Search for T-invariance violation in $K_{\mu 3}^{+}$ decay

S. R. Blatt, R. K. Adair, J. K. Black, M. K. Campbell,* H. Kasha, and M. P. Schmidt
Department of Physics, Yale University, New Haven, Connecticut 06511

L. B. Leipuner, R. C. Larsen, and W. M. Morse
Brookhaven National Laboratory, Upton, New York 11973

(Received 24 September 1982)

The transverse polarization of muons from the decay $K^{+}\rightarrow\pi^{0}\mu^{+}\nu_{\mu}$ was measured at Brookhaven National Laboratory. Having detected and measured 2.1×10^{7} $\mu^{+}\rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu}$ decays we found that the T-violating component of muon polarization perpendicular to the K^{+} decay plane $P_{n}=-0.0031\pm0.0053$. Combining this result with our result for $K_{\mu 3}^{0}$, we obtain as a measure of T- (and therefore CP-) invariance violation $\text{Im}\xi=-0.010\pm0.019$.

I. INTRODUCTION

The present paper describes an extension of our earlier searches for T-invariance violation in $K_{\mu 3}$ decays by measuring the transverse polarization of the muon from the decay of K^{+} mesons; similar measurements on muons from K_{L}^{0} decay are discussed in an earlier publication.[1] There are two particular reasons for varying the charge composition of the particles involved. First, there is no Coulomb interaction between the products of the K^{+} decay: since only one of the particles, the muon, is electrically charged, there can be no substantial polarization due to the final-state interaction which would be large enough to mask a spontaneous T-invariance violation. Second, backgrounds from a charged-K-meson beam generate different systematic errors than backgrounds from a neutral beam. A well focused and collimated charged beam could be constructed which was more nearly monochromatic than a neutral beam. These considerations offset difficulties of detecting neutral pions from the $K_{\mu 3}^{+}$ decay. The $K_{\mu 3}^{+}$ experiment was thus undertaken to increase the sensitivity of the search for T (and thus CP) violation outside the K^{0}-$\bar{K}^{0}$ system by enlarging the previous $K_{\mu 3}^{0}$ data sample significantly. Moreover, the additional data would be free of the systematic masking effect of final-state interactions and this data could be accumulated at a faster rate because of reduced backgrounds.

The experimental procedures used were broadly similar to those used earlier in our measurements of $K_{\mu 3}^{0}$ decays.[1] The main differences in the new experimental setup consisted in the use of a momentum-analyzed K^{+} beam instead of a K_{L}^{0} beam and the use of a lead-glass array for the detection of the neutral pions from the K^{+} decays instead of the scintillation counters required for the detection of the charged pions from the K_{L}^{0} decays. There were also numerous secondary differences (the counter arrays were somewhat modified due to the different kinematic region chosen, different anticoincidence counters were used because of different backgrounds, etc.), but these changes were relatively minor. The same polarimeter, slightly improved, was used to measure the CP-violating μ^{+} polarization component perpendicular to the production plane.

A short description of the experiment and of its results has been published earlier in the form of a letter.[2]

The consequences of a possible noninvariance under time reversal were discussed in 1957 by Lee, Oehme, and Yang.[3] In his Brookhaven lectures the same year, Lee[4] showed that the product $\vec{s}_{2}\cdot(\vec{p}_{1}\times\vec{p}_{2})$, where $\vec{p}_{i}$ are the momenta of particles in the final state and $\vec{s}_{i}$ their spins, is odd under T reversal. A search for violation of T invariance in $K_{\mu 3}$ decays, where the relevant triple product is $\vec{s}_{\mu}\cdot(\vec{p}_{\pi}\times\vec{p}_{\mu})$, was suggested by Sakurai.[5] In the absence of final-state interactions, the observation of an expectation value proportional to that product, which defines the muon polarization normal to the decay plane, is evidence of a violation of time-reversal invariance and, from the CPT theorem, of CP invariance. Sakurai also pointed out that in the case of $K_{\mu 3}^{0}$ a small CP-violating polarization could be masked by an electromagnetic final-state interaction between the muon and π^{+} decay products.

During the period of almost two decades that have elapsed since the discovery that CP is not an exact symmetry of nature,[6] CP-violation effects have been observed only in the decay of the K^0-$\bar{K}^0$ system. All the observations can be described in terms of a single complex parameter ϵ which is the ratio of the CP-forbidden and CP-allowed amplitudes for the decays of neutral K mesons into two pions:

$$\epsilon = \text{Amp}(K_L^0 \to 2\pi)/\ \text{Amp}(K_S^0 \to 2\pi)$$

and

$$|\epsilon| = 2.3 \times 10^{-3}$$

(for a review see Ref. 7). Moreover, only the magnitude of ϵ is determined by CP-violating effects; the phase is derived from non-CP-violating properties of the K_S^0 and K_L^0. This description of CP-violating phenomena is consistent with a model in which CP violation is due to a "superweak" fifth force[8] of strength $10^{-9}G_f$ acting in first order with $|\Delta S| = 2$.

Gauge theories, though not the original "standard model,"[9] are open to several phenomenological possibilities which accommodate CP violation. It has been shown[10] that at least one CP-violating phase is allowed in the quark amplitudes when there are six quarks. This result carries no prediction as to the strength of the violation, and when experimental observations of the K_S^0-K_L^0 system are used to normalize the CP-violating strength, some properties of the resultant conclusions are similar to those expected from the superweak model. Among other things, CP-violating quark phases lead to no observable effects in the muon polarization in $K_{\mu 3}$ decay.

Another class of models invokes a spontaneous CP violation which would be due to the exchange of particles of an enlarged Higgs sector, consisting of at least two doublets. A complex phase could then exist between the vacuum expectation values of the Higgs fields.[11] A more precise measurement of the CP-forbidden muon polarization component in $K_{\mu 3}$ decay would constrain the choices which are *a priori* possible.

II. EXPERIMENTAL APPARATUS

A. Overview of the method

The apparatus[12] consisted of an axially symmetric detector centered on the axis of the K^+ beam. A perspective view of the main elements of the detector is shown in Fig. 1. In a typical event the muon from $K^+ \to \pi^0 \mu^+ \nu_\mu$ decay was partially identified by hits in counters A or B, M, and F that defined a trajectory which passed through the steel toroidal magnet and was focused by that magnet into the aluminum polarimeter. The muon identification was confirmed by the detection of the positron from the decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ within a few μs of the muon coming to rest in the polarimeter. The neutral pion

