HEPAP Subpanel Report on

the RSVP Project

June 2, 2005

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1 Introduction

In a letter dated Feb. 11, 2005, Dr. Staffin of DOE and Dr. Turner of NSF charged HEPAP to appoint a subpanel to carry out a scientific assessment of the Rare Symmetry Violating Processes (RSVP) program (see Appendix A for the full text of the letter). The committee members (listed in Appendix B) met several times during March and April, and submitted this report at the beginning of June, 2005.

The RSVP program consists of two experiments, MECO and KOPIO; both are designed to search for rare decay processes which, if observed at a rate significantly above the predicted Standard Model value, would constitute exciting evidence for new fundamental interactions. MECO and KOPIO both propose to run in parasitic mode at the Brookhaven AGS, with the primary costs for AGS operations borne by the RHIC program. Beyond this, the two experiments are very different: MECO is a search for muon-to-electron conversion, while KOPIO will search for K_L^0 decays to $\pi^0 \nu \overline{\nu}$. The two experiments will not run concurrently, as they require different beam conditions.

The charge requests an analysis of the scientific value of the KOPIO and MECO experiments in the context of the current and planned US and international programs in experimental high-energy physics. It further asks for an assessment of any change in scientific value since 1999, when RSVP was approved by the NSF for Major Research Equipment (MRE) funding in a competitive, proposal-driven process. Prior to the MRE award, both experiments had received scientific approval from the Brookhaven Physics Advisory Committee, MECO in 1997, and KOPIO in 1998.

This report is organized as follows. In Section 2, the main findings and conclusions are presented in the Executive Summary. In Sections 3 and 4, the MECO and KOPIO experiments, respectively, are described and discussed in the context of similar and related experiments, the underlying theoretical issues are discussed and an assessment of the overall scientific value of each experiment is provided. In Section 5, we summarize the main conclusions.

2 Executive Summary

Value:

The strength of both RSVP experiments is their ability to find new physics by detecting a signal differing significantly from Standard Model expectations. Such a discovery would be exciting evidence for new fundamental interactions. This scientific value is unchanged since the RSVP MRE was proposed in 1999.

MECO is sensitive to lepton-flavor violation in both the $\mu \to e\gamma$ interaction and in more exotic interactions, such as those directly mediated by leptoquarks.

KOPIO's measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$ is sensitive to new CP-violating interactions. While KOPIO would not add much to our knowledge of the CKM parameters (η will be known to better than 5% by 2015 from B_d and B_s mixing, relying on lattice calculations for a ratio of hadronic matrix elements), it will probe new physics at the TeV scale in models with minimal flavor violation. In the context of other models, KOPIO is sensitive to even higher mass scales.

Goals:

MECO needs to make a substantial improvement over the current μ-to-e conversion limit of 6.1×10^{-13} in titanium, equivalent to 3.9×10^{-13} in aluminum. It also needs to be able to cover the domain of the planned $\mu \to e\gamma$ experiment MEG, which would reach the equivalent of 2.6×10^{-16} if μ-to-e conversion occurs through the same mechanism as $\mu \to e\gamma$. A minimum single-event sensitivity of 10^{-16} is required, consistent with the MECO goal of 2×10^{-17}, allowing for somewhat larger backgrounds and/or less than perfect detector performance. A sensitivity of 10^{-15} is not an adequate level for MECO.

A goal of 100 events for KOPIO at the Standard Model rate is appropriate. With a signal-to-background ratio of 2, this would give a 5-σ statistical effect for an intrinsic rate 75% greater than the Standard Model prediction. The 100-event level would be achieved with 6000 hours of running at the expected performance. A sensitivity of 10 events for KOPIO at the Standard Model rate is not an adequate goal.

Competition:

Proposals for other experiments measuring the same decays and with similar goals exist for both KOPIO and MECO, but these proposals are not as well developed and in any case the time-scale for RSVP would allow it to reach its goals first. There are also proposals for related experiments, which in general are complementary.

• There is a Letter-of-Intent for an experiment (PRIME) at the PRISM muon facility at JPARC, to measure μ-to-e conversion with a sensitivity goal of 10^{-18}. It is likely that PRISM and PRIME at J-PARC will be carried out after MECO.

• There is a Letter-of-Intent for an experiment to measure $K_L^0 \to \pi^0 \nu\overline{\nu}$ at JPARC with a goal of 100 events. There is a pilot experiment, E391a, at 12 GeV PS at KEK, with a sensitivity of about 10^{-10}, about a factor of three higher than the Standard Model expectation.

• The MEG experiment at PSI could find evidence for a $\mu e \gamma$ coupling before MECO. Such a discovery would provide additional motivation for MECO.

• There are prospective $K^+ \to \pi^+ \nu\overline{\nu}$ experiments at CERN and JPARC. This channel is sensitive to new contributions from both CP-violating and CP-conserving interactions, whereas the $K_L^0 \to \pi^0 \nu\overline{\nu}$ decay is sensitive only to CP-violating interactions. However, the neutral decay mode has the advantages of smaller theoretical uncertainties and greater sensitivity to new CP-violating physics, due to the smaller Standard Model amplitude. If the charged K experiments were to find evidence for new physics, it would increase interest in the KOPIO result.

Context:

In recent years we have learned that neutrinos have mass and large mixing angles, violating (neutral-)lepton flavor conservation. B-meson decays violate CP and the best-measured modes conform to the predictions of the CKM model. No direct sign of a Higgs boson has been seen, but electroweak measurements indicate it should have a low mass. The nature of dark matter remains a mystery, as does that of the newly discovered dark energy. The primary consequences for RSVP of these developments are an increased interest in lepton-flavor violation and a decreased opportunity for KOPIO to contribute to the determination of CKM parameters.

RSVP is complementary to LHC: discoveries at LHC would likely increase interest in RSVP. If LHC sees only a single Standard-Model Higgs, there would still be interest in RSVP experiments since their sensitivity extends beyond the reach of LHC.

The U.S. domestic experimental program in high energy physics is shrinking dramatically with the cancellation of CKM and BTeV and the scheduled completions for BaBar (2008), CESR (2008), and the Tevatron collider (2009). RSVP represents a major fraction of the anticipated accelerator-based program in the U.S.

With resources after 2009 increasingly concentrated in LHC and (we hope) ILC, there is need for more modest-sized experiments for a balanced program and for increased opportunities for students.

While the B factories and LHCb are positioned to cover B physics extensively, the completion of the search for new phenomena in flavor physics requires that both the charged and neutral rare K-decay experiments be completed to the level expected in the Standard Model.

Comparisons:

To characterize the importance of MECO and KOPIO, we compare them to three existing/proposed experiments of generally comparable cost (100 - 300 M$): reactor or accelerator experiments designed to measure θ_{13} in neutrino oscillations, the search for neutrinoless double beta decay, and a future cryogenic cold-dark-matter search.

• The angle θ_{13} in neutrino oscillations is both a fundamental parameter of the Standard Model and a crucial input for future neutrino experiments. It could be beyond the reach of the proposed experiments, in which case they would only provide upper limits.

• The cosmological evidence for dark matter is overwhelming, but we do not know if future cryogenic dark-matter searches will be sensitive enough to detect it. These experiments are complementary to the LHC, which may find particle candidates for the dark matter.

• Whether neutrinos are their own antiparticles is an important fundamental question, with implications for both cosmology and particle physics, but answering it may be beyond the scope of the proposed neutrinoless double beta decay experiments.

• KOPIO and MECO share with the three comparison experiments the capability to affect dramatically our understanding of fundamental interactions.

• The three comparison experiments are responses to specific discoveries: dark matter, neutrino masses, and neutrino mixing. KOPIO and MECO are well-motivated searches for physics beyond the Standard Model, "long-shots" with potentially high payoffs.

Limiting cost:

We assume that NSF will bear only the incremental cost of running the AGS for RSVP. The opportunities provided by RSVP would not justify the full cost of running the AGS.

3 MECO

3.1 Outline of Experiment

The MECO experiment is designed to measure the rate in aluminum for the conversion of a muon to an electron in the field of a nucleus with a single-event sensitivity of 2×10^{-17}, normalized to the muon-capture rate. This is the quoted sensitivity for a detection of five events with a background of 0.5 events when the branching ratio is 10^{-16}; we present the capability in this way because we believe it is important to detect at least several events to establish the observation of μ-to-e conversion. The current proposal calls for five years of running with 24 productive weeks per year, averaging 90 hours per week split equally with KOPIO. As a result of slippage in the schedule, completion of commissioning is now planned for mid-FY11 and thus a completion of the experiment in FY16.

In μ-to-e conversion the nuclear recoil balances energy and momentum and the resulting conversion electron has an energy just below that of the muon mass. More precisely, the electron energy E_0 will be equal to m_μ minus the sum of the nuclear binding energy of the muon and the kinetic energy carried away by the recoiling nucleus. Observation of μ-to-e conversion would be evidence for lepton-flavor violation in the charged-lepton sector. The previous best limit is from the SINDRUM II experiment (6.1×10^{-13} for capture on titanium, equivalent to 3.9×10^{-13} on aluminum)[2].

