An Experiment to measure the branching ratio $K^+ \to \pi^+ \nu\bar{\nu}$

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We discuss an experiment to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio to ~20%. The detector would consist of the E787 detector with some modifications.

1 Introduction

The rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ is a flavor changing neutral current, mediated in the standard model by heavy quark loop diagrams, and in particular, is sensitive to the CKM matrix element $|V_{td}|$. The theoretical prediction for this branching ratio is very clean: the hadronic matrix element can be determined from the $K^+ \to \pi^0 e^+ \nu$ branching ratio via an isospin transformation, the long distance contributions are negligible, and the QCD corrections (next to leading order) bring the theoretical uncertainty to 7% [2].

The branching ratio as predicted by the standard model is between 0.6—$3.0{\times}10^{-10}$ with a most probable value of 1×10^{-10}. Over the next few years the E787 experiment at the AGS is expected to reach a single event sensitivity of a few$\times 10^{-11}$ and should therefore observe $K^+ \to \pi^+ \nu\bar{\nu}$. This working group studied the feasibility of a cost-effective experiment to measure the $K^+ \to \pi^+ \nu\bar{\nu}$ branching ratio to $< 20\%$ on the AGS2000 time scale.

2 The E787 experiment

The results from the 1989-91 data set [1] represent a single event sensitivity of $\sim 1 \times 10^{-9}$ with an expected background level of 1×10^{-10} from $K_{\mu 2}$ and 1×10^{-10} from $K_{\pi 2}$. The upgrades of the experiment between 1991 and 1995 appear to have reduced the expected background levels (based on preliminary analysis on the 1995 data) to $K_{\mu 2} \sim 3 \times 10^{-12}$ and $K_{\pi 2} \sim 1 \times 10^{-11}$. Further improvements in the $K_{\pi 2}$ rejection are currently proceeding. For the typical conditions of the 1995 run: 15 Tp protons per pulse (ppp), a stopped kaon rate of KB = 1.2 M/spill, a deadtime of 25% and an online photon veto loss of 10%, E787 can expect a sensitivity of 1/3 event per year of 16 weeks of production data taking. It is expected that with further improvements E787 may reach a sensitivity of 1/2 event per year and should see $\sim$ 2–3 events by 1999 (assuming no non-Standard Model physics). The rate dependence of the acceptance has been measured from the 1995 data. Approximately 50% of the incident kaons for which the detector was live are lost. From the 1996 data we have seen that this rate dependent acceptance loss is proportional to the incident flux at the upstream end of the detector. This rather large rate dependent loss implies that E787 will not be able to gain much sensitivity by simply increasing the kaon flux without further improvements to the detector..

3 A new experiment

In the following discussion, the experience and lessons learned from E787 provide the foundation for a new experiment. The experiment is based upon the techniques and technology of E787 because the extensive measurements and analysis of E787 provide a high level of confidence in projecting a new experiment to the required sensitivity. The level of background rejection achieved by E787 is sufficient for a relatively clean and convincing measurement of $K^+ \to \pi^+ \nu \bar{\nu}$. The primary requirement is to stop more K^+ near the center of the detector. Most of the improvements call upon the AGS and beam line to provide more stopping kaons and the trigger and DAQ to process the increase with no additional deadtime; modest upgrades to the E787 detector are also envisioned. These improvements, for the most part, entail no increase in incident kaons.

1. Many of the acceptance losses suffered by E787 are proportional to the incident flux of particles (K^+ or π^+) entering the detector. A significant reduction in the incident flux was achieved when the LESBI beam line was upgraded to the LESB3 beam line in 1992. This beam improved the number of K^+ per targeted proton, and also improved the K^+:π^+ ratio from about 1:3 to 3:1. Thus the kaon flux was increased by a factor of three with no additional losses in acceptance.

   The most important factor remaining that we wish to exploit in this new experiment is to improve the fraction of incident K^+ that come to rest near the center of the apparatus. We find that only 1/6 of the K^+ being transported at 790 MeV/c incident on our detector can be brought to rest in the kaon stopping target. Most of the rest interact or scatter in the degrader just upstream of the stopping target, and cause accidentals that cause acceptance losses. By removing some of the degrader and transporting a lower momentum K^+ beam, the fraction of the incident kaons stopping in the target increases. The increase in sensitivity is directly proportional to the increase in the stopping fraction. During the 1995 run E787 ran at 790 MeV/c; during the 1996 run the momentum was lowered to 730 MeV/c and 710 MeV/c. For a new experiment, we propose to lower the momentum to $<$ 600 MeV/c. At 600(550) MeV/c we expect an increase of sensitivity of $\times$1.7(2.0) compared to 790 MeV/c. A design for a 600 MeV/c beamline was discussed wherein the number of incident kaons per proton is not reduced with respect to the present LESB3 beamline. An alternative to this new beamline would be to increase the number of protons on target by $\times$1.9(2.7) at 600(550) MeV/c, using LESB3. By making modest changes to the last quadrupoles and Cerenkov counter, thereby allowing LESB3 to be shortened, the number of protons on target may need to be increased by only a factor of 1.4(1.9).

