SEARCH FOR T-VIOLATION in $K_{\mu 3}$ DECAY
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Abstract

We have designed a new experiment (E923) at the BNL-AGS to search for the T-violating polarization of the muon normal to the decay plane of the $K^+ \rightarrow \mu^+ \pi^0 \nu$ decay. The experiment aims to search for T-violation beyond the Standard Model; such a search is motivated by the need for a stronger CP violation source to account for the baryon asymmetry of the Universe. The experiment will be performed with in-flight decays from an intense ($2 \times 10^7 K^+/sec$) 2 GeV/c separated $K^+$ beam in an existing beam-line at the AGS. We expect to analyze more than 10$^9$ events to obtain the sensitivity of $\delta P_1 = \pm 0.00013$ at 1 $\sigma$, corresponding to the sensitivity of $\pm 0.0007$ to $\text{Im} \xi$, an improvement by 40 over the present limit on the same measurement.

Introduction

Recently we examined the possibility of measuring various muon decay asymmetries that are sensitive to P, T or CP symmetries [1]; these are tabulated in Table 1. Experimentally, CP violation has only been observed in the neutral kaon system so far. Although a theoretical description of the CP-violation in the neutral kaon system exists through the complex phase in the Standard Model CKM matrix, part or all of these phases could be consequences of deeper causes that have so far eluded experiments. Over the last decade experiments at FNAL and CERN directed towards the measurement of the direct $K_L^0 \rightarrow \pi\pi$ transition or $\xi_\rho$ have been inconclusive in revealing the true nature of CP-violation. Over the next decade ambitious efforts towards understanding CP-violation and the CKM matrix elements are planned with...
new $\xi^L$ experiments and B-factories. The importance of these efforts is undeniable, yet it must also be important to investigate the possibility that some or all of the CP-violation comes from effects outside the minimal Standard Model, particularly the CKM matrix.

The CPT invariance of local quantum field theories requires that CP violation is equivalent to T-violation. Therefore, it would be particularly interesting to look for direct violation of T-invariance outside the neutral kaon system.

It should also be noted that CP-violation is required to generate the observed baryon asymmetry of the universe, and it is now accepted that the CP-violation embodied in the CKM matrix does not have sufficient strength for this purpose [2]. Physics beyond the Standard Model that could generate the baryon asymmetry can also generate CP or T violating muon polarizations in the kaon decay modes in Table 1.

Muon polarizations from kaon decays have a rich phenomenology. In the case of $K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$ new measurements could lead to important constraints on the Standard Model CKM parameters, in particular the Wolfenstein parameters $\rho$ and $\eta$. It is, however, difficult to reach the level of sensitivity needed to measure these parameters well with current technology. Nevertheless, the experimental difficulties should be compared to the difficulties facing the rare kaon decay measurement of $K_L \to \pi^0\nu\bar{\nu}$, which is sensitive to the same physics.

As shown in Tables 1 and 2 for many cases limits on the muon polarization will probe new physics beyond the Standard Model. In particular, the polarization will be sensitive to the physics of a more complicated Higgs sector or leptoquarks that could give rise to CP or T violation outside the Standard Model. The other source of CP violation needed for baryogenesis could be the motivation for such searches. In the case of $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$ decays large gains in the sensitivity to amplitudes not allowed in the Standard Model are possible with current detector techniques and available beams. Therefore we have designed the new experiment to focus on these measurements.

$$K^+ \to \pi^0\mu^+\nu$$

The transverse or out of plane muon polarization ($P_T^\mu(K_{\mu3})$) in this decay has been analyzed by many authors [3, 4, 5]. The out of plane polarization is expected to be zero to first order in the Standard Model because of the absence of the CKM phase in the decay amplitude. It has been shown that any arbitrary models involving effective V or A interactions cannot produce this type of polarization. Irreducible backgrounds, i.e., final state interactions (FSI),
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<tbody>
<tr>
<td>(1) $K^+ \rightarrow \pi^0 \mu^+\nu$</td>
<td>0.032</td>
<td>0.0</td>
<td>$\sim 10^{-6}$</td>
<td>$\leq 10^{-3}$</td>
<td>[3]</td>
</tr>
<tr>
<td>(2) $K^+ \rightarrow \mu^+\nu\gamma$</td>
<td>$5 \times 10^{-3}$</td>
<td>0.0</td>
<td>$\sim 10^{-3}$</td>
<td>$\leq 10^{-3}$</td>
<td>[19]</td>
</tr>
<tr>
<td>(3) $K_L \rightarrow \mu^+\mu^-$</td>
<td>$7 \times 10^{-9}$</td>
<td>$\sim 10^{-4}$</td>
<td>0.0</td>
<td>$\leq 10^{-2}$</td>
<td>[22,23]</td>
</tr>
<tr>
<td>(4) $K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>$5 \times 10^{-8}$</td>
<td>$\sim 10^{-2}$</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 10^{-3}$</td>
<td>[24-29]</td>
</tr>
<tr>
<td>(5) $K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>0.0</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 10^{-3}$</td>
<td>$\sim 10^{-3}$</td>
<td>[30,5]</td>
</tr>
<tr>
<td>(6) $K^+ \rightarrow \pi^+\mu^+\mu^-$</td>
<td>$\sim 6 \times 10^{-2}$</td>
<td>$\sim 0.0$</td>
<td>$\sim 0.1$</td>
<td>$[30,5]$</td>
<td></td>
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Table 1: The decay modes and the polarization asymmetries or correlations of interest.

