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# Background enhancement of CPT reach at an asymmetric $\phi$ factory

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## Abstract

Photoproduction of neutral-kaon pairs is studied from the perspective of CP and CPT studies. Interference of the  $P$ - and  $S$ -waves, with the former due to diffractive  $\phi$  production and the latter to  $f_0/a_0$  production, is shown to enhance the CPT reach. Results are presented of Monte Carlo studies based on rates expected in future experiments. © 2001 Published by Elsevier Science B.V.

## 1. Introduction

Neutral-meson oscillations provide a sensitive tool for testing CPT symmetry [1]. Impressive bounds have been achieved in experiments with both  $K$  mesons [2,3] and  $B_d$  mesons [4]. Although the CPT theorem [5] guarantees that the standard model preserves CPT by virtue of its construction as a Lorentz-invariant quantum field theory, violations of CPT could be exhibited in a more fundamental description of nature that incorporates physics at the Planck scale [6]. For example, CPT and Lorentz violation may naturally arise in string theory [7] and could lead to effects in the various neutral-meson systems [8]. It is, therefore, valuable to identify additional possibilities for future experiments with exceptional sensitivity to CPT violation.

In the  $K$  system, CPT bounds of a few parts in  $10^{19}$  now exist on the ratio of the kaon–antikaon mass

difference to the kaon mass [2,3]. Future improvements over these bounds are expected from specialized experiments at kaon factories, such as KLOE at DAPHNE [9]. Indeed, it has long been recognized that high-luminosity  $\phi$  factories are ideal for studies of CP and CPT violation [10] because a decaying  $\phi$  meson produces a well-defined flux of  $C$ -odd  $K_S K_L$  pairs.

In the present work, we study the possibility that interference effects between the  $C$ -odd wave and a coherent  $C$ -even  $K^0 \bar{K}^0$  background could be used to enhance further the sensitivity to parameters describing the weak  $K^0$  and  $\bar{K}^0$  decay amplitudes. At an  $e^+e^-$  collider, the  $\phi$  mesons are essentially the only source of  $K^0 \bar{K}^0$  pairs. However, such studies potentially suffer from a  $C$ -even background from the decay [11]  $\phi \rightarrow \gamma f_0(980) \rightarrow \gamma K^0 \bar{K}^0$ . Fortunately, recent measurements by the SND and CMD-2 Collaborations report [12] a branching ratio  $B(\phi \rightarrow \gamma f_0) = 1.9\text{--}3.5 \times 10^{-4}$ , which is insignificant for CP and CPT studies [13].

Here, we consider instead hadronic production, where a different mechanism exists. In particular, in

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photoproduction near the  $\phi$  meson peak, a significant  $S$ -wave background has been measured and attributed to the decays of the  $f_0(980)$  and  $a_0(980)$  mesons [14, 15]. In what follows, we show how differences in the angular distributions of the  $S$  and  $P$  waves could be exploited for CP and CPT studies.

Nature is believed to be described at low energies by a quantum field theory. The CPT theorem then suggests that any violations of CPT invariance must be accompanied by Lorentz violation. At the level of the standard model, small violations of Lorentz and CPT invariance can be introduced via additional terms in the Lagrangian, which yields a general standard model extension [16]. In this general context, it turns out that neutral-meson oscillations provide a unique sensitivity to a class of parameters for CPT violation associated with flavor-changing effects in the quark sector [17]. In fact, to leading order in small parameters, tests with neutral mesons are independent of all others performed to date, including comparative measurements in Penning traps [18], spectroscopy of hydrogen and antihydrogen [19], measurements of muon properties [20], clock-comparison experiments [21], observations of the behavior of a spin-polarized torsion pendulum [22], measurements of cosmological birefringence [16,23], and observations of the baryon asymmetry [24].

