the critical temperatures with both ordered and disordered starts. In Fig. 2 we see that for SU(2) in five dimensions the two runs stabilize at different values, indicative of a first-order transition. In contrast, for SO(2) in four dimensions these runs show large fluctuations and continue to converge slowly, suggesting a higher-order transition.

In Fig. 2 I also show the results of similar runs with the four-dimensional SU(2) model at $\beta = 2.35$. This corresponds to a temperature in the middle of the slow-convergence region alluded to above. The two runs converge after about thirty iterations, while fluctuations are considerably controlled relative to those seen in the SO(2) model. I feel that the reduced convergence in this region is not evidence for a phase transition, but rather a consequence of the critical nature of four dimensions.

At low β (high temperature) the points follow the strong-coupling limit

$$P = 1 - \tfrac{1}{2}\beta + O(\beta^3) \quad \text{for SO(2)}, \tag{9}$$

$$P = 1 - \tfrac{1}{4}\beta + O(\beta^3) \quad \text{for SU(2)}. \tag{10}$$

The large-β behavior can be estimated by keeping only those terms in the action which are quadratic in parameters describing the group manifold. This yields a Gaussian path integral and implies

$$P \xrightarrow[\beta \to \infty]{} n/\beta d, \tag{11}$$

where n is the number of group generators and d is the dimensionality of space-time. The functions in Eqs. (9)–(11) are plotted along with the "data" in Fig. 1. Note that this inverse-β behavior at large β is approached in all the models. I do not expect any further phase transitions for β above the onset of this spin-wave behavior.

In conclusion, I have presented Monte Carlo evidence that the confinement phase of SU(2) lattice gauge theory in four dimensions extends to all values of coupling. This means that the continuum limit of this theory simultaneously exhibits confinement and asymptotic freedom. Of course this is not an analytic proof; indeed, there could exist a subtle transition not readily observable in the average plaquette. I regard this as unlikely in the light of the extreme clarity of the transitions seen with the other models.

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[1]K. G. Wilson, Phys. Rev. D 10, 2445 (1974).
[2]A. A. Migdal, Zh. Eksp. Teor. Fiz. 69, 810 (1975), and 69, 457 (1975) [Sov. Phys. JETP 42, 413 (1975), and 42, 473 (1975)]; L. P. Kadanoff, Rev. Mod. Phys. 49, 267 (1977).
[3]M. Creutz, L. Jacobs, and C. Rebbi, Phys. Rev. Lett. 42, 1390 (1979).
[4]M. Creutz, L. Jacobs, and C. Rebbi, to be published.
[5]K. Binder, in *Phase Transitions and Critical Phenomena*, edited by C. Domb and M. S. Green (Academic, New York, 1976), Vol. 5B.

Limits on *CP*-Invariance Violation in $K_{\mu 3}$ Decays

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Measurements of the polarization of μ^+ from the decay of $K_L{}^0$ mesons gives a mean value of 0.0021 ± 0.0048 for the polarization in the direction $(\vec{p}_\pi \times \vec{p}_\mu)$ normal to the plane of decay. The ratio of the normal to the transverse polarization in the c.m. system is 0.0041 ± 0.0092 and the value of $\mathrm{Im}\xi$ is deduced to be 0.012 ± 0.026, not significantly different from $\mathrm{Im}\xi = 0.008$ expected if the decay were invariant under CP (or T).

