Particle Physics with Kaons, Muons and Neutrinos

– Summary of JHF K-Arena Working Groups 1a/1b –

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ABSTRACT

We discuss the prospects for rare $K$ and $\mu$ decays and neutrino physics at Japan Hadron Facility (JHF) at KEK.

I INTRODUCTION

The areas of rare $K$ and $\mu$ decays and of neutrino oscillations are very active at the present time, and there is little reason to doubt that this will continue to be the case in the JHF era. Our session featured talks describing the present status and projected future activity in these areas.

II RARE $K$ DECAY

A $K \to \pi\nu\bar{\nu}$

At present the rare $K$ decays on which most interest is focussed are the charged and neutral versions of $K \to \pi\nu\bar{\nu}$. In the Standard Model (SM), these are sensitive to respectively the modulus and the imaginary part of the Cabbibo-Kobayashi-Maskawa (CKM) element $V_{td}$, as shown in Eqs. 1 and 2:

$$B(K^+ \to \pi^+\nu\bar{\nu}) = \frac{\tau_K + \alpha^2 B(K^+ \to \pi^0e^+\nu)}{V_{ud}^2 2\pi^3 \sin^4 \theta_W} \times \sum_{\ell=e,\mu,\tau} |V_{\ell d}^* V_{\ell d} X_{N\ell} + V_{\ell s}^* V_{\ell d} X(m_{\ell})|^2 \quad (1)$$
where the $X$'s are functions [1] of quark masses, corrected by QCD where necessary [2]. The branching ratios are written in terms of the very well-measured rate of $K_{e3}$, eliminating the otherwise problematical hadronic matrix element. Isospin breaking corrections to this relation are contained in the factors $r_{K+}$ and $r_{K_{L}}$ which are close to 1 and very well determined [3]. QCD corrections have been carried out to next-to-leading-logarithmic-order [2], and the residual uncertainty is at the few percent level for the charged channel, and negligible for the neutral. Possible long distance effects have been investigated for both the charged [4] and neutral [5] channels and found to be negligible. Thus it is possible to make rather precise SM predictions for these decays [2] [6], given input parameters such as $m_t$, $|V_{td}|$ and $|V_{cb}|$. In principle, one could extract $|V_{td}|$ to around 5% from a measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$, and $\eta$ to about 1% from a measurement of $B(K_{L} \to \pi^0 \nu \bar{\nu})$. Fig.1 shows the relationship of these decays to the unitarity triangle, and a comparison with what can be learned from $B$ decays on this subject. Recently there has been much theoretical work on the effects of non-SM physics on these decays. Predictions have been made in two-Higgs doublet models [7], a four-generation scenario [8], left-right models [9], lepto-quark models [10], and several variants of supersymmetry [11]. This work implies that such new physics tends to affect the $K$ sector quite differently than it does the $B$ sector. Thus the motivation for pursuing these modes is extremely strong and is likely to remain so into the era of JHF.

\[
B(K_L \to \pi^0 \nu \bar{\nu}) = \frac{r_{K_L} \alpha^2 B(K^+ \to \pi^+ e^+ \nu) \tau_{K_L}}{V_{us}^2 2\pi^2 \sin^4 \theta_W} \times 3[Im(V_{td}^* V_{td}) X(m_t)]^2
\]

(2)

FIGURE 1. Diagram of the contribution of the charged and neutral FCNC kaon decay $K \rightarrow \pi \nu \bar{\nu}$.

By the principle of the conservation of agony, the fact that the motivation to
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study these processes is so strong implies that the difficulty of actually measuring them is correspondingly strong. The branching ratios predicted by the Standard Model are \((0.6 - 1.5) \times 10^{-10}\) for the charged and \((1 - 3) \times 10^{-11}\) for the neutral decay. Moreover, the signature for these processes is rather poor. Pions are extremely common decay products of kaons, and the unobservable neutrino pair means that there is at best a very weak kinematic signature. One is basically forced to prove a negative, i.e. that one observed a pion from kaon decay which was not accompanied by any other visible particles. To do this at the level of one part in ten billion is a real challenge.

\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

Nonetheless there is no lack of challengers. Brookhaven AGS E787 has been in pursuit of the charged mode for several years. Fig. 2 shows the detector, an elaborately instrumented solenoidal spectrometer [12] situated at the end of the world’s best low energy separated beamline. This provides a \(~75\%\) pure beam of some 6 million \(K^+\) per AGS spill, of which about 1.5 million stop and decay in a highly segmented scintillating stopping target. Daughter pions are momentum analyzed in a small foil-cathode drift chamber [13] immersed in a 1-T field, and subsequently range out in a cylindrical array of scintillators and straw chambers (the “range stack”). They are distinguished kinematically from muons by comparing their range, energy, and momentum, and also via their characteristic decay pattern after coming to rest \((\pi \rightarrow \mu \rightarrow e)\). The latter is recorded with 500 MHz transient digitizers. The range stack is surrounded by a cylindrical lead-scintillator photon veto array, and the upstream and downstream faces of the detector are plugged with (undoped) CsI endcap vetoes [14].

The E787 experiment in its present form has been taking data since 1995. Somewhat surprisingly, a very convincing \(K^+ \rightarrow \pi^+ \nu \bar{\nu}\) event was discovered in an initial analysis of the 1995 data alone [15], yielding a branching ratio of \(B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (4.2^{+0.7}_{-3.5}) \times 10^{-10}\). This is consistent within statistics with the SM estimate, but \(3 - 4\) times higher. The 1995-7 data set should yield a sensitivity at least 2.5 times greater, and a long run is scheduled to begin in the summer of 1998. With any luck, this should eliminate or confirm the possibility of a large violation of the SM in this mode. It is important to note that the estimated background in the analysis that produced the event corresponds to about \(4 \times 10^{-11}\). This is within shooting distance of the level of background suppression needed for making an accurate measurement at the SM level. Thus it appears possible to exploit this very challenging reaction to study short distance effects both SM and non-SM.

Elements of the E787 collaboration are interested in pursuing this physics to the next order of magnitude in sensitivity [16]. Straightforward optimization of the running conditions (proton supply, beam momentum, duty cycle) along with machine availability expected in the RHIC era imply that one could get a sensitivity of \(~2.5\) SM events/year without big improvements in the detector.
Figure 2. Schematic of AGS-787 detector.

Reasonable upgrades should allow this to be doubled. Thus 10 - 15 events at the SM level seem attainable.

To get still a further factor 10, the CKM experiment, discussed at the present workshop by Herman White [17], has been proposed for the Fermilab Main Injector (FMI). Fig 3 shows the proposed detector.

