Project Title: Charged Kaons at the Main Injector

Executive Summary

One of the most profoundly surprising results in all of particle physics was the discovery in 1964 of CP violation in the decays of the neutral kaon, the K_L. In our present-day standard model of particle physics, the interaction of the three generations of quarks with the Higgs field leads to the quark masses, to the mixing (changing) of quarks from one type to another, and to this CP violation. After many breakthroughs in the experiment and theory of quark flavors, we can now understand that the 1964 experiment was the first to see the indirect effects of the top quark, some three generations before the discovery of the heaviest quark.

About one-quarter of the experimental particle physics community is now working in quark flavor physics, a field which continues to produce new and exciting results. The scientific interest is now turning to the use of CP violation as an extraordinarily sensitive probe for many of the most plausible varieties of new physics. One gets specific predictions for such anomalous effects in theoretical models with non-minimal Higgs sectors, extra dimensions, or various versions of supersymmetry, to name a few. Just as in 1964, one hopes to see first signs of the new physics in CP violation. Such new physics would manifest itself in an inconsistency of various CP measurements with the hypothesis that they are due entirely to the single parameter allowed in the standard model. CKM represents the next frontier of CP studies using kaons. All studies of the future of quark flavor physics point to the unique advantages of the decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ in testing for new physics, when combined with measurements of B decays.

- By measuring 100 clean events of this type CKM will determine the parameter V_{td}, which quantifies the overlap of the top quark and the down quark, with 10% accuracy.
- The theoretical uncertainties contribute negligibly to this accuracy.
- It is important to compare this measurement of V_{td} with those inferred from B decay in order to isolate contributions from new physics.

The primary difficulties are experimental, due to the facts that the branching ratio is 10^{-10} and only one of the decay products is seen. BNL E-787, which has seen two such events, has already demonstrated the ability to control the background to the needed level. Doing the experiment with a high energy separated K^+ beam, rather than with stopped kaons, removes a limit on the rate capability. The only other decay mode that contributes to the overall campaign is the related decay $K_L \rightarrow \pi^0\nu\bar{\nu}$ for which the state-of-the-art sensitivity is still 5 orders of magnitude from that needed. It would be best to have both of these measurements, which are complementary, but the charged decay in CKM has lower technical risk that the needed sensitivity and background are achievable.

The CKM project is close to being ready for a baseline review. The experiment was given scientific approval after a rigorous review by the Fermilab Physics Advisory Committee in 2001. Fermilab is preparing for a first review of CKM by their Office of Project Management (Temple review), as a path for a baseline review by the Office of Science (Lehman review). The scale and complexity of the CKM experiment is approximately equal to that of the KTeV experiment, which was completed successfully at Fermilab in 1999. This comparison gives additional support to the present funding estimate which the Temple review will further refine. The experiment and beamline could be built and ready to operate by late in the decade. The CKM collaboration includes several groups who have completed difficult experiments in kaon decay. The collaboration is expected to include about 100 or more physicists at the time of data-taking.

Scientific Importance

Quark flavor physics

Particle physics presently faces a serious shortcoming in our understanding. The whole observable universe around us is dominated by matter with only tiny amounts of anti-matter seen. Our understanding of the physics controlling the very early epoch after the Big-Bang produces equal amounts of matter and anti-matter. The only observed process which distinguishes matter from anti-matter is the rather small *CP violation* seen in the decays of mesons. With this process alone we cannot explain how we got to the matter dominated universe we have today

The scientific issue is not primarily to understand the evolution after the big bang. There must be additional processes which distinguish matter from anti-matter; new physics processes of which we are now ignorant. Our inability to get today's matter dominated universe correct is not surprising if we're completely neglecting some of the physics.

The framework which describes particle physics today, the *Standard Model*, describes all present observations with no compelling deviations; save the one discussed above. It has more parameters than we would like and we know it will run into trouble at higher energies. These ideas motivate the push toward the energy frontier with machines like the LHC.