In the  $K$  system, experiments have reached a sensitivity of parts in  $10^{20}$  to certain parameters for CPT violation in the standard model extension [2,3,17]. At leading order, four coefficients control CPT violation for kaons. Experiments can therefore place four independent CPT bounds, only two of which have been obtained to date. The photoproduction of  $\phi$  mesons offers a distinct experimental arena with the potential to bound new combinations of parameters, a possibility which may well merit careful investigation. However, with the exception of a few remarks below, the scope of the present exploratory work is limited to the demonstration that a background-enhanced CPT reach is possible in photoproduction.

## 2. Theory for $S$ – $P$ interference

In the reaction  $\gamma p \rightarrow X p \rightarrow K^0 \bar{K}^0 p$  with  $J^{PC}(X) = 1^{--}(\phi)$ ,  $0^{++}(f_0)$  or  $0^{++}(a_0)$ , the  $K^0 \bar{K}^0$  wave

function in the rest frame of the pair can be written as

$$|i\rangle = h \int d^2\hat{q} \left[ a^P(\hat{q}) |K_S(\hat{q}) K_L(-\hat{q})\rangle + a^S(\hat{q}) (|K_L(\hat{q}) K_L(-\hat{q})\rangle - |K_S(\hat{q}) K_S(-\hat{q})\rangle) \right]. \quad (1)$$

Here, the first term represents the  $P$ -wave and comes from the  $\phi$  decay and other coherent odd-parity backgrounds with  $a^P(\hat{q}) = \sum_m a_m^1 Y_{1m}(\hat{q})$ , where  $\hat{q}$  is a unit vector. The second term comes from  $S$ -wave and other even-parity backgrounds with  $a^S = \frac{1}{2} a_0^0 Y_{00}(\hat{q})$ . The photoproduction amplitudes  $a_m^J = a_m^J(s, t, m_{K\bar{K}})$  describe the dynamics of the production process. Since  $K\bar{K}$  photoproduction is dominated by helicity-nonflip diffraction for which the  $a_{\pm 1}^{\pm 1}$  coefficients are the largest, the subsequent  $K\bar{K}$  evolution is best studied in the  $s$ -channel helicity system, with the  $z$ -axis defined in the direction opposite to the direction of flight of the outgoing nucleon in the  $K\bar{K}$  rest frame [25]. In general an incoherent  $S$ -wave background is also present but is largely irrelevant for our analysis. We comment on its effect later.

The normalization  $h$  in Eq. (1) is chosen so that the  $K\bar{K}$  photoproduction rate is given by

$$\frac{dN_{K\bar{K}}}{dt dm_{K\bar{K}} d^2\hat{q}} = F \frac{d\sigma(\gamma p \rightarrow K\bar{K} p)}{dt dm_{K\bar{K}}} W(\hat{q}), \quad (2)$$

where  $F$  is the photon flux. In this equation, the  $K\bar{K}$  angular distribution  $W(\hat{q})$  is taken to be unit normalized,  $\int d\hat{q} W(\hat{q}) = 1$ , and is given by

$$W(\hat{q}) = \sum_{JJ'} W_{JJ'} = \sum_{Jm, J'm'} \rho_{mm'}^{JJ'} Y_{Jm} Y_{J'm'}^*. \quad (3)$$

Here,  $\rho_{mm'}^{JJ'} \equiv a_m^J a_{m'}^{J'*}$  are elements of the spin density matrix. Summation over nucleon helicities is implicit.

The two kaons decay into final states  $f_\alpha$ ,  $\alpha = 1, 2$ , with amplitudes given by

$$A(K_{S(L)} \rightarrow f_\alpha) = a_{\alpha, S(L)} \exp(i\phi_{\alpha, S(L)}) \times \exp(-im_{S(L)} t_\alpha - \Gamma_{S(L)}^\alpha t_\alpha/2), \quad (4)$$

where  $\Gamma_{S(L)}^\alpha$  are the corresponding partial decay widths. For convenience, we define as usual for each fixed  $\alpha$  the parameter

$$\eta_\alpha \equiv |\eta_\alpha| \exp(i\phi_\alpha) = a_{\alpha, L}/a_{\alpha, S} \quad (5)$$

as the ratio of the amplitude for the transition between  $f_\alpha$  and  $K_L$  to that between  $f_\alpha$  and  $K_S$ . For the moment, the  $f_\alpha$  are kept general.