It represents a completely orthogonal approach to that of E787, wherein the experiment is done in flight at a $K^+$ momentum of $\sim 22$ GeV/c. This requires a new RF-separated beam. The experiment features phototube read-out RICHs for identification of $K^+$ and $\pi^+$ and measurement of their velocities, as well as momentum analysis, hermetic photon vetoing, and a crude hadronic calorimeter used as a muon veto. Many other decay modes could also be studied by this detector. This proposal has recently been submitted to the Fermilab PAC [18].

In principle, either technique could be used at JHF. The yield of 22 GeV/c $K^+$ from a 50 GeV primary is only about 3 times less than that from a 120 GeV primary. Since CKM only requires $3 \times 10^7 K^+/pulse$, there should be beam to burn at JHF.

At this Workshop, T. Shinkawa talked about a possible JHF experiment based on an extrapolation of the E787 technique, which would yield similar sensitivity to CKM [19]. The incident $K^+$ flux would be about 7 times than that of E787, and the acceptance roughly 6 times higher. With long runs, this could yield some 50 events/year. The magnetic field would be increased, resulting in better
momentum resolution, the detector would be made considerably more granular to stand up to the increased rates, and counters would be read out by fine mesh PMTs that can operate in a magnetic field. The latter would allow considerably more light to be collected, resulting in better time resolution than is possible in E787. Faster photon vetoes would be deployed, so that the photon veto deadtime could be kept under control.

Thus there are two possible approaches to doing a high statistics $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment at JHF.

2 $K_L \rightarrow \pi^0 \nu \bar{\nu}$

This reaction has been known for some time to be the most incisive window into the question of CP-violation in the $K$ system [20]. However there are as yet no results from experiments dedicated to its study. The best sensitivity thus far stems from a one-day test run of the KTeV experiment at FNAL (see Fig. 4) discussed at this Workshop by R. Rey [21]. They obtained an upper limit of $B(K_L \rightarrow \pi^0 \nu \bar{\nu}) < 1.6 \times 10^{-8}$ at 90% c.l. [22]. This experiment is expected to eventually reach the $10^{-8}$ level. Since in the SM a measurement is expected to require better than $10^{-11}$/event sensitivity, one has a long way to go. At this Workshop we heard three talks on possible dedicated experiments to close this gap, including one that is directed eventually to JHF [23].
T. Numao [24] discussed BNL AGS-926 [25], an experiment that exploits the advantages of working at very low kaon momentum. A conceptual apparatus is shown in Fig. 5. A $K_L$ beam of average momentum $\sim 750\text{MeV/c}$ can be obtained from a 24 GeV primary by using a very large production angle. The accelerator beam can be microbunched on extraction [26], allowing the velocity of the $K_L$ to be measured by time of flight. The microbunching also makes the experiment insensitive to much of the rates and potential backgrounds stemming from neutrons in the beam. The decay vertex can be determined by measuring the directions as well as the energies of the $\pi^0$ gammas, and since the production point of the $K_L$ is thereby known, this ties down the $K_L$ direction. The direction and the velocity allow the momentum to be determined, so that one can transform into the $K_L$ c.m. In this system, $\pi^0$'s from the main background reaction, $K_L \rightarrow \pi^0\pi^0$, have a unique energy, and can thus be kinematically rejected. This reduces the need for an otherwise very challenging level of photon vetoing power ($K_L \rightarrow \pi^0\pi^0$ is some 8 orders of magnitude more copious than $K_L \rightarrow \pi^0\nu\bar{\nu}$).

Other advantages of working at low energy are the possibility of a relatively compact detector, the low probability of a beam neutron creating a $\pi^0$, and the suppression of background from hyperon decay. The experiment aims to collect some 70 events with a 10 : 1 signal/background ratio in three years of running.

R. Rey discussed the KAMI approach to probing $K_L \rightarrow \pi^0\nu\bar{\nu}$ [27]. This exploits the very high proton intensity projected to be available at the Fermilab Main Injector (FMI) to make a pencil $K_L$ beam. The present KTeV CsI detector would remain the heart of the detector, but, as shown in Fig. 6, the apparatus

FIGURE 4. Schematic of the KTeV detector as configured for special $K_L \rightarrow \pi^0\nu\bar{\nu}$ run.
would be telescoped to match the lower beam energy (120 GeV vs 800 GeV). This would allow a relatively high acceptance (~7%) to be maintained, moderating the need for very high $K_L$ rates. The present photon veto system would be extensively upgraded to make it more nearly hermetic. One of the main challenges of this approach is the need for extremely good photon vetoing efficiency. This must get into the ballpark of $10^{-6}$/photon inefficiency for some photons, and needs to be better than $10^{-2}$ even in the beam for high energy photons. The requirement of photon vetoing can be relaxed by tightening the $\pi^0 p_T$ cut, but at a substantial cost in acceptance. If this should not prove to be necessary, the first stage of the experiment would collect about 30 events/year with a 2:1 signal/background. The goal of the second stage, in which the production target is moved closer to the detector, is to collect 124 events/year with a 3:1 signal/background ratio.

T. Inagaki discussed KEK E391a [23], the first dedicated $K_L \rightarrow \pi^0 \nu \bar{\nu}$ experiment. It is similar in concept to the KAMI idea, but optimized for (5x) lower energy (see Fig. 7). E391a features a very carefully designed pencil beam, an hermetic photon veto system and crystal photon detectors. Very high single-photon efficiency is needed to suppress the $K_L \rightarrow \pi^0 \pi^0$ background, and studies of this are in progress at the INS-ES. As in all attempts to detect $K_L \rightarrow \pi^0 \nu \bar{\nu}$, a high vacuum is needed in the beam region to minimize $\pi^0$ production from neutrons. In this case, virtually the entire apparatus is in a vacuum. An outer chamber provides $10^{-3}$ Torr, and an inner chamber $10^{-7}$ Torr. The acceptance of the detector is designed to be ~7%, similar to the case of KAMI. The beam intensity available at the KEK PS is insufficient to get beyond a sensitivity of $10^{-10}$/event, i.e. not enough to see this decay mode if the Standard Model is correct. However, the experiment will serve as a test bed for a very similar effort at JHF where the intensity is sufficient to get a great many events with a detector of this acceptance.
B  \(CP/T\) and related experiments

H. White [28] reported on the \(CP/T\) Experiment, which was recently proposed for the Main Injector at Fermilab. The object of this initiative is to study \(CP\) violation and probe \(CPT\) in the \(KL - K_s\) system. Fig 8 shows the layout of the proposed detector.

