Published by Institute of Physics Publishing for SISSA
Received: October 12, 2006
Accepted: November 13, 2006
Published: December 4, 2006

Determination of CP and CPT violation parameters in the neutral kaon system using the Bell-Steinberger relation and data from the KLOE experiment

The KLOE collaboration, Giancarlo D'Ambrosio[a] and Gino Isidori[b]

F. Ambrosino,[a] A. Antonelli,[b] M. Antonelli,[b] C. Bacci,[c] P. Beltrame,[d] G. Bencivenni,[b] S. Bertolucci,[b] C. Bini,[e] C. Bloise,[b] S. Bocchetta,[c] V. Bocci,[e] F. Bossi,[b] D. Bowring,[b,f] P. Branchini,[c] R. Caloi,[e] P. Campana,[b] G. Capon,[b] T. Capussela,[a] F. Ceradini,[c] S. Chi,[b] G. Chiefari,[a] P. Ciambrone,[b] S. Conetti,[f] E. De Lucia,[b] A. De Santis,[e] P. De Simone,[b] G. De Zorzi,[e] S. Dell'Agnello,[b] A. Denig,[d] A. Di Domenico,[e] C. Di Donato,a S. Di Falco,[g] B. Di Micco,[c] A. Doria,[a] M. Dreucci,[b] G. Felici,[b] A. Ferrari,[b] M. L. Ferrer,[b] G. Finocchiaro,[b] S. Fiore,[e] C. Forti,[b] P. Franzini,[e] C. Gatti,[b] P. Gauzzi,[e] S. Giovannella,[b] E. Gorini,[h] E. Graziani,[c] M. Incagli,[g] W. Kluge,[d] V. Kulikov,[i] F. Lacava,[e] G. Lanfranchi,[b] J. Lee-Franzini,[b,l] D. Leone,[d] M. Martini,[b] P. Massarotti,[a] W. Mei,[b] S. Meola,[a] S. Miscetti,[b] M. Moulson,[b] S. Müller,[b] F. Murtas,[b] M. Napolitano,[a] F. Nguyen,[c] M. Palutan,[b] E. Pasqualucci,[e] A. Passeri,[c] V. Patera,[b,m] F. Perfetto,[a] L. Pontecorvo,[e] M. Primavera,[h] P. Santangelo,[b] E. Santovetti,[n] G. Saracino,[a] B. Sciascia,[b] A. Sciubba,[b,m] F. Scuri,[g] I. Sfiligoi,[b] A. Sibidanov,[b,k] T. Spadaro,[b] M. Testa,[e] L. Tortora,[c] P. Valente,[e] B. Valeriani,[d] G. Venanzoni,[b] S. Veneziano,[e] A. Ventura,[h] R.Versaci,[b] G. Xu,[b,j]

[a] *Dipartimento di Fisica dell'Università "Federico II" e Sezione INFN, Napoli, Italy*
[b] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[c] *Dipartimento di Fisica dell'Università "Roma Tre" e Sezione INFN, Roma, Italy*
[d] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[e] *Dipartimento di Fisica dell'Università "La Sapienza" e Sezione INFN, Roma, Italy*
[f] *Physics Department, University of Virginia, Charlottesville, VA, USA*
[g] *Dipartimento di Fisica dell'Università e Sezione INFN, Pisa, Italy*
[h] *Dipartimento di Fisica dell'Università e Sezione INFN, Lecce, Italy*
[i] *Institute for Theoretical and Experimental Physics, Moscow, Russia*
[j] *Institute of High Energy Physics of Academia Sinica, Beijing, China*
[k] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[l] *Physics Department, State University of New York at Stony Brook, USA*
[m] *Dipartimento di Energetica dell'Università "La Sapienza", Roma, Italy*
[n] *Dipartimento di Fisica dell'Università "Tor Vergata" e Sezione INFN, Roma, Italy*

E-mail: Mario.Antonelli@lnf.infn.it, matteo.palutan@lnf.infn.it, gdambros@na.infn.it, Gino.Isidori@lnf.infn.it.

Abstract: We present an improved determination of the CP and CPT violation parameters $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ based on the unitarity condition (Bell-Steinberger relation) and on recent results from the KLOE experiment. We find $\mathrm{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5}$ and $\mathrm{Im}(\delta) = (0.4 \pm 2.1) \times 10^{-5}$, consistent with no CPT violation.

Keywords: e+-e- Experiments.

JHEP12(2006)011

Contents

1. Introduction

The three discrete symmetries of quantum mechanics, charge conjugation (C), parity (P) and time reversal (T), are known to be violated in nature, both singly and in bilinear combinations. Only CPT appears to be an exact symmetry of nature. Exact CPT invariance holds in quantum field theory, which assumes Lorentz invariance (flat space), locality and unitarity [1]. Testing the validity of CPT invariance therefore probes the most fundamental assumptions of our present understanding of particles and their interactions. These hypotheses are likely to be violated at very high energy scales, where quantum effects of the gravitational interaction cannot be ignored [2]. On the other hand, since we still lack a consistent theory of quantum gravity, it is hard to predict at which level violation of CPT invariance might become experimentally observable.

The neutral kaon system offers unique possibilities for the study of CPT invariance. From the requirement of unitarity, Bell and Steinberger have derived a relation, the so-called Bell-Steinberger relation (BSR) [3]. The BSR relates a possible violation of CPT invariance ($m_{K^0} \neq m_{\overline{K}^0}$ and/or $\Gamma_{K^0} \neq \Gamma_{\overline{K}^0}$) in the time-evolution of the K^0–$\overline{K}^0$ system to the observable CP-violating interference of K_L and K_S decays into the same final state f. Strictly speaking, evidence of CPT violation found via the BSR could just be a failure of the unitarity assumption. However, unitarity is also one of the main hypotheses of the CPT theorem; thus the BSR allows a test of the basic assumptions of quantum field theories.

JHEP12(2006)011

In this work we use recent results from the KLOE experiment to improve the determination of the phenomenological CP- and CPT-violating parameters $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ by means of the BSR. Our analysis benefits in particular from three new measurements: i) the branching ratio $\mathrm{BR}(K_L \to \pi^+\pi^-)$ [4], which is relevant to the determination of $\mathrm{Re}(\epsilon)$; ii) the new upper limit on $\mathrm{BR}(K_S \to \pi^0\pi^0\pi^0)$ [5], which is necessary to improve the accuracy on $\mathrm{Im}(\delta)$; and iii) the measurement of the semileptonic charge asymmetry A_S [6], which allows, for the first time, the complete determination of the contribution from semileptonic decay channels *without assuming unitarity*.

A determination of $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ using the BSR was performed by CPLEAR [7] in 1999. In the analysis of ref. [7], some of the parameters of the semileptonic channels were evaluated together with $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ from a combined fit to the time-dependent semileptonic asymmetries *imposing the constraint of the* BSR. A recent update of the determination of $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ is given in ref. [8]. In this latter analysis, however, some of the results of the CPLEAR fit [7], *which used the unitarity constraint*, have been used as input again to the BSR. It is not clear whether this fact *was accounted for* in [8].