The production rate  $R(t_1, t_2; \hat{q})$  of the final state  $f_\alpha$  with momentum direction of  $f_1$  specified by the solid angle  $\hat{q}$  is

$$R(t_1, t_2, \hat{q}) = \int dm_{K\bar{K}} dt \frac{dN_{K\bar{K}}(f_1, f_2)}{dt dm_{K\bar{K}} d^2\hat{q}}. \quad (6)$$

This expression can be expanded as

$$R(t_1, t_2, \hat{q}) = N_{K\bar{K}} \left( |M_{PP}| W_{PP} + \sum_{m=0,1} |M_{PS}^m| W_{PS}^m + |M_{SS}| W_{SS} \right), \quad (7)$$

where  $N_{K\bar{K}} = F\sigma(\gamma p \rightarrow K\bar{K}p)$  is the rate for kaon pair production integrated over  $t$  and  $m_{K\bar{K}}$  in the region of the  $\phi$  peak. The two angular distributions  $W_{PP}$  and  $W_{SS}$  are determined by Eq. (3). The remaining ones are

$$W_{PS}^0 = \frac{\sqrt{3}}{4\pi} |\rho_{00}^{10}| \cos\theta, \\ W_{PS}^1 = -\frac{\sqrt{6}}{4\pi} |\rho_{10}^{10}| \sin\theta \cos\phi, \quad (8)$$

assuming that  $P$ - and  $S$ -waves are produced via natural-parity  $t$ -channel exchanges, i.e., via Pomeron and  $\rho$  or  $\omega$  mesons, respectively [26]. In the general case there is an additional contribution to  $S$ - $P$  interference, identical in form to the second term in Eq. (7) but with  $\cos\phi$  replaced by  $\sin\phi$  in  $W_{PS}^1$  and with a shifted phase  $\phi_B^1 \rightarrow \phi_B^1 + \pi/2$  (see below). The coefficients  $M_{JJ'}$  are given by

$$|M_{PP}| = \Gamma_S^1 \Gamma_S^2 e^{-\Gamma T/2} [|\eta_2|^2 e^{\Delta\Gamma t/2} + |\eta_1|^2 e^{-\Delta\Gamma t/2} - 2|\eta_1\eta_2| \text{Re} e^{i(\Delta m t + \Delta\phi)}], \\ |M_{SS}| = \Gamma_S^1 \Gamma_S^2 [e^{-\Gamma_S T} + |\eta_1\eta_2|^2 e^{-\Gamma_L T} - 2|\eta_1\eta_2| e^{-\Gamma T/2} \text{Re} e^{i(\Delta m T - \phi_1 - \phi_2)}], \\ |M_{PS}^m| = 2\Gamma_S^1 \Gamma_S^2 e^{-\Gamma T/4} \text{Re} e^{i\phi_B^m} \\ \times \sum_{\alpha=1}^2 \pm |\eta_\alpha| e^{\mp(\Delta\Gamma/2 + i\Delta m)t/2} \\ \times [e^{-(\Gamma_S - i\Delta m)\frac{T}{2} - i\phi_\alpha} - |\eta_1\eta_2| e^{-(\Gamma_L + i\Delta m)\frac{T}{2} + i\phi_\alpha}], \quad (9)$$

with the upper (lower) sign corresponding to  $\alpha = 1(2)$ , and  $\bar{\alpha} = 1$  for  $\alpha = 2$  and vice versa. The phases  $\phi_B^m$ ,  $m = 0, 1$ , arise from the elements  $\rho_{m0}^{PS} = |\rho_{m0}^{PS}| e^{i\phi_B^m}$  of the spin density matrix. For convenience, we have also introduced the definitions  $\Delta\Gamma = \Gamma_S - \Gamma_L$ ,  $\Delta m = m_L - m_S$ ,  $t = t_2 - t_1$ ,  $\Gamma = \Gamma_S + \Gamma_L$ ,  $m = m_L + m_S$ , and  $T = t_1 + t_2$ .