\(CP/T\) is designed to share the RF-separated \(K\) beam mentioned above in connection with the CKM experiment. It would be tuned to 25 rather than 22 GeV/c, and the intensity would be rather higher (2 \( \times \) 10^8 instead of 3 \( \times \) 10^7 per spill). A 10cm W target would be positioned at the entrance of the hyperon magnet such that a \(K^0\) beam at 36\(\mu\)sr would be defined. The average \(K^0\) momentum at production would be about 17 Gev/c. There would be roughly 5000 \(K_S\) and 2000 \(K_L\) decays per spill in a 20m evacuated decay region. This would be followed by a simple drift chamber spectrometer, a triggering hodoscope, an electromagnetic calorimeter, and a muon detector. The menu of the experiment is quite diverse. They would attempt to measure \(CPT\) violation directly in semileptonic decays, through high precision measurements of the phase-differences \((\phi_{+-} - \phi_0)\) and \((\phi_{+-} - \phi_0)\) in \(K^0 \rightarrow 2\pi\) decay, and also via the Bell-Steinberger relation [29]. It is thought possible to reach a precision that corresponds to probing the Planck scale in certain theories. They also expect to reach a single event sensitivity of \(\sim 10^{-10}\) for rare \(K_S\) decays. Table 1 summarizes their goals and compares them with current data.

Now it is clear that one could mount a very similar experiment at JHF 50-GeV PS. The 25 GeV/c \(K^+\) production cross section at 50 GeV is only about a factor 3 lower than at 120 GeV, and the available protons/hour are 6 times more at
JHF 50-GeV PS than at the FMI. However at this workshop, M. Aoki [30] has proposed a bold alternative to accessing at least some of the physics of CP/T at JHF 50-GeV PS. It is based on using a very high intensity ~ 1 GeV/c negative pion beam (see Section III D below) to make a tertiary strangeness-exchange beam off a thin foil target. At this momentum, the only possible strangeness producing reaction is $\pi^- p \rightarrow K^0 \Lambda$, and there is a nearby s-channel resonance that enhances it. $K^0$ in the few hundred MeV/c region are produced. If the $\Lambda$ is detected, the $K^0$ is completely determined kinematically. The numbers are truly remarkable. He envisions a beam of $10^{12}$ $\pi^-$/pulse impinging on a 1-mm Si target wherein about $2 \times 10^{-5}$ of the pions produce $K^0$. If $\Lambda \rightarrow \pi^- p$ is required, one can sample $2 \times 10^8 K \rightarrow 2\pi$ decays/pulse, or 6 trillion events in a 100-day run. Table 2 compares this audacious approach with CP/T, and with a CP/T-like experiment that used the full available intensity at JHF 50-GeV PS.
C T-violating $\mu^+$ polarization in $K^+$ decays

CP-violation in addition to that given by the SM is required to explain the observed baryon asymmetry of the universe [31]. This motivates investigating low-energy 'windows' where such effects are cleanly identifiable. The CKM model gives no observable $T$-violating (out-of-decay-plane) muon spin polarization in $K^+\to\pi^0\mu^+\nu$ ($K^+_\mu3$), $\varphi_T = \bar{s}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)/|\vec{p}_\pi \times \vec{p}_\mu|$, allowing such a window. In addition, a number of promising attempts to go beyond the Standard Model predict a finite polarization at a level that is likely to become experimentally accessible. Furthermore, the search in $K^+_\mu3$ decay is especially clean since the final-state interaction, which would mimic $T$-odd effects in the other modes, is

\begin{table}[h]
\centering
\caption{Comparison of $CP/T$-type experiments}
\begin{tabular}{|l|c|c|c|}
\hline
 & $CP/T$ at FNAL & $CP/T$ at JHF & $\pi^-p\to\Lambda K^0$ \\
\hline
Incident & 25 GeV/c $K^+$ & 25 GeV/c $K^+$ & 1 GeV/c $\pi^-$ \\
Intensity/pulse & $2.4 \times 10^8$ & $3.4 \times 10^9$ & $10^{12}$ \\
$K^0$ yield/pulse & $2.3 \times 10^3$ & $3.2 \times 10^5$ & $2 \times 10^7$ \\
$\sigma$(exchange) & 11 $\mu$b & 11 $\mu$b & 1 mb \\
Acceptance & 100%? & 100%? & 50% \\
$\delta Z$(required) & 1 mm & 1 mm & 30 $\mu$m \\
$\gamma_{\beta\epsilon}\epsilon$ & $\sim 80$ cm & $\sim 80$ cm & $\sim 3$ cm \\
Target $\delta Z$ & 10 cm & 10 cm & 1 mm \\
Vertex $\delta Z$ & 3 cm & 3 cm & 0.8 mm \\
$\delta <\gamma_{\beta\epsilon}\epsilon>$ & $< 1\%$ & $< 1\%$ & $\sim 2\%$? \\
$K\pi 2$ & $2.5 \times 10^{10}$ & $3.5 \times 10^{11}$ & $> 5 \times 10^{12}$ \\
$\Delta\phi_{+-}$(statistical) & $0.03^\circ$ & $0.01^\circ$ & 0.002$^\circ$ \\
$\Delta M_{K^0}/M_{K^0}$ & $2 \times 10^{-20}$ & $6 \times 10^{-21}$ & $2 \times 10^{-21}$ \\
\hline
\end{tabular}
\end{table}
known to be very small, of the order of about $10^{-6}$.

If $T$ is conserved, the $f_+(q^2)$ and $f_-(q^2)$ form factors that multiply the $(\vec{p}_K + \vec{p}_\pi)$ and $(\vec{p}_K - \vec{p}_\pi)$ terms respectively in the $K_{\ell3}$ amplitude are relatively real ($\vec{p}_i$ represents the four momentum vector of particle $i$). Therefore $T$ violation can be characterized by the size of the imaginary part of the ratio $Im\xi \equiv Im(f_-/f_+)$. This quantity is in turn approximately proportional to the component of polarization transverse to the $K_{\mu3}$ decay plane; $\varphi_T = (0.2 - 0.3) Im\xi$, depending on the phase space sampled.

Among possible new interactions beyond the SM, $\varphi_T$ in $K_{\mu3}^+$ is known to arise only from a scalar interaction (not from vector or axial-vector interactions [32]). Therefore, it is sensitive to, for instance, extensions of the Higgs sector such as three Higgs doublet models (3HDM) [33]. In 3HDM, the interference between SM-model $W$-exchange and charged-Higgs exchange leads to a finite $\varphi_T$ if there is a large non-zero imaginary phase in the charged-Higgs mass matrix. In particular, $\varphi_T$ becomes large if the ratio of Higgs vacuum expectation value, $v_2/v_3$, is large [34]. Supersymmetry can also induce an observable $\varphi_T$ if there is substantial family mixing in quark-squark-gluino couplings [35]. Supersymmetric models with $R$-parity breaking and leptoquark models also predict sizeable effects on $\varphi_T$ [36].

$\varphi_T$ in $K^+ \rightarrow \mu^+\nu\gamma$ decay, where the decay plane is determined by the muon and photon momentum vectors, is complementary to that in $K_{\mu3}^+$ decay; since the former could have new effective interactions of vector, axial-vector, and pseudoscalar types, whereas the latter can have only a scalar new interaction. In

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**FIGURE 9.** Schematic layout of the KEK-E246 detector, (a) side and (b) end view.
particular, in supersymmetric models with squark-family mixing, $W_R$ boson exchange can give a value of $\varphi_T$ as large as a few percent [37]. However, this decay suffers from final-state interactions of the order of $10^{-3}$.

