Experimental Studies of Rare K^+ Decays

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Experiment E865 at the BNL AGS is a search for the lepton number violating decay $K^+ \rightarrow \pi^+ \mu^+ e^-$ with an expected sensitivity of 3×10^{-12} . The experimental apparatus involves a magnetic spectrometer with two Čerenkov counters, a calorimeter and a muon detector for particle identification. In addition, other rare K^+ decays are studied. The experiment has been collecting data since 1995, and preliminary results are presented.

1 Introduction

In spite of its successes, the Standard Model of particle physics is still regarded as an incomplete theory. Many attempts have been made to extend the Standard Model to a higher level of symmetry. Some of these extensions, such as supersymmetry and technicolor, permit lepton number violating decays. E865 at the Alternating Gradient Synchrotron (AGS) in Brookhaven National Laboratory is a continuing effort in search of the lepton number violating decay, $K^+ \rightarrow \pi^+ \mu^+ e^-$. An observation of such decays will have a great impact on our understanding of physics beyond the Standard Model, and the absence of such decays in a high sensitivity experiment provides a stringent constraint on theoretical models. Such experiments are unique in their sensitivity to new physics beyond the Standard Model, because they effectively probe physics at the mass scale of 100 TeV.

In addition, the measurements of rare decays and precision measurements of the no-so-rare decays provide a strong test of the Standard Model. The E865 detector can be used to study most of the K^+ decays that involve three charged particles. The rare decays $K^+ \rightarrow \pi^+ e^+ e^-$ and $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ are highly suppressed due to the absence of flavor changing neutral current. The precise measurement of the branching ratio as well as the form factor provides a direct test of the chiral perturbation theory. Similarly, the decay $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$ is also of interest.

$K^+ \rightarrow \mu^+ \nu e^+ e^-$ can be used to study the structure dependent part of the radiative decay. The charge asymmetry in $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ is a probe for direct CP violation. In $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$, we can study the $\pi\pi$ scattering, as well as search for possible T-violation. Through $K^+ \rightarrow \pi^+ \pi^0$ decay, rare decays of π^0 s, such as $\pi^0 \rightarrow e^+ e^-$ and $\pi^0 \rightarrow e^+ e^- e^+ e^-$ can also be studied.

The detector design was based primarily on its predecessor, AGS E777/E851, which reached the upper bound on the $K^+ \rightarrow \pi^+ \mu^+ e^-$ branching ratio of 2.4×10^{-10} , and measured the decays $K^+ \rightarrow \pi^+ e^+ e^-$ and $\pi^0 \rightarrow e^+ e^-$.^{1,2,3}

In this paper, we will describe the E865 detector, summarize the current status of the experiment, provide a future prospect of the experiment.

2 Detector

An unseparated 6 GeV beam with two stages of collimation is used for this experiment. With 10^{13} proton on target, it yields 7×10^7 K^+ 's in the beam, along with 20 times more pions and protons. The detector follows a decay volume 5 meters long immediately downstream of the last quadrupole. Figure 1 is the plan view of the detector, showing the π, μ, e tracks schematically.

The detector design is dictated by three basic requirements: particle identification to reject background, precision tracking to provide kinematic constraints, and the ability to operate in a high rate environment.

The 48D48 dipole magnet separates particles

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Figure 1: The plan view of the E865 detector

by charge (negative to beam left, positive to beam right) and reduces the low momentum charged particle background that come from the decay volume. The proportional chambers (P1-P4) along with the 120D36 dipole magnet form the momentum analyzing spectrometer system. Trigger hodoscope D requires that the charged particles come from the decay volume outside the beam region, and the trigger hodoscope A along with the shower counter identifies the charged shower cluster. The hodoscopes B and C in the muon stack are used to identify muons.

There are two gas filled Čerenkov counters (C1 and C2) at atmospheric pressure which are divided by thin membranes into left and right sides. Since the left side of the apparatus must detect electrons from the $\pi\mu e$ decay, and since a major source of potential background is misidentification of the π^- from $\pi^+\pi^+\pi^-$ decays, this side of the Čerenkov counters is filled with hydrogen. On the right side the major potential background is from $K^+ \rightarrow \pi^+\pi^0$; $\pi^0 \rightarrow e^+e^-\gamma$ events. Thus the Čerenkov counters on this side are filled with a lower threshold gas (CO_2 or methane) to veto efficiently positrons.

Downstream of P4 is an electromagnetic calorimeter consisting of 600 $11.4 \times 11.4 \text{ cm}^2$, 15 radiation lengths long Pb-scintillator sandwich modules, read out by wavelength shifting fibers

in a shashlik configuration. Downstream of the calorimeter is a stack of twelve planes of muon detector, each consisting of a wall of proportional tubes with x and y readout, separated by steel absorber plates.

With this apparatus we identify electrons as those particles giving light in the appropriate Čerenkov counters and having pulse height in the calorimeter consistent with the momentum measured in the spectrometer. Muons are seen as particles giving no light in the Čerenkov counters, minimum ionizing pulse height in the calorimeter, and a range in the muon stack consistent with their momentum. Pions have no light in the Čerenkov counters, and a range shorter than that expected for minimum ionizing particles.

In the normal data acquisition mode, we trigger on three charged particle final states with either μ^+e^- signature or e^+e^- signature with a high e^+e^- invariant mass. For normalization purposes, we also take prescaled $K^+ \rightarrow \pi^+\pi^+\pi^-$ events and $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow e^+e^-\gamma$ events.

3 Current Status

The experiment was approved in 1990. The beam was commissioned in 1993, and an engineering run occurred in 1994. We collected physics data in the second half of the run in 1995 (11 weeks), as well

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Figure 2: Mass distribution of the reconstructed $K^+ \rightarrow \pi^+ e^+ e^-$ events

as in the 1996 run (16 weeks).

