K^0_S

$I(J^P) = \frac{1}{2}(0^-)$

K^0_S MEAN LIFE

For earlier measurements, beginning with BOLDT 58B, see our 1986 edition, Physics Letters **170B** 130 (1986).

OUR FIT is described in the note on "*CP* violation in K_L decays" in the K^0_L Particle Listings. The result labeled "OUR FIT Assuming *CPT*" ["OUR FIT Not assuming *CPT*"] includes all measurements except those with the comment "Not assuming *CPT*" ["Assuming *CPT*"]. Measurements with neither comment do not assume *CPT* and enter both fits.

VALUE (10^{-10} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.8954 ±0.0004 OUR FIT		Error includes scale factor of 1.1. Assuming *CPT*			
0.89564±0.00033 OUR FIT		Not assuming *CPT*			
0.89589±0.00070		[1,2] ABOUZAID	11	KTEV	Not assuming *CPT*
0.89623±0.00047		[1,3] ABOUZAID	11	KTEV	Assuming *CPT*
0.89562±0.00029±0.00043	20M	[4] AMBROSINO	11	KLOE	Not assuming *CPT*
0.89598±0.00048±0.00051	16M	LAI	02C	NA48	
0.8971 ±0.0021		BERTANZA	97	NA31	
0.8941 ±0.0014 ±0.0009		SCHWINGEN...	95	E773	Assuming *CPT*
0.8929 ±0.0016		GIBBONS	93	E731	Assuming *CPT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.8965 ±0.0007		[5] ALAVI-HARATI	03	KTEV	Assuming *CPT*
0.8958 ±0.0013		[6] ALAVI-HARATI	03	KTEV	Not assuming *CPT*
0.8920 ±0.0044	214k	GROSSMAN	87	SPEC	
0.905 ±0.007		[7] ARONSON	82B	SPEC	
0.881 ±0.009	26k	ARONSON	76	SPEC	
0.8926 ±0.0032 ±0.0002		[8] CARITHERS	75	SPEC	
0.8937 ±0.0048	6M	GEWENIGER	74B	ASPK	
0.8958 ±0.0045	50k	[9] SKJEGGEST...	72	HBC	
0.856 ±0.008	19994	[10] DONALD	68B	HBC	
0.872 ±0.009	20000	[9,10] HILL	68	DBC	

[1] The two ABOUZAID 11 values use the same full KTeV dataset from 1996, 1997, and 1999. The first enters the "assuming *CPT*" fit and the second enters the "not assuming *CPT*" fit.

[2] ABOUZAID 11 fit has Δm, τ_S, ϕ_ϵ, Re(ϵ'/ϵ), and Im(ϵ'/ϵ) as free parameters. See Im(ϵ'/ϵ) in the "K^0_L *CP* violation" section for correlation information.

[3] ABOUZAID 11 fit has Δm and τ_S free but constrains ϕ_ϵ to the Superweak value, i.e. assumes *CPT*. This τ_S value is correlated with their $\Delta m = m_{K^0_L} - m_{K^0_S}$ measurement in the K^0_L listings. The correlation coefficient $\rho(\tau_S, \Delta m) = -0.670$.

[4] Fit to the proper time distribution.

[5] This ALAVI-HARATI 03 fit has Δm and τ_S free but constrains ϕ_{+-} to the Superweak value, i.e. assumes *CPT*. This τ_S value is correlated with their $\Delta m = m_{K^0_L} - m_{K^0_S}$ measurement in the K^0_L listings. The correlation coefficient $\rho(\tau_S,\Delta m) = -0.396$. Superseded by ABOUZAID 11.

[6] This ALAVI-HARATI 03 fit has Δm, ϕ_{+-}, and τ_{K_S} free. See ϕ_{+-} in the "K_L *CP* violation" section for correlation information. Superseded by ABOUZAID 11.

[7] ARONSON 82 find that K_S^0 mean life may depend on the kaon energy.