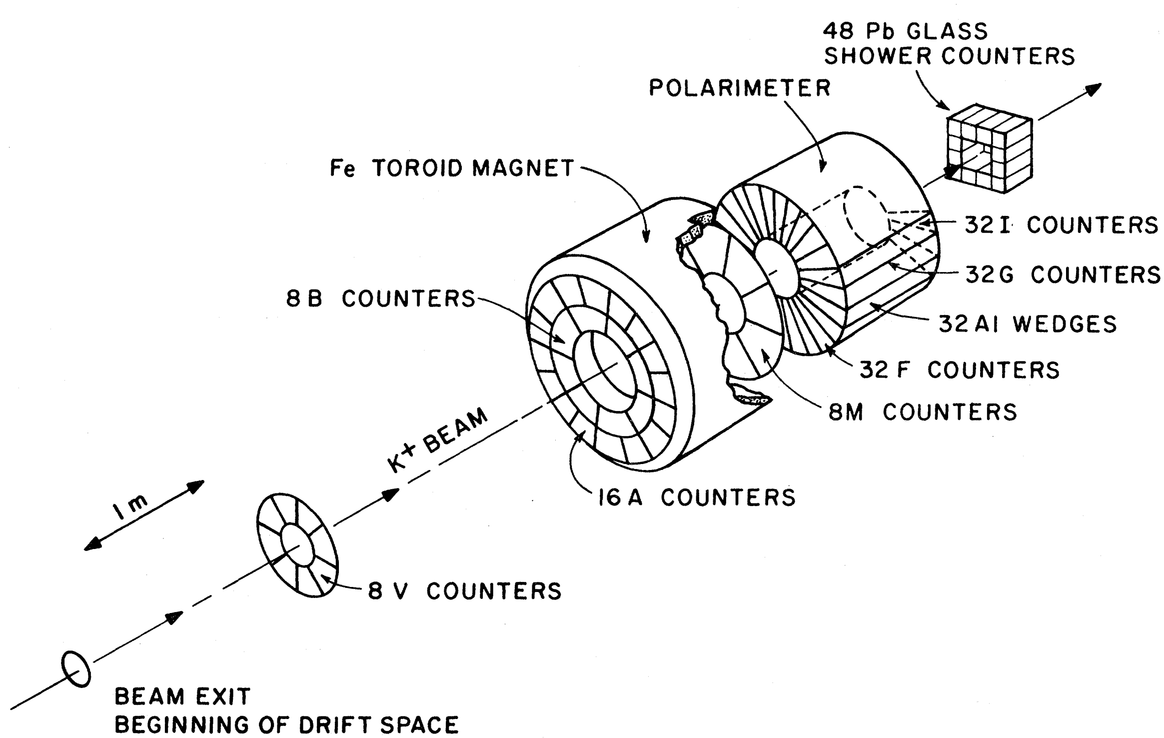

FIG. 1. A schematic perspective view of the experimental apparatus indicating the major components of the detector. Dimensions are given in the text.

which decays quasi-instantaneously into two photons was detected if one of the photons, with energy greater than 1.2 GeV, hit the lead-glass array, located symmetrically about the beam axis downstream from the polarimeter.

We were seeking a T- (or CP-) violating component of muon polarization normal to the decay plane in the K-meson rest frame. We designed the selection of events to accept events in which the K-meson beam direction was nearly in the decay plane in the center-of-mass system. In the laboratory frame, the beam direction was also in the decay plane for these events. By selecting events in which the pion direction was along the beam line, we ensured that the T-violating decay correlation $\vec{s}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)$, defined in the center-of-mass system, would be determined by measuring $\vec{s}_\mu \cdot (\vec{p}_K \times \vec{p}_\mu)$ in the laboratory frame.

Figure 2 shows two possible orientations of the products of the K-meson decay. In the first class of events, the pion is moving with the K meson and the CP-violating polarization of the muon can be taken to be out of the figure. In the second class, the pion is moving opposite to the boost direction and in the laboratory frame is moving forward with only a small momentum. In this case the CP-violating polarization is into the figure, and thus has an opposite sign to that of the first case. The energy of the photon from the pion decay which is detected in the first class of events is much larger than the photon energy detected in the second class, and it was possible to choose an energy cut which essentially only passed events belonging to the first class. This avoided a partial cancellation of the CP-violating polarization of the first class of events by that of the second class, which would be of opposite sign. The energy cut (at 1.2 GeV for a 4-GeV beam) also served to eliminate spurious low-energy hits in the lead glass.

Although two photons are produced in the pion decay, only one was detected in our array. The two photons are emitted back-to-back in the rest frame, and the kinematics of the $K_{\mu 3}$ decay are such that in the boost to the laboratory frame the opening angle between the two is always greater than 10 degrees. The lead glass array, on the other hand, subtended a maximum angle of 7 degrees as seen from the decay zone through the openings in the toroid and polarimeter. Thus only one photon would be expected to be detected in the array, and the event selection was designed so that the only events selected were those with localized showers, in which only one region of the lead glass was hit. This eliminated spurious signals due to the coincidence of two or more separate showers whose total energy was more than 1.2 GeV.

The components of the muon polarization in the laboratory frame can be described in terms of three components P_L, P_t, and P_n which lie along mutually orthogonal axes. The longitudinal polarization P_L lies along the muon momentum vector, and the components P_t and P_n are the transverse components in and normal to the decay plane $(\vec{p}_K \times \vec{p}_\mu)$, respectively. The toroidal magnet was designed to focus the muon so that it entered the polarimeter approximately parallel to the K-meson beam line. Thus, if the muon stopped in the polarimeter, its polarization component P_t was radially normal to the beam axis while the CP-violating component P_n was perpendicular to the plane containing both the muon and the beam axis.

The geometry of the polarimeter [Fig. 3(a)] allowed both P_t and P_n to be analyzed. Each of the 32 aluminum wedges in the polarimeter was flanked by two counters, labeled here U and D, with both the wedges and the counters being distributed radially about the beam axis. We measured the detection asymmetry between the two counters U and D,

$$A = (U - D)/(U + D) ,$$

for all aluminum wedges of the polarimeter. We thus looked for the polarization of the muon normal

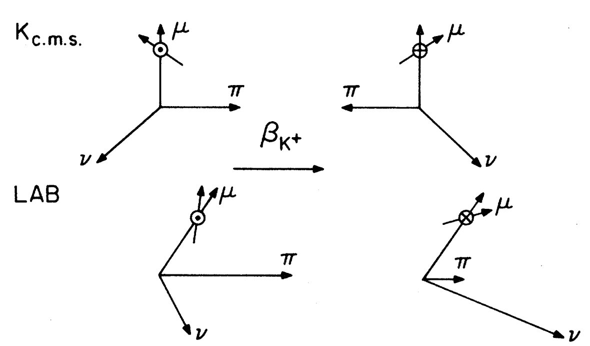

FIG. 2. Two orientations of the $K_{\mu 3}^{+}$ decay products and of the muon polarization, in the kaon rest frame and in the laboratory system.

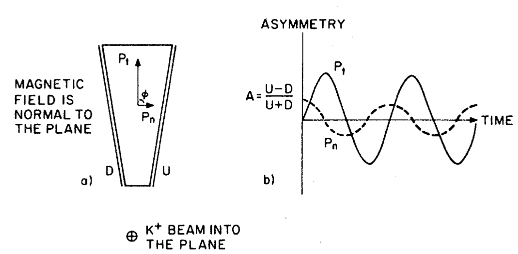

FIG. 3. (a) Schematic representation of the transverse components of muon polarization (see text) in the polarimeter, as seen along the beam line. (b) Schematic representation of the contributions of the transverse polarizations to the asymmetry for an ensemble of precessing muons.

to the production plane for 32 orientations of that plane around the beam axis.

