Limits on *CP*-Invariance Violation in $K_{\mu3}{}^+$ Decays

M. K. Campbell, J. K. Black, S. R. Blatt, H. Kasha, M. P. Schmidt, and R. K. Adair
Department of Physics, Yale University, New Haven, Connecticut 06520

and

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

(Received 1 July 1981)

The *CP*-nonconserving polarization of μ^+ from $K_{\mu3}$ decays in the direction $(\vec{p}_\pi \times \vec{p}_\mu)$ normal to the plane of decay was measured to be $(-3.0 \pm 4.7)\times 10^{-3}$ for events such that $(\vec{p}_\mu \cdot \vec{p}_\nu) = 0$. The value of $\mathrm{Im}\xi$ is then -0.016 ± 0.025. This null result places constraints on certain models of *CP* nonconservation through the exchange of Higgs bosons.

PACS numbers: 13.20.Eb, 11.30.Er

The scores of experimental measurements made in the period—almost two decades—which has followed the discovery of *CP* nonconservation by Christenson *et al.*[1] have resulted in the important, though disappointing, conclusion that the only *CP* nonconserving phenomena we have observed can be described by a model in which there is but one free parameter, $|\eta| = 2.3\times10^{-3}$, the portion of K_S state in the K_L amplitude. In the past, lacking a credible model of the strong and weak interactions, it was convenient to describe *CP*-nonconservation models in terms of their form in perturbation theory: a "superweak" $|\Delta S| = 2$ interaction with a strength of about $10^{-9}G_f$ acting in first order or a "milliweak" interaction acting in second order with a strength of about $10^{-3}G_f$. The superweak interaction, weaker than the weak interaction in second order, will not generate *CP*-nonconserving effects observable with present techniques, outside of the K^0-$\bar{K}^0$ system results which are known.

With the maturation of quantum chromodynamics (QCD), it is now more useful to consider *CP* nonconservation within the framework of QCD models. In particular, it is attractive to consider *CP* nonconservation as resulting, phenomenologically, from phase differences occurring between six or more quark amplitudes[2] or phase differences occurring between two or more Higgs doublets.[3,4] Weinberg[3] has pointed out that if *CP* nonconservation in particle interactions derives from *CP*-nonconserving phases in the Higgs sector, one should expect small muon polarizations in the direction normal to the plane of decay in $K_{\mu3}$ decays. Zhitnitskii[4] has shown, for a particular model of *CP* nonconservation in the Higgs sector, that *CP*-nonconserving muon polarizations of the order of 5×10^{-3} can be expected. We report here measurements of $K_{\mu3}{}^+$ decays which lead to interesting limits on such polarizations.

Our measurements were made at the Brookhaven National Laboratory alternating-gradient synchrotron on K^+ meson decays from a nonseparated, short, 3.95-GeV, positive beam of particles produced in the forward direction by the interaction of 28-GeV protons on a one mean-free-path platinum target. The momentum acceptance, dp/p, was about 0.10; the solid angle was about 4×10^{-5} sr.

A schematic diagram of the muon-polarization detection equipment is shown in Fig. 1. Of the K^+ mesons passing through the 5-m drift space, about one in 25 000 decays through the $K_{\mu3}$ mode 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 while a γ ray from the decay of the π^0 converts in the Pb-glass counter array located on the beam axis. The path of acceptable muons is determined by the hodoscope arrays V, A, B, M, F, and $\bar{I}$, while the direction of the polarization of the muons which stop in the polarimeter is determined by a measurement of the direction of emission of the e^+ from the μ^+ decay through analyses of signals generated in the counters G.