[8] CARITHERS 75 measures the Δm dependence of the total decay rate (inverse mean life) to be $\Gamma(K_S^0) = \left[(1.122 \pm 0.004) + 0.16(\Delta m - 0.5348)/\Delta m\right] 10^{10}$/s, or, in terms of mean life, CARITHERS 75 measures $\tau_s = (0.8913 \pm 0.0032)\ - 0.238\ [\Delta m -\ 0.5348]$ (10^{-10} s). We have adjusted the measurement to use our best values of ($\Delta m =$ 0.5293 ± 0.0009) (10^{10} $\hbar$ s^{-1}). Our first error is their experiment's error and our second error is the systematic error from using our best values.

[9] HILL 68 has been changed by the authors from the published value (0.865 $\pm$ 0.009) because of a correction in the shift due to η_{+-}. SKJEGGESTAD 72 and HILL 68 give detailed discussions of systematics encountered in this type of experiment.

[10] Pre-1971 experiments are excluded from the average because of disagreement with later more precise experiments.

K_S^0 DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
			Hadronic modes	
Γ_1	$\pi^0\pi^0$		(30.69$\pm$0.05) %	
Γ_2	$\pi^+\pi^-$		(69.20$\pm$0.05) %	
Γ_3	$\pi^+\pi^-\pi^0$		($3.5\ ^{+1.1}_{-0.9}$) $\times 10^{-7}$	
			Modes with photons or $\ell\bar{\ell}$ pairs	
Γ_4	$\pi^+\pi^-\gamma$	[*a*,*b*]	(1.79$\pm$0.05) $\times 10^{-3}$	
Γ_5	$\pi^+\pi^- e^+ e^-$		(4.79$\pm$0.15) $\times 10^{-5}$	
Γ_6	$\pi^0\gamma\gamma$	[*a*]	(4.9 $\pm$1.8) $\times 10^{-8}$	
Γ_7	$\gamma\gamma$		(2.63$\pm$0.17) $\times 10^{-6}$	S=3.1
			Semileptonic modes	
Γ_8	$\pi^\pm e^\mp \nu_e$	[*c*]	(7.04$\pm$0.08) $\times 10^{-4}$	
Γ_9	$\pi^\pm \mu^\mp \nu_\mu$	[*c*,*d*]	(4.56$\pm$0.20) $\times 10^{-4}$	
			***CP* violating (*CP*) and $\Delta S = 1$ weak neutral current (*S1*) modes**	
Γ_{10}	$3\pi^0$	*CP*	< 2.6 $\times 10^{-8}$	CL=90%
Γ_{11}	$\mu^+\mu^-$	*S1*	< 2.1 $\times 10^{-10}$	CL=90%
Γ_{12}	e^+e^-	*S1*	< 9 $\times 10^{-9}$	CL=90%
Γ_{13}	$\pi^0 e^+ e^-$	*S1* [*a*]	($3.0\ ^{+1.5}_{-1.2}$) $\times 10^{-9}$	
Γ_{14}	$\pi^0\mu^+\mu^-$	*S1*	($2.9\ ^{+1.5}_{-1.2}$) $\times 10^{-9}$	

[*a*] See the Particle Listings below for the energy limits used in this measurement.

[*b*] Most of this radiative mode, the low-momentum γ part, is also included in the parent mode listed without γ's.

[c] The value is for the sum of the charge states or particle/antiparticle states indicated.

[d] Not a measurement. Calculated as 0.666·B($\pi^\pm e^\mp \nu_e$).

