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# PHYSICS AT THE PLANCK SCALE: TESTS OF CPT INVARIANCE AT THE FERMILAB MAIN INJECTOR

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## Abstract

It is possible that CPT-violating amplitudes with sizes of order $m_K$ / $m_{Planck}$ contribute to processes involving K mesons. We describe several tests of CPT invariance that could be carried out at the Fermilab Main Injector. To our surprise we find that one experiment, a precision measurement of the CP-violating charge asymmetry in semileptonic K decays, can be performed with sufficient statistical accuracy to detect the presence of CPT-violating amplitudes of size $m_K$ / $m_{Planck}$ which generate a mass difference between $K^0$ and $\overline{K}^0$.

## Introduction

In the context of field theories, reasonable assumptions such as Lorentz invariance and the connection between spin and statistics results in invariance of physical systems under the combined operations of charge conjugation, parity, and time reversal— CPT. Because the success of such theories provides the underpinnings of most of our current understanding of elementary particle physics, CPT invariance is generally held to be valid at current energy scales, and such an assumption has not been seriously contradicted by experiment.

Besides establishing various relationships among decay amplitudes, CPT invariance guarantees the equality of masses and lifetimes between particles and antiparticles, even if charge conjugation itself is violated. It is here that the most stringent tests of CPT are found. The most powerful of these is $\delta m$, the $K^0$- $\overline{K}^0$ mass difference, inferred from the measured $K_L$-$K_S$ mass difference and other parameters of the neutral-kaon system to be $\delta m \, / \, m_K \leq 6 \times 10^{-19}$.(1)

With its deep connections to Lorentz invariance and other cornerstones of physics, one might not expect violations of CPT at all. Such violations may in fact occur at the Planck mass scale(2),(3) of $1.2 \times 10^{19}$ GeV/$c^2$ where conditions necessary for CPT symmetry (e.g. locality) might not hold. This scale is out of direct reach of current or currently foreseeable technology, so this might seem to be a particularly unpromising

line of experimental effort. However, if CPT-violating effects do occur in the K system at a scale of $m_K/m_{Planck} = 4 \times 10^{-20}$, current limits on $\delta m$ are less than two orders of magnitude from this. Of course, one could argue that a search in the neutral kaon system assumes many things, notably that the CPT violation occurs in strangeness-changing interactions. It is also possible that the appropriate scale is, say, $(m_K/m_{Planck})^2$. However, the prospect of probing Planck-scale physics is certainly a tantalizing one.

## CP, T, and CPT in the Neutral K System

### Mixing and $\varepsilon$

CP violation has only been observed in the existence of a charge asymmetry in the semileptonic decays $K_L \to \pi\mu\nu$, $K_L \to \pi e\nu$ and in the decay $K_L \to \pi\pi$.(4) The dominant source of CP violation is a T-violating asymmetry in the transition rates $K^0 \leftrightarrow \bar{K}^0$: $\Gamma(\bar{K}^0 \to K^0) > \Gamma(K^0 \to \bar{K}^0)$. This asymmetry causes both the (nonmixing) mass eigenstates, $K_L$ and $K_S$, to contain slightly more $K^0$ than $\bar{K}^0$. Neglecting normalizations,

$$|K_S> \sim (1+\varepsilon)|K^0> + (1-\varepsilon)|\bar{K}^0> \quad \text{and} \quad |K_L> \sim (1+\varepsilon)|K^0> - (1-\varepsilon)|\bar{K}^0>.$$

The $\Delta S = \Delta Q$ rule requires $K^0 \to \pi^- l^+ \nu$ and $\bar{K}^0 \to \pi^+ l^- \bar{\nu}$ so the observed charge asymmetry in a $K_L$ beam is proportional to $\mathrm{Re}(\varepsilon)$. Note that the same charge asymmetry would be observed in a pure $K_S$ beam. The magnitude and phase of $\varepsilon$ are $(2.259 \pm 0.018) \times 10^{-3}$ and $(43.67 \pm 0.13)^{o}$ respectively.(5) Since $CP(|K^0>) = |\bar{K}^0>$ and $CP(|\bar{K}^0>) = |K^0>$, the mass eigenstates are not CP eigenstates. The CP eigenstates $K_1$ and $K_2$ are

$$|K_1> \sim |K^0> + |\bar{K}^0> \text{ and } |K_2> \sim |K^0> - |\bar{K}^0>.$$

In terms of $K_1$ and $K_2$ one may write

$$|K_S> \sim |K_1> + \varepsilon|K_2> \text{ and } |K_L> \sim |K_2> + \varepsilon|K_1>.$$

Because the $|\pi\pi>$ final state from K decay must have CP = +1, a pure $K_L$ beam will yield $\pi\pi$ decays from the beam's small $K_1$ component.