As outlined above, the measurements were liable to suffer from systematic errors which were likely to mask the small effects we were trying to measure. The U and D counters belonging to each wedge would have to be perfectly matched in their efficiency. Second, the CP-violating component P_n we want to measure is 2–3 orders of magnitude smaller than the P_t and P_L components of the muon polarization. The experiment was therefore designed as a null measurement method with respect to a possible bias in the up-down asymmetry and, likewise, the measurement was in first order independent of the two large CP-allowed components of muon polarization. This was achieved by placing the polarimeter in a uniform axial magnetic field of 55 G, whose direction changed every accelerator pulse. The spins of the muons stopped in the aluminum precessed around the direction of this field. For an ensemble of muons, the asymmetry varies sinusoidally as a function of ωt, where $\omega/2\pi$ is the precession frequency equal to 745 kHz. A difference in the detection efficiency of the U and D counters is then reflected as a shift of the axis of symmetry of the sinusoid from $A=0$ which can be easily taken into account and which does not affect the fitted asymmetry. Figure 3(b) shows the contributions to A from P_t and P_n, the CP-conserving and CP-violating polarizations, respectively. The CP-conserving polarization P_t varies as $\sin\omega t$ while the CP-violating component P_n varies as $\cos\omega t$. Thus by reversing the magnetic field each pulse and thus changing the sign of ω, and adding the contributions obtained for the different field directions, we achieved a first-order cancellation of the sine amplitude. As a consequence of this cancellation, it was possible to isolate the relatively small component P_n from the much larger component P_t.

After passage through the toroid the muon momentum was, on the average, parallel to the beam line so that for muons stopping in the polarimeter P_L was directed along the beam axis, in the direction of the magnetic field, and thus did not contribute to the precessing asymmetries.

B. The beam design

The secondary 4-GeV/c unseparated positive kaon beam was produced at 0° by the interaction of the 28-GeV/c proton beam, extracted from the Brookhaven Alternating Gradient Synchrotron (AGS), with a 10-cm-long platinum target. The target was rectangular in cross section, 7.6 mm wide and 10 mm high. The secondary-beam optics are shown in Fig. 4. Dipole $D1$ bent the beam 18° through narrow brass collimators which had two channels accepting 4- and 28-GeV/c particles, respectively. The secondary beam, which had a 10% full width at half maximum momentum bite,

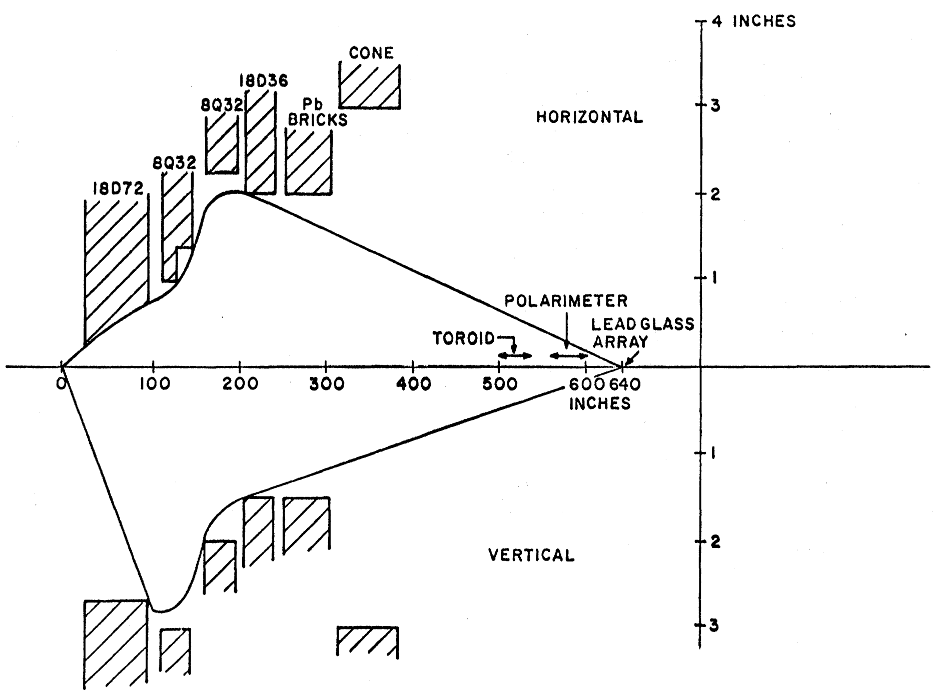

FIG. 4. The collimators and beam optics for the 4-GeV beam line.

was then focused by the quadrupole magnets $Q1$ and $Q2$ and momentum reconstituted by dipole magnet $D2$. The target image was 16.25 m downstream, essentially at the downstream end of the experimental apparatus. The deflection produced by the dipole magnet also served to shield the beam line from the primary interaction region. To reduce the halo from the beam, poured lead collimators were located in the focusing magnets, in the dipole $D2$, and in the 1.5-m space following the last magnet.

A 1.75-m-long concrete collimator, hollowed out in the shape of a cone, followed the last magnet. The upstream half-meter of the collimator was packed with paraffin for neutron absorption around an opening 3 in. high and 4 in. wide. The beam then traveled through the collimator and through the experimental apparatus in a helium-filled bag to minimize scattering, into a lead and uranium beam stop. The beam stop was surrounded by blocks of paraffin and boron designed to slow down and absorb the neutrons.

For a typical primary beam intensity of 4.3×10^{10} protons per pulse on target, the secondary beam contained 3.6×10^{6} K mesons, 4.3×10^{7} pions, and 2.1×10^{7} protons at 4.0 ± 0.4 GeV/c.

C. Decay zone and hodoscope

A 5-m decay zone began at the upstream end of the concrete cone collimator, 7.63 m downstream from the target. A ring of 8 counters (V), with an inner radius of 9.1 cm and outer radius of 31.2 cm, located at 10.1 m downstream from the target, divided the decay zone approximately into two halves. At the downstream end of the decay zone there were two concentric ring-shaped arrays of scintillation counters: the 16-counter A array (inner radius 33.7 cm, outer radius 57.4 cm) and the 8-counter B array (inner radius 18.6 cm, outer radius 36.6 cm, overlapping the A ring). The A counters were paired into eight logical counters for most of the analysis. The response of the V counters was used to provide information concerning the decay position; the A and B counters differentiated between decays generating large and small muon transverse momenta. Thus we were able to classify the events into four categories: AV, BV, $A\bar{V}$, and $B\bar{V}$ where the different categories contained events with somewhat different decay kinematics.

The fourth hodoscope ring M was located behind the toroidal focusing magnet. This counter array had an inner radius of 19.5 cm and an outer radius of 52 cm, was segmented into 8 counters, and was used in further defining the muon trajectories.

D. Toroid

The toroidal magnet was designed to focus positive muons into the polarimeter while degrading their energy. This dual function was achieved by an annular core which increased in thickness with the distance from the beam axis, and a complementary annulus of unmagnetized steel which equalized the amount of material traversed by muons at different distances from the beam axis (Fig. 5).

The magnet core and the complementary plug were constructed of 18-cm-thick machined laminations of 1010 steel. The magnet was wound with 704 turns of No. 12 wire at a constant pitch, with half of the turns wound clockwise and half counterclockwise, in order not to introduce an axial component to the magnetic field which would have introduced a screw sense to the focusing action of the toriod. A current of 13 A flowing in the wire produced a saturated magnetic field of 1.5 T in the core, which had an inner radius of 18 cm and an outer radius of 61 cm. The thickness of the toroidal assembly along the beam axis was 71 cm, presenting 560 g/cm^2 of iron along the muon path to degrade the muon energy by 830 MeV on the average. This mass also served to shield the polarimeter from backgrounds associated with the beam. The mean multiple scattering angle in the toroid was 8.5°.

