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Letter of Intent

HIGH PRECISION, HIGH SENSITIVITY K^0 PHYSICS AT THE MAIN INJECTOR

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We are very interested in the potential of the Main Injector for a variety of high precision, high sensitivity measurements with neutral kaons. From all that we know today, it appears that experiments with a K_L branching ratio sensitivity of 10^{-10} per hour, even for a four body decay mode, are achievable. We are seriously evaluating the feasibility of such measurements.

The advantages of using higher energy kaons and some of the physics objectives and possible beam and detector parameters were discussed in the appended document which concentrated on CP violation studies. The accessible physics includes the $K_L \to \pi^0 e^+ e^-$ decay mode, which, in the standard model, has a large contribution from "direct" CP violation, a very high sensitivity experiment on ε'/ε, measurements of the parameters η_{+-0} and η_{000} governing the size of CP violation in 3π decays, and studies of the interference between K_L and K_S decays to $\pi^0 e^+ e^-$.

These studies would involve running in both a K_L and a K_S beam configuration. After the enclosed document was written, the workshop on Physics at the Main Injector was held at Fermilab and the viability of such measurements was reaffirmed. In addition, it looks as though high sensitivity studies of possible flavor violation ($K_L \to \mu e$) are also feasible. While probably not all of these measurements can be performed simultaneously, we believe that there will be a rather sophisticated "core" detector (including high rate drift chambers and TRD's and very high precision electromagnetic calorimetry) which will be common for most of the measurements. The very attractive feature at the Main Injector of year-round running means that more than one such topic could be addressed during each "run".

There are other important physics issues which can also be addressed including studies of the $\pi^0 \mu\mu$ and $\pi^0 \gamma\gamma$ decay modes, K_{e4} decays, double-Dalitz decays, etc, and the sensitivity to these will be also be evaluated.

It should be obvious that such measurements are highly challenging and to convince ourselves (and review committees) that such studies are feasible will require a great deal of work: rates are comparable to those at the SSC and backgrounds to the $\pi^0 e^+ e^-$ mode need to be simulated and rejected at the 10^{-14} level so that the flux of high energy kaons at the Main Injector can be exploited. The experience gained with the current generation of experiments at the 10^{-10} to 10^{-11} level will be most important.

We anticipate that a proposal could be submitted in 1990; formal approval in 1991 would then give three years for construction of the detector to be ready for physics in 1994 which we understand is the scheduled date for the turn-on of the Main Injector. We are happy with the recent endorsement of the Fermilab upgrade by HEPAP and we hope that it will be funded in such a way that the Main Injector will be operational for fixed target physics in a timely manner.

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CP VIOLATION IN THE KAON SYSTEM WITH THE FERMILAB UPGRADE

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INTRODUCTION

We briefly review the status of experiments addressing very rare processes and CP nonconservation in the kaon system and discuss the prospects for improvements at current facilities. We stress the role of the new Main Injector at Fermilab as a source of high energy kaons which will not be surpassed in intensity by any planned facility. Experiments with a branching ratio sensitivity of 10^{-10} per hour appear possible.

CURRENT STATUS

The best experiments searching for lepton flavor violation in kaon decays are presently being done at BNL. These include the modes $K_L \to \mu e^{(1)}$ and $K^+ \to \pi^+ \mu e^{(2)}$ where the limits are now between 10^{-9} and 10^{-10}. Another experiment at BNL just getting underway using stopped kaons is studying the mode $K^+ \to \pi^+ +$"nothing"(3) and that effort will very likely reach the goal of 10^{-10} in sensitivity where there is a good chance of seeing a signal.

In the area of CP nonconservation, again an experiment at BNL has the best limit on the size of the transverse polarization of the muon in $K_{\mu 3}$ decays(4). With respect to studies of ϵ'/ϵ, the E731(5) experiment at Fermilab has the largest number of $K_L \to 2\pi^0$ decays (over 300K) with the smallest background from $3\pi^0$ decays (less than 0.5%). The best limit on the parameter η_{+-0} again comes from an experiment(6) at Fermilab as does that for the mode $K_L \to \pi^0 e^+ e^-$(5) which has received a great deal of attention(7) recently.

A conclusion that one could draw from the above discussion is that, in spite of the much reduced proton flux at the Fermilab Tevatron, for those modes with π^0's in the final state, the higher energy facility has the advantage. This we believe to be the case as we will argue below.

PROSPECTS FOR IMPROVEMENT

We discuss here likely improvements, primarily in the experiments addressing CP nonconservation. The lepton flavor violation experiments will no doubt be improved at BNL with the planned upgrades of that lab. It is clear that experiments with stopping kaons will also benefit from increased intensity as they appear to be presently limited by a lack of flux. Further improvements in this area are likely with a "kaon factory" as has been proposed in Canada.