Our presentation is organized as follows. In section 2 we outline the meaning of the BSR and the approach used to maximize the sensitivity obtainable from the presently available data. In section 3 we examine experimental inputs, including a re-analysis of the semileptonic channels, and obtain a best estimate for errors and correlations. The extraction of $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$ is discussed in section 4.

2. Theoretical framework

Within the Wigner-Weisskopf approximation, the time evolution of the neutral kaon system is described by [9]

$$i\frac{\partial}{\partial t}\Psi(t) = H\Psi(t) = \left(M - \frac{i}{2}\Gamma\right)\Psi(t)\,, \tag{2.1}$$

where M and Γ are 2×2 time-independent Hermitian matrices and $\Psi(t)$ is a two-component state vector in the K^0–$\overline{K}^0$ space. Denoting by m_{ij} and Γ_{ij} the elements of M and Γ in the K^0–$\overline{K}^0$ basis, CPT invariance implies

$$m_{11} = m_{22} \quad (\text{or } m_{K^0} = m_{\overline{K}^0}) \qquad \text{and} \qquad \Gamma_{11} = \Gamma_{22} \quad (\text{or } \Gamma_{K^0} = \Gamma_{\overline{K}^0})\,. \tag{2.2}$$

The eigenstates of eq. (2.1) can be written as

$$K_{S,L} = \frac{1}{\sqrt{2\left(1+|\epsilon_{S,L}|^2\right)}}\left((1+\epsilon_{S,L})\,K^0 \pm (1-\epsilon_{S,L})\,\overline{K}^0\right), \tag{2.3}$$

$$\begin{aligned}\epsilon_{S,L} &= \frac{-i\mathrm{Im}\,(m_{12}) - \frac{1}{2}\mathrm{Im}\,(\Gamma_{12}) \pm \frac{1}{2}\left(m_{\overline{K}^0} - m_{K^0} - \frac{i}{2}\left(\Gamma_{\overline{K}^0} - \Gamma_{K^0}\right)\right)}{m_L - m_S + i(\Gamma_S - \Gamma_L)/2} \\ &\equiv \epsilon \pm \delta\,,\end{aligned} \tag{2.4}$$

such that $\delta = 0$ in the limit of exact CPT invariance.

Unitarity allows us to express the four elements of Γ in terms of appropriate combinations of the kaon decay amplitudes $\mathcal{A}_i$:

$$\Gamma_{ij} = \sum_f \mathcal{A}_i(f)\mathcal{A}_j(f)^*, \qquad i,j = 1,2 = K^0, \overline{K}^0, \tag{2.5}$$

where the sum runs over all the accessible final states. Using this decomposition in eq. (2.4) leads to the BSR: a link between $\mathrm{Re}(\epsilon)$, $\mathrm{Im}(\delta)$, and the physical kaon decay amplitudes. In particular, without any expansion in the CPT-conserving parameters and neglecting only $\mathcal{O}(\epsilon)$ corrections to the coefficient of the CPT-violating parameter δ, we find

$$\left(\frac{\Gamma_S+\Gamma_L}{\Gamma_S-\Gamma_L}+i\tan\phi_{\mathrm{SW}}\right)\left(\frac{\mathrm{Re}(\epsilon)}{1+|\epsilon|^2}-i\mathrm{Im}(\delta)\right)=\frac{1}{\Gamma_S-\Gamma_L}\sum_f \mathcal{A}_L(f)\mathcal{A}_S^*(f), \tag{2.6}$$

where $\phi_{\mathrm{SW}} = \arctan\big(2(m_L-m_S)/(\Gamma_S-\Gamma_L)\big)$. We stress that, in contrast to similar expressions which can be found in the literature, eq. (2.6) is exact and phase-convention independent in the exact CPT limit: any evidence for a non-vanishing $\mathrm{Im}(\delta)$ resulting from this relation can only be attributed to violations of: i) CPT invariance; ii) unitarity; iii) the time independence of M and Γ in eq. (2.1).

The advantage of the neutral kaon system is that only a few decay modes give significant contributions to the r.h.s. in eq. (2.6). Only the $\pi\pi(\gamma)$, $\pi\pi\pi$ and $\pi\ell\nu$ modes turn out to be relevant up to the 10^{-7} level.[1]

The products of the corresponding decay amplitudes are conveniently expressed in terms of the α_i parameters defined below.

2.1 Two-pion modes

For two-pion states, we define the ratios α_i as:

$$\alpha_i \equiv \frac{1}{\Gamma_S}\langle\mathcal{A}_L(i)\mathcal{A}_S^*(i)\rangle = \eta_i\ \mathrm{BR}(K_S\to i)\,, \qquad i=\pi^0\pi^0\,,\ \pi^+\pi^-(\gamma), \tag{2.7}$$

where $\pi^+\pi^-(\gamma)$ denotes the inclusive sum over bremsstrahlung photons, and $\langle\ldots\rangle$ indicates the appropriate phase-space integrals. The η_i parameters in eq. (2.7) are the usual amplitude ratios: $\eta_i = \mathcal{A}_L(i)/\mathcal{A}_S(i)$.

The contributions from $\pi^+\pi^-\gamma$ direct-emission (DE) amplitudes not included in $\alpha_{\pi^+\pi^-(\gamma)}$ are collected together in the term

$$\alpha_{\pi\pi\gamma_{\mathrm{DE}}} = \alpha_{\pi\pi\gamma_{\mathrm{E1-S}}} + \alpha_{\pi\pi\gamma_{\mathrm{E1-L}}} + \alpha_{\pi\pi\gamma_{\mathrm{DE\times DE}}}\,, \tag{2.8}$$

where

$$\begin{aligned}\alpha_{\pi\pi\gamma_{\mathrm{E1-S}}} + \alpha_{\pi\pi\gamma_{\mathrm{E1-L}}} &= \frac{1}{\Gamma_S}\big(\langle\mathcal{A}_L(\pi\pi\gamma)\mathcal{A}_S^*(\pi\pi\gamma_{\mathrm{E1}})\rangle + \langle\mathcal{A}_L(\pi\pi\gamma_{\mathrm{E1}})\mathcal{A}_S^*(\pi\pi\gamma)\rangle\big)\\ &= \Delta B(K_S\to\pi\pi\gamma_{\mathrm{DE}})\ \eta_{+-} + (\eta_{+-\gamma}-\eta_{+-})\ \mathrm{BR}(K_S\to\pi\pi\gamma).\end{aligned} \tag{2.9}$$

Here $\mathcal{A}_{L,S}(\pi\pi\gamma)$ and $\mathcal{A}_{L,S}(\pi\pi\gamma_{\mathrm{E1}})$ denote the leading bremsstrahlung and the electric-dipole DE amplitudes, respectively. Their interference cannot be trivially neglected. $\mathrm{BR}(K_S\to\pi\pi\gamma)$ indicates the branching fraction for decays with the emission of a real photon with minimum energy equal to the cut used in the corresponding $\eta_{+-\gamma}$ measurement. $\Delta B(K_S\to\pi\pi\gamma_{\mathrm{DE}}) = \mathrm{BR}(K_S\to\pi\pi\gamma)^{\mathrm{exp}} - \mathrm{BR}(K_S\to\pi\pi\gamma)^{\mathrm{th-IB}}$ is the

[1] Note that all quantum numbers of a chosen final state f have to be equal between K_S and K_L decays in order to allow for interference between the two amplitudes in the r.h.s. of eq. (2.6).

