The Brookhaven Rare Kaon Decay Program

Laurence S. Littenberg
Physics Department
Brookhaven National Laboratory
Upton, N.Y. 11973 USA

ABSTRACT

The results of the current generation of rare kaon decay experiments at Brookhaven National Laboratory are reviewed. The present status of and future plans for such experiments are discussed.

Introduction

The experiments constituting the Brookhaven rare decay program are enumerated in Table I. There are now enough that it is no longer possible to do justice to all of them in a talk of finite length. I will concentrate on those which are currently running or analyzing data from previous runs.

<table>
<thead>
<tr>
<th>EXPERIMENT</th>
<th>MODES</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>E780</td>
<td>$K_L \to \mu e, ee, \mu \mu, \pi^0 e^+ e^-$</td>
<td>finished</td>
</tr>
<tr>
<td>E845*</td>
<td>$K_L \to \pi^0 e^+ e^-, \pi^+ e^+ e^-, \pi^+ e^+ e^-$</td>
<td>finished, analyzing</td>
</tr>
<tr>
<td>E777</td>
<td>$K^+ \to \pi^+ e^- \mu^+, \pi^+ e^- \mu^-$</td>
<td>finished</td>
</tr>
<tr>
<td>E851*</td>
<td>$K^+ \to \pi^0 e^+ e^-$, $\pi^0 e^- e^+$</td>
<td>finished, analyzing</td>
</tr>
<tr>
<td>E865*</td>
<td>$K^+ \to \pi^+ e^- \mu^+, \pi^+ e^- \mu^-$</td>
<td>in construction</td>
</tr>
<tr>
<td>E791</td>
<td>$K_L \to \mu e, ee, \mu \mu$</td>
<td>finished, analyzing</td>
</tr>
<tr>
<td>E871*</td>
<td>$K_L \to \mu e, ee, \mu \mu$</td>
<td>in construction</td>
</tr>
<tr>
<td>E787</td>
<td>$K^+ \to \pi^+ \nu \bar{\nu}, \pi^+ \mu^+ \mu^-$</td>
<td>continuing</td>
</tr>
</tbody>
</table>

* This experiment is a "descendent" of the experiment listed above it

Table 1: BNL Rare Kaon Decay Experiments

Much of my talk can be summed up in Fig. 1 which is a kind of map of the subject of K decay measured off in units of decay rate (sec$^{-1}$) so that charged and neutral decay modes can be fairly compared. Many of the milestones mentioned in Dr. Marciano's excellent talk 1 can be seen. The moral of this map is that the study of K decay has yielded important discoveries and insights from its inception until the present, and that there is little reason to think it will cease to do so as it is pushed to greater and greater sensitivity. The vertical lines represent the various BNL initiatives. They are solid down to the point representing the present results, and then become dashed to indicate planned future improvements. The progress indicated by these lines is great indeed. Comparing the length of these lines to the "density of discoveries" on the map, one is led to expect some important surprises before too long.
Figure 1: The history of K decay and the place of the present BNL program in it.
Fig. 2 shows the apparatus of the BNL-Yale collaboration E845. This was the world's first dedicated $K_L \rightarrow \pi^0 e^+ e^-$ experiment. It was optimized to search for $K_L$ decays with $e^\pm$ and $\gamma\gamma$ in the final state (the lead filter at the back was used to veto penetrating particles). Several million $K_L$ (along with $\sim 3 \times 10^8$ neutrons) impinged on the detector during each 1-second AGS spill. A simple one-magnet drift chamber spectrometer measured $e^\pm$ momenta and a lead glass array detected $\gamma\gamma$. The latter was also used to identify the $e^\pm$. An atmospheric hydrogen Čerenkov counter completed the particle identification.

Fig. 3 shows the distribution in final state effective mass vs the square of the angle between the initial and final states (collinearity angle) of the candidate $\pi^0 e^+ e^-$ events which passed all cuts on particle i.d., $m_{\gamma\gamma}$, timing, etc. There are no events within the $3\sigma$ contour around the expected signal position, which allowed a 90% c.l. upper limit of $B(K_L \rightarrow \pi^0 e^+ e^-) < 5.5 \times 10^{-9}$ to be set. This represents about a 400-fold improvement in the sensitivity for this decay in force before the current round of BNL experiments began.

$K_L \rightarrow \pi^0 e^+ e^-$ is of great interest from the point of view of CP-violation because the "direct" (decay amplitude) contribution is expected to be of the same order as the "indirect" (state-mixing) contribution. This is to be contrasted with the well-known case of $K^0 \rightarrow 2\pi$ where the corresponding ratio is expected to be more like $\frac{1}{1000}$. However this advantage is diluted by the extremely small branching ratio for the former process, which is expected to be $\leq 7$ of order $10^{-11}$. E845, although the most sensitive experiment yet of this type, still falls more than two orders of magnitude short of this level. However, this experiment has had a very large effect indeed on the attempt to exploit $K_L \rightarrow \pi^0 e^+ e^-$. This is implicit in Fig. 4, which shows the four-body effective mass distribution for $K_L \rightarrow e^+ e^- \gamma\gamma$ candidates in which the $\gamma\gamma$ mass is not constrained to lie in the $\pi^0$ region. A clear peak at the $K_L$ mass is observed. This marks the discovery of the previously unseen decay mode $K_L \rightarrow e^+ e^- \gamma\gamma$. The measured branching ratio, $(6.6 \pm 3.2) \times 10^{-7}$ for both $k_\pi > 5$ MeV, agrees well with the QED calculation for $K_L \rightarrow e^+ e^- \gamma$ accompanied by a hard bremsstrahlung $(5.81 \times 10^{-7})$.

Unfortunately, the bremsstrahlung gammas do not all line up with the $e^+$ and $e^-$ as might be naively assumed. An interference effect allows a considerable fraction of events to have gammas at large angles with respect to the charged tracks. What is more, the $m_{\gamma\gamma}$ spectrum extends far beyond $m_{\pi\pi}$. These characteristics make this process a formidable background to $K_L \rightarrow \pi^0 e^+ e^-$. As explored by Greenlee, the kinematic distinction between background and signal in this case is not sufficient to eliminate the problem. One tends to be stuck with backgrounds of order $\frac{2 \times 10^{-11} \Delta m_{\pi\pi}}{\Delta m_{\gamma\gamma}^2}$ where $\Delta m_{\gamma\gamma}$ is the width of the mass cut around $m_{\pi\pi}$ that one can afford to use. Since this is linear in the resolution, it is very hard to make
Figure 3: Square of the target reconstruction angle vs \( m_{\ell^+\ell^-} \).

Figure 4: \( m_{\ell^+\ell^-\gamma\gamma} \) with no constraint on \( m_{\gamma\gamma} \).

large gains. Now this is the bad news. The BNL program also produced some good news for the study of \( K_L \rightarrow \pi^0 e^+ e^- \), in the section on E777 below.

