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Future Stopped $K^+ \to \pi^+ \nu\overline{\nu}$ Experiment

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Abstract

Some aspects of a future experiment using stopped K^+s which could confirm the single-event observation of Brookhaven E787 and obtain a statistically interesting determination of Standard Model parameters are discussed.

The recently reported evidence for an observed event consistent with the rare decay $K^+ \to \pi^+ \nu\overline{\nu}$[1] has sharpened the focus on this process as a test of higher-order effects in the Standard Model and as a direct measure of the CKM matrix element V_{td}. Since the experimental approach of BNL E787 has demonstrated capability to reveal a signal in the face of 10 orders of magnitude of background, it is of great interest to explore the full potential of the method to obtain a sample of several tens of events from which compelling physics conclusions could be drawn.

A fundamental challenge of this measurement, in addition to its expected 10^{-10}-level branching ratio, is the lack of an unambiguous signal which is convincing on its own. It is a 3-body decay whose phase space is largely overlapped by the dominant decay branches, as well as by background sources such as the beam in the experiment. Every background source must be thoroughly understood and rejected with high confidence to a level well below the intended sensitivity in order to expose the signal. This powerful rejection comes with a price and great care is necessary to maintain a reasonable and unbiased acceptance for a valid signal. The acceptance that was determined for the published event from the 1995 run was 0.0016; clearly, in the quest for higher sensitivity there are gains to be made if this number can be improved.

In subsequent running periods, changes were made to address this question. In the E787 experiment, a huge amount of data is obtained from 500-MHz digitizers covering virtually all the scintillation detector systems. These data are rich in information about a candidate event, but efficient processing both for trigger decisions and for off-line evaluation is challenging, and improvements are continually sought. For example, in 1996, the intermediate level trigger which makes a crude pion identification from the data from the range-stack

Figure 1: Transient digitizer data from both ends of the pion stopping layer in the rangestack. Typical fits to the pion stopping pulse, the $\pi \to \mu$ decay, and a third accidental hit are shown.

transient digitizers was refined to give an anticipated 20% increase in acceptance. In 1997, acceptance for the $\pi \to \mu \to e$ decay chain was opened up for another potential 8% gain.

Other refinements to the digitizer data analysis being studied have been aimed at identifying accidental hits in the range stack cleanly so they can be discarded without suffering acceptance losses. Figure 1 is an example of a fit to a pion stop and decay with a nearby accidental hit. Although it is not clear yet how effective this work will be at reducing accidental losses, it appears that the modified pulse-shape fitting routines which have been developed will lead to better results for the pion-decay identification, which may also yield acceptance gains. Overall, with these and other gains, it is reasonable to expect that the acceptance with the present running conditions could increase by up to 50%. Moreover, a nearly complete second analysis, independent from the one used to identify the 1995 event, gives some indication that even further gains may be possible.

Although analysis refinements may continue to reduce the acceptance losses

Figure 2: Effective stopping K rate (ordinate, arbitrary units) as a function of proton rate (abscissa, 10^{12}/spill), for four incident K momenta with fixed acceptance (A = 0.50) defined by accidental rates.

from accidental hits in the detector, ultimately the sources of accidental activity must be addressed. One important source is the incident beam. The process of degrading the K^+ energy to stop in the target is in itself a messy and inefficient process. It has been found in recent running and tests in E787 that improvements in accidental rate per stopped K^+ are obtained by lowering the incident beam momentum and reducing the amount of degrader material in the beam.

This is illustrated in Figure 2 where effective stopping rate verses incident proton beam intensity is plotted for several K^+ momenta. The effect of data acquisition deadtime causes the curve to level off and accidental losses lead to a decrease at higher rates. When these factors are included, the effective stopping K^+ rate at lower momentum continues to increase to higher levels as a function of incident beam, provided that deadtime limitations are not

Figure 3: Layout of the K550 beamline design. Units on both axes are in meters.

reached, and that higher proton beam intensity is available to compensate for lower K^+ production rates.

The LESB3 beamline at BNL has a nominal design momentum P of 800 MeV/c and an excellent K/π ratio of > 3 typically, which is achieved by using two stages of K/π separation in conjunction with mass slits and collimators. However, the channel is too long (19.6 m) to yield acceptable K^+ intensity below $\sim$650 MeV/c. In order to produce intense pure beams at lower momentum, the beamline must be made much shorter and the momentum-bite and solid-angle acceptance must also be increased. There are some helpful factors in the design; for example, the separating power for DC separators is $\propto P^{-3}$ for a given electric field. Also, it is possible to reduce the propagation of higher-order optics effects when the elements are short and close together, and of course the required magnetic field strengths are lower for lower P.