Various anticoincidence counters reduce the two backgrounds which constrain the acceptable event rate due to accidental counts in the polarimeter muon decay (positron) detector counters, G, and due to accidental coincidences between γ rays from the π^0-π^+ K-decay mode and muons from $K_{\mu2}$ decays. Other backgrounds were not important. The data handling was directed and the data were collected through a Fastbus[5] electronic logic system with a data transfer capability near 10^9 bits/sec and the analysis of this data was conducted on-line so that the results of the measurements were known at any time as the

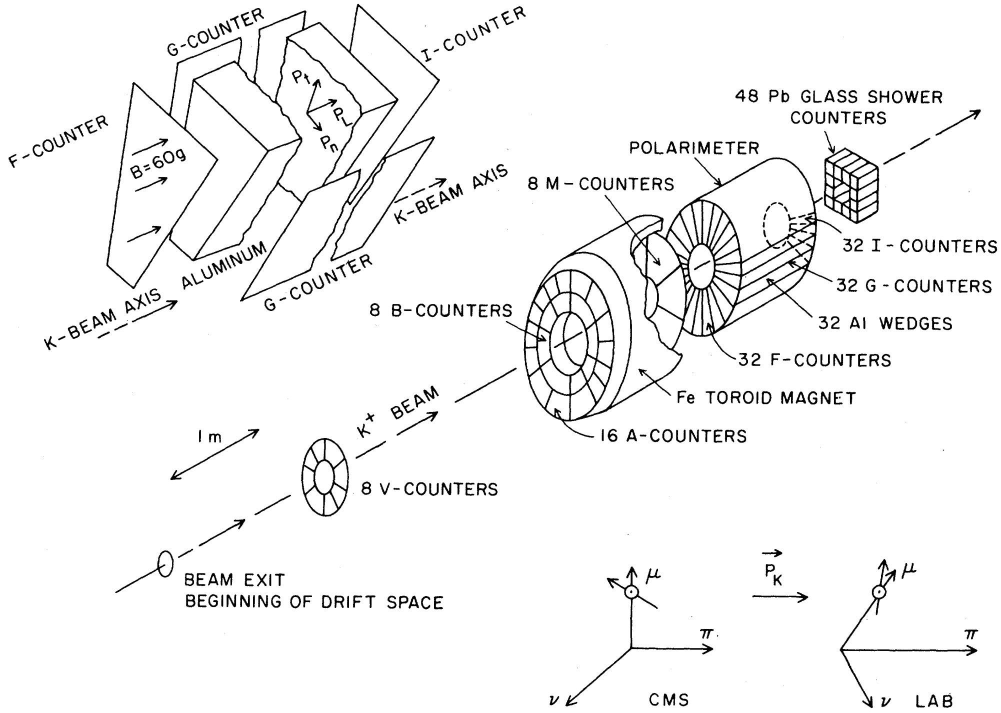

FIG. 1. The central figure shows a schematic view of the basic experimental apparatus, where the different hodoscopes are designated by capital letters. The upper diagram represents an exploded view of a polarimeter element, showing the vector polarizations of a stopped muon; and the lower drawing presents a schematic view of the relationship between the momentum and spin vectors of the $K_{\mu 3}$ decay products in the center-of-mass system and laboratory systems.

experiment proceeded. All of the results presented here were available within minutes of the termination of the experimental run.

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 a selected class of events where the direction of the K beam lies in (or at a very small angle to) the plane of decay. The lower diagram of Fig. 1 suggests the character of the accepted decays in the center-of-mass system and in the laboratory system for the type of events selected by the hodoscope counters and the Pb-glass array through appropriate trigger logic. Through the requirement that events are to be accepted only if more than 1.2 GeV energy is deposited in the Pb-glass by a photon derived from the decay of the π^0, events are selected such that the π^0 must travel nearly in the forward direction (typically, within 30 mrad of the K-beam line) so that the condition that the K beam must lie in the decay plane is substantially satisfied.

The upper diagram of Fig. 1 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 $\vec{p}_K \times \vec{p}_\mu$; the component P_t is perpendicular to 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 in windings about the polarimeter circumference. Here, U represents counts recorded in the clockwise counter, looking downstream, and D represents the counts in the counterclockwise counter. For each of the 32 counters, clocks are started upon the recording of the set of counter hits which signifies that an acceptable 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 $A_t(t) = A_t \sin\omega t$ and the normal (CP-nonconserving) polarization will produce an amplitude of the form $A_n(t) = A_n \cos\omega t$. The frequency, ω, is determined by the sign and magnitude of the axial field and the sign of ω is reversed every pulse (every three seconds). This results in a cancellation of the CP-conserving amplitude, $A_t(t)$, so that the magnitude of any CP-nonconserving amplitude, $A_n(t)$, can be determined without interference from the large CP-conserving amplitude. Conversely, the addition of the signed amplitude, pulse by pulse, results in a measure of $A_t(t)$.