E845 also studied the process which is the 'parent' of \( K_L \rightarrow e^+ e^- \gamma \gamma \), i.e. \( K_L \rightarrow e^+ e^- \gamma \). Previous to this work, the world supply of this decay mode was four\(^3\). E845 increased this to about 1000, allowing detailed studies to be done\(^1\). Ignoring radiative corrections, the differential decay spectrum for this decay can be written\(^1\)

\[
\frac{d\Gamma}{dz} = \frac{2\alpha^2}{3\pi} \frac{(1-z)^3}{z^2} \left(1 + \frac{2m_e^2}{m_K^2}\right) \left(1 - \frac{4m_e^2}{m_K^2}\right)^{1/2} |f(z)|^2
\]

(1)
where \( x = m_{ee}^2/m_K^2 \), and the form factor is defined such that \( f(0) = 1 \). The data points in Fig. 5 show the \( f(x)^2 \) extracted from this experiment. The dotted line is the result of a fit to a form factor which is assumed to vary like the \( \rho \) propagator. This sort of dependence has been seen in other \( K_L \) decays in which virtual photons are involved\(^{12} \), as well as in analogous \( \eta \) decays\(^{13,14} \). There is a fairly clear indication that the data points rise faster with \( x \) than does the \( \rho \) propagator. The model of Bergström et al.,\(^{15} \) which includes a vector-vector transition, \( K_L \to K^+\gamma \), gives a noticeably better fit. The solid line in Fig. 5 is a best fit to this model, from which a parameter \( \alpha_{K^+} = -0.28 \pm 0.083^{+0.054}_{-0.034} \) was extracted. This parameter represents the strength of the vector-vector transition with respect to that of the pseudoscalar-pseudoscalar transition (wherein \( K_L \to \pi, \eta, \eta' \to \gamma\gamma' \)):

\[
f(x) = \frac{m_\rho^2}{m_\rho^2 - m_{ee}^2} + C\alpha_{K^+} \left[ \frac{4}{3} - \frac{m_\rho^2}{m_K^2 - m_{ee}^2} - \frac{m_\omega^2}{9(m_\rho^2 - m_{ee}^2)} - \frac{2m_\pi^2}{9(m_\rho^2 - m_{ee}^2)} \right]
\]

(2a)

where

\[
x \equiv \frac{m_{ee}^2}{m_K^2}
\]

(2b)

and

\[
C \equiv \sqrt{8\pi\alpha - 1.1 \times 10^{-5}} f_{K^+\pi^+} f_{K^+\pi^-} \approx 2.5
\]

(2c)

It should be noted that data for the Dalitz decay of the \( K_L \) is now better than that for the \( \eta \). A remeasurement of the latter would be very interesting for purposes of comparison. The branching ratio extracted from this data is \( B(K_L \to e^+e^+\gamma) = (9.1 \pm 0.4^{+0.5}_{-0.3}) \times 10^{-6} \). This is to be compared to the theoretical expectation of \( (9.6 \pm 0.4) \times 10^{-6} \).

The final physics result from E845 I will discuss is another "child" of \( K_L \to e^+e^-\gamma \), i.e. \( K_L \to e^+e^-e^+e^- \). Fig. 6 shows the square of the collinearity angle vs \( m_{eeee} \) distribution for tracks meeting electron identification and geometry criteria in this experiment. There are six very clean events, which yield \( B(K_L \to e^+e^-e^+e^-) = (5 \pm 2 \pm 3) \times 10^{-8} \). This is to be compared with the theoretical expectation\(^{17} \) of \( 3.36 \times 10^{-8} \) and the recent NA31 measurement\(^{18} \), \( (4 \pm 3) \times 10^{-8} \), based on 0 events. The results of E845 are summarized in Table II.

Figure 5: Square of the form factor in \( K_L \to e^+e^-\gamma \)
Table II: Results of E845

<table>
<thead>
<tr>
<th>Mode</th>
<th>result</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \pi^0ee$</td>
<td>$&lt; 5.5 \times 10^{-9}$</td>
<td>search for new scalars</td>
</tr>
<tr>
<td></td>
<td></td>
<td>non-S.M. CP-violation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>future: S.M. CP-violation</td>
</tr>
<tr>
<td>$K_L \to e^+e^-\gamma$</td>
<td>$(9.1 \pm 0.4^{+0.2}_{-0.3}) \times 10^{-6}$</td>
<td>c.f. $(9.6 \pm 0.4) \times 10^{-6}$ (theory)</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{K^\ast} = -0.28 \pm 0.083^{+0.054}_{-0.034}$</td>
<td>i.e. something needed besides the $\rho$</td>
</tr>
<tr>
<td>$K_L \to e^+e^-\gamma\gamma$</td>
<td>$(6.6 \pm 3.2) \times 10^{-7}$</td>
<td>c.f. $5.8 \times 10^{-7}$ for $k^+5\text{MeV}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>background to $K_L \to \pi^0ee$</td>
</tr>
<tr>
<td>$K_L \to e^+e^-e^+e^-$</td>
<td>$(5 \pm 2 \pm 3) \times 10^{-8}$</td>
<td>c.f. $3.6 \times 10^{-8}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>background to $K_L \to e^+e^-$</td>
</tr>
</tbody>
</table>

I next turn to the first of the two lepton flavor violation (LFV) initiatives at BNL. Decays such as $K_L \to \mu^\pm e^\mp$ and $K^+ \to \pi^+\mu e$ which violate conservation of lepton flavor are of particular current interest because although they are strictly forbidden in the minimal Standard Model (SM), they are predicted to occur at accessible levels by many of the proposed extensions to that Model. What is more, the mass scales probed by current and near-future experiments are extremely high. Eq. (3) relates the branching ratio for $K_L \to \mu e$ as mediated by a hypothetical horizontal gauge boson $H^+$, to that for $K^+ \to \mu^+\nu$.

\[
B(K_L \to \mu e) = B(K^+ \to \mu^+\nu) \times \frac{\tau_L}{\tau_+} \times \left[ \frac{M_H g_H^2}{M_H g_W^2 \sin \theta_C} \right]^2
\]  

(3)
For $g_H = g_W$, the current 90% c.l. upper limit\textsuperscript{21} of $3.3 \times 10^{-11}$ on $B(K_L \rightarrow \mu e)$ corresponds to $M_H > 110$ TeV which is a formidable large scale, even in the era of the SSC.

The experiment which obtained the above limit is E791, a UC Irvine, UCLA, LANL, U of Pennsylvania, Stanford, Temple, and William & Mary collaboration. It was carried out in the B5 beam line of the AGS. A very intense $K_L$ beam ($\sim 50 MHz$) impinged on an 8m-long evacuated decay tank at the upstream end of the detector. Rates from decaying $K_L$ and from interactions of the much larger flux of neutrons accompanying the $K_L$ made the environment of this detector an extremely challenging one. The apparatus, shown in Fig. 7, was designed to detect the two-body leptonic decays $K_L \rightarrow \mu^+\mu^-$, $K_L \rightarrow e^+e^-$, as well as $K_L \rightarrow \mu^\pm e^\mp$. It consisted of a double arm drift-chamber spectrometer equipped with trigger scintillation hodoscopes and particle identification devices. The latter included an atmospheric gas Čerenkov counter and a lead glass array for electrons, and a hadron filter and a tracking rangefinder for muons. The two magnets, each of which spanned both arms, had equal but opposite bending powers of $\Delta p_T \sim 300$MeV/c. The five drift chamber modules were deployed so as to allow two independent measurements of momentum. The resulting mass resolution of this spectrometer for calibration $K_L \rightarrow \pi^+\pi^-$ decays was $\sim 1.4$MeV/c.

At first glance these kinematically over-constrained, two-lepton final states ought to be readily separable from the more copious $K_L$ decay modes. As the sensitivity goals increase, however, this becomes more and more challenging technically. One must maintain very good resolution and particle identification in the face of extremely high rates. In the case of $K_L \rightarrow \mu e$, the leading background is due to $K\pi\pi$ decay ($K_L \rightarrow \pi e\nu$)
in which the $\pi$ is mistaken for a $\mu$ through punch-through or decay. Since $Ke3$ constitute roughly 40% of all $K_L$ decays, and such misidentification can produce a $K_L \rightarrow \mu e$ topology in ~10% of the $Ke3$ events, this leads to a formidable trigger problem. To cope with this, E791 developed highly sophisticated triggering and data acquisition systems. Although fought to a stand-still at the trigger level, this background had to be confronted again in the off-line analysis. Moreover, in the course of this analysis, a second, unanticipated, background by which $Ke3$ could contaminate $K_L \rightarrow \mu e$ was discovered. In this version, both the $\pi$ and the $e$ are misidentified, the former as an $\mu$ and the latter as a $\mu$. This background is less amenable to kinematic suppression, since unlike the single misidentification background, it can generate apparent effective masses $\gtrsim m_K$. Fortunately, it is more vulnerable to suppression via particle identification.