Table 2: The decay modes and asymmetries discussed by the working group. The asymmetries are numbered as in Table 1. The rest of the columns are: the known branching ratio, the estimated Standard Model value, the value due to final state interactions, the maximum possible value allowed by non-standard physics, and the theoretical reference.
to the out of plane polarization in this decay are expected to be small ($\sim 10^{-6}$) and therefore can be ignored [6]. Therefore, the existence of a non-zero value of this polarization will be a definite signature of new physics. In particular, some multi-Higgs and leptoquark models could produce such a polarization. In multi-Higgs models a charged Higgs particle mediates an effective scalar interaction that interferes with the Standard Model decay amplitude; in such models the polarization could be as large as $10^{-3}$ without conflicting with other experimental constraints including the measurements of the neutron electric dipole moment and the branching fraction for $B \rightarrow X\tau\nu$, or $b \rightarrow s\gamma$ [7-12]. In Table 3 we have listed many such constraints and translated them into a limit on the T-violating polarization in $K_{\mu3}$ decays. As can be seen the T-violating muon polarization is the best probe of this physics. The out of plane polarization of $\tau$'s in $B \rightarrow D\tau\nu$ decays has recently been examined in the same context [13]. Depending on the phase space examined a factor of 30 enhancement of the lepton polarization is possible in B semileptonic decays to $\tau$ relative to $K^{+} \rightarrow \mu^{+}\pi^{0}\nu$ decay. Therefore a measurement of the $\tau$ out of plane polarization within $\pm0.4\%$ is needed to match the sensitivity that we have proposed for $K^{+} \rightarrow \mu^{+}\pi^{0}\nu$ decays. Such a measurement with B decays needs high statistics and is possible with the proposed next generation B-factories if the $\tau$ polarization can be analyzed with high efficiency.

The best previous experimental limits were obtained almost 15 years ago with both neutral

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value (or 95% C.L.)</th>
<th>$\bar{P}<em>{\mu} &lt; m</em>{h} \sim 2m_{W}$</th>
</tr>
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<tbody>
<tr>
<td>$d_{n}$ [7]</td>
<td>$&lt; 1.2 \times 10^{-25}e - cm$ (95% C.L.)</td>
<td>$&lt; 0.064$</td>
</tr>
<tr>
<td>$d_{e}$ [8]</td>
<td>$&lt; 1.7 \times 10^{-26}e - cm$ (95% C.L.)</td>
<td>$-$</td>
</tr>
<tr>
<td>$\xi_{e}$ [9]</td>
<td>$(1.5 \pm 0.8) \times 10^{-3}$</td>
<td>$-$</td>
</tr>
<tr>
<td>$m_{K_{L}} - m_{K_{S}}$ [10]</td>
<td>$(3.510 \pm 0.018) \times 10^{-6}eV$</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td>$B(b \rightarrow s\gamma)$ [11]</td>
<td>$(2.32 \pm 0.67) \times 10^{-4}$</td>
<td>$-0.009 &lt; P_{\mu}^{T} &lt; 0.007$</td>
</tr>
<tr>
<td>$P_{T}^{\mu}(K_{\mu3})$ [15]</td>
<td>$(2.72 \pm 0.34) \times 10^{-2}$</td>
<td>$&lt; 0.008$</td>
</tr>
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</table>

Table 3: Constraints on $P_{\mu}^{T}$ for 3HDM [18] from various measurements. For details see Ref. [3] and [4]. Also see Ref. [17]. We have assumed that the 3 vacuum expectation values have the same ratios as the third generation masses; $v_{1} : v_{2} : v_{3} : m_{b} : m_{t} : m_{\tau}$; and $m_{t} \sim 170GeV$ and $m_{h} \sim 2m_{W}$. (−) means that there is no significant constraint. All constraints obtained are at 95% confidence level.
and charged kaons [15] at the BNL-AGS. The experiment with $K^+$ decays produced a measurement of the transverse polarization, $P^T_{\mu} = 0.0031 \pm 0.0053$. The combination of both experiments could be interpreted as a limit on the imaginary part of the ratio of the hadron form factors, $Im \xi = Im(f_-/f_+) = -0.01 \pm 0.019$. This limit is mostly independent of theoretical models and the experimental acceptance. By using the approximate formula, $P^T_{\mu} \approx 0.183 \times Im \xi$, one may reinterpret the above measure of $Im \xi$ as a combined limit on the polarization, $P^T_{\mu} \approx -0.00185 \pm 0.0036$. This 1980 era measurement was based on $1.2 \times 10^7 K^0_L$ and $2.1 \times 10^7 K^+ \! \rightarrow \! \mu^+ \pi^0$ decays to $\mu^+ \pi^0$ and was limited by statistics and backgrounds.