JHEP12(2006)011

DE contribution to the BR, obtained subtracting the computed bremsstrahlung spectrum from the measured spectrum (see appendix A).

We have generically denoted by $\alpha_{\pi\pi\gamma_{\rm DE\times DE}}$ the contribution arising from the product of two DE amplitudes (electric or magnetic). Given the strong experimental suppression of DE amplitudes, this term turns out to be safely negligible being of $\mathcal{O}(10^{-8})$ or less [11].

2.2 Three-pion modes

For three-pion states we define

$$\alpha_i \equiv \frac{1}{\Gamma_S}\langle \mathcal{A}_L(i)\mathcal{A}_S^*(i)\rangle = \frac{\tau_{K_S}}{\tau_{K_L}}\eta_i^* \,\mathrm{BR}(K_L \to i), \qquad i = 3\pi^0\,,\ \pi^0\pi^+\pi^-(\gamma). \tag{2.10}$$

Note that in this case the amplitudes are not necessarily constant over the phase space. As a result, the η_i appearing in eq. (2.10) should be interpreted as appropriate Dalitz-plot averages. In particular, the $\pi^+\pi^-\pi^0$ final state is not a CP eigenstate. For decays to $\pi^+\pi^-\pi^0$ the η parameter can be expressed as

$$\begin{aligned}\eta_{+-0} = {}& \frac{\left\langle \mathcal{A}_L^*(\pi^+\pi^-\pi^0,\ CP=+1)\mathcal{A}_S(\pi^+\pi^-\pi^0,\ CP=+1)\right\rangle}{\langle|\mathcal{A}_L(\pi^+\pi^-\pi^0)|^2\rangle} + \\ & + \frac{\left\langle \mathcal{A}_L^*(\pi^+\pi^-\pi^0,\ CP=-1)\mathcal{A}_S(\pi^+\pi^-\pi^0,\ CP=-1)\right\rangle}{\langle|\mathcal{A}_L(\pi^+\pi^-\pi^0)|^2\rangle}.\end{aligned} \tag{2.11}$$

The experimental bounds on η_{+-0} reported by CPLEAR [10] correspond to this average, when neglecting the contribution of $\mathcal{A}_L(\pi^+\pi^-\pi^0,\ CP=+1)$. This is indeed a good approximation, because the K_L decay amplitude to a $CP=+1$ $\pi^+\pi^-\pi^0$ state is suppressed both by CP violation and a centrifugal barrier. Given the poor direct experimental information on η_{000}, in the neutral case it turns out to be more convenient to set a bound on $|\alpha_{\pi^0\pi^0\pi^0}|$ by means of the relation

$$|\alpha_{\pi^0\pi^0\pi^0}|^2 = \frac{\tau_{K_S}}{\tau_{K_L}}\,\mathrm{BR}(K_L \to 3\pi^0) \times \mathrm{BR}(K_S \to 3\pi^0)\ . \tag{2.12}$$

This relation is based on the well-justified assumption that the K_L (K_S) decays to $3\pi^0$ are dominated by a single CP conserving (violating) amplitude with the same behaviour over phase space [11].

2.3 Semileptonic modes

In the case of semileptonic channels, the standard decomposition is [12]

$$\begin{aligned}\mathcal{A}(K^0 \to \pi^- l^+\nu) &= \mathcal{A}_0(1-y)\,,\\ \mathcal{A}(K^0 \to \pi^+ l^-\nu) &= \mathcal{A}_0^*(1+y^*)(x_+ - x_-)^*\,,\\ \mathcal{A}(\overline{K}^0 \to \pi^+ l^-\nu) &= \mathcal{A}_0^*(1+y^*)\,,\\ \mathcal{A}(\overline{K}^0 \to \pi^- l^+\nu) &= \mathcal{A}_0(1-y)(x_+ + x_-)\,,\end{aligned} \tag{2.13}$$

where x_+ (x_-) describes the violation of the $\Delta S = \Delta Q$ rule in CPT conserving (violating) decay amplitudes, and y parametrizes CPT violation for $\Delta S = \Delta Q$ transitions. Assuming

JHEP12(2006)011

lepton universality, and expanding to the first non-trivial order in the small CP- and CPT-violating parameters, one obtains

$$\begin{aligned}\sum_{\pi\ell\nu}\langle\mathcal{A}_L(\pi\ell\nu)\mathcal{A}_S^*(\pi\ell\nu)\rangle &= 2\Gamma(K_L\to\pi\ell\nu)\big(\mathrm{Re}(\epsilon)-\mathrm{Re}(y)-i(\mathrm{Im}(x_+)+\mathrm{Im}(\delta))\big)\\ &= 2\Gamma(K_L\to\pi\ell\nu)\big((A_S+A_L)/4-i(\mathrm{Im}(x_+)+\mathrm{Im}(\delta))\big)\,. \end{aligned}\tag{2.14}$$

The dependence of $\mathrm{Re}(y)$ has been eliminated by taking advantage of the relation $\mathrm{Re}(\epsilon)-\mathrm{Re}(y)=(A_S+A_L)/4$ [12], where $A_{L,S}$ are the observable semileptonic charge asymmetries. The parameter $\mathrm{Im}(x_+)$ can be measured using the appropriate time-dependent decay distributions [13], while $\mathrm{Im}(\delta)$ is one of the two outputs of the BSR. In order to get rid of the explicit $\mathrm{Im}(\delta)$ dependence, it is convenient to define

$$\begin{aligned}\alpha_{\pi\ell\nu} &\equiv \frac{1}{\Gamma_S}\sum_{\pi\ell\nu}\langle\mathcal{A}_L(\pi\ell\nu)\mathcal{A}_S^*(\pi\ell\nu)\rangle + 2i\frac{\tau_{K_S}}{\tau_{K_L}}\,\mathrm{BR}(K_L\to\pi\ell\nu)\mathrm{Im}(\delta)\\ &= 2\frac{\tau_{K_S}}{\tau_{K_L}}\,\mathrm{BR}(K_L\to\pi\ell\nu)\big((A_S+A_L)/4-i\mathrm{Im}(x_+)\big)\ . \end{aligned}\tag{2.15}$$