The *Standard Model* describes the observed matter, antimatter asymmetry; *CP violation* in the jargon of particle physics, in terms of a quantum mechanical mixing between the quarks produced by the strong interaction and their decays via the weak interaction. A complex phase in this mixing matrix generates the matter, anti-matter asymmetry. An important connection in getting to the physics underlying the *Standard Model* is the relationship between the pattern of quark mixings and the analogous mixings recently discovered in the neutrino sector. Neutrino mixings appears to be quite large while quark mixings are small.

How can we demonstrate the existence of new matter, anti-matter asymmetric processes?

Is the *Standard Model* description of *CP violation* complete? If so then all weak particle decays which differentiate matter and anti-matter should be predictable in terms of the 4 parameters of the quark mixing matrix (the Cabibbo Kobayashi, Maskawa, or CKM matrix). Two of the 4 CKM parameters are relatively well measured. The other two give the real and imaginary parts of the small CKM matrix elements which control *CP violation* in the *Standard Model*. If there are new processes at work in the weak decays of the particles we can now study then these parameters will be inadequate to describe the data from all weak decays. The observation of a compelling inconsistency of this kind would be direct evidence for new matter, anti-matter asymmetric processes. At a minimum it takes 3 different measurements to test the *Standard Model*.

The operative word above is *compelling*. In order to falsify the *Standard Model* as a complete description of *CP violation* we require at least 3 highly reliable experimental measurements of weak decay observables where the theoretical relationship between the observables and the two underlying CKM matrix parameters is reliable and robust. When three measurements cannot be fit with two parameters the first explanations will be to fault the measurements and/or the theory. There are four candidate measurements which particularly meet the criteria of experimental accessibility and theoretical robustness, two in B meson decays and two with kaons decays.

In the B meson systems the decay asymmetry in the $B^0 \rightarrow \psi K^0_s$ decays is now being well measured in both the US and Japan. The other candidate is the comparison of mixing in the decays of the B^0_s and B^0_d mesons. Presently there are only upper limits on B^0_s mixing, but a measurement can be expected soon from the experiments producing these mesons. In kaon decays the two observables are the decay rates of the ultra-rare decay modes $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$. Two $K^+ \to \pi^+ \nu \bar{\nu}$ events have been observed. This observation demonstrates the enormous sensitivity and background control required ($\sim 10^{-11}$) but is statistically insufficient for a precise measurement. At present there is only an upper limit for $K_L \to \pi^0 \nu \bar{\nu}$ at 10^5 times the expected rate.

The pair of B system measurements are orthogonal to each other in the CP-parameter space of the *Standard Model*, the pair of kaon measurements are nearly orthogonal; each kaon measurement is nearly parallel to one of the B measurements. A precision measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ can provide a third measurement, in concert with the results in hand and expected from B meson decays, in order to directly test the *Standard Model* description of *CP violation*.

The weak decays of heavy mesons, kaons and B mesons, are uniquely sensitive laboratories for such measurements. We can select decay modes which are dominated by loop diagrams involving virtually produced heavy particles, like top quarks, which give direct access to the small matrix elements which control *CP violation* in the *Standard Model*. There is significant sensitivity at energy scales well above that which can be reached, even with the LHC. For example, the first evidence for the charmed quark came from the measurement of the decay rate of $K_L \to \mu^+ \mu^-$ even though the charmed quark is three times as massive as a kaon. The limits on lepton number violating interactions (with full Fermi couplings), from decays like $K_L \to \mu^+ e^-$, is at the >200 TeV level; more than 10 times the scale accessible at the LHC.

