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Kaon Physics at High Intensity Machines

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The motivation for and present activity in rare kaon decay experiments are described. The reach of present and future accelerators for this physics is discussed.

My subject today is what one could hope to achieve in the field of K-decay physics with a high-intensity proton synchrotron that came on-line sometime after 1990. The EHF is of course one such machine and similar proposals have been fielded by LASL in the US and by TRIUMF in Canada. I am assuming that such a machine would be capable of producing a few times 10^{14} protons/second in the 30 GeV energy range (~10 < E < 60 GeV have been discussed).

To assess the usefulness of an EHF-class machine, one must not only enumerate the physics opportunities and estimate how well such a machine could exploit them, but also predict to what extent currently operating facilities will have preempted these opportunities. To do a really proper job one should also factor in the effects of likely progress in related fields (e.g. heavy quark decay) on defining the physics opportunities as they will appear in 1990 or so. Be warned that this may call more for the talents of an haruscapist than those of a mere physicist!

I. Introduction

From the early history of particle physics kaon decays have been a source of fertile mysteries and profoundly stimulating surprises: the τ-θ puzzle, the $\Delta I = 1/2$ rule, CP-violation, the absence of strangeness-changing neutral currents, etc. In addition the kaon system has proved to be the graveyard of a thousand wrong theories. There's no reason to believe that it will cease to serve either of these functions in the near future. Today we search for lepton-flavor violation and evidence of a fourth generation in K decay, but given experiments that are not too myopic, we could be surprised in ways we have hardly even imagined.

Presently there is strong interest in kaon decay as a hunting grou[nd for] violations of the Standard Model. For all its successes this model has many serious deficiencies: the large number of unexplained parameters, the lack of an explanation for the repetition of families, and the "hierarchy" problem, among others. There is also the problem of CP violation whose seductively natural explanation in the model has been called into question by recent theoretical and experimental work as discussed at this conference. Attempts to probe the limits of the Standard Model generally fall into three categories. The first and most straightforward of these is simply to raise the energy as far as possible above the electroweak scale to get out of the region in which the model seems to work so well. This is the approach of the collider builders. A second approach is to measure the Standard Model parameters as precisely as possible in the hope of finding inconsistencies or deviations from prediction. This approach will certainly be exploited at any future hadron facility as has been amply discussed at this conference. Although this category may include some studies of kaons, it is the third approach in which kaons really come into their own: the search for processes suppressed or forbidden by the Standard Model. If the decay $K^0_L \to \mu e$ is observed at any level whatsoever, it is an unambiguous signal for new physics. There is no Standard Model physics background of the kind that for example clouds the search for unbalanced p_T events at the CERN SPPS. Of course there is potential background due to the limitations of instrumentation, but the signature is simple, clean, and overconstrained. The scale probed by current searches for this process can estimated by comparing the rate of $K^0_L \to \mu e$ mediated by a hypothetical "horizontal" boson with that of normal $K^+ \to \mu\nu$ decay mediated by the W (see Figure 1). Assuming that the new coupling is full strength, the mass of the horizontal boson will have to be > 200 TeV in order for $K^0_L \to \mu e$ not to be seen at the 10^{-12} level. This is a far higher scale than can be probed at any extant or even at any proposed collider. Furthermore, it turns out that in

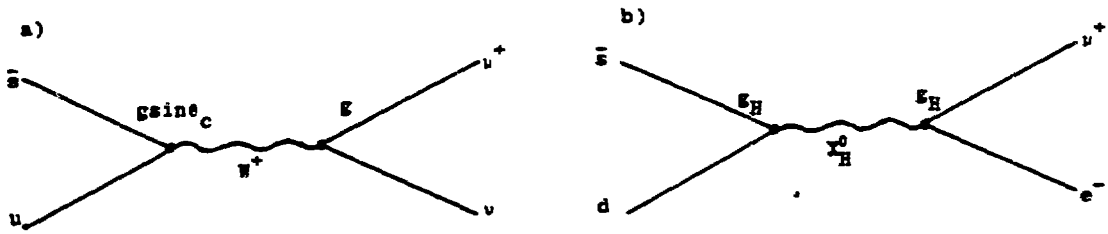

FIGURE 1

Comparison of $K^0_L \to \mu^+e^-$ via horizontal boson exchange with $K^+ \to \mu^+\nu$ via W exchange.

virtually all of the theoretical approaches which go beyond the Standard Model, technicolor, supersymmetry, compositeness, left-right symmetry, etc., $K^0{}_L \to \mu e$ is predicted to occur at some level (see Figure 2). It should be strongly emphasized that whatever motivated these models, a desire to explain the weak mass scale, CP violation, or the observed repetition of families, an aesthetic repugnance toward spontaneous symmetry breaking, a passion to unify all the forces, etc., there was no specific intention to produce lepton flavor violation. The fact that this violation occurs in such diverse approaches suggests that it is a very natural signal for physics beyond the Standard Model.

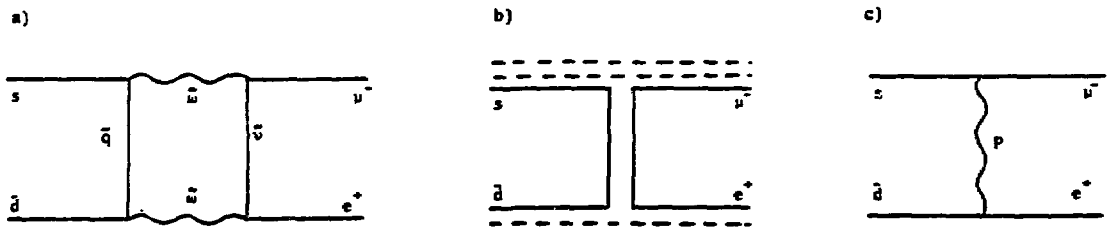

FIGURE 2
Possible contributions to $K^0{}_L \to \mu e$: a) supersymmetric loop, b) constituent exchange, c) leptoquark exchange.

Other examples of K decays forbidden in the Standard Model but predicted by new models are $K^+ \to \pi^+\mu^+e^-$, $K^0{}_L \to \pi^0\mu e$, and $K^+ \to \pi^+X^0$ (where X^0 is a light neutral scalar or pseudoscalar).

TABLE 1 - Suppressed K Decay Modes

Mode	suppressed by	to	current u.l.
$K^0_L \to e^+e^-$	G.I.M. & helicity	$\sim 3 \times 10^{-12}$	$\sim 10^{-8}$
$K^0_L \to \pi^0e^+e^-$	G.I.M. & CP-conservation	$\sim 10^{-11}$	2.3×10^{-6}
$K^0_L \to \mu^-\mu^+\gamma$	CP-conservation	$\sim .001$	1.
$K^+ \to \pi\nu\bar{\nu}$	G.I.M.	$\sim 10^{-10}$	1.4×10^{-7}

There is also potential for dramatic discoveries in K decays that are suppressed but not entirely forbidden by the Standard Model. Table 1 lists four such processes, giving in each case the reason for suppression, the expected branching ratio and the current upper limit. $K^0{}_L \to e^+e^-$ is especially sensitive to possible new scalar or pseudoscalar interactions (e.g. Higgs) since these would not be subject to the large helicity suppression of the Standard Model. $K^0_L \to \pi^0 e^+ e^-$ is expected to be suppressed down to ~ 10^{-6} by G.I.M.[1] and then further suppressed by CP conservation down to ~10^{-11}. Since the current u.l. is 2.3×10^{-6} [2], this allows a window of opportunity of ~ 10^5 for the appearance of new physics. This decay is of particular interest to kaon factory proponents because of its small predicted branching ratio and its potential importance to the study of CP-violation. A large direct CP-violation (roughly equal to that of the state mixing component) is predicted[3] for this mode. In the Standard Model, μ^+ polarization in $K^0_L \to \mu^+\mu^-$ is suppressed by CP-conservation to P_L ~ .001 [4] unless the Higgs mass is very small (<< 5 GeV)[5]. The presence of new physics can raise this value considerably[4-6]. Since polarization is an interference effect, relatively modest efforts can yield very sensitive limits on the amplitude for new kinds of CP-violating interactions. P_L is currently completely unmeasured, but an upcoming AGS experiment[7] proposes to measure it to ~ 15%. Such an experiment is appropriate for a kaon factory since it requires good systematics and high statistics for a rather rare process (B.R. ~ 10^{-8}). The last process in Table 1, $K^+ \to \pi^+\nu\bar{\nu}$, represents perhaps the cleanest available test of higher order electroweak effects in the Standard Model. It is virtually unique in its freedom from long distance effects. G.I.M. suppression reduces the expected branching ratio to ~ 10^{-10} [8-12] whereas the current upper limit is 1.4×10^{-7} [13], leaving a window of ~ 1000 for observing possible new physics. The motivation for studying this mode will be discussed more fully below.

