Introduction to KAON2019 – Experiments –

T Yamanaka
Department of Physics, Osaka University, 1-1 Machikaneyama, Toyonaka, Osaka 560-0043, JAPAN
E-mail: taku@champ.hep.sci.osaka-u.ac.jp

Abstract. The KAON2019 is the 11th conference in the series which started in 1988. Many kaon experiments have evolved during these years. In this talk, challenges and developments of the experiments for $Re(\epsilon'/\epsilon)$ and rare $K \to \pi\pi\pi$ decays are reviewed.

1. Introduction
The KAON Conference series started from the Rare Decay Symposium held in 1988 in Vancouver, Canada. The symposium covered a wide range of topics: rare kaon decays, pion and muon decays, B decays, and CP violation. Since then, there has been KEK Workshop on Rare Kaon Decays (1991, KEK), Workshop on Kaon Decay Physics (1996, Orsay), KAON99 (University of Chicago), KAON 2001 (Pisa), KAON 2005 (Northwestern University), KAON 2007 (Frascati), KAON 2009 (Tsukuba), KAON 2013 (University of Michigan, Ann Arbor), and KAON 2016 (University of Birmingham). In this talk, I will give a brief overview on how some kaon experiments have evolved in the past 31 years.

2. Direct CP violation
One of the main topics in the early KAON Conferences was to test whether there is a direct CP violation. The CP-violating $K_L \to \pi\pi$ decay is caused by a small admixture of a CP-even component in the $K_L$ amplitude, $K_{even}$, decaying to the CP-even $\pi\pi$ state. Such an admixture, $K_L \simeq K_{odd} + \epsilon K_{even}$, is caused by a complex phase in the $K^0 - \bar{K}^0$ mixing amplitude. In the Standard Model, the phase is introduced naturally by a box diagram involving three generations of quarks [1]. On the other hand, the Superweak model [2] proposed in 1964 explains that the phase is introduced by a very weak unknown interaction that changes the strangeness by 2. Even after twenty years, it was not clear which model was correct. One method to answer this question was to see whether CP is violated in the decay itself as $K_{odd} \to \pi\pi$, whose amplitude is parametrized by $\epsilon'$. The Standard Model can introduce a complex phase in the decay through a penguin diagram. The model predicted the $Re(\epsilon'/\epsilon)$ to be $O(10^{-3})$. On the other hand, the Superweak model cannot introduce such a phase in the $\Delta S = 1$ interaction, meaning the $Re(\epsilon'/\epsilon)$ should be 0. Thus the question was whether the ratio $\epsilon'/\epsilon$ is 0 or not.

The $Re(\epsilon'/\epsilon)$ was measured through the double ratio of branching ratios:

$$R = \frac{BR(K_L \to \pi^+\pi^-)/BR(K_S \to \pi^+\pi^-)}{BR(K_L \to \pi^0\pi^0)/BR(K_S \to \pi^0\pi^0)}$$

$$= 1 + 6Re(\epsilon'/\epsilon).$$

\[1\] \[2\]
To reduce the error on the $Re(e'/e)$ to $O(10^{-4})$, more than a million events were necessary for each decay mode, and systematic errors had to be controlled to a level less than 0.1%.

The major issue was the acceptance difference between the $K_L$ and $K_S$ decays. This was due to a difference in their decay vertex distributions, which resulted from the large difference between the $K_L$ and $K_S$ lifetimes. The CERN NA31 experiment had separate targets for the $K_L$ and $K_S$ runs, and the $K_S$ production target was moved along the beam line to mimic the $K_L$ decay distribution. NA31 collected the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay modes simultaneously, and did not have a magnetic spectrometer to make their acceptances similar. The FNAL E731 experiment, on the other hand, had a pair of $K_L$ and $K_S$ beams. $K_S$’s were regenerated by placing carbon blocks in one of the two $K_L$ beams. By having the $K_L$ and $K_S$ beams, E731 collected the four decay modes simultaneously. The acceptances were calculated with Monte Carlo simulations, and they were checked with high statistics $K_L \rightarrow \pi^0\pi^0$ events. Initially, the statistics of $K_L \rightarrow \pi^0\pi^0$ events were limited in the E731 experiment because one of the photons was required to be converted to an $e^+e^-$ pair in a thin lead sheet to trigger the events. To collect the $\pi^0\pi^0$ events without converting photons, E731 introduced new trigger logic to count the number of clusters in the electromagnetic calorimeter, as well as a fast data acquisition system based on FASTBUS to increase the bandwidth. The final results of the two experiments did not agree: $Re(e'/e) = (23 \pm 6.5) \times 10^{-4}$ (3 $\sigma$ away from 0) from NA31 [3], and $Re(e'/e) = (7.4 \pm 5.2 \pm 2.9) \times 10^{-4}$ (consistent with 0) from E731 [4].