Calculation of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay rate in the context of the Standard Model is universally acknowledged in the theoretical community to be very robust, and hence is on the short list of weak decays that can decisively challenge our understanding of quark-flavor changing interactions. This is a new development for kaon physics; previous measurement of CP-violating phenomena in the kaon system have been notoriously difficult to interpret in the context of the underlying quark-level dynamics. This clear connection to quark-level physics results from normalization of the $K^+ \to \pi^+ \nu \bar{\nu}$ process to the well measured $K^+ \to \pi^0 e^+ \nu$ decay, which largely eliminates dependence on the hadronic matrix element. The small residual theoretical uncertainty (5%) of the $K^+ \to \pi^+ \nu \bar{\nu}$ decay rate can be further reduced by application of Lattice QCD techniques which are particularly accurate for weak decay processes that have a single hadron in the initial and final state.

The CKM Experiment (Charged Kaons at the Main-Injector) – physics goals

CKM is an experiment [*http://www.fnal.gov/projects/ckm/Welcome.html*] whose primary scientific goal is the measurement of the branching ratio of the ultra-rare charged kaon decay $K^+ \to \pi^+ \nu \bar{\nu}$ by observing a large sample of $K^+ \to \pi^+ \nu \bar{\nu}$ decays with small background. Our physics goal is to measure the magnitude of the Cabibbo, Kobayashi, Maskawa matrix element V_{td} with a statistical precision of about 5% based upon a ~100 event sample with total backgrounds of less than 10 events. This decay mode is known to be theoretically clean. The only significant theoretical uncertainty in the calculation of this branching ratio is due to the charm quark contribution. A 10% measurement of the branching ratio will yield a 10% total uncertainty on the magnitude of V_{td}. The branching fraction predicted by the *Standard Model* for this mode is $(8 \pm 2) \times 10^{-11}$. The KOPIO experiment at BNL is proposing the measure the branching fraction of $K_L \to \pi^0 \nu \bar{\nu}$ where the standard model prediction is $\sim 2 \times 10^{-11}$.

The CKM apparatus is a tagged charged kaon decay spectrometer of unparalleled rate capability with excellent spatial and temporal resolution for both photons and charged particles. We've identified 12 rare and ultra-rare K^+ decay modes where we have sensitivity well beyond existing measurements. Studies for lepton flavor violating processes, T-odd decay asymmetries, form-factors and chiral perturbation theory tests are all possible. The design criteria for the apparatus was to consider only $K^+ \to \pi^+ \nu \bar{\nu}$, allowing no design compromises for the dominant physics goal. Having achieved that in 2001 detailed studies of specific other physics topics is now underway.

In addition to rare decays, CKM will make precision measurements of the K^+ semi-leptonic branching fractions and form factors with much higher statistics than presently exist. One goal is to improve the measurement of the Cabibbo angle (V_{us}). If the uncertainties in the theory can be reduced, an order of magnitude improvement in V_{us} (1%$\to$0.1%) is ambitious but probably possible. If needs be CKM could even re-measure V_{ud} from pion β-decay. New precision measurements of V_{us} and V_{ud} can address the current $+2\sigma$ discrepancy in the unitary relation of the first row of the CKM matrix. The priorities of all of these measurements will be shaped by the existing measurements and state of theory at a time nearer to the beginning of data taking for CKM.

The CKM Facility

The CKM Facility consists of a high flux separated K^+ beam and a kaon decay detector. The Main Injector serves as the high-flux proton source for the CKM experiment. A 22 GeV/c secondary beam, produced by Main Injector 120 GeV protons will be transported to the MP9 detector hall in the Fermilab Meson Laboratory with a conventional beam line. The beamline is designed for 2 stations of Super-Conducting Radio Frequency (SCRF) cavities which separate the kaons from the pions and protons in the secondary beam. SCRF is required to accommodate the long beam pulses required in order to minimize detector rates. The beam incident on the decay detector is 50MHz, 70% of which are kaons.

The SCRF cavities, which operate in a transverse (deflecting) mode at 3.9GHz, are being developed at Fermilab based on experience from the 1.3GHz accelerating mode cavities developed for TESLA. This separator technique was originally invented by Panofsky 40 years ago. A separated beamline with SCRF was built and successfully operated at CERN in 1977.