Fig. 8 shows the two-body effective mass vs the square of the transverse momentum for $K_L \rightarrow \mu e$ candidates from the 1990 run of E791. Since the signal region is devoid of events, a 90% c.l. upper limit of $B(K_L \rightarrow \mu e) < 7.1 \times 10^{-11}$ can be derived. Combined with previous years' data, this yields the above-mentioned limit of $B(K_L \rightarrow \mu e) < 3.3 \times 10^{-11}$. This represents the highest sensitivity ever achieved in a $K$ decay experiment.

Fig. 9 is a clear demonstration of E791's capacity to detect rare decays. It shows the effective mass vs the square of the collinearity angle of $K_L \rightarrow \mu^+\mu^-$ candidates from the 1990 run. A clear peak is evident at $m_{\mu\mu} \approx m_K$ and very small angle. There are some 372 events in the signal region of $\pm 6$ MeV/c$^2$ and < 2 $m_{\mu\mu}^2$. Extrapolating backgrounds from outside the signal region results in an estimate of 23 events, leaving 349 $K_L \rightarrow \mu^+\mu^-$s. Normalizing on $K_L \rightarrow \pi^+\pi^-$ yields $B(K_L \rightarrow \mu^+\mu^-) = (6.96 \pm 0.40 \pm 0.22) \times 10^{-9}$ where the first error is statistical and the second systematic. This is to be compared with the combined result of their 1988 and 89 running, $B(K_L \rightarrow \mu^+\mu^-) = (7.0 \pm 0.5) \times 10^{-9}$. Fig. 10 shows the $\mu^+\mu^-$ effective mass spectrum for all three years' running. It contains roughly 700 signal events.

Now the above result is very close to the so-called "unitarity limit" on $B(K_L \rightarrow \mu^+\mu^-)$ given by the diagram in Fig. 11a. The contribution of this diagram to the imaginary part of the amplitude for $K_L \rightarrow \mu\mu$ has been known for a long time. It gives a lower limit for $B(K_L \rightarrow \mu\mu)$ in terms of the measured branching ratio for $K_L \rightarrow \gamma\gamma$.

$$B(K_L \rightarrow \mu\mu)|_{\gamma\gamma} = \left( \frac{m_\mu}{m_K} \right)^2 \frac{\alpha^2}{2\beta^2} \ln^2 \left( \frac{1 + \beta\mu}{1 - \beta\mu} \right) B(K_L \rightarrow \gamma\gamma)$$

(4)

$$= 1.195 \times 10^{-5} B(K_L \rightarrow \gamma\gamma)$$

$$= 6.81 \times 10^{-9}$$

The small difference between the measured branching ratio and what is given by Eq. (4) hinders the effort to extract information on the weak diagrams, shown in Fig. 11b, which contribute to the real part of
this process. Such information would be very valuable in constraining Standard Model parameters such as \( \text{Re } V_{ud} \) and \( m_{\tau} \), and attempts to get at it have a long history. The problem is that there are other possible contributors to the real part of \( K_L \rightarrow \mu^+\mu^- \). These are not expected to be very large, but at the moment one is working with a quantity \( \approx (0.2 \pm 0.6) \times 10^{-9} \).

Replacing \( m_\mu \) in Eq. (4) with \( m_\sigma \) gives the corresponding limit for \( K_L \rightarrow e^+e^- \). It is far smaller, approximately \( 3 \times 10^{-12} \). The weak contribution is also suppressed by a similar factor, so that there is a window for new interactions down to this level. The suppression is due to helicity, so that this window is of particular interest in looking for new scalar or pseudoscalar interactions. E791 has established a 90% c.l. limit of \( B(K_L \rightarrow ee) < 4.7 \times 10^{-11} \).

The experience of carrying out E791 convinced the experimenters that the potential of the AGS for the study of these decays was far from exhausted. Thus they have proposed a successor experiment, E871. This UC Irvine, Stanford, Temple, University of Texas, and William & Mary collaboration will make use of the additional intensity given by the AGS Booster to reach sensitivities of \( \sim 10^{-12} \). Aside from increasing the reach for LFV interactions in \( K_L \rightarrow \mu \) to about 200 TeV, this should be sufficient to see a couple of examples of \( K_L \rightarrow e^+e^- \). They should also collect of order \( 10^8 \) \( K_L \rightarrow \mu^+\mu^- \) events, enough to have a fighting chance to extract useful information on the weak contribution. Details are given in the talk by Professor Molzon at this conference.
Complementing the $K_L \rightarrow \mu e$ search discussed above, there has been an equally ambitious program whose primary object is the search for the closely related process $K^+ \rightarrow \pi^+ \mu e$. Although three-body phase space and the fact that $\tau_{K^+} \approx \tau_{K_L}/4$ render this process somewhat less sensitive than $K_L \rightarrow \mu e$ to generic LFV interactions, there are cases, such as that of a purely vector interaction, that cannot contribute to the $K_L$ decay. This makes it essential to probe $K^+ \rightarrow \pi \mu \mu$ as well. There are also a number of other very interesting $K^+$ decay modes that make charged beam experiments very attractive. The first experiment in this program was E777, whose apparatus is shown in Fig. 12. This was a BNL, FNAL, PSI, Washington, Yale collaboration.

A 6 GeV/c positive beam containing $\sim 10 M^2 K^+$ and roughly 20 times more $\pi^+$ and $\mu$ per spill impinged on a vacuum decay region. An upstream dipole separated the $K^+$ decay products by sign and kicked them
out of the beam region. Their momenta were then measured by an MWPC spectrometer and their identities determined by two layers of gas Č counters, a lead-scintillator shower counter, and a steel plate/proportional tube muon range array. To exploit in the trigger the infrequent appearance of an e$^-$ in a K$^+$ beam, the apparatus was configured to detect only the $\pi^+\mu^+e^-$ charge combination. The two sides of the apparatus were configured differently. On the right (positive track) side, the Č counters were filled with CO2 at atmospheric pressure to assure good positron rejection. The muon range identifier was confined to the right side. On the left (negative track) side, the Č counters were filled with $H_2$ at atmospheric pressure. This minimized the probability that heavy particles would be mistaken for electrons.

The leading backgrounds to this process originate from daughter particle misidentification and/or decay in $K^+ \rightarrow \pi^+\pi^+\pi^-$ and $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow e^+e^-\gamma$. These processes are not all bad: they also served to calibrate and normalize the experiment. The demands on kinematical reconstruction and particle identification power necessary to get down to the $10^{-10}$ level in this decay are considerable. Three-body effective mass resolution of $\sim 5\text{MeV}/c^2$, and wrong particle rejection $\geq 10^8$ were achieved.

Fig. 13a shows the distribution of vertex miss distance (S) versus three body effective mass for calibration $K^+ \rightarrow \pi^+\pi^+\pi^-$. The rectangular box shows the $3\sigma$ acceptance region for these events. Fig. 13b shows the corresponding distribution for $K^+ \rightarrow \pi^+\mu^+e^-$ candidates. The increase in Q-value with respect to $K^+ \rightarrow \pi^+\pi^+\pi^-$ requires a larger signal region. There are no accepted events, allowing a 90% c.l. upper limit $B(K^+ \rightarrow \pi^+\mu^+e^-) < 2.1 \times 10^{-10}$ to be set$^{28}$. This represents a 20-fold improvement over the results of previous experiments. This data can also be used to search for the LFV decay $\pi^0 \rightarrow \mu^+e^-$. Events consistent with the decay sequence $K^+ \rightarrow \pi^+\pi^0$, $\pi^0 \rightarrow \mu^+e^-$ are not found, allowing a 90% c.l. limit $B(\pi^0 \rightarrow \mu^+e^-) < 1.6 \times 10^{-8}$ to be set. This represents about a fourfold improvement of our knowledge of this process$^{29}$.