To improve the accuracy on the $Re(e'/e)$ by another order of magnitude to resolve the difference, both groups built new experiments, CERN NA48 and Fermilab KTeV E832, with new beam lines and new detectors. The two experiments became similar; they both used magnetic spectrometers to measure the momentum of charged tracks, and collected the four decay modes simultaneously. KTeV E832 used a regenerator as before, but NA48 had a fixed $K_S$ target producing a $K_S$ beam pointing to the same position in the detector as the $K_L$ beam. The first results from the new beam experiments were $(18.5 \pm 4.5 \pm 5.8) \times 10^{-4}$ by NA48 [5], and $(28.0 \pm 3.0 \pm 2.8) \times 10^{-4}$ by E832 [6], clearly away from 0. These results killed the Superweak model as a sole source of CP violation, and supported the Standard Model. One should note that this was done before a CP violation was observed in the B system.

One problem with the $e'/e$ measurements was that although they rejected the Superweak model, they could not set constraints on the $\rho$ and $\eta$ CKM matrix parameters due to a large cancelation between electroweak and gluon penguin diagrams. Precise Lattice QCD calculations have long been waited for, and recent developments are reported in this conference.

### 3. Rare kaon decays

Until the 1980’s, the Brookhaven National Laboratory (BNL) had been the center of rare kaon decay experiments because it delivered high intensity 24-30 GeV protons. The $K_L \rightarrow \mu\nu, \mu\mu, e\mu$ decays had been studied by the BNL E780, E791, and E871 experiments, and the $K^+ \rightarrow \pi\mu\nu, \pi e e, \pi\mu\mu$ decays had been studied by the BNL E865 experiment. However, one event triggered a phase transition. In 1988, the BNL E780 group reported one $K_L \rightarrow \pi^0 e^+ e^-$ event, and set an upper limit $BR(K_L \rightarrow \pi^0 e^+ e^-) < 3.2 \times 10^{-7}$ [7] while its theoretical prediction was $O(10^{-11})$. This triggered high energy kaon experiments to join the rare kaon decay search. In particular, high energy kaon experiments have higher acceptances for multi-body decays, and better energy measurements and veto efficiencies for the decay modes with photons in the final states. The FNAL E799 experiment was specifically designed to study rare kaon decays with 800 GeV protons. The upper limit on the $BR(K_L \rightarrow \pi^0 e^+ e^-)$ was eventually lowered to $2.8 \times 10^{-10}$ (90% CL) [8].

Unlike the $K_L \rightarrow \pi\pi$ decays, the $K_L \rightarrow \pi^0\nu\pi$ decay does not have a gluon penguin contribution, and it is thus theoretically cleaner. However, besides $\gamma$ and $Z^0$ penguin diagrams, the $K_L \rightarrow \pi^0 e^+ e^-$ decay has a CP-violating diagram with one virtual photon, and a CP-
To extract the penguin diagram contributions, the virtual photon contributions had to be subtracted. The $K_L \rightarrow \pi^0 \gamma \gamma$ decay mode was used to understand the CP-conserving contribution, and it offered a testing ground for Chiral Perturbation Theory and the Vector Dominance Model.

