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Experimental constraints on models of CP violation

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Abstract

Experimental constraints on models of CP violation. M. P. Schmidt, R. K. Adair, J. K. Black, S. R. Blatt, M. K. Campbell, H. Kasha (Yale University), R. C. Larsen, L. B. Leipuner, W. M. Morse (Brookhaven National Laboratory). A review is presented of the experimental efforts at the Brookhaven AGS to study the nature of CP violation in the decays of kaons. The current research focuses on sensitive searches for a violation of time-reversal (T) invariance in the decay $K\to\pi\mu\nu_\mu$ as evidenced by a nonzero component of muon polarization normal to the decay plane. The ongoing program of research includes a study of direct CP violation in the decays of neutral kaons through a precise (1%) measurement of $|\eta_{oo}|/|\eta_{+-}|$, the ratio of the CP violating amplitudes for the decays of neutral kaons into neutral and charged two pion final states. Results will be presented on the decay $K_L^O\to\pi^-\mu^+\nu_\mu$, where we have found the ratio of T violating to T conserving transverse polarization of the muons to be $<\overline{P_n/P_t}>=0.004\pm0.009$, consistent with T invariance. Preliminary results for the polarization of muons in the decay $K^+\to\pi^o\mu^+\nu_\mu$ will be discussed.

We report here on an experimental program at the Brookhaven AGS to search for a milliweak violation of time reversal (T) invariance through a measurement of muon polarization in the decay $K \to \pi\mu\nu$. Muon polarization is determined by the detection of the positron momentum in the weak decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. The T violating correlation of interest is $\vec{S}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)$, that is the component of muon polarization normal to the decay plane as defined in the kaon rest frame. This component of polarization P_n will result from the complex interference of the two amplitudes describing the decay of the kaon. In $K_{\mu 3}$ decays this phase is equal to the ratio of the T violating and T conserving transverse polarization components of the muon (as observed in the kaon rest frame): $\phi = (P_n/P_t)_{cms}$. More traditionally one has $P_n \propto \mathrm{Im}\xi$ where $\xi \equiv f_-/f_+$ is the ratio of the form factors describing the hadronic vertex of the $K_{\mu 3}$ decays.

A search for a T violating muon polarization in $K_{\mu 3}$ decay is a sensitive test of those gauge models in which the exchange of Higgs bosons is important in CP violation. As shown by Weinberg[1] an extension of the Higgs sector (from one to three complex doublets) allows for a genuine CP violating phase, even if there exist only four quark flavors. If charged Higgs exchange is largely responsible for CP violation observed in $K^0 - \bar{K}^0$ systematics, then it is estimated that milliweak (that is of order $\varepsilon \sim 2 \times 10^{-3}$) effects are expected in $K_{\mu 3}$ decays. The T violating component of polarization arises due to the spin zero nature of the Higgs bosons which contribute solely to that piece of the decay amplitude for which the total angular momentum of the lepton pair is zero. The usual W boson exchange can contribute to both the spin zero and spin one amplitudes. Similar effects are not expected to be observable in neutron β decay as the coupling of Higgs bosons to quarks and leptons is proportional to the mass of the fermions. We note that no such T violating effects in $K_{\mu 3}$ decays are expected from the Kobayashi-Maskawa[2] model in which a CP violating phase is allowed in the gauge couplings of six flavors of quark.

The $K^0_{\mu 3}$ experiment was conducted in a 6° neutral beam which traveled through the center of a cylindrically symmetric detector (Fig. 1). Positive muons from decays ($K^0_L \to \pi^- \mu^+ \nu_\mu$) occuring in the 5 meter drift space upstream of the detector were focused by the steel toroidal magnet and brought to rest in the aluminum polarimeter. The path of the muons was determined from the coincidence of scintillation counter pulses from the hodoscopes labeled A-B, M, F and G. Field Programmable Logic Arrays (FPLA's) were used to determine the azimuthal position of stopping muons in the segmented polarimeter and to abort events for which one unambiguous muon stop was not found.