The successful prediction$^{30}$ of the rate of the GIM-suppressed decay $K^+ \rightarrow \pi^+e^+e^-$ was one of the early triumphs of the Standard Model. However long distance effects are important in this process and detailed predictions remain a challenge to theorists$^{8,7,31,32}$. More data is very welcome. E777 has made a major contribution to the study of this decay, having increased the number of observed events from tens$^{33}$.
The result of a fit to this parameterization is shown in Fig. 18. The value of the constant $a^2$ by Ecke and De Rafael compared with data. Note that the deviation in each case the statistical error precedes the systematic error. Fig. 17 shows the $M_{ee}$ spectrum given by this fit compared with data. Note that the deviation from a pure vector spectrum is relatively large. In the region above $M_{ee} = 130$ MeV one then see a clear band of $K^+ \to \pi^+ e^+ e^-$ events at $M_{ee} \approx m_K$.

The histogram in Fig. 15 is the projection of Fig. 14 for events with $M_{ee} > 150$ MeV. The shaded curve is the estimated background. The shape of this curve is obtained by plotting $M_{ee}$ for events whose reconstructed $K^+$ trajectory originated outside the production target. The background shape is then normalized to the data in the interval 400 < $M_{ee}$ < 440 MeV. Also shown in Fig. 15 is the result of a Monte Carlo simulation. The theoretical input to this was a vector spectrum modified by an empirical form factor:

$$d\Gamma/dM_{ee} \propto M_{ee}^2(1 + \lambda M_{ee}^2/m_e^2)^2$$

(5)

The constant $\lambda$ of Eq. (5) and an overall normalization factor are allowed to vary in the fit. The latter is absolutely normalized to $K\pi2$ Dalitz events to extract a branching ratio. The $\chi^2$ contours of this fit are shown in Fig. 16.

The results of this fit are $B(K^+ \to \pi^+ e^+ e^-) = (2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ and $\lambda = 0.105 \pm 0.035 \pm 0.015$, where in each case the statistical error precedes the systematic error. Fig. 17 shows the $M_{ee}$ spectrum given by this fit compared with data. Note that the deviation from a pure vector spectrum is relatively large. In the case of $K^+ \to \pi^0 e^+ e^-$, for example, the parameter corresponding to $\lambda$ has a value $\approx 0.03$.

A promising approach to decays such as $K^+ \to \pi^+ e^+ e^-$ which are not short-distance dominated is that of Chiral Perturbation Theory (ChPT). This approach was applied to $K^+ \to \pi^+ e^+ e^-$ by Ecker, Pich and De Rafael. They parameterized the mass spectrum as $d\Gamma/dM_{ee} = 16 M_{ee}^3 \Gamma_p^2 |\phi_e|^2/m_K^2$ where $\phi_e = -(\phi_K + \phi_\pi + w_+$), $\phi_K$ and $\phi_\pi$ are known functions of $M_{ee}^2$, $\Gamma_p$ is a product of $G_F^2$ and other fundamental constants which equals $1.37 \times 10^{-22}$ GeV, and $w_+$ is parameter that must be extracted from the data. The result of a fit to this parameterization is shown in Fig. 18. The values of the parameters extracted are...
Figure 15: $M_{\pi e e}$ distribution for events with $M_{\pi e} > 150\text{MeV}$. Histogram is data; solid curve is Monte Carlo; shaded region is the estimated background (from Ref. 34).

Figure 16: $\chi^2$ contours for $B(K^+ \to \pi^+ e^+ e^-)$ vs $\lambda$ (from Ref. 34).

$B(K^+ \to \pi^+ e^+ e^-) = (2.99 \pm 0.22) \times 10^{-7}$ and $w_+ = 0.89^{+0.24}_{-0.14}$. It can be counted as a success of the approach, that this value of $w_+$ is only about 2$\sigma$ from that predicted for the observed branching ratio. Now to the extent that one credits the ChPT approach, this result is good news for attempts to extract the direct CP-violating component of $K_L \to \pi^0 e^+ e^-$. This is because the presence of a relatively large indirect contribution to CP-violation in $K_L \to \pi^0 e^+ e^-$ would make such an extraction problematical. The indirect contribution is given by $|\epsilon|^2 \Gamma_{K^0 \to \pi^0 e^+ e^-}$. Thus a small value for $\Gamma_{K^0 \to \pi^0 e^+ e^-}$ would be good news. In
the approach of Ecker, Pich, and DeRafael, the rate for $K_S^+ \rightarrow \pi^0\nu\bar{\nu}$ is given by the same formula as that for $K^+ \rightarrow \pi^+\nu\bar{\nu}$, except that $\hat{\phi}_S$ is replaced by $\hat{\phi}_K$, which equals $2\phi_K + \frac{1}{8}\ln\left(m_K^2/m_K^2\right) + w_+$. This is a very weak function of $M_{ee}$, i.e. $\hat{\phi}_S \approx w_+ - 0.75$. Then $\Gamma_{K_S^+ \rightarrow \pi^0\nu\bar{\nu}}$ is largest when $w_+$ is largest, and at $1\sigma$, the indirect CP-violating contribution to $B(K_L^+ \rightarrow \pi^0\nu\bar{\nu})$ must be less than $1.6 \times 10^{-12}$. Before this experiment, there was no evidence that $w_+$ was not on the negative side of the parabolic function of Fig. 18, so that the indirect contribution to $K_L^+ \rightarrow \pi^0\nu\bar{\nu}$ could easily have been an order of magnitude larger than $1.6 \times 10^{-12}$.

The $K^+ \rightarrow \pi^+\nu\bar{\nu}$ data discussed above will be augmented by a factor 3 or 4 by the results of dedicated run (E851) taken with the detector reoptimized for this mode. Data from E851 will also be used to search for

Figure 17: $M_{ee}$ spectrum for events with $470 < M_{ee} < 512$MeV. Solid line is the result of the Monte Carlo with $\lambda = 0.105$ (from Ref. 34).

Figure 18: $x^2$ contours for $B(K^+ \rightarrow \pi^+\nu\bar{\nu})$ vs $w_+$ (from Ref. 34). The parabolic curve is the relationship predicted by Ref. 32.
Table III: Results of E777/851

<table>
<thead>
<tr>
<th>Mode</th>
<th>Result</th>
<th>Reference</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+e^-\mu^+$</td>
<td>$&lt; 2.1 \times 10^{-10}$</td>
<td>Ref. 28</td>
<td>$M_H &gt; 57$ TeV</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+e^+e^-$</td>
<td>$(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$</td>
<td>Ref. 34</td>
<td>500 events</td>
</tr>
<tr>
<td></td>
<td>$\lambda = 0.105 \pm 0.035 \pm 0.015$</td>
<td></td>
<td>suggests $K_S \rightarrow \pi^0e^+e^-$ small</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+X^0; X^0 \rightarrow e^+e^-$</td>
<td>$&lt; 1.1 \times 10^{-6}$</td>
<td>Ref. 34</td>
<td>$150 &lt; m_{ee} &lt; 340$ MeV</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+X^0; X^0 \rightarrow e^+e^-$</td>
<td>$&lt; 4.5 \times 10^{-7}$</td>
<td>Ref. 35</td>
<td>$100$ MeV $&lt; m_{ee}$ for $\tau_X &lt; 10^{-13}$ sec.</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu^+e^-$</td>
<td>$&lt; 1.6 \times 10^{-8}$</td>
<td>Ref. 28</td>
<td></td>
</tr>
</tbody>
</table>

Figure 19: Proposed E865 detector

the process $\pi^0 \rightarrow e^+e^-$. One 'tags' the $\pi^0$ from the copious $K\pi 2$ decay. Previous results on $B(\pi^0 \rightarrow e^+e^-)$ have been somewhat confusing. The earliest experiments obtained a rate much higher than that of the unitarity contribution while later results called this into question. A definitive experiment is needed.

Table III summarises the results of E777/851 thus far. The success of this program and the prospect of much increased proton flux from the Boosted AGS has led to the proposal (now approved) of a successor experiment, E865. Fig. 19 shows the initial design for the detector. E865 is presently a collaboration of BNL, INR-Moscow, Dubna, New Mexico, PSI, Basel, Pittsburgh, Tbilisi, Yale, and Zurich. The aim of this experiment is to improve on the sensitivity of E777 to $K^+ \rightarrow \pi^+e^-\mu^+$ by a factor of 70, to nearly the $10^{-12}$/event level. In addition, a large menu of other physics can be pursued.