The observed breakdown[1] in CP or T invariance, noted in K_L decays, can be described by either of two sets of theoretical conjectures. It is possible that a moderately weak (milliweak) CP-nonconserving force acts in second order or that a much weaker (superweak) CP-nonconserving force acts in first order to induce the CP-nonconserving effects. If a superweak interaction accounts for the CP-nonconserving effects which have been observed in the K_L decay systematics, we cannot expect to see the consequences of the interaction in other processes at a level presently detectable. If a milliweak interaction is responsible, CP-nonconserving effects should show up at observable levels elsewhere, in particular in an electric dipole moment of the neutron,[2] in a correlation between the nuclear spin and the plane of decay in nuclear β decay,[3] and in a polarization of muons normal to the plane of decay in $K_{\mu 3}$ decays. At this time, measurements of the neutron electric dipole moment give negative results[2] at the level predicted by wide classes of milliweak theories, while the nuclear β-decay experiments are almost as sensitive if the light- (u and d) quark transitions contribute fully to the CP-nonconserving interaction. The measurements of muon polarization in K decays, which are likely to indicate CP nonconservation if s-quark transitions are especially important, have not been quite so sensitive.[4] We present here the results of an experiment which extends the level of sensitivity of the K-decay measurements.

The manifestation of CP nonconservation in the systems described above can be defined in terms of the interference of two kinematically separate amplitudes: In the absence of CP nonconservation the amplitudes are relatively real; the existence of an imaginary component indicates CP-invariance violation. For K_1^0 decays to $\pi^- + \mu^+ + \nu$, it is convenient to consider, as a measure of CP nonconservation, the phase between A_u, the amplitude for the production of μ^+ with spin aligned in the direction of the muon momentum, and A_d, the amplitude for the muon spin opposed to the direction of momentum. The magnitudes of both amplitudes are functions of T_π and T_μ, the kinetic energies of the decay particles in the c.m. system, and then the position of the decay configuration on the Dalitz plot. For a given value of T_μ, A_d^2 and A_u^2 vary almost linearly with T_π where A_u is zero when T_π is at a minimum and A_d is zero when T_π has its maximum value. From elementary considerations of the character of the $V-A$ interaction, we can expect the mean values of $(A_d/A_u)^2$ to be of the order of $(1-\beta_\mu)/(1+\beta_u)$.

It then follows simply that the transverse polarization of the muon in the plane of decay will be equal to $2\,\mathrm{Re}(A_u{}^*A_d)/(A_u{}^2+A_d{}^2)$ while the polarization normal to the decay will be equal to $2\,\mathrm{Im}(A_u{}^* \times A_d)/(A_u{}^2+A_d{}^2)$. The ratio P_n/P_t will then be equal to the angle $\mathrm{Im}(A_u{}^*A_d)/\mathrm{Re}(A_u{}^*A_d)$ which we take as a measure of CP nonconservation and which, for milliweak models, we expect to be of the order of $\epsilon = 2\times 10^{-3}$ which parameterizes CP nonconservation in the K_L-to-K_S transitions.[1]

It is also convenient, and conventional, to consider the decay, $K_L{}^0 \to \pi^- + \mu^+ + \nu$, in terms of invariants constructed from a hadron current and the lepton current. Two hadron currents can be constructed from the quantities available and it is useful to consider CP nonconservation in terms of the interference of amplitudes proportional to these currents and thus to the factors $f_+(q^2)(P_K + P_\pi)$ and $f_-(q^2)(P_K - P_\pi)$, where q^2 is the four-momentum transfer, $(P_K - P_\pi)^2$. The possible CP nonconservation can then be expressed in terms of the value of $\mathrm{Im}\xi$, where $\xi = f_-/f_+$, as the value of $\mathrm{Im}\xi$ will be proportional[5] to P_n. The previous best measurement[4] gives $\mathrm{Im}\xi \approx -0.085 \pm 0.064$. The average muon polarization in the direction $\vec{p}_\pi \times \vec{p}_\mu$ is equal to 0.21 $\mathrm{Im}\xi$, for $\mathrm{Re}\xi = 0$, where p_a is the three-momentum of particle a

A schematic diagram of the muon-polarization detection equipment is shown in Fig. 1. The $K_L{}^0$ mesons, produced at an angle of 6°, from the interactions with a platinum target of 28-GeV protons from the Brookhaven alternating-gradient synchrotron (AGS) accelerator, travel about 7 m through clearing magnets and collimators into a 5-m drift space. About 2% of the decays which occur in the drift space result in $\pi^- + \mu^+ + \nu$ events such that the μ^+ is focused by the 1.2-m-diam toroidal magnet through a further steel absorber to stop in the 1500-kg aluminum polarimeter, where the direction of polarization of the μ is determined by a measurement of the direction of emission of the e^+ from the μ^+ decay. The active volume of the polarimeter extends from a radius of 20 cm to a radius of 50 cm and is 90 cm long. The μ^- are defocused by the toroidal magnet such that few stop in the polarimeter.