The next generation experiment(8) studying the 2π decays of the neutral kaon is likely to require 10^8 $K_L \rightarrow 2\pi^0$ events: such a sample would permit a measurement of ϵ'/ϵ with a statistical precision of better than 10^{-4} where the Standard Model would be definitive in its non-zero prediction. Even putting aside systematic effects for the moment, such a level of statistics would be very difficult to collect at the Tevatron.

Closely coupled with the issue of a non-zero ϵ'/ϵ is the size of the branching ratio for $K_L \rightarrow \pi^0 e^+ e^-$ which very likely has a large contribution in lowest order that is "direct" CP violation(7). At BNL(9), KEK(10), and FNAL(11) there are proposals to search for this mode with sensitivities in the range of 10^{-10} to 10^{-11}. While this represents a significant advance over the present limit which is in the 10^{-8} range, unless there are some surprises, such a sensitivity will likely not be enough to definitively make an observation: the Standard Model predictions(7) generally fall in the range of a few times 10^{-12} to a few times 10^{-11}.

We believe that in the future the best place to perform these experiments will be at the new Main Injector(12) which has been proposed at Fermilab as a major part of the upgrade of that laboratory in the next decade.

THE MAIN INJECTOR

While this has been proposed in large measure to significantly increase the luminosity for the FNAL collider experiments, for our purposes we are concerned with its use as a source of high energy, high intensity extracted protons for kaon production.

The parameters of the extracted protons are the following:

energy	120 GeV
intensity	3.0×10^{13}
spill length	1.9 sec
repetition time	3.8 sec
duty cycle	50%
microstructure	debunched

An important factor is the ability of the Injector to provide extracted beam year-round, during both fixed target and collider operations.

The available proton flux would be about 100 times that at the Tevatron and the new facility would be operating in the mid-1990's.

In the next sections, we describe the possible use of this facility for neutral beam experiments addressing the issue of CP nonconservation. The kaon flux in the energy region $E>15$ GeV which is useful for the experiments under consideration will significantly exceed that at other facilities.

THE NEUTRAL BEAM

In the figure, we show a model neutral beam and detector configuration which could address CP nonconservation with very great sensitivity.

First, 25m of magnetized collimation are used as a dump for the charged secondaries and non-interacting primary protons. Calculations indicate that this will reduce the flux of muons through the detector to well below the rate from the kaon decays themselves. The solid angle is chosen to be only 36μstr resulting in a relatively small beam hole (35cm x 35cm) at the end of the detector, 55m from the target. The decay region is 20m in length. The targeting angle is 20mr thereby reducing the neutron flux by a factor of 40 compared to 0^0. The neutron (and non-decaying kaon) beam is transported through the detector in vacuum.

The instantaneous rates(13) in the beam are the following:

kaons	2.2×10^9 Hz
neutrons	1.9×10^9 Hz
kaon decays (total)	1.3×10^8 Hz
kaon decays (15 GeV<E<50 GeV)	3.3×10^7 Hz

THE DETECTOR

The model detector shown in the figure is configured to have high acceptance for kaon decays with energy greater than 15 GeV. It has a cross-sectional area of 3m x 3m and consists of high precision drift chambers, an electromagnetic and hadronic calorimeter, TRD modules, and a "γ shield" covering the entire decay region and detector to detect γ's emitted backwards in the center-of-mass system.

The acceptance of this detector is high: 16% for the $\pi^0 e^+ e^-$ mode with the requirement of 1 GeV minimum photon energy. Thus the sensitivity of such an experiment will be about 10^{-10} per hour of running. This should be compared to the currently best attained limit(1) (for a two-body mode) of about 10^{-10} per experiment.

We point out that the above design is conservative in that there is a great deal more flux available were one to use a beam of greater solid angle and/or equip the beam region with detectors to increase the acceptance. Thus, should detector advances permit, there is the potential for measurements of even greater sensitivity although the relatively modest configuration is already quite an advance and appears adequate to address the physics.

We do not want to underestimate the considerable difficulties in performing such high sensitivity measurements. The rates in the detector are very high: there are 1.4 tracks per kaon decay in the decay region which traverse the first chamber. This then implies that the singles rates in that chamber will be 1.6×10^8 Hz. Thus the conditions are not unlike the environment at the SSC although of course the multiplicity is greatly reduced. The wire pitch will need to be on the order of 3mm; in such a case, the rate on the hottest wire would be 6.6×10^5 Hz. The electromagnetic calorimeter would consist of perhaps 20,000 cells of high resolution, radiation-hard material. Triggering and data acquisition pose significant challenges. Much work in the simulation and study of possible backgrounds is needed.

Even so, we believe that the advantages of the higher energy range are most significant and lead to the conclusion that such experiments are best done using the extracted beam at the Main Injector.

