\[
I(j^P) = \frac{1}{2}(0^{-})
\]

**K^0 MASS**

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>497.648±0.022 OUR FIT</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>497.648±0.022 OUR AVERAGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>497.625±0.001±0.031 655k</td>
<td>LAI</td>
<td>02 NA48</td>
<td>K^0_L beam</td>
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<tr>
<td>497.661±0.033 3713</td>
<td>BARKOV</td>
<td>87B CMD</td>
<td>e^+ e^- → K^0 L K^0 S</td>
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<tr>
<td>497.742±0.085 780</td>
<td>BARKOV</td>
<td>85B CMD</td>
<td>e^+ e^- → K^0 L K^0 S</td>
<td></td>
</tr>
</tbody>
</table>

• • • We do not use the following data for averages, fits, limits, etc. • • •

| 497.44 ±0.50 | FITCH | 67 OSPK |
| 498.9 ±0.5 | BALTAY | 66 HBC | K^0 from pp |
| 497.44 ±0.33 2223 | KIM | 65B HBC | K^0 from pp |
| 498.1 ±0.4 | CHRISTENS... | 64 OSPK |

\[ m_{K^0} - m_{K^±} \]

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
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<th>DOCUMENT ID</th>
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<td></td>
<td></td>
<td></td>
<td>Error includes scale factor of 1.2.</td>
</tr>
</tbody>
</table>

• • • We do not use the following data for averages, fits, limits, etc. • • •

| 3.95 ±0.21 417 | HILL | 68B DBC | + | K^+ d → K^0 pp |
| 3.90 ±0.25 9 | BURNSTEIN | 65 HBC | | |
| 3.71 ±0.35 7 | KIM | 65B HBC | − | K^- p → nK^0 |
| 5.4 ±1.1 | CRAWFORD | 59 HBC | + | |
| 3.9 ±0.6 | ROSENFELD | 59 HBC | | |

**K^0 MEAN SQUARE CHARGE RADIUS**

<table>
<thead>
<tr>
<th>VALUE (fm^2)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
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<tr>
<td>−0.077±0.010 OUR AVERAGE</td>
<td></td>
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<tr>
<td>−0.077±0.007±0.011 5037</td>
<td>ABOUZAID</td>
<td>06 KTEV</td>
<td>K^0 → π^+ π^- e^+ e^-</td>
<td></td>
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<tr>
<td>−0.090±0.021</td>
<td>LAI</td>
<td>03C NA48</td>
<td>K^0_L → π^+ π^- e^+ e^-</td>
<td></td>
</tr>
<tr>
<td>−0.054±0.026</td>
<td>MOLZON</td>
<td>78</td>
<td>K_S regen. by electrons</td>
<td></td>
</tr>
</tbody>
</table>

• • • We do not use the following data for averages, fits, limits, etc. • • •

| −0.087±0.046 | BLATNIK | 79 | VMD + dispersion relations |
| −0.050±0.130 | FOETH | 69B | K_S regen. by electrons |

**T-VIOLATION PARAMETER IN K^0-\bar{K^0} MIXING**

The asymmetry \( A_T = \frac{\Gamma(\bar{K}^0 \rightarrow K^0) - \Gamma(K^0 \rightarrow \bar{K}^0)}{\Gamma(K^0 \rightarrow \bar{K}^0) + \Gamma(K^0 \rightarrow \bar{K}^0)} \) must vanish if \( T \) invariance holds.

**ASYMMETRY A_T IN K^0-\bar{K^0} MIXING**

<table>
<thead>
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<th>VALUE (units x 10^{-3})</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
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<tr>
<td>6.6±1.3±1.0</td>
<td>640k</td>
<td>1 ANGELOPO...</td>
<td>98 CPLR</td>
<td></td>
</tr>
</tbody>
</table>