In order to maximize the sensitivity of the detector to the T violating component of polarization, events were selected such that the K^0_L laboratory momentum was very nearly in the $K_{\mu 3}$ decay plane as defined in the kaon rest frame. For such events the T violating component of polarization in the laboratory is normal to the plane defined by the laboratory momenta of the kaon and the muon, that is $P_n \propto \vec{S}_\mu \cdot (\vec{P}_K \times \vec{P}_\mu)$. Figure 2 illustrates possible decay product orientations, in the kaon rest frame and the laboratory, for two classes of events. Due to the steepness of the K^0_L production spectrum, the finite acceptance of the detector and the energy (~ 1 GeV) required for the muon to penetrate the toroid and stop in the polarimeter, the event selection is strongly biased towards those events of class P(M) where the pion is emitted forward (backward) in the kaon rest frame. This yields a net T-violating component of polarization which defines a screw sense about the beam line.

The event selection was accomplished by fast trigger logic which required, in coincidence with the muon, a pion hit in the D-E hodoscope (for class P) or in an A-B counter adjacent to that hit by the muon (for class M). Monte Carlo calculations show that about 6% of all $K^0_{\mu 3}$ decays with muons stopping in the polarimeter would fulfill the event selection criteria yielding $\langle P_n \rangle = 1.8 \times 10^{-3}$ for $\mathrm{Im}\xi = 0.01$ and $\mathrm{Re}\xi \sim 0$.

After coming to rest in the aluminum polarimeter, muon spins precessed with a period of 1.2 μsec in a 60 G axial magnetic field. The positron from the muon decay was detected by one of the two G counters flanking the muon stop position. Each G counter was associated with a "clock" which was gated on for 6.4 μsec by the fast trigger. The detection of the positron thus recorded the time and direction of the muon decay.

As indicated in Fig. 3, the geometry of the polarimeter and the applied magnetic field allowed a measurement of two components of the muon polarization in the laboratory: P_t, the T conserving transverse polarization, and P_n, the T violating component. For the ensemble of muons the polarization was determined from the amplitude of the asymmetry, $A = (R - L)/(R + L)$, in the number of positrons detected to the right (R) or the left (L) of the muon stop position. Reversing the direction of the precession field before each beam pulse allowed an independent determination of the P_t and P_n components. This is understood by noting that the contribution to the asymmetry from the P_t component reverses under a reversal of the field direction, whereas the contribution from the P_n component is invariant.

The curves of Fig. 4 show the measured asymmetry, A, plotted as a function of time for the 12 million events collected. The upper curves show the expected sinusoidal dependence of A_t, the asymmetry due to the T conserving polarization P_t. The lower curves (note the change in the vertical scale) show the time dependence of the T violating asymmetry A_n with representative errors. The curves on the left display the data from the on-line analysis. The "damping" of the sinusoid in the A_t plot is due to random clock stops caused by neutron fluxes in the detector cave. The curves on the right show a simple Fourier analysis fit to the data with the period fixed and the background subtracted.

The least squares fit to the amplitude $A_t(0)$ imply a T conserving polarization of $P_t = 0.40 \pm 0.06$, which is consistent with Monte Carlo expectations and serves to calibrate the detector. For the T violating data the fit implies a value for the polarization $P_n = 0.0016 \pm 0.0053$ which is consistent with zero.[3]

Using the calculated sensitivity of the detector this value of P_n leads to a value for the T violating phase $\phi = (P_n/P_t)_{cms} = 0.003 \pm 0.010$ which is consistent with time reversal invariance, and should be compared with the value 0.002 that we suggest as a central value to be expected from milliweak theories. In terms of the traditional kaon form factor ratio ξ our result corresponds to a value $Im\xi = 0.009 \pm 0.028$, which is not significantly different than the value 0.008 expected from the electromagnetic final state interactions between the outgoing π^- and μ^+.

