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Physics Prospects of the KTeV Experiment at Fermilab

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KTeV is a new Fermilab fixed target experiment which will search for direct CP violation in the neutral kaon system. In addition, we will make precision measurements of other CP and CPT violating parameters and make high sensitivity studies of rare kaon decays. The detector has been commissioned and is currently taking data. The physics goals and detector performance are presented.

1 CP Violation

Within the framework of the Standard Model, the CP violating decay $K_L^0 \rightarrow 2\pi$ arises primarily from an asymmetry in the rate of $K^0 - \overline{K^0}$ transitions. This effect, known as "indirect" CP violation, can be described by the standard $K^0 - \overline{K^0}$ $\Delta S = 2$ W-box diagrams and is parametrized by ϵ. If we define $K_L^0 \approx K_2 + \epsilon K_1$, where the $K_2(K_1)$ is a CP-odd(CP-even) eigenstate, then indirect CP violation in the decay $K_L \rightarrow 2\pi$ occurs because it includes a small admixture of CP-even K_1. By contrast, "direct" CP violation occurs when the K_2 component of the K_L^0 decays via a $\Delta S = 1$ transition. The strength of this transition, which can be described by strong and electromagnetic penguin diagrams, is governed by the parameter ϵ'. The measured quantity, ϵ'/ϵ, can be expressed through the double ratio

$$\begin{aligned} R &= \frac{\Gamma(K_L^0 \rightarrow \pi^+\pi^-)/\Gamma(K_s^0 \rightarrow \pi^+\pi^-)}{\Gamma(K_L^0 \rightarrow \pi^0\pi^0)/\Gamma(K_s^0 \rightarrow \pi^0\pi^0)} \\ &= \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \\ &\approx 1 + 6Re(\epsilon'/\epsilon), \end{aligned} \tag{1}$$

where $\eta_{+-} \approx \epsilon + \epsilon'$ and $\eta_{00} = \epsilon - 2\epsilon'$. Calculations of the Re$(\epsilon'/\epsilon)$ depend on the interference between the various penguin diagrams and are sensitive to the top mass. Predictions[1] give a value of between $(-1 - 15) \times 10^{-4}$. Other models, such as Superweak[2], account for CP violation only through direct $\Delta S = 2$ couplings, with the direct CP violating parameter $\epsilon' = 0$.

The NA31 experiment at CERN, has measured[3] a value of ϵ'/ϵ of $(23 \pm 3.5 \pm 6) \times 10^{-4}$, while the Fermilab experiment E731 measured[4] $(7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$. These numbers differ by $\sim 1.8\sigma$ and suggest different conclusions as to whether there is a direct CP violating effect. It is experimentally compelling to measure ϵ'/ϵ more precisely to learn whether there is a contribution from direct CP violation. There are three new experiments being developed to precisely measure ϵ'/ϵ: the KLOE detector at DAΦNE (1998), the NA48 experiment at CERN (April 1997), and the KTeV experiment at Fermilab, which came online in August of this year.

2 Physics Goals

The Kaons at the TeVatron program[a] is a new fixed target experiment at Fermilab designed to study the properties of the neutral kaon system. The experimental program has two distinct phases. The first phase will focus on making a high precision measurement of ϵ'/ϵ with a combined statistical and systematic error of 1×10^{-4}. This measurement will be discussed in greater detail in Section 4. In addition to determining ϵ'/ϵ, KTeV will will precisely measure $\phi_{+-} - \phi_{00}$, ϕ_{+-}, τ_s, Δm, $\eta_{+-\gamma}$, and $\phi_{+-\gamma}$, as well as other decays.