The CKM detector shown in figure 1 is composed of systems to redundantly measure the incident K^+ and decay π^+, (spectrometers) and systems to tag particles associated with decay processes (veto systems). The spectrometers are built from Ring Imaging CHerenkov detectors and ultra-low mass magnetic spectrometers using high rate multi-wire proportional chambers and strawtube drift chambers. The whole may be thought of as the superposition of two spectrometers, one of which measures the velocity (masses) and the other the momentum of the of the two charged particles in the decay event.

The likelihood for a successful measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ with the CKM technique is bolstered by the detector design philosophy: Only proven and battle-tested detector technologies will be employed. The technical challenge of the CKM experiment is not to develop new detector technologies, but rather to demonstrate that well established tracking and particle identification technologies can be understood and controlled to extraordinary levels of precision. To this end redundancy is designed in at every feasible level so that detector performance, and ultimately all backgrounds, can be *measured*. This demonstration has been the focus of an R&D cycle that has recently completed, and a compelling case (discussed below) exists now that the required level of systematic detector control is in hand.

Project Readiness

State of the Experimental Art

The field of rare kaon decay experiments has evolved to a point where one can sensibly argue that the required CKM single event sensitivity of 1×10^{-12} for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ decay (100 Standard Model events) is within reach. The current state of the rare kaon decay art is in the 10^{-11}-10^{-12} sensitivity range, which includes landmarks such as the discovery of two $K^+ \rightarrow\pi^+\nu\bar{\nu}$ events with a branching fraction of 16^{+18}_{-8} x 10^{-11} (BNL-E787), and precision measurement (Fermilab-KTeV) of the T-odd $K_L\rightarrow\pi^+\pi^-e^+e^-$ process where backgrounds are controlled to the 10^{-11} range. The Brookhaven E787 experiment has convincingly shown that backgrounds to $K^+ \rightarrow\pi^+\nu\bar{\nu}$ can be held to less than the 2×10^{-11} level. This level of background control is demonstrated from the *data*, and does not rely on a detailed simulation of expected background processes. These data-based background control techniques are critical to ultra-rare decay experiments, where background processes are often subtle conspiracies that are difficult to predict and simulate accurately.

This difficulty is well illustrated by the history of $K_L \rightarrow \pi^0e^+e^-$ searches which serves as an important lesson. The $K_L\rightarrow\pi^0e^+e^-$ decay channel was heralded in the 1980's as a process with a very clean signature that would be an incisive probe of CP-violation in the Standard Model, with a physics impact comparable to $K_L\rightarrow\pi^0\nu\bar{\nu}$. Backgrounds were simulated and expected to be small. The gulf of five orders of magnitude between the demonstrated experimental sensitivity and the expected Standard Model level was to be navigated by powerful new beamlines and detectors. The experiments were built and successfully mounted, but then nature weighed in: A very careful simulation of backgrounds involving photons followed up by measurements has shown clearly that the $K_L\rightarrow\pi^0e^+e^-$ process is hopelessly background limited by the radiative process $K_L\rightarrow e^+e^-\gamma\gamma$ These radiative backgrounds are in fact the main impetus that has led theorists and experimenters away from well constrained modes such as $K_L\rightarrow\pi^0e^+e^-$ to the more experimentally challenging $K \rightarrow \pi\nu\bar{\nu}$ channels.

The CKM approach to observing $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is an *in-flight* technique in which decays are analyzed from a K^+ beam that is minimally disrupted as it traverses a hermetic detection volume shown in figure 1. The in-flight approach employs very fast particle identification techniques that are enabled by the higher energies of in-flight decays, which together with the non-invasive design of the detector permits operation at decay rates that are significantly higher (x6) than the previous experiment. The discovery of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ by the Brookhaven E787 experiment was the result of a decade long campaign using the *stopped-kaon* technique, where kaons in a high intensity charged beam are brought to rest inside of a hermetic detector where the subsequent decay products are precisely measured. This technique relies on recording the full $\pi^+\rightarrow\mu^+\rightarrow e^+$ decay chain to provide necessary background rejection, and hence is fundamentally rate-limited by the relatively long μ^+ lifetime.