The $K \rightarrow \pi \nu \bar{\nu}$ decay modes are free from the virtual photon contributions. In the Standard Model, the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay mode is effectively sensitive to $|V_{td}|$, and its branching ratio is predicted to be $(9.11 \pm 0.72) \times 10^{-11}$ [9]. The $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay mode is sensitive to $\text{Im}(V_{td})$, and the branching ratio is predicted to be $(3.00 \pm 0.30) \times 10^{-11}$ [9]. The theoretical uncertainties are small ($\sim 2\%$). If the measured branching ratio is different from the Standard Model predictions, it signifies the existence of new physics beyond the Standard Model.

In general, there are many difficulties in rare decay experiments. First, because the signal events are rare, even rare background events have to be suppressed. Also, a high rate kaon beam is needed to increase the sensitivity, but it increases the accidental hit rates in the detector. The high rate accidental hits lower the signal acceptance, and increase accidental-related background events.

3.1. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

The signature of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is a single $\pi^+$ coming out from a $K^+$ decay. There are backgrounds caused by: 1) scattered beam $\pi^+$'s, 2) misidentifying the $\mu^+$ in the $K^+ \rightarrow \mu^+ \nu$ decay as $\pi^+$, and 3) not observing two photons from the $K^+ \rightarrow \pi^+ \pi^0$ decay.

There are two approaches to study the decay, using stopped kaons decays, and using in-flight kaon decays.

The merit of using stopped kaons is that the laboratory frame is the same as the center of mass frame. The KEK E10 experiment had chambers and range counters above a $K^+$ stopping target to track and distinguish pions from muons based on the deposited energy and range. To further identify the $\pi^+$, the waveforms from the range counters were recorded to observe the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain. From KEK E10, an upper limit, $BR < 1.4 \times 10^{-7}$ (90\% CL) [10], was set.

The BNL E787 and E949 experiments also used stopped kaons, but with many improvements over KEK E10. They had two stages of electromagnetic separators in the beam to have a high $K^+/\pi^+$ ratio. They also had cylindrical range counters and hermetic photon veto counters to increase the coverage. The range counters were equipped with wave form digitizers to identify $\pi^+$'s with the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain. In addition, they had a magnetic spectrometer to measure the momentum of the $\pi^+$'s. Although E949 was terminated before completion, the experiments measured $BR = (1.73^{+1.15}_{-1.06}) \times 10^{-10}$ based on 7 observed events [11].

To increase the statistics significantly, the in-flight decay method was proposed. This method has several advantages. By not having a stopping target, there are no background events caused by scattered $\pi^+$'s, and no accidental rates due to hadronic interactions in the target. Also, by using high energy $K^+$, muons are easier to veto with an iron shield, and there is no need to wait for the long $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay chain at a high rate environment. By measuring the incident $K^+$ momentum $p_K$ and the pion momentum $p_\pi$, the missing mass $m_{\text{miss}}^2 = (p_K - p_\pi)^2$ can be used to suppress backgrounds from the $K^+ \rightarrow \mu^+ \nu(\gamma)$ and $K^+ \rightarrow \pi^+ \pi^0(\gamma)$ decays. The challenge is how to suppress the $\pi^+$ contamination in the beam. For high energy $K^+$, an electromagnetic separator cannot be used. The FNAL CKM experiment chose to use the Panofsky scheme, a scheme in which transverse RF is applied at two locations in the beam line to kick pions and kaons in the opposite directions. After several years of preparation, the FNAL CKM was canceled, but the decay-in-flight method was realized in the CERN NA62 experiment.