Almost any of the CP-violating processes could also have been entered in Table 1. The Standard Model has a natural place for CP-violating effects[14] but it is now known that the predicted levels are rather small, perhaps embarassingly so[15]. Therefore it is important to pursue these processes as far as one can, something a hadron facility will be ideally placed to do.

A program of experiments probing the physics discussed above is currently underway at Brookhaven National Laboratory. I will discuss the aims of this program, what the future may hold for kaon decay experiments at BNL, and also the problems that will have to be addressed in pursuit of this physics at a future hadron facility.

II. Lepton flavor violation.

Although lepton flavor violation is predicted in almost all theoretical attempts to go beyond the Standard Model, these predictions are quite diverse not only in the level of but also in the pattern of that violation. There are potentially a great number of such processes, many outside the kaon system (e.g. $e^+ + e^- \rightarrow \mu e$, $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu \rightarrow e$ conversion in the field of a nucleus, $\tau \rightarrow \mu\gamma$, $b \rightarrow \mu e$, etc.). Generally speaking, production or formation processes cannot compete with decays in sensitivity. Moreover the supply of heavy quarks and leptons is not yet sufficient to make studies of their decays competitive with similar studies of light particles. This leaves rare decays of kaons and muons as the most effective probes. Since there are few regularities in the model predictions, one must study all accessible processes. In the case of muon decays this has been pursued vigorously for many years now at the pion factories[16], and branching ratio sensitivities in the 10^{-11} - 10^{-12} range have been achieved. Thus there is a reasonable basis on which to predict the problems and performance of the generation of experiments that seek to go to 10^{-13} [17]. By contrast, kaon decay experiments which aim to go to the 10^{-11} - 10^{-12} level are only now being launched at BNL[18]. This makes attempts to prognosticate the 10^{-13} level experiments that might be attempted at a future hadron facility much more problematic.

The lepton flavor changing K decays currently being pursued are $K^0_L \rightarrow \mu e$ and $K^+ \rightarrow \pi\mu e$. For couplings of equal strength, the predicted branching ratio of the K^0_L decay is about 50 times higher than that of the K^+ decay, owing to phase space and the fact that the K^+ total decay rate is four times that of the K^0_L. Since the K^+ decay is not fundamentally easier to detect, one might ask why it's necessary to do this kind of experiment as well. The answer is that if the interaction responsible for the lepton flavor violation is vector or scalar in nature, $K^0_L \rightarrow \mu e$ won't go. A second motivation invokes the concept of generation number that arises in many of the models[19]. Generation number +1 is attributed to first generation fermions such as e^- or u-quark; their antiparticles have generation number -1. Generation number +2 is attributed to second generation fermions such as μ^- and c-quark, and so on. It is simple to verify then that the reaction $K^+ \rightarrow \pi^+\mu^+e^-$ conserves this quantum number, whereas the reaction $K^+ \rightarrow \pi^+\mu^-e^+$ violates it by two units. If lepton flavor violation were observed, it would be very interesting to know whether it obeyed, ignored, or even preferred to violate generation number. Unfortunately this is not possible in any practical K^0 experiment since in a K^0_L beam one has no way of knowing whether a particular μe charge state originated from a K^0 or a $\bar{K}^0$. Finally, the three body decay allows one to study not only a rate of lepton flavor violation but the dependence of its matrix element on two variables.

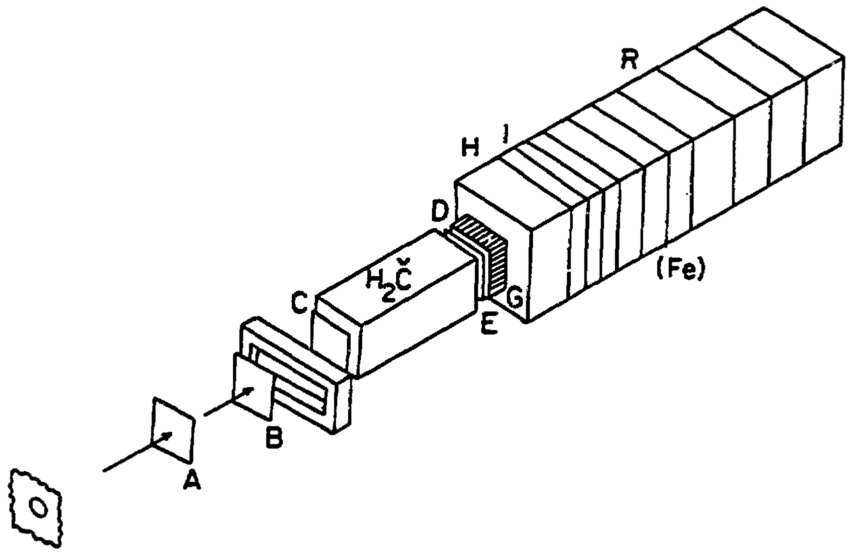

FIGURE 3

The Yale-BNL $K^0_L \rightarrow \mu e$ spectrometer (E780).

Figure 3 is a schematic of the apparatus of AGS E780, a search for $K^0_L \rightarrow \mu e$ and e^+e^- [20]. A 0 degree neutral beam containing about 80 million K^0_L and perhaps 30 times as many neutrons/pulse[21] impinges on a 3m evacuated decay tank. The useful K^0_L's spectrum extends from 4 to 20 GeV/c, peaking near 8 GeV/c. Thus about 1.2% of the K^0_L's decay in the tank. Oppositely charged tracks emanating from a common vertex are bent parallel to the beam by a dipole magnet whose p_T kick is set to equal that of the decays being sought. This serves to maximize the acceptance for the signal at the expense of background decays, all of which have smaller Q-values than $K^0_L \rightarrow \mu e$ or e^+e^-. This technique also simplifies triggering. The trajectories of the charged tracks are measured by four sets of mini-drift chambers, two placed before and two after the magnet. These chambers have a position resolution of ~ 150 μ and a memory time of < 100 nsec. Electron identification is made via an atmospheric hydrogen Cerenkov counter and an array of lead glass Cerenkov counters. The lead glass can also serve to give a prompt estimate of the electron energy for triggering purposes. Muons are identified by a hadron filter and muon range array. The acceptance of the apparatus is about 6% so that in a nominal 1000 hour (~ one million AGS pulse) run, the expected sensitivity is $2.3 \times [10^6 \times 8 \times 10^7 \times 0.012 \times 0.06]^{-1} = 4 \times 10^{-11}$. The experiment is not beam limited so that if the rates prove manageable it may be possible to push the limit to 10^{-11}. This is to be compared to the present effective limit of ~ 10^{-8}.

It is expected that the main background to $K^0_L \to \mu e$ will stem from the copious $K^0_L \to \pi e \nu$ decay in which the daughter pion itself decays to $\mu\nu$ in the apparatus. At this point the background is topologically equivalent to the signal and so is impossible to distinguish from it via particle identification alone. However kinematic and tracking quality constraints are effective enough that an extremely improbable sequence of events must occur for the background to become indistinguishable from the signal. First, the K-e3 decay must give very little momentum to the neutrino so that the initial kinematics are as similar as possible to those of the signal. Secondly, the pion must decay near the center of the dipole magnet so that the event will not unmask itself through a poor vertex or upstream-downstream mis-matching. Thirdly, the π decay plane must coincide with the bending plane of the magnet so that there is no giveaway "kink" in the non-bending plane. Fourthly the sense of the π decay must be opposite the sense of the magnet kick, giving the composite π-μ trajectory an apparent momentum higher than that of its components. This can then compensate for the missing Q carried off by neutrinos. This chain of events which occurs at the 10^{-11} level is typical of the unlikely combinations of circumstances that can bedevil rare decay experiments. Here the best defense is good resolution that forces each link in the chain to be less and less probable. Unfortunately it is very difficult to push the resolution much beyond what is currently being achieved because multiple scattering is already beginning to dominate position determination error. This is exacerbated by the effects of high rates (e.g. one would like as many wires as possible to keep the occupation of each reasonably low, but more wires mean more multiple scattering). To go beyond this level of background rejection E780 has added the muon range array mentioned above. Since the true momentum of the emerging background muon is lower than that measured by the spectrometer, the range will appear to be too short. A 10% determination of the range is expected to yield a further factor of about four in rejection. Thus the 10^{-11} level in sensitivity may be attained if the apparatus can stand up to the rates. E780 had an engineering run last year and is expected to take some usable physics data this June.