Currently an experiment is in progress at the KEK-PS, E246 [16], to measure $P^T_{\mu}$ with a new technique of using a stopping $K^+$ beam and measuring the muon decay direction without spin precession. They expect to reach a sensitivity of $9 \times 10^{-4}$ ($Im \xi < 4 \times 10^{-3}$) with $1.8 \times 10^7$ events. The experiment will try to minimize systematics by using the cylindrical symmetry of the apparatus and by using the backward-forward $\pi^0$ symmetries of the decay at rest. The results of this experiment will be very valuable to future experiments. Preliminary results from their recent data are reported elsewhere in this proceedings.

$$K^+ \rightarrow \mu^+ \nu \gamma$$

The $T$ violating out of plane polarization of the muon in this decay also probes non Standard Model physics similar to the $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay. The former can be caused by an effective pseudo-scalar interaction, while the latter by an effective scalar interaction. In addition, it is also sensitive to non-Standard Model vector and axial vector couplings. Therefore searches for $T$ violation in both decay modes are complementary [19]. The $T$ violating polarization in $K^+ \rightarrow \mu^+ \nu \gamma$ could be $\sim 10^{-3}$ without violating other experimental bounds. It is estimated [20,21] that the electro-magnetic FSI for this interaction can induce an out of plane muon polarization of the same order of magnitude. An accurate theoretical calculation will be needed to subtract the FSI from any observation. On the other hand, this FSI induced effect could be considered a useful calibration point for the apparatus that will also be used for the new $K^+ \rightarrow \pi^0 \mu^+ \nu$ experiment.

**Detector Design**

The E923 experiment will be performed with 2 GeV/c electro-statically separated charged kaons decaying in flight. The beam intensity will be $2 \times 10^7 K^+$/s/spill with $3 \times 10^{13}$ protons
Figure 1: Schematic of the detector. A typical $K^+ \rightarrow \mu^+ \pi^0 \nu$ events is superimposed.

on target every 3.6 sec. Figure shows the plan view of the experiment. The basic workings of the experiment are the same as the experiment in Ref. [15]. The detailed design is, however, optimized for a high intensity 2 GeV beam. The cylindrically symmetric detector is centered on the kaon beam. The $K^+_\mu^3$ decays of interest occur in the decay tank; the photons from the $\pi^0$ decay are detected in the calorimeter; the muon stops in the polarimeter. The decay of the stopped muon is detected in the polarimeter by wire chambers, which are arranged radially with 96 graphite wedges that serve as absorber medium. The hit pattern in the polarimeter identifies the muon stop as well as positron direction relative to the muon stop. By selecting events with $\pi^0$ moving along the beam direction and muon moving perpendicular to the beam direction in the $K^+$ center of mass frame, the decay plane coincides with the radial wedges. A non-zero transverse muon polarization causes an asymmetry between the number of muons that decay clockwise versus the number counter-clockwise. To reduce systematic errors, a weak solenoidal magnetic field along the beam direction (70 gauss or a precession period of $\sim 1\mu$s) with polarity reversal every spill is applied to the polarimeter. If there is an initial muon transverse polarization, there will be a small shift in the phase of the sinusoidal oscillation in the measured asymmetry. The difference in the asymmetry for the
two polarities is proportional to the T-conserving muon polarization in the decay plane, while
the sum is proportional to the T-violating muon polarization normal to the decay plane. Both
components will have the same frequency but will be 90 degrees apart in phase.

Compared to the previous in-flight experiment, this experiment has much better background rejection and event reconstruction. The separated $K^+$ beam should greatly reduce the accidental rate. The polarimeter is finely segmented and the analyzing power is higher. The positron signature is defined by the coincidence of signals in a pair of neighboring wedges. The larger calorimeter makes it possible to measure both photons and to reconstruct the $\pi^0$ momentum for a large fraction of the events. Together with the muon trajectory, the events can be fully reconstructed. The detector acceptance and background rejection is optimized using GEANT simulation.