In our design, we detect the possible existence of the CP-forbidden polarization normal to the plane of decay by measuring the polarization of the muons in the laboratory system, in the direction $\vec{p}_K \times \vec{p}_\mu$, for selected classes of events where the direction of the K beam lies in (or at a very small angle to) the plane of decay. The two diagrams of Fig. 1, labeled type P (for plus) and type M (for minus), suggest, schematically, the character of the decays in the center-of-mass system and the laboratory system for the two basic types of events selected by the computer hodoscope system and the associated trigger logic.

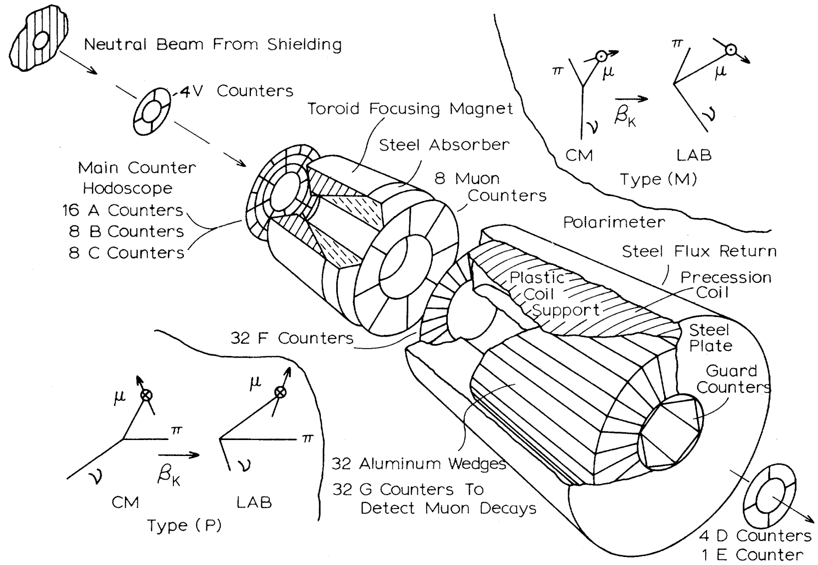

FIG. 1. A schematic representation of the basic measuring system. The direction of polarization of muons from K mesons which decay in the drift space between the exit from the shielding to the ABC hodoscopes is measured in the polarimeter assembly. The diagrams to the upper right and lower left show characteristic decay configurations for the two classes of events considered here.

The CP-forbidden polarization normal to the plane of decay in the c.m. system is transferred to the normal to the plane defined by the beam direction and the muon decay in the lab system only for these two classes of events. Note that the component of polarization of the muons directed into or out of the paper, P_n, is opposite directions for the two classes of events and that the component in the plane of decay, perpendicular to the K beam, P_t, is also oppositely directed for the P and M events. For both sets of events, the trigger logic selects a muon which passes through either an A counter or a B counter and then through a "muon" counter and an F counter to stop in the polarimeter. Anticoincidence counters, not shown in Fig. 1, reject muons which pass through the polarimeter. Then the class-P events are defined by the requirement of a coincidence in the C, D, or E counters which register the passage of the pion, while the class-M events are selected by the requirement of a coincidence in an A or B counter which is adjacent (in azimuthal angle) to the A or B counter which recorded the muon passage. Information from the V counters is stored but not used in the trigger or analysis. Of the 2% of the decays which generate a μ^+ which stops in the polarimeter, about 6% satisfy the trigger requirement which defines the events as belonging to class M or P. Since only about 25% of these stopped muons decay such that the positron is detected in the G counters, our measurements are then made on about one of 3300 $K_L{}^0$ decays in the drift space. Our results are based on a total of 12×10^6 events. Another 2×10^6 events were recorded under different conditions to check systematic effects and trigger backgrounds. We concluded from these studies that the systematic uncertainties were quite small compared to the statistical errors and that false or incorrectly identified events comprised less than 5% of our sample and contributed little to our reported uncertainties.

