J. Koester, and A. Wattenberg, Phys. Rev. D 5, 2720 (1972).

[9]*Proceedings of the Conference on ππ and Kπ Interactions at Argonne National Laboratory, 1969,* edited by F. Loeffler and E. Malamud (Argonne National Laboratory, Argonne, Ill., 1969).

[10]T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957); G. Luders and B. Zumino, Phys. Rev. 106, 385 (1957).

Study of the Decay $A_2 \to \eta\pi$ via the Reaction $\pi^- p \to \eta\pi^- p$ at 6.0 GeV/c*†

A. W. Key
National Accelerator Laboratory, Batavia, Illinois 60510, and Physics Department, University of Toronto, Toronto 181, Canada

and

G. Conforto,‡ M. A. Kramer,§ and D. Underwood‖
The Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637

and

R. M. Mobley¶
National Accelerator Laboratory, Batavia, Illinois 60510

and

R. Prepost, D. H. Tompkins, and M. S. Witherell
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 1 December 1972)

The reaction $\pi^- p \to \eta\pi^- p$ at 6.0 GeV/c has been studied at the Argonne zero-gradient synchrotron using optical spark chambers. About 1400 events have been obtained in the range $0.80 < M_{\eta\pi} < 1.55$ GeV/c^2, yielding approximately 1000 events of the type $A_2^- \to \eta\pi^-$, with $0.27 < |t| < 0.42$ (GeV/c)^2. No structure is discernible within the A_2 mass spectrum with an experimental resolution of 7.1 MeV/c^2 [full width at half-maximum (FWHM) $=16.7$ MeV/c^2]. A single D-wave Breit-Wigner distribution fits the data with a high confidence level yielding the parameters $M_0 = 1.323 \pm 0.003$ GeV/c^2 and $\Gamma_0 = 0.108 \pm 0.009$ GeV/c^2 for the A_2.

An optical spark-chamber experiment has been performed at the Argonne zero-gradient synchrotron to study the reaction

$$\pi^- p \to X^- p; \quad X^- \to \eta\pi^-; \quad \eta \to \gamma\gamma \qquad (1)$$

for an X^- mass in the range from threshold to 1.5 GeV/c^2. This paper presents the analysis of the mass range $0.80 < M_x < 1.55$ GeV/c^2. For this mass range, a beam momentum of 6 GeV/c and a range in t (the four-momentum squared to the