<u>Direct CP Violation and $\varepsilon'$</u>

A second possible source for CP violation would be the existence of a non-zero amplitude for the decay $K_2 \rightarrow \pi\pi$. It is necessary that $Amp(K^0 \rightarrow \pi\pi) \neq Amp(\bar{K}^0 \rightarrow \pi\pi)$ if the $K_2$ is to decay into $\pi\pi$. In particular, the quantity

$$\varepsilon' \equiv \frac{1}{\sqrt{2}} \frac{A_2 - \bar{A}_2}{A_0 + \bar{A}_0} e^{i(\delta_2 - \delta_0)}$$

must be nonzero where

$$A_0 \equiv Amp(K^0 \rightarrow \pi\pi|_{I=0}), \quad \bar{A}_0 \equiv Amp(\bar{K}^0 \rightarrow \pi\pi|_{I=0})$$
$$A_2 \equiv Amp(K^0 \rightarrow \pi\pi|_{I=2}), \quad \bar{A}_2 \equiv Amp(\bar{K}^0 \rightarrow \pi\pi|_{I=2}).$$

$\delta_2$ and $\delta_0$ are final state interaction phase shifts suffered by the pions moving away from the kaon decay vertex. After defining

$$\eta_{+-} \equiv \frac{\mathrm{Amp}(K_L \to \pi^+\pi^-)}{\mathrm{Amp}(K_S \to \pi^+\pi^-)} \quad \text{and} \quad \eta_{00} \equiv \frac{\mathrm{Amp}(K_L \to \pi^0\pi^0)}{\mathrm{Amp}(K_S \to \pi^0\pi^0)},$$

some algebra reveals that $\eta_{+-} = \varepsilon + \varepsilon'$ and $\eta_{00} = \varepsilon - 2\varepsilon'$. A nonzero $\varepsilon'$ would split the values of the two $\eta$'s by $3\varepsilon'$. Searches for this "direct" CP violation through measurements of $\mathrm{Re}(\varepsilon'/\varepsilon)$ are underway at Fermilab and CERN; results so far are inconclusive.[6] Since CPT invariance forces $\bar{A}_I = A_I^*$ and since the $\pi\pi$ phase shifts have been well measured, the phase of $\varepsilon'$ is known to be $(48 \pm 8)^o$. $\mathrm{Arg}(\eta_{+-})$ has been determined to be $(44.6 \pm 1.2)^o$; recent results from Fermilab E731 and CERN NA31 indicate that $\mathrm{Arg}(\eta_{00})$ is within three degrees of $\mathrm{Arg}(\eta_{+-})$.[5],[6]

CPT violation parameters

Two different avenues for CPT violation suggest themselves. The first is a CP-violating, but T-conserving mixing of $K^0$ and $\bar{K}^0$ to produce the mass eigenstates. This corresponds to a situation where the $K_S$ contains, for example, an excess of $K^0$ while the $K_L$ contains an excess of $\bar{K}^0$. The CPT violating parameter $\Delta$ enters into the description of $K_S$ and $K_L$ like this:

$$|K_S> \sim (1+\varepsilon+\Delta)|K^0> + (1-\varepsilon-\Delta)|\bar{K}^0> \quad \text{and} \quad |K_L> \sim (1+\varepsilon-\Delta)|K^0> - (1-\varepsilon+\Delta)|\bar{K}^0>.$$

Note the sign switch between $\varepsilon$ and $\Delta$ in the $K_L$ expression. The component of $\Delta$ which is perpendicular to $\varepsilon$ in the complex plane, $\Delta_{\perp}$, corresponds to a $K^0$ - $\overline{K}^0$ mass difference, while the component parallel to $\varepsilon$ corresponds to a lifetime difference.[1]

A second possible route to CPT violation is through a CPT-violating relationship among the various $K \rightarrow \pi\pi$ decay amplitudes. Because $A_I - A_I^* = 2i\,\mathrm{Im}(A_I)$ and $A_I + A_I^* = 2\mathrm{Re}(A_I)$, the phase of $\varepsilon'$ would be shifted from its value of $(48 \pm 8)^o$ by a CPT-disallowed relationship such as $\overline{A}_I \neq A_I^*$.