MECO received scientific approval from the Brookhaven Physics Advisory Committee in 1997, just one year before the discovery of atmospheric neutrino oscillations by the Super-Kamiokande experiment. The subsequent confirmation of this result and the observation of neutrino oscillations in both solar and reactor neutrinos have definitively proved that lepton flavor is not conserved. That lepton-flavor violation in the neutrino sector is now well established does not diminish the scientific motivation for MECO. Although neutrino oscillations offer a means by which μ-to-e conversion can occur within the Standard Model, the expected rate is very low, on the order of 10^{-48}, well beyond any current or future experiment. The scientific motivation for MECO and related experiments is to obtain evidence for particles that have not yet been observed and whose virtual presence can boost the rate for μ-to-e conversion by many orders of magnitude beyond the Standard Model prediction. MECO is sensitive to the existence of heavy particles that can be directly observed only at the highest energy accelerators, such as the Large Hadron Collider, and its sensitivity extends to particles with masses beyond the reach of the LHC.

A related reaction is the decay $\mu \to e\gamma$. Like $\mu \to e$ conversion, this process would conserve energy, angular momentum, and electric charge, but has never been observed. A $\mu \to e\gamma$ mechanism would necessarily contribute to μ-to-e conversion, but some μ-to-e conversion mechanisms would not generate $\mu \to e\gamma$. For models in which a photon mediates the conversion process, the rate for $\mu \to e\gamma$ is directly related to the rate for $\mu \to e$ conversion and depends on the atomic number of the capture nucleus. The rate for $\mu \to e$ conversion in the field of an aluminum nucleus ($Z = 13$), for example, is $1/380$ of the rate for $\mu \to e\gamma$, while for titanium ($Z = 22$) the ratio is $1/240$. However, the mean time for capture of a muon in orbit around titanium is much shorter than for aluminum, making it experimentally much more challenging to separate the $\mu \to e$ conversion signal from from prompt backgrounds. Aluminum is the currently proposed target material for MECO, while many of the earlier $\mu \to e$ conversion experiments used a titanium target. The MECO Collaboration is still making a final evaluation of these two materials, but for the purposes of the report we will refer to the target as aluminum.

In the decay at rest of a free muon, the electron energy is limited to $m_\mu/2$, far from the energy resulting from μ-to-e conversion. However, when a muon bound to a nucleus decays, the endpoint of the electron energy spectrum occurs when the two neutrinos are emitted with very little energy and the nuclear recoil balances the momentum of the electron. This mimics the signature of the $\mu \to e$ conversion process, resulting in a single electron with maximum energy close to m_μ. This background is strongly suppressed in the energy region of interest as it varies as $(E_0 - E)^5$. A second unavoidable background is radiative muon capture: $\mu(Z, N) \to \nu_\mu(Z - 1, N + 1)\gamma$, followed by conversion of the photon into an asymmetric e^+e^- pair with a low-energy positron that escapes detection.

Other backgrounds arise from sources that are not intrinsic to the disappearance of the muon. These include pions that stop in the target, producing gammas with energies up to 140 MeV, electrons in the putative muon beam that scatter in the target, and inevitably, cosmic rays.

These backgrounds dictate the structure of the experiment. To discriminate against decay-in-orbit and radiative muon capture, excellent electron energy resolution is required. To discriminate against the prompt backgrounds associated with the beam, a pulsed beam is used and events are taken only from a window between the pulses. Occupied buckets (of width 30 ns) are separated by 1350 ns and only the last 700 ns are used for observing signal. To reach extreme sensitivities, a very intense proton beam is required: 2×10^{13} protons per second, comparable to the intensity now achieved. Additionally, the extinction of the beam between pulses needs to reach the level 10^{-9} relative to the intensity during the spill. Achieving this level of extinction for high beam intensity is one of the primary challenges for this experiment and several of the important backgrounds will scale with the achieved level of extinction. The experiment has adopted a conservative approach by including two different techniques in the beamline upgrades to improve the extinction between pulses.

The defining feature of MECO's design is the system of magnets used to capture the produced pions, transport the resulting decay muons to stopping target, capture the decay electrons, and then measure their momenta. See Fig. 1. The design and procurement of the MECO magnets is estimated to cost $57M and take 66 months. The production and stopping-target regions have solenoidal fields with higher field strengths at one end, which reflect particles into the active volumes. The stopping target consists of 17 aluminum disks, each 0.2 mm thick. Straw tubes provide the tracking in the 1-T field. The energy resolution is stated to be 0.3% rms. A crystal calorimeter downstream of the tracker provides the trigger.

A number of experimental challenges must be overcome by MECO, in addition to achieving the extraordinary level of extinction betwee beam bunches. All detector elements must operate in vacuum, introducing significant design issues and some operational risks. The straw tracker must operate in a very high rate environment. Even a very low level of track reconstruction errors in this difficult environment has the potential to introduce measurement errors and therefore backgrounds. Overall, the experiment is a difficult and ambitious undertaking.

3.2 Previous and Future μ-to-e Conversion Experiments

3.2.1 TRIUMF 1988

The TRIUMF experiment [3] used a hexagonal TPC in a 0.9-T axial magnetic field. The full-width-at-half-maximum (FWHM) resolution on the electron energy was 4.5 MeV. The stopping target was titanium, dispersed to a low density to minimize energy-loss and multiple scattering for the outgo-

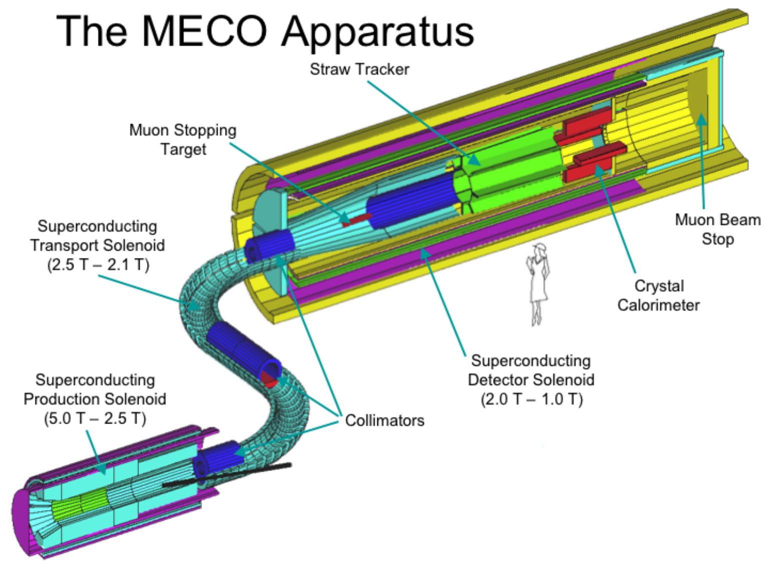

Figure 1: The MECO detector.[1]

ing electron. A total of 0.9×10^{13} muons were stopped in the target. No electrons were observed in the window $96.5 \leq P_e \leq 106$ MeV/c, in which 85% of the signal events should have fallen. Events immediately below this window were consistent with the expectation for muon decay-in-orbit, while those above were consistent with the cosmic-ray background anticipated on the basis of beam-off measurements. The detection efficiency for μ-to-e conversion was 0.056, resulting in a 90% CL limit for the ratio of conversion to capture in titanium of 4.6×10^{-12}.

3.2.2 SINDRUM II

SINDRUM II [4] used drift chambers for tracking inside a 1.2-T solenoidal field, together with scintillating plastic hodoscopes. The momentum resolution on positrons from $\pi^+ \rightarrow e^+\nu$ was 1.5% FWHM and the MECO proposal cites 2.5 MeV for the SINDRUM II resolution for electrons at 100 MeV. Variation in energy loss in the target dominated the resolution. No events were seen above 100.6 MeV/c. The 90% CL limit for the ratio of conversion to capture was set at 4.3×10^{-12}. With additional running this limit was improved to 6.1×10^{-13}[2].

3.2.3 PRIME at PRISM (Japan)

PRISM (Phase Rotated Intense Slow Muon source) [5] would be part of a Japanese neutrino factory source. The beam momentum would be 68 MeV/c, with $10^{11} - 10^{12}$ μ/s. PRISM would use a Fixed Field Alternating Gradient (FFAG) synchrotron to produce this spectacular beam with a uniform intensity over a momentum range $\pm 3\%$ about its nominal value. The pion contamination would be nearly zero, thanks to the long decay path for particles making five turns of the PRISM ring. Extinction of the beam between pulses seems to be controllable. The Letter of Intent for this ambitious project was submitted in 2003.

PRIME [6] is a proposed experiment that would use the PRISM muon beam, with a goal of setting a limit of better than 10^{-18} for the ratio of μ-to-e conversion to μ capture. The detector for PRIME is also very ambitious. The electron energy resolution goal is 350 keV FWHM. The instantaneous event rate will be very high, with about $10^{10} - 10^{11}$ μ per bunch. A target design has 20 layers of 50-μm aluminum. This is adequate to stop 80% of the muons, given their energy. The thin layers minimize energy loss by the outgoing electrons. A curved solenoidal spectrometer will transport to the electron detector only those outgoing electrons with momentum above 90 MeV. A candidate design for the tracker uses straw tubes and has an intrinsic momentum resolution of 100 keV. The net momentum resolution, 235 keV, is dominated by energy-loss variation in the stopping target. PRIME also submitted a Letter of Intent in 2003.