By and large, the approach is very similar to that of E777. This allows the proponents to rely strongly on their experience with the previous experiment in estimating the rates, resolutions, background rejection.
factors, etc. of E865. One of the most important innovations is the newly designed 6 GeV/c unseparated K+ beam shown in Fig. 20. The augmented AGS intensity will be used both to supply more K+ to the apparatus and to allow a longer beam channel. The latter permits better collimation and the reduction of beam halo. It is calculated that with $1.2 \times 10^{13}$ protons per spill, this beam will deliver seven times more K+ than were available in E777, in a rate environment that is no worse than that of the earlier experiment.

The second largest improvement factor of E865 is the increased acceptance which will be three times that of E777. This is mainly due to increasing the aperture of the spectrometer magnet (M2 in Fig. 19) both vertically and horizontally. In addition, the muon identifier will extend over both sides of the beam. Improvements in triggering and added chamber redundancy are expected to increase the product of triggering and reconstruction efficiencies by about a factor 1.5. Finally, it is planned to run E865 a factor 2.3 longer than E777 was run. The product of these improvements is the factor of 70 mentioned above.

Of course the background rejection power of the experiment must improve commensurately. A number of steps will be taken to facilitate this. A fourth PWC plane will be added to each chamber station. This added redundancy improves the efficiency as mentioned above, but it also helps in rejecting offline background, both through improved position resolution and spurious hit rejection. Since the momentum resolution of E777 was dominated by multiple Coulomb scattering, it can be improved by using aluminum high voltage wires in place of the stainless steel used in the earlier experiment. It should also be possible to reduce the material presented to daughter tracks by the Čerenkov counters.

A number of improvements will be made in particle identification. Much has been learned about the limitations on E777's Čerenkov counter efficiencies, and remedies will be applied. The electromagnetic shower counters will be replaced by fine-sampling fiber read-out devices and the longitudinal granularity of the muon identifier will be increased.

The goal is to create a versatile detector that can serve as a K+ decay facility. At least 50,000 $K^+ \rightarrow \pi^+\mu^+\mu^-$ decays should be collected, allowing subtle features of the dynamics to be probed. Data samples of tens of thousands of decays such as $K^+ \rightarrow \pi^+\mu^+\mu^-$ and $K^+ \rightarrow \pi^+\gamma\gamma$ should also be achievable. Special runs could be made to explore topics such as CP-violating asymmetries in $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$. With a further upgrade to the muon identifier, one could study the polarization of the $\mu^+$ in $K^+ \rightarrow \pi^+\mu^+\mu^-$, and the
CP-violating component of the $\mu^+$ in $K\mu 3$ decay. There is also the possibility of studying CP-violation in $K\ell 4$ decay, among other exciting opportunities.

$K^+ \to \pi^+ \nu \bar{\nu}$

Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ can test the induced flavor-changing neutral current structure of the Standard Model. Fig. 21 shows the leading short distance contributions to this process. These are basically the diagrams of Fig. 11b, with internal and external lepton lines reversed. The branching ratio (for a single neutrino flavor) is given by:

$$B(K^+ \to \pi^+ \nu_1 \bar{\nu}_1) = B(K^+ \to \pi^0 e^+ \nu) \times \frac{\alpha^2}{8\pi^2 \sin^4 \theta_W} \sum_{j=e,t} V^*_{j1} V_{j3} D(z_j)^2 / V^2 U_{33}$$  \hspace{1cm} (6a)$$

where

$$D(z) \equiv \frac{1}{8} \left[ 1 + \frac{3}{(1 - z)^2} \right] \left( \frac{4 - z}{1 - z} \right)^2 [z \ln z \right.$$  \hspace{1cm} (6b)$$

$$z_j \equiv (m_j/M_W)^2$$  \hspace{1cm} (6c)$$

Long distance contributions to this decay are very small\(^{10,39}\). QCD corrections have been calculated\(^{7,40}\) and found to be small and reasonably unambiguous, once the CKM angles and $m_t$ are known. Their influence on $B(K^+ \to \pi^+ \nu \bar{\nu})$ can be roughly estimated by multiplying the charm term in Eq. (6) by 0.7. Calculations of the branching ratio using recent constraints on the CKM angles and $m_t$\(^{10,41-43}\) give a range of $\sim 0.6 - 4 \times 10^{-10}$ for three $\nu$ generations. I emphasize that this process offers the prospect of SM parameter constraints that are largely free of 'hadronic engineering' and other theoretical uncertainties. This is not yet feasible, however, since the experimental limit is still about a factor ten higher than the predicted range. Thus at the moment there is still a window for possible new physics. Such non-Standard physics\(^{44}\) comes in at least four categories. The first is that in which the final state is indeed $\pi^+ \nu \bar{\nu}$ but there are non-SM intermediate states, e.g. SUSYons replace their normal partners in the loops of Fig. 21. In the second category, the final state is $\pi^+ \nu \nu'$, e.g. $\nu_e \bar{\nu}_\mu$. Thus almost any LFV model that contributes to $K^+ \to \pi^+ \mu e$ contributes here. In the third category, the final state is $\pi^+ X^0 X^0$ where $X^0 \neq \nu$. Candidates for $X^0$ include majorons\(^{45}\), lightest SUSY particle\(^{10,46}\), etc. Finally, there are the cases where there is only a single undetectable particle, i.e. $K^+ \to \pi^+ \nu \bar{\nu}$ and its observation at any
level implies physics beyond the Standard Model. There have been many candidates proposed for this $X^*$ over the years, including axions$^{46}$, light Higgs, familons$^{47}$, and hyperphotons$^{48}$. 

Figure 22: The E787 detector: (a) side view; (b) end view
Prior to the current round of AGS experiments, the measured upper limit on $B(K^+ \rightarrow \pi^+\nu\bar{\nu})$ was $1.4 \times 10^{-7}$, which is more than 200 times the SM prediction. The search for this process is made difficult by the lack of an easily exploitable signature, the near freedom from kinematic constraint, and the formidable backgrounds. In an attempt to meet these challenges, a major new initiative was launched by the E787 collaboration of BNL, Princeton, and TRIUMF.

Fig. 22 shows the solenoidal stopping $K^+$ detector built by this collaboration. A beam of $\sim 1.5 \times 10^6$ $K^+$ (along with $\sim 3 \times 10^6$ $\pi^+$ and $\sim 1.5 \times 10^6$ $p$) from the LESB-1 passed through a Fitch type Čerenkov counter and two MWPC stations of three planes each. It then impinged on a BeO degrader which slowed the $K^+$ momentum from $800\text{MeV}/c$ to $\sim 300\text{MeV}/c$. In 1991, the last section of the degrader was replaced by a 10cm long lead glass counter which served to veto both beam pions and final state photons. $K^+$ exiting the degrader travelled through crossed scintillator hodoscopes into a scintillating fiber stopping target. About 20% of the $K^+$ registered by the Čerenkov counter actually stopped in this target. Approximately 2 $\text{nsec}$ after a $K^+$ entered the target, a gate was opened for decay $\pi^+$'s emerging transversely. Fig. 23 shows an end view of such an event in the stopping target. This target consists of 2269 2mm round fibers epoxyed by sixes into triangles, each of which was read out by a 1 cm phototube. The momentum of the pions was measured in a small cylindrical drift chamber upon which a 1 T field was imposed. The drift chamber surrounded the target and was itself surrounded by a 24-sector cylindrical array of scintillation counters and MWPCs referred to as the “range stack”. Each sector consisted of a 52 cm long x 6.35mm thick triggering counter followed by twenty 182 cm x 19.5mm counters interspersed with two MWPC planes as shown in Fig. 22. The range stack completed the measurement of the $\pi^+$ kinetic energy and range. The range stack scintillation counters were also instrumented to record the decay sequence ($\pi \rightarrow \mu \rightarrow e$). Surrounding the range stack were four layers of non-projective 1mm lead/5mm scintillator shower counter (the “barrel veto”). Similar vetoes covered the upstream and downstream faces of the drift chamber, completing a nearly hermetic photon veto system. The rejection of $\pi^0$s from $K\pi2$ was $O(10^6)$. Fig. 24 shows a $K\pi2$ event in which both $\gamma$s converted in the barrel veto. The barrel veto had sufficient resolution ($\sigma_E/E \approx 8%/\sqrt{E}$) and granularity ($\Delta\phi = 7.5^\circ$) to reconstruct $\gamma$s for physics analysis.