We note that the existence of a CP-nonconserving polarization defines a screw direction. Conversely, systematic errors can simulate a CP-nonconserving effect only if those uncertainties effect a screw direction. In recognition of this, the design and the construction of the apparatus were conducted to avoid deviations from cylindrical symmetry. This symmetry of the apparatus, together with the selection of a well-defined Fourier component of $A_n(t)$, serves to reduce systematic uncertainties to a level less than 10^{-3} in the polarization, appreciably below that of the statistical uncertainties.

The results of the experiment are shown in the graphs of Fig. 2 which present the results from the analysis of 2×10^7 events. The upper graphs show, to the left, the CP-conserving amplitude $A_t(t)$ and, to the right, the data plotted modulo the time cycle and with the background subtracted. The lower graphs show similar plots of the CP-nonconserving amplitude $A_n(t)$. The dashed curve shows the best fit to $\cos\omega t$, the measure of CP-nonconserving polarization. The two amplitudes are $A_t = -0.069\,20 \pm 0.000\,43$ and $A_n = -0.000\,29 \pm 0.000\,46$, where the signs of the amplitudes reflect the conventions used. The ratio of these polarizations $A_n/A_t = (4.2 \pm 6.7) \times 10^{-3}$ is just the phase difference (modulo π) between the muon amplitude with positive helicity and the amplitude with negative helicity. In the absence of time-reversal violation (or CP nonconservation under the assumption of CPT invariance) this phase must be 0 (or π), and hence the error in the null result is an excellent measure of the sensitivity of the experiment.

We can calculate $P_t(\text{lab})$ knowing the systematics of $K_{\mu 3}{}^{+}$ decays and the acceptance of our apparatus over the Dalitz plot of the decay kinematics. From such a calculation, accurate to a few percent with use of Monte Carlo methods, we find $P_t(\text{lab}) = 0.857$ and, then, $P_n(\text{lab}) = (-3.6 \pm 5.7) \times 10^{-3}$. Again, from the Monte Carlo calculation, we find $P_n(\text{c.m.})/P_n(\text{lab}) = 1.17$ and, for the set of events selected by the apparatus, we have $P_n(\text{c.m.}) = (-4.2 \pm 6.7) \times 10^{-3}$. The differences between the laboratory and center-of-mass

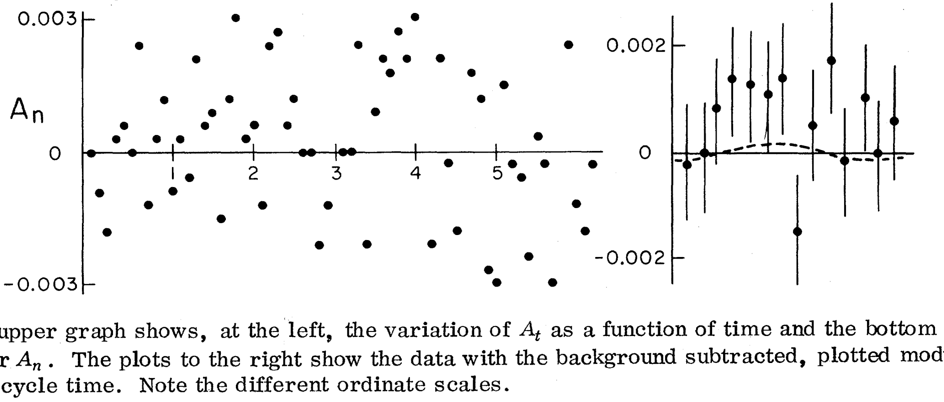

FIG. 2. The upper graph shows, at the left, the variation of A_t as a function of time and the bottom graph shows similar data for A_n. The plots to the right show the data with the background subtracted, plotted modulo 1.2 μsec, the precession cycle time. Note the different ordinate scales.

quantities are not large and then insensitive to uncertainties in the calculations.