3.3 Related Experiments, Past and Future

Lepton-flavor violation could appear in decays with no hadrons present, like $\mu \to e\gamma$, $\mu \to eee$, $Z \to e\mu$, $\tau \to \mu\mu e$, or processes that involve hadrons, like $\mu N \to eN$, $K \to \mu e$, $K \to \pi\mu e$, $D \to \mu e$, etc. The connection between these would depend on the nature of the lepton-flavor-violating interaction. Among the tests of lepton-flavor conservation listed in the 2004 *Review of Particle Physics* a number stand out and are reproduced in the Table 1.

3.3.1 MEGA: 1985-1995

The signal for $\mu^+ \to e^+\gamma$ is the back-to-back monochromatic final state particles. In MEGA [7], the positron's energy was measured with MWPCs in a 1.2-T solenoidal field, with resolution $\sigma = 0.21 - 0.36$ MeV, depending on the track topology. The photon's energy was measured with pair spectrometers following Pb conversion foils. The photon resolution was limited by multiple scattering in the converters to 3.3%−5.7% FWHM. The resolution of the angle between the positron and photon directions was also limited by multiple

Process	90% CL limit
BF($\mu \to e\gamma$)	1.2×10^{-11}
BF($\mu \to eee$)	1.0×10^{-12}
BF($\pi^0 \to \mu^+ e^-$)	3.8×10^{-10}
BF($K_L \to \mu^\pm e^\mp$)	4.7×10^{-12}
BF($K^+ \to \pi^+ \mu^+ e^-$)	2.8×10^{-11}

Table 1: Some limits on charged-lepton-number violation extracted from *RPP* 2004, p.84

scattering and was $\sigma = 0.067$ and $\sigma = 0.116$ rad for conversions in the inner and outer converters. Background was dominated by random coincidences between positrons from ordinary decay, $\mu^+ \to e^+\nu\bar{\nu}$, and decay with inner bremsstrahlung, $\mu^+ \to e^+\nu\bar{\nu}\gamma$. Timing information was used to discriminate against this background. A year of computing reduced 4.5×10^8 events on tape to 3971 candidates. The efficiency for signal was about 3.5×10^{-3}. A maximum-likelihood analysis yielded zero signal events and $30 \pm 8 \pm 15$ inner bremsstrahlung events. The final limit for $\Gamma(\mu^+ \to e^+\gamma)/\Gamma(\mu^+ \to e^+\nu\bar{\nu})$ was 1.2×10^{-11} at 90% CL.

3.3.2 MEG

The MEG μ-to-$e\gamma$ experiment [8] at PSI, whose goal is a sensitivity near 5×10^{-14} (capable of setting a 90% CL limit of about 1×10^{-13}), should be ready for data-taking in 2006, with completion by 2008-9. This is to be followed by a second phase, with still greater sensitivity. If μ-to-e conversion is photon-mediated, the first-phase MEG experiment has sensitivity about one order of magnitude less than that of MECO. MECO is sensitive additionally to lepton-flavor changing interactions that do not involve a photon. The great sensitivity of MEG results from the intense PSI proton beam, a liquid-xenon photon calorimeter, and a positron spectrometer with an advanced design.

3.4 Theory for MECO

The Standard Model with the apparently very small neutrino masses gives essentially no charged-lepton-flavor-changing neutral currents. As in the quark sector, these processes are suppressed by mixing angles and differences of squares of fermion masses, divided by M_W^2. Though the neutrino mixing angles are large, the masses are miniscule. New physics can produce flavor-changing currents either by modifying the known currents, like the electromagnetic current, or by introducing new forces, such as leptoquarks or new gauge bosons that connect particles of the same electric charge but from different generations of quarks or lepton.

It is a triumph of the Standard Model that it suppresses neutral-flavor changing neutral currents. Indeed, the Standard Model was, in some sense, invented to do just that. However, adding new particles, in particular supersymmetric particles, reintroduces the problem of suppressing neutral-flavor changing currents. Even when a scheme is devised to provide suppression, in general there are effects that can be observed with sufficiently sensitive tests. In supersymmetry we cannot expect that the mass eigenstates for the sleptons are aligned exactly as the lepton mass eigenstates are.

3.4.1 μ-to-e conversion in grand-unified supersymmetry

Barbieri and Hall [12], and Barbieri, Hall, and Strumia [13] showed that in grand-unified supersymmetric theories, if the supersymmetry breaking occurs above the grand-unification scale, flavor-changing neutral currents will be induced in the leptonic sector as a consequence of the large Yukawa coupling that must be present to give the t quark its mass. Just as in the quark sector, flavor-changing neutral currents arise in the lepton sector as an incomplete cancellation among the three generations. If the masses of the three generations are identical, the particles can be redefined so that no mixing occurs and neutral currents are absent. If the masses differ, then the strength of the neutral flavor-changing currents depends on the differences of squares of masses and on the mixing matrix.

With grand unification, the CKM-like matrix for the leptons is similar to that for the quarks. To make sure that the neutral lepton-flavor-changing currents aren't too large, one can postulate that the slepton masses are identical at a very high mass scale, say the Planck mass. However, the $\tilde{\tau}$ (super partner of the τ) has a big coupling to the top quark through a superpartner of a Higgs, which contributes to the $\tilde{\tau}$ mass, but not to that of the $\tilde{e}$ or $\tilde{\mu}$. The end result is that the $\tilde{\tau}$ has a lower mass than the $\tilde{e}$ or $\tilde{\mu}$. [In SU(5), only the $\tilde{\tau}_R$ has a lower mass since the t_L and τ_L don't belong to the same representation. In SO(10), both the $\tilde{\tau}_R$ and $\tilde{\tau}_L$ have lower masses since there is a single representation containing all the quarks or squarks of a generation.] This mass difference, together with the charged-lepton CKM matrix, is responsible for the residual flavor-changing neutral currents.

The mixing matrix for neutrinos, unlike the CKM matrix, has large off-diagonal components. Supersymmetric models incorporating such a matrix find enhanced lepton-flavor violation when right-handed neutrinos are included [14].

If we imposed equality of the slepton masses below grand unification, this mass splitting would not occur because the coupling of the $\tilde{\tau}$ to the t quark through the (super) Higgs is suppressed because the Higgs in question has a mass above the grand unification scale and because there is no interaction between the $\tilde{\tau}$ and the t quark below the scale of grand unification.

In grand-unified SUSY models with supersymmetry breaking at the Planck scale typical rates for μ-to-e conversion relative to μ capture are in the $10^{-15} - 10^{-16}$ range. Failure to find conversion at this level would suggest that if there is low-mass supersymmetry, the supersymmetry breaking occurs below the unification scale (or perhaps that there is no unification).

3.4.2 Other models for μ-to-e conversion

The underlying transition $\mu u \to eu$ or $\mu d \to ed$ might be the result of the exchange of a neutral leptoquark L, where the L changes the muon to a quark and a quark to an electron. Alternatively, it might be the result of a new gauge interaction connecting different generations, with some suppression because the transition of a muon to an electron changes generation, while the quark interaction conserves generation. Another possibility is that R-parity-violating supersymmetry could introduce interactions leading to μ-to-e conversion. Unlike the situation with grand-unified supersymmetry, there is no particular scale that presents itself for such new interactions. A strength of μ-to-e conversion is that it is sensitive to new interactions whose mass scale is enormous. Using the current limit on μ-to-e conversion, one finds [9] a scale of order 300 TeV.

4 KOPIO

4.1 Outline of Experiment

KOPIO (BNL E926) seeks to observe the very rare decay $K_L^0 \to \pi^0 \nu\bar{\nu}$, for which the branching fraction is expected to be about 3×10^{-11} in the Standard Model. Experimentally, this mode is challenging for several reasons: (1) the small branching ratio requires the experiment to run with extremely high beam fluxes; (2) neutral beams contain more neutrons than K_L^0's and cannot be momentum-selected; (3) there are no charged particles in the initial state or the final state, and the final state contains two unobservable neutrinos; and (4) there are copious sources of photons from other K_L^0 decays. KOPIO addresses these challenges by employing innovative and powerful techniques.

The novel feature in the KOPIO approach to $K_L^0 \to \pi^0 \nu\bar{\nu}$ is the use of time-of-flight to determine the momentum of the K_L^0. This provides kinematic information that is very powerful in rejecting backgrounds, since decays can be analyzed in the center-of-mass. To make the time-of-flight measurement, the AGS must provide beams with a microbunched structure in which the extracted protons reside in bunches of rms width of 200 psec or less, while the proton flux between microbunches is suppressed by a factor of 10^{-3} (the so-called extinction). This must be achieved while delivering close to 1×10^{14} protons/spill, with a long flat-top of about 5 sec. The neutral-beam channel views the proton target at a large angle (42.5 degrees), chosen both to soften the K_L^0 spectrum to make the time-of-flight measurement possible and to improve the K_L^0/n ratio. The expected fluxes are about 3×10^8 K_L^0/spill in the momentum range between 0.5 and 1.5 GeV/c and several times 10^{10} neutrons/spill. The detector is pictured in Fig. 2.