In Section 3, we construct an asymmetry  $A_{12}(\hat{q})$  to extract parameters sensitive to CP and CPT violation. However, we can already note here that the term in the production rate proportional to  $|M_{SS}|$  is independent of  $t$  and consequently is absent from the numerator of any asymmetry defined as a  $t$ -sensitive difference of production rates. In contrast, this term does contribute to the denominator of such an asymmetry, thereby making the modulation of the signal harder to see. An incoherent even-parity background merely renormalizes this term, further increasing the background but not directly influencing the signal.

The decay rate exhibits some interesting and potentially useful properties. Consider first the case where  $f_1 = f_2$ , i.e., both kaons decay to the same final state. Then, it follows from the structure of the initial wave function that all terms either independent of or quadratic in the background (the first and third terms in Eq. (7)) are invariant under the transformation  $t \rightarrow -t$ , whereas the linear term (proportional to  $M_{PS}$  in Eq. (7)) changes sign. Among the consequences is that the asymmetry  $A_{12}(\hat{q})$  defined in the next section contains a term *linear* in the background. This may provide a means of measuring  $\rho^{PS}$ , as discussed below. If instead we consider the case of different decays occurring at the same time  $t_1 = t_2$ , then the terms either independent of or quadratic in the  $S$ -wave amplitude are invariant under the transformation  $f_1 \leftrightarrow f_2$ , whereas the linear term changes sign. Also, as expected,  $R(T/2, T/2, \hat{q}) \propto |M_{SS}|$ .

### 3. Background enhancement

The parameters sensitive to CP or CPT violation are best extracted from singly and doubly integrated asymmetries. Define

$$R(|t|, \hat{q}) = R^+(|t|, \hat{q}) - R^- (|t|, \hat{q}) \quad (10)$$

and

$$R(\hat{q}) = \int_0^{T_L} d|t| R(|t|, \hat{q}), \quad (11)$$

where

$$R^\pm(|t|, \hat{q}) = \int_0^{T_L} dt_1 \int_0^{T_L} dt_2 \delta(t_1 - t_2 \pm |t|) R(t_1, t_2, \hat{q}). \quad (12)$$

Here, the time  $T_L$  is related to the acceptance for detecting  $K_L$ . Assuming a maximum distance of  $d_L = 5$  m between the primary vertex and the detector, together with a boost factor  $\gamma_K \sim 5$  corresponding approximately to  $E_\gamma = 10$  GeV photons, we get

$$T_L \Gamma_L = \frac{d_L}{\beta_K \gamma_K} \Gamma_L \sim 6.5 \times 10^{-2}, \quad (13)$$

which leads to  $S_L = 1 - \exp(-T_L \Gamma_L) \sim 6\%$  acceptance for  $K_L$  detection.

The signal can be parametrized by an asymmetry  $A_{12}(\hat{q})$ , defined as

$$A_{12}(\hat{q}) = \frac{\int_0^{T_L} d|t| [R^+(|t|, \hat{q}) - R^-(|t|, \hat{q})]}{\int d^2 \hat{q} \int_0^{T_L} d|t| [R^+(|t|, \hat{q}) + R^-(|t|, \hat{q})]}. \quad (14)$$