E. Polarimeter

The polarimeter consisted of 32 elements (cells) arranged azimuthally around the beam line. Each cell consisted of an aluminum wedge surrounded by four scintillation counters (Fig. 6). Counter F covered the upstream face of the wedge and signaled the entrance of a muon into the cell while counter I on the opposite face vetoed the event in case the

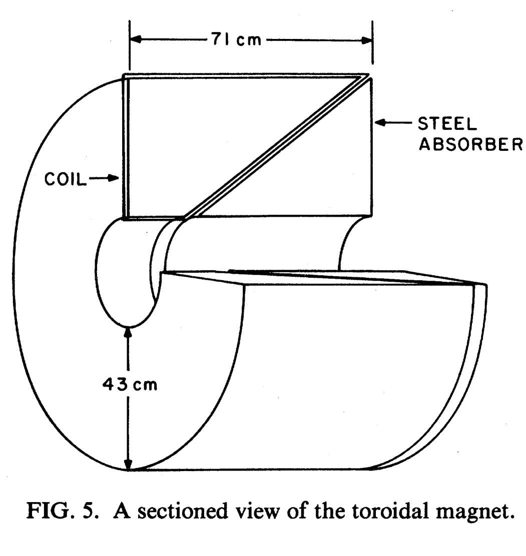

FIG. 5. A sectioned view of the toroidal magnet.

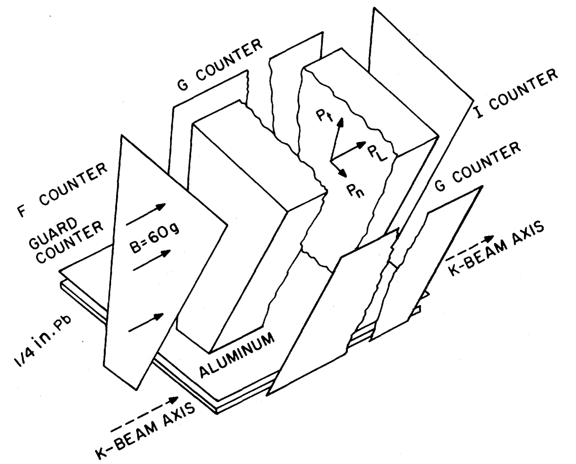

FIG. 6. A polarimeter cell.

muon left the cell passing through this counter. The other two counters (G) which covered the two faces of the cell along the radial separations from the neighboring cells served to intercept the decay positrons emitted about the perpendicular to the production plane. Each of the flanking G counters consisted of a sandwich of two 3.2-mm-thick counters operated in coincidence to reduce background. The wedges were cast and machined from No. 356 No-Heat Aluminum, measured 91.5 cm along the beam direction, 30.5 cm radially, and covered an azimuth sector of 11.25°.

The polarimeter presented 250 g/cm^2 of aluminum to muons parallel to the beam line. Given the energy needed to pass through the toroid magnet, muons in the energy range between 830 and 1430 MeV stopped in the polarimeter.

To precess the spin of the muons, an axial magnetic field of 55 G was applied to the polarimeter. This field was directed either parallel or antiparallel to the beam line so that the muon spin precessed about this axis. The field was generated by a solenoidal coil with a diameter of 1.25 m wound on a plastic shell surrounding the polarimeter assembly. The coil consisted of 482 turns of 3.2 mm$\times$3.2 mm copper wire wound in two layers of opposite pitch. Except for circular openings 36 cm in diameter for the entrance and exit of the beam, the entire assembly was surrounded by a shell of SAE 1010 steel, formed by two 12.7-mm-thick end plates connected by a 6.4-mm-thick cylinder. The shell served to return the solenoid magnetic flux enhancing the field uniformity. It also acted as a magnetic shield, on one hand shielding the polarimeter from stray magnetic fields (especially the Earth's field) measured to be 525 mG, and protecting the counter phototubes from stray fields due to the solenoid. With a current of 10 A in the solenoid coil, the axial field was measured to be 55 G and was found to be uniform over the active polarimeter volume to 1%.

To achieve the cancellation of the transverse polarization component in the plane of production P_t the field direction was reversed between beam pulses, once every 2.5 s. The relaxation time constant of the solenoid was 0.08 s guaranteeing the absence of transient fields during the 1-s beam spill. The axial field was measured to have the same magnitude in both directions within an uncertainty of ± 30 mG. The current was supplied by a constant-current power supply and was switched each pulse by a relay. The use of any current-sensing devices on the coil side of the relay was avoided in order to prevent introducing an asymmetry between the positive and negative current directions.

The stray magnetic field from the polarimeter affected the gain of the phototubes. As the magnetic field was switched for each pulse, the efficiency of the lead-glass trigger and the event rate changed. To counteract this effect, the entire lead-glass array was magnetically shielded with 1.27-mm steel plates. This reduced but did not eliminate the effect, and caused an incomplete cancellation of the sinusoidal wave in the cosine fit. Since the sine and cosine are orthogonal functions and the phase of the cosine is fixed this does not affect the fitted amplitude of the cosine wave.

E. Photon detection

The photons from π^0 decays were detected in a lead-glass calorimeter. This detector consisted of 48 lead-glass blocks arranged as shown in Fig. 7. The center hole was designed to allow the charged beam, which was focused at the lead-glass array, to pass through. The blocks of Schott SF5 glass were 25.4 cm (about 10 radiation lengths) long, and measured 57.2 mm$\times$57.2 mm in cross section. They were viewed by RCA 8575 photomultiplier tubes attached to their downstream end. Scintillation counters placed in front of the photon detector served as a veto for charged particles in the $K_{\mu 3}$ trigger and as a trigger for the muons used for calibration.

Each phototube base sent out two signals: one to an active analog adder (LeCroy 127FL), and one to a discriminator followed by a latch. The output of the adder was passed to a discriminator set to reject events such that the total energy deposited in the calorimeter was smaller than 1.2 GeV. In this way, only photons were accepted which could have originated from a pion moving forwards in the K^+ rest frame. It was necessary to add the signals from all lead-glass blocks as the electromagnetic shower

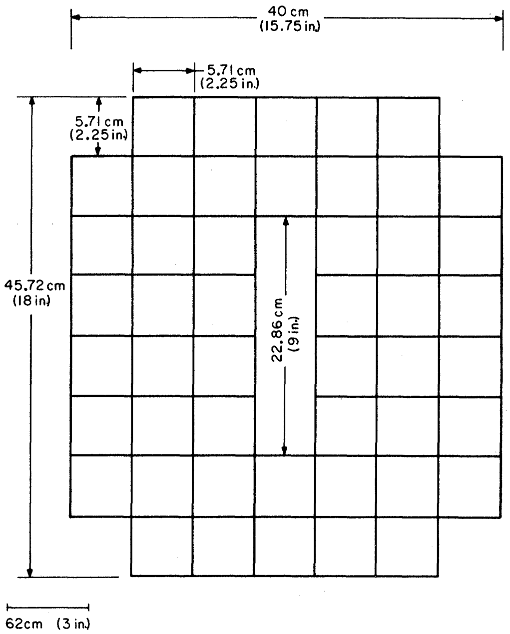

FIG. 7. A diagram of the lead-glass array.

often extended over several blocks. The discriminator of each counter was set at a level above the energy deposited by the passage of a muon through the glass. The latched information on the lead-glass-array hit pattern was examined by the on-line analysis program and any event such that noncontiguous elements were hit, was discarded. The lead glass was calibrated in a test beam of electrons which are almost identical to photons in shower development. The energy resolution was determined to be $15\%/\sqrt{E}$, where E is measured in GeV. Muons passed completely through the lead glass depositing energy by Cherenkov radiation, which, for the energy range we are interested in, is independent of energy. It was found that a signal from a muon passing straight through the lead glass corresponded to an electron of energy 340 MeV. During the running of the experiment the lead glass was calibrated *in situ* every few days by using the scintillation counters in front of the lead glass as a trigger for muons and measuring the pulse height of the signals. The amplitude of this signal was adjusted by varying the voltage applied to the base of the phototube.