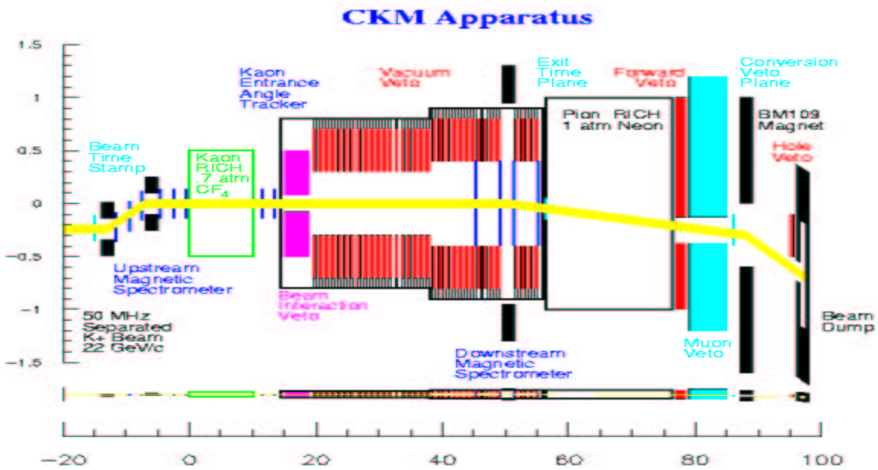

Figure 1: CKM Apparatus

The CKM in-flight technique is a new approach in the field of $K^+ \to \pi^+ \nu \bar{\nu}$ measurement following the long and successful history of in-flight rare kaon experiments that populate the current sensitivity reach of 10^{-11}-10^{-12}. Indeed, the sensitivity frontier is now defined by the in-flight observations of the process $K_L \to e^+ e^-$, with a sensitivity of $2\text{x}10^{-12}$ (4 clean events seen, Brookhaven experiment E871).

State of Current and Future $K \to \pi \nu \bar{\nu}$ Initiatives

There is a broad consensus in the flavor physics community that precision measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$ should be the focus of the next round of kaon experiments. The last round of kaon experiments has been successfully executed and is now in the final analysis phase. Among the discoveries already in the literature from this last round are: establishment of decay amplitude CP-violation through measurement of Re(ε'/ε) (Fermilab-KTeV/CERN-NA48), discovery of a large T-odd asymmetry in $K_L \to \pi^+ \pi^- e^+ e^-$ decays (Fermilab-KTeV) and discovery of the $K^+ \to \pi^+ \nu \bar{\nu}$ process at Brookhaven (BNL-E787). These are just three of many measurements from the last round that have rewritten the Particle Data Book. Based on this history of success and opportunities provided by the existence of next generation proton sources (Fermilab Main Injector, an upgraded Brookhaven AGS, and the Japan Proton Accelerator Research Complex (J-PARC, formerly JHF)), the kaon physics community has embraced the $K \to \pi \nu \bar{\nu}$ challenge.

The neutral $K_L \to \pi^0 \nu \bar{\nu}$ mode is widely recognized as significantly more challenging than the charged mode, since the existing limit established by the Fermilab KTeV experiment is five orders of magnitude above the target sensitivity. Two collaborations are now attacking the neutral mode, the KOPIO experiment in the United States, and the E391 experiment in Japan. Both these efforts are in the R&D phase and propose orthogonal techniques. The Japanese effort is an in-flight technique where the detector is a hermetic kaon decay bottle. Their strategy is to concentrate on vetoing all backgrounds within this bottle and only minimally reconstruct the candidate $K_L \to \pi^0 \nu \bar{\nu}$ decays. The Japanese group is now operating a pilot version of this detector, and plans full operation with the existing KEK proton source in 2004. The run at KEK has a goal of reducing the existing limit on $K_L \to \pi^0 \nu \bar{\nu}$ by two to three orders of magnitude. If this intermediate step is successful the Japanese group hopes to move the experiment to J-PARC which can provide a much higher proton source flux.