In the second phase, the experiment will collect a large sample of rare K_L^0 decays. Rare decays provide windows into a variety of physics topics such as lepton number violation, long and short distance physics, and parity violation. The rare decay modes which have the most potential to provide information about CP violation are $K_L^0 \rightarrow \pi^0 \ell^+ \ell^-$, where $\ell = e, \mu, \nu$. These decays are predicted to have large direct CP violating contributions to their amplitudes. Unfortunately, the branching fractions for these decay modes are extremely small, of $O(10^{-11} - 10^{-12})$,

[a] KTeV is a collaboration of Arizona, Chicago, Colorado, Elmhurst, Fermilab, Osaka, Rice, Rutgers, UCLA, UCSD, Virginia and Wisconsin.

and, in addition, detecting the neutrino mode is experimentally difficult. The $K_L^0 \to \pi^0 \ell^+ \ell^-$ limits set[5] by the previous FNAL experiment, E799I, dominate the world average. E799I measured limits for $\pi^0 e^+ e^-$ and $\pi^0 \mu^+ \mu^-$ of 4.3×10^{-9} and 5.1×10^{-9}, respectively. The limit set for $\pi^0 \nu\overline{\nu}$ was 5.8×10^{-5}. At KTeV, we expect to reach the single event sensitivity of 10^{-11} for the electron and muon modes, and 10^{-8} for the neutrino mode. If the branching ratios are at the predicted level, KTeV will only set limits on these decays. Thus for the next generation of experiment, the 2π decays of neutral kaons provides the best system with which to measure direct CP violation.

3 The Detector and its Performance

KTeV will employ the same technique to measure ϵ'/ϵ as was developed during the latter part of data taking by its experimental predecessor E731. [10] The technique involves simultaneous collection of all four decay modes in the double ratio. This is achieved by generating two nearly identical, parallel beams of K_L^0 and K_S^0 and configuring the experiment to simultaneously record charged and neutral 2π decays from the K_L^0 and K_S^0 beams. By simultaneously collecting data for the four decay modes, systematic effects such as changes in beam conditions, detector inefficiencies, and backgrounds from other decay modes cancel to first order in the double ratio.

Although the method to measure ϵ'/ϵ is the same, the beam and the detector used to collect the data are entirely new.[6] The primary considerations are that the detector have excellent electromagnetic calorimetry, precision tracking, a large aperture, uniform field analysis magnet, hermetic photon veto coverage, and a data aquisition system which could handle a high trigger rate environment.

The KTeV beam has been designed to provide intense beams of K_L^0 with reduced backgrounds from neutral and muon beam halo. Protons with an intensity of 3.5×10^{12} protons per pulse are incident with a 4.5mrad angle on a beryllium-oxide target. The beam is collimated and sent through a series of muon sweeping magnets, ultimately producing two parallel neutral beams. Initial running indicates the neutron to kaon ratio is approximately 1:1. The kaons decay in a vacuum vessel which ends at a Kevlar window 160m downstream from the target. Contained within the vessel are the regenerator and 6 photon veto counters.

In the ϵ'/ϵ phase of running, a regenerator, which is located 125m downstream of the target, is placed in one of the K_L^0 beams in order to coherently regenerate the K_S^0 component of the beam. The regenerator is comprised of 85 modules of scintillator which are each instrumented with two photomultiplier tubes. The total amount of material is $1.8\lambda_I$, resulting in ~3% coherent regeneration for a 65 GeV kaon beam. The regenerator position is alternated once a minute to reduce systematic effects from the beams and detector. The regenerator is moved out of the beams for rare decay running.

The photon veto system consists of 10 counters: 6 located in the vacuum vessel, 3 in the charged spectrometer system, and 1 just upstream of the CsI calorimeter. By making the system more hermetic and lowering the photon veto threshold (100 MeV), the $3\pi^0$ background will be lower than in E731.

Charged particle momenta are analyzed with a large aperture analysis magnet and four drift chambers, two located upstream and two downstream of the magnet. The KTeV drift chamber frames are the same as were used in E731, but the field wires have been restrung with aluminum wires, thereby reducing the amount of scattering material. The chambers also have lower gas gains and have been instrumented with new, low noise preamplifiers. Initial calibration constants for KTeV have yielded single hit resolutions of better than 100μm. The analysis magnet is new and has a larger aperture and more uniform field than E731. The p_t kick of the magnet has been increased to 400 MeV/c for ϵ'/ϵ running. Helium bags are located between the drift chambers to reduce multiple scattering. The momentum resolution is expected to be 0.35% for an average pion track momentum of 35 GeV/c, a factor of two better than the previous experiment.