The 1995 data were processed through a first pass that required a 3 track vertex and a second pass with mild particle identification requirements.

A sample of $K^+ \rightarrow \pi^+ e^+ e^-$ events have been selected from the 1995 data. Figure 2 shows the distribution of the reconstructed $\pi^+ e^+ e^-$ mass, when the $e^+ e^-$ mass is required to be over 150 MeV.

The same data sample is used to search for $\pi^0 \rightarrow e^+ e^-$ decay, when the lower $e^+ e^-$ mass region is examined and the $\pi^+ e^+ e^-$ mass is required to be at the kaon mass. We expect to improve the branching ratio measurement of this decay.

Since the trigger does not discriminate against events with more than 3 charged tracks, we have also collected a large sample of events with 5 tracks. Among them, the most common decay channel is $K^+ \rightarrow \pi^+ \pi^0$ followed by $\pi^0 \rightarrow e^+ e^- e^+ e^-$. The five tracks reconstruct to the kaon mass and the full beam momentum. Figure 3b is the $e^+ e^- e^+ e^-$ mass distribution of the 1300 events selected from the 1995 data.

Another interesting decay mode that involves $e^+ e^-$ pair is the radiative $K_{\mu 2}$ decays with an internal photon conversion. Our preliminary analysis has shown that we can reconstruct such decays

Figure 3: Mass distribution of the reconstructed $\pi^0 \rightarrow e^+ e^- e^+ e^-$ events, in $K^+ \rightarrow \pi^+ \pi^0$ decays.

with relatively low background, by assuming the nominal kaon momentum.

With the good energy resolution and fine segmentation of the calorimeter, decays with photons in the final state can also be fully reconstructed. Study of the decays $K^+ \rightarrow \pi^+ \pi^0 \pi^0$, followed by $\pi^0 \rightarrow \gamma \gamma$ for one of the neutral pion and $\pi^0 \rightarrow e^+ e^- \gamma$ for the other, shows a good photon detection efficiency. The search for $K^+ \rightarrow \pi^+ \pi^0 e^+ e^-$, followed by $\pi^0 \rightarrow \gamma \gamma$, is still in progress.

The 1996 run has seen significant improvements in parts of the apparatus. The primary trigger rate was reduced after the D counter was installed. The proportional chambers are now operating more efficiently. The Čerenkov counter accidental trigger rate was reduced by a factor of two. And software reconstruction efficiency was improved. Currently we are taking data at beam intensity of 7×10^{12} protons on target per pulse.

4 Prospects

Before the 1997 run, we expect to have two upgrades. A new DAQ system will increase the throughput by a factor of 2, which should allow us to take 30% more beam, reaching the design goal of the experiment. A novel scintillating pixel detector is being constructed, and will go directly

into our beam line. This will measure the beam position with an array of $7 \times 7 \text{ mm}^2$ pixels at the entrance to the decay volume, and enable us to determine better the kinematics of the decays that involves neutrinos. We expect to pursue measurements of $\mu^+ \nu e^+ e^-$, $e^+ \nu e^+ e^-$ and $\pi^+ \pi^- e^+ \nu$ in the next run.

With 16 weeks of AGS running in 1997, we expect to do at least a factor of two better for all the decay modes we are studying. In addition, a few more triggers may be implemented.

At the end of the 1996 run, we installed a trigger that enhances the e^+ identification. This allowed us to trigger on $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$, although at a somewhat reduced intensity. Preliminary study shows that 1000 events/hours can be obtained, and we expect to take at least 300,000 events in the next run. This will provide a much improved measurement of the $\pi\pi$ phase shift and K_{e4} form factors, and a search for possible T-violation.

Another trigger was also tested at the end of the 1996 run, in which we required two muons in the final state to search for $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, a decay with expected branching ratio of 5×10^{-8} . At high intensity, the trigger is overwhelmed by the accidental coincidence of beam halo muons, while at low intensity, $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays followed by $\pi \rightarrow \mu \nu$ decays determine the lower bound. With 15 hours of dedicated data taking at about a quarter of the nominal beam intensity, a sample of $\pi\mu\mu$ data were collected. A preliminary analysis shows that there is a clear signal of 19 events in the signal region, most of which can be attributed to the decay $K^+ \rightarrow \pi^+ \mu^+ \mu^-$, as shown in Figure 4. We will continue to investigate the improvement to this trigger, and will take more data in this mode.

It has been suggested⁴ that a new measurement of the K_{e3} branching ratio be made since the knowledge of V_{us} depends on it. E865 has the capability of determining the ratio of $K_{e3}/K_{\pi 2}$ to a significantly better precision than the existing result. We anticipate to study this decay with the beam pixel detector in the next run.

Beyond 1997, we are investigating the possibility of searching for CP violation in the $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ decays, where the difference in the decay kinematics of the odd pion for K^+ and K^- decays is a direct violation of CP invariance. Although obtaining sufficient statistics is within the

Figure 4: Mass distribution of the reconstructed $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ events. Below the kaon mass, there are background events from $K^+ \rightarrow \pi^+ \pi^+ \pi^-$ decays, followed by $\pi \rightarrow \mu \nu$ decays

capability of the apparatus, it remains to be determined to what level the systematic errors may limit the search.

5 Summary

E865 is successfully taking copious K^+ decay data. We will not only improve the search for $K^+ \rightarrow \pi^+ \mu^+ e^-$ by about a factor of 50, but also study a variety of other K^+ decays. Such measurements contribute to the constraints on extension of the Standard Model, test of the chiral perturbation theory, and search for CP violation outside the neutral kaon system.

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