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ANGELOPOULOS 98

measures the asymmetry
$$A_T = \frac{\Gamma(K^0_{t=0} \rightarrow e^+ \pi^- \nu_{t=\tau}) - \Gamma(K^0_{t=0} \rightarrow e^- \pi^+ \nu_{t=\tau})}{\Gamma(K^0_{t=0} \rightarrow e^+ \pi^- \nu_{t=\tau}) + \Gamma(K^0_{t=0} \rightarrow e^- \pi^+ \nu_{t=\tau})}$$
as a function of the neutral-kaon eigentime $\tau$. The initial strangeness of the neutral kaon is tagged by the charge of the accompanying charged kaon in the reactions $p p \rightarrow K^- \pi^+ + K^0$ and $p p \rightarrow K^+ \pi^− + \overline{K}^0$. The strangeness at the time of the decay is tagged by the lepton charge. The reported result is the average value of $A_T$ over the interval $1 \tau_s < \tau < 20 \tau_s$. From this value of $A_T$ ANGELOPOULOS 01B, assuming $CPT$ invariance in the $e \pi \nu$ decay amplitude, determine the $T$-violating as $\Delta S - \Delta S$ conserving parameter (for its definition, see Review below) $4 \text{Re}(\epsilon) = (6.2 \pm 1.4 \pm 1.0) \times 10^{-3}$.

CPT INVARIANCE TESTS IN NEUTRAL KAON DECAY


The time evolution of a neutral kaon state is described by
$$\frac{d}{dt} \Psi = -i\Lambda \Psi , \quad \Lambda \equiv M - \frac{i}{2} \Gamma \quad (1)$$
where $M$ and $\Gamma$ are Hermitian $2 \times 2$ matrices known as the mass and decay matrices. The corresponding eigenvalues are $\lambda_{L,S} = m_{L,S} - \frac{i}{2} \gamma_{L,S}$. $CPT$ invariance requires the diagonal elements of $\Lambda$ to be equal. The $CPT$-violation complex parameter $\delta$ is defined as
$$\delta = \frac{\Lambda_{K^0 \overline{K}^0} - \Lambda_{K^0 \overline{K}^0}}{2(\lambda_L - \lambda_S)}$$
$$= \delta_\parallel \exp(i\phi_{SW}) + \delta_\perp \exp(i(\phi_{SW} + \pi/2)) \quad (2)$$
where we have introduced the projections $\delta_\parallel$ and $\delta_\perp$ respectively parallel and perpendicular to the superweak direction $\phi_{SW} = \tan^{-1}(2\Delta m/\Delta \gamma)$, where $\Delta m = m_L - m_S$ and $\Delta \gamma = \gamma_S - \gamma_L$, the positive mass and width differences between $K_L$ and $K_S$. These projections are linked to the mass and width difference between $K^0$ and $\overline{K}^0$:
$$\delta_\parallel = \frac{1}{4} \frac{\gamma_{K^0} - \gamma_{\overline{K}^0}}{\sqrt{\Delta m^2 + \left(\frac{\Delta \gamma}{2}\right)^2}} , \quad \delta_\perp = \frac{1}{2} \frac{m_{K^0} - m_{\overline{K}^0}}{\sqrt{\Delta m^2 + \left(\frac{\Delta \gamma}{2}\right)^2}} \quad (3)$$
Re(δ) can be directly measured by studying the time evolution of the strangeness content of initially pure $K^0$ and $\bar{K}^0$ states, for example through the asymmetry

$$A_{CPT} = \frac{P[\bar{K}^0 \to K^0(t)] - P[K^0 \to \bar{K}^0(t)]}{P[\bar{K}^0 \to K^0(t)] + P[K^0 \to \bar{K}^0(t)]} = 4 \text{Re}(\delta)$$

(4)

where $P[a \to b(t)]$ is the probability that the pure initial state $a$ is seen as state $b$ at proper time $t$. This method has been used by tagging the initial strangeness with strong interactions and the final strangeness with the semileptonic decay (a more appropriate combination of semileptonic rates allows to be independent of any direct $CPT$ violation in the decay itself) and yields today’s best value of $\text{Re}(\delta)$, compatible with zero with an error of $\sim 3 \times 10^{-4}$.