The detailed form of this asymmetry is somewhat involved. For simplicity, we adopt the approximations  $\Gamma_S \simeq \Gamma \simeq 2\Delta m \gg \Gamma_L$ , which are well justified experimentally. With these approximations, the coefficients in the expressions that follow hold to about 5%. Since for either semileptonic or  $2\pi$  decays the ratio  $r \equiv \eta_2/\eta_1$  is one to about 0.1%, it is also useful to write  $r = 1 + \kappa$ , where  $\kappa \ll 1$  and  $\kappa$  can be zero for certain final states. Combining these approximations and definitions, we find

$$A_{12}(\hat{q}) = \left( \left[ \frac{\Gamma_S}{\Gamma_L} \kappa S_L + 2 \sin \Delta\phi \right] W_{PP}(\hat{q}) + \frac{1}{5} \sum_{m=0}^1 \left( \frac{A_1^m}{|\eta_1|} + \frac{A_2^m}{|\eta_2|} \right) W_{PS}^m(\hat{q}) \right) \times \left[ \int d^2 \hat{q} \left[ \left( \frac{\Gamma_S}{\Gamma_L} S_L - 2 \cos \Delta\phi \right) W_{PP}(\hat{q}) + \frac{1}{2|\eta_1 \eta_2|} W_{SS}(\hat{q}) \right] \right]^{-1}, \quad (15)$$

where  $\Delta\phi = \phi_1 - \phi_2$  and

$$A_i^m = \cos(\phi_\beta^m - \phi_i) + 3 \sin(\phi_\beta^m - \phi_i). \quad (16)$$

To gain insight into the content of the asymmetry  $A_{12}(\hat{q})$ , consider first decays into the same final state,  $f_1 = f_2$ . Then,  $r = 1$ ,  $\kappa = 0$ ,  $\eta_1 = \eta_2 \equiv \eta$ , and  $A_1^m = A_2^m \equiv A^m$ . The expression (15), therefore, simplifies considerably. If the final states consist of the same  $2\pi$  mode, then we find

$$A_{12}(\hat{q}) \sim \frac{\frac{2}{5|\eta|} \sum_{m=0}^1 A^m W_{PS}^m(\hat{q})}{\int d^2 \hat{q} \left[ \frac{\Gamma_S}{\Gamma_L} S_L W_{PP}(\hat{q}) + \frac{1}{2|\eta|^2} W_{SS}(\hat{q}) \right]}. \quad (17)$$

This provides a means to measure  $\phi$  if the background is known (or possibly a means to determine the background if  $\phi$  is known). For example, the present bounds on CPT are limited by the precision to which  $\phi_1$  and  $\phi_2$  are known (roughly, a degree). Results of similar appearance arise for, say, semileptonic final states. The situation is also interesting for  $f_1 = 2\pi^0$  and  $f_2 = \pi^+ \pi^-$ . Then,  $|\eta_\alpha| \simeq 10^{-3}$  and  $r \simeq 1 + 3 \operatorname{Re} \epsilon'/\epsilon$ . The issue to resolve is under what circumstances  $W_{SP} \neq 0$  enhances or masks the signal.

The existing data on  $S$ - $P$  interferometry with  $E_\gamma \lesssim 10$  GeV come from two experiments, at DESY [14] and Daresbury [15]. Both experiments clearly identify a significant  $S$ -wave background under the dominant  $P$ -wave signal. Since in diffraction  $\rho_{11}^{11}$  is the largest element of the spin density matrix, one would expect  $S$ - $P$  interference to be dominated by the  $W_{PS}^1$  term, i.e., by  $\rho_{10}^{10}$ . However, in the limit  $t' = t - t_{\min} \rightarrow 0$ , the  $S$ -wave production is dominated by nucleon helicity-flip and so  $\rho_{00}^{10}$  should dominate. This is consistent with the DESY results where  $t_{\max} \sim 0.2$  GeV. Nonetheless, the higher- $t$  data from Daresbury ( $t_{\max} = 1.6$  GeV) do indicate the presence of  $\rho_{10}^{10}$ , and this despite the neglect of its contribution in the partial-wave analysis appropriate to the low- $t$  behavior. Using Eq. (17), it follows that a nonvanishing azimuthal dependence in the  $S$ - $P$  interference due to  $\rho_{10}^{10}$  would significantly enhance the sensitivity to the weak phases  $\phi_i$ .