The energy resolution for the calorimeter is required to be 1% for 15 GeV photons. Pure CsI was chosen because of its light output, speed, and radiation hardness. The calorimeter is located 186m downstream from the target and comprises 3100 crystals of 50cm length ($27X_0$). The blocks closer to the beams have a transverse cross section of $(2.5cm)^2$ while the outer blocks are $(5.0cm)^2$. The non-uniformity of scintillation light along the

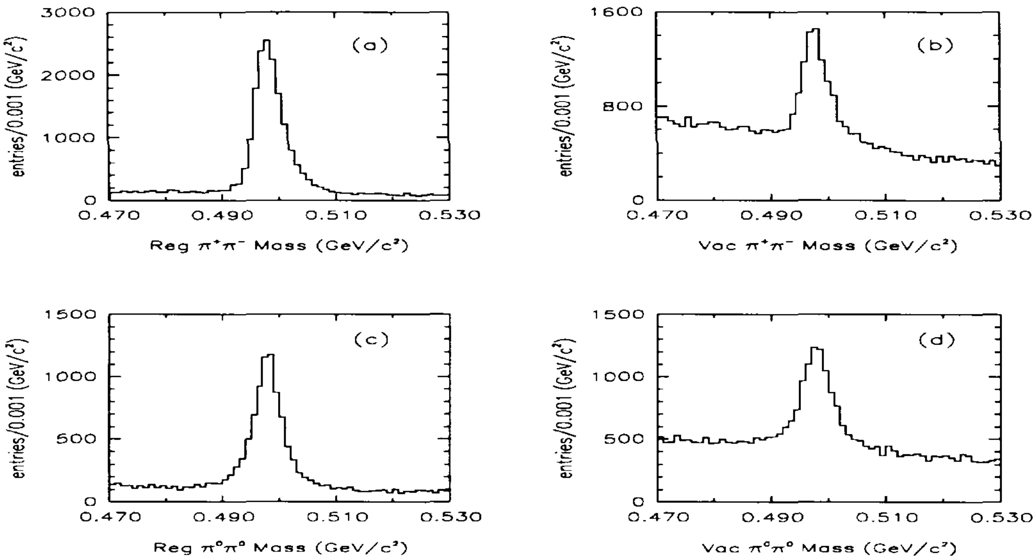

Figure 1: Online plot of reconstructed kaon mass for (a)regenerator beam $\pi^+\pi^-$ events, (b)vacuum beam $\pi^+\pi^-$ events, (c)regenerator beam $\pi^0\pi^0$ events, (d)vacuum beam $\pi^0\pi^0$ events.

length of the crystal is less than 5%, thereby improving the energy resolution by minimizing errors from shower fluctuations. Because of the difficulty of growing 50cm long crystals with our performance specifications, most of the crystals are actually two 25cm long crystals which are glued together. The uniformity specification is achieved by tuning the wrapping along the length of each crystal with various grades of reflective mylar. The light is measured with 5 and 6 stage Hamamatsu photomultiplier tubes. The signal from the tube is digitized using an innovative readout system. The primary features of this "digital photomultiplier base" are its low noise performance, deadtimeless operation, and 16-bit dynamic range.[11] A detailed discussion of the calorimeter and its performance can be found in these proceedings.[12] A plot of the kaon mass for $K^0_{L,S}$ decays into 2π which was generated online can be seen in Figure 1. The resolution was 2.1 MeV for charged mode was 2.9 MeV for neutral mode.

Electron/pion identification is made with the CsI and 8 transition radiation detectors (TRD), which are located upstream of the CsI. Beam test results[7] yielded an e/π rejection rate for the CsI of better than 700:1 for 95% electron efficiency. The TRDs add an additional factor of $\sim$100 to the rejection rate.[8] Muon identification is made with filter steel and 3 banks of muon scintillator counters. In order to reduce the amount of scattering material in the beam, the TRDs will be moved out of the detector during ϵ'/ϵ running. In this running mode, the 2π triggers are configured to veto events with activity in the muon counters.