A second AGS experiment, E791 [7], represents an even more ambitious pursuit of this physics. This experiment, schematically depicted in Figure 4, requested in the proposal a proton intensity on target equal to the

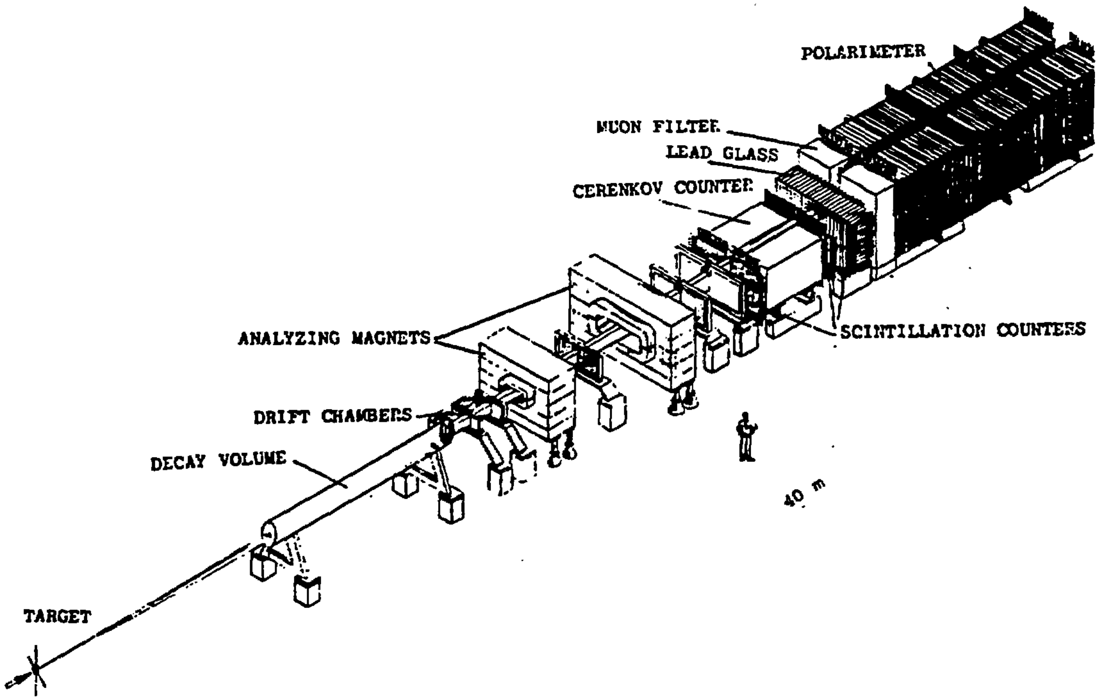

FIGURE 4

The UCLA-LANL-Penn-Stanford-Temple-William&Mary rare decay spectrometer (E791).

entire primary beam of the AGS at the time. This flux would result in the remarkable figure of 5 x 10^8 incident K^0_L/pulse of which ~ 1.4 x 10^7/pulse would decay in the 8m decay tank. Since these K's would be accompanied by ~ 2 x 10^{10} neutrons/pulse, great efforts were made to minimize the amount of material in the path of the beam (it is conducted in vacuum through the apparatus). As in E780, this experiment uses gas and lead glass C counters to identify electrons and a range measurement to identify muons. The two magnets are run at equal fields but opposite polarities, thus restoring the incident particle directions. The measurement of these angles, combined with the lead glass estimate of the electron energy, allows an approximate on-line determination of the μe effective mass. In addition, the resulting redundancy in momentum measurement is expected to reduce the Ke3-generated background discussed above more than tenfold, thus allowing a measurement at the 10^{-12} level. The anticipated statistical sensitivity is also commensurate with this goal. The acceptance of the device is ~ .06, and it is planned to run for a nominal 2000 hours, giving a branching ratio limit of 2.3 x [2 x 10^6 x 1.4 x 10^7 x .06]$^{-1}$ ~ 10^{-12}. The sensitivity will be similar for $K^0_L \rightarrow e^+e^-$ which ought to be sufficient to detect this decay at the S.M.

level. The experiment will also attempt to measure final states containing photons so that, for example, it will probe $K^0_L \rightarrow \pi^0 e^+ e^-$ to the few 10^{-11} level. Finally, the muon range measurement will actually be made in a marble, drift-plane polarimeter that (in a future phase of the experiment) will allow determination of μ^+ polarization in $K^0_L \rightarrow \mu^+\mu^-$ to about 15%. It is planned to take test data for this experiment this coming Fall, with real data taking commencing early next year.

It is probably not possible at the present AGS to pursue $K^0_L \rightarrow \mu e$ much beyond 10^{-12}. A substantial fraction of the circulating protons is used in E791, the beam aperture (~100μsr) is already very large for such a high rate situation, and the acceptance of the device is reasonably large. Even with the present parameters, it's not clear if the instrumentation, which is pretty much state of the art, can stand up to the rates. Thus one must wait for changes in the machine environment for significant further progress. The AGS is currently building an accumulator/booster[22] which will raise the proton intensity to at least 5 x 10^{13}/pulse. Further improvements are also under discussion, but these would not take effect until the 1990's. Thus I assume that the raw rate will be available to go beyond E791 by a factor 5. How well this could be exploited won't really be clear until E791 has run at full intensity. The best I can do is to outline some of the problems that can already be anticipated. I am guided in this by the E791 proposal[7] and by the AGS II Task Force Report[23].

At the anticipated rate, an average of 1.4 extra K decay events will be present within the memory time of the E791 chambers along with each accepted event. This turns out to imply that at least one hit in 25-50% of the accepted events will be "contaminated" by an accidental hit in the same drift cell. This estimate does not include the effects of neutron-engendered events, muon halo, etc., and so is sure to be a lower limit. Given the potential impact of the observation of $K^0_L \rightarrow \mu e$, clearly one could not accept a large fraction of contaminated events. Thus improvements in the chambers will be needed to get beyond the 10^{-12} level. These improvements would not be trivial ones, since as discussed above, the obvious expedient of reducing the wire spacing increases the multiple scattering, thus compromising the momentum resolution, kink recognition, goodness of vertex fit, etc. that are crucial for background rejection. The residual K-e3 induced background in E791 is estimated to be a fraction of 10^{-13} [24] so, while acceptable for the current experiment, would start to get dangerous if the statistical sensitivity increased by a factor 5 at the cost of significantly compromising the resolution. Another background, estimated to come in at $\sim 10^{-13}$ [24] in E791 is due to random coincidences between an electron from K-e3 decay and a muon from a virtually simultaneous K-μ3 decay. This kind of background increases quadratically with rate and so would contribute at the 4×10^{-13} level. This alone would raise the 90% c.l. upper limit that could otherwise be achieved from 2×10^{-13} to $\sim 8 \times 10^{-13}$. This background could be attacked by improving the timing scintillators (not easy at high rates) and by attempting to detect and veto on at least one of the pions that accompanies each lepton. Now given that these and other problems could eventually be overcome, the sensitivity for $K^0_L \to \mu e$ could be further improved to $\sim 10^{-13}$ at a K factory (or by the addition of a stretcher ring to improve the AGS duty factor from ~ 0.4 to ~ 1.0). One could then raise the average intensity by a factor 2.5 with no concomitant increase in the instantaneous rates.