The diagram of Fig. 2 shows a section of the polarimeter together with vectors representing the components of polarization of the stopped muons. The component P_n, present if CP invariance is violated, lies in the direction of the vector $\vec{p}_K\times\vec{p}_\mu$; the component P_t is perpendicular to the direction of the beam and lies in the decay plane, while the third component, P_L, is in the direction of the beam. The polarization component P_t is determined by measuring the U-D decay asymmetry as a function of time as the muon precesses in a 60-G axial magnetic field produced by a current which passes through windings about the polarimeter circumference. Here, U represents counts recorded in the clockwise counter, looking downstream, and D the counts in the counterclockwise counter. For each of the 32 counters, clocks are started upon the recording

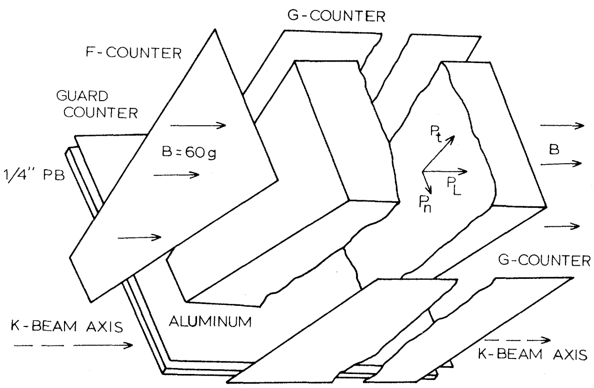

FIG. 2. An (exploded) view of a polarimeter section showing the position of guard counters and electron detection counters. The components of the muon polarization are shown in their relationship to the polarimeter elements.

of the set of counter hits which signifies that a muon stops in the polarimeter; the clock is stopped by the count recorded when a decay positron passes through the counter. As the muon precesses, the ratio $A=(U-D)/(U+D)$ will vary sinusoidally with the precession frequency. The (CP-allowed) transverse polarization will produce an amplitude of the form $A_t(t)=CA_t(0)\sin(\alpha t)$ and the normal (CP-forbidden) polarization will generate an amplitude of the form $A_n(t)=CA_n(0)\times\cos(\alpha t)$, where $C=0.13\pm 0.015$ is the effective analyzing power of the polarimeter and is determined from our previous measurements on aluminum polarimeters.[5] The frequency, α, is determined by the sign and magnitude of the axial magnetic field and in our experiment was about equal to $2\pi\times 8.333\times 10^5$ Hz. During the experiment, the sign of the axial field, and then the sign of α, was reversed every pulse. This resulted in a cancellation of the CP-conserving amplitude, $A_t(t)$, so that the magnitude of any CP nonconserving amplitude, $A_n(0)$, could be determined without interference of the large CP-conserving amplitudes. Conversely, the addition of the signed amplitude, pulse by pulse, resulted in a measure of $A_t(0)$ uncontaminated by any possible admixture of the CP-nonconserving amplitude $A_n(t)$.