In terms of $\varepsilon$, $\varepsilon'$, and $\Delta$, $\eta_{+-} = \varepsilon + \varepsilon' - \Delta$ and $\eta_{00} = \varepsilon - 2\varepsilon' - \Delta$. A nonzero value of $\Delta$ will shift both $\eta$'s in the same direction in the complex plane and will split the $K_L$ and $K_S$ semileptonic charge asymmetries. An unusual $\varepsilon'$ phase will split the $\eta$'s apart without affecting the charge asymmetries.

## Experimental investigation of CPT violation

### Overview

A comparison ot the semileptonic charge asymmetries for $K_L$ and $K_S$ decays yields information about $\mathrm{Re}(\Delta)$. $\mathrm{Arg}(\eta_{+-})$ - $\mathrm{Arg}(\eta_{00})$ ,when combined with a value of $\mathrm{Re}(\varepsilon'/\varepsilon)$, determines the phase of $\varepsilon'$. $\mathrm{Arg}(\eta_{+-})$ - $\mathrm{Arg}(\varepsilon)$ and $\mathrm{Arg}(\eta_{00})$ - $\mathrm{Arg}(\varepsilon)$ provide determinations of $\varepsilon' - \Delta$ and $-2\varepsilon' - \Delta$, respectively. We will discuss an experiment to measure Re($\Delta$). Because of the relationship between $\Delta_\perp$ and $\delta m$, the $K^0$ - $\bar{K}^0$ mass difference, the semileptonic rate study is the most interesting of the possible measurements. It is conceivable that physics at the Planck scale (or string compactification scale) will give rise to processes which generate a nonzero $\delta m$, of size $\delta m/m_K \approx m_K/m_{Planck} = 4 \times 10^{-20}$. The current experimental limit is $\delta m/m_K < 6 \times 10^{-19}$, only a factor of 25 larger than $m_K/m_{Planck}$. Note that $\delta m$ will be zero if CPT is conserved while $\Delta m$, the $K_L$-$K_S$ mass difference, is not [$\Delta m = (3.521 \pm 0.014) \times 10^{-6}$ eV].(5)

The interpretation of a precision measurement of Arg($\eta_{+-}$) - Arg($\eta_{00}$) as a CPT test is complicated by the fact that the $\eta_{+-}$ - $\eta_{00}$ phase difference can be small, but nonzero, in a CPT-invariant universe. Arg($\eta_{+-}$) - Arg($\eta_{00}$) is known to be within three degrees of zero; Fermilab E773 will measure it to an accuracy of 1/2 degree in the near future. The utility of measurements considerably more precise than this would require improved measurements of the phase of $\varepsilon$ and the value of Re($\varepsilon'/\varepsilon$).

Re($\Delta$) and the semileptonic charge asymmetry experiment

The semileptonic charge asymmetry is

$$\delta \equiv \frac{\Gamma(K \to \pi^- l^+ \nu) - \Gamma(K \to \pi^+ l^- \bar{\nu})}{\Gamma(K \to \pi^- l^+ \nu) + \Gamma(K \to \pi^+ l^- \bar{\nu})}.$$

Neglecting violation of the $\Delta S = \Delta Q$ rule, the behavior of $\delta$ as a function of proper time should depend only on the relative probabilities that a beam kaon be a $K^0$ or a $\bar{K}^0$.

Allowing for CPT violation, the charge asymmetry in a pure $K_L$ beam will be approximately $4Re(\varepsilon+\Delta)$ while that in a pure $K_S$ beam will be $4Re(\varepsilon-\Delta)$. Small $\Delta S = \Delta Q$ violations will not mimic CPT violation unless the $\Delta S = \Delta Q$ amplitudes are also CP violating.

