RARE KAON DECAY FROM E949 AT BNL: $K^+ \to \pi^+ \nu \bar{\nu}$

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In the first year of physics run, the E949 experiment at Brookhaven National Laboratory has already collected $1.8 \times 10^{12}$ kaons stopping in the target. Additional evidence for the rare charged kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ has been observed. Combined with previous results from the E787 experiment, the branching ratio is measured to be $\text{Br}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$.

1 Introduction

The understanding of flavor dynamics is of fundamental importance in elementary particle physics. The study of $K$ and $B$ decays plays a crucial role in this respect. In particular, the precise measurement of the rare kaon decays $K^+ \to \pi^+ \nu \bar{\nu}$ and $K^0_L \to \pi^0 \nu \bar{\nu}$ is regarded as a theoretical ideal for the understanding of CP violation in the Standard Model (SM). These modes provide a clean environment for extraction of the CP violation related elements in the Cabibbo-Kobayashi-Maskawa quark mixing matrix. The unitarity triangle can be completely determined by the measurement of these two modes, giving a chance to confirm the golden relation $(\sin 2\beta)_{\pi \nu \bar{\nu}} = (\sin 2\beta)_{J/\psi K_s}$, a key ingredient for the existence of universal unitarity triangle in the SM and its extensions with minimal flavor violation. Experimentally, only the charged mode studies have achieved sensitivity comparable to the SM prediction $(0.67^{+0.23}_{-0.27}) \times 10^{-10}$.

In this talk, the first result from E949 experiment at the Alternating Gradient Synchrotron (AGS) of Brookhaven National Laboratory (BNL) is presented using a data set with $1.8 \times 10^{12}$ stopping charged kaons.

2 Backgrounds in E949

Like its predecessor E787, the E949 detector is designed to clearly identify $K^+ \to \pi^+ \nu \bar{\nu}$, with a charged kaon decaying to a charged pion in the momentum region $221 < P < 229$ MeV/c with no other associated observable products. Potential backgrounds come from $K^+ \to \mu^+ \nu_\mu (\gamma)$ (due to $\mu^+$ misidentified as $\pi^+$ and mis-measured kinematics or missed photon), $K^+ \to \pi^+ \pi^0$ (due to missed photon and mis-measured kinematics), beam backgrounds (due to incoming $\pi^+$ mis-identified as $K^+$ or $\pi^+$ faking $K^+$ decay at rest or $K^+$ decay in flight or two incoming beam particles), or charge exchange background (due to $K^+ n \to K^0 p$, $K^0_L \to \pi^+ l^- \nu_l$ with $l^-$ undetected). Because of the huge background (see Table 1), the experiment is rather challenging, requiring both powerful and redundant background rejection tools. Most of the details on how the E949 detector suppresses the background processes are the same as E787. Table 1 lists the basic tools for rejecting the backgrounds that can look like $K^+ \to \pi^+ \nu \bar{\nu}$.

3 Detector upgrades

E949 contains several various upgrades to the E787 detector. Here only the most important changes are described. For the beam counters, the B4 hodoscope in front of the target fibers were redesigned to improve the position measurement of the incoming beam, leading to a factor of $\sqrt{2}$ improvement. To gain more rejection of photons, E949 increased the thickness and solid angle of the active mate-
Table 1. Comparison of signal and background yields normalized to single signal event production and the selection criteria (cuts) for suppressing the backgrounds. The kinematic cuts are defined as those using the momentum, energy and range in scintillator. PID is defined as either pion identification with TD (see text) or kaon identification using the B4 dE/dx. PV is for the photon veto and the timing cuts are for the delayed coincidence cuts.

| Cut                  | Events       | Kinematic cuts | PID | PV | Timing cuts |
|----------------------|--------------|----------------|-----|----|-------------|
| $K^+ \rightarrow \mu^+ \nu_\mu$ | 63430000000 | Yes            | Yes | –  | –           |
| $K^+ \rightarrow \pi^+ \pi^0$          | 21130000000 | Yes            | –   | Yes| –           |
| $K^+ \rightarrow \mu^+ \nu_\mu \gamma$ | 550000000   | Yes            | Yes | Yes| –           |
| Beam background          | 25000000    | –              | Yes | –  | Yes         |
| $K^+ n \rightarrow K^0 p, K^0 \rightarrow \pi^+ l^- \nu$ | 46000       | –              | –   | Yes| Yes         |
| $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ | 1           | Yes            | Yes | Yes| Yes         |

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Although each cut setting should be based on sufficient statistics, bias can still occur and may cause a problem in background estimate. In order to have unbiased cuts, the full data set was randomly divided into 1/3 and 2/3 parts. Cut tuning was conducted only on the 1/3 sample, in which three specific sub-data groups were also selected to simplify the analysis. By applying both loose beam background cuts and photon veto, we skimmed out a sample dominated by $K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$ background for tuning the pion particle ID which involves positive identification of the $\pi \rightarrow \mu \rightarrow e$ decay chain in the range stack using the transient digitizers (TD) and the kinematic cuts. The sample with $K^+ \rightarrow \pi^+ \pi^0$ dominant background was selected by using both loose beam background cuts and loose TD cuts. Finally, applying both loose TD cuts and photon veto, we obtained a sample dominated by the beam background.