The completed $K^0_{\mu 3}$ experiment is considered the first of a program to detect milliweak CP violation in $K_{\mu 3}$ decays, and Brookhaven is well suited for such precision measurements. This summer we have begun collecting data on muon polarization in the decay $K^+ \rightarrow \pi^0\mu^+\nu_\mu$. The experiment is performed in a monochromatic (4 GeV/c) beam and we have replaced the D-E hodoscope (Figure 1) with a lead glass array ($\sim$ 8 radiation lengths) in order to detect γ-rays from π^0 decays. The requirement of a high energy γ-ray ($E_\gamma > 1.2$ GeV) enhances the selection of events where the π^0 is emitted forward in the kaon rest frame, thus increasing the sensitivity by about 30% compared to the $K^0_{\mu 3}$ experiment. In addition the polarimeter is now shielded from direct view of the production target which reduces the neutral backgrounds associated with the beam. Another advantage of the $K^+_{\mu 3}$ experiment is the absence of final state effects as there is only one charged particle, the muon, in the decay products.

It is worth noting that we are employing a prototype of the Brookhaven Fast Bus[4] for data acquisition which will facilitate our expectation of collecting events at a rate (∿ 150/pulse) ten times that of the $K^0_{\mu 3}$ experiment. The collection of 150 million events would allow a measure of the CP violating phase ϕ to $\pm$ 0.003, well within the range expected from milliweak models of CP violation.

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Figure Captions

Fig. 1. An isometric view of the experimental apparatus indicating the major components of the detector.

Fig. 2. (a) Orientations of the decay products and the muon polarization in the kaon rest frame and the laboratory system for a typical P class event.

(b) Orientations of the decay products and the muon polarization the kaon rest frame and the laboratory system for a typical class M event.

Fig. 3. (a) Schematic representation of the components of muon polarization 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.

Fig. 4. Asymmetry as a function of time: total event sample.

References

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2. M. Kobayashi and T. Maskawa, Prog. of Theor. Phys. 49, 652 (1973).

3. Results have been published: M.P. Schmidt, et al., Phys. Rev. Lett. 43, 556 (1979), and W.M. Morse, et al., Phys. Rev. D21, 1750 (1980).