III. DATA COLLECTION AND PROCESSING

The data collection and processing system was designed to facilitate the continual monitoring of the quality of the data being collected and to allow the analysis to proceed on line. As a consequence of these data-handling procedures, almost-complete analyses leading to definitive experimental conclusions were available continually throughout the experiment. Within 10 minutes of the finish of data taking, results hardly inferior to the conclusions presented in this final paper were available. The unusually thorough continuous monitoring provided information to the experimenters about the quality of the beam and the integrity of the apparatus.

The fast trigger, generated in the first stage of data collection, consisted of a coincidence between a muon tracked through the hodoscope and a photon detected in the lead-glass array. The muon trigger was divided into four types: $(A\cdot M\cdot F)$, $(B\cdot M\cdot F)$, $(V\cdot A\cdot M\cdot F)$, and $(V\cdot B\cdot M\cdot F)$. The element of the V array, if present, was required to be in line with the element of the A or B array. Some multiple scattering in the toroid was allowed; the element of the M array could involve one counter to either side of the element in the A or B array. The photon trigger was generated by adding the signals from the 48 individual lead-glass elements and demanding that this signal correspond to a deposited energy greater than 1.2 GeV.

Certain conditions inhibited the trigger: if more than one A or B counter were hit or if any of the guard counters used to detect muons from the primary beam dump were hit, the trigger would be vetoed. Signals from the guard counters in front of the lead-glass array were also used as a veto. About 50 nsec were needed to generate a complete trigger signal. The coincidence timing was however 4 nsec, to prevent triggering on charged particles.

The second stage of data processing employed a FASTBUS (Ref. 13) data-handling system. Our FASTBUS system, largely designed and constructed by us, is intended as a prototype of a standard system to be considered as a replacement for CAMAC. Our system handles information at a rate of about 10^9 bits per second. A coincidence between the trigger signal and the signals from the hodoscope counters, delayed in coaxial cable to match the time required to complete the trigger logic, was formed to set FASTBUS latches which recorded in-time counter hits. The FASTBUS processor was also triggered initiating the second stage of data processing.

In this second stage, the processor read the latches containing the status of all 192 counters. The address of any counter hit in coincidence with the trigger was written to a FASTBUS module of FIFO (first in first out) buffer memory of 4096 16-bit words with a cycle time of 100 ns. This buffer memory was read asynchronously by the host computer in the course of the analysis of events.

A number of aborts could terminate the event processing during the second stage of data processing. A very tight (4 ns) coincidence between the M hodoscope and the lead-glass array was queried. If the result was false the event was aborted. The processor rejected any events in which there was more, or less, than one F counter hit. The pattern of F's and G's was used by a FASTBUS cell-finder logic element to determine which aluminum wedge in the polarimeter contained the stopped muon. If there was no unambiguous choice, the event was aborted. Possible aborts disposed of, the processor then queried the FASTBUS clocks (described below) for the time that the positron from muon decay was detected, and this information was sent to the memory followed by a word indicating the end of event.

The FASTBUS clocks consisted of 32 TDC (time-to-digital conversion) channels, one for each G counter, of 10-MHz scalers which counted up to 6.4 μs. All channels started counting the 100-ns "ticks" of the clock upon the receipt of a common trigger. A specific channel was stopped when it received a signal at the corresponding clock stop input. A signal present at the veto input would cause all channels to ignore a signal at any stop input. This signal, generated by anticoincidence counters, prevented the FASTBUS clocks from responding to most spurious counts not originating from muon decay but generated by background particles passing into and through the polarimeter counters.

The signal at the trigger input, which was taken directly from the trigger board, was used to start the clocks at the time the muon entered the polarimeter. The signal from each appropriate G counter was put into the stop input of the respective clock. Signals from the G counters were also used in an adding circuit which gave an output signal when three or more inputs were asserted at the same time. The logical *OR* of this signal and the counters surrounding the polarimeter, the F's and the P's, was used at the veto input. The total logic was such as to erect a box of counters around each G counter which acted in anticoincidence with the G counter to nullify any false recording of a particle passing into the box as a muon decay. During the readout of an event, the processor calculated the address of the two G's surrounding the wedge containing the stopped muon. The time of the stop for that particular channel was read from the TDC where the times were coded as numbers running from 0 to 63 where each count represented 100 nsec. A time of 64 indicated that no stop signal was received within 6.4 μs of the trigger for that particular channel.

The muon could undergo large angular deflections through multiple scattering in traversing the toroid and polarimeter before coming to rest. The polarimeter wedge in which the muon came to rest then might not lie directly behind the F counter through which the muon entered the polarimeter. A logical element called the cell finder was used to track the muon through the polarimeter and identify the wedge containing the stopped muon. For each F counter there were five possible wedges allowed for the muon to come to rest, two to either side of the F counter and one directly behind it. The distribution of stops, measured and monitored continuously, was in accord with estimates of the multiple scattering of the muons.

A cell, defined as an F counter and the two G counters on either side of the aluminum wedge behind the F counter, is considered to contain a stopped muon when one and only one of these three counters is hit. An additional constraint is then applied that the I counter behind the wedge must not be hit; i.e., the particle must enter, and not leave, the cell. During the processing of the event the three 32-bit words from the latches for the F, G, and I counters were written into the cell finder. The cell finder contained the logical truth tables in field-programmable-logic arrays (FPLA's) and the I-counter masking was done with discrete AND gates. 50 ns after the last word was written into the cell finder a 32-bit word containing a bit set for each cell containing a muon was available in the output register. If the processor received an abort signal from external hardware, or if it detected an error in the data, the event was aborted. The host computer could at any time read data out of the memory provided at least one complete event was stored.

IV. DATA ANALYSIS

The data collected in the course of the experiment amounted to 20.8×10^{6} $K_{\mu 3}^{+}$ complete events such that the muon decay was detected. This sample was collected during 1500 h of accelerator running time. With an incident proton beam of 4.3×10^{10} protons per second the calculated K-meson flux was 3.6×10^{6} per second, of which 5.8×10^{5} K mesons decayed per second in the 5-m decay space. Typically, the accelerator repetition rate was a beam pulse every 3 sec; the nominal beam-spill period was 1 sec, though time structure of the beam reduced the effective spill time, for our experiment, to an appreciably smaller effective time.

Of the 18 500 $K_{\mu 3}$ decays occurring per pulse on the average, about 36 satisfied the various trigger requirements and produced a muon decay. In $\frac{1}{3}$ of the muon decays we could detect the positron and thus determine the direction of polarization of the muon. Over the course of the experiment we thus averaged 12 such good events per pulse. The event rate was limited by accidental backgrounds rates which, in turn, depended strongly on the time structure of the beam. This structure, which was monitored continuously, varied with the operation of the accelerator. Under the most favorable accelerator running conditions we recorded more than 20 events per pulse.