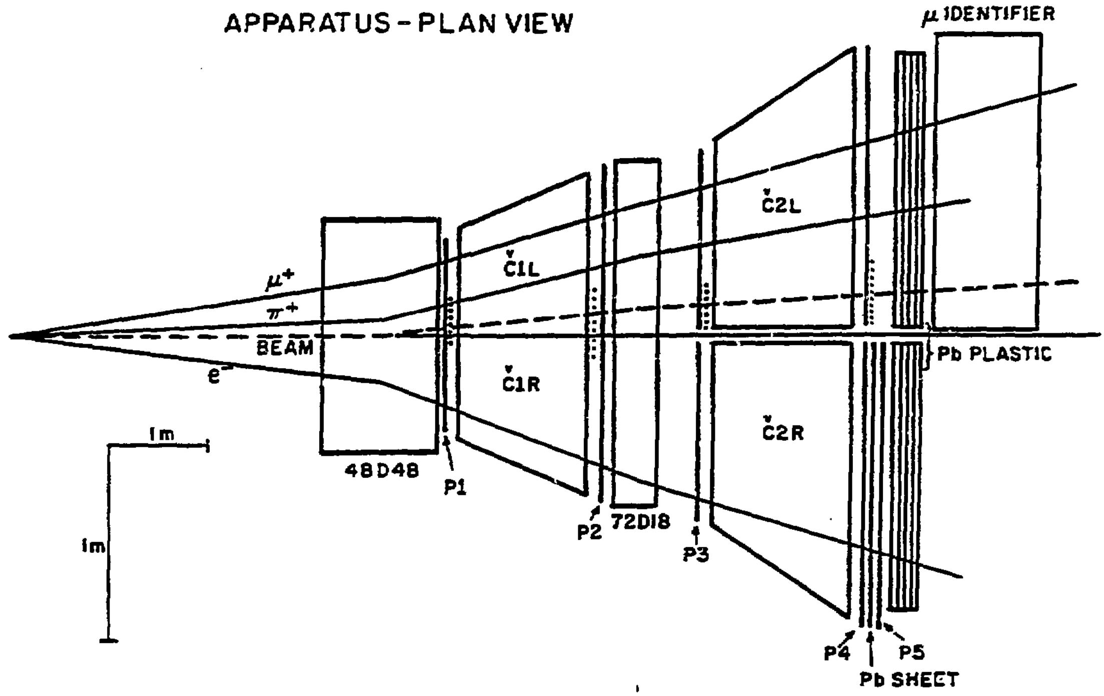

FIGURE 5

The BNL-SIN-Yale-Washington $K^+ \to \pi\mu e$ spectrometer (E777).

Lepton flavor violation experiments of the second type are represented at the AGS by E777 [25]. Figure 5 shows the $K^+ \to \pi^+\mu^+e^-$ spectrometer for this experiment. A 6 GeV/c positive beam containing 3×10^7 K^+, and about 20 times that many π^+ and p/burst impinges on a 5m decay tank, wherein $\sim$ 11% of the K^+ decay. After the decay region, a 48D48 magnet precedes any detector elements. This magnet serves to kick the K^+ daughter particles out of the high rate beam region and to separate them by sign. The former property allows the beam region of the subsequent MWPC spectrometer to be deadened without loss of acceptance and the latter property allows the particle i.d. systems on the two sides of the beam to be separately optimized. The acceptance of the spectrometer is ~ .06, which in a nominal 1000 hr run, allows a sensitivity of $2.3 \times [10^6 \times 3 \times 10^7 \times .11 \times .06]^{-1} \sim 10^{-11}$. The resolution for M_K is ~ 1%. On the negative (e) side there are two layers of atmospheric H_2 Cerenkov counters separated by the spectrometer magnet. Set in coincidence, these have extremely low efficiency for particles heavier than electrons. They are followed by a shower counter for further positive electron identification. On the positive (π,μ) side, there are also two layers of gas Cerenkov counters, but these are filled with a mixture of CO_2 and N_2, optimized to be extremely efficient for electrons, and set in veto. Behind them is a second shower counter, also set in veto, and finally a muon range array. In $K^+ \to \pi\mu e$, unlike $K^0_L \to \mu e$, particle identification pays off handsomely, so that the experimenters have concentrated much effort on this aspect of their detector. To reach a sensitivity of 10^{-11}, their rejection requirements are $\pi,\mu \to e : < 10^{-7}$, $e \to \mu : < 10^{-6}$, $e \to \pi : < 10^{-5}$, $\pi \to \mu : < 10^{-2}$. Much of the anticipated background stems from $K^+ \to \pi^+\pi^-\pi^+$ in which various of the daughter pions either decay to leptons or are mistaken for them by the particle i.d. system. A second source of background is the sequential decay $K^+ \to \pi^+\pi^0$ (B.R. = .21) followed by $\pi^0 \to ee\gamma$ (B.R. = .012), in association with $e \to \mu$ misidentification. This background is potentially very dangerous since the misattribution of the muon mass to the electron tends to compensate for the energy carried off by the unseen photon. This background is also the leading contributor to the trigger since it constitutes the most copious source of K^+-generated e^-'s.

In addition to $K^+ \to \pi\mu e$, E777 is sensitive to several other interesting decay modes, most notably $K^+ \to \pi^+ ee$. This is particularly topical because of the recent discovery in heavy ion collisions[26] of correlated $e^+ - e^-$ peaks that suggest the existence of a new boson of mass 1.7 MeV. It has recently been suggested[27,28] that this boson is a close relative of the original Weinberg-Wilczek axion[29,30]. In this model, $K^+ \to \pi^+$ axion is expected to have a branching ratio $> 10^{-7}$. If so, E777 should be able to detect it fairly easily.

It's also possible in this type of experiment to tag the π^0's from $K^+ \to \pi^+\pi^0$ for use in studies of rare π^0 decays. This is in fact the method by which the decay $\pi^0 \to e^+e^-$ was discovered[31]. E777 should be able to collect several hundred examples of this decay.

This experiment is the furthest along of any of the BNL rare decay series and should be taking physics data this June.

In the course of the AGS II Task Force workshop[23], the proponents of E777 made estimates of how far an experiment of this type could be pushed at the AGS. They concluded that 1) the present experiment is not at all beam limited and is conservative in design, 2) the experiment could be pushed to $\sim 10^{-12}$ by improving the chamber time resolution from 30 nsec to 5 nsec and by running twice as long, 3) at that point the leading anticipated background, arising from the presence of random tracks (presumably muons), would come in at $\sim 3 \times 10^{-13}$, 4) a further factor 2 could be obtained if a stretcher were built. They considered the use of a separated K^+ beam as a possible improvement but concluded that it would not be useful unless its intensity were >> 1% of that of an unseparated beam.

These extrapolations are conservative compared to those made for $K^0_L \to \mu e$. The situation ought to be much clearer in about a year when at least one experiment of each type will have had a chance to look at real data.

III. $K^+ \to \pi^+$ + nothing

Here "nothing" refers to a neutral particle or particles that interacts with matter too weakly to be detected in any apparatus of practical size. The only known candidate for such a particle is of course the neutrino. A single neutrino recoiling against the π is excluded by angular momentum conservation among other laws so that the discovery of such a process would provide an unambiguous signal for new physics. The signature for this process is the appearance of an apparently unaccompanied pion with a unique momentum in the parent K center of mass. This is reasonably tractable from an experimental point of view as long as the momentum is significantly greater than 205 MeV/c (which corresponds to a recoiling π^0 from the copious process $K^+ \to \pi^+\pi^0$). Over the years many candidates for such a new particle have been proposed. One of the most interesting is of course the axion[29,30]. It has long been assumed that the "standard" axion was ruled out, partly by its failure to be observed in experiments of this sort[13,32], and that the only viable species of axion remaining was the so-called "invisible" one[33] that could not possibly show up in K decay. However recent events put this decay in a new light. For one thing it has been realized that the interpretation of this kind of experiment is more complicated than previously appreciated[34]. For axion masses above 1 MeV or so, the axion decay length is short enough that in most events decay gammas or electrons appear in the apparatus, possibly compromising the trigger.

For another, it has been pointed out[35] that axions based on mass scales much higher than the weak scale are not necessarily invisible to kaon decay. Even if it is hopelessly invisible, Wilczek has pointed out[36] that in theories with a global family symmetry, the axion tends to have a visible companion christened by him, the "familon". This particle is the Goldstone boson arising from the breaking of the family symmetry. The familon will participate in flavor changing decays such as $\mu \rightarrow e^+f$ and $K^+ \rightarrow \pi^+f$. The branching ratio for the latter process is estimated to be 2.7×10^{14} GeV^2/F^2 where F is the symmetry breaking scale. F should be of the same order as that of the axion which is limited to the range 10^9 - 10^{12} GeV by astrophysical[37] and cosmological[38] constraints. This translates to a branching ratio range of 2.7×10^{-5} to 2.7×10^{-11}. The current upper limit is 4.5×10^{-8} [13], so that a range of a factor 1600 remains to be explored. Since this entire range is within the reach of current technology, this promising approach to the family problem can be verified or disproved by near-term experiments. One should also note that this is a case in which a rare kaon decay experiment is sensitive to mass scales far above those accessible at any planned or even conceived-of collider.