In order to handle the higher beam intensities, KTeV has designed a new trigger and data aquisition system.[9] The lower level trigger configurations, level 1 and level 2, are similar to the previous experiment, although the trigger processing time has been reduced. The level 1 trigger is designed to handle rates up to $\sim$ 300 kHz. The level 2 processing takes 1.5 μs and has an expected output rate of $\sim$10 kHz. Readout commences upon a level 2 accept and takes a maximum of 10 μs. The third trigger level involves software processing of events. Events are fully reconstructed and loose analysis cuts are applied to reduce backgrounds before writing events to tape. Level 3 rejection is expected to be $\sim$90%. The level 3 is designed to handle 20 kHz of 8 kB events (the average KTeV event size) without any adding additional dead time. The data aquisition live time has increased from 42% in the previous experiment to 70%. The data aquisition system has enough VME memory to buffer data from an entire spill (4.6 GB). Detailed detector monitoring is also done online.

4 The ϵ'/ϵ Measurement

The previous generation of experiments measured ϵ'/ϵ with a precision of $(6-7)\times 10^{-4}$. In the case of the E731 experiment, the statistical error dominated the measurement error. To reduce the statistical error, KTeV will increase the intensity of the beam by a factor of 5, improve the data aquisition live time by a factor of 2, and increasing the running time for the experiment. The KTeV goal is to collect 10^7 CP violating $2\pi^0$ decays, thereby reducing the statistical error by a factor of 5.

At this level, reduction of systematic errors will also be crucial. The dominant systematic error from the E731 measurement came from the neutral energy scale. By choosing pure, radiation hard CsI for the electromagnetic calorimeter, we are assured of similar electron and photon showering with little change in response over the entire running period. This is critical, since we perform the energy calibration for the calorimeter using $K_L^0 \rightarrow e^{\pm}\pi^{\pm}, \overline{\nu}$ decays, but the physics mode of interest is $2\pi^0$. The neutral energy scale is directly related to the decay vertex Z position. An error in the scale effects the ϵ'/ϵ measurement because it influences the number of decays which are accepted within a chosen Z region. The second largest systematic error to the previous measurement came from cross-over decays from the regenerator beam which are misidentified as coming from the K_L^0 beam. Better collimation and a fully active regenerator reduce the probability of these type of events. The regenerator is instrumented to be fully active, allowing rejection of backgrounds produced from incoherent regeneration and inelastic scattering in the regenerator. In addition, the regenerator alternates between beams, thereby reducing many systematic effects from the detector. Backgrounds are addressed by reducing beam halo and multiple scattering within the detector, improving the $e-\pi$ particle identification, and increasing the photon veto coverage. "Accidental" activity, *i.e.* activity within the detector which is not correlated with the physics event of interest, contributes background to the sample and is reduced with improvements in beam conditions and improved timing resolution within the detector. Because the K_L^0 and K_S^0 vertex distributions are extremely different, a potential source of systematic error comes from the uncertainty of the acceptance. The detector acceptance is controlled by carefully monitoring the detector alignments and defining apertures. In addition, large samples of $K_L^0 \rightarrow e^{\pm}\pi^{\pm}, \overline{\nu}$ and $3\pi^0$ events will be collected to map the detector geometry and to tune the detector geometries in Monte Carlo, which ultimately is used in determining the acceptance.

5 Conclusions

KTeV has started taking hadron beam. Initial indications are that the detector will meet or exceed its design specifications. The detector is currently configured for ϵ'/ϵ data taking. The KTeV run plan is to switch between running the ϵ'/ϵ and rare decay programs. We anticipate that in the near future KTeV will be able to achieve the goals of its physics program, reducing the error on ϵ'/ϵ by almost an order of magnitude and significantly improving on measurements of many rare decays.

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