A current experiment is KEK-PS E246 which seeks to probe this process to a sensitivity of $\varphi_T = \pm 0.0013$ for $K_{\mu3}$ by using stopped $K^+$s. $\varphi_T$ in $K^+ \to \mu^+ \nu \gamma$ decay is also being sought. The E246 detector consists of a 12-fold superconducting toroidal magnet spectrometer with a CsI(Tl) photon detector array and muon polarimeters located at the exit of the toroidal magnet gaps, as seen in Fig.9. Since statistics dominates over systematics in E246 and the apparatus is capable of operating with a much higher kaon flux, the experimenters have submitted a proposal for transporting the experiment to the AGS [38], where a result some four times more sensitive is possible. A second approach [39] being advocated is to instead push the in-flight technique of the most recent previous experiment of this type [40] (also carried out at the AGS). The object of this proposal is to reach a sensitivity of $\varphi_T = \pm 0.00013$. This corresponds to an uncertainty of roughly $7 \times 10^{-4}$ in $\Im \xi$. A schematic apparatus for this experiment is shown in Fig 10. A 2 GeV/c separated beam provides the $K^+$. Some $2 \times 10^7$ $K^+$s/pulse impinge on a decay tank in which $\sim 5 \times 10^6$ of them decay. Photons from $\pi^0$'s are detected in a "shashlyk" calorimeter and $\mu^+$'s penetrate the calorimeter and are tracked into the polarimeter where they range out. Muon
decay electrons are tracked through at least two segments of the cylindrically symmetric polarimeter. One compares the rates of clockwise-going and counterclockwise-going muon decays. In E923, there are 96 segments as compared to 32 in Ref. [40]. To properly align the decay plane with the detector, $K^+$ decays in which the $\pi^0$ points along the beam and the $\mu^+$ approximately perpendicular to it in the $K^+$ center of mass are selected by the trigger. There is no spectrometer magnet, but a $\sim 70$ G solenoidal field is imposed on the polarimeter to precess the muons. The polarity of this field is frequently reversed. The precession technique is very effective in controlling systematic errors, at a modest cost in statistical power.

An experiment of either type could readily be launched at JHF 50-GeV PS, and clearly could be pushed further than at the AGS if the systematics allowed. For example, the yield of $2 \text{GeV/c} K^+$ per second at JHF 50-GeV PS should be about 6 times that at the AGS.

However at this workshop Y. Kudenko suggested a new variant of the stopped $K^+$ approach [41]. He would retain KEK-246’s crystal calorimetry technique but discard the muon spectrometer in favor of a non-magnetic design (see Fig 11). The photon calorimeter would be a high quality CsI device with a preshower detector composed of CsI with fiber readout or converter plus wire chamber. The desired resolutions are $\sigma_{x,y} \sim 1.5 \text{mm}, \sigma_{\theta} \sim 5 \text{mrad}$. The polarimeter would consist of $4 - 5 \text{mm}$ plates interspersed with MWPCs, with scintilla-
tors arrayed radially for determining the muon trajectory in the polarimeter. The $\gamma$-veto/calorimeter outside the polarimeter would be a conventional lead-scintillator device. Monte Carlo studies were described that indicate that it would be possible to keep backgrounds at an acceptably low level, in spite of the absence of a magnet. The acceptance could be made about an order of magnitude higher than what is proposed for AGS-923. Using a kaon intensity of $2 \times 10^6$/sec, and running for $10^7$ seconds, about $6.5 \times 10^9$ events could be collected. The precision anticipated would be similar to that claimed for AGS-923, $\varphi_T = \pm 0.00012$. This experiment should be relative simple to build and have very good systematics. It could also do quite well on other physics topics such as probing $T$-violating muon polarization in $K^+ \rightarrow \mu^+ \nu \gamma$, where a sensitivity of $\varphi_T = \pm 0.0002$ could be achieved.

### III RARE MUON DECAYS

Although the Standard Model has had amazing success in explaining all measurements so far, there are still many fundamental questions in particle physics which the Standard Model cannot address. Many experiments therefore focus on discovery of new phenomena to elucidate the underlying fundamental truth. In the minimal Standard Model, lepton flavor conservation is built in by hand with the assumption of vanishing neutrino masses. In fact, virtually any new physics or interaction beyond the Standard Model would predict lepton flavor violation (LFV) at some level. LFV processes of major current interest are those with muons such as $\mu^+ \rightarrow e^+ \gamma$, $\mu^- N \rightarrow e^- N$ conversion in nuclei, $\mu^+ \rightarrow e^+ e^- e^-$ and muonium-antimuonium conversion. Historical progress in various LFV searches is shown in Fig.12, in which the experimental upper limits have been continuously improved at a rate of about two orders of magnitude per decade for about 50 years since the first LFV experiment by Pontecorvo et al. in 1947 [42]. In general, a search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of about $10^{-12}$ in a branching ratio could explore a mass scale of several hundred TeV, which is not accessible directly by present accelerators.

Recently considerable interest in LFV processes has arisen based on supersymmetric (SUSY) extensions to the Standard Model, in particular supersymmetric grand unified theories (SUSY-GUT) [43]. In many models of SUSY-GUT, LFV can be naturally introduced. For instance, in supergravity-mediated SUSY models, radiative corrections in the renormalization group evolution from the GUT scale to the weak-energy scale lead to finite mixing in the slepton mass matrix even when it is assumed to be diagonal at the Plank scale. Recently, Barbieri and Hall found that the slepton mixing thus generated is very large owing to the surprisingly large top-quark Yukawa coupling [44]. Then, $\mu^+ \rightarrow e^+ \gamma$ occurs due to this slepton mixing through loop diagrams. The predicted branching ratio is at a level which near-future experiments can reach. For instance, in SU(5) SUSY-GUT models, the prediction for $\mu^+ \rightarrow e^+ \gamma$ can be given approximately by [44],
where \( I(y_t) \) is a function of the top-quark Yukawa coupling \((y_t)\) and \( V_{ij} \) is the Cabbibo-Kobayashi-Maskawa quark mixing matrix (at the GUT energy scale). \( m_{\mu} \) and \( m_{\mu} \) are respectively the mass of the muon and smuon. The branching ratio of \( \mu^+ \to e^+ \gamma \) predicted in SUSY SU(5) models [45] is shown in Figure 13. It ranges from \( 10^{-15} \) to \( 10^{-13} \) for a right-handed slepton mass of 100 to 300 GeV/c\(^2\). The effect of higher dimensional operators in SU(5) SUSY-GUT was considered, and the branching ratio was found to be enhanced for large \( \tan \beta \) [46]. The SO(10) SUSY GUT models give an even larger value of \( 10^{-13} \) to \( 10^{-11} \) via an enhancement of \( (m_{\mu}^2/m_{\mu}^2) \sim 100 \) [44]. This is because of the existence of loop diagrams whose magnitude is proportional to the \( \tau \)-lepton mass in such models.