WHY HIGHER ENERGY?

Similar fluxes could be found at a "kaon factory" were one to reduce the energy range of the beam. In this section we detail the advantages of using higher energy kaons made from high energy protons for the CP nonconservation studies discussed above. These involve the rejection of backgrounds, the optimization of acceptance, and particle identification. These considerations are largely based upon our experience with E731.

1.Electromagnetic energy resolution

Perhaps most important is the $1/\sqrt{E}$ term in the energy resolution of electromagnetic calorimeters. Resolution is at a premium in such experiments as there are many backgrounds which can be discriminated against primarily by means of good resolution. This is particularly true as the intensity increases and dominant backgrounds result from accidental overlapping of in-time and out-of-time decays.

2.Rejection of backward gammas

Both for detection of the $\pi^0\pi^0$ and the $\pi^0e^+e^-$ decay modes, there are significant backgrounds with extra soft photons. In the former case, there is the dominant $\pi^0\pi^0\pi^0$ mode while in the latter case, Dalitz decays with missing photons are important. These extra photons are simply boosted to a higher energy in the laboratory making their detection easier. The ability to efficiently reject such events has been a key factor in the low background levels in both $\pi^0\pi^0$ and $\pi^0e^+e^-$ obtained by the E731 experiment.

3.Fixed thresholds

Kaon production obeys approximate scaling (the x dependence is roughly proportional to $(1-x)^3$) so that the same rates are in principle available at a lower energy machine if one simply scales the energies. However, there are important features of the detector which do not scale and one of these is the threshold in an electromagnetic detector. The model configuration discussed above uses a 1 GeV threshold and, in practice in kaon experiments, a threshold in this range has been used no matter what the beam energy. This is because there is a significant rate of effectively minimum ionizing "showers" in the electromagnetic calorimeter and the effective energy of these "showers" is roughly 1/2 GeV. The 1 GeV threshold is chosen to effectively discriminate against this background.

4.The beam dump

Another factor which does not scale with energy is the required thickness of the beam dump. Hadronic showers grow logarithmically rather than linearly with energy so that experiments can be situated relatively closer to the target at the higher energy facility and this results in a beam with the same range of P_T having a smaller dead region (due to the beam hole) in the detector. Thus the acceptance will be greater. As we mention below, this feature makes the study of K_S decays easier as well.

5.Particle identification

At higher energy, one has much better π/e separation in the calorimeter and this is important in rejecting, for example, radiative Ke_3 decays with an accidental overlapping photon. In addition, higher energy secondaries permit the use of multiple stages of TRD's giving added π/e separation.

Finally we point out the advantages in having a high acceptance detector. Obviously this is desirable to achieve maximum sensitivity. However, there is another more important advantage. The higher the acceptance the greater the ability to observe with the detector that an accidental overlap did indeed occur: the accidental events are themselves kaon decays and it is clear that high acceptance helps greatly in identifying the presence of an additional decay in the event.

There is a useful figure of merit which can be employed to compare different configurations. This is the ratio of the "acceptable flux" to the singles rate in the detector, where "acceptable flux" is defined to be the decay rate in the energy region of interest times the acceptance in that energy region. For the model configuration discussed above, that figure is 3.4% which is considerably greater than for any of the current experiments.

K_S PHYSICS

Finally we would like to point out that although the model configuration above concentrated upon the CP violating K_L decays, there are considerable advantages at higher energy for K_S decays as well. This results primarily from the fact that one can be situated relatively closer to the target. This opens up another realm of physics including CP violation in 3π decays (η_{+-0} and η_{000}) and other rare K_S

decays, including $\pi^0 e^+ e^-$. It may in fact be necessary to study the interference between K_S and K_L decays to $\pi^0 e^+ e^-$ to establish a "direct" CP violating effect.

SUMMARY

We have pointed out the considerable advantages of the use of high energy kaons for studies of CP nonconservation. We do not claim to have proved that one can reach sensitivities of the order of 10^{-13} per 1000 hour experiment, only that the flux is there at high energy where one has the best opportunity. A factor of 100 increase in flux at the Tevatron would perhaps be the most desirable scenario for the experiments that we are considering here; given the impossibility of this option, we find that the Main Injector is considerably more appealing than a 30 GeV "kaon factory". Such a facility would have a greater proton flux than at the Main Injector; however, we have argued that for the same sensitivity, if one chooses to operate in the same beam energy range ($E>15$ GeV), the singles rates would be a great deal higher (from all the lower energy decays) while if a scaled energy range is chosen, there would be more serious difficulties with resolution, particle identification and low energy backgrounds.