The CERN NA62 experiment does not separate pions and kaons, but uses a differential Cherenkov counter with achromatic ring focusing (KTAG) to identify $K^+$'s in the high rate beam. The $\pi^+$ in the decay is identified by a Ring Imaging Cherenkov Counter (RICH). The
muons are suppressed by 2 orders of magnitude by the RICH and 4-6 orders of magnitude by a system of calorimeters including a liquid Kr calorimeter which is now used as a photon veto. The momentum of each incident $K^+$ is measured with Si silicon pixel detectors, and the momentum of pions is measured with a magnetic spectrometer which utilizes straw tube trackers. The photons from the $K^+ \rightarrow \pi^+\pi^0$ decays are detected with the liquid Kr calorimeter, and lead glass rings surrounding the decay volume. In the 2% of collected data, NA62 observed 1 event where $0.152 \pm 0.027$ ADCs to form triggers and to record the waveforms. With the data collected in 2015, KOTO set a limit, $BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) < 1.4 \times 10^{-9}$ (90% CL) [12]. The newest result from the NA62 is presented in this conference.

3.2. $K_L \rightarrow \pi^0\nu\bar{\nu}$

Using the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay as a probe to search for new physics was first proposed by L. Littenberg at the Snowmass Workshop in 1988 and in a paper [13]. In the paper, he also set a limit, $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) < 7.6 \times 10^{-3}$ (90% CL), from the work of Cronin et al.

Although the decay is clean theoretically, it is experimentally difficult because the incoming $K_L$ cannot be detected and the only signature is two photons from the decay. Nevertheless, the FNAL KTeV E799-II experiment had a 1-day special run to collect 2-cluster events, reconstructed the decay vertex position by assuming that the two photons originated from a $\pi^0$, and set a limit, $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) < 1.6 \times 10^{-6}$ (90% CL), based on 1 observed event [14]. To explicitly identify the decay, KTeV E799-II used the $\pi^0$ Dalitz decay. The decay vertex was reconstructed from the $e^+e^-$ tracks, the $\pi^0$ was identified with the invariant mass of $e^+e^-\gamma$, and the transverse momentum of the $\pi^0$ was also reconstructed. Based on no observed events, an improved limit, $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7}$ (90% CL), was set [15].

The BNL KOPIO experiment [16] was designed to have more constraints for the event reconstruction as follows. To measure the momentum of the $K_L$, short proton pulses hitting the production target were to produce bunched low energy $K_L$’s peaking at 0.65 GeV/c momentum. The direction of a photon was to be measured with a converted $e^+e^-$ pair to find the decay vertex. The velocity of the $K_L$ was to be measured based on its flight path length and flight time. The $K_L \rightarrow \pi^0\pi^0$ background with two photons from the same $\pi^0$ was to be rejected by reconstructing the invariant mass of the two photons. The $K_L \rightarrow \pi^0\pi^0$ background with two photons from different $\pi^0$’s was to be rejected by reconstructing the $\pi^0$ momentum in the CM frame. The experiment was planned to measure the branching ratio of $K_L \rightarrow \pi^0\nu\bar{\nu}$ with < 10% uncertainty. Unfortunately, the experiment was not funded.

The KEK E391a experiment [17] took a simpler approach. Because the $K_L \rightarrow \pi^0\pi^0$ background is suppressed mostly by detecting extra photons in any experiment, E391a made a hermetic photon veto system and an electromagnetic calorimeter covering the decay region. Most of the detector components were placed in vacuum to avoid dead materials such as beam pipes that would absorb photons before detection. This was the first dedicated experiment to search for the $K_L \rightarrow \pi^0\nu\bar{\nu}$ decay. With six months of running time, a new limit, $BR(K_L \rightarrow \pi^0\nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% CL) [18], was set.

The J-PARC KOTO experiment pushed E391a’s approach with the high intensity proton beam of J-PARC. KOTO reuses many components of the E391a detector system, but has many improvements. It has a new two-stage collimator system to suppress beam halos. The calorimeter was replaced with finer and longer CsI crystals used for the FNAL KTeV experiment; they improved the photon – neutron separation based on cluster shape, and reduced photon veto inefficiency due to punch-throughs. For the photon veto detectors placed in the beam downstream of the calorimeter, lead-aerogel Cherenkov modules originally designed for KOPIO are used. The upstream face of the calorimeter is covered by two layers of 3-mm-thick scintillators to veto charged particles and minimize hadronic interactions in the scintillators. All the signals from the detector components are digitized by 125-MHz 14-bit or 500-MHz 12-bit ADCs to form triggers and to record the waveforms. With the data collected in 2015, KOTO
improved the upper limit on the branching ratio set by E391a by an order of magnitude, to \( BR(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9} \) (90% CL) [19]. After the 2015 run, a new cylindrical photon veto detector was installed, and in 2018, new trigger logic that counts the number of clusters in the calorimeter, using the same algorithm for FNAL E731, was installed. After the 2018 run, the calorimeter was upgraded to add a new photon/neutron identification capability. The status of the 2016–2018 run data analysis and the calorimeter upgrade are presented in this conference.