4. See the paper submitted by L. Leipuner, et al., to these proceedings.

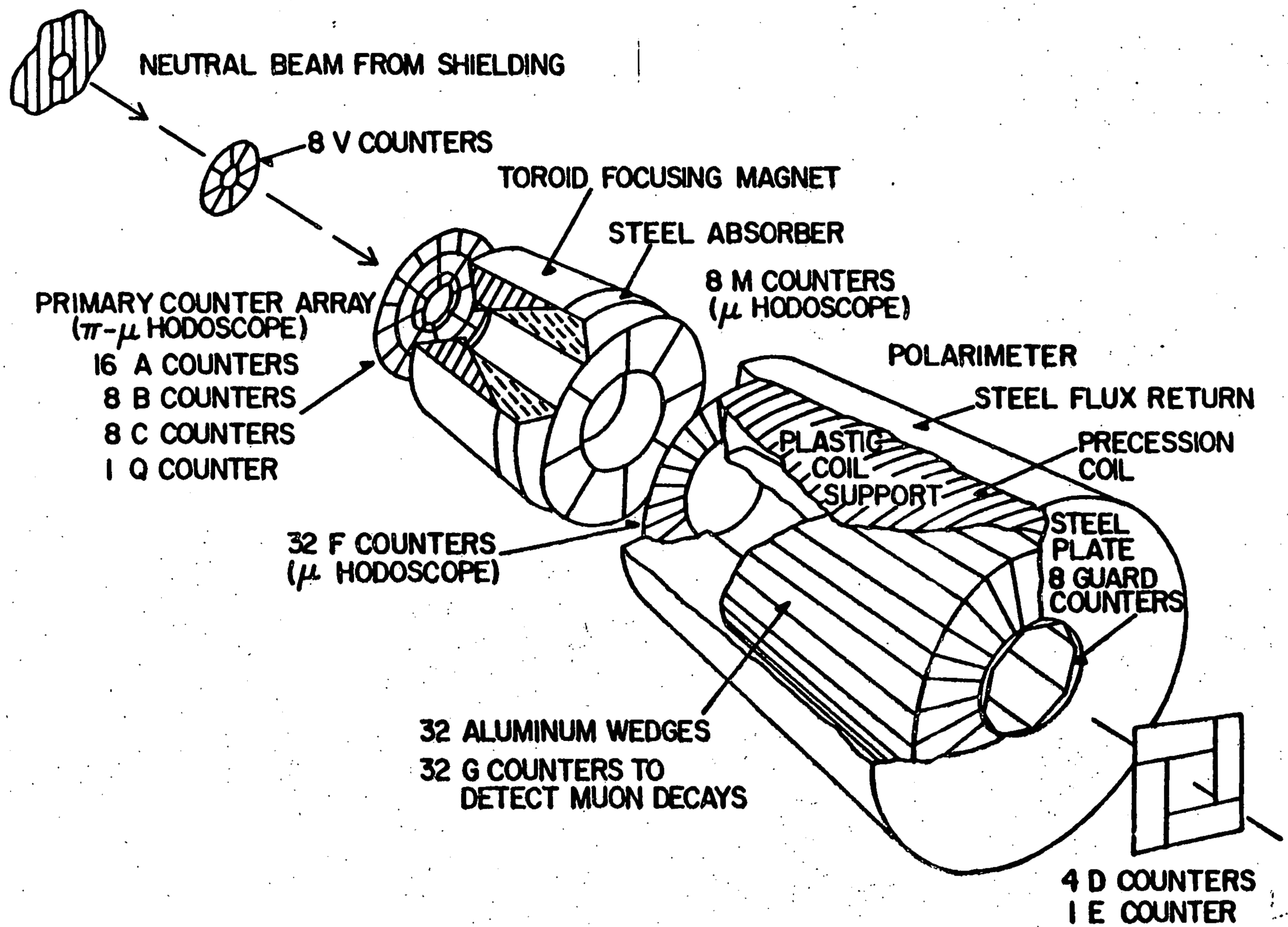
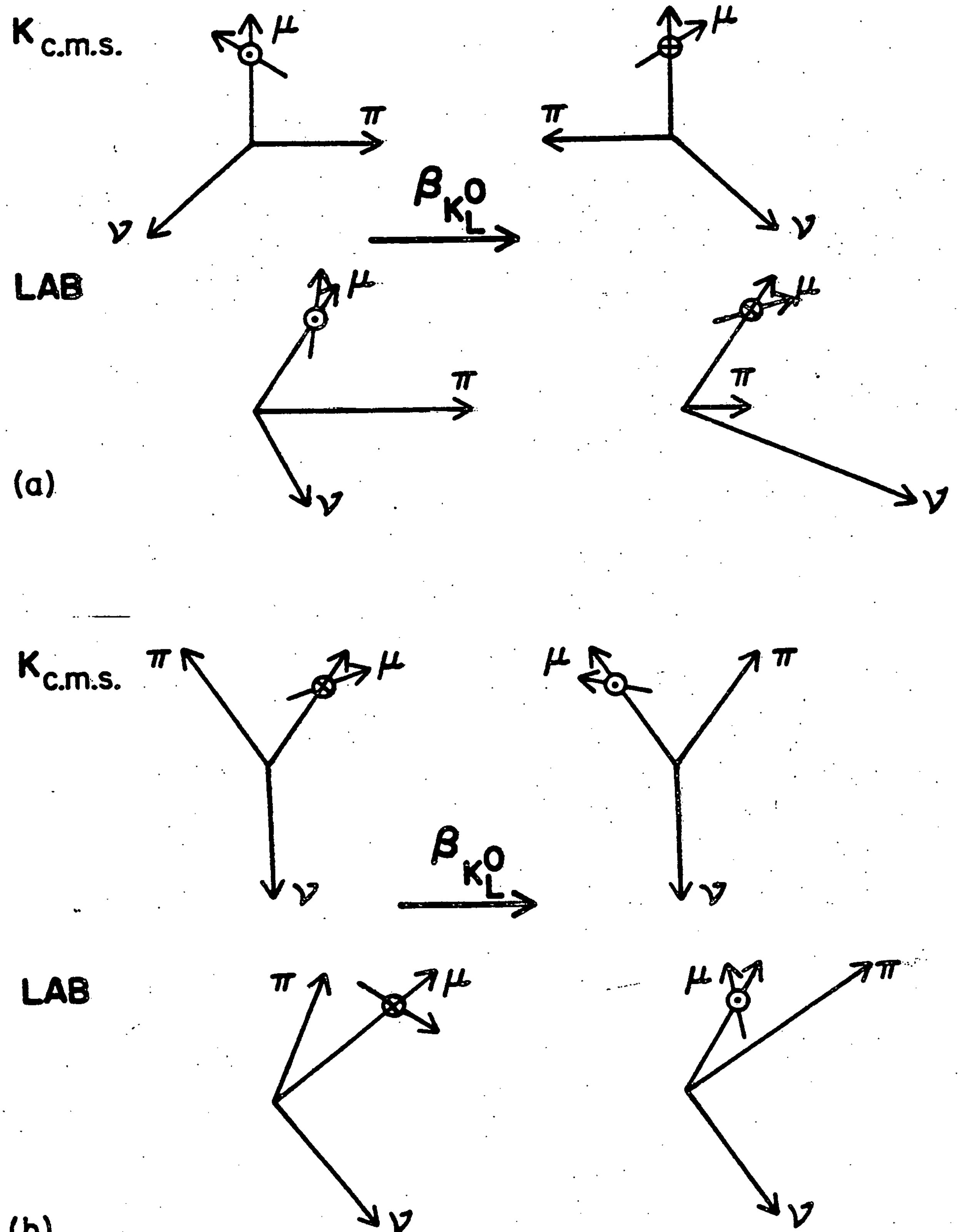