2.4 Determination of $\mathrm{Re}(\epsilon)$ and $\mathrm{Im}(\delta)$

The α_i parameters defined in eqs. (2.7), (2.8), (2.10), and (2.15) can be determined (or bounded) in terms of measurable quantities. Taking into account these definitions (in particular the non-standard expression for $\alpha_{\pi\ell\nu}$), the solution to the unitarity relation in eq. (2.6) is

$$\begin{pmatrix}\dfrac{\mathrm{Re}(\epsilon)}{1+|\epsilon|^2}\\ \mathrm{Im}(\delta)\end{pmatrix} = \frac{1}{N}\begin{pmatrix}1+\kappa(1-2b) & (1-\kappa)\tan\phi_{\mathrm{SW}}\\ (1-\kappa)\tan\phi_{\mathrm{SW}} & -(1+\kappa)\end{pmatrix}\begin{pmatrix}\Sigma_i\mathrm{Re}(\alpha_i)\\ \Sigma_i\mathrm{Im}(\alpha_i)\end{pmatrix},\tag{2.16}$$

where $\kappa=\tau_{K_S}/\tau_{K_L}$, $b=\mathrm{BR}(K_L\to\pi\ell\nu)$, and

$$N=(1+\kappa)^2+(1-\kappa)^2\tan^2\phi_{\mathrm{SW}}-2\,b\,\kappa(1+\kappa)\ .\tag{2.17}$$

3. Experimental input to the α parameters

The experimental inputs needed for the determination of the α_i are the K_L and K_S branching ratios, the amplitude ratios η_i, and the K_L and K_S lifetimes. All experimental inputs used in the determination of the decay amplitudes are summarized in table 1. For the determination of the neutral kaon decay rates and the K_L lifetime we combine the measurements listed below.

1. The absolute K_L BR's from KLOE [21];
2. The KLOE K_L lifetime [20];
3. The KLOE ratio $\mathrm{BR}(K_L\to\pi^+\pi^-)/\mathrm{BR}(K_L\to\pi\mu\nu)$ [4]. This result is inclusive of final state radiation, therefore the DE contribution in the process $K_L{\to}\pi^+\pi^-$ is subtracted using the result from ref. [18];

	Value	Source
τ_{K_S}	0.08958 ± 0.00005 ns	PDG [14]
τ_{K_L}	50.84 ± 0.23 ns	KLOE average
$m_L - m_S$	$(5.290 \pm 0.016) \times 10^9$ s^{-1}	PDG [14]
BR($K_S \to \pi^+\pi^-$)	0.69186 ± 0.00051	KLOE average
BR($K_S \to \pi^0\pi^0$)	0.30687 ± 0.00051	KLOE average
BR($K_S \to \pi\ell\nu$)	$(11.77 \pm 0.15) \times 10^{-4}$	KLOE [6]
BR($K_L \to \pi^+\pi^-$)	$(1.933 \pm 0.021) \times 10^{-3}$	KLOE average
BR($K_L \to \pi^0\pi^0$)	$(0.848 \pm 0.010) \times 10^{-3}$	KLOE average
ϕ_{+-}	$(43.4 \pm 0.7)^\circ$	PDG [14]
ϕ_{00}	$(43.7 \pm 0.8)^\circ$	PDG [14]
$R_{S,\gamma}$ ($E_\gamma > 20$MeV)	$(0.710 \pm 0.016) \times 10^{-2}$	E731 [18]
$R_{S,\gamma}^{\mathrm{th-IB}}$ ($E_\gamma > 20$MeV)	$(0.700 \pm 0.001) \times 10^{-2}$	KLOE MC [19]
$\lvert\eta_{+-\gamma}\rvert$	$(2.359 \pm 0.074) \times 10^{-3}$	E773 [17]
$\phi_{+-\gamma}$	$(43.8 \pm 4.0)^\circ$	E773 [17]
BR($K_L \to \pi^+\pi^-\pi^0$)	0.1262 ± 0.0011	KLOE average
η_{+-0}	$\big((-2 \pm 7) + i(-2 \pm 9)\big) \times 10^{-3}$	CPLEAR [10]
BR($K_L \to 3\pi^0$)	0.1996 ± 0.0021	KLOE average
BR($K_S \to 3\pi^0$)	$< 1.5 \times 10^{-7}$ at 95% CL	KLOE [5]
ϕ_{000}	uniform from 0 to 2π	
BR($K_L \to \pi\ell\nu$)	0.6709 ± 0.0017	KLOE average
$A_L + A_S$	$(0.5 \pm 1.0) \times 10^{-2}$	$K_{\ell 3}$ average
Im(x_+)	$(0.8 \pm 0.7) \times 10^{-2}$	$K_{\ell 3}$ average

Table 1: Input values to the Bell-Steinberger relation. Results from [14] are those evaluated without assuming CPT invariance. The KLOE average and the $K_{\ell 3}$ average are described in section 3 and section 3.3, respectively.

4. The precise KLOE determination of $R_S = \mathrm{BR}(K_S \to \pi^+\pi^-)/\mathrm{BR}(K_S \to \pi^0\pi^0)$ [16], and the value of R_S/R_L from the world average of $Re(\epsilon'/\epsilon)$ [14], with $R_L = \mathrm{BR}(K_L \to \pi^+\pi^-)/\mathrm{BR}(K_L \to \pi^0\pi^0)$. These measurements are used to determine the value of $\mathrm{BR}(K_L \to \pi^0\pi^0)$.

The combination of all of the above listed measurements, referred to as the KLOE average, accounts for all correlation effects, and is obtained by renormalizing the sum of K_L branching ratios to $1 - \mathrm{BR}(K_L \to \gamma\gamma)$. This procedure yields very small corrections to the published BR values [21]. The results with errors and correlation coefficients are given in table 2.

For the K_S lifetime we use the average $\tau_{K_S} = 0.08958 \pm 0.00006$ ns [14] obtained without assuming CPT invariance.

JHEP12(2006)011

	Value	Correlation coefficients							
$\mathrm{BR}(K_L\to\pi^\pm e^\mp\nu)$	0.4009(15)	1							
$\mathrm{BR}(K_L\to\pi^\pm\mu^\mp\nu)$	0.2700(14)	-0.31	1						
$\mathrm{BR}(K_L\to\pi^+\pi^-\pi^0)$	0.1262(11)	-0.01	-0.14	1					
$\mathrm{BR}(K_L\to\pi^0\pi^0\pi^0)$	0.1996(20)	-0.54	-0.41	-0.47	1				
$\mathrm{BR}(K_L\to\pi^+\pi^-)$	$1.933(21)\times10^{-3}$	-0.15	0.50	-0.06	-0.23	1			
$\mathrm{BR}(K_L\to\pi^0\pi^0)$	$8.48(10)\times10^{-4}$	-0.14	0.49	-0.06	-0.23	0.97	1		
τ_{K_L} (ns)	50.84(23)	0.16	0.21	-0.26	-0.13	0.07	0.06	1	
R_S	2.2549(54)	0.00	0.00	0.00	0.00	0.00	-0.21	0.00	1

Table 2: Values, errors, and correlation coefficients for all parameters included in the KLOE average: the dominant K_L BR's, K_L lifetime and R_S.