The experiment will collect approximately 550 events per AGS pulse per 3.6 seconds. Thus the statistical accuracy of the polarization measurement in a 2000 hr ($2 \times 10^6$ pulses) run will be:

$$\delta P_T \approx \frac{1.20^{+1.2}_{-0.7} \cdot 2^{+2}_{-1}}{0.35(2 \times 10^6 \cdot 550)^{\frac{1}{3}}} \approx 1.3 \times 10^{-4}$$

where $\sqrt{1.2}$, $\sqrt{2}$, 0.35, are dilution factors in the analyzing power due to backgrounds, the precession magnetic field, and the muon decay, respectively. The sensitivity to $Im\xi$ is given by

$$\delta Im\xi \approx \frac{\delta P_T}{0.2} \approx 7 \times 10^{-4}$$

where 0.2 is a kinematic factor that includes the acceptance in the Dalitz plot and the orientation of the decay in the center of mass.

This new experiment is optimized to study muon polarization in $K^+ \to \mu^+\pi^0\nu$ decays. Nevertheless, we have investigated the feasibility of measuring T-violation in $K^+ \to \mu^+\nu\gamma$. The event selection and analysis of $K^+ \to \mu^+\nu\gamma$ will be very similar to $K^+ \to \mu^+\pi^0\nu$ events except that events containing more than 1 photon will be vetoed to reject background from $K^+ \to \mu^+\pi^0\nu$, $K^+ \to \pi^+\pi^0$, and $K^+ \to \pi^+\pi^0\pi^0$ events. Further background rejection will be achieved by matching the measured muon range in the polarimeter with the muon energy from a constrained fit to the photon momentum, the muon direction, and the known kaon momentum. We expect to collect $\sim 100$ events per AGS pulse. However, the signal to background ratio with out current design will be about 0.3. Two improvements to the detector will reduce the backgrounds further: If the decay volume can be surrounded by photon veto counters with a veto threshold of 10 MeV to detect the low energy photons from
\( \pi^0 \) decays, the background level can be reduced to about 10\%. Secondly, if the calorimeter resolution can be improved (we have assumed \( \sigma(E)/E \sim 8%/\sqrt{E} \)) then the muon range match can be made narrower, thus separating the signal and background better. We are currently calculating the sensitivity that can be gained with these modest improvements for the transverse muon polarization in \( K^+ \rightarrow \mu^+ \nu \gamma \).

**Systematic Errors**

With such high statistical power, systematic issues will become the main concern. The cylindrical symmetry of the apparatus and the precession technique (see [15]) will cancel most systematic errors to first order. We have identified several sources of systematic error and are working on strategies to either eliminate or calibrate them with data. Angular misalignment of the polarimeter wedges will need to be controlled by aligning the opposite side wedges with respect to each other. There could be systematic shifts in detector time calibration which depend on the sign of the magnetic field that precesses the muons in the polarimeter. Stray magnetic fields could precess the muons before they come to rest or alter the magnitude of the precession field inside the polarimeter. We are currently working on techniques to precisely align the detector and effectively shield stray magnetic fields. Other sources of systematic errors are beam and calorimeter misalignments combined with non-uniform efficiencies as well as momentum dispersion within the beam. We have found that these sources contribute at second order and can easily be reduced further with proper analysis techniques.

The experiment will collect a large sample of data including \( K^+ \rightarrow \mu^+ \nu \), \( K^+ \rightarrow \pi^+ \pi^0 \), and \( K^+ \rightarrow \pi^0 \mu^+ \nu \) events in different parts of the decay phase space. The muon decay asymmetries from these various ensembles of events can be measured to understand the detector systematics to very high accuracy. We will use the T-conserving component of the muon polarization to calibrate the analyzing power throughout the detector.

**Conclusion**

We have examined the measurement of the out of plane muon polarization in \( K^+ \rightarrow \mu^+ \pi^0 \nu \) decays in detail. This measurement will not be sensitive to the Standard Model CP violation physics. Nevertheless, it can be performed with great sensitivity; approaching \( \delta P \sim 10^{-4} \) which is well beyond both the current direct limit of \( \sim 5.3 \times 10^{-3} \). Although the electric dipole moments of the neutron and electron are considered more favorably for T violation outside
the Standard Model they do not cover the entire spectrum of models. At the moment the measurement of $T$ violating polarization in $K^+ \rightarrow \mu^+\pi^0\nu$ decays is well justified and should be considered complementary to other efforts in understanding CP violation. We are also examining the sensitivity for transverse polarization measurement in $K^+ \rightarrow \mu^+\nu\gamma$ decays after some improvements to the present design of E923. There is presently no direct limit on such a measurement, and therefore a sensitive experiment to measure this polarization will be quite interesting and complementary to the $K^+ \rightarrow \mu^+\pi^0\nu$ measurement. The experiment E923 has been approved by the Brookhaven National Laboratory. We are currently developing the detectors and the techniques to achieve the required level of systematic control.

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REFERENCES