As an alternative it has been proposed to compare the semileptonic charge asymmetries for $K_L$ and $K_S$

$$A_{L,S} = \frac{R(K_{L,S} \to \pi^- \ell^+ \nu) - R(K_{L,S} \to \pi^+ \ell^- \bar{\nu})}{R(K_{L,S} \to \pi^- \ell^+ \nu) + R(K_{L,S} \to \pi^+ \ell^- \bar{\nu})} ,$$

$$A_S - A_L = 4 \text{Re}(\delta) .$$

(5)

$A_L$ has been accurately measured. $A_S$ has been recently measured with tagged $K_S$ at $\phi$ factories, however not yet with the required accuracy. Note however that Eq. (5) assumes $CPT$ invariance in the $\Delta S = -\Delta Q$ semileptonic decay amplitude.
Figure 1: CP- and CPT-violation parameters in $2\pi$ decay.

$\delta_\perp$ can be obtained from the measurement of the $\pi\pi$ decays $CP$-violation parameters $\eta_{+-}$ and $\eta_{00}$. Figure 1 shows the various contributions to $\eta_{\pi\pi}$ [1]. The $T$-violation parameter $\epsilon_T$

$$
\epsilon_T = i \frac{\Lambda_{K^0\bar{K}^0}^2 - \Lambda_{K^0\bar{K}^0}^2}{\Delta \gamma (\lambda_L - \lambda_S)}
$$

has been defined in such a way that it is exactly aligned along the superweak direction [4]. $A_I$ (resp. $B_I$) is the $CPT$-conserving (resp. violating) decay amplitude for the $\pi\pi$ Isospin $I$ state, $\epsilon'$ is the direct $CP/CPT$-violation parameter [$\epsilon' = 1/3(\eta_{+-} - \eta_{00})$] and $\delta\phi = \frac{1}{2} [\varphi_T - \arg(A_0^*A_0)]$ is the phase difference between
the $I = 0$ component of the decay amplitude and the matrix element $\Gamma_{K^0\bar{K}^0}$. From Fig. 1 one obtains

$$\delta_\perp = |\eta_{+-}|(\phi_{SW} - \frac{2}{3}\phi_{+-} - \frac{1}{3}\phi_{00})$$

$$- \frac{\text{Re}(B_0)}{\text{Re}(A_0)} \sin(\phi_{SW}) + \delta \phi \cos(\phi_{SW}).$$

(7)

The present accuracy on the term $|\eta_{+-}|(\phi_{SW} - \frac{2}{3}\phi_{+-} - \frac{1}{3}\phi_{00})$ is $2.6 \times 10^{-5}$. $\delta \phi$ gets contributions from CP violation in semileptonic and $3\pi$ decays [2,3] and can only be neglected at the present time if one assumes that $\eta_{000}$ is not significantly larger than $\eta_{+-0}$. Furthermore, $B_0$ is not directly measured, so additional assumptions (for example, CPT conservation in the decay which implies $B_0 = 0$) or a combination with other measurements are necessary to obtain $\delta_\perp$.

If one assumes unitarity, one can measure $\text{Im}(\delta)$ using the Bell-Steinberger relation which relates $K_S$ and $K_L$ decay amplitudes into all final states $f$:

$$\text{Re}(\epsilon_T) - i\text{Im}(\delta) = \frac{1}{2(i\Delta m + \frac{1}{2}(\gamma_L + \gamma_S))} \times \sum A_{fL}A_{fS}^*.$$  

(8)

Since the $\pi\pi$ amplitudes dominate, the result relies also strongly on the $\phi_{\pi\pi}$ phase measurements. The advantage is that $B_0$ does not enter. Using all available data, one obtains a value of $\text{Im}(\delta)$ compatible with zero with a precision of $2 \times 10^{-5}$. The precision here is limited by the measurement of $\eta_{+-}$.

The results on $\text{Re}(\delta)$ and $\text{Im}(\delta)$ can be combined to obtain $\delta_\parallel$ and $\delta_\perp$ and therefore the $K^0-\bar{K}^0$ mass and width difference shown in Fig. 2. The current accuracy is a few $10^{-18}$ GeV for both.

If one assumes that CPT is conserved in the decays ($\gamma_{K^0} = \gamma_{\bar{K}^0}$, $\delta_\parallel = 0$, $B_I = 0$), the phase of $\delta$ is known, and the $\delta_\perp$ and
Bell-Steinberger methods are identical. One in this case obtains a limit for $|m_{K^0} - m_{\overline{K}^0}|$ of $4.7 \times 10^{-19}$ GeV (90%CL).