2. Increase the spill length. Currently we run with a 1.6 sec spill every 3.6 sec (40% duty factor); in the AGS2000 era, with an accumulator, the inter-spill period can be reduced to 1 sec. The direct increase in sensitivity with the accumulator is $\frac{1.6/2.6}{1.6/3.6} = 1.4$. This requires no additional protons per pulse (ppp). If an accumulator is not built we could increase the duty factor by compensating with additional protons. By increasing the spill length to 3.2 sec (62% Duty Factor) we can increase our sensitivity per hour by $\times$1.4, while requiring $\times$2 more protons. These would keep the instantaneous rates and acceptance constant, but increase the sensitivity (KB/hour).

3. Bunched beam. The general idea of using a bunched beam would be to reduce the rates in the detector at the time the kaon decays ("π time") and perhaps also at the time the pion decays, by increasing rate at the time the incident kaons arrive. Currently the detector is live for K decays up to 60ns (and for π decays for up to an additional 80ns), so we need the RF period to be larger than 60ns (up to 140ns). The time of flight difference between K^+'s and π^+'s is $\sim$20ns, so we actually need the RF period to be larger than 80ns. For a stopped kaon rate (KB) that is $\times$4 that of E787 (KB = 4 MHz), we could consider bunched beam with a 10 MHz frequency. At an RF frequency of 10 MHz, we would have an average of 0.4 K/bucket and a 80ns period with no additional beam particles. The probability of more than one stopped kaon per pulse compared to exactly one is less than 25%. E787 has taken some data to quantify the potential improvements

from a bunched beam. If, by means of a bunched beam, the rates in the detector elements at π time can be reduced by $\times 2$ per incident K, the proton flux could be increased by $\times 2$ with little or no acceptance loss. In this case the sensitivity increase would be $\times 2$.

4. Take advantage of the increased running time in the RHIC era. If RHIC runs for 40 weeks/year and we assume 90% of this time is available for SEB; we will have $\times 2$ more running per year (36 weeks vs. 18 weeks in pre-AGS2000 era).

5. Increased flux. All previous assumptions have kept the instantaneous flux constant. With modest improvements to the online RS photon veto, additional demultiplexing of the TD's, and further detector upgrades it may be possible to increase the incident flux by $\sim \times 2$ with little loss in acceptance and little loss in background rejection.

As a conservative approach we assume that the combined improvements from points 3) and 5) above give an increase in sensitivity of $\times 2$ (instead of $\times 4$). The net increase in sensitivity per year from these improvements is 1.7 $\times 1.4 \times 2 \times 2 = \times 10$. In order to achieve this increase we need an increase in the number of protons on target by 1.4 $\times 2 \times 2 = \times 5.6 = 85$ Tp. This would lead to an expected $\sim$3 events per year.

3.1 Cost

A summary of the estimated cost of capital equipment is shown in Table 1. The sensitivity improvement and additional protons needed are also shown for each of the proposed improvements. This table assumes that the momentum will be lowered to 600 MeV/c and that the beamline shortened by $\sim$2m. It assumes that the AGS Accumulator is not built, but the spill length and cycle time are increased to 3.2 sec and 5.2 sec, respectively. It also assumes that a combined factor of two increase in sensitivity is achieved by bunching the beam and/or running at higher instantaneous rates.

4 Conclusion

We believe that the goal of making a significant measurement of $|V_{td}|$ is quite exciting, since it would allow the CKM model of CP violation to be critically tested. Such a measurement can be accomplished via a determination of the branching ratio for the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ based on $\sim 10-20$ events with an expected background level of $< 10\%$ of the signal. Though this can not be done by the present AGS, LESB3, or E787 detector, we expect that realistic improvements in all these components can be achieved in the AGS2000 era. We require several years of 40 week runs of SEB during the RHIC era with

action	Sens./yr.	ppp	cost
lower **p**(short beam)	×1.7	×1.4	$200k
duty factor	×1.4	×2.0	–
longer runs	×2	×1	–
bunched beam	×2	×2	$1–500k
trigger/DAQ mods			$400k
detector mods			$400k
total	×9.5	×5.6 (85Tp)	$1500k

Table 1: Proposed increases in sensitivity per year with associated increases in protons on target and estimated cost of capital equipment. Increases in sensitivity are compared to 1995.

80TP on target, a modestly shortened LESB3 line, an increased AGS duty factor, and significant, but currently achievable improvements in the E787 detector and DAQ systems. We expect that the total cost for the required modifications to the LESB3 line and the E787 detector and DAQ will be under $1500k. We note that on the same timescale far greater resources are being expended to extract equivalent information from the B system.

5 References

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