High-statistics experiments measuring all elements of the spin density matrix are clearly needed. An experiment of this type has recently been proposed for Jefferson Lab [27]. With the planned accelerator-energy upgrade, this experiment would have access to

approximately  $10^5 \gamma p \rightarrow K \bar{K} p$  events per day (compare, for example, the total of 3500 events collected at DESY). Existing experimental results fail to provide definitive estimates for the two most relevant elements of the spin density matrix,  $\rho_{00}^{10}$  and  $\rho_{10}^{10}$ . The magnitude of  $\rho_{00}^{10}$  has been estimated to be of the order of a few percent, while no unique prediction for the phases has been found.

The scales partially controlling the rates and the asymmetry  $A_{12}(\hat{q})$  are given by

$$\begin{aligned} |W_{PP}| &\sim O(\rho_{11}^{11}) = 1, \\ |W_{PS}|/|\eta| &\sim O(|\rho^{10}|)/|\eta| \\ &\sim |W_{SS}|/|\eta| \sim O(|\rho^{00}|)/|\eta| \equiv s. \end{aligned} \quad (18)$$

Examining the expressions given in the above expressions for the numerator and denominator of  $A_{12}(\hat{q})$ , one discovers also a natural scale for  $2\pi$  decays given by

$$\begin{aligned} a &= O(\kappa S_L \Gamma_S / \Gamma_L) \sim O(2 \sin \Delta \phi) \\ &\sim O(S_L |\eta| \Gamma_S / \Gamma_L) \sim 10^{-2} - 10^{-1}. \end{aligned} \quad (19)$$

The relative sizes of  $s$  and  $a$  therefore provide a separation into distinct regimes, to be considered in turn.

If  $s < a$ , the asymmetry is dominated by the term  $2 \sin \Delta \phi \sim 6 \text{Im} \epsilon' / \epsilon$ , while sensitivity to the usual  $3 \text{Re} \epsilon' / \epsilon$  is suppressed due to the acceptance factor  $S_L$ . Terms proportional to the  $S$ -wave background are roughly an order of magnitude smaller. Thus, depending on the phase of the coherent background, it may be feasible to extract information about  $\phi_\alpha$ .

If  $a < s$  the contribution from  $s$  dominates the numerator. As  $s$  grows, the denominator acquires nontrivial  $s$  dependence. This case is potentially very important because  $\epsilon' / \epsilon$  is no longer a factor and so the whole measurement can focus on improving the bounds on  $\phi_\alpha$ . If an experiment can be set up in this regime, it would represent a novel means of measuring two of the more elusive quantities in CP physics and of bounding CPT. This appears to be the most favorable case. Since  $s = O(|\rho^{10}|)/|\eta| \simeq 10^3 |\rho^{10}|$ , this corresponds to a  $|\rho^{10}|$  magnitude of greater than  $O(10^{-3})$ . However, it cannot be arbitrarily large, since for  $s \gg a_1$  the signal becomes background dominated. Although there is still information in the modulations via the asymmetry, the signal falls off as  $1/s$  due

to the quadratic contributions in the denominator, and so measurements become harder. The current experimental situation seems to favor values of  $s$  of the order of  $O(10^{-2})$ , i.e., with the  $K_S K_S$  decays from the  $S$ -wave dominating the denominator.

#### 4. Simulation

In a real experiment, the limit of the twice-integrated asymmetry would not be taken, and instead the complexities of the full system would need to be simulated. As an initial contribution along these lines, we have implemented a preliminary Monte Carlo study assuming a flux of  $5 \times 10^8 \gamma/s$  as expected in the later phase of the proposed photon experiments at Jefferson Lab. This translates into  $O(10^{10}) K_S K_L$  pairs from  $\phi$  decay per year.