Furthermore, the recent experimental hints of non-vanishing neutrino masses and mixing suggested by the atmospheric neutrino anomaly might suggest additional LFV contributions in SU(5) SUSY-GUT models [47]. Such a model includes a heavy right-handed Majorana neutrino of \( 10^{14} \) – \( 10^{15} \) GeV with a \( \nu_{\mu} - \nu_{\tau} \) mixing of \( \sin^2(2\theta_{\mu\tau}) \sim 1 \) (as suggested by the Super Kamiokande). This contribution also enhances LFV by a factor of about \( (m_\tau/m_{\mu})^2 \) over the minimal SU(5) SUSY-GUT models.

Another class of SUSY models is gauge-mediated SUSY breaking, which in general do not lead to LFV since the messenger-matter interaction is flavor-
blind. However, there have been discussions of mechanisms to generate LFV such as messenger-matter mixing. In such models, a large branching ratio for $\mu^+ \rightarrow e^+\gamma$ is possible [48]. SUSY models with R-parity breaking also tend to predict a large $\mu^+ \rightarrow e^+\gamma$ branching ratio, which is sensitive to those couplings of R-parity breaking ($\lambda$ and $\lambda'$) which are not constrained strongly by the limits on proton decay [49].

In the SUSY-GUT models, the $\mu^- - e^-$ conversion process in nuclei, for instance in $^{27}Al$, has about 1/250 the branching ratio of $\mu^+ \rightarrow e^+\gamma$. Therefore, a search for $\mu^+ \rightarrow e^+\gamma$ at the level of $10^{-14}$ is comparable to that for $\mu^- - e^-$ conversion in nuclei at the level of $10^{-16}$. The nuclear dependence of the latter has also been calculated taking account of relativistic atomic effects, Coulomb distortion, finite nuclear size and nucleon distribution [50]. It was found that the ratio of $\mu - e$ conversion to $\mu^+ \rightarrow e^+\gamma$ varies from 389 for $^{27}Al$ to 238 for $^{48}Ti$, and increases again to 342 for $^{208}Pb$. On the other hand, extra logarithmic enhancement of $\mu^- - e^-$ conversion (and also $\mu^+ \rightarrow e^+e^-e^+$) over $\mu^+ \rightarrow e^+\gamma$ in loop diagrams has also been discussed [51]. It happens only when light charged fermions are involved in the loop diagrams. Therefore, it could occur for SUSY models with R-parity breaking, but not for R-parity conserving SUSY models or SUSY-GUT models.

**FIGURE 13.** Predictions of $\mu^+ \rightarrow e^+\gamma$ branching ratio in SU(5) SUSY models.
FIGURE 14. Predictions of $\mu^+ \rightarrow e^+\gamma$ branching ratio in SU(5) SUSY models with right-handed Majorana neutrino as a function of $m_{\tilde{e}_R}$ when the Yukawa coupling constant of $\nu_\tau$ is as large as that of top quark.

A $\mu^+ \rightarrow e^+\gamma$

The event signature of $\mu^+ \rightarrow e^+\gamma$ is a positron and a photon in coincidence, moving collinearly back-to-back with energy equal to a half of the muon mass ($m_\mu/2 = 52.8$ MeV). There are two major backgrounds to a search for $\mu^+ \rightarrow e^+\gamma$. One is a physics (prompt) background from radiative muon decay, $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$, where $e^+$ and photon are emitted back-to-back with the two neutrinos carrying off little energy. The other background is an accidental coincidence of an $e^+$ in a normal muon decay, $\mu^+ \rightarrow e^+\nu\bar{\nu}$, accompanied by a high energy photon. The sources of the latter might be either $\mu^+ \rightarrow e^+\nu\bar{\nu}\gamma$ decay, or external bremsstrahlung or annihilation-in-flight of $e^+$s from normal muon decay. Detector resolutions must be excellent to eliminate these backgrounds.

A recent search was done by the MEGA collaboration at Los Alamos National Laboratory (LANL). The MEGA detector consisted of eight cylindrical chambers for positron tracking and pair spectrometers for photon detection. They were placed inside a superconducting solenoid magnet. MEGA completed its data-taking in 1995. A preliminary new limit of $4.2 \times 10^{-11}$ with $16\%$ of the data analyzed was reported in this workshop [52]. A direct extrapolation to all the MEGA data of $(3 - 6) \times 10^{-12}$ was also expected.

A new experiment on $\mu^+ \rightarrow e^+\gamma$ with a sensitivity of $10^{-14}$ is being considered at PSI where a surface muon beam of a few $\times 10^8$/sec is available [53]. In their
Letter of Intent, the options being considered for a positron spectrometer are a solenoidal-field spectrometer with a limited solid angle or a ring-image-focusing spectrometer. The options for a photon detector are liquid-Xe or high-speed luminous inorganic crystals such as Ce-doped ortho-silicates or ortho-aluminates of Yttrium, Lutetium and/or Ytterbium.

For a future JHF experiment, the use of polarized muons for a search for $\mu^+ \rightarrow e^+\gamma$ has been proposed for further improvement in the background rejection [54]. It would be carried out with the high intensity muon source mentioned in Section III-D.

**B $\mu^- - e^-$ Coherent Conversion in Nuclei**

The event signature of $\mu^- - e^-$ coherent conversion in nuclei is a monoenergetic single electron of $(m_\mu - B_\mu)$ MeV emitted from muon capture (where $m_\mu$ and $B_\mu$ are the muon mass and the binding energy of the 1s muonic atom respectively). Major backgrounds are muon decay in orbit from a muonic atom (in which the $e^-$ endpoint energy is the same as the energy of the signal), radiative pion and muon capture and cosmic rays. It is generally not subject to accidental background but the beam purity and the efficiency of cosmic-ray vetoing are crucial.

The ongoing experiment is SINDRUM II at PSI. The 1993 run with a Ti target gave a 90 % C.L. upper limit of $B(\mu^-Ti \rightarrow e^-Ti) < 6.1 \times 10^{-13}$, $B(\mu^-Ti \rightarrow e^+Ca(g.s.)) < 1.7 \times 10^{-12}$, and $B(\mu^-Ti \rightarrow e^+Ca(e.s.)) < 3.6 \times 10^{-11}$ where $g.s$ and $e.s$ are ground state and excited state transitions, respectively. Also for Pb, it gave $B(\mu^-Pb \rightarrow e^-Pb) < 4.6 \times 10^{-11}$. For the next stage of the experiment, the "pion-muon converter" (PMC) which consists of a straight superconducting solenoid magnet of 8.5 m in length, designed to reduce beam pion contamination, is being prepared. With this PMC, a sensitivity of $2 \times 10^{-14}$ is the goal of upcoming runs [55].