The next generation of experiments are being planned to collect \( O(10^2) \) \( K_L \to \pi^0\nu\bar{\nu} \) decay events. One is the CERN KLEVER experiment which utilizes the NA62 detector, and the other is the J-PARC KOTO Step 2 experiment. Both plans are presented in this conference.

4. More kaon experiments

In addition to the experiments described above, there are other kaon experiments.

The OKA experiment at IHEP, Russia makes a clean \( K^\pm \) beam separated from \( \pi^\pm \) by applying RF with the Panofsky’s scheme. The experiment has been studying the \( K^+\mu^+\nu\bar{\nu} \) decay to measure the \( F_V - F_A \), as well as the \( K^+ \to \pi^+\pi^-\pi^0\gamma \) decay.

The KLOE-2 is a unique experiment that produces \( K_S K_L \) and \( K^+K^- \) pairs from the \( e^+e^- \to \phi \) production. The physics topics cover the studies on CPT, CKM parameters, lepton flavor violation, and \( K_S \) decays. The KLOE-2 has 3 times higher luminosity than KLOE with a crab-waist collision, as well as many detector upgrades.

The LHCb experiment is yet another unique facility to study \( K_S \) and hyperons. Although the experiment was not originally designed to study kaons, the open geometry without a target works as a \( K_S \) factory. The best limit on the \( BR(K_S \to \mu^+\mu^-) \) has been set [20], and many other decay modes are planned to be studied.

The status and results from these experiments are presented in this conference also.

5. Summary

In the past 31 years, the Kaon Conference series has been the place for the kaon physics community to give theoretical directions, bring up new ideas, show the status of experiments, and announce new results. We are here again just like a family to hear the newest results and developments in the kaon physics. Let the conference begin.

6. Acknowledgements

This work is supported by JSPS KAKENHI JP16H06343.

References

[1] Kobayashi M and Maskawa K 1973 Prog. Theo. Phys. 49 652
[2] Wolfenstein L 1964 Phys. Rev. Lett. 13 562
[3] Barr G D et al. 1993 Phys. Lett. B 317 233
[4] Gibbons l K et al. 1993 Phys. Rev. Lett. 70 1203
[5] Fanti V et al. 1999 Phys. Lett. B 465 335
[6] Alavi-Harati A et al. 1999 Phys. Rev. Lett. 83 22
[7] Jastrzembski E et al. 1988 Phys. Rev. Lett. 61 2390
[8] Alavi-Harati A et al. 2004 Phys. Rev. Lett. 93 021805
[9] Buras A J et al. 2015 JHEP 11 033
[10] Asano Y et al. 1981 Phys. Lett. 107B 159
[11] Artamonov A V et al. 2009 Phys. Rev. D 79 092004
[12] The NA62 Collaboration 2019 Phys. Lett. B 791 156
[13] Littenberg L S 1989 Phys. Rev. D 39 3322
[14] Adams J et al. 1990 Phys. Lett. B 247 240
[15] Alavi-Harati A et al. 2000 Phys. Rev. D 61 072006
[16] KOPIO Collaboration 2005 KOPIO project conceptual design report
[17] Inagaki T et al. 1996 KEK Internal 96 13
[18] Ahn J K et al. 2010 Phys. Rev. D 81 072004
[19] Ahn J K et al. 2019 Phys. Rev. Lett. 122 021802
[20] Aaij R et al. 2017 Eur. Phys. J. C 77 678