The information from each event which satisfied all of the software requirements was written on magnetic tape which could later be analyzed in detail. A summary of the event, containing only information about the event type and the time and direction of the muon decay, was written onto a data file on a disk. The contents of this file could be analyzed at any time during the experiment, even while new data were being collected, to determine current polarization asymmetries for each class of events and for the sum of all classes. The information taken from this analysis was used to monitor the sensitivity of the apparatus and measure the amount of background. The result of the experiment was thus essentially known at any time for all data collected up to that time. The availability of the experimental results, in addition to information about the quality of the data being collected as derived from monitors of the detector performance and beam quality, provided the experimenters with the ability to quickly identify and correct malfunctions.

Data collected on tape was used for a variety of detailed studies: for example, a comparison of results obtained during beam pulses of high and low intensity was used to assess the background and evaluate the analyzing power of the polarimeter.

B. Muon decay and muon asymmetry

To measure the polarization of muons stopped in a wedge of the polarimeter we detected the positrons from their decay in G counters placed between the aluminum wedges. The signals from these counters were used to stop clocks associated with each wedge. These clocks were started by the trigger circuitry, as described previously, and counted up to 6.4 μs (in 0.1-μs increments) while waiting for a decay. The clocks would also be stopped by interactions of neutral particles from various background sources, and by accidental charged particles. Although a clock veto was constructed using the counter box which surrounded each wedge, not all background particles could be intercepted with a 100% efficiency. Considering both valid muon clock stops and the random background, the time distribution of clock stops can be written as an exponential plus background:

$$dN/dt=Ae^{-t/\tau}+B\ ,$$

where A and B are constants.

The data were fit to the above formula using the FUMILI least-squares fitting program with the results

$$A=(6.616\pm0.004)\times10^{5}\ ,$$

$$\tau=(2.1803\pm0.003)\times10^{-6}\ ,$$

$$B=(1.232\pm0.002)\times10^{5}\ .$$

The lifetime given by this fit is 2.5 standard deviations smaller than the accepted value of $2.197\,12\times10^{-6}$ s. Although this does not affect the asymmetry measurement, it is interesting to know the source of the disagreement: When we consider that the clocks stop on the first signal received, the exponential decay is changed to

$$dN/dt=A(e^{-t/\tau}+B)e^{-t/\lambda}\ ,$$

where $\lambda=256$ is calculated from the unvetoed accidental rate in the G counters. Using this we arrive at a muon lifetime of 2.198 ± 0.003 μs which is in excellent agreement with the accepted value.

Using a least-squares fit to the total data sample collected during the experiment, we find that the clock stops consisted of 75% μ^+ decays and 25% background. These random background counts were a major limiting factor in the rate of data collection and are discussed in detail in the next section.

The measured asymmetry of the positrons from muon decay,

$$A=(U+D)/(U-D)\ ,$$

was used to determine the transverse and normal components of the muon polarization. The cylindrical symmetry of the detector allowed us to combine the data from all 32 polarimeter sections. We define U as the intensity of positrons detected by the counter flanking the wedge on the clockwise side, looking downstream, and D is the corresponding quantity on the counterclockwise side. The $+$ and $-$ subscripts indicate the direction of the axial field in the polarimeter and thus the direction of muon spin precession, with $+$ indicating the field directed upstream, and the spin of the μ^+ precessing clockwise about the beam axis.

Combining the intensity distribution with the background parametrization, we obtain

$$U_{\pm}(t)=e^{-t/\lambda}\{N^{+}[1+\alpha\cos(\pm\omega t+\phi_U)]e^{-t/\tau}+B\}\ ,$$

$$D_{\pm}(t)=e^{-t/\lambda}\{N^{+}[1+\alpha\cos(\pm\omega t+\phi_D)]e^{-t/\tau}+B\}\ ,$$

where $\phi_{U,D}$ is the initial azimuthal angle of the muon spin about the field direction, as measured from the normal to the central plane of the polarimeter wedge (the decay plane), and $\omega = g_\mu eB/2mc$ is the precession frequency [Fig. 3(a)]. The T-conserving transverse polarization lies initially in the decay plane so that $\phi_{U,D} \approx \pm\pi/2$ (+ for the D, − for the U counter). The T-conserving asymmetry is then

$$A_t(t) = \frac{(U_+ - D_+) - (U_- - D_-)}{U_+ + D_+ + U_- + D_-}$$

$$= [A_t(0)/C(t)]\sin\omega t ,$$

where

$$C(t) = 1 + (B/N^+)e^{t/\tau} .$$

For the T-violating, normal component of polarization, $\phi \approx 0$ for the U counter and π for the D counter, and the T-violating asymmetry is

$$A_n(t) = \frac{(U_+ - D_+) + (U_- - D_-)}{U_+ + D_+ + U_- + D_-}$$

$$= [A_n(0)/C(t)]\cos\omega t$$

with C as above and $A_n(0) = \eta P_n$. Note that $t = t_{\text{meas}} + t_0$, where t_0 is the instrumental delay.

The measured asymmetries A_t and A_n as a function of time are shown in Fig. 8. The T-conserving asymmetry A_t clearly exhibits a sinusoidal form, with the amplitude decreasing with time due to the background dilution, as expressed in the factor $C(t)$. From a least-squares fit to the entire event sample, we obtain $\omega/2\pi = 745$ kHz and $t_0 = 0.018$ μs, consistent with measurements made on the solenoidal field and clock electronics, respectively.

For the total event sample of 20.8×10^6 events, the fitted values for the asymmetry amplitudes are

$$A_t(0) = 0.0753 \pm 0.0018$$

and

$$A_n(0) = -0.000\,34 \pm 0.000\,58 ,$$

A_n being consistent with zero and therefore with time-reversal invariance.

C. Backgrounds

The two major backgrounds in this experiment acted only to dilute the data, and did not introduce a spurious asymmetry. The first background consisted of triggers which did not originate from $K_{\mu 3}^{+}$ decay. The second was false clock stops, i.e., particles

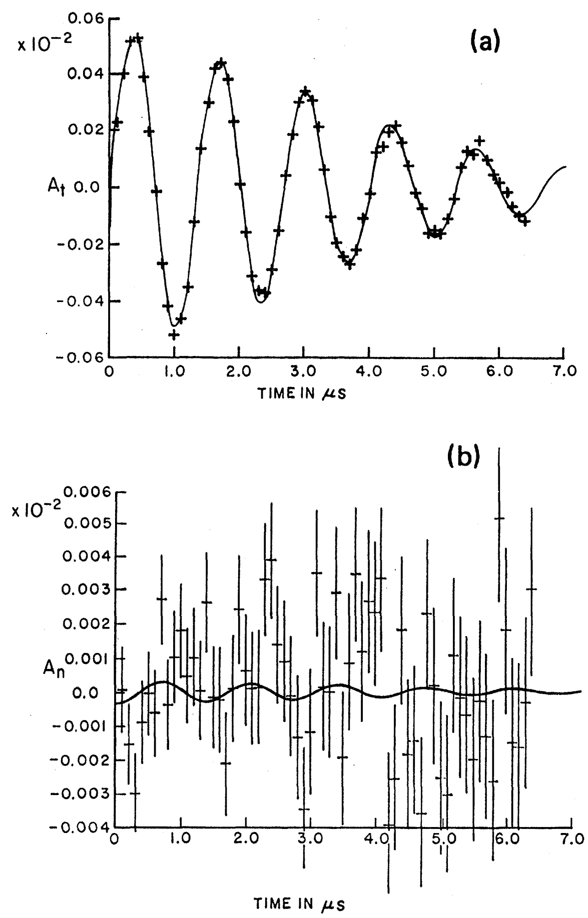

FIG. 8. Asymmetry data (2.1×10^7 μ^+ decays) (a) fit to the CP-allowed polarization component, and (b) fit to the CP-violating polarization component.

detected in the polarimeter after a trigger which were not positrons from muon decay.