We assume for definiteness that the only nonvanishing amplitudes are the  $P$ -wave helicity nonflip at both photon and nucleon vertices,  $a_1^n$ , the  $P$ -wave single helicity flip at photon and nucleon vertices,  $a_0^f$ , the  $S$ -wave nucleon helicity nonflip,  $b^n$ , and  $S$ -wave single nucleon flip,  $b^f$ . In terms of these amplitudes, the nonvanishing elements of the spin density matrix are then given by

$$\begin{aligned} \rho_{11}^{11} &= \rho_{-1-1}^{11} = 2|a_1^n|^2, & \rho_{00}^{11} &= 2|a_0^f|^2, \\ \rho_{10}^{10} &= -\rho_{-10}^{10} = 2a_1^n b^{f*}, & \rho_{00}^{10} &= 2a_0^f b^{f*}, \\ \rho_{00}^{00} &= 2|b^f|^2 + 4|b^n|^2. \end{aligned} \quad (20)$$

We adopt the choice  $|a^f| \sim |b^f| \sim |b^n| = 0.1$ . Together with  $\rho_{11}^{11} \sim 0.5$ , which is fixed by the condition  $1 = \text{tr} \rho = 2\rho_{11}^{11} + \rho_{00}^{11} + \rho_{00}^{00}$ , this leads to  $\rho_{00}^{11} \sim \rho_{00}^{00} \sim 0.01$ , which is consistent with the low- $t$  DESY results.

For simplicity, we limit attention to the case where both neutral kaons decay to  $\pi^+ \pi^-$  states. With the rates given above, the  $P$ -wave contributes about  $10^4 \gamma p \rightarrow (K^0 \bar{K}^0)^P p \rightarrow 2(\pi^+ \pi^-) p$  events. Similarly, the  $(K_S K_S)^S$  in the  $S$ -wave yields approximately  $O(10^7)$  events. We adopt the former as the number of generated events.

Under the above conditions, we have simulated  $R(|t|, \hat{q})$  and extracted the asymmetry  $A_{12}$ . The result is shown in Fig. 1. The solid and histogram lines correspond to the theoretical prediction and the simulation, respectively. The sensitivity to the phase  $\phi_\alpha = \phi_{+-}$

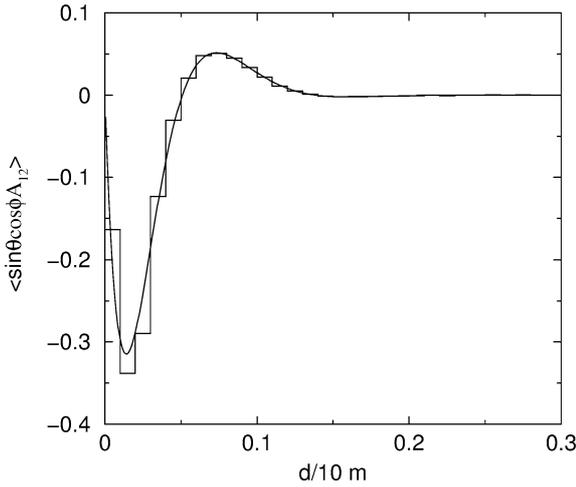


Fig. 1. Theoretical prediction (solid) vs. Monte Carlo (steps) simulations of  $A_{12}$  as a function of the relative decay distance  $d$  as measured in the lab.

can be displayed by comparing the magnitudes of differences in the asymmetry simulated with  $\phi_\alpha^{\text{MC}} = 45^\circ$  with theoretical predictions. In Fig. 2, these differences are plotted for three theoretical predictions, calculated using  $\phi_\alpha = \phi_\alpha^{\text{MC}}$  (circles),  $\phi_\alpha = \phi_\alpha^{\text{MC}} + 1^\circ$  (squares), and  $\phi_\alpha = \phi_\alpha^{\text{MC}} + 10^\circ$  (triangles). Inspection of the two figures, in particular Fig. 2, suggests that with the anticipated number of events it should be possible in principle to extract the weak phases to within  $O(1^\circ)$  accuracy. With a full partial wave analysis, the sensitivity might be enhanced by another order of magnitude.