The above numbers are relevant to the subclass of decays selected by the specific character of the experimental design and a more universal expression of the results is necessary. For the kinematic region such that $\vec{p}_\mu \cdot \vec{p}_\nu = 0$, we have $P_n = (-3.0 \pm 4.7) \times 10^{-3}$. We can also express the result in terms of the value of ξ, the conventional ratio of form factors used in discussion of $K_{\mu 3}$ decays; taking $\mathrm{Re}\,\xi = 0$, we find $\mathrm{Im}\,\xi = -0.016 \pm 0.025$.

According to the calculations of Zhitnitskii, CP nonconservation in the Higgs sector leads to a polarization, for P_n where $\vec{p}_\mu \cdot \vec{p}_\nu = 0$ and T_μ is of the order of 100 MeV, such that

$$P_n = \frac{(m_\mu m_K)}{(8 m_0^2)^{1/2}} \frac{v_2^2}{v_3^2} = -4.63 \times 10^{-3} \frac{v_2^2}{v_3^2},$$

where the value of m_0 is set equal to 2 GeV by the measured K^0-$\bar{K}^0$ CP-nonconserving effects and v_2^2/v_3^2 is defined by the gauge transformation properties of the Higgs doublets and not otherwise determined experimentally: Zhitnitskii expects this number to be of the order of one. For this experiment, the limits set are of the magnitude expected and serve to constrain the free parameter to be less than two.

Somewhat stronger constraints can be invoked if we compound these results with those from our previous measurements[6] of P_n from the $K_{\mu 3}$ decays of K_L^0 mesons where we found $\mathrm{Im}\,\xi = 0.001 \pm 0.030$. The experiments are quite similar and the uncertainties are almost wholly statistical. Therefore, we feel that it is permissible to add the results of the two measurements to derive a value of $\mathrm{Im}\,\xi = -0.010 \pm 0.019$ and $P_n = (-1.85 \pm 3.60) \times 10^{-3}$. Although this null result cannot exclude the possibility that the CP-nonconserving effects which are known from observations of the K^0-$\bar{K}^0$ system derive from CP-nonconserving phases in the Higgs sector, we can conclude that such mechanisms do not make unusually large contributions to $K_{\mu 3}$ decays.

This work was supported by the U. S. Department of Energy.

---

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

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

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

[4] A. R. Zhitnitskii, Yad. Fiz. 31, 1024 (1980) [Sov. J. Nucl. Phys. 31, 529 (1981)]; however, calculations by A. I. Sanda, Phys. Rev. D 23, 2647 (1981), and by N. G. Deshpande, Phys. Rev. D 23, 2654 (1981), suggest that such Higgs models may lead to unacceptably large values of ϵ'.

[5] L. B. Leipuner *et al.*, IEEE Trans. Nucl. Sci. 28, 333 (1981).

[6] W. M. Morse *et al.*, Phys. Rev. D 21, 1750 (1980).

Superstrong Force with a Heavy Axion

S.-H. H. Tye
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

(Received 17 April 1981)

A new, superstrong force (analogous, to, but much stronger than, quantum chromodynamics) is introduced to the Peccei-Quinn extension of the standard model of weak and electromagnetic interactions. Strong CP nonconservation is naturally suppressed and the resulting heavy axion is compatible with the present experimental bounds. The strength of this new force and some of its properties are discussed.

PACS numbers: 12.20.Hx, 14.80.Kx

The discovery of pseudoparticle solutions[1] in non-Abelian gauge theories has far-reaching consequences in quantum chromodynamics (QCD). The QCD vacuum must have a nontrivial topological structure,[2] labeled by a new parameter θ_c, and the effective QCD Lagrangian becomes

$$L_{\mathrm{eff}} = L_{\mathrm{QCD}} + (i\,\theta_c g^2/32\pi^2) G_{\mu\nu}{}^a \tilde{G}^{a\mu\nu}, \qquad (1)$$

where $\tilde{G}^{a\mu\nu}$ is the dual of the QCD field stress tensor $G^{a\mu\nu}$ and g is the QCD coupling constant. The presence of the second term violates P and CP invariances, both of which are known to be excellent symmetries of strong interactions. In fact, the experimental bound on the electric dipole moment of the neutron[3] implies $\theta_c < 10^{-8}$. This means that θ_c must be extremely small if not exactly zero. It is possible, although highly unlikely, that nature just so happens to have a