The principal backgrounds KOPIO must face are the decays $K_L^0 \to \pi^0\pi^0$, $K_L^0 \to \pi^0\pi^0\pi^0$, $K_L^0 \to \pi^+\pi^-\pi^0$, and $K_L^0 \to \pi^\pm e^\mp \nu\gamma$. Key to the experiment, therefore, is operating with a hermetic detector capable of vetoing extra photons or charged particles. For instance, the probability for *missing* both photons from a π^0 decay can be no more than 10^{-8}. To achieve this level of rejection it is necessary to operate detectors with exceedingly low energy thresholds (2 MeV), making them sensitive to false vetoes (and the resulting deadtime) from a daunting number of possible sources. The vacuum decay tank will be surrounded with a Pb-scintillator photon-veto system lined with a layer of scintillator to veto charged particles. To improve the reconstruction of π^0's, KOPIO will employ an active pre-radiator in front of the forward calorimeter. This device will provide an angular resolution of about 25 mrad for the direction of photons, making it possible to obtain a π^0 vertex in some cases. Because of the enormous flux of neutrons, a specialized photon-veto detector that is blind to neutrons is needed to operate in

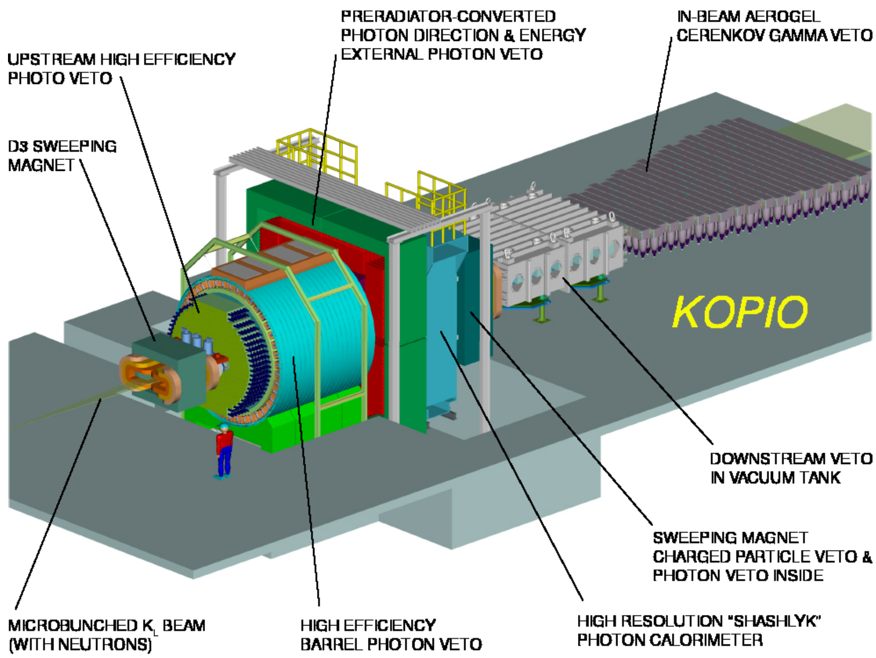

Figure 2: The KOPIO detector.[15]

the neutral beam. KOPIO is developing a Cherenkov detector, constructed of Pb sheets and aerogel, for this purpose.

While KOPIO involves risk, it appears to be doable. Extensive simulations have been performed that support the conclusion that backgrounds can be suppressed to the required level. Refinements to these simulations can and should be made, but no show-stoppers have been identified. Beam tests at the earliest possible date should test the ability of subsystem prototypes to achieve the required performance, but such tests are a normal part of design and construction of a state-of-the-art detector.

An important lesson from similar experiments in the past is that success requires time and commitment. Unexpected problems will emerge. With time and effort they can probably be solved, but arbitrary or inflexible running scenarios may not be consistent with the success of an experiment such as KOPIO. A contingency plan to modify or upgrade parts of the detector, and to take more data than initially projected, should be part of the RSVP program.

4.2 Other $K_L^0 \to \pi^0 \nu\bar{\nu}$ Experiments

The KTeV experiment, which was not designed to search for $K_L^0 \to \pi^0 \nu\bar{\nu}$, set an upper limit on the branching fraction of 5.9×10^{-7} (90% CL). A dedicated $K_L^0 \to \pi^0 \nu\bar{\nu}$ search, known as KAMI (Kaons at the Main Injector), was proposed for Fermilab by the KTeV collaboration, but not approved.

A dedicated $K_L^0 \to \pi^0 \nu\bar{\nu}$ experiment is underway in Japan. Currently running at the KEK Proton Synchrotron (PS), E391a is limited by the proton flux available at the PS (about 2×10^{12} per spill at 12 GeV). The target sensitivity of the experiment is around the 10^{-10} level, so E391a is not competing with KOPIO. Its purpose is primarily to test and further develop an experimental technique for the $K_L^0 \to \pi^0 \nu\bar{\nu}$ search that can ultimately be transferred to J-PARC [10]. E391a does not employ the same strategy as KOPIO. Rather than utilize K_L^0 time-of-fight to obtain a kinematic constraint, E391a relies upon forming a "pencil beam" so that the direction of K_L^0 flight is well known. Then the momentum component of decay photons transverse to that direction can be used to reject backgrounds, since the kinematic endpoint for photon p_T is larger in $K_L^0 \to \pi^0 \nu\bar{\nu}$ than in most background modes, such as $K_L^0 \to \pi^0 \pi^0$. This is the same technique that KAMI would have employed. Excellent rejection of events based on vetoes of extra photons or charged particles is of course necessary, so that a hermetic detector is once again required.

A letter of intent from the E391a collaboration for a J-PARC experiment has been submitted. The possible schedule for such an experiment is uncertain. The J-PARC experiment would also use the pencil-beam technique rather than the time-of-flight approach of KOPIO.

4.3 Related Experiments

While KOPIO is novel, experiments with some important common features have been performed in the past at the Brookhaven AGS. For instance, a rare K_L^0 decay experiment achieved single-event sensitivities for $K_L^0 \to \ell^+ \ell^-$ modes similar to that needed by KOPIO for $K_L^0 \to \pi^0 \nu\bar{\nu}$. Many similar neutral beam issues had to be faced, but there was no requirement to operate a hermetic veto system. The BNL E787/E949 detector operated with a photon-veto system that was nearly hermetic and achieved rejection as good as needed for KOPIO at low energies, but the beam environment was that of a low-energy separated K^+ beam and the size of the veto system was substantially smaller. While direct comparisons are not possible, successful experiments such as these show that dedicated teams can perform difficult, ground-breaking rare kaon-decay experiments at the BNL AGS. However, it should be noted that in both instances cited, it was necessary to perform major detector upgrades mid-way through the experimental program.

4.4 Status of $K^+ \to \pi^+\nu\bar{\nu}$ Experiments

The $K^+ \to \pi^+\nu\bar{\nu}$ decay has been observed by the BNL E787 experiment (2 events) and its follow-on E949 (1 event)[11]. The measured branching fraction is [11]

$$B(K^+ \to \pi^+\nu\bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10},$$

consistent with the prior Standard Model expectation. Running of E949 ended prematurely, preventing it from accumulating a sample that would have likely consisted of about 10 events. E787/949 ran with a low-energy, electrostatically separated K^+ beam. Charged kaons came to rest in a scintillating-fiber stopping-target. Redundant measurements of the outgoing π^+ provided both momentum and range. The identity of the π^+ was established by observing the full $\pi \to \mu \to e$ decay chain. A hermetic lead-scintillator veto system provided π^0-rejection of about 10^{-7} to suppress the dominant background process, $K^+ \to \pi^+\pi^0$. The additional rejection was achieved kinematically, by restricting the acceptance to the small range of π^+ energy (in the CM) between peaks from the $K^+ \to \pi^+\pi^0$ and $K^+ \to \mu^+\nu$ decays.

An experiment, known as CKM (Charged Kaons at the Main Injector), was proposed to measure $B(K^+ \to \pi^+\nu\bar{\nu})$ with higher precision using the Fermilab Main Injector, but the Particle Physics Project Prioritization Panel (P5) ranked it below BTeV and recommended that it not go forward [16]. CKM would have searched for $K^+ \to \pi^+\nu\bar{\nu}$ decays in flight and was projected to be able to observe about 100 events with signal/background of about 10. The experiment would have employed a superconducting RF-separated 22-GeV K^+ beam. The in-flight method for this measurement relied upon ring-imaging Cherenkov counters with phototube readout for particle identification. A large photon-veto system, similar to that of KOPIO, would have been needed, although the required level of performance was somewhat less stringent (owing primarily to the higher energy of the π^0's and resulting photons). Very recently, the Fermilab Program Advisory Committee rejected a descoped version of CKM.

A letter of intent for a measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$ at CERN has been recently submitted. It is a continuation of the NA48 experiment, referred to as NA48/3. Its goal is to observe 100 events if the branching fraction is at the Standard Model level, commencing around 2009.