The trigger circuitry was designed to accept events such that there was a coincidence between a particle identified as a muon, by the penetration through the steel toroid, and a high-energy γ ray converting in the Pb-glass counters. With the addition of kinematic constraints defined by the positions of the counters, the trigger served to accept $K_{\mu 3}$ decays and reject other events. The resolution time of the trigger, determined by the requirement of a tight timing coincidence between the Pb-glass counter and the smallest scintillation counter to pass the muon, was 4 ns. By requiring this coincidence between a muon following a well-defined track and a photon depositing more than 1.2 GeV into the lead-glass calorimeter most random triggers were suppressed. The FASTBUS electronics checked subsequently that the muon had not left the polarimeter by passing through an I counter. Charged particles incident on the lead-glass array were vetoed at the trigger stage by a set of scintillation counters covering the front face of the array. In addition, the software cuts included an examination of the hit pattern in the lead glass to ensure that the energy deposited was due to only one electromagnetic shower. The required energy threshold of 1.2 GeV discriminated strongly against straight-through charged particles which may have leaked through the anticoincidence counters.

The other major K^+ decay modes are $K^+ \rightarrow \mu^+ \nu_\mu$ (63.5% branching ratio), $\pi^+\pi^0$ (21.2%), $\pi^+\pi^0\pi^0$ (1.73%), $\pi^+\pi^+\pi^-$ (5.6%), $\pi^0 e^+ \nu_e$ (4.8%), and $\mu^+\nu_\mu\gamma$ (0.53%). These could not mimic a $K^+_{\mu 3}$ decay in our apparatus, but a coincidence of a muon from $K_{\mu 2}$ and of a photon from one of the π decay modes could. Although the branching ratio for the radiative decay $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ is $\frac{1}{7}$ that for $K^+_{\mu 3}$, the photon produced in $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ has generally too low an energy to trigger a latch hit.

A majority of the spurious triggers were generated by accidental coincidences between muons stopping in the polarimeter, which did not originate from $K_{\mu 3}$ decay, with a photon also generated through another process. Such muons were generated largely through $K_{\mu 2}$ decays and through the decays of pions, produced in various ways with moderately high momentum transfer, to muons while the pions were traversing the drift space. Muons from $K_{\mu 2}$ decay will generate a transverse polarization but no *CP*-violating component while the muons from pion decay would have no appreciable polarization perpendicular to the beam axis. The effect of an acceptance of these background muons was to dilute the data, i.e., the magnitude of the *CP*-conserving polarization would be reduced.

In a special test, we removed the requirement for a lead-glass response from the trigger logic, and determined that the trigger muon acceptance rate was 18 000 per pulse. We also measured that the rate for neutral particles entering the lead glass was 80 000 per pulse. The expected chance coincidence rate of the tight timing logic for these two rates was 5.7 events per pulse. Since we only detected the positron from muon decay in $\frac{1}{3}$ of the events, this leaves us with 1.9 background events per pulse. The number of events due to false triggers was thus less than 16%. These false events involve muons which are mostly longitudinally polarized, and so act only to decrease the effective sensitivity of the polarimeter and do not cause a false *T*-violating signal.

Accidental counts in the polarimeter counters, mimicking a muon decay, led to a second major background problem. The *G* counters, placed in the slots between the wedges, were used to detect the positron from the muon decay. A pair of counters was placed in each slot and a coincidence of the two counters was required for a logical *G*-counter signal. The coincidence rate for one such set of *G* counters, under normal running conditions, was about 50 000 per pulse. Charged particles entering the polarimeter accounted for 67% of these, and were removed by employing the veto counters. Each of the polarimeter wedges, and then each *G* counter, was surrounded by guard counters which were used to veto apparent muon decays (clock stops) which were actually due to particles entering the polarimeter.

Those background counts in the *G* counters which could not be removed by the anticoincidence logic could be divided, phenomenologically, into two categories. Part of this flux was related directly to the beam spill, and was believed to be due mostly to low-energy photons scattering in the polarimeter together with effects of low-energy neutrons, of the order of a few MeV, produced through nuclear evaporation processes by primary proton interactions in the target and by secondary beam interactions in the beam dump. Shielding between the toroid and polarimeter reduced this background to some extent. A second part of this background appeared to come from sources which were not closely correlated in time with the beam. Thermal neutrons absorbed in the aluminum wedge material produced such backgrounds through the capture γ rays generated in the course of the neutron absorption by the neutrons and through the subsequent radioactive decay of the ^{28}Al. The ^{28}Al decay, with a half-life of 2.3 min, was identified through measurements of the time structure of the backgrounds in the *G* counters and shown to contribute about 4% to that background. Including the prompt photons from the absorption of neutrons by ^{27}Al, we find that about 15% of these backgrounds were caused by the capture in aluminum of thermal and epithermal neutrons. We reduced this category of background somewhat by placing paraffin and boron in front of the polarimeter to absorb the thermal neutrons, and slow down and absorb epithermal and evaporation neutrons, but there was not enough space near the apparatus to place enough such material to reduce this kind of background substantially.

D. Systematic sources of error

A spurious *T*-violating effect could be produced in our apparatus only by an asymmetry defining a net screw sense in the detection of muon decays with respect to the laboratory kaon decay plane. We carefully constructed and mounted the apparatus to avoid such asymmetries, and thus reduced the systematic uncertainties to much less than the statistical uncertainties of the experiment.

The rotation of the transverse polarization P_t out of the decay plane, thus generating a component which would mimic a CP-violating polarization P_n, could result from a screw sense produced by misalignments in the apparatus. The apparatus was constructed such that the angular alignment of the various arrays was accurate to better than 2 mrad. Such a systematic shift would induce a false component of less than $2\times 10^{-3}P_t$ which is appreciably smaller than the statistical uncertainties in the experiment. A Monte Carlo analysis of the effects of misalignments of individual elements in an array indicated that errors which might follow from such aberrations would be an order of magnitude smaller.

The reversing magnetic field used in the polarimeter avoided systematic errors due to possible asymmetries in the detection efficiency of the polarimeter. The axial field for the two polarities was required to be equal to avoid any screw sense generated by the direction of the current in the solenoid, and to avoid contamination of the CP-violating polarization (which varied as $\cos\omega t$) by a term $P_t\cos(\omega t)\sin(\Delta\omega t)$, with $\Delta\omega$ the difference in the precession frequencies for the two directions. We measured the solenoidal fields in the slots in the polarimeter in which the counters were placed and determined that

$$\Delta\omega/\omega \leq 5\times 10^{-4} ,$$

so that the contribution to P_n was less than 0.001.