The other approach to measuring $K_L \to \pi^0 \nu \bar{\nu}$ is the KOPIO experiment, which is part of the ‘‘Rare Symmetry Violating Processes” (RSVP) Major Research Equipment (MRE) proposal in the National Science Foundation (NSF). The RSVP proposal has been approved within the NSF and is now awaiting funding. The KOPIO collaboration also draws a significant level of support from Canadian funding agencies. The KOPIO design employs an in-flight technique, that strives to extract maximal kinematical information from $K_L \to \pi^0 \nu \bar{\nu}$ decay candidates which leads to less reliance on detector systems to veto background processes. The KOPIO experiment proposes to use the Brookhaven AGS as a high intensity proton source. The collaboration is largely composed of groups from the Brookhaven E787 experiment, and they plan to migrate background control and measurement techniques that were pioneered in BNL-E787 to the KOPIO experiment.

It is difficult to estimate what timeline will lead to a precision measurement of $K_L \to \pi^0 \nu \bar{\nu}$ even though both $K_L \to \pi^0 \nu \bar{\nu}$ groups are enthusiastic and composed of extremely competent experimenters. First the process must be observed, and the expected branching fraction is four orders of magnitude less than the current limit. At this point it is healthy and wholly appropriate to approach this formidable challenge from two independent paths. The configuration of these two groups and their funding sources is such that the Department of Energy (DoE) will not play a leading role in these experiments.

In contrast the Department of Energy has played a leading role in the discovery and current research on $K^+ \to \pi^+ \nu \bar{\nu}$: The Brookhaven experiment has published observation of two events, and is now analyzing a comparable data set collected in a second generation run of the apparatus in 2002 known as experiment E949. The DoE has also been the major partner in development of CKM experiment, and is now positioned to be the leader in construction and execution of the CKM experiment. The CKM proposal to observe 100 events grew from the confluence of the following events in the late 1990’s:

- Successful operation of the Fermilab Main Injector, which will serve as the proton source for the high intensity charged kaon beam.
- Ring Imaging CHerenkov counters reached a level of maturity that they could be considered as a core detector system. The photomultiplier tube based system perfected by the Fermilab SELEX experiment serves as a model for similar systems in the CKM experiment.
- Design of a feasible high energy *separated* K^+ beam, where the majority of charged particles entering the decay detector are actually kaons. In the absence of separation, the beam is overwhelmingly composed of charged pions which turns a challenging rate environment into a fatal one.

These developments have attracted leading members of the SELEX, KTeV, BNL-E787, BNL-E871, Hyper-CP, CDF and IHEP-ISTRA experiments to design and propose the CKM experiment. The collaborating groups bring unmatched experience in rare kaon decay measurements including $K^+ \to \pi^+ \nu \bar{\nu}$, and broad experience in very high-rate beam and detector technology. Acknowledging the now programmatic nature of measuring $K^+ \to \pi^+ \nu \bar{\nu}$, eleven physicists are joint members of the Brookhaven E949 experiment and CKM. The CKM collaboration currently has 50 members, and will likely grow two twice this number.

In response to the recent call for Letters Of Intent (LOI) by J-PARC, a Japanese kaon physics group has submitted an LOI to J-PARC for a new stopped $K^+ \to \pi^+ \nu \bar{\nu}$ experiment.

State of Approvals and Formal Reviews

In the spring of 2001 the Fermilab Program Advisory Committee (PAC) extensively reviewed the CKM and the KAMI (KAons at the Main Injector, which proposed to measure $K_L \to \pi^0 \nu \bar{\nu}$) proposals. The CKM review process formally began in 1998 when the Fermilab PAC determined that the CKM initiative had sufficient promise to merit support as an R&D project. Between the formation of the R&D project and Fermilab approval in 2001, the CKM experiment was subjected to six outside reviews that addressed the physics case, detector design and technology, beamline design and technology, and the cost estimate. Notable in this series of reviews was a 3-day intensive review of the experimental methods that was staffed by seven distinguished external experts in kaon physics.