4.5 Effective Number of Events at KOPIO

The charge to the panel quantifies the KOPIO running by the number of events obtained at the Standard Model rate. However, the number of signal events obtained from a dataset depends on the background contamination

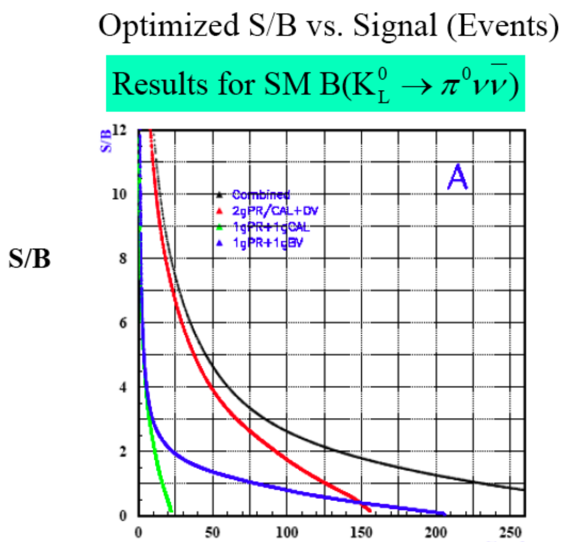

Figure 3: The highest curve gives the ratio S/B of total number of signal to background events accepted as a function of the number of signal events accepted for 12,000 hours of running of KOPIO. [15]

accepted. Equivalently, the ratio S/B is a function of the number of signal events S. To obtain the maximum information, a maximum likelihood fit should be done, taking into account the likelihood that each event is signal. The information in a sample of events can then be quantified by referring to a standard S/B, which we choose to be $S/B = 2$.

From Fig. 3, provided to us by the KOPIO proponents [15], we see that, to a good approximation and scaling from 12,000 hours to 6,000 hours,

$$S/B = 120/S; \qquad B = S^2/120 \tag{1}$$

Here S and B are the total number of events, i.e. when $S = 120/2$, $S/B = 2$, so $B = 30$. We imagine ordering events by their "quality." We collect all of them up to some quality and have S signal events and B background events. Now consider the last little contribution dS. The corresponding bit of background is $dB = SdS/60$, so the marginal B/S is $dB/dS = S/60$. We now calculate the "effective" number of signal events as

$$S_{eff} = \int_0^S dS' \frac{1}{1 + dB/dS} = \int_0^S dS' \frac{1}{1 + (S'/60)} = 60 \ln(1 + (S/60)) \tag{2}$$

By counting each event at its marginal value, we simulate the advantage of a likelihood calculation over a cut-and-count analysis. In particular, for

$S = 60$ (i.e. $S/B = 2$) , $S_{eff} = 41.6$, while for $S = 120$, $S_{eff} = 65.9$. Scaled to 60, the latter becomes $65.9 \times (60/41.6) = 95$. Thus the full sample would have information equivalent to that of 95 events obtained with a total $S/B = 2$.

Beyond $S = 120$, our approximation $S/B = 120/S$ fails. It is not too bad an approximation to ignore these events, which have a marginal $S/B < 1/2$ since the 30 events added in going to $S = 150$ are weighted by a factor less than 1/3.

These numbers are reasonably close to these provided by the KOPIO Collaboration [17]: in 6000 hours there would be 65 events with $S/B > 2$ and that there would be altogether effectively 90 events of this same quality when properly weighted.

4.6 Sensitivity of KOPIO to New Physics

If the New Physics increases the rate to $1 + x$ times the Standard Model rate, the total number of events will be $(1 + x)S + B$ and the statistical significance in σs of the New Physics will be, on average,

$$\Delta = \frac{xS}{\sqrt{S[1 + x + (B/S)]}} \tag{3}$$

Thus the sensitivity to New Physics at some number Δ of standard deviations is given by

$$x = \frac{1}{2}\frac{\Delta^2}{S}\left[1 + \sqrt{1 + \frac{4S}{\Delta^2}(1 + (B/S))}\right] \tag{4}$$

In particular, this gives for $S = 100$, $B/S = 1/2$, $\Delta = 5$, the value $x = 3/4$: KOPIO would be sensitive to a 75% increase in the rate at the 5-σ level. In Fig. 4 we show the results when we require a 5-σ effect with $S/B = 2$. These results are similar to those furnished by the KOPIO Collaboration, shown in Fig. 5

4.7 KOPIO's impact on the Status of the CKM matrix

The CKM matrix

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{5}$$

is specified completely in terms of four parameters:

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda(1 + iA^2\lambda^4\bar\eta) & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \bar\rho - i\bar\eta[1 - \lambda^2/2]) & -A\lambda^2(1 + i\lambda^2\bar\eta) & 1 \end{pmatrix} + \mathcal{O}(\lambda^4) + i\mathcal{O}(\lambda^7). \tag{6}$$

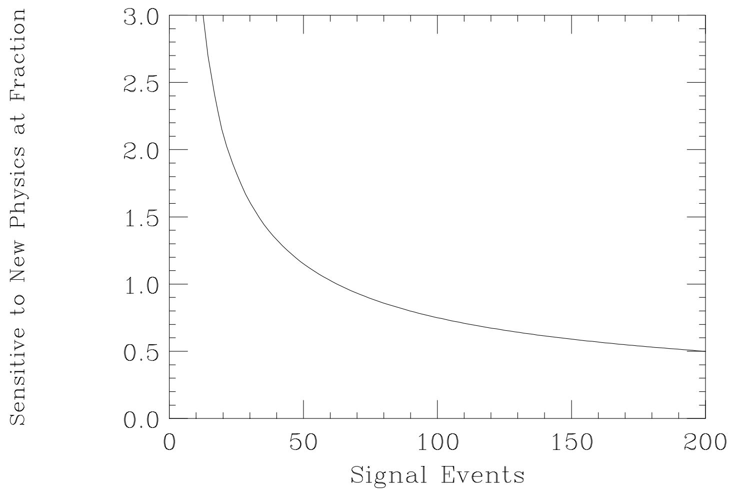

Figure 4: The fraction x that New Physics would have to be relative to the Standard Model rate for $K_L^0 \to \pi^0\nu\overline{\nu}$ for the signal to have 5-σ significance as a function of the number of *Standard Model* signal events obtained with $S/B = 2$. We consider here only the possibility $x > 0$.

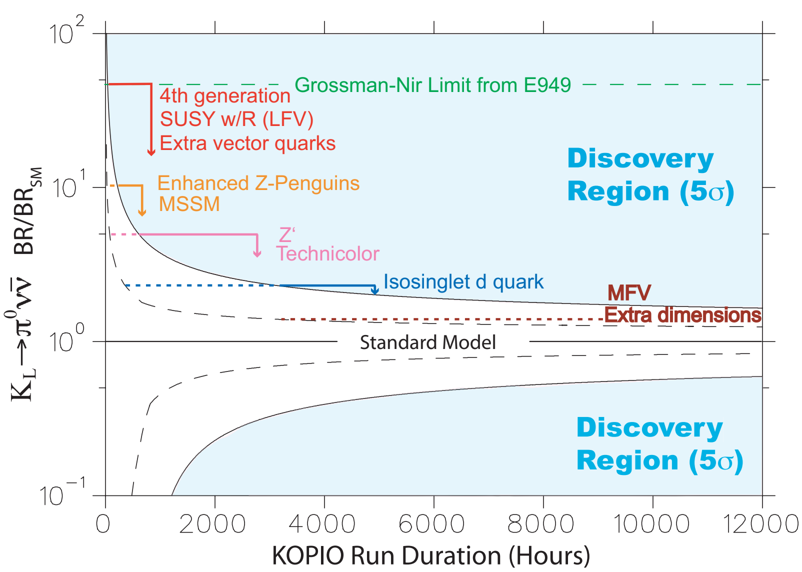

Figure 5: Sensitivity of the KOPIO experiment given as the ratio of observed $K_L^0 \to \pi^0\nu\overline{\nu}$ events to that expected in the Standard Model, as a function of running hours. The shaded region is covered at 5-σ while the dashed line indicates the 95% CL limit.[17]

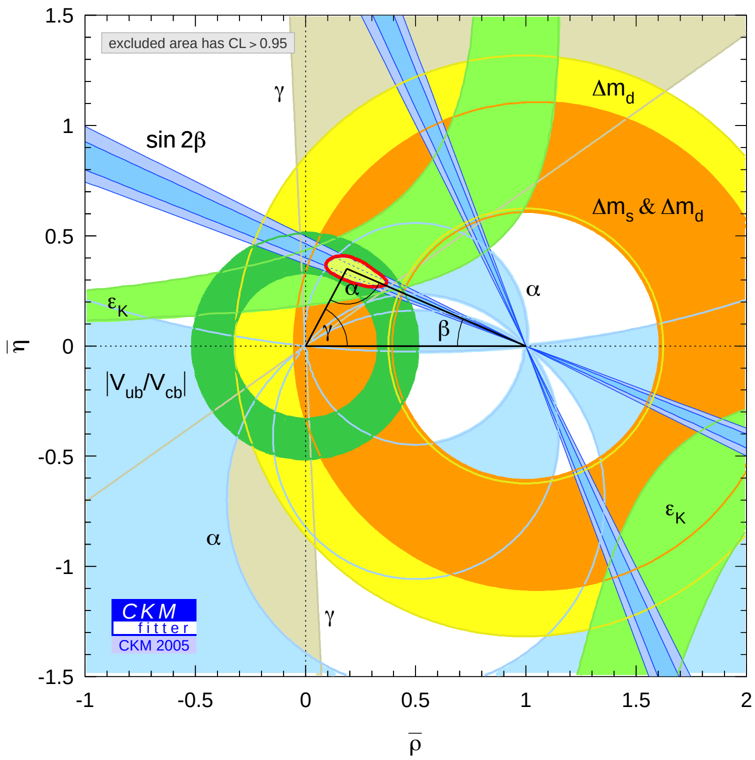

Figure 6: Present status of the determination of $(\bar{\rho}, \bar{\eta})$, from the CKMfitter Collaboration[18].