There is a new proposal E940 at BNL-AGS called the MECO (Muon Electron Conversion) experiment which aims to search for $\mu^-Al \rightarrow e^-Al$ at better than $10^{-16}$ sensitivity [56]. The setup consists of a graded high-field superconducting solenoid for muon capture (of about 1.2 m bore and 4 m length), a curved transport solenoid system which selects momentum and sign of charged particles [57], and a detector with good energy resolution ($\sigma_{RMS} < 300$ keV) which observes only the 105-MeV signal electrons in a second axially graded solenoidal field. A pulsed proton beam of about 1 MHz with pulse length of 50 nsec is used to minimize beam-associated backgrounds, in particular from pions. A rate of about $10^{11} \mu^-$ per cycle stopping in a thin Aluminum target is expected. A schematic layout of the MECO detector is shown in Fig.15.
Another class of muon LFV process is muonium-to-antimuonium conversion ($\mu^+e^- \rightarrow \mu^-e^+$), in which the lepton flavor number changes by two units ($\Delta L_{e/\mu} = \pm 2$). A new experiment was carried out at PSI. Its experimental setup is shown in Fig.16 [58]. Muonium atoms ($Mu$) are produced in vacuum from a SiO$_2$ powder target. The antimuonium signature is an energetic $e^-$ from $\mu^-$ decay, observed in a magnetic spectrometer, simultaneous with a dissociated $e^+$ after $\mu^-$ decay. The $e^+$ is detected by micro-channel plate detectors after electrostatic acceleration. A preliminary 90% C.L. upper limit on the conversion probability of $P(Mu \rightarrow Mu) \leq 8 \times 10^{-11}$, or equivalently on the coupling constant $G_{Mu\overline{Mu}} \leq 0.003G_F$, was obtained. It was emphasized that a new-generation experiment with less background can be done using an appropriate pulsed beam with an interval of 6 to 10 times muon lifetimes.

Another interesting use of a muonium is precision spectroscopy to study QED. The two new experiments were reported [58]. One is to measure the muonium hyperfine splitting of the ground state at LANL (E1054) and the other is to measure Doppler-free two-photon transition between the 1s and 2s muonium state at RAL (E709).
A New Intense Source of Secondary Beams

A highly intense source of secondary beams such as pions, muons and neutrinos is being considered at JHF to carry out various experiments including LFV searches. For conventionally designed muon beam lines, JHF is expected to have only a slightly higher beam intensity for \( \mu^+ \) and \( \mu^- \) than those at PSI where a surface \( \mu^+ \) beam of \( 3 \times 10^8 \) sec is currently available. However, some new ideas on a source as intense as \( 10^{11} - 10^{12} \) particles/sec have appeared recently in conjunction with \( \mu^+\mu^- \) collider R&D [59]. The idea consists of (a) high magnetic-field capture of pions at the production target, (b) phase rotation to make a longitudinal momentum compaction, and (c) ionization cooling of muons [60]. Such an approach could be adopted to construct a unique muon source with high intensity, high brightness, and low momentum spread [61]. A schematic layout of the preliminary design is shown in Fig.17. Such a beam would be crucial to carry out LFV searches with stopped muons, since they allow higher muon stopping efficiency with less background and a thinner muon-stopping target (or even a gas target).

In contrast to the case of a \( \mu^+\mu^- \) collider which will run at a few Hz, the time structure of a muon beam at JHF has to be continuous or semi-continuous to carry out coincidence experiments. To do this, special approaches such as (1) microbunched extraction of protons from a 50-GeV machine [62] and (2) superconducting rf cavities for phase rotation/ionization cooling [63] are being considered. The time structure of microbunched extraction will depend on experimental requirements. For example, searches for \( \mu^+ \rightarrow e^+\gamma \) and \( \mu^+ \rightarrow e^+e^-e^+ \) need a high repetition rate of a few 10 MHz to 100 MHz, whereas a \( \mu - e \) con-
version experiment requires a slower repetition of a few 100 kHz with high beam extinction between beam pulses. Similar plans for intense muon sources also exist at the muon facility at RAL/ISIS [64] and at TRIUMF [65].

IV PRECISION MUON EXPERIMENTS

A \( g_\mu - 2 \)

There is currently an experiment to measure the muon \( g - 2 \) [66] running at the Brookhaven AGS. This is an updated version of the last \( g - 2 \) experiment [67] done at CERN a number of years ago. The aim is to improve the precision on the muon anomalous magnetic moment by approximately 20-fold to a level of \( \pm 0.35 \) parts per million. This is sufficiently precise to make a significant measurement of the weak contribution to \( a_\mu (= \frac{g_\mu - 2}{2}) \), which has recently been calculated [68] to be \( 1.3 \pm 0.03 \) ppm. The previously problematical hadronic contribution, whose determination requires experimental input, has been tied down by recent results on \( \tau \) decay [69]. It is now thought to be \( \leq \pm 0.8 \) ppm, and this can be expected to improve somewhat in the next few years. Thus the stage is set for a critical test of the Standard Model in this measurement. Many alternative models predict detectable effects, including those incorporating W and/or lepton substructure [70], leptoquarks [71], the two Higgs doublet model [72], and supersymmetry [73]. It is particularly sensitive to SUSY if the parameter \( \tan \beta \) should happen
to be large. This is true in the currently fashionable gauge-mediated version of supersymmetry [74].

Fig. 18 shows the 14m diameter superferric storage ring which was constructed to store muons and precess their spins. An average magnetic field uniformity of one part in $10^6$ is necessary for this experiment. The field is 1.45 T so that muons of momentum 3.094 GeV/c are stored. At this "magic" momentum, electrostatic quadrupoles can be used to provide vertical focussing without changing the relative orientation of the muon spin with respect to its momentum. The ring is a continuous C-magnet with the open side inward. Pb-Sci-fi calorimeters are placed at 24 positions around the inside of the ring. These detect $e^\pm$ from muon decay. A high energy threshold for these detectors imposes a strong correlation between the direction of the $e^\pm$ and the spin of the parent muon. Thus one can measure the muon spin precession frequency.

![FIGURE 18. A view of the $g - 2$ storage ring and its detectors.](image)

This experiment took its first physics data in the summer of 1997. Although the data taking period was rather abbreviated, they will soon publish a value of the $g - 2$ of the positive muon that is similar in precision to the comparable CERN measurement. The first run used pion injection to get muons into the g-2 ring. Over the next couple of years, the experiment will run with the much more efficient muon injection in order to meet their goals. With the experienced gained in the Brookhaven effort, the superior muon flux available, and the march of technology over the next few years, it seems likely that a further advance in measuring $g - 2$ could be made at JHF.
B The Muon Electric Dipole Moment

Also at the Brookhaven AGS there is a letter of intent [75] to measure the muon electric dipole moment to $10^{-24} \text{ e cm}$, a factor $10^6$ improvement over previous work. At this level, the measurement can constrain some versions of supersymmetry [76] and would be competitive in this sense with current limits on the electron and neutron EDMs.