The leading backgrounds to $K^+ \rightarrow \pi^+\nu\bar{\nu}$ are the copious $K\pi2$ and $K\mu2$ ($K^+ \rightarrow \mu^+\nu$) decays. As mentioned above, the former can be suppressed by a factor $\sim 10^6$ by vetoing on the photons from the $\pi^0$. In addition, each of these two-body processes can be kinematically suppressed since, in the absence of resolution effects, its charged daughter has a unique momentum in the $K^+$ center of mass (which for E787 is also the lab system). The resolution of the detector for the $205\text{MeV}/c \pi^+$ from $K\pi2$ decay was 2.7%
in momentum ($p$), and 3.8% in both range ($R$) and in kinetic energy ($T$). A cut placed some $10\text{MeV}/c$ (in equivalent momentum for $T$ and $R$) above the peak yielded a rejection factor of several thousand to one. The kinematic rejection of $K\mu_2$ was even better. $K\mu_2$ can also be rejected via particle identification of the $\mu^+$. In this energy range, the relations between $R$, $T$, $p$, $dE/dx$, etc. are quite different for pions and muons. It is even more effective to exploit the different decay chains: $\pi^+ \rightarrow 4\text{MeV}\mu^+ + (26\text{nsec}) \rightarrow e^+ (2.2\mu\text{sec})$, versus $\mu^+ \rightarrow e^+ (2.2\mu\text{sec})$. Fig. 25 shows the phototube signals due to a pion in a sequence of range stack scintillators. The $4\text{MeV}$ muon has a range of only about 1mm, so that all three pulses can be required to originate from the same region of the counter. Custom 500 MHz, 8-bit transient digitizers were developed to record the decay sequences without deadtime.

Most other potential backgrounds, such as $K^+ \rightarrow \mu^+\nu\gamma$, have relatively small branching ratios and can be suppressed by combinations of the above methods. In addition, the experiment was initially designed to utilize only the high momentum part of the $\pi^+$ spectrum ($p > p_{K\pi2}$), an optimization which costs about a factor five in sensitivity, but which confines the search region to momenta higher than that of $\pi^+$ from any significant $K^+$ decay mode. As is discussed below, efforts subsequently were made to exploit the softer part of the $p_{\pi}$ spectrum.

A background made dangerous by the poor signature and lack of constraints noted above is that caused by a beam $\pi^+$ which scatters into the acceptance of the apparatus. For this to fool the analysis, the pion must be missed by the beam instrumentation and must also follow closely a $K^+$ which stops in the target but does not decay within the $50\text{nsec}$ $K$-decay gate.

Final results of the 1988 run and preliminary 1989 results are available at this time. Fig. 26 displays the $R$ versus $T$ distribution for the preliminary 1989 sample of $K^+ \rightarrow \pi^+\nu\nu$ candidates, along with Monte Carlo $K^+ \rightarrow \pi^+\nu\nu$ results. The rectangular box drawn in the figure indicates the fiducial acceptance region above the $K\pi2$ and below the $K\mu2$. In the absence of measuring errors, signal events would lie along a trajectory approximating the diagonal of the box. The residual events below and to the right of the box are $K\pi2$ events in which the $\pi^0$ has been missed. As there are no events in the signal region, a 90% c.l. upper limit of $B(K^+ \rightarrow \pi^+\nu\nu) < 5 \times 10^{-9}$ can be extracted from this data. The corresponding limit for $K^+ \rightarrow \pi^+X^0$ is considerably better, since in that case there no phase space loss. One obtains $B(K^+ \rightarrow \pi^+X^0) < 1 \times 10^{-9}$ for $m_X = 0$. These results represent approximately a 30-fold improvement over previous data.
If, instead of attributing the residual $K\pi 2$ peak of Fig. 26 to $\gamma$ veto inefficiency, it is attributed to the process $K^+ \rightarrow \pi^+\pi^0; \pi^0 \rightarrow X^0X^0$, a limit on the branching ratio of $\pi^0$ to unseen particles can be obtained. Since this measurement is not limited by statistics, the $\gamma$ veto cuts were tightened considerably beyond those used in the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ analysis. The resulting 90% c.l. upper limit for this process, which includes $\pi^0 \rightarrow \nu\bar{\nu}$, is $B(\pi^0 \rightarrow X^0X^0) < 8 \times 10^{-7}$. This result, which is based on the 1988 data sample, represents a 30-fold improvement on the previous direct limit on this decay, and an 8-fold improvement over a recent indirect limit. However, it is still a factor 500 short of the SM prediction for $\pi^0 \rightarrow \nu\bar{\nu}$ with $m_\nu = 35\text{MeV}$.

Confining the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ acceptance to the high-momentum end of the $\pi^+$ spectrum is not only costly in sensitivity, it gives the experiment somewhat of the aspect of a pin-hole camera. Although in the Standard Model, the momentum spectrum goes like $p_\pi^2$, peaking at the high end, non-SM contributions are not constrained to follow this distribution. For these reasons, a continuing effort has been made to access the part of the spectrum with $p_\pi < p_{K\pi2}$. As expected, this brings added problems of background rejection. The most serious is due to $K\pi 2$ wherein the $\pi^0$ is missed by the veto system and the $\pi^+$ interacts undetected in the stopping target. This $\pi^+$ must lose more than about 8MeV of kinetic energy, but preserve its identity in this interaction. Other backgrounds that have to be confronted are $K^+ \rightarrow \pi^+\pi^0\gamma, K\mu 2\gamma$ and $K\pi 4$. The main changes with respect to the $p_\pi > p_{K\pi 2}$ analysis are that photon veto cuts had to be tightened considerably, and additional cuts on beam and target reconstruction had to be devised. Fig. 27;a shows the momentum versus kinetic energy distribution for events satisfying all selection criteria. The dashed line indicates the signal region for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ ($T_\pi < 100\text{MeV}$ and $p_\pi < 192\text{MeV}/c$. There has also been a cut limiting the range to $< 27\text{cm}$. The observed events outside the signal region are consistent with $K\pi 2$ in which the photons have been missed. Fig. 27;b shows Monte Carlo events subjected to the same criteria. Since no events are observed within the signal region, a 90% c.l. upper limit of $2 \times 10^{-8}$ can be set. Although
the acceptance in this region is about equal to that above the $K\pi 2$, the resulting limit is quite a bit weaker because the trigger for this data was not completed until late in the 1989 run. Still this limit represents a factor $\sim 50$ improvement on the previous search in this kinematic region.

Another recent result from E787 is a limit on the rare decays $\pi^0 \rightarrow \gamma X^0$ and $\pi^0 \rightarrow \gamma X^0 X'^0$. The former is of interest in the search for possible new spin-1 particles such as light gauge bosons associated with certain extensions of the Standard Model which feature an extra U(1)$_{\text{em}}$, hyperphotons, paraphotons, axigluons, etc. The only possible SM signal is a version of the three-body reaction, $\pi^0 \rightarrow \gamma \nu \bar{\nu}$. Since this is calculated to occur at about the $10^{-18}$ level, one can be sure that any observed signal indicates new physics. As in the case of the search for $\pi^0 \rightarrow \nu \bar{\nu}$ discussed above, one uses $K\pi 2$ decays as a source of tagged $\pi^0$'s. In this case, however, the observation of a $\gamma$ as well as that of a $\pi^+$ is required. Of course an irreducible background to this search is produced by the inefficiency of the E787 detector for single $\gamma$'s, which Monte Carlo estimates to be $\mathcal{O}(10^{-3})$. Since this simulation depends on hard-to-model photonuclear reactions, one cannot confidently assign observed events to background. The analysis is basically the search for $K\pi 2$ events with one missing $\gamma$. After cuts to establish clean, analyzable $K\pi 2$ events, and to remove events with merged gammas, extra energy associated with the $\pi^+$, etc., eight events remain. The invariant missing mass squared distribution for these events is shown in Fig. 28, along with the shape expected for a massless missing particle. Fig. 29 shows the 90% c.l. limits as a function of missing mass which have been extracted from this data. These are typically $\sim 5 \times 10^{-4}$, and represent the first reported limit on this decay. Also shown are the limits on $\pi^0 \rightarrow \gamma XX'$ under two assumptions for the form of the matrix element (the masses of $X$ and $X'$ are assumed to be equal).