Here the matrix has been expanded in powers of the small parameter $\lambda \simeq 0.22$ and is unitary to order λ^3 in the real part and to order λ^6 in the imaginary part. To achieve percent accuracy on $\bar{\eta}$ an expansion to this order is necessary. The parameter λ is determined from $K_{\ell 3}$-decays and is known with 1% accuracy, while $A\lambda^2$ is obtained from an analysis of the moments of the inclusive semileptonic B-meson decay rate and is known to 1.5%. This error includes roughly equal contributions from theory and experiment, and it seems unlikely that the theory error could be significantly reduced in the near (10-year) future.

The pair $(\bar{\rho}, \bar{\eta})$, together with the points $(0,0)$ and $(1,0)$ determine a “unitarity” triangle in the $\bar{\rho}$-$\bar{\eta}$ plane. The current status of the determination of these parameters is depicted in Fig. 6. The wedges emanating from the point $(1,0)$ show the allowed region from the determination of $\sin 2\beta$, the annulus centered at the origin shows the constraint from semileptonic $b \rightarrow u$ and $b \rightarrow c$ decays and the circles centered about the point $(1,0)$ show the regions allowed by the $B^0 - \overline{B}^0$ and $B_s - \overline{B}_s$ mass differences (measurement of ΔM_d and limit on ΔM_s, respectively).

The rate for $K_L^0 \to \pi^o \nu\bar{\nu}$ is proportional to $\bar{\eta}^2$. A precise rate measurement translates into a precise determination of $\bar{\eta}$. How well will $\bar{\eta}$ be determined by 2012? A simple analysis can be performed whereby we assume β and λ are known exactly (they are determined much more accurately than the other parameters we consider) and then $\bar{\eta}$ is determined from one other measurement. We consider three measurements that are likely to improve in the future:

- *Semileptonic $b \to u\ell\nu$.* This determines $|V_{ub}|$. The error in $\bar{\eta}$ is estimated to be $\delta\bar{\eta}/\bar{\eta} \approx 2\delta v/v$, where $v = |V_{ub}/V_{cb}|$ and where we use the reasonably well known values for the parameters. Hence, even a 5% determination of v would only give 10% accuracy in $\bar{\eta}$.

- *$\Delta M_d/\Delta M_s$.* This gives $\delta\bar{\eta}/\bar{\eta} = \delta v/v$ where $v = |V_{td}/V_{ts}|$. In this case the experimental error is expected to be negligible, once ΔM_s is measured. The predominant error will be from the lattice determination of the SU(3) breaking parameter $\xi \equiv f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}}$. It is expected that $\delta v/v = \delta\xi/\xi$ will be at the 1%–2% level in 10 years [19].

- *γ measurements.* From a determination of the unitarity triangle angle γ one obtains $\delta\bar{\eta}/\bar{\eta} \approx 0.5\delta\gamma/\gamma$ if we use typical values for the parameters of the triangle. A theoretically clean determination of γ can be made by measuring six time-integrated decay rates with $B^0 \to D^0 K^{0*}$ self-tagged through $K^{0*} \to K^+\pi^-$ and $D_{\rm CP} \to K^+K^-$ (or $\pi^+\pi^-$). LHC-B expects a precision of 13% in the determination of γ after one year of running [20], so it seems likely that by 2012 a determination of $\bar{\eta}$ at the 5% level will be available from γ measured at the LHC-B. Measurements of γ in $B^+ \to DK^+$ and similar modes by BaBar [21] and Belle [22] have reached precisions of 25 - 30% with about 200 fb^{-1} of data. Together, the experiments might ultimately have 2 - 3 ab^{-1}, perhaps achieving a 10% measurement of γ.

4.8 Theoretical Uncertainties in the $K \to \pi\nu\bar{\nu}$ decay amplitude

In the Standard Model of Electroweak interactions the decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L^0 \to \pi^0\nu\bar{\nu}$ arise from $W^\pm$-box and Z^0-penguin diagrams. The one-loop diagrams involve charge-2/3 quarks, so the rates depend on the masses of the charm and top quarks. The low-energy effective Hamiltonian for the decays is

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} \sum_{\ell=e,\mu,\tau} \mathcal{C}^\ell \bar{s}_L\gamma_\mu d_L\, \bar{\nu}_L^\ell \gamma^\mu \nu_L^\ell + \text{h.c.} \tag{7}$$

The index $\ell = e, \mu, \tau$ denotes the lepton flavor. The dependence on the charged-lepton mass, resulting from the box-graph, is negligible for the top contribution. In the charm sector this is the case only for the electron and the muon, but not for the τ-lepton. In the standard model the coefficients $\mathcal{C}^\ell$ that encode the dependence on the masses are

$$\mathcal{C}^\ell = \frac{\alpha}{2\pi \sin^2 \Theta_W} \left(V_{cs}^* V_{cd} X_{NL}^\ell + V_{ts}^* V_{td} X(x_t) \right). \tag{8}$$

Explicit expressions for the functions X_{NL}^ℓ and $X(x_t), (x_q = m_q^2/M_W^2)$ can be found in Ref. [23]. The GIM mechanism implies that $X_{NL}^\ell \propto x_c - x_u$. The suppression of charm relative to top contributions is partially compensated by the larger CKM factors, $V_{ts}^* V_{td}/V_{cs}^* V_{cd} \sim A\lambda^4$.

The decay rate is computed in terms of the vector current form factors $f_\pm$ defined by:

$$\langle \pi^0 | \bar{s}_L \gamma_\mu d_L | K^0 \rangle = -\frac{f_+(q^2)}{2\sqrt{2}} (p_K + p_\pi)_\mu - \frac{f_-(q^2)}{2\sqrt{2}} (p_K - p_\pi)_\mu, \tag{9}$$

$$\langle \pi^+ | \bar{s}_L \gamma_\mu d_L | K^+ \rangle = \frac{f_+(q^2)}{2} (p_K + p_\pi)_\mu + \frac{f_-(q^2)}{2} (p_K - p_\pi)_\mu, \tag{10}$$

where isospin invariance has been invoked to relate the charged and neutral cases. Only the f_+ form factor is relevant since the contribution of f_- to the rate is suppressed by a factor of the square of the neutrino mass. Ignoring f_-, the amplitudes are given by

$$\langle \pi^+ | \mathcal{H}_{\rm eff} | K^+ \rangle = \frac{2G_F}{\sqrt{2}} \sum_\ell \mathcal{C}^\ell f_+(q^2) (p_K + p_\pi)_\mu \bar{\nu}_L^\ell \gamma^\mu \nu_L^\ell, \tag{11}$$

$$\langle \pi^0 | \mathcal{H}_{\rm eff} | K_L^0 \rangle = -\frac{2G_F}{\sqrt{2}}\, i \sum_\ell {\rm Im}\, \mathcal{C}^\ell \; f_+(q^2) (p_K + p_\pi)_\mu \bar{\nu}_L^\ell \gamma^\mu \nu_L^\ell. \tag{12}$$

Note that since K_L^0 is nearly a CP eigenstate, the K_L^0 decay amplitude is proportional to the imaginary part of $\mathcal{C}^\ell$ only. The differential decay rate into a particular neutrino species is

$$\frac{d\Gamma^\ell}{dq^2} = \frac{G_F^2 |c^\ell|^2}{96\pi^3 m_K^2} p_\pi f_+^2 [(m_K^2 - m_\pi^2)^2 - q^2(2m_K^2 + 2m_\pi^2 - q^2)], \tag{13}$$

where $c^\ell = \mathcal{C}^\ell$ for the charged mode and $c^\ell = i{\rm Im}\mathcal{C}^\ell$ for the neutral mode.

The charged decay rate can be written in terms of the semileptonic-decay rate to eliminate uncertainties from the determination of the form factor f_+[23]:

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa_+ A^4 X^2(x_t) \frac{1}{\sigma} \left[(\sigma\bar{\eta})^2 + (\rho_0 - \bar{\rho})^2 \right], \tag{14}$$

where $\kappa_+ = 4.11 \times 10^{-11}$ using the semileptonic rate, $\sigma = (1 - \lambda^2/2)^{-2}$, and $\rho_0 - 1 \simeq 0.39$[24]. If only the contribution from the top quark were considered, the final factor would instead have been $[\bar{\eta}^2 + (1-\bar{\rho})^2]$. Theoretical uncertainties in $\rho_0 - 1$ arise from perturbative QCD ($\sim \pm 0.07$) and from non-perturbative effects from higher-dimension operators suppressed by powers of m_c ($\sim \pm 0.02$)[25]. In addition, non-perturbative effects from non-local operators involving the up-quark increase the central value of $\rho_0 - 1$ by about 0.04 (with a 50% uncertainty)[24]. While these estimates of the non-perturbative effects are reasonable, we can not rule out significantly larger non-perturbative contributions.