An excerpt from the technical review summary follows:

> *Overall, the Committee believes that a plausible case was made that CKM could be successfully completed. The proponents have asked themselves numerous probing questions and performed convincing studies as a result. There remain some potential show-stoppers (notably if they are unable to construct straw chambers which work in vacuum), and there are outstanding issues such as neutron-induced rates in the 25 tons of veto scintillator, and rates in counters in the beam. However, overall the Committee's impression of the design is positive. Particularly relevant for the physics measurement are redundancies that will allow background to be estimated in a convincing manner from the data.*

This technical review was critical input to the PAC, which wrote the following in June of 2001 after their deliberations:

> *The basic physics criterion that the Committee imposed in these experiments is then the following: Can the experiment, considered on its own, credibly establish a discrepancy with the values of the CKM parameters observed in B physics? This criterion includes the capability to acquire a large enough event sample and an apparatus that can likely reduce the background to a small fraction of the signal. But it also includes the capability to use the experimental data to prove that an observed discrepancy with the Standard Model prediction is not the result of an unforeseen background reaction and is thus directly attributable to new physics.*
>
> *After extensive review the Committee has concluded that the CKM experiment could meet this criterion, despite the difficulty of the measurement. The experiment is based on an innovative technique that will provide redundant measurements of the momentum vectors of the initial* K^+ *and the final* π^+*. This and other features of the experiment give us confidence that the backgrounds can be understood from data, and thus that the substantial resources required by this experiment will be productively spent. The Committee recommends that this experiment be given Stage-I approval.*
>
> *At the same time, the Committee has concluded that the KAMI experiment does not meet this criterion. … it recommends rejection of the KAMI proposal …*

In the summer of 2001 the Fermilab Director accepted this advice, and granted Stage-I approval for CKM, while rejecting the KAMI proposal. The rejection of the KAMI proposal was a major blow to kaon physics, particularly given the competence and experience of the proponents. These decisions and level of consideration illustrate the seriousness of the review process. Motivated by remarks of the technical review committees CKM initiated a program of R&D after Stage-I approval . This R&D program is now largely complete, and the results are outlined in the following section.

State of Technical Readiness

The Main Injector serves as the high-flux proton source for the CKM experiment. This accelerator has been fully operational now for several years and reliably provided beam for the 1999 fixed target run. The proton flux required for CKM is a small fraction of the Main Injector capability.

Exploiting TESLA techniques and infrastructure, the CKM experiment, together with the Fermilab Beams and Technical Divisions, have developed advanced prototype SCRF cavities that have demonstrated the required field strengths. A full prototype of the first (of six) cryostats with cavities is under design now with completion expected before 2005.

In the CKM detector it is critical to minimize the material traversed by the kaon beam in order to control backgrounds from interactions. In the downstream magnetic spectrometer, the chosen technology is thin-wall tracking straws traversing the evacuated decay volume. Thin-walled straws have been successfully employed in High Energy Physics experiments for many years now, but never while operating in vacuum. The potential risk associated with this extension of a familiar technology was flagged by the technical review process, and has stimulated a serious R&D program that is near completion. There is now a strawtube prototype operating in vacuum. The vacuum tracker designs are now leaving the R&D phase and entering an engineering cycle.

The technical review committee also flagged the importance of high-performance photon veto technology. The success of the CKM experiment is particularly reliant on the ability to tag high energy (>1GeV) photons with an extraordinary level of efficiency. This reliance has likewise stimulated a serious R&D program which culminated in the fall of 2002 with a full beam test of a CKM photon veto prototype at Jefferson Lab. This beam test has demonstrated that real prototypes can tag high energy electromagnetic showers with an inefficiency of less than $2x10^{-5}$, which exceeds the CKM experimental requirement.