In addition to particles related to axions, various non-standard Higgs[39] and other candidates have been proposed in the literature. More recently, the idea of the existence of hyperphotons has been revived[40] to explain some apparent anomalies in the measurement of the gravitational constant. These would constitute another candidate for the X^0 in the process $K^+ \rightarrow \pi^+X^0$. The predicted rate for $K^+ \rightarrow \pi^+$ hyperphoton is already in some trouble with the observed upper limit[41] so that near-term experiments must either see this process or rule out this idea.

These examples should convince you that the process $K^+ \rightarrow \pi^+X^0$ is an important window for new physics, even if you do not take some of the current candidates for X^0 very seriously. The process $K^+ \rightarrow \pi^+X^0X^{0\prime}$ provides an equally important window. Although not completely without contribution from known physics, this channel is unique in its freedom from long-distance effects down to ~ 10^{-13}. Therefore short-distance phenomena, whether Standard Model or new, can be pursued to that level. This contrasts with other decays of current interest such as $K^0_L \rightarrow \mu^+\mu^-$ or $K^+ \rightarrow \pi^+e^+e^-$ wherein "soft" physics obscures possible new phenomina. In $K^+ \rightarrow \pi^+\nu\bar{\nu}$, we have one of the only practical tests of higher order electroweak effects. Figure 6 shows the lowest order Standard Model contributions to this decay. QCD corrections are relatively small (~ 20%) and reasonably well understood[10,11]. The remaining indeterminacy is almost entirely a function of

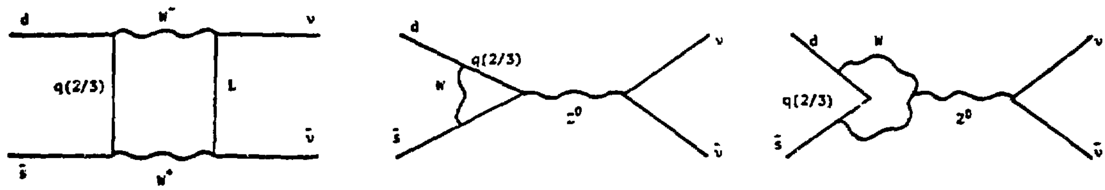

FIGURE 6

Contributions to $K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model.

the uncertainty in Standard Model parameters such as the t-quark mass and the Kobayashi-Maskawa angles. Roughly:

$$BR(K^+ \to \pi^+\nu\bar{\nu}) \approx 6.1\times10^{-7}\left|D(x_c) + \sin\theta_2(\sin\theta_2 + \sin\theta_3 e^{i\delta})D(x_t)\right|^2 \quad \{1\}$$

where θ_2, θ_3, and δ are K-M angles, and $x_i \equiv (m_i/m_W)^2$. $D(x) \sim .004$ for $m_i = m_c$, ~ 1 for $m_i \sim 60$ GeV, and $\sim \sqrt{x_i}$ for $m_i = 40$ - 100 GeV. Originally, the large $D(x_t)/D(x_c)$ ratio seemed to imply dominance of the t-quark contribution, and a value for the branching ratio of a few x 10^{-9} [9-11]. However, as emphasized in a recent calculation[12], the unexpectedly large value found for τ_b[42] leads to rather low upper limits for $\sin\theta_2$ and $\sin\theta_3$, reducing the t-quark contribution to O(c-quark contribution). The result of this calculation is shown in Figure 7. If m_t is regarded as known only to be $\gtrsim$ 35 GeV, the predicted branching ratio is somewhere between 3 x 10^{-11} and 6 x 10^{-10}. This range of uncertainty is likely to be reduced considerably in the near future. If, for example, a top quark mass of 40 GeV is verified, and τ_b settles down to within a few percent of 1 psec, the predicted upper limit will diminish to ~ 8 x 10^{-11}. This would leave a clear window of opportunity for the discovery of new physics of > 1000 below the current experimental upper limit of 1.4 x 10^{-7} [13].

A small selection of the many non-S.M. contributions that have been proposed for the process $K^+ \to \pi^+ X^0 X^{0\prime}$ is given in Figure 8. Nearly any mechanism for lepton flavor violation (horizontal gauge bosons, leptoquarks, constituent exchange, etc.) can lead to final states like that of Fig. 8 a). Although in most models the measured value of the K_L - K_S mass difference tends to constrain such contributions to be rather small, in principle large effects can obtain. Figure 8 b) gives an example of a contribution arising from supersymmetry, $K^+ \to \pi^+\tilde{\gamma}\tilde{\gamma}$, via squark exchange[43]. If the photinos are light enough to be produced in this process, it could occur at a rate as high as the current upper limit. Other, higher order, supersymmetric processes have been estimated to contribute at or below the

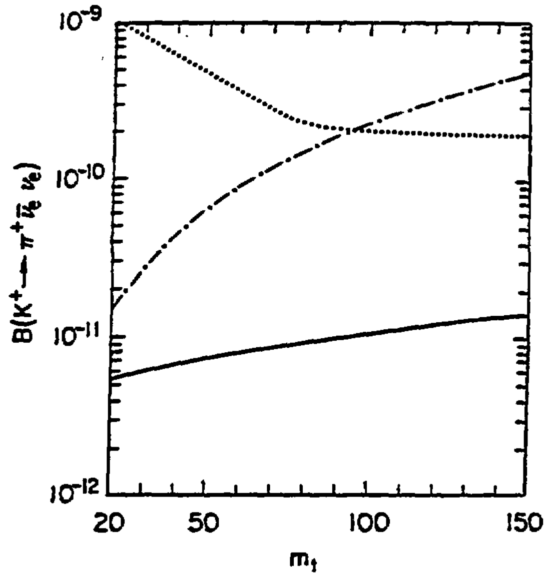

FIGURE 7

Prediction for $BR(K^+ \to \pi^+ \nu_e \bar{\nu}_e)$ as a function of top quark mass (from Ref 12). Assuming all neutrinos massless, multiply by three to get the total branching ratio for $K^+ \to \pi^+ \nu\bar{\nu}$. The dotted line is an upper limit based on the observed rate of $K^0_L \to \mu^+\mu^-$. The solid and chain-dashed lines represent the limits based on the b-quark lifetime, the rate for b -> ceν, and the upper limit for b->u/b->c.

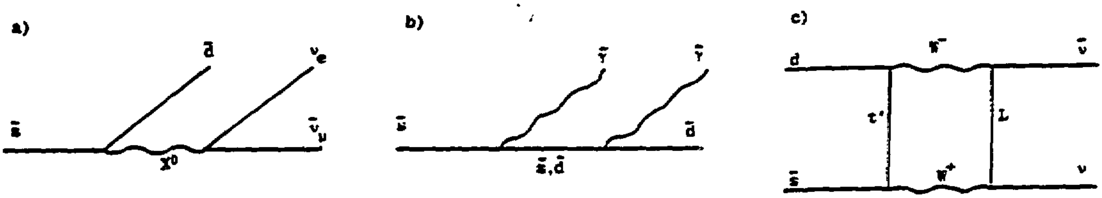

FIGURE 8

Possible non-Standard Model contributions to $K^+ \to \pi^+ X^0 X^{0\prime}$.
a) Horizontal gauge boson exchange leading to $\pi^+ \nu_e \bar{\nu}_\mu$; b) $K^+ \to \pi^+ \gamma\gamma$ via squark exhange; c) Contribution of fourth quark generation to $K^+ \to \pi^+ \nu\bar{\nu}$.

S.M. level[11,44,45]. Perhaps the most intriguing possibility is that of the contribution of a fourth generation of fermions, as illustrated in Fig. 8 c). The tight limits on the K-M angles discussed above have caused problems in accommodating the observed value of the CP violating parameter ε in the K-M model of CP violation[46]. This has led several workers[47] to propose a fourth generation whose quarks are more strongly coupled to light quarks than are those of the third generation. Since a straightforward extrapolation of {1} implies that B.R.($K^+ \rightarrow \pi^+\nu\nu$) ~ $\theta^4 m_{t'}{}^2$, clearly a dramatic effect may be expected[48,49]. The largest branching ratio compatible with a constraint due to the observed value of $K^0{}_L \rightarrow \mu^+\mu^-$, is $\lesssim 10^{-8}$. Since AGS 787 [51] expects to have a sensitivity of ~ 10^{-10}/event within a year or two, it is quite possible that this decay mode will give the first solid evidence for the existence of a fourth generation.