As detailed elsewhere $^3, 5$, two uncorrelated cuts giving large background rejection were selected to perform a so-called bifurcated analysis on a single background. By sequentially inverting one of the cuts and counting the events observed, we estimated the background inside the signal region when both cuts were applied. Table 1 gives the two uncorrelated cuts for each background.

To check if the cut pairs are uncorrelated, the regions near, but outside, the signal re-
region (outside the box) was examined by loosening both cuts and checking if the observed number of events was consistent with the estimated background level. As shown in Figure 1, the observation agrees with the prediction as the cuts are loosened. Using a one-parameter fit to the ratio of $N_{\text{obs}}/N_{\text{pred}}$, we obtained $0.83^{+0.12}_{-0.11}$, $1.15^{+0.25}_{-0.21}$ and $1.06^{+0.29}_{-0.35}$ for $K^+ \rightarrow \pi^+\pi^0$, $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \mu^+\nu_\mu \gamma$, respectively. These results are consistent with the expected 1.0. The errors on the constant terms are assigned as systematic uncertainties and are used in the final determination of the branching ratio.

The final background estimates are given in Table 2. The background estimates for E787 are given for comparison. Since we had much confidence on the cuts used in control of the $K^+ \rightarrow \pi^+\pi^0$ background, we loosened the cuts in order to look into a larger signal region. Consequently, the $K^+ \rightarrow \pi^+\pi^0$ background level increases in E949.

5 Branching ratio measurement

In E949, the final acceptance for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ was estimated to be $0.0022 \pm 0.0002$, slightly higher than $0.0020 \pm 0.0002$ of E787. The final acceptance was checked with a measurement of the $K^+ \rightarrow \pi^+\pi^0$ branching ratio, which was measured to be $0.219 \pm 0.005$, in agreement with the PDG value of $0.211 \pm 0.001$ within two standard deviations. The stability of this branching ratio measurement throughout the run is shown in Figure 2.

The signal box was opened after the background study and acceptance estimate were completed. One candidate was observed inside the box. Figure 3 shows the range versus kinetic energy for the events surviving all the selection criteria. The events outside this box are from the $K^+ \rightarrow \pi^+\pi^0$ background due to photons escaping detection.

Because the background level in Table 2 was for the total number inside the signal box, knowing the fact that the background

| Item       | E949         | E787         |
|------------|--------------|--------------|
| $N_K$      | $1.8 \times 10^{12}$ | $5.9 \times 10^{12}$ |
| $\pi^+\pi^0$ | $0.216 \pm 0.023$ | $0.034 \pm 0.007$ |
| $\mu^+\nu_\mu(\gamma)$ | $0.068 \pm 0.011$ | $0.062 \pm 0.045$ |
| Beam bkg   | $0.009 \pm 0.003$ | $0.025 \pm 0.016$ |
| CEX        | $0.005 \pm 0.001$ | $0.025 \pm 0.008$ |
| Total bkg  | $0.298 \pm 0.026$ | $0.146 \pm 0.049$ |

Table 2. Total stopping kaons and background estimates in E949 and E787. The charge exchange background estimate is from Monte Carlo. The kaon regeneration rate and beam profile are from measurement for the process of $K^+n \rightarrow K_S^0p$. The $\pi^+\pi^0$ background, we loosened the cuts in order to look into a larger signal region. Consequently, the $K^+ \rightarrow \pi^+\pi^0$ background level increases in E949.

Figure 1. The outside-the-box study backgrounds $K^+ \rightarrow \pi^+\pi^0$ and $K^+ \rightarrow \mu^+\nu_\mu(\gamma)$. The open circles are for the predicted backgrounds and the open triangles are for the observed backgrounds.

We also considered the possibility that other backgrounds could sneak into the signal region through possible unknown loopholes in our procedures. Limitations on such effects came from the outside-box study which used data very close to the signal box. We carefully examined the background events which failed only a single cut.
distribution inside the box is not uniform, we used the background distributions to evaluate the background probability for a candidate event and to improve the estimate of the branching ratio. It was found that the E949 candidate event was closer to the muon background region than the previous E787 events, reducing its contribution to the final branching ratio measured to be $\text{Br}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$.

6 Conclusion

The first physics run of E949 has been successfully carried out with a factor of two higher beam intensity than E787. One new candidate event of $K^+ \to \pi^+ \nu \bar{\nu}$ was observed. The central value of the branching ratio is approximately twice the SM prediction, and the 1σ confidence interval includes the SM and up to 4.0 times the SM. Completion of the remaining 80% of running time already approved by the U.S. Department of Energy’s Office of High Energy Physics should indicate whether new physics is increasing this branching ratio.

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