CONSTRAINED FIT INFORMATION

An overall fit to 4 branching ratios uses 5 measurements and one constraint to determine 4 parameters. The overall fit has a χ^2 = 0.1 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\left\langle \delta x_i \delta x_j \right\rangle / (\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{\text{total}}$. The fit constrains the x_i whose labels appear in this array to sum to one.

x_2	−100		
x_8	−6	4	
x_9	−1	−3	0
	x_1	x_2	x_8

K^0_S DECAY RATES

$\Gamma(\pi^\pm e^\mp \nu_e)$ — Γ_8

VALUE (10^6 s^{-1})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.1 ±1.6	75	[1] AKHMETSHIN	99	CMD2	Tagged K^0_S using $\phi \to K^0_L K^0_S$
7.50±0.08		[2] PDG	98		
seen		BURGUN	72	HBC	$K^+ p \to K^0 p \pi^+$
9.3 ±2.5		AUBERT	65	HLBC	ΔS=ΔQ, *CP* cons. not assumed

[1] AKHMETSHIN 99 is from a measured branching ratio B($K^0_S \to \pi e \nu_e$)= $(7.2 \pm 1.4) \times 10^{-4}$ and $\tau_{K^0_S} = (0.8934 \pm 0.0008) \times 10^{-10}$ s. Not independent of measured branching ratio.

[2] PDG 98 from K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm e^\mp \nu_e) = \Gamma(K^0_L \to \pi^\pm e^\mp \nu_e)$.

$\Gamma(\pi^\pm \mu^\mp \nu_\mu)$ — Γ_9

VALUE (10^6 s^{-1})	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •		
5.25±0.07	[1] PDG	98

[1] PDG 98 from K^0_L measurements, assuming that $\Delta S = \Delta Q$ in K^0 decay so that $\Gamma(K^0_S \to \pi^\pm \mu^\mp \nu_\mu) = \Gamma(K^0_L \to \pi^\pm \mu^\mp \nu_\mu)$.

K^0_S BRANCHING RATIOS

Hadronic modes

$\Gamma(\pi^0\pi^0)/\Gamma_{total}$ — Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN
0.3069±0.0005 OUR FIT				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.335 ±0.014	1066	BROWN	63	HLBC
0.288 ±0.021	198	CHRETIEN	63	HLBC
0.30 ±0.035		BROWN	61	HLBC

$\Gamma(\pi^+\pi^-)/\Gamma_{total}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.6920±0.0005 OUR FIT					
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.670 ±0.010	3447	DOYLE	69	HBC	$\pi^- p \to \Lambda K^0$

$\Gamma(\pi^+\pi^-)/\Gamma(\pi^0\pi^0)$ — Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
2.255 ±0.005 OUR FIT					
2.2549±0.0054		[1] AMBROSINO	06C	KLOE	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
2.2555±0.0012±0.0054		[2] AMBROSINO	06C	KLOE	
2.236 ±0.003 ±0.015	766k	[2] ALOISIO	02B	KLOE	
2.11 ±0.09	1315	EVERHART	76	WIRE	$\pi^- p \to \Lambda K^0$
2.169 ±0.094	16k	COWELL	74	OSPK	$\pi^- p \to \Lambda K^0$
2.16 ±0.08	4799	HILL	73	DBC	$K^+ d \to K^0 p p$
2.22 ±0.10	3068	[3] ALITTI	72	HBC	$K^+ p \to \pi^+ p K^0$
2.22 ±0.08	6380	MORSE	72B	DBC	$K^+ n \to K^0 p$
2.10 ±0.11	701	[4] NAGY	72	HLBC	$K^+ n \to K^0 p$
2.22 ±0.095	6150	[5] BALTAY	71	HBC	$K p \to K^0$ neutrals
2.282 ±0.043	7944	[6] MOFFETT	70	OSPK	$K^+ n \to K^0 p$
2.12 ±0.17	267	[4] BOZOKI	69	HLBC	
2.285 ±0.055	3016	[6] GOBBI	69	OSPK	$K^+ n \to K^0 p$
2.10 ±0.06	3700	MORFIN	69	HLBC	$K^+ n \to K^0 p$

[1] This result combines AMBROSINO 06C KLOE 2001-02 data with ALOISIO 02B KLOE 2000 data. $K^0_S \to \pi^+\pi^-$ fully inclusive.