Figure 26: Range versus kinetic energy for residual $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidates in E787: (a) 1989 preliminary data; (b) Monte Carlo. The box outlines the search region.
Figure 27: $T^{\pi}$ vs $p^{\pi}$ distribution for: (a) surviving events in the below-the-$K\pi2$ sample of E787; (b) Monte Carlo $K^+ \rightarrow \pi^+\nu\bar{\nu}$ events.

Figure 28: $m_X^2$ distribution for surviving $\pi^0 \rightarrow \gamma X$ candidates in E787. The solid line gives the expected resolution, assuming $m_X = 0$.

E787 is also sensitive to a number of other $K^+$ decays. Results based on 1988 data for $K^+ \rightarrow \pi^+\mu^+\mu^-$ and $K^+ \rightarrow \pi^+\gamma\gamma$ have been available for some time, while analysis of later data continues. The former decay is of course closely related to the process $K^+ \rightarrow \pi^+e^+e^-$ discussed above. In the model of Ecker et al., given the E777 result$^{34}$, the predicted$^{32}$ branching ratio is $6 \times 10^{-8}$. E787 found three candidates for this decay$^{34}$ from the 1988 data sample. Conservatively attributing these to background, a 90% c.l. upper limit of $2.3 \times 10^{-7}$ was set. This represents an improvement of a factor 10 over previous data$^{65}$. Several tens of $K^+ \rightarrow \pi^+\mu^+\mu^-$ events are expected to already be on tape as a result of the subsequent E787 running. Light Higgs can also be sought in this topology ($K^+ \rightarrow \pi^+H; H \rightarrow \mu^+\mu^-$). The 1988 data was used to rule out Standard Model Higgs in this mass range, but non-SM scalars are still possible and will be searched for.
E787 used the same three-body data sample to set a limit on the SM-allowed process $K^+ \to \mu^+ \nu \mu^+ \mu^-$, which is expected $^{66}$ at $\sim 3 \times 10^{-9}$. The 90% c.l. upper limit derived, $B(K^+ \to \mu^+ \nu \mu^+ \mu^-) < 4.1 \times 10^{-7}$, is the first in the literature.

The second processes, $K^+ \to \pi^+ \gamma \gamma$, offers a critical test for modern theoretical treatments $^{67,68}$ of long distance effects in K decays. After an analysis whose main task was to eliminate $K\pi2$ background, no examples of this decay were found in the range $0 < m_{\gamma\gamma} < 100\text{MeV}/c^2$. Assuming a three-body phase space matrix element, at 90% c.l., $B(K^+ \to \pi^+ \gamma \gamma) < 10^{-8}$ was obtained $^{71}$. This represents an eightfold improvement in sensitivity over previous results $^{10}$ which were analysed under the same assumptions. The expected branching ratio $^{66,68}$ is not much smaller than the above limit, but the predicted $p_{\pi^+}$ spectrum peaks in a region of phase space ($m_{\gamma\gamma} \approx 2m_{\pi}$), not accessed by this data. To improve the sensitivity to the predicted matrix element, a new trigger was added to E787. Data presently in hand may be sufficient to see a signal at the predicted level.

The $K^+ \to \pi^+ \gamma \gamma$ sample was also used to look for new light neutrals via $K^+ \to \pi^+ \chi^0$; $\chi^0 \to \gamma \gamma$. Upper limits of roughly $10^{-7}$ at 90% c.l. were set $^{71}$ for $m_{\gamma\gamma} \leq 90\text{MeV}/c^2$.

As mentioned above, some of the E787 results discussed here stem from a two week engineering run during 1988. The rest stem from the 1989 run, which comprised about six times the sensitivity of the 1988 run. In 1990 and 1991, data sets about equal to that of 1989 were collected. The sum of these runs should allow a $K^+ \to \pi^+ \nu \bar{\nu}$ branching ratio sensitivity $\sim 10^{-9}$/event if all goes well, with commensurate increases in the data samples for the other decay modes discussed here.

Table IV summarizes E787 results obtained thus far.

To pursue the search for $K^+ \to \pi^+ \nu \bar{\nu}$ to the sensitivity predicted by the Standard Model, the E787 collaboration $^{72}$ proposed a major upgrade to their beam and detector. This proposal was accepted by the BNL management in 1989 and the upgrade is now well underway. The first order of business was to procure the necessary factor of 10 in $K^+$ stopping rate. The added intensity of Boosted AGS could be expected to provide up to half of this, but if nothing were done to increase beam purity the reaction products of beam $\pi^+$ striking the degrader would lead to unsustainable random veto losses. Thus a new beam, the LESB3 was designed to provide twice the $K^+$ per incident proton, with fewer than 0.5$\pi^+$ per $K^+$. The beam instrumentation will also be upgraded.
Table IV: E787 results

<table>
<thead>
<tr>
<th>Mode</th>
<th>result</th>
<th>Gain wrt previous data</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \to \pi^X^0 )</td>
<td>(&lt; 1.0 \times 10^{-6} ) 38 (100)</td>
<td>new particle search; future: find/rule out familon</td>
<td></td>
</tr>
<tr>
<td>( K^+ \to \pi^+\nu\bar{\nu} )</td>
<td>(&lt; 5.0 \times 10^{-6} ) 28 (100)</td>
<td>constrains new physics; future: KM angles, ( m_T )</td>
<td></td>
</tr>
<tr>
<td>( K^+ \to \pi^+\mu\mu )</td>
<td>(&lt; 2.3 \times 10^{-7} ) 10 (100)</td>
<td>should be discovered in this data, S.M. study</td>
<td></td>
</tr>
<tr>
<td>( K^+ \to \mu^+\nu\mu\mu )</td>
<td>(&lt; 4.1 \times 10^{-7} ) 2.4M (24M)</td>
<td>Higgs hunting ground; no previous limit</td>
<td></td>
</tr>
<tr>
<td>( K^+ \to \pi^+\gamma\gamma )</td>
<td>(&lt; 10^{-5} ) 8 (20)</td>
<td>Long distance effects</td>
<td></td>
</tr>
<tr>
<td>( K^+ \to \pi^X^0; X^0 \to \gamma\gamma \leq 10^{-7} )</td>
<td>(&lt; 10^{-5} ) 8 (20)</td>
<td>( m_{X^0} \leq 90 \text{MeV}/c^2 )</td>
<td></td>
</tr>
<tr>
<td>( \pi^0 \to \nu\bar{\nu} )</td>
<td>(&lt; 8 \times 10^{-7} ) 10 (( &gt; 20 )) Also search for new light particles</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \pi^0 \to \gamma X^0 )</td>
<td>(&lt; 5.3 \times 10^{-4} ) 1900 (1900)</td>
<td>New light vectors no previous limit</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 30 shows the detector in its planned ultimate configuration. Nearly every system is being upgraded. To further reduce random vetoes through better time resolution, the lead-scintillator sandwich end cap vetoes are being replaced by pure CsI vetoes read out by high-field phototubes. When the veto upgrade is completed with the addition of a pure CsI liner for the present barrel liner, the \( \pi^0 \) rejection power of the detector is expected to improve by at least one order of magnitude.