It's interesting to note, in light of these speculations, the potential sensitivity of the momentum spectrum of the π^+ in $K^+ \rightarrow \pi^+\nu\bar{\nu}$ to the mass of the final state neutrinos[51]. It has even been pointed out recently[52] that the shape of the spectrum is sensitive to the Dirac or Majorana nature of the neutrino. Figure 9 illustrates these points for the case of three generations, and corresponding effects would be present in the case of four. In the absence of a strongly coupled fourth generation such effects would be unobservable in the present round of experiments. However if τ-decay or other methods do not overtake this technique, it would provide a strong incentive for pushing the sensitivity of this type of experiment at a future facility. There are several other motivations for pursuing this process even if the branching ratio does not prove dramatically large. Most important is simply to obtain a positive result in the S.M. range, thus verifying that sensible higher order electroweak corrections can be made. An accurate branching ratio measurement would constitute a valuable benchmark for studies of S.M. parameters. Exactly how such a measurement might be used depends on both what its value turns out to be and on progress in other areas. For example, if the t-quark remains elusive or controversial, but much progress is made on determining the K-M parameters (e.g. through measurements of $b \rightarrow u/b \rightarrow c$, ε', etc.), the $K^+ \rightarrow \pi^+\nu\bar{\nu}$ branching ratio could help give an approximate value for m_t. If m_t is determined elsewhere, BR($K^+ \rightarrow \pi^+\nu\nu$) could help to determine the K-M parameters. One possible scenario is that m_t is determined via the observation of toponium, $\sin\theta_3$ is determined by a measurement of $b \rightarrow u/b \rightarrow c$, and future measurements reduce the error on τ_b to a negligible level. Then from the measurement of the $b \rightarrow ce\nu$ branching ratio one has[12]:

$$|U_{bc}| = |\sin\theta_3 + \sin\theta_2 e^{i\delta}| = .059\left[\frac{1\text{psec}}{\tau_b}\right]^{1/2} \qquad \{2\}$$

Clearly, under the above assumptions {1} and {2} can be solved simultaneously for $\sin\theta_2$ and $\cos\delta$! This is overstating the case, since the

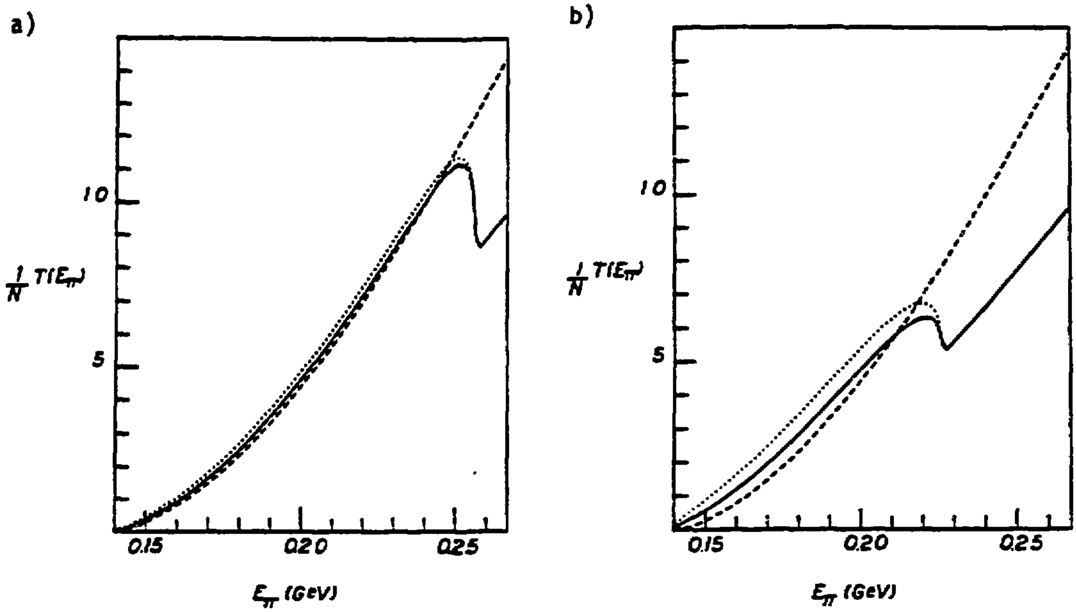

FIGURE 9

C.m. energy spectrum of π^+ from $K^+ \to \pi^+\nu\bar{\nu}$ in the case of three neutrinos, dashed line: all have mass 0, solid line: one has Dirac mass m_ν MeV, dotted line: one has Majorana mass m_ν MeV. a) m_ν=50 MeV, b) m_ν=100 MeV (from Ref 52).

instability of these solutions with respect to experimental errors and theoretical uncertainties renders this particular procedure problematical, but a valuable constraint on $\sin\theta_2$ and $\cos\delta$ should be obtained. If one could in fact extract $\cos\delta$ in this manner it would be possible to remove an uncomfortable element of circularity from discussions of CP violation and the Standard Model. If we knew, independent of direct CP measurements, that $\sin\theta_2\sin\theta_3\sin\delta \neq 0$, we would be certain that the Standard Model predicts at least some CP violation. At the moment this cannot at all be said to be established.

Unlike the lepton flavor changing processes discussed above, whose signals show up as correlated peaks in several kinematic variables, $K^+ \to \pi^+X^0X^{0'}$ is a poor signature reaction that presents an experimental challenge of a different order. Crudely speaking the two kinds of reactions are mirror images of one another. In the lepton flavor changing reactions the signal is a peak and backgrounds are smooth distributions. In $K^+ \to \pi^+X^0X^{0'}$, the most copious potential backgrounds ($K^+ \to \mu^+\nu$ and $K^+ \to \pi^+\pi^0$) yield peaks while the signal is a smooth distribution. Although one can exploit this fact to eliminate much background, there is an important difference between the positive and negative use of peaks. When one is retaining a peak as a signal, a small loss of the total is inconsequential, whereas when rejecting a peak, a tiny residual (in this case even 10^{-8}) can be catastrophic. Thus additional non-kinematic rejection factors are essential. Against $K^+ \to \mu^+\nu$, for example, one can use π-μ identification techniques, and against $K^+ \to \pi^+\pi^0$, one can veto on the daughter γ's. There are also potential backgrounds, stemming from less copious processes like $K^+ \to \mu^+\nu\gamma$, which yield smooth distributions and so must be rejected by non-kinematic methods. To optimize these techniques, all experiments of this type have used stopping K^+ beams. In addition to the extremely powerful methods of π-μ discrimination available at low energies, the stopping geometry presents several additional advantages. Relatively intense separated low energy K^+ beams with π/K ratios as low as 3:1 are readily available. Stopping the K's allows $\gtrsim$ 1/3 of them to decay usefully, as opposed to $\leq$ 10% for in-flight experiments. Thus, for example, the ratio of useful K^+/total beam in E787 is ten times that of E777. Another advantage is the small effective size of the source (in E787 a cylinder 10 cm in diameter by 20cm long). This allows large geometrical coverage for both acceptance and vetoing. Finally, since one is working in the center of mass one can exploit the kinematic peculiarities of the signal and potential backgrounds in a straightforward manner even at the trigger level.