3.1 Two-pion modes

The $\pi\pi(\gamma)$ terms are the largest. The value of $\alpha_{\pi\pi}$ of eq. (2.7) is evaluated as:

$$\alpha_{\pi\pi} = \left(\frac{\tau_{K_S}}{\tau_{K_L}} \times \mathrm{BR}(K_L \to \pi\pi) \times \mathrm{BR}(K_S \to \pi\pi)\right)^{1/2} e^{i\phi_{\pi\pi}} .$$

The values of $\mathrm{BR}(K_S\to\pi^+\pi^-)$ and $\mathrm{BR}(K_S\to\pi^0\pi^0)$, given in table 1, are determined from R_S using the constraint $\mathrm{BR}(K_S \to \pi^+\pi^-) + \mathrm{BR}(K_S \to \pi^0\pi^0) + \mathrm{BR}(K_S \to \pi\ell\nu) = 1$; the value of $\mathrm{BR}(K_S \to \pi\ell\nu)$ is determined from the KLOE measurement of $\mathrm{BR}(K_S \to \pi e\nu)$ [6] assuming lepton universality. For $\mathrm{BR}(K_L \to \pi^+\pi^-)$ and $\mathrm{BR}(K_L \to \pi^0\pi^0)$, we use the values from the KLOE average, which are in agreement with recent measurements from KTeV [15]. Finally, the values of ϕ_{+-} and ϕ_{00}, the phases of η_{+-} and η_{00}, are taken from the PDG fit [14] without assuming CPT invariance.

Figure 1 shows the 68% and the 95% CL contours for $\alpha_{\pi^+\pi^-}$ and $\alpha_{\pi^0\pi^0}$. We find:

$$\begin{aligned} \alpha_{\pi^+\pi^-} &= \big((1.115 \pm 0.015) + i(1.055 \pm 0.015)\big) \times 10^{-3} , \\ \alpha_{\pi^0\pi^0} &= \big((0.489 \pm 0.007) + i(0.468 \pm 0.007)\big) \times 10^{-3} . \end{aligned}$$

Following the discussion in section 2.1, we determine $\alpha_{\pi^+\pi^-\gamma_{\mathrm{DE}}}$ from the measurement of $\eta_{+-\gamma}$ from ref. [17] and $\mathrm{BR}(K_S \to \pi^+\pi^-\gamma)$ from the measurement of $R_{S,\gamma} = \mathrm{BR}(K_S \to \pi^+\pi^-\gamma)/\mathrm{BR}(K_S \to \pi^+\pi^-)$ [18]. The photon energy threshold was 20 MeV for both measurements. The value of $R_{S,\gamma}^{\mathrm{th-IB}} = \big(\mathrm{BR}(K_S \to \pi\pi\gamma)/\mathrm{BR}(K_S \to \pi\pi)\big)^{\mathrm{th-IB}} = (0.700 \pm 0.001) \times 10^{-2}$ is calculated using the KLOE MC generator, which is described in ref. [19]. Figure 2(a) shows the 68% and the 95% CL contours for $\alpha_{\pi^+\pi^-\gamma_{DE}}$. We find a very small contribution:

$$\alpha_{\pi^+\pi^-\gamma_{DE}} = \big((5 \pm 7) + i(6 \pm 7)\big) \times 10^{-7} .$$

3.2 Three-pion modes

Until the recent results from KLOE [5] and NA48 [8] became available, the limiting contribution to the CPT test was due to the $3\pi^0$ final state. The upper limit on $|\alpha_{\pi^0\pi^0\pi^0}|$ is

JHEP12(2006)011

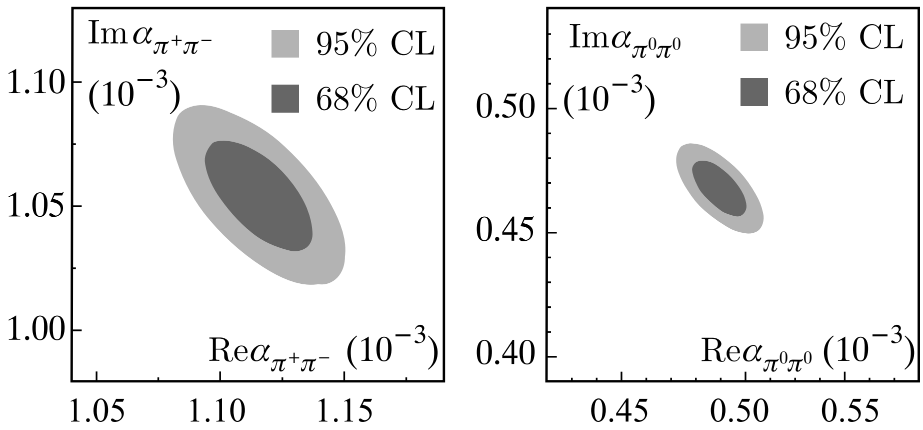

Figure 1: Representation of $\alpha_{\pi^+\pi^-}$ and $\alpha_{\pi^0\pi^0}$ in the complex plane. In each case, the two ellipses represent the 68% and the 95% CL contours.