The prediction for the branching fraction for the neutral mode[23],

$$B(K_L^0 \to \pi^0 \nu \bar{\nu}) = \kappa_L (1 + \lambda^2) A^4 X^2(x_t) \bar{\eta}^2 \tag{15}$$

has smaller theoretical uncertainties. Here $\kappa_L = 1.80 \times 10^{-10}$ and we note that this coefficient includes a factor of λ^8. Thus a 1% uncertainty in λ results in a 4% uncertainty in the derived $\bar{\eta}$. The coefficients of the effective Hamiltonian are determined from physics at an energy scale of order m_t because the imaginary component is associated with V_{td} and thus with diagrams containing the t quark. This makes the perturbative calculation more reliable. Moreover, the non-perturbative corrections are negligibly small since they are suppressed by $(\Lambda_{\rm QCD}/m_t)^2$. The main theoretical uncertainty is from the NLL order QCD correction ($\sim 2\%$). At present the largest uncertainties are from the error in the experimental values of $|V_{cb}|$ and the top quark mass, $\delta B/B = 4\,\delta|V_{cb}|/|V_{cb}| \oplus 2.3\,\delta m_t/m_t$. At present, the top quark mass is known to about 3% while $\delta|V_{cb}|/|V_{cb}| = 1.5\%$[26] with roughly equal contributions from theory and experiment, so the former error dominates slightly. The determination of the top quark mass should improve dramatically in the LHC era, leaving the error in V_{cb} as controlling. It is conceivable that this error will be reduced somewhat in the future. However, the dominant contribution to the theory error seems irreducible so it is unlikely that the error will be reduced below 1%. This is, however, more than adequate for an experiment with the order of 100 events.

4.9 Beyond the Standard Model

As a starting exploratory analysis of effects of new physics we can allow the coefficients $\mathcal{C}^\ell$ of the effective hamiltonian, Eq. (7), to deviate from their fixed standard model values. The expression for the rate, Eq. (13), is still appropriate. In particular note that the charged and neutral modes have identical expressions except for the overall coefficients, $({\rm Re}\,\mathcal{C}^\ell)^2 + ({\rm Im}\,\mathcal{C}^\ell)^2$ and $({\rm Im}\,\mathcal{C}^\ell)^2$ for K^+ and K_L^0 decays, respectively. Several observations:

1. The K_L^0 decay is CP-violating. This is why the rate depends only on the imaginary part of the coefficient. If the new physics does not give

CP-violating effects, it will not show up in K_L^0, but it may still show up in K^+ if the effect is large enough.

2. If the new physics shows up through $\mathrm{Im}\,\mathcal{C}^\ell$, then it will contribute to both the K^+ and K_L^0 decay amplitudes. As stated in the previous section, at present the SM uncertainty in the rates is about 10% and 4% for K^+ and K_L^0 respectively, and both could be reduced in the future. Note, however, that the standard model decay rate for $K_L^0 \to \pi^0\nu\bar{\nu}$ is smaller than for $K^+ \to \pi^+\nu\bar{\nu}$, and this enhances the neutral mode's sensitivity to deviations from the standard model.

3. If for each neutrino species there is a new contribution with an amplitude for $K^+ \to \pi^+\nu\bar{\nu}$ relative to the standard amplitude with the top quark contribution alone

$$\frac{\delta\mathcal{C}^\ell}{\mathcal{C}_t^\ell} = \frac{\delta_r + i\delta_i}{1 - \bar{\rho} - i\bar{\eta}} \tag{16}$$

the fractional change in the branching fraction is

$$\delta BF(K^+ \to \pi^+\nu\bar{\nu}) = \frac{2(\rho_0 - \bar{\rho})\delta_r - 2\bar{\eta}\delta_i}{(\rho_0 - \bar{\rho})^2 + \bar{\eta}^2} = 1.56\,\delta_r - 0.43\,\delta_i \tag{17}$$

where we have used the approximate values $\bar{\rho} = 0.20, \bar{\eta} = 0.33$. The corresponding equation for $K_L^0 \to \pi^0\nu\bar{\nu}$ is simply

$$\delta BF(K_L^0 \to \pi^0\nu\bar{\nu}) = -\frac{2\delta_i}{\bar{\eta}} = -6.1\delta_i \tag{18}$$

CP-conserving mechanisms contribute only to δ_r, while CP-violating mechanisms contribute to both δ_r and δ_i. In particular a new CP-conserving contribution will show up, at some level, in $K^+ \to \pi^+\nu\bar{\nu}$ and a new CP-violating contribution will show up, again at some level, in $K_L^0 \to \pi^0\nu\bar{\nu}$, the new real and imaginary amplitudes may lead to canceling (or enhanced) contributions to the rate for the charged decay. Of course, a priori, new contributions are as likely to lead to decreased as increased rates.

4. The main ingredient in the analysis is isospin symmetry. It can be straightforwardly extended to more general forms of the effective hamiltonian. (The Nir-Grossman bound is the statement that the charged K^+ rate is always larger than the K_L^0 one).

If the new physics parametrized by the effective hamiltonian of Eq. (7) is characterized by a new energy scale Λ and involves a coupling g^2 of magnitude similar to the electroweak coupling, but is otherwise unsupressed, then the deviation from the standard model is characterized by $\Delta\mathcal{C}^\ell \sim (M_W/\Lambda)^2$. Let us assume the decay is sensitive to fractional deviations r from the standard model rate. Then the scale that one probes through this experiment is given by

$$\left|1+\frac{(M_W/\Lambda)^2}{A^2\lambda^5/(16\pi^2)}\right|^2 \sim 1+r \tag{19}$$

Experimentally accessible values of r at KOPIO give an energy reach of $\sim 10^5$ GeV for using $r = 0.75$. However, any such new physics is likely to produce other large flavor-changing neutral processes that would have been already detected.

The above estimate assumes no small couplings in the new physics amplitudes. A fairly general approach that has small couplings in the amplitudes is minimal flavor violation (MFV)[27, 28, 29]. In the absence of quark Yukawa couplings the standard model has an $SU(3)^3 \times SU(3)^3 \times SU(3)^3$ flavor symmetry, corresponding to rotations of the left-handed quark doublets and the (up and down) right-handed quark singlets. In MFV it is assumed that the quark Yukawa couplings are the only source of flavor violation. The above estimate is then somewhat relaxed. Roughly,

$$\left|1+\frac{(M_W/\Lambda)^2}{1/(16\pi^2)}\right|^2 \sim 1+r \tag{20}$$

In this case the energy reach is 1.6 TeV for $r = 0.75$. A more detailed analysis was performed in Ref. [28]. One of the authors (G. Isidori) has kindly provided an update with the following input assumptions: $\delta|V_{cb}|/|V_{cb}| = 2\%$, $\delta\eta/\eta = 5\%$, $\delta\rho/(1-\rho) = 4\%$.The branching fractions are shown in Fig. 7. The Standard Model branching fractions correspond to $\Lambda \to \infty$. The right and left sides of the plot correspond to the assumptions of constructive and destructive interference, respectively, between the standard model and new physics contributions.

Supersymmetric (SUSY) models have withstood the test of time, although there is no evidence to support them. SUSY scenarios that naturally avoid unacceptably large flavor-changing neutral currents are the so-called minimal gravity-mediated and gauge-mediated models. In such scenarios it would be difficult to get observable effects in the K decays considered here. However, in more general scenarios (that still have minimal SUSY particle content) it is possible to get large deviations from the standard model in the neutral mode while still being compatible with all other existing data [30].

New physics that contributes to $K_L^0 \to \pi^0\nu\bar{\nu}$ may well contribute to rare B decays, like $B \to X_s\mu^+\mu^-$ and $B_s \to \mu^+\mu^-$, which will be well studied at the LHC. For the B-system the estimate in Eq. (19) changes to

$$\left|1+\frac{(M_W/\Lambda)^2}{A\lambda^2/(16\pi^2)}\right|^2 \sim 1+r \tag{21}$$

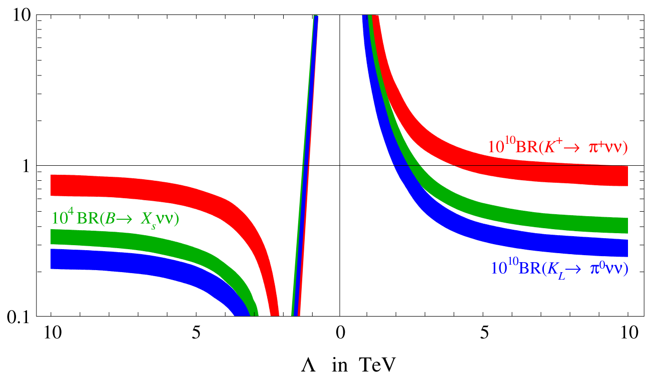

Figure 7: Branching ratios of various processes involving $d_i \to d_j \nu\bar{\nu}$ transitions as functions of the scale of the effective hamiltonian. The bands represent 1σ uncertainties, taking into account the expected accuracy in the determination of the CKM parameters in 2010. This figure is an adaptation of the figure that appeared in [28] and was kindly provided by G. Isidori.

so for the same fractional deviation r KOPIO is sensitive to scales larger by a factor of $\lambda^{-3/2} \sim 10$. However, in MFV Eq. (20) holds in both the K and B systems. Hence, for the same fractional deviation r the B and K systems are sensitive to comparable scales of new physics, Λ.