[2] Includes radiative decays $\pi^+\pi^-\gamma$.

[3] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all $K^0 = 0.345 \pm 0.005$.

[4] NAGY 72 is a final result which includes BOZOKI 69.

[5] The directly measured quantity is $K^0_S \to \pi^+\pi^-$/all $\overline{K}^0 = 0.345 \pm 0.005$.

[6] MOFFETT 70 is a final result which includes GOBBI 69.

$\Gamma(\pi^+\pi^-\pi^0)/\Gamma_{total}$ — Γ_3/Γ

VALUE (units 10^{-7})	EVTS	DOCUMENT ID		TECN	COMMENT
$3.5^{+1.1}_{-0.9}$ OUR AVERAGE					
$4.7^{+2.2+1.7}_{-1.7-1.5}$		[1] BATLEY	05	NA48	
$2.5^{+1.3+0.5}_{-1.0-0.6}$	500k	[2] ADLER	97B	CPLR	
$4.8^{+2.2}_{-1.6}\pm1.1$		[3] ZOU	96	E621	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$4.1^{+2.5+0.5}_{-1.9-0.6}$		[4] ADLER	96E	CPLR	Sup. by ADLER 97B
$3.9^{+5.4+0.9}_{-1.8-0.7}$		[5] THOMSON	94	E621	Sup. by ZOU 96

[1] BATLEY 05 is obtained by measuring the interference parameters in K_S, $K_L \to \pi^+\pi^-\pi^0$: Re(λ) = 0.038 ± 0.008 ± 0.006 and Im(λ) = −0.013 ± 0.005 ± 0.004; the correlation coeff. between Re(λ) and Im(λ) is 0.66 (statistical only).

[2] ADLER 97B find the *CP*-conserving parameters Re(λ) = (28 ± 7 ± 3) × 10^{-3}, Im(λ) = (−10 ± 8 ± 2) × 10^{-3}. They estimate B($K^0_S \to \pi^+\pi^-\pi^0$) from Re($\lambda$) and the K^0_L decay parameters. See also ANGELOPOULOS 98C.

[3] ZOU 96 is from the the measured quantities $|\rho_{+-0}| = 0.039^{+0.009}_{-0.006} \pm 0.005$ and $\phi_\rho = (-9 \pm 18)^\circ$.

[4] ADLER 96E is from the measured quantities Re(λ) = $0.036 \pm 0.010^{+0.002}_{-0.003}$ and Im(λ) consistent with zero. Note that the quantity λ is the same as ρ_{+-0} used in other footnotes.

[5] THOMSON 94 calculates this branching ratio from their measurements $|\rho_{+-0}| = 0.035^{+0.019}_{-0.011} \pm 0.004$ and $\phi_\rho = (-59\pm48)^\circ$ where $|\rho_{+-0}|e^{i\phi_\rho}$ = A($K^0_S \to \pi^+\pi^-\pi^0$, $I = 2$)/A($K^0_L \to \pi^+\pi^-\pi^0$).

Modes with photons or $\ell\overline{\ell}$ pairs

$\Gamma(\pi^+\pi^-\gamma)/\Gamma(\pi^+\pi^-)$ — Γ_4/Γ_2

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	COMMENT
2.59±0.08 OUR AVERAGE					
2.56±0.09	1286	RAMBERG	93	E731	p_γ >50 MeV/c
2.68±0.15		[1] TAUREG	76	SPEC	p_γ >50 MeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.10±0.22	3723	RAMBERG	93	E731	p_γ >20 MeV/c
3.0 ±0.6	29	[2] BOBISUT	74	HLBC	p_γ >40 MeV/c
2.8 ±0.6		[3] BURGUN	73	HBC	p_γ >50 MeV/c

[1] TAUREG 76 find direct emission contribution <0.06, CL = 90%.

[2] BOBISUT 74 not included in average because p_γ cut differs. Estimates direct emission contribution to be 0.5 or less, CL = 95%.