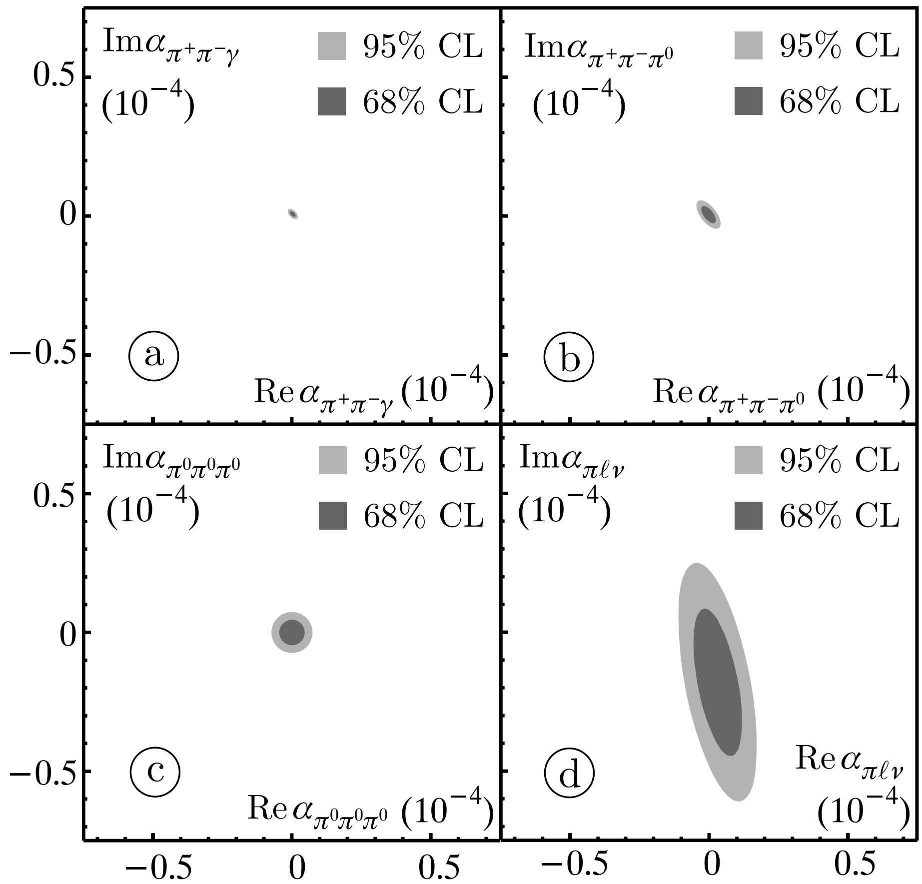

Figure 2: Bounds of the α values for three-body decays of K_S, K_L. Note that the same scale is used for all plots.

evaluated from eq. (2.12) using the KLOE upper limit $\mathrm{BR}(K_S \to 3\pi^0) < 1.5 \times 10^{-7}$ at 95%

	value	Correlation coefficients			
$\mathrm{Re}(\delta)$	$(3.0 \pm 3.4) \times 10^{-4}$	1			
$\mathrm{Im}(\delta)$	$(-1.5 \pm 2.3) \times 10^{-2}$	0.44	1		
$\mathrm{Re}(x_-)$	$(0.2 \pm 1.3) \times 10^{-2}$	-0.56	-0.97	1	
$\mathrm{Im}(x_+)$	$(1.2 \pm 2.2) \times 10^{-2}$	-0.60	-0.91	0.96	1

Table 3: Values, errors, and correlation coefficients for $\mathrm{Re}(\delta)$, $\mathrm{Im}(\delta)$, $\mathrm{Re}(x_-)$, and $\mathrm{Im}(x_+)$ measured by CPLEAR.

	value	Correlation coefficients				
$\mathrm{Re}(\delta)$	$(3.4 \pm 2.8) \times 10^{-4}$	1				
$\mathrm{Im}(\delta)$	$(-1.0 \pm 0.7) \times 10^{-2}$	-0.27	1			
$\mathrm{Re}(x_-)$	$(-0.07 \pm 0.25) \times 10^{-2}$	-0.23	-0.58	1		
$\mathrm{Im}(x_+)$	$(0.8 \pm 0.7) \times 10^{-2}$	-0.35	-0.12	0.57	1	
$A_S + A_L$	$(0.5 \pm 1.0) \times 10^{-2}$	-0.12	-0.62	0.99	0.54	1

Table 4: Values, errors, and correlation coefficients for $\mathrm{Re}(\delta)$, $\mathrm{Im}(\delta)$, $\mathrm{Re}(x_-)$, $\mathrm{Im}(x_+)$, and $A_S + A_L$ obtained from a combined fit ($K_{\ell 3}$ average).

CL [5] and the value of $\mathrm{BR}(K_L \to 3\pi^0)$ from the KLOE average. The phase ϕ_{000} is taken as uniform in $\{0, 2\pi\}$. For $\alpha_{\pi^+\pi^-\pi^0}$, eq. (2.10), we use $\mathrm{Re}(\eta_{+-0})$ and $\mathrm{Im}(\eta_{+-0})$ as measured by CPLEAR [10] and the value of $\mathrm{BR}(K_L \to \pi^+\pi^-\pi^0)$ from the KLOE average, all given in table 1.

The 68% and the 95% CL contours for $\alpha_{\pi^+\pi^-\pi^0}$, and the 95% CL contour for $\alpha_{\pi^0\pi^0\pi^0}$ are shown in figures 2(b) and 2(c), respectively. We find:

$$
\begin{aligned}
\alpha_{\pi^+\pi^-\pi^0} &= \big((0 \pm 2) + i(0 \pm 2)\big) \times 10^{-6}, \\
|\alpha_{\pi^0\pi^0\pi^0}| &< 7 \times 10^{-6} \quad \text{at } 95\% \text{ CL}.
\end{aligned}
$$

3.3 Semileptonic modes

For the determination of $\alpha_{\pi\ell\nu}$ from eq. (2.15), we combine the KLOE measurement [6] of the K_S semileptonic charge asymmetry A_S for K_S semileptonic decays, the PDG average [14] for K_L semileptonic charge asymmetry A_L, and the CPLEAR time-dependent measurement of $K^0$and $\overline{K}^0$ semileptonic rates [13]. The original CPLEAR result is given in table 3.

We have improved this result by adding the measurement of $A_S - A_L = 4[\mathrm{Re}(\delta) + \mathrm{Re}(x_-)] = (-2 \pm 10) \times 10^{-3}$ [6, 14]. The results, referred to as the $K_{\ell 3}$ average, are given in table 4. Finally, for $\mathrm{BR}(K_L \to \pi\ell\nu)$ we use the sum of K_{e3} and $K_{\mu 3}$ branching ratios from the KLOE average. Figure 2(d) shows the 68% and the 95% CL contours for $\alpha_{\pi\ell\nu}$. We find:

$$
\alpha_{\pi\ell\nu} = \big((0.3 \pm 0.6) + i(-1.8 \pm 1.8)\big) \times 10^{-5}\,.
$$

JHEP12(2006)011

	value	Correlation coefficients			
Re(ϵ)	$(159.6 \pm 1.3) \times 10^{-5}$	1			
Im(δ)	$(0.4 \pm 2.1) \times 10^{-5}$	-0.17	1		
Re(δ)	$(2.3 \pm 2.7) \times 10^{-4}$	0.20	-0.22	1	
Re(x_-)	$(-2.9 \pm 2.0) \times 10^{-3}$	-0.25	0.37	-0.49	1

Table 5: Summary of results: values, errors, and correlation coefficients for Re(ϵ), Im(δ), Re(δ), and Re(x_-).

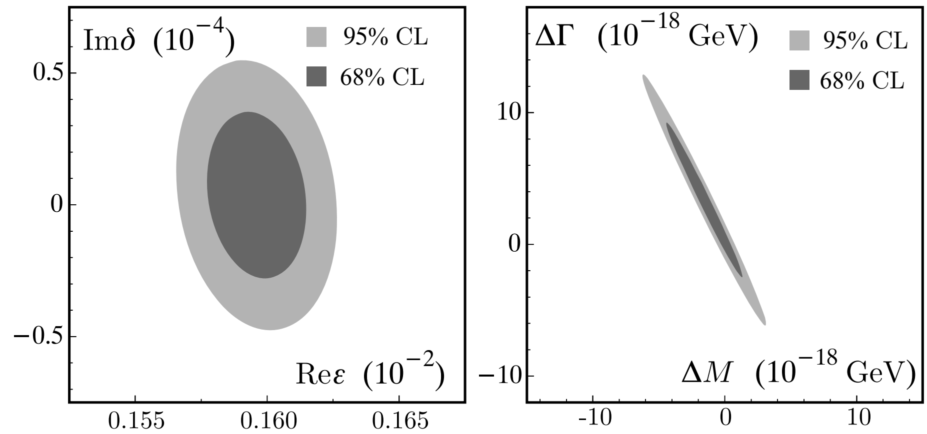

Figure 3: Left: allowed region at 68% and 95% CL in the Re(ϵ), Im(δ) plane. Right: allowed region at 68% and 95% CL in the $\Delta M, \Delta\Gamma$ plane.