Within the context of conventional quantum field theory, with CPT violation at the level of the standard model described by the Lorentz-violating standard model extension, the effect of CPT violation on an oscillating neutral meson depends on the meson velocity magnitude and orientation [17]. However, in simulating the double-pion decays of the kaons, we have taken the CPT-sensitive phases to be independent of orientation for simplicity. This corresponds to the case where nonzero CPT-violating phases are determined by the timelike component of the parameter  $\Delta a_\mu$  in the standard model extension. For this situation, boosting the meson with a boost factor  $\gamma$  enhances the CPT-violation effect, inducing a corresponding additive change in  $\phi_\alpha$  by an amount  $\gamma - 1$ , i.e.,  $\phi_\alpha(\gamma) = \gamma\phi_\alpha(1)$ . Thus, an  $O(1^\circ)$  sensitivity to

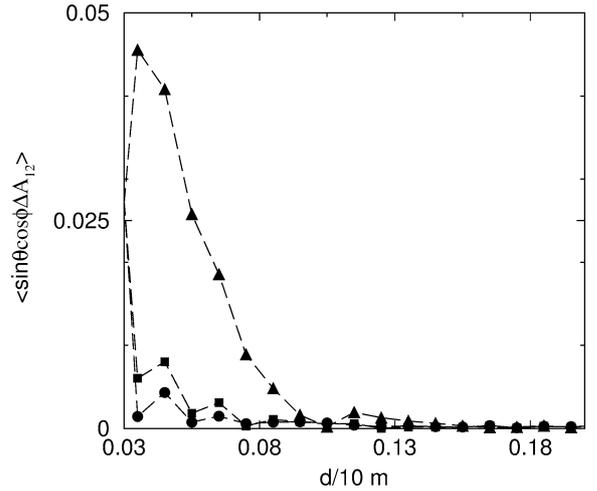


Fig. 2. Sensitivity of the simulated asymmetry to the weak phase  $\phi_\alpha$ .

$\phi_\alpha$  in a photoproduction experiment with boost factor  $\gamma \sim O(10)$  is comparable to a  $O(0.1^\circ)$  sensitivity to  $\phi_\alpha$  in a similar experiment at rest.

It would evidently be interesting to study also the prospects for enhanced CPT reach in the more general case of orientation-dependent effects. The orientation dependence leads to additional possibilities for CPT signals, including notably sidereal-time dependence [17]. This has recently been used by the KTeV Collaboration to obtain a CPT bound in the kaon system that is independent of all previous bounds [3]. In the present context, a complete analysis is likely to require more detailed input regarding the angular distribution of the kaon momentum spectrum and the detector performance. With a favorable scenario, bounds on all four independent coefficients for CPT violation in the kaon system could be obtained.

## 5. Summary

This work has investigated some aspects of the CP and CPT sensitivity that could be attained by experiments involving photoproduction of neutral-kaon pairs. The photoproduction mechanism generates a coherent  $P$ -wave as usual, but also yields a coherent  $S$ -wave along with an incoherent background. The magnitude of the coherent  $S$ -wave is presently uncertain but could be significant. Under favorable circum-

stances, the resulting CPT sensitivity could be comparable to that attainable at conventional  $\phi$  factories. Both analytical calculations and Monte Carlo simulation indicate that interference between the  $P$ - and  $S$ -waves might lead to an enhancement of an order of magnitude in the existing CPT reach.

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