The $g-2$ ring would be extensively modified to allow this measurement. It would be necessary to reduce the ring momentum from the “magic” value to $\sim 500 \text{ MeV/c}$ at which point it becomes practical to generate a radial electric field large enough to cancel the $g-2$ precession. The EDM precession then would operate without competition. As in the case of $g-2$, the muon’s parity-violating decay measures its spin direction. The signal is an asymmetry between upward and downward-going electrons as a function of time. This can be done with the present $g-2$ electron detectors, but to reduce systematic errors associated with controlling the vertical position of the muons, detectors would be placed on the top and bottom of the vacuum chamber. These would also be optimized for the lower electron energies. Great efforts are needed to control unwanted components of the electric field. The precision needed on mechanical alignment is extremely challenging.

To reach $10^{-24} \text{ e cm}$, the muon current must be 500 times higher than that of the present $g-2$ measurement. Therefore the ring must be converted to strong focussing, and the beam and target systems modified. A lithium lens is proposed for the latter. Pions of $900 \text{ MeV/c}$ would be collected so that decay muons emitted backward in the pion center of mass have the desired $500 \text{ MeV/c}$ momentum and can be transmitted to the $g-2$ ring. This experiment could use the maximum intensity anticipated for the AGS in future years. To reach the sensitivity goal, about $100 TP/1.25$ second cycle is required. The AGS would be run in single bunch single fast extracted mode at $13.4 \text{ GeV/c}$. A total of $10^{15}$ stored muons would be accumulated. Since the AGS muon flux is rather marginal for this experiment, it could benefit from being done at JHF.

V NEUTRINO OSCILLATION PHYSICS

There are several experimental hints of neutrino masses, such as the solar neutrino deficit problem ($\Delta m^2 \sim 10^{-5} \text{ eV}^2$), the atmospheric neutrino anomaly ($\Delta m^2 \sim 10^{-3} - 10^{-2} \text{ eV}^2$) and the LSND evidence of $\nu_\mu - \nu_e$ oscillation ($\Delta m^2 > 0.1 \text{ eV}^2$ and $\sin^2(2\theta) > 0.003$). In addition, a neutrino in the mass region of a few eV would be a good candidate for hot dark matter.

Super-Kamiokande recently reported their preliminary results [77]. The solar neutrino deficit was confirmed to be consistent with the former Kamiokande results and no day-night effect was observed. They also measured a $\nu_\mu/\nu_e$ ratio smaller than expected for atmospheric neutrinos which is consistent among all
the data sets of sub-GeV events, fully-contained and partially-contained multi-
GeV events. Furthermore a strong zenith angle distribution was observed for
the sub-GeV and multi-GeV data, in particular in the $\nu_\mu$ events. All these
indications are consistent with the $\nu_\mu - \nu_\tau$ oscillation hypothesis, whose allowed
region is centered at somewhat smaller $\Delta m^2$ values than the Kamiokande result.
This small ratio of $\nu_\mu/\nu_e$ in the atmospheric neutrinos was also confirmed by
Soudan-2 [78].

The neutrino oscillation probability is given by

$$P(\nu_1 \rightarrow \nu_2) = \sin^2(2\theta) \sin^2(1.27 \frac{\Delta m^2 (eV^2)}{E_\nu (GeV)} \cdot \frac{L(km)}{L}),$$

(5)

where $\sin \theta$ is the neutrino mixing amplitude and $\Delta m^2 \equiv m_1^2 - m_2^2$. $L$ and
$E_\nu$ are the distance between neutrino production and detection, and neutrino
energy respectively. In terrestrial neutrino oscillation experiments with reactors
and accelerators, the latter mass regions mentioned above (other than the solar
neutrino region) have been mostly explored. The experimental status of some
of those presented in this workshop is discussed below.

A Reactor Experiments

Reactors produce $\bar{\nu}_e$ of a few MeV in energy, and $\bar{\nu}_e - \bar{\nu}_x$ disappearance is
probed. The most recent experiment was done by CHOOZ in France [79]. The
distance between the reactor and the detector is about 1 km, and the average
energy of $\bar{\nu}_e$ is 3 MeV. The CHOOZ detector consists of a 5 ton Gd-doped
liquid scintillator tank surrounded by $\sim 107$ ton liquid scintillator shielding
regions. It is located about 100 m underground and the cosmic-ray background
is significantly reduced (by a factor of about 300). The detection of $\bar{\nu}_e$ is based on
$\bar{\nu}_e + p \rightarrow n + e^+$ with energy threshold of 1.8 MeV. A coincidence measurement
was done between annihilation of photons from $e^+$ and the neutron capture
by Gd which is followed by $\gamma$-ray emission of 8 MeV with 31 $\mu$sec lifetime.
The data taking started before the reactors went into full operation. Fig.20
includes their first result which already excludes the region of $\nu_\mu - \nu_e$ oscillation
suggested by the atmospheric neutrino anomaly. A further large scale experiment
called KamLAND which has a 1000 ton liquid scintillation detector in the former
Kamiokande location is being prepared in Japan.

There is a plan for a reactor experiment in Taiwan for which a collaboration
between Taiwan and mainland China has been formed [80]. The pilot project is
to perform a neutrino experiment with a 600 kg CsI crystal calorimeter to study
low-energy neutrino interactions from their power-plant reactors.

B Short Baseline Experiments

The high energy neutrino beams created by accelerators are mostly dominated
by muon neutrinos ($\nu_\mu$ or $\bar{\nu}_\mu$), which are produced by pion and kaon decays. The
FIGURE 19. Contour plot of $\Delta m^2$ vs. $\sin^2(2\theta)$ for $\nu_\mu - \nu_e$ oscillation with the expected constraint from dump neutrino experiment at M arena of JHF 3-GeV Booster.

detection of neutrinos is based on the charged weak current interaction, $\nu_l + N \rightarrow l + X$ ($l = e, \mu, \tau$), where $N$ and $X$ are respectively a nucleon and a hadronic final state. NOMAD and CHORUS are short-baseline high energy neutrino oscillation experiments at CERN. They probe $\nu_\mu - \nu_\tau$ oscillation in the mass region related to hot dark matter. They use a wide-band neutrino beam of average beam energy of about 27 GeV produced by 450 GeV protons from the CERN SPS. These two detectors are located about 820 m away from the beam dump. The CHORUS detector [81] uses emulsions with a total mass of 800 kg and scintillating fiber tracking. Behind the tracking devices, a magnetic spectrometer for momentum determination and a lead-scintillating fiber calorimeter follow. A $\tau$ lepton created in the charged weak current interaction of a $\nu_\tau$ and its subsequent decay kink are detected in the emulsion. From the data taken up to November 1997, they give a preliminary limit of $\sin^2(2\theta) \leq 2.2 \times 10^{-3}$ for large $\Delta m^2$ [81]. Their final limit is expected to be $\sin^2(2\theta) \leq 2 \times 10^{-4}$. Also, to confirm the ability of $\nu_\tau$ detection by emulsion, the DONUTS experiment (E872) was carried out at Fermilab using a $\nu_\tau$ beam produced by $D_s$ and $\tau$ decays [81]. An emulsion target and fiber trackers were placed after a 15-m steel shield. The analysis is underway.