4. Results

Inserting the values of the α parameters into eq. (2.16), we obtain:[2]

$$\mathrm{Re}(\epsilon) = (159.6 \pm 1.3) \times 10^{-5}, \qquad \mathrm{Im}(\delta) = (0.4 \pm 2.1) \times 10^{-5}\,, \tag{4.1}$$

where all correlations among the input data are taken into account, including that from the direct determination of Im(δ) from the semileptonic decays. The complete information is given in table 5.

The allowed region in the Re(ϵ), Im(δ) plane at 68% CL and 95% CL is shown in the left panel of figure 3. A small correlation between Re(ϵ) and Im(δ) is evident, which is due to the semileptonic term. With the new KLOE data used in the present analysis, the process giving the largest contribution to the size of the allowed region is now $K_L \to \pi^+\pi^-$, through the uncertainty on ϕ_{+-}. Besides the $\pi\pi$ final states, only the semileptonic term gives an appreciable contribution ($\sim 10\%$) to the error on Im(δ). Our results, eq. 4.1, are a significant improvement over those of CPLEAR [7]:

$$\mathrm{Re}(\epsilon) = (164.9 \pm 2.5) \times 10^{-5}, \qquad \mathrm{Im}(\delta) = (2.4 \pm 5.0) \times 10^{-5}.$$

[2]The accuracy on Re(ϵ) improves by about 30% with inclusion of the KTeV measurement of BR($K_L \to \pi^+\pi^-$) [15].

Note also that the central value of $\mathrm{Re}(\epsilon)$ is quite different: this is due to the new measurement of $\mathrm{BR}(K_L\to\pi^+\pi^-)$ [4]. The accuracy on $\mathrm{Im}(\delta)$ is comparable with that reported in ref. [8] and in the PDG compilation [14]. However, we stress that the BSR analysis of ref. [8] is questionable: some of the results of the CPLEAR fit [7], which used the unitarity constraint, have been used as input to a different unitarity test (with partially updated input values).

The limits on $\mathrm{Im}(\delta)$ and $\mathrm{Re}(\delta)$ can be used to constrain the mass and width difference between K^0 and $\overline{K}^0$ via

$$\delta = \frac{i(m_{K^0} - m_{\overline{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\overline{K}^0})}{\Gamma_S - \Gamma_L} \cos\phi_{\mathrm{SW}} e^{i\phi_{\mathrm{SW}}} [1 + \mathcal{O}(\epsilon)] \,.$$

The allowed region in the $\Delta M = (m_{K^0} - m_{\overline{K}^0}), \Delta\Gamma = (\Gamma_{K^0} - \Gamma_{\overline{K}^0})$ plane is shown in the right panel of figure 3. The strong correlation reflects the high precision of $\mathrm{Im}(\delta)$ compared to $\mathrm{Re}(\delta)$. Since the total decay widths are dominated by long-distance dynamics, in models where CPT invariance is a pure short-distance phenomenon, it is useful to consider the limit $\Gamma_{K^0} = \Gamma_{\overline{K}^0}$. In this limit (i.e. neglecting CPT-violating effects in the decay amplitudes), we obtain the following bound on the neutral kaon mass difference:

$$-5.3 \times 10^{-19}\ \mathrm{GeV} < m_{K^0} - m_{\overline{K}^0} < 6.3 \times 10^{-19}\ \mathrm{GeV} \quad \text{at 95 \% CL} \,.$$

Our result represents a significant improvement with respect to $|m_{K^0} - m_{\overline{K}^0}| < 12.7 \times 10^{-19}$ GeV at 90% CL, obtained by CPLEAR [10].

Acknowledgments

This work was supported in part by DOE grant DE-FG-02-97ER41027; by the E.U. contract MRTN-CT-2006-035482 "FLAVIAnet"; by the German Federal Ministry of Education and Research (BMBF) contract 06-KA-957; by Graduiertenkolleg 'H.E. Phys. and Part. Astrophys.' of Deutsche Forschungsgemeinschaft, Contract No. GK 742; by INTAS, contracts 96-624, 99-37; by TARI, contract HPRI-CT-1999-00088.

A. The $\pi\pi\gamma$ contribution to the α_i

By construction, the leading contribution of the $\pi\pi\gamma$ state to the unitarity sum, namely the interference of the K_L and K_S bremsstrahlung amplitudes, is included in $\alpha_{+-(\gamma)}$. The largest sub-leading term missing in $\alpha_{+-(\gamma)}$ is the DE-bremsstrahlung interference, which we include in $\alpha_{\pi\pi\gamma_{\mathrm{E1-S(L)}}}$ of eq. (2.8). To evaluate this contribution, we introduce the total (IB+DE) amplitude ratio

$$\eta_{+-\gamma}(E_\gamma) = \frac{\mathcal{A}_L(\pi\pi\gamma_{\mathrm{IB+E1}})}{\mathcal{A}_S(\pi\pi\gamma_{\mathrm{IB+E1}})} = \eta_{+-} + \epsilon'_{+-\gamma}(E_\gamma) \tag{A.1}$$

This ratio is an observable quantity which can be measured in an interference experiment [17]. As explicitly indicated, $\eta_{+-\gamma}$ depends on the photon energy and it can be decomposed into the energy-independent parameter η_{+-} and the direct-CP-violating term $\epsilon'_{+-\gamma}$. In the $E_\gamma \to 0$ limit $\epsilon'_{+-\gamma} \propto E_\gamma^2$ [11]. Using eq. (A.1), we can write

$$
\begin{aligned}
\frac{1}{\Gamma_S}\langle \mathcal{A}_L(\pi\pi\gamma)\mathcal{A}^*_S(\pi\pi\gamma_{\rm E1}) + &\mathcal{A}_L(\pi\pi\gamma_{\rm E1})\mathcal{A}^*_S(\pi\pi\gamma)\rangle = \\
&= \frac{1}{\Gamma_S}\left\langle\, \eta_{+-}\ \left(\mathcal{A}_S(\pi\pi\gamma)\mathcal{A}^*_S(\pi\pi\gamma_{\rm E1}) + \mathcal{A}_S(\pi\pi\gamma_{\rm E1})\mathcal{A}^*_S(\pi\pi\gamma)\right) + \right. \\
&\qquad \left. + \epsilon'_{+-\gamma}\mathcal{A}_S(\pi\pi\gamma)\mathcal{A}^*_S(\pi\pi\gamma)(1+\delta_{\rm E1})\right\rangle \\
&\approx \eta_{+-}\Delta B(K_S \to \pi\pi\gamma_{\rm DE}) + \frac{1}{\Gamma_S}\int dE_\gamma \epsilon'_{+-\gamma}\frac{d\Gamma(K_S\to\pi\pi\gamma)}{dE_\gamma}
\end{aligned}
\tag{A.2}
$$