![Figure 2: $K^0 - \overline{K}^0$ mass vs width difference.](image)

Footnotes and References

‡ Many authors have a different definition of the $T$-violation parameter, $\epsilon = (\Lambda_{K^0\overline{K}^0} - \Lambda_{\overline{K}^0K^0})/(2(\lambda_L - \lambda_S))$. $\epsilon$ is not exactly aligned with the superweak direction. The two definitions can be related through $\epsilon = \epsilon_T + i\delta\phi$.

CP-VIOLATION PARAMETERS

In $K^0\bar{K}^0$ mixing, if CP-violating interactions include a $T$ conserving part then

$$|K_S⟩ = [|[K_1] + (ε + δ)|K_2]|/\sqrt{1 + |ε + δ|^2}$$

$$|K_L⟩ = [|[K_2] + (ε - δ)|K_1]|/\sqrt{1 + |ε - δ|^2}$$

where

$$|K_1⟩ = [|[K^0] + |\bar{K}^0]|/\sqrt{S}$$

$$|K_2⟩ = [|[K^0] - |\bar{K}^0]|/\sqrt{2}$$

and

$$|\bar{K}^0⟩ = CP|K^0⟩.$$ 

The parameter $δ$ specifies the CP-violating part.

Estimates of $δ$ are given below assuming the validity of the $ΔS = ΔQ$ rule.

See also THOMSON 95 for a test of $CPT$-symmetry conservation in $K^0$ decays using the Bell-Steinberger relation.

REAL PART OF $δ$

A nonzero value violates $CPT$ invariance.

<table>
<thead>
<tr>
<th>VALUE (units 10^{-3})</th>
<th>EVTS</th>
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<th>TECN</th>
<th>COMMENT</th>
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</thead>
<tbody>
<tr>
<td>2.9 ± 2.6 ± 0.6</td>
<td>1.3M</td>
<td>3 ANGELOPO... 98f CPLR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4 ± 2.8</td>
<td>6481</td>
<td>5 DEMIDOV 95 K_{f3} reanalysis</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3 If $ΔS = ΔQ$ is not assumed, ANGELOPOULOS 98f finds $Re(δ) = (3.0 ± 3.3 ± 0.6) × 10^{-4}$.

4 APOSTOLAKIS 99b assumes only unitarity and combines CPLEAR and other results.

5 DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.

IMAGINARY PART OF $δ$

A nonzero value violates $CPT$ invariance.

<table>
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<th>COMMENT</th>
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<tbody>
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<td>- 0.2 ± 2.0</td>
<td>6 LAI 05A NA48</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 2.4 ± 5.0</td>
<td>7 APOSTOLA... 99b RVUE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 90 ± 290 ± 100</td>
<td>1.3M</td>
<td>8 ANGELOPO... 98f CPLR</td>
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<tr>
<td>2100 ± 3700</td>
<td>6481</td>
<td>9 DEMIDOV 95 K_{f3} reanalysis</td>
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</table>

6 LAI 05A values are obtained through unitarity (Bell-Steinberger relations), improving determination of $n_{1000}$ and combining other data from PDG and APOSTOLAKIS 99b.

7 APOSTOLAKIS 99b assumes only unitarity and combines CPLEAR and other results.

8 If $ΔS = ΔQ$ is not assumed, ANGELOPOULOS 98f finds $Im(δ) = (-15 ± 23 ± 3) × 10^{-3}$.

9 DEMIDOV 95 reanalyzes data from HART 73 and NIEBERGALL 74.
**Re(y)**

A non-zero value would violate CPT invariance in $\Delta S = \Delta Q$ amplitude. $\text{Re}(y)$ is the following combination of $K_{e3}$ decay amplitudes:

$$\text{Re}(y) = \text{Re}(\frac{A(K^0 \rightarrow e^- \pi^+ \nu_e)}{A(K^0 \rightarrow e^+ \pi^- \bar{\nu}_e)} - \frac{A(K^0 \rightarrow e^- \pi^+ \nu_e)}{A(K^0 \rightarrow e^+ \pi^- \bar{\nu}_e)})$$

<table>
<thead>
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<th>TECN</th>
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</thead>
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<tr>
<td>0.4±2.5</td>
<td>13k</td>
<td>AMBROSINO 06E</td>
<td>KLOE</td>
</tr>
</tbody>
</table>

* • • • We do not use the following data for averages, fits, limits, etc. • • •

0.3±3.1

10 They use the PDG 04 (web update) for the $K_\ell^0$ semileptonic charge asymmetry and PDG 04 (CP review, CPT NOT ASSUMED) for Re($\epsilon$).