There will be a workshop at Fermilab in the Spring of 1989 on the subject of Physics with the Upgrade. At the workshop, there will be studies in the following areas for kaon physics:

1. High resolution, radiation resistant calorimetry
2. Drift chambers in a 10^8 Hz environment
3. The "γ shield"
4. TRD's for kaon decays
5. Triggering
6. Data acquisition
7. K_L and K_S beam design
8. Charged beam design and experiments
9. Background simulation

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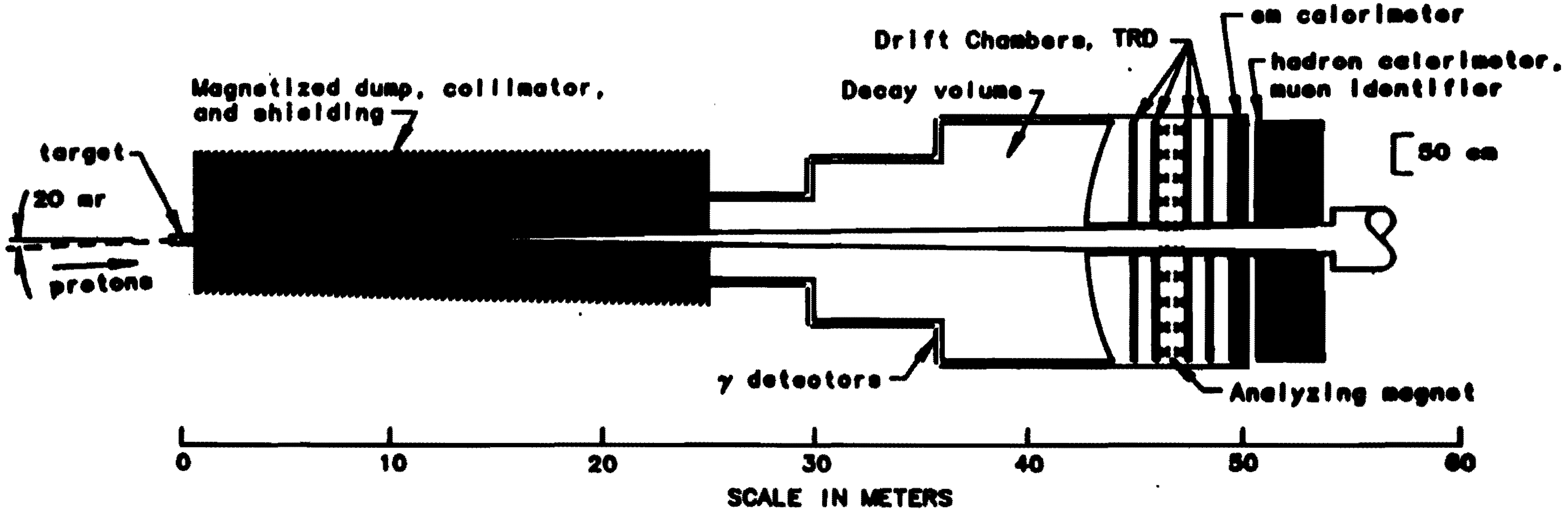
Model neutral kaon apparatus using the Main Injector



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2. BNL E777: BNL, SIN, Washington, Yale collaboration. Contribution to the Munich conference.
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5. FNAL E731: Chicago, Elmhurst, Fermilab, Princeton, Saclay collaboration. M. Woods et. al., Phys. Rev. Lett. 60, 1695(1988); L.K. Gibbons et. al., Phys. Rev. Lett. 61, 2661(1988). G.D. Barr et. al., Phys. Lett. B214(1988) 303 [CERN NA31 group] have an equally good limit on $K_L \rightarrow \pi^0 e^+ e^-$ with, however, more background.
6. FNAL E621: Michigan, Minnesota, Rutgers collaboration. See the letter of intent from this group to Fermilab for an upgrade, June 1988, for the latest result.
7. See Dib, Dunietz, and Gilman, SLAC-PUB-4762 and Flynn and Randall, UCB-PTH-88-29 and references therein for very recent work on this mode.
8. Such an experiment would be necessary should E731 and NA31 disagree significantly. Even in the case of consistency, eventually ε'/ε should be better measured as the theory becomes more refined and other KM parameters (as well as the top quark mass) are better determined.
9. BNL E-845: BNL, Yale collaboration.
10. KEK E-164: Kyoto, KEK collaboration.
11. FNAL P799: Chicago, Elmhurst, Fermilab, Princeton collaboration.
12. FNAL proposal to be submitted to DOE, January 1989.
13. The rate for kaons is calculated using the empirical formula for meson production of A.J. Malensek, Fermilab FN-341(1981). The neutron flux is calculated based upon the data of R.T. Edwards et. al., Phys. Rev. D18(1978) 76. Losses due to a radiator to convert photons [3" Pb] and a moderator to increase the kaon to neutron ratio [18" Be] are included. Both are in reasonable agreement with the fluxes determined in the Fermilab experiments.