If one could produce a pure $K_S$ beam, one could measure $\delta_S$ directly and compare it to $\delta_L$ determined by the same detector exposed to a $K_L$ beam. Since this is not possible, it is necessary to extract $\Delta$ by studying the interfence between $K_S$ and $K_L$ decays downstream of a target. The observed semileptonic decay downstream of a target is a function of many things: acceptance, reconstruction efficiency, magnitude and phase of $\varepsilon$, magnitude and phase of $\Delta$, relative amounts of $K^0$ and $\bar{K}^0$ leaving the production target. We have investigated the statistical sensitivity of a possible CPT experiment at the Main Injector, leaving study of systematic difficulties for a later date. Our assumptions are naïve: our toy detector has uniform (and perfectly known) acceptance in a decay volume which is $10^{-9}$ seconds of proper time long. We assume there are no backgrounds to our $K_{e3}$ signal (neglecting the copious $K_S \to \pi^+\pi^-$ mode). We assume we have a monochromatic K beam and can reconstruct the energy of the detected kaons unambigously. We generate proper time spectra for $K_{e3}$ decays using specific values for six parameters: $|\varepsilon|$, Arg($\varepsilon$), $|\Delta|$, Arg($\Delta$), the dilution factor D (defined as the difference in the $K^0$ and $\bar{K}^0$ fluxes leaving the target divided by the sum of the fluxes), and the total target K flux. We jitter the contents of each bin in the time spectrum using a Gaussian distribution with $\sigma = \sqrt{n_{bin}}$ and then use MINUIT[8] to fit for the six parameters. Note that $\Delta_\perp \approx 10^{-5}$ corresponds to $\delta m/m_K \approx m_K/m_{Planck}$[1]; we use a conservative value for D of 0.2.[9] The K yield expected in the proposed Main Injector high intensity neutral beam will be in excess of $10^9$ kaons per second.(10) Here is a set of results from one of the fits, assuming 10% detection efficiency and $10^{15}$ kaons leaving the target.

| Parameter | True value | Fit value |
|---|---|---|
| Target K flux | $1.0 \times 10^{15}$ | $1.0 \times 10^{15} \pm 1.7 \times 10^9$ |
| $\lvert\Delta\rvert$ | $1.0 \times 10^{-5}$ | $(1.05 \pm 0.20) \times 10^{-5}$ |
| Arg($\Delta$) | $133.6^o$ | $(117.0 \pm 12.4)^o$ |
| $\lvert\varepsilon\rvert$ | $2.274 \times 10^{-3}$ | $(2.280 \pm 0.002) \times 10^{-3}$ |
| Arg($\varepsilon$) | $43.6^o$ | $(43.7 \pm 0.05)^o$ |
| D | 0.2 | $0.2 \pm (0.2 \times 10^{-5})$ |

There were about $4 \times 10^{12}$ (!!) detected decays in this sample. These results are typical: $10^{15}$ target kaons give several standard deviations of sensitivity to a CPT-violating mass difference between K and $\overline{K}$. The results of the MINUIT fits are insensitive to initial values of the trial parameters. When the fit algorithm is given an "infinite statistics" sample, the algorithm converges to the correct parameter values.

Discussion

The $K^0$ beam at the Main Injector will be capable of producing $2.2 \times 10^9$ kaons per second during extraction with a 50% duty factor.(10) Neglecting deadtime, this would yield $10^{15}$ target kaons in less than two weeks. Available K flux will not be a limiting factor in the ability of a semileptonic CPT violation search to reach its goals. The experiment will have to overcome problems associated with running in a very high rate environment. The experiment trigger will need to reject nonleptonic kaon decays quickly without introducing significant bias in the $K_{e3}$ sample. To be able to record trillions of semileptonic decays, it will be necessary to analyze data in realtime, storing only a small amount of information about each event. Even if each trigger can be processed in 1 μsec, with one byte per event written to tape, the full event sample will require several thousand 8mm cassette tapes.

The detector will need to be designed to eliminate systematic acceptance and reconstruction efficiency differences between the $\pi^+e^-\bar{\nu}$ and $\pi^-e^+\nu$ final states. In addition, it will probably be necessary to employ tricks involving several targets at different distances from the spectrometer to remove systematic uncertainties associated with imperfect knowledge of acceptance. Fortunately, the CPT-violating signal is an unusual time evolution of the charge asymmetry, not its value at a particular proper time. This dependence on a change in the charge asymmetry should cancel many systematic effects associated with charge-dependent efficiencies. However, the need to control systematics at the required level will be a difficult challenge, and warrants further study.

## Conclusions

There is a fair chance that a CPT violation experiment can be carried out at the Fermilab Main Injector with a level of statistical sensitivity sufficient to observe the existence of CPT-violating amplitudes of size $m_K$ / $m_{Planck}$. Ample K flux will be available but the data taking rates are high, the number of events to be processed and stored in realtime is large, and strict control of systematic uncertainties crucial. However, the possible physics payoff is enormous: a first observation of the workings of the fundamental interactions at the Planck scale.

## References

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