The curves of Fig. 3 show the basic data for the most important results. The upper curves show, to the left, the total amplitude $A_t(t)$ summed over both classes of events, P and M, where the M amplitudes are multiplied by -1 to take into account the different signs which we expect and observe. The curve to the right shows the same data plotted modulo the cycle time and with the background subtracted. The lower curves show similar plots of the CP-nonconserving amplitudes. The amplitudes of the two classes of events, evaluated by least-squares analyses, are $A_t=0.0543\pm 0.00063$ and $A_n=0.00028\pm 0.00063$. This leads

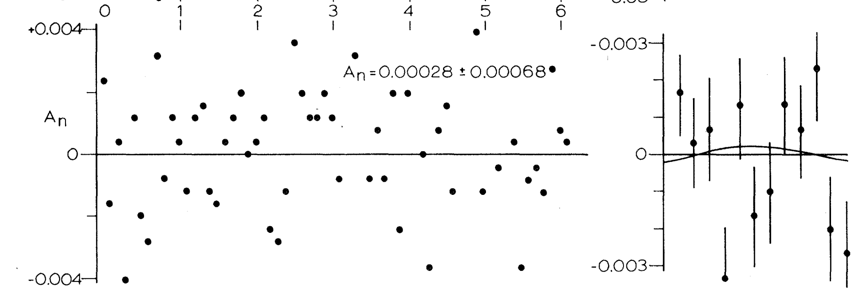

FIG. 3. The top curve shows the variation of A_t as a function of time and the bottom curve shows A_n. Note the different scales. The curves to the right show the same data with the background subtracted modulo 1.2 μsec, the precession cycle time.

to a value of $P_t = 0.42$, consistent with Monte Carlo estimates of the polarizations expected for this class of events, and a value of $P_n = 0.0021 \pm 0.0048$ for the CP-nonconserving component of polarization. From the Monte Carlo calculations, we find $\mathrm{Im}\xi = P_n/0.18 = 0.012 \pm 0.026$ to be compared with the value of $\mathrm{Im}\xi = 0.008$ to be expected from final-state[6] interactions in the absence of CP nonconservation. As a consequence of the character of the experimental design, the conclusions concerning CP nonconservation (or $\mathrm{Im}\xi$) are quite insensitive to variations and uncertainties in the Monte Carlo calculations and in the incident K_L beam spectra. We believe that the best measure of the sensitivity of the experiment is the mean value of P_n/P_t measured in the c.m. system which is equal to the angle between the amplitudes A_u and A_d and is found to be equal to 0.004 ± 0.0092. This result is to be compared with the value of 0.002 that we suggest as a central value to be expected for milliweak theories.

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[1]An excellent review of CP-nonconservation measurements is given by K. Kleinknecht, Annu. Rev. Nucl. Sci. 26, 1-50 (1976). References to earlier work on $K_{\mu 3}$ decays are found in N. Barash-Schmidt *et al.*, Phys. Lett. 75B, 70 (1978).

[2]W. B. Dress *et al.*, Phys. Rev. D 15, 9 (1977).

[3]R. M. Baltrusaitis and F. P. Calaprice, Phys. Rev. Lett. 38, 464 (1977).

[4]J. Sandweiss *et al.*, Phys. Rev. Lett. 30, 1002 (1973). These authors report a value of $\mathrm{Im}\xi \approx -0.06 \pm 0.045$. However, they used a value of $\mathrm{Re}\xi \approx -0.60$ in their calculations instead of the value of ≈ 0.0 which is now known to be correct. The value of $\mathrm{Im}\xi$ which we attribute to them then represents our estimate of the effect of this change on their results. We wish to thank Professor Sandweiss for the benefit of discussions on this point as well as for his advice on many other aspects of our experiment.

[5]C. M. Ankenbrandt *et al.*, Phys. Rev. D 3, 2582 (1971).

[6]E. S. Ginsberg and J. Smith, Phys. Rev. D 8, 3887 (1973); N. Byers, S. W. MacDowell, and C. N. Yang, in *Proceedings of the International Seminar on High Energy Physics and Elementary Particles, Trieste, 1965* (International Atomic Energy Agency, Vienna, 1965), p. 953, and private communication.