5 Conclusions

This Committee was unanimous in reaching the main conclusion: both MECO and KOPIO are well-motivated, ambitious experiments that target new physics of fundamental importance in promising - and so far unexplored - territory. The theoretical motivations for both experiments are well-founded and the sensitivities they hope to reach are well-matched to predictions of many popular models for new physics. Moreover, the theoretical uncertainties for the Standard Model rates are small: at the 4% level for KOPIO and negligible for MECO, where no significant SM signal is expected.

There is strong experimental interest in these rare decays, with approved experiments at KEK and PSI and letters-of-intent at JPARC and at CERN in these and related decay modes such as $\mu \to e\gamma$ and $K^+ \to \pi^+\nu\bar{\nu}$. An experiment for this latter mode was also approved by the FNAL PAC, but was later canceled due to lack of funding. This level of interest and activity around the world attests to the importance of these searches, and a shared sense that experiments may finally be reaching the sensitivities required for revolutionary discoveries.

For both experiments, there is a long history of prior searches and incrementally improving limits, as experimental techniques have developed and accelerator beams have become more intense. This history provides the foundation for the ambitious goals of RSVP: MECO is designed for a sensitivity that is almost four orders of magnitude better than previous experiments, while KOPIO's goal is the observation of 100 events at the SM rate, a factor of 300 improvement over the experiment in progress at KEK. The committee believes that both KOPIO and MECO are likely to set the best limits on these processes and could make the first observations in these processes in conflict with the Standard Model, if the experiments are constructed and operated on the proposed schedule. However, other experiments still in the planning stage could offer serious competition if there are further delays. We note the significant delay that has already occurred between the MRE approval and the availability of funding and recognize the risks to RSVP that this has engendered.

MECO employs a novel approach, collecting muons in the graded magnetic field and the transporting them through a curved solenoid, to achieve a dramatic improvement over previous experiments. This will enable MECO to extend the limit substantially or, better yet, discover violation of charged-lepton number. MECO's design range provides a major step beyond previous experiments and will allow it to check any discovery made by the pending MEG experiment for $\mu \to e\gamma$. MECO's range also corresponds well to the scale set by grand-unified SUSY models, which lead to charged-lepton-number violation.

KOPIO, too, employs a novel approach, using time-of-flight information to determine the K_L^0 momentum, which provides an important kinematic constraint. The beam's microbunch structure is thus an essential factor in addressing the challenge of background π^0s from the standard K_L^0 decays.

The experimental challenges facing KOPIO and MECO should not be understated; these challenges have been thoroughly reviewed by others, including, most recently, a panel headed by Prof. Stan Wojcicki of Stanford. Assuming that the goals are met on the planned schedule, the final results from these two experiments at full sensitivity would be available in 2015 - 2016. By this time, the Large Hadron Collider (LHC) experiments will be mature and any new physics at the TeV scale should have been discovered and significantly explored through direct production. However, this committee concluded that new discoveries at the LHC would likely heighten interest in the observation of the expected virtual effects in rare decays, providing new handles on the properties of any new particles and their couplings. Should the LHC fail to find any evidence for new physics, the RSVP experiments would still be important for their sensitivity to new physics above the TeV scale.

The Subpanel chose to compare the RSVP experiments to other existing or planned intermediate-sized experiments: a measurement of θ_{13} in a reactor or accelerator-based neutrino experiment, a search for neutrinoless double decay, and a cryogenic search for cold-dark-matter. These are ambitious experiments, which, if successful, would have dramatic impact, just as would MECO and KOPIO. While the three comparison experiments are responses to specific discoveries – neutrino masses and mixing, and dark matter – the RSVP experiments, while well-motivated theoretically, are "long-shots" with potentially high payoffs.

Cost and schedule were outside the scope of the Subpanel, but the charge asked that the fiscal environment be considered. From the approximate cost figures available, the Subpanel concluded that NSF ought not proceed if that would require NSF to carry the full cost of operating the AGS over a period of years.

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A Charge

U.S. Department of Energy
and the
National Science Foundation

February 11, 2005

Professor Fred Gilman
Chair, HEPAP
Physics Department
Carnegie-Mellon University
5000 Forbes Avenue
Pittsburgh, PA 15213

Dear Professor Gilman:

The National Science Foundation's Directorate for Mathematical and Physical Sciences and the Department of Energy's Office for High Energy Physics request that HEPAP appoint a subpanel to provide advice on the scientific value of the Rare Symmetry Violating Processes (RSVP) project in the context of the US and world programs.

The RSVP project has two scientific thrusts: The Muon to Electron Conversion (MECO) subproject seeks to detect lepton-flavor violating processes in search of the effects of supersymmetric states up to an effective mass of approximately 3000 TeV. KOPIO, which stands for the process K_0 going to π_0 plus a neutrino-antineutrino pair, will provide a measure of CP violation that is uniquely free of hadronic corrections and other CP conserving processes, in addition to providing measurement of another rare process that could reveal evidence of physics beyond the standard model.

The RSVP project was proposed to the NSF in the fall of 1999 and has undergone an extensive review process. RSVP's role in the context of the US particle physics program has been discussed in recent HEPAP reports, e.g., Quantum Universe. RSVP was approved by the National Science Board (NSB) in October 2000 for inclusion in the NSF budget request; and funds were appropriated for a FY 2005 start. A Project Director and Deputy Director were appointed in 2004; and they began organizing a series of focused external reviews to examine the highest risk aspects of the project. The project is preparing for a rigorous baseline review by the NSF in spring 2005, after which the NSB will consider authorizing funds to begin construction activities. However, this series of focused reviews and the ongoing work to baseline the project have revealed the likelihood of significantly higher costs, both for construction and operations, than were estimated previously.

RSVP addresses compelling questions at the frontier of particle physics. Furthermore, it was judged that this project was a timely investment, because of three favorable circumstances at the time. First, since the AGS infrastructure was being operated to provide an injector for the high-priority RHIC project, RSVP could be operated at modest incremental costs in a parasitic mode. Second, RSVP would broaden the field of particle physics with discovery class experiments at the sensitivity frontier, complementing the investments at the energy frontier. Third, the NSF saw an opportunity to explore a new paradigm, namely, an NSFsponsored, university-led particle physics project that would exploit the world-class infrastructure developed by DOE over the years.

The real possibility of significantly higher construction and operation costs has created the need to revisit the scientific importance of RSVP in the context of the US particle physics program. Expert advice from the community is central to future decisions about the most appropriate way to respond to the changing circumstances. For this purpose, we turn to HEPAP. The subpanel is charged to provide an in-depth *scientific* analysis of the scientific value of RSVP, **not** to conduct an additional *technical* analysis or *cost* analysis. The Project Director and Deputy Director are managing the development of the project's technical, cost, and schedule baseline; and the baseline plan will be reviewed rigorously by the NSF in spring 2005.

The specific questions we ask the subpanel to address are the following:

1. Evaluate the science value of MECO in the context of the US investment in elementary particle physics, assuming three cases, achieving sensitivities of 10^{-17}, 10^{-16}, and 10^{-15}.
2. Evaluate the science value of KOPIO in the context of the US investment in elementary particle physics, assuming two cases, observation of 10 events and 100 events (at the rate predicted by the standard model).
3. Place the science value of each in the context of the US elementary particle physics program, broadly defined, recognizing the fiscal environment and the impact on other potential investments at NSF and DOE. How has this context changed since 1999, when the proposal was submitted?
4. Place the scientific value of each in the context of the international elementary particle physics program and assess any potential overlap or complementarity with work being planned elsewhere. How has this context changed since 1999?

We ask that this be done on a compressed timeframe, with at least an interim report by May 15, 2005, followed by a final report by July 1, 2005. Thank you very much for your assistance in this important matter.

Sincerely,

Dr. Robin Staffin Associate Director Office of High Energy Physics Department of Energy	Dr. Michael S. Turner Assistant Director Mathematical and Physical Sciences National Science Foundation
cc: Aesook Byon-Wagner, DOE Bruce Strauss, DOE Marsha Marsden, DOE	Joseph Dehmer, NSF John Lightbody, NSF Marvin Goldberg, NSF

B Membership and Subpanel Meetings

The members of the Subpanel are

Gordon Baym (Illinois)	Jack Ritchie (U. Texas, Austin)
Robert Cahn (LBNL, Chair)	Natalie Roe (LBNL)
Curtis Callan (Princeton)	Abe Seiden (UCSC)
Benjamín Grinstein (UCSD)	Stew Smith (Princeton)
JoAnne Hewett (SLAC)	Frank Wilczek (MIT)
Harrison Prosper (Florida State)	Mark Wise (Caltech)

The schedule of meetings was

- March 3 (phone)
- March 24 (Berkeley)
- April 1 (MIT)
- April 14 (phone)
- April 28 - 29 (Princeton)