Leakage of the axial solenoid field outside of the solenoid affected the efficiency of the lead-glass counters. The change in sign of this leakage field, which was measured to be about 0.3 G, resulted in a change in the gain of the counters and an asymmetry of about 3% in the number of events obtained in the two polarities. Since this type of asymmetry does not generate a screw sense and does not affect the accuracy of the measurements, no great effort was made to reduce the effect.

Other possible screw-sense asymmetries could be generated by the simultaneous linear displacements of two different arrays. For instance, if the A or B hodoscopes were displaced upward, causing (for instance) a 1% up-down asymmetry in the trigger, and if the polarimeter similarly displayed a 1% asymmetry in the horizontal direction, a maximum screw-sense asymmetry of the order of 0.0001 could be generated. We monitored such asymmetries and the position of the arrays throughout the experiment to ensure that the contribution of such screw-sense asymmetries was negligible.

V. RESULTS AND CONCLUSIONS

The measured asymmetries A_t and A_n can be related in several ways to the physical parameters used in various descriptions of CP violation. The T-violating normal polarization component P_n is related to A_n by $A_n=\eta P_n$, where η is the analyzing power of the polarimeter. We determined η by comparing the calculated transverse polarization P_t with the measured corresponding asymmetry A_t using a small portion of the complete data set consisting only of events collected when the beam intensity was quite low. Since the background from accidental coincidences increases as the square of the beam intensity, this data has a relatively small background contamination. From measurements of the asymmetries found in this low-intensity sample, an analyzing power η of $(11\pm1)\%$ was determined. Using this value for the analyzing power, we obtained a value for the T-violating polarization component $P_n=-0.0031\pm0.0053$ for the whole of the data.

In terms of ξ, the conventional ratio of hadronic form factors used in $K_{\mu 3}$-decay phenomenology,[1] this result corresponds to

$$\mathrm{Im}\xi=-0.016+00.025 .$$

The result can also be quoted independently of the value of η and thus free of any uncertainty in it if we consider the ratio of the two measured asymmetries,

$$A_n/A_t=-(4.2\pm6.2)\times10^{-3} ,$$

which is the complex phase difference (modulo π) between the muon amplitude with positive helicity and the amplitude with negative helicity. In the absence of time-reversal violation this phase must be 0 (or π) and hence the error of the above null result is an excellent measure of the sensitivity of the experiment.

We can sharpen the constraint somewhat considering that the results can be combined with those of our previous measurements[1] of P_n from the $K_{\mu 3}$ decays of K_L^0 mesons where we found

$$\mathrm{Im}\xi=-0.004\pm0.030 .$$

The experiments are quite similar, the same polarimeter was used in both, and since the uncertainties are almost wholly statistical, it is permissible to combine the results of the two measurements to derive a value of

$$\mathrm{Im}\xi=-0.010\pm0.019$$

and

$$P_n=(-1.85\pm3.60)\times10^{-3} .$$

In the framework of gauge theories a null result for the T-violating muon polarization in $K_{\mu 3}$ decay is consistent with the Kobayashi-Maskawa model of *CP* violation[10] in which *CP* violation is due to a free complex phase in the quark amplitudes. Although a null result can be achieved in a class of models based on $SU(2)\times U(1)$ gauge theories which ascribe the *CP* violation to spontaneous symmetry breaking in the Higgs sector if the scalar particles are very massive ($\sim$TeV),[14] *T*-odd correlations of leptons of finite magnitude are predicted by Weinberg-type models with lighter Higgs particles as well. Zhitnitskii[15] calculates P_n for the kinematic region where the momenta of the muon and of the neutrino are at 90° to each other such that

$$P_n = \frac{(m_\mu m_K)}{\sqrt{8} m_0^2} \frac{v_2^2}{v_3^2} = -4.63\times 10^{-3} \frac{v_2^2}{v_3^2} ,$$

where the value of m_0 (the Higgs-boson bare mass) is calculated to be 2 GeV/c^2 and the factor v_2^2/v_3^2 is a ratio, expected to be of the order of 1, of the squares of unknown complex numbers v_j which depend on the gauge-transformation properties of the Higgs doublets. Setting that parameter to 1, the predictions are just within our experimental limits.

A similar calculation has been conducted by Cheng,[16] using penguin-diagram contributions as calculated by Deshpande[17] and, independently, by Sanda.[18] These calculations, which account for the experimental value of the ϵ'/ϵ ratio, give for the range of m_0 values from 11 to 19 GeV/c^2, a smaller value of Imξ,

$$-6.8\times 10^{-4} r < \mathrm{Im}\xi < -2.0\times 10^{-3} r ,$$

where $r = v_2^2/v_3^2$ is again the ratio of the Higgs-field vacuum expectation values. This is to be compared with our result of Im$\xi = -0.010\pm 0.019$ for the combined K^+ and K^0 data.

The measurements thus constrain the magnitude of *T*-invariance violation in $K_{\mu 3}$ decays, and therefore the extent to which *CP* violation may exist outside the K^0-$\bar{K}^0$ system. The result precludes an unexpectedly large contribution from the Higgs sector, yet it does not invalidate "superweak" descriptions of the *CP*-invariance violation.

ACKNOWLEDGMENTS

We wish to thank the staff of the Brookhaven AGS for the close support and cooperation which made the experiment possible. This research was supported in part by the U.S. Department of Energy under Contract No. AC02-76ER03075.

---

*Present address: Enrico Fermi Institute, University of Chicago, Chicago, IL.

[1] W. M. Morse, L. B. Leipuner, R. C. Larsen, M. P. Schmidt, S. R. Blatt, M. K. Campbell, D. M. Grannan, M. J. Lauterbach, H. Kasha, and R. K. Adair, Phys. Rev. D 21, 1750 (1980).

[2] M. K. Campbell, J. K. Black, S. R. Blatt, H. Kasha, M. P. Schmidt, R. K. Adair, W. M. Morse, L. B. Leipuner, and R. C. Larsen, Phys. Rev. Lett. 47, 1032 (1981).

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

[4] T. D. Lee and C. N. Yang, Brookhaven Report No. BNL 443 (T-91), 1957 (unpublished).

[5] J. Sakurai, Phys. Rev. 109, 980 (1958).

[6] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).

[7] K. Kleinknecht, Annu. Rev. Nucl. Sci. 29, 1 (1976).

[8] L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).

[9] S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8),* edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968).

[10] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[11] S. Weinberg, Phys. Rev. Lett. 37, 657 (1976).

[12] S. R. Blatt, Ph.D. thesis, Yale University, 1981 (unpublished).

[13] L. Leipuner *et al.* IEEE Trans. Nucl. Sci. 28, 333 (1981); D. Makowiecki *et al., ibid.* 28, 360 (1981); M. K. Campbell *et al., ibid.* 28, 43 (1981); M. K. Campbell, Ph.D. thesis, Yale University, 1981 (unpublished).

[14] G. C. Branco and A. I. Sanda, Phys. Rev. D 26, 3176 (1982).

[15] A. R. Zhitnitskii, Yad. Fiz. 31, 1024 (1980) [Sov. J. Nucl. Phys. 31, 529 (1981)].

[16] Hai-Yang Cheng, Phys. Rev. D 26, 143 (1982).

[17] N. G. Deshpande, Phys. Rev. D 23, 2654 (1981).

[18] A. I. Sanda, Phys. Rev. D 23, 2647 (1981).