A shortcoming of the CKM proposal noted by the technical review committee and the Fermilab PAC was the absence of plausible trigger and data acquisition system to handle the torrent of data expected from this high rate experiment. Although this is less of an *in principle* concern for the technique, it is still critical to the success of the experiment and can significantly affect the cost. After receiving Scientific Approval, the CKM collaboration embarked on a program to understand and simulate the data flow from the experiment in detail. This has led to a trigger/data-acquisition model built entirely from commodity data switches and PCs that are *available today*. The collaboration have tested this model with a serious prototype built from commodity components, and the performance matches expectation. The further evolution of processing power afforded by Moore's law will only reduce the cost of this implementation by the time the experiment is actually acquiring data.

All CKM detector systems have now been prototyped and tested with recent test-beam runs or data from previous experiments. The performance of each CKM system is determined from *data*, and not simulation. This R&D cycle has significantly reduced the technical risk of the experiment, and allows us to now fully engineer and cost the experiment.

Scope and Expected Cost of the Experiment

The CKM proposal submitted in 2001 included a cost estimate of $56M (FY2001). This estimate includes detector and beamline system M&S and SWF, with an overall 30% contingency. After external review, the contingency was raised to 60% since a Lehman-level of costing basis was not available at the time, which raised the cost estimate to $68M (FY 2001). The cost estimate has since been globally increased to include G&A overhead (16% on M&S, 28% on SWF) yielding a current estimate of $90M. These costs do not include operating expenses of the detector, beamline or the associated proton-source complex. Since Stage-I approval, the CKM collaboration has been refining the cost estimate. The successful operation of key prototypes will reduce costs and contingency, and a detailed analysis of G&A overhead will likely reduce costs as well. At this point the CKM cost estimate is expected to be in the range of $70M and $90M in the previously described metric.

In order to understand the scope of CKM and the impact on the field, it is worth considering the recently completed KTeV experiment. The KTeV experiment is very similar to CKM in terms of physics scope, collaboration size, detector size & complexity and channel count. The KTeV detector and beamline M&S was $24M (FY1995) which escalates to $29M (FY2001). This is comparable to the CKM M&S, which is estimated to be $29M (FY2001). The KTeV timeline was five years from scientific Stage-I approval (1991) to first beam (1996), with a funding profile that occurred simultaneously with Main Injector construction, the first run (Run-I) of the Tevatron collider, and preparation of several other experiments which were operated in the 1996 run. The KTeV experiment collected data in 1996/1997, and again in 1999. The 85 collaborators that compose KTeV have produced 29 journal publications now with more to come.

Summary

Measurement of $K^+ \to \pi^+ \nu \bar{\nu}$ has long been recognized as a particularly incisive probe of physics beyond the Standard Model. This sensitivity arises from the very high mass reach of virtual loop processes within the kaon, and the quantitative certainty with which Standard Model physics contribute to these processes. This sensitivity is very much a broad reach of discovery, since the loop processes are an integral over *all* high-mass physics up to and beyond our current energy frontier. Advances in this ‘‘Sensitivity Frontier” have been fueled by the ever-increasing power of proton accelerators, detector technology and modern computing. The DoE Office of Science has been *the* major partner in this adventure, and is well positioned to continue that leadership in this decade by embracing the physics mission of the CKM experiment.

The CKM experiment proposes an innovative technique based on sound technologies to push the Sensitivity Frontier in rare charged kaons decays by the next order of magnitude. This new technique has withstood intense scrutiny by a wide range of experts in the field, and the experiment is now in a position to be fully engineered and costed. The CKM collaboration is built from battle-tested proponents spanning a wide range of expertise; including those who delivered much of the impressive physics portfolio from the last round of kaon experiments. The next step for the CKM experiment is clear: The scientific approval granted by Fermilab needs to be ratified, and the resources required to successfully engineer the experiment must be allocated.

We have an important measurement to make and have made a compelling case to the HEP community that these techniques and this collaboration can successfully carry out this measurement.