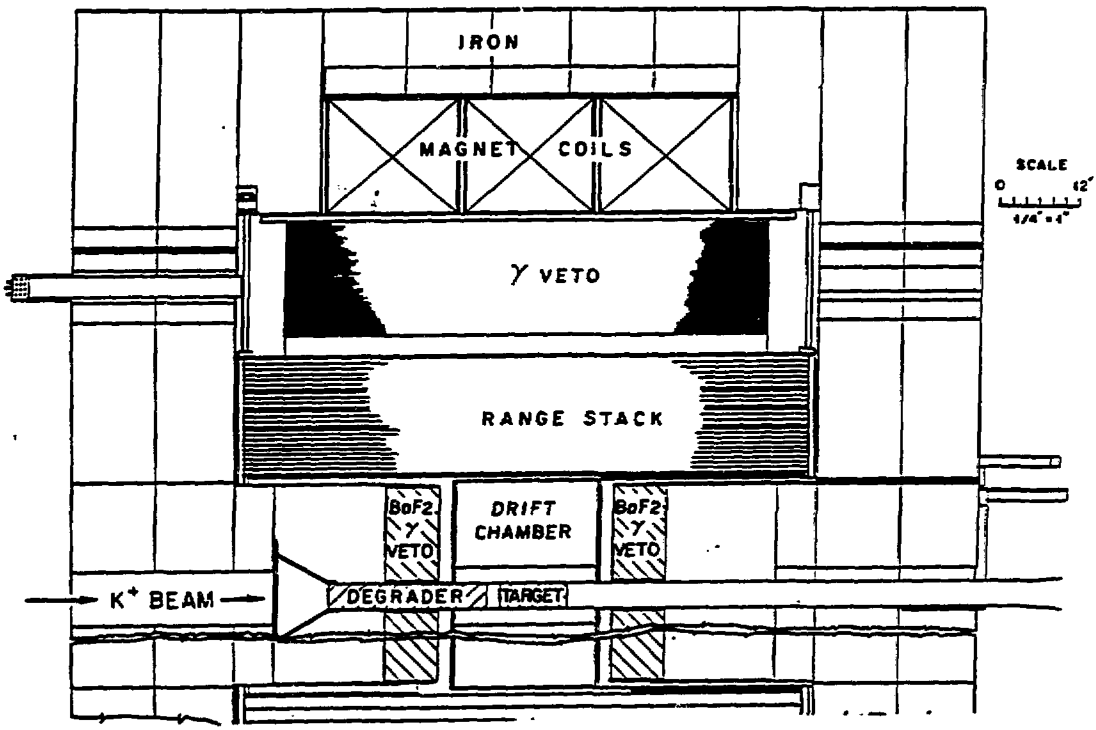

FIGURE 10

The BNL-Princeton-TRIUMF $K^+ \to \pi^+\nu\bar{\nu}$ (E787).

It is perhaps not surprising that the apparatus of E787, shown in Figure in Figure 10, bears a resemblance to certain e^+e^- colliding beam detectors, another type of apparatus that is designed to operate in the center of mass. A separated beam of ~ 10^6 K^+ impinges on a BeO degrader. About 1/3 of the K^+ penetrate the degrader and stop in a highly segmented live target. The target is constructed out of scintillating fibers and has an effective granularity of ~ 4 x 4 mm. This imaging of the decay region is essential for rejecting many of the improbable combinations of processes that begin to constitute backgrounds as the sensitivity is pressed toward 10^{-10}. For example a small fraction of the incoming K^+'s charge exchange off carbon nuclei in the target, and a small fraction of the resulting $K^0{}_L$ are so soft that they are still within the target two nsec later when the stopping gate opens. A small fraction of these decay before leaving the target. If the decay is $K^0{}_L \to \bar{\pi}^+ \ell^- \nu$ and the lepton happens to be eaten by the target, the event can look like $K^+ \to \pi^+ \nu\bar{\nu}$. The fiber target tends to expose these imposters since nearly always either the K^+ to $K^0{}_L$ vertex gap will be visible, or the lepton will be evident, or both. The segmentation also allows the π^+ energy and range in the target to be accurately determined. As shown in Fig. 10, the entire apparatus is enclosed in a 3 m i.d. solenoid run at 1T. Charged particles emerging from the target transverse to the beam are momentum analyzed to 1 or 2% in a small drift chamber, and then range out in a cylindrical array of scintillators and chambers. At this point the range, the momentum, and since the apparatus is almost entirely live, the energy are all well measured, allowing a relative rejection of muons of greater than 10^4. This is still not nearly enough and is therefore augmented by requiring the observation of the stopped pion's decay to $\mu^+\bar{\nu}$, and of that muon's subsequent decay to $e^+\nu\bar{\nu}$. Since this requires remaining sensitive for 5-10 μsec in a high rate environment, the range stack is finely segmented (~ 350 elements, further segmented by an effective factor $\gtrsim$ 5 via end-to-end timing). Finally, the entire apparatus is hermetically encased in photon vetoes. These are mainly finely divided lead-scintillator shower counters (1mm Pb/5mm scintillator) augmented in the forward and backward directions by extremely fast BaF2 crystal counters[53]. The vetoes are designed to be sensitive from 20 to 220 MeV. The required rejection of π^0's is ~ few x 10^{-6}.

Although the geometric acceptance of the apparatus is ~ 50%, the total efficiency is more like 1.5%. This discrepancy represents a price paid to pull out an uncooperative signal at the 10^{-10} level. The largest single loss is the rejection of all π^+ softer than those recoiling against π^0's. This costs a factor 5, but confines the acceptance to a region barren of π^+

stemming from any significant K^+ branch. Of course for $m_{X^0} < m_{\pi^0}$, the sensitivity for $K^+ \rightarrow \pi^+ X^0$ does not suffer this loss and is correspondingly greater. In a nominal 2200 hour run, the sensitivity for $K^+ \rightarrow \pi^+ X^0 X^{0\prime}$ is then $2.3 \times [2 \times 10^6 \times 3 \times 10^5 \times .015]^{-1} = 2 \times 10^{-10}$.

Many other interesting decay modes can also be studied with this apparatus: $K^+ > \pi^+\mu^- e^+$ (versus $K^+ \rightarrow \pi^+\mu^+ e^-$ for E777), $K^+ \rightarrow \pi^+ e^+ e^-$ (especially sensitive to low m_{ee}), $K^+ \rightarrow \pi^+\mu^+\mu^-$, $K^+ \rightarrow \pi^+\gamma\gamma$, and $K^+ \rightarrow \mu^+\nu_{heavy}$ among others. This experiment is under construction and expects to take test data this winter

To what extent could E787 be improved upon? This was addressed by the AGS II Task Force[23] and by similar groups under the auspices of LAMPF and TRIUMF[54]. First, E787 is not flux limited. The LESB II at the AGS has ~ three times the K^+ intensity of the LESB I in which E787 is situated, albeit with several times the relative pion contamination. The AGS booster will further increase the available intensity by 3-4. If sufficient resources were applied to the problem it would be possible to have ten times the K^+ stop rate with a π/K ratio similar to that of LESB I. A better optimum would probably be to sacrifice a factor 2-3 of this flux in the interest of a purer beam. π/K^+ ratios of ~ 1/1 have been discussed[55]. This would imply only ~ 3x greater singles rates than in E787 so that one could hold one's own vis a vis the background via increased segmentation. However to justify the increased statistical sensitivity it is necessary to do better. One scheme[54] involves raising the magnetic field from 1 to 3 T so that pion trajectories are more axial than radial at the range stack. This would allow the π's to be stopped in a much thinner layer of scintillator. This advantage could be translated into improvements in range resolution (via finer segmentation), energy resolution (better light collection), and photon vetoing (compact geometry allows BaF2 to be afforded everywhere). In addition the momentum resolution, which is multiple scattering limited in E787, could be improved by the ratio of the B-field strengths. Under these circumstances one could hope to reach ~ 5×10^{-11} sensitivity, which would cover nearly the entire Standard Model range.

At the EHF or other kaon factory, one would appreciate an immediate further gain in usable flux of ~ 2.5 owing to the 100% duty factor. In all an order of magnitude more flux could certainly be obtained, but there is little left to be gained in beam purity. Barring great advances in photon vetoing technology then, I would not like to predict survival in a beam more intense than a few x 10^7. For triggering, which will certainly be a problem at this rate, and for reasons of general experimental hygiene one would probably choose to give up some flux in the interest of decreasing the effective source size. I would guess at this point the level of ~ 2×10^{-12}/event could be reached.

IV. Summary and Conclusions.

In Table 2 I have summarized the present status of, near-term goals for, and possible future progress on seven rare K decay modes. In some cases I have inserted optimism factors meant to account for unanticipatable future technical advances to bring my estimates of the ultimate levels achievable to the figures shown. This optimism has been tempered to reflect the certainty that unanticipatable problems will also appear. Although the "easy" orders of magnitude of progress are likely to be creamed off by the AGS, large windows of opportunity remain. If the BNL rare K program is not pushed with the utmost vigor after the construction of the AGS Booster, these windows will be large indeed. And the stakes are high. Remember that for the lepton-flavor changing reactions and for $K^+ \rightarrow \pi^+ X^0$, a positive result will signal the advent of new physics beyond the Standard Model.