There are two short-baseline neutrino oscillation experiments running with medium energy. One is LSND, which claims the evidence of neutrino oscillation of $\nu_\mu - \nu_e$, and the other is KARMEN. Both experiments use neutrino beams from pion and muon decay at rest ($\pi^+ \rightarrow \mu^+\nu_\mu; \mu^+ \rightarrow e^+\bar{\nu}_e\nu_e$), and recently pion decay in flight was also used by LSND. To confirm or refute the LSND effect with much better statistics, a new project called BooNe is proposed at Fermilab
BooNe is a detector of pure mineral oil with a 445-ton fiducial region (5.5 m radius) and 776 tons in total (6 m radius). It would use a neutrino beam from the Fermilab 8 GeV Booster ring. The initial phase of BooNe is called Mini-BooNe which is a single detector located at 1000 m, and the second phase is a pair of detectors at 500 m and 1000 m. Mini-BooNe has recently been approved by Fermilab PAC.

At the M arena of JHF, neutrino sources at the 3-GeV proton beam dump, either from pion decay at rest (DAR) or in flight (DIF), are being discussed [83]. It is expected that there will be about $10^7 \nu/s/cm^2/sec$ from DAR at 20 m away from the beam dump, and about $10^{11} - 10^{12} \nu/s/sec$ from DIF if a special high-intensity muon channel planned at the M arena, which is called “Super-Super Muon Channel”, is built at the M arena. The expected constraint is shown in Fig.19.

C Long Baseline Experiments

There are two long baseline neutrino oscillation experiments being currently prepared: K2K in Japan and MINOS in US. K2K (KEK-PS E362) will provide a
neutrino beam from KEK to Super-Kamiokande [84]. The distance is about 250 km, and the average energy of the neutrino beam produced by 12-GeV KEK-PS is about 1.4 GeV. KEK will measure $\nu_\mu$ disappearance and $\nu_e$ appearance, although the latter is not likely according to the exclusion of CHOOZ. The region of sensitivity in $\Delta m^2$ vs. $\sin^2(2\theta)$ is shown in Fig.20. A one kton front detector, which is located about 1 km away from the beam dump, will serve as neutrino flux and spectrum monitor. At Super-Kamiokande, the neutrino detection is the same as their atmospheric neutrino detection. The beam line is scheduled to be commissioned in January, 1999.

MINOS is a neutrino oscillation experiment from Fermilab to the Soudan mine about 730 km away [85]. An average neutrino energy of 15 GeV is created by 120 GeV protons from the Main Injector Ring. MINOS aims to cover $\Delta m^2 > 10^{-3}$ eV$^2$ and $\sin^2(2\theta) > 10^{-2}$ by varying the neutrino energy. The near detector is located at Fermilab. The far detector of 8 ktons consists of 730 layers of magnetized iron plate toroids (of 1 inch thickness and 8 m diameter) alternating with plastic scintillator planes (of 4 cm thickness). The scintillator planes are made of arrays of extruded plastic strips read out by wavelength shifting fibers. This project is scheduled to start in the year 2003.

In Europe, long baseline experiments using a neutrino beam of an average energy of 29 GeV from CERN to Gran Sasso, whose distance is about 732 km, are being discussed. Several experiments are proposed. One is ICARUS which is a liquid Argon TPC, and a 600 ton prototype will be installed in Gran Sasso. The second proposal is NOE which is composed of magnetized iron-scintillator stacks of 10 ktons. The third proposal is NICE, a 2.4 kton TRD plus 4.3 kton calorimeter. The fourth proposal is a 27 kton water ring-imaging Cerenkov detector called AQUA-RICH. The fifth proposal is called OPERA [86] whose design consists of alternating layers of 1 mm-thick lead and pairs of 50 $\mu$m emulsion plates with 3 mm gap in between, followed by a magnetized iron muon spectrometer. The total weight of lead-emulsion trackers is 750 ton. The sensitivity goal is $\Delta m^2 < 10^{-3}$ eV$^2$ and $\sin^2(2\theta) < 2 \times 10^{-3}$.

At JHF 50-GeV PS, a high intensity narrow-band neutrino beam whose energy is well above the $\tau$ lepton appearance threshold of 3.5 GeV can be produced by a 50-GeV proton beam of 10 $\mu$A. Although the scenario would be depend on the results of K2K and other experiments, the primary goal is to observe $\nu_\tau$ appearance [87]. The detection of $\nu_\tau$ at Super-Kamiokande is being studied. One possibility is the simultaneous detection of recoil protons from $\nu_\tau n \rightarrow \tau^- p$ and muons from $\tau \rightarrow \mu \nu \bar{\nu}$ decay. The identification of protons at Super-Kamiokande can be easily done via their short range and their Cerenkov angle. The acoplanarity condition of muons and protons with respect to the neutrino beam can be useful for further event identification. The main background is from $\nu_\mu$ charged current processes ($\nu_\mu n \rightarrow \mu^- p$) and neutral current processes ($\nu_\mu n \rightarrow \nu_\mu \pi p$) with misidentification of the $\pi$ as a $\mu$.

For the far-future, high-intensity neutrino and antineutrino sources from a muon accumulator ring, for which a very intense muon source could be made
available in connection with a $\mu^+\mu^-$ collider, has been discussed [88]. If $O(10^{20})$ muons per year were available, hundreds of charged neutrino interactions in a 10 kton detector on the other side of the Earth could be possible.

VI CONCLUSION

If the JHF 50-GeV PS were available today, it is clear that the menu of kaon, muon, and neutrino physics that could be addressed with it would be superb. Cutting edge issues in flavor physics, including CP violation, an incisive probe into certain classes of SUSY GUTs, and new insight into the elusive nature of the neutrino could immediately be pursued. Undoubtedly in the years before this accelerator is built, the physics landscape will change, partly driven by results from the experiments discussed above.

However we are confident that the potential of the JHF 50GeV PS will still be great, as long as the ancillary beam lines and experimental equipment are kept commensurate with the accelerator, and there are sufficient resources for efficient utilization of the machine.

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