A design study for a new K550 beamline optimized for the 500 – 550-MeV/c range has been carried out,[2] and the conceptual layout is shown in Figure 3. The design envisions several features aimed at minimizing the length and increasing the acceptance. Two separators are retained, but each is reduced from 2.16 m in length to 1.2 m, and the operating high voltage is increased from 600 kV to 750 kV. At this voltage the crossed magnetic fields must be external

Beamline (length)	P (MeV/c)	dec.$\times\ell$	$\propto P^2$	$\Delta P \Delta\Omega$ (%msr)	$\epsilon_{K\mathrm{stop}}$	$R\|_{\mathrm{accept.}}$
LESB3	800	0.038	1.51	50	0.16	0.70
(19.6 m)	710	0.025	1.19	60	0.23	[1.0]
	650	0.018	[1.0]	60	0.27	1.17
K550	550	0.028	0.72	100	0.34	1.48
(14.7 m)	500	0.020	0.59	110	0.37	1.61

Table 1: Effect of beam momentum on effective stopped K^+ rate $R|_{\mathrm{accept.}}$ for constant acceptance defined by accidental rate. See text.

to the electric field regions. These will be incorporated as dipole components in combined-function quadrupoles immediately upstream and downstream of both separators. The sextupole fields for second-order optics corrections will also be included in quadrupoles to save length. The front-end elements will be shortened and/or increased in aperture to increase the solid angle $\Delta\Omega$ from 12.5 msr to 15.6 msr. An important additional benefit of the drastically reduced distance between the dipoles is reduced momentum dispersion which leads to a large increase in momentum acceptance $\Delta P/P$ from 4% to 6.4%. These two factors combine to double the acceptance. Finally, compact superconducting quadrupoles for the last two elements will allow the final drift to the stopping target in the detector to be reduced. Overall, the length is reduced by 5 m to 14.7 m. The design is compatible with the existing proton beam and detector axes, requiring only that the production target be moved downstream and the detector upstream.

The potential gains are summarized in Table 1 both for LESB3 and for the new K550 design. The third column is the K^+ decay factor for the beamline length; the fourth column, $\propto P^2$, gives the normalized combined effect of the momentum bite and the K^+ production; the fifth column is the momentum and solid angle acceptance, which can increase with lower momentum if mass slits are opened up to take advantage of increased K/π separation; the sixth column is the K^+ stopping efficiency. The last column gives the relative effective stopped K^+ rate, $R|_{\mathrm{accept.}}$, and is a normalized product of the previous four columns after multiplying by another factor which assumes additional proton beam to maintain a constant incident K^+ rate, *i.e.*, a constant accidental rate in the detector, and thus a constant acceptance.

The upgrades to the AGS including the Booster in 1992 and more recently, a so-called 'barrier bucket' injection technique, have promise to increase proton intensity to $\sim 10^{14}$ /spill.[3] In addition to providing the protons needed to compensate for lower K^+ production at low momentum, the potential to deliver even higher beam intensity if it can be accommodated by the experiment exists. Other modifications to the operating mode of the AGS to increase the effective rate of stopping K^+s are being investigated, such as increasing the macro duty factor by increasing the spill length. For example, the present $\sim$2-s acceleration segment of the $\sim$3.6-s spill period needs to be extended only slightly in order to greatly increase the beam injected from the Booster, and the extracted spill duration can be extended from the present 1.6 s as necessary so that the increased beam is delivered at the same instantaneous rate with a higher duty factor. For future consideration in AGS beam development, preliminary Monte Carlo studies[4] of the time structure of beam related activity in the detector seem to indicate that a micro-bunched beam time structure may help to supress accidentals by defining a valid arrival time for K^+s.

There are several other improvements being considered for the detector. As the sensitivity is increased, the ability to reject background must also increase. One major area of effort as been to design more efficient photon veto systems. A modification to the main cylindrical barrel veto surrounding the detector has been developed[5] which is expected to yield a factor of three in π^0 rejection from the $K_{\pi 2}$ background. In this system, a gap between the range stack and barrel, as well as the outer two layers of the range stack will be filled with additional lead-scintillator layers.

Since there are prospects for higher proton current even than would be needed to maintain the present incident K^+ rate with lower momentum and higher duty factor, it will become necessary to increase the rate capability of most detector systems. Various schemes of finer segmentation, including the use of scintillating fibers with high light output, of the rangestack and beam instrumentation are under study. Faster scintillator materials, *e.g.*, barium fluoride may also be used especially in the innermost layers of the endcap photon vetos.

Finally, there is interest in attempting to extend the search for the $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ signal into the phase space region below the $K_{\pi 2}$ peak. There, background rejection is much more difficult compared to the hitherto restricted signal region between the $K_{\pi 2}$ and $K_{\mu 2}$ peaks. In earlier attempts in E787[6] the sensitivity in the lower region was background limited at the 10^{-8} level. Subsequent improvements in the detector and analysis may have yielded a factor of three or more in background rejection in this region, but another factor of 10^3 will be needed. If successful, a factor of two in acceptance would be opened up, as would the eventual possibility of determining the spectrum shape.

In summary, several approaches are underway and others are yet to be explored in detail which could allow a stopped K^+ experiment such as E787 to reach a single-event sensitivity for $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ of 10^{-11} or less in the next few years. Depending on the true branching ratio, $10 - 100$ events could be observed. Most of the techniques under consideration for improving the detector, accelerator and beamline would be applicable to a future study of this decay at JHF. That proposed new facility has in its conceptual plan for the K-Arena[7] provision for a stopped K^+ beamline of about 1 GeV/c. Based on the experience gained from BNL E787, perhaps a lower momentum should be considered.

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