NEUTRAL BEAM FROM SHIELDING
8 V COUNTERS
TOROID FOCUSING MAGNET
STEEL ABSORBER
8 M COUNTERS
(μ HODOSCOPE)
PRIMARY COUNTER ARRAY
(π-μ HODOSCOPE)
16 A COUNTERS
8 B COUNTERS
8 C COUNTERS
1 Q COUNTER
POLARIMETER
STEEL FLUX RETURN
PLASTIC
COIL
SUPPORT
PRECESSION
COIL
STEEL
PLATE
8 GUARD
COUNTERS
32 F COUNTERS
(μ HODOSCOPE)
32 ALUMINUM WEDGES
32 G COUNTERS TO
DETECT MUON DECAYS
4 D COUNTERS
1 E COUNTER

Fig. 1


K c.m.s.
μ
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K c.m.s.
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(b)

Fig. 2

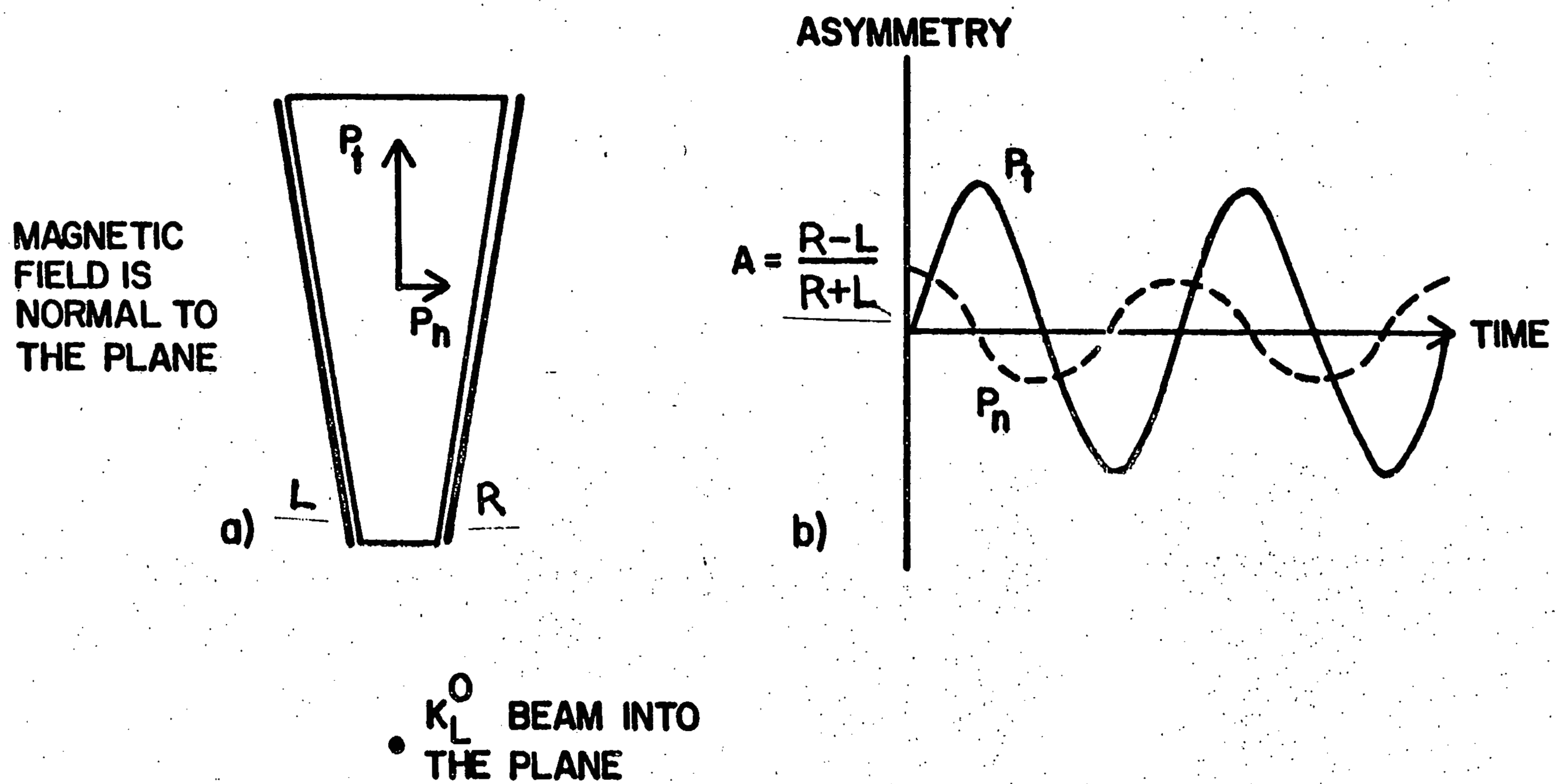
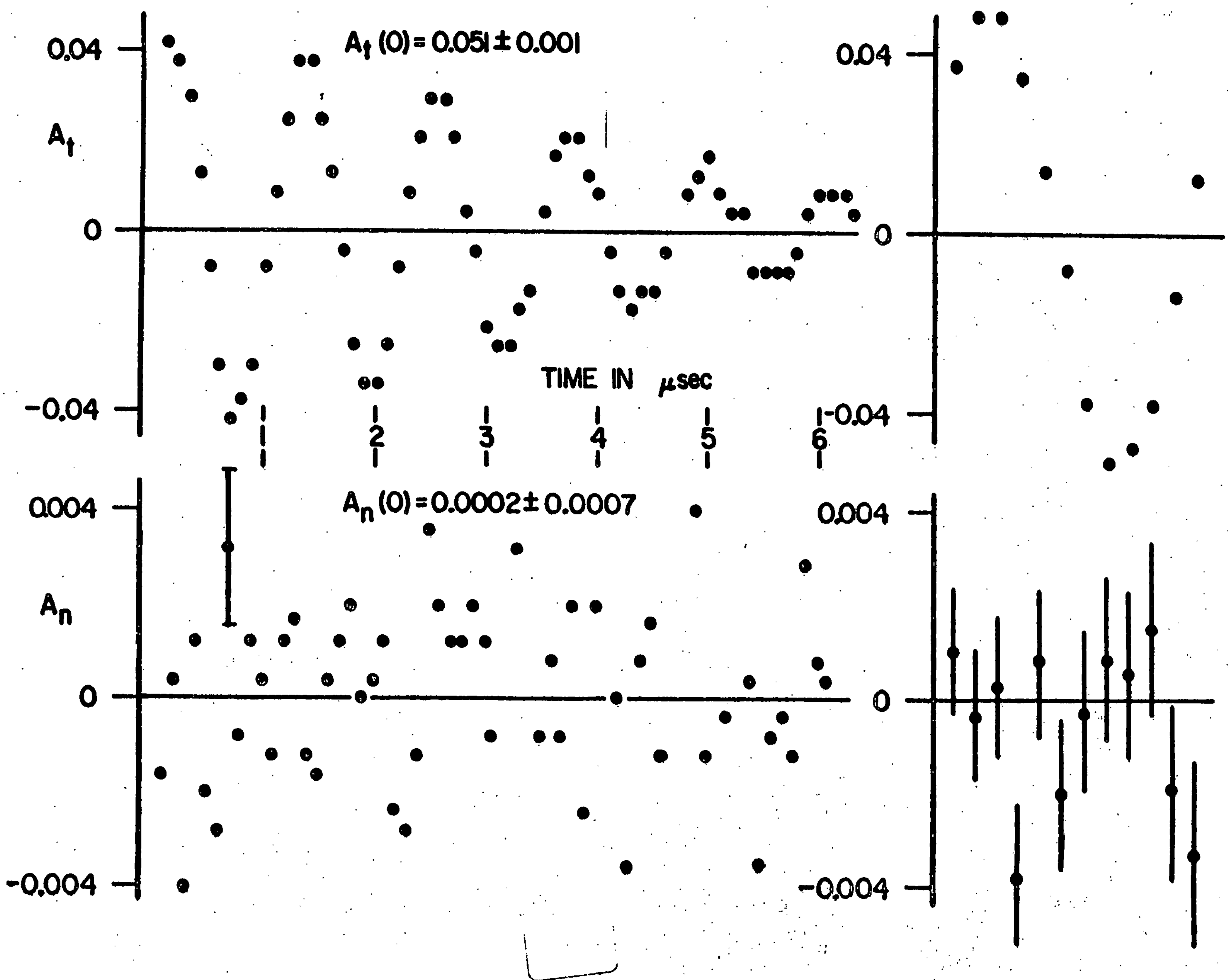

MAGNETIC
FIELD IS
NORMAL TO
THE PLANE
P_t
P_n
L
R
a)
K_L^0 BEAM INTO
THE PLANE
ASYMMETRY
$A = \frac{R-L}{R+L}$
P_t
P_n
TIME
b)

Fig. 3



$A_t(0) = 0.051 \pm 0.001$
A_t
0.04
0
-0.04
TIME IN μsec
1
2
3
4
5
6
$A_n(0) = 0.0002 \pm 0.0007$
A_n
0.004
0
-0.004

Fig. 4