where $\delta_{\rm E1} = \mathcal{A}_S(\pi\pi\gamma_{\rm E1})/\mathcal{A}_S(\pi\pi\gamma)$ is a very small overall correction factor which can be safely neglected and $\Delta B(K_S \to \pi\pi\gamma_{\rm DE}) = {\rm BR}(K_S \to \pi\pi\gamma)^{\rm exp} - {\rm BR}(K_S \to \pi\pi\gamma)^{\rm th-IB}$ is the deviation of the observed $K_S \to \pi\pi\gamma$ decay rate from that inferred from a pure bremsstrahlung spectrum. By construction, the integral on the right-hand side of eq. (A.2) is infrared safe. Since at present there is no evidence for a non-vanishing ${\epsilon'}_{+-\gamma}$ [17], in eq. (2.9) we replace this integral with the product $(\eta_{+-\gamma} - \eta_{+-}) \times {\rm BR}(K_S \to \pi\pi\gamma)$, where ${\rm BR}(K_S \to \pi\pi\gamma)$ indicates the branching fraction for a real photon emission with minimum photon-energy cut equivalent to that used in the corresponding $\eta_{+-\gamma}$ measurement ($E_\gamma^{\rm cut} =$ 20 MeV in ref. [17]). The contribution to eq. (A.2) generated by $K_{L,S} \to \pi\pi\gamma$ amplitudes with $E_\gamma < E_\gamma^{\rm cut}$ vanishes in the limit $E_\gamma^{\rm cut} \to 0$ and can be safely neglected.

References

[1] G. Lueders, *Proof of the TCP theorem*, *Ann. Phys. (NY)* **2** (1957) 1 *reprinted in Ann. Phys. (NY)* **281** (2000) 1004.

[2] See e.g. J. Bernabeu, J. Ellis, N.E. Mavromatos, D.V. Nanopoulos and J. Papavassiliou, *CPT and quantum mechanics tests with KAONS*, hep-ph/0607322;
V.A. Kostelecky and R. Lehnert, *Stability, causality and Lorentz and CPT violation*, *Phys. Rev.* **D 63** (2001) 065008 [hep-th/0012060] and references therein.

[3] J.S. Bell and J. Steinberger, *Proceedings Oxford Int. Conf. on Elementary Particles* (1965).

[4] KLOE collaboration, F. Ambrosino *et al.*, *Measurement of the branching ratio of the $K_L \to \pi^+\pi^-$ decay with the KLOE detector*, *Phys. Lett.* **B 638** (2006) 140 [hep-ex/0603041].

[5] KLOE collaboration, F. Ambrosino *et al.*, *A direct search for the CP-violating decay $K_S \to 3\pi^0$ with the kloe detector at DAPHNE*, *Phys. Lett.* **B 619** (2005) 61 [hep-ex/0505012].

[6] KLOE collaboration, F. Ambrosino *et al.*, *Measurement of the branching fraction and charge asymmetry for the decay $K_S \to \pi e\nu$ with the KLOE detector*, *Phys. Lett.* **B 636** (2006) 173 [hep-ex/0601026].

[7] CPLEAR collaboration, A. Apostolakis *et al.*, *Determination of the T- and CPT-violation parameters in the neutral kaon system using the Bell-Steinberger relation and data from CPLEAR*, *Phys. Lett.* **B 456** (1999) 297.

[8] NA48 collaboration, A. Lai *et al.*, *Search for CP-violation in $K^0 \to 3\pi^0$ decays*, *Phys. Lett.* **B 610** (2005) 165 [hep-ex/0408053].

[9] V. Weisskopf and E.P. Wigner, *Calculation of the natural brightness of spectral lines on the basis of Dirac's theory*, *Z. Phys.* **63** (1930) 54–73;
T.D. Lee, R. Oehme and C.N. Yang, *Remarks on possible noninvariance under time reversal and charge conjugation*, *Phys. Rev.* **106** (1957) 340.

[10] CPLEAR collaboration, A. Angelopoulos *et al.*, *Physics at CPLEAR*, *Phys. Rept.* **374** (2003) 165.

[11] G. D'Ambrosio and G. Isidori, *CP-violation in KAON decays*, *Int. J. Mod. Phys.* **A 13** (1998) 1 [hep-ph/9611284].

[12] L. Maiani, G. Pancheri and N. Paver, *The Second DAΦNE Physics Handbook* (Frascati, 1995).

[13] CPLEAR collaboration, A. Angelopoulos *et al.*, *T-violation and CPT-invariance measurements in the CPLEAR experiment: a detailed description of the analysis of neutral-kaon decays to $e\pi\nu$*, *Eur. Phys. J.* **C 22** (2001) 55.

[14] Particle Data Group, W.-M. Yao et al., *Review of particle physics J. Phys.* **G 33** (2006) 1.

[15] KTeV collaboration, T. Alexopoulos *et al.*, *Measurements of K_L branching fractions and the CP-violation parameter $|\eta_\pm|$*, *Phys. Rev.* **D 70** (2004) 092006 [hep-ex/0406002].

[16] KLOE collaboration, F. Ambrosino *et al.*, *Precise measurement of $\Gamma(K_s \to \pi^+\pi^-\gamma)/\Gamma(K_s \to \pi^0\pi^0)$ with the KLOE detector at DAFNE*, hep-ex/0601025.

[17] J.N. Matthews et al., *Phys. Rev. Lett.* **75** (1995) 2806.

[18] E731 collaboration, E.J. Ramberg *et al.*, *Simultaneous measurement of K_S and K_L decays into $\pi^+\pi^-\gamma$*, *Phys. Rev. Lett.* **70** (1993) 2525.

[19] C. Gatti, *Monte carlo simulation for radiative KAON decays*, *Eur. Phys. J.* **C 45** (2006) 417 [hep-ph/0507280] and references therein.

[20] KLOE collaboration, F. Ambrosino *et al.*, *Measurement of the K_L meson lifetime with the KLOE detector*, *Phys. Lett.* **B 626** (2005) 15 [hep-ex/0507088].

[21] KLOE collaboration, F. Ambrosino *et al.*, *Measurements of the absolute branching ratios for the dominant K_L decays, the K_L lifetime and V_{us} with the KLOE detector*, *Phys. Lett.* **B 632** (2006) 43 [hep-ex/0508027].

JHEP12(2006)011