The present \( K^+ \) stopping target is being replaced by a much improved model. Advances in scintillating fiber technology now allow accurately square fibers of dimension 5mm to be produced. This results in a five times brighter target with far less "dead" (non-scintillating) material. One of the major principles of design of E787 was the minimization of dead material in which unseen interactions could produce backgrounds. Several of the upgrades benefit this aspect of the experiment. A new central drift chamber is being built which will present five times less mass to the particles being measured than does the present jet chamber. This is expected to improve the momentum resolution by a factor of two. More importantly it will produce a large reduction in the tail of the momentum resolution function. The present range stack chambers will be replaced with straw tube arrays. These also have only about 1/5 the mass of the chambers they are replacing.

Nine of the inner layers of range stack scintillator are presently multiplexed into three layers of phototubes. This economy measure has proved somewhat inimical to the effort to measure \( K^+ \to \pi^+\nu\bar{\nu} \) in the region of phase space below the \( K\pi2 \). Demultiplexing the counter readouts will alleviate this, as well as providing a number of other benefits including improved particle identification through \( dE/dx \), easier triggering for three-body decays, lower individual element rates, etc.
Summary and prospects

Table V and Table VI summarize the impressive achievements of the present round of AGS K decay experiments. For some of these processes our sensitivity has improved by more than four orders of magnitude. The mass scales being probed by LFV searches are already far beyond what can be accessed at the SSC for similar interactions. For other highly-suppressed processes, such as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, much of the initially very large windows for new physics have been explored, eliminating many proposed theories, and constraining others. For still others, such as $K^+ \rightarrow \pi^+ e^+ e^-$ and $K_L \rightarrow e^+ e^- \gamma$, large data samples have been accumulated where mere handfuls of events had been previously available, permitting the extraction of valuable dynamical information. The discovery of the decay mode $K_L \rightarrow e^+ e^- \gamma$ has changed the course of efforts to study CP-violation in rare K decay. Other potentially interesting modes such as $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma \gamma$ almost certainly be discovered when the data presently recorded is fully analyzed (if they are not, this will perhaps be even more interesting!).
Table V: BNL Rare K Decays

<table>
<thead>
<tr>
<th>Mode</th>
<th>BNL result</th>
<th>Gain wrt previous data</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \rightarrow \mu e$</td>
<td>$&lt; 3.3 \times 10^{-11}$</td>
<td>180000</td>
<td>$M_H \gtrsim 100$ TeV c.f. 10 TeV for SSC</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu e$</td>
<td>$&lt; 2.1 \times 10^{-10}$</td>
<td>22</td>
<td>complementary to $K_L \rightarrow \mu e$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>$&lt; 5 \times 10^{-9}$</td>
<td>28 (100)</td>
<td>constrains new physics; future: KM angles, $m_T$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ X^0$</td>
<td>$&lt; 1.0 \times 10^{-9}$</td>
<td>38 (100)</td>
<td>new particle search; future: find/rule out familon</td>
</tr>
<tr>
<td>$K_L \rightarrow \pi^0 ee$</td>
<td>$&lt; 5.5 \times 10^{-9}$</td>
<td>420</td>
<td>search for new scalars, non-S.M. CP-violation; future: S.M. CP-violation</td>
</tr>
<tr>
<td>$K_L \rightarrow e^+ e^-$</td>
<td>$&lt; 4.7 \times 10^{-11}$</td>
<td>4200</td>
<td>new scalar interactions?</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ ee$</td>
<td>520 events</td>
<td>13 (45)</td>
<td>search for new scalars, S.M. study</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \mu \mu$</td>
<td>$&lt; 2 \times 10^{-7}$</td>
<td>10 (100)</td>
<td>should be discovered in this data, S.M. study</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \gamma \gamma$</td>
<td>$&lt; 10^{-6}$</td>
<td>8 (20)</td>
<td>Long distance effects</td>
</tr>
<tr>
<td>$K_L \rightarrow \mu^+ \mu^-$</td>
<td>$7.0 \pm 0.5 \times 10^{-9}$</td>
<td>15 (30)</td>
<td>see weak effects? ($\text{S.M.} &gt; 6.83 \times 10^{-9}$)</td>
</tr>
</tbody>
</table>

Fig. 31 summarises the progress made and that projected for several of the most interesting rare modes. Data taken in the next round of AGS experiments should push the mass reach of K decay to $\approx 200$ TeV. The window of opportunity for new physics in suppressed decay modes such as $K^+ \rightarrow \pi^+ + \text{nothing}$ and $K_L \rightarrow e^+ e^-$ will be fully exploited. If nothing unexpected is discovered in these modes, the data will serve to measure or constrain important Standard Model constants, such as $|V_{td}|$. In other modes, such as $K_L \rightarrow \mu^+ \mu^-$ the statistics should approach the point at which similar information can be extracted. Several new opportunities for the study of CP-violation will be explored. The potential for new discoveries in any of these areas is very high. It should also be kept in mind that the most important discoveries often occur in areas that seem peripheral to the main action. Thus any of the apparently less interesting processes on the list, even those which are measured mainly because they come "for free", could yield a dramatic surprise.

This vision of the future of K decay at the AGS includes only the presently approved program. However there is certainly room for new initiatives. In Fig. 31 the line indicating progress in $K_L \rightarrow \pi^0 e^+ e^-$ ends just as the search is really getting interesting. I believe that with suitable cleverness an experiment at the AGS could go further than at any other extant facility. I believe an experiment aimed at the closely related process $K_L \rightarrow \pi^0 \mu^+ \mu^-$ might be even more felicitous. This could be combined with studies of other
Table VI: BNL Rare K Decays, continued

<table>
<thead>
<tr>
<th>Mode</th>
<th>BNL result</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \gamma e^+e^-$</td>
<td>919 events</td>
<td>(were 4), measured form factor</td>
</tr>
<tr>
<td>$K_L \to \gamma \gamma e^+e^-$</td>
<td>17 events</td>
<td>(discovery), bkrgnd to $K_L \to \pi^0 ee$</td>
</tr>
<tr>
<td>$K_L \to e^+e^-e^+e^-$</td>
<td>6 events</td>
<td></td>
</tr>
<tr>
<td>$K^+ \to \mu^+\nu\mu\mu$</td>
<td>$&lt; 4.1 \times 10^{-7}$</td>
<td>First limit, Higgs hunting ground</td>
</tr>
<tr>
<td>$\pi^0 \to \mu e$</td>
<td>$&lt; 1.6 \times 10^{-8}$</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \to \nu \bar{\nu}$</td>
<td>$&lt; 8 \times 10^{-7}$</td>
<td>10-fold improvement</td>
</tr>
<tr>
<td>$\pi^0 \to \gamma X$</td>
<td>$&lt; 5.3 \times 10^{-4}$</td>
<td>first limit</td>
</tr>
</tbody>
</table>

interesting processes such as $K_L \to \mu^+\mu^-\gamma$, and $K\mu4$. There is also no reason why a search for the cleanest probe of direct CP-violation in the K system$^{78}$, $K_L \to \pi^0 \nu \bar{\nu}$, could not be done at the AGS as well as anywhere. Finally, there is room for the wonderful K-decay experiment that no one has thought of yet.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Acknowledgements

I wish to thank R. Cousins, S. Kettell, Y. Kuno, P. Meyers, W. Marciano, W. Molson, W. Morse, and M. Zeller for fruitful conversations other assistance with this paper.

This work was supported by the U.S. Department of Energy under contract DE-AC02-76CH00016.
BNL Rare K Decay Program:

Figure 31: Top of vertical solid lines indicates sensitivity status before current AGS program. Solid-dashed interfaces indicate announced results. Bottom of dashed lines indicate anticipated sensitivity of proposed or possible AGS Booster-era experiments.

References

1. W. Marciano, this Workshop.


16. W.M. Morse et al., Results from AGS E845: $K_L^0 \rightarrow \pi^0 e^+e^-$, e$^+e^-$, BNL-46282, May 1991.


27. W. Molzon, this Workshop.


72. In 1992 the E787 collaboration was augmented by groups from KEK and INS-Tokyo.
END

DATE FILMED

1/25/93