11 Constrained by Bell-Steinberger (or unitarity) relation.

**Re(x-)**

A non-zero value would violate CPT invariance in decay amplitudes with $\Delta S \neq \Delta Q$.

$x_-$, used here to define $\text{Re}(x_-)$, and $x_+$, used below in the $\Delta S = \Delta Q$ section are the following combinations of $K_{e3}$ decay amplitudes:

$$x_\pm = \frac{1}{2} \left( \frac{A(K^0 \rightarrow \pi^- e^+ \nu_e)}{A(K^0 \rightarrow \pi^- e^- \bar{\nu}_e)} \pm \frac{A(K^0 \rightarrow \pi^+ e^- \bar{\nu}_e)}{A(K^0 \rightarrow \pi^+ e^+ \nu_e)} \right).$$

<table>
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<tr>
<th>VALUE (units $10^{-3}$)</th>
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<th>TECN</th>
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<tbody>
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<td>AMBROSINO 06E</td>
<td>KLOE</td>
<td>Tagged $K^0_S$</td>
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</tbody>
</table>

* • • • We do not use the following data for averages, fits, limits, etc. • • •

-0.5±3.0

12 APOSTOLA... 99b CPLR

2±13 ±3

650k ANGELOPOULOS 98f

12 Uses PDG 04 (web update) for the $K_\ell^0$ semileptonic charge asymmetry and Re($\delta$) from CPLER, ANGELOPOULOS 98f.

13 Constrained by Bell-Steinberger (or unitarity) relation.

$|m_{K^0} - m_{\bar{K}^0}| / m_{\text{average}}$

A test of CPT invariance. “Our Evaluation” is described in the “Tests of Conservation Laws” section. It assumes CPT invariance in the decay and neglects some contributions from decay channels other than $\pi \pi$.

<table>
<thead>
<tr>
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<tr>
<td>&lt; $10^{-18}$ (CL = 90%) Our Evaluation</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

* • • We do not use the following data for averages, fits, limits, etc. • • •

$(-3±4) \times 10^{-18}$

14 ANGELOPOULOS 99b

14 ANGELOPOULOS 99b assumes only unitarity and combines CPLER and other results.

$(\Gamma_{K^0} - \Gamma_{\bar{K}^0})/m_{\text{average}}$

A test of CPT invariance.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
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</thead>
<tbody>
<tr>
<td>$(7.8±8.4) \times 10^{-18}$</td>
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<td></td>
</tr>
</tbody>
</table>

15 ANGELOPOULOS 99b assumes only unitarity and combines CPLER with other results.

Correlated with $(m_{K^0} - m_{\bar{K}^0}) / m_{\text{average}}$ with a correlation coefficient of $-0.95$. 
TESTS OF $\Delta S = \Delta Q$ RULE

$\text{Re}(x_+)$

A non-zero value would violate the $\Delta S = \Delta Q$ rule in CPT conserving transitions. $x_+$ is defined above in the $\text{Re}(x_-)$ section.

$\text{VALUE (units } 10^{-3} \text{) EVTS DOCUMENT ID TECN}$

$\text{ VALUE EVTS DOCUMENT ID TECN}$

-0.8 ± 3.1 OUR AVERAGE
-0.5 ± 3.6 13k 16 AMBROSINO 06E KLOE
-1.8 ± 6.1 17 ANGELOPO... 98D CPLR

$\text{Re}(x_+)$ can be shown to be equal to the following combination of rates:

$$\text{Re}(x_+) = \frac{1}{2} \left( \Gamma(K^0_S \rightarrow \pi e \nu) - \Gamma(K^0_L \rightarrow \pi e \nu) \right)$$

which is valid up to first order in terms violating CPT and/or the $\Delta S = \Delta Q$ rule.

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