If such signals are seen at BNL or in a first round of EHF experiments, high statistics follow-up stuides will be mandatory. For these it will no longer be necessary to be 100% background free so that much more of the flux available at the EHF could be exploited.

BNL experiments may manage to see a few events of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ and $K^0_L \rightarrow \pi^0 e^+ e^-$, but the substantial samples of these processes needed to exploit their potential for the study of CP can only be obtained at an EHF-type facility. It's also possible that these decays or $K^0_L \rightarrow e^+ e^-$ could turn out to be anomalously suppressed in which case a program to detect them at lower levels would assume the greatest urgency. Finally it should be kept firmly in mind that there are other channels such as $K^+ \rightarrow \pi^+ \pi^+ e^- \bar{\nu}$ and $K^+ \rightarrow \pi^- \mu^+ \mu^-$ [56] that are forbidden or greatly suppressed by the Standard Model but which are not predicted in any of the fashionable extensions to that model. By and large these channels have not been seriously pursued for many years and they could well yield the greatest possible rewards!

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TABLE 2 - Status and prospects for rare K decays

Mode	Current u.l.	Goal of BNL experiments	Achievable at BNL w/booster	Achievable at K factory
$K_L^0 \to \mu e$	$\sim 10^{-8}$	10^{-12}	2×10^{-13}	few x 10^{-14}
$K^+ \to \pi^+\mu^+e^-$	5×10^{-9}	10^{-11}	10^{-12}	few x 10^{-13}
$K^+ \to \pi^+\mu^-e^+$	7×10^{-9}	10^{-10}	10^{-12}	few x 10^{-13}
$K_L^0 \to e^+e^-$	$\sim 10^{-8}$	10^{-12}	2×10^{-13}	few x 10^{-14}
$K_L^0 \to \pi^0e^+e^-$	2.3×10^{-6}	10^{-11}	2×10^{-12}	few x 10^{-13}
$K^+ \to \pi^+X^0X^{0\prime}$	1.4×10^{-7}	2×10^{-10}	5×10^{-11}	$\sim 4 \times 10^{-12}$
$K^+ \to \pi^+X^0$	5×10^{-8}	4×10^{-11}	10^{-11}	$\sim 10^{-12}$

References

1) S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2 (1970) 1285.

2) A.S. Carroll et al. Phys. Rev. Lett. 44 (1980) 525.

3) F.J. Gilman and M.B. Wise, Phys. Rev. D21 (1980) 21.

4) P. Herczeg, Phys. Rev. D27 (1983) 1512.

5) F.J. Botella and C.S. Lim, Phys. Rev. Lett. 56 (1986) 1651.

6) D. Chang and R.N. Mohapatra, Phys. Rev. D30 (1984) 2005.

7) AGS E791 (UCLA, LASL, Pennsylvania, Stanford, Temple, William & Mary collaboration).

8) M.K. Gaillard and B.W. Lee, Phys. Rev. D10 (1974) 897.

9) E. Ma and J. Okada, Phys. Rev. D18 (1978) 4219.

10) T. Inami and C.S. Lim, Prog. Theor. Phys. 65 (1981) 297.

11) J. Ellis and J.S. Hagelin, Nucl. Phys. B217 (1983) 189.

12) F.J. Gilman and J.S. Hagelin, Phys. Lett. 133B (1983) 443.

13) Y. Asano et al. Phys. Lett. 107B (1981) 159.

14) M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.

15) L. Wolfenstein, CMU-HEP 86-3, to be published in Annual Review of Nuclear and Particle Science

16) C.M. Hoffman, LA-UR-86-1728 (1986) submitted to The Proceedings of the Seventh Workshop on Grand Unification, Toyama City, Japan, April 16-18, 1986.

17) H.K. Walter, these proceedings.

18) L.S. Littenberg, Status of Rare Decay Experiments, in: Flavor Mixing in Weak Interactions, ed. L.-L. Chau (Plenum Press, N.Y., 1984) 509-542.

19) R. Cahn and H. Harari, Nucl. Phys. B176 (1980) 135.

20) AGS E780 (BNL-Yale Collaboration).

21) Typically for slow extracted beam running, the AGS produces a 1 second pulse containing ~ 1.6×10^{13} protons every 2.5 seconds.

22) BNL 34989R (April 1985).

23) Report of the AGS II Task Force, G.A. Smith,ed., 1984.

24) Reference 7 and R. Cousins, private communication.

25) AGS E777 (BNL, SIN, Wahington, Yale collaboration).

26) T. Cowen et al. Phys Rev Lett 56 (1986) 444.

27) R. Peccei et al. Phys. Lett. B172 (1986) 435.

28) L.M. Krauss and F. Wilczek, Phys. Lett. B173 (1986) 189.

29) S. Weinberg, Phys. Rev. Lett. 40 (1978) 223.

30) F. Wilczek, Phys. Rev. Lett. 40 (1978) 279.

31) J. Fischer et. al. Phys. Lett. 73B (1978) 364.

32) T. Goldman and C.M. Hoffman, Phys. Rev. Lett. 40 (1977) 220; J. Kandaswamy, et al. Phys. Lett. 74B (1978) 377.

33) M. Dine et al. Phys. Lett. 104B (1978) 199; J. Kim, Phys. Rev. Lett. 43 (1979) 193.

34) M. Zeller, private communication.

35) H. Georgi et al. Phys. Lett. B169 (1986) 73 and references cited therein.

36) F. Wilczek, Phys. Rev. Lett. 49 (1982) 1549.

37) D. Dicus et al. Phys. Rev. D18 (1978) 1829.

38) J. Preskill et al. Phys. Lett. B120 (1983) 127; L. Abbot and P. Sikivie, Phys. Lett. B120 (1983) 133; M. Dine and W. Fischler, Phys. Lett. B120 (1983) 137.

39) M. B. Wise, Phys. Lett. 103B (1981) 121.

40) J.N. Wilford, New York Times 8 Jan 1986, 1; E. Fischbach et. al., Phys. Rev. Lett. 56 (1986) 3.

41) M. Suzuki, Phys. Rev. Lett. 56 (1986) 1339; S.H. Aronson et al. Phys. Rev. Lett. 56 (1986) 1342.

42) E. Fernandez et al. Phys. Rev. Lett. 51 (1983) 1022; N. S. Lockyer et al. Phys. Rev. Lett. 51 (1983) 1316.

43) R.E. Shrock, The value of experiments on decays of the type $K \to \pi$ + missing neutral(s), in: Proceedings of the 1982 DPF Summer Study On Elementary Particle Physics and Future Facilities, eds. R. Donaldson et al. (Snowmass, Co., 1982) pp 291-297; M. Suzuki, U.C.B. preprint UCB-PTH-82/8.

44) M. K. Gaillard et al. Phys. Lett. 123B (1983) 241.

45) S. Bertoline and A. Masiero, NYU/TR1/86 (1986).

46) E. de Rafael, this conference.

47) M. Gronau and J. Schechter, Phys. Rev. D31 (1984) 1665; A.A. Anselm, et al. Phys. Lett. 156B (1985) 102; I.I. Bigi, Z. Phys. C27 (1985) 303; U. Turke, et al. Nucl. Phys. B258 (1985) 313.

48) U. Turke, Phys. Lett. 168B (1986) 296.

49) W. Marciano, private communication. Marciano stresses that the largest branching ratios for $K^+ \to \pi^+ \nu\bar{\nu}$ will result not from large t' - light quark mixing angles, but from the case wherein t - light quark mixing angles get large. This latter case is allowed because the presence of the fourth generation releases the apparant constraint the long τ_b puts on these angles.

50) AGS 787 (BNL, Princeton, TRIUMF collaboration).

51) N.G. Deshpande and G. Eilam, Phys. Rev. Lett. 53 (1984) 2289.

52) J.F. Niéves and P.B. Pal, Phys. Rev. D 32 (1985) 1849.

53) C.L. Woody et al., BNL37343, IEEE Trans. Nucl. Sci. NS-33 (1985).

54) D.L. Bryman, TRIUMF Kaon Factory Proposal, Vancouver, B.C., p. 3-26; D.L. Bryman et al., LAMPF II Task Force on Rare Decays, unpublished (1986).

55) D.E. Lobb, π/K separation and kaon beam design, in: Proc. Conf. on Interactions Between Particle and Nuclear Physics, Steamboat Springs, 1984, ed. R.E. Mischke, AIP Conf. Proc. No. 123 p. 933.

56) J. Abad et al. Phys. Rev. D30 (1984) 1488.