[3] BURGUN 73 estimates that direct emission contribution is 0.3 ± 0.6.

$\Gamma(\pi^+\pi^- e^+ e^-)/\Gamma_{total}$ — Γ_5/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
4.79±0.15 OUR AVERAGE					
4.83±0.11±0.14	23k	[1] BATLEY	11	NA48	2002 data
4.69±0.30	676	[2] LAI	03C	NA48	1998+1999 data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
4.71±0.23±0.22	620	[2,3] LAI	03C	NA48	1999 data
4.5 ±0.7 ±0.4	56	LAI	00B	NA48	1998 data

[1] BATLEY 11 reports $[\Gamma(K^0_S \to \pi^+\pi^- e^+ e^-)/\Gamma_{total}]$ / $[B(K^0_L \to \pi^+\pi^-\pi^0)]$ / $[B(\pi^0 \to e^+ e^- \gamma)] = (3.28 \pm 0.06 \pm 0.04) \times 10^{-2}$ which we multiply by our best values $B(K^0_L \to \pi^+\pi^-\pi^0) = (12.54 \pm 0.05) \times 10^{-2}$, $B(\pi^0 \to e^+ e^- \gamma) = (1.174 \pm 0.035) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best values. Also a limit on the absolute value of the interference between bremsstrahlung and E1 transition is given : $< 4 \times 10^{-7}$ at 90% C.L.

[2] Uses normalization $BR(K_L \to \pi^+\pi^-\pi^0)*BR(\pi^0 \to e^+ e^-) = (1.505 \pm 0.047) \times 10^{-3}$ from our 2000 Edition.

[3] Second error is 0.16(syst)±0.15(norm) combined in quadrature.

$\Gamma(\pi^0\gamma\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
4.9±1.6±0.9		17	[1] LAI	04	NA48	$m^2_{\gamma\gamma}/m^2_K > 0.2$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<33	90		LAI	03B	NA48	$m^2_{\gamma\gamma}/m^2_K > 0.2$

[1] Spectrum also measured and found consistent with the one generated by a constant matrix element.

$\Gamma(\gamma\gamma)/\Gamma_{total}$ — Γ_7/Γ

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.63 ±0.17 OUR AVERAGE			Error includes scale factor of 3.1.			
2.26 ±0.12 ±0.06		711	[1] AMBROSINO	08C	KLOE	$\phi \to K^0_S K^0_L$
2.713±0.063±0.005		7.5k	[2] LAI	03	NA48	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.58 ±0.36 ±0.22		149	LAI	00	NA48	
2.2 ±1.1		16	[3] BARR	95B	NA31	
2.4 ±0.9		35	[4] BARR	95B	NA31	
< 13	90		BALATS	89	SPEC	
2.4 ±1.2		19	BURKHARDT	87	NA31	
<133	90		BARMIN	86B	XEBC	

[1] AMBROSINO 08C reports $(2.26 \pm 0.12 \pm 0.06) \times 10^{-6}$ from a measurement of $[\Gamma(K^0_S \to \gamma\gamma)/\Gamma_{total}] \times [B(K^0_S \to \pi^0\pi^0)]$ assuming $B(K^0_S \to \pi^0\pi^0) = (30.69 \pm 0.05) \times 10^{-2}$.

[2] LAI 03 reports $[\Gamma(K^0_S \to \gamma\gamma)/\Gamma_{total}]$ / $[B(K^0_S \to \pi^0\pi^0)] = (8.84 \pm 0.18 \pm 0.10) \times 10^{-6}$ which we multiply by our best value $B(K^0_S \to \pi^0\pi^0) = (30.69 \pm 0.05) \times 10^{-2}$. Our first error is their experiment's error and our second error is the systematic error from using our best value.

[3] BARR 95B result is calculated using $B(K_L \to \gamma\gamma) = (5.86 \pm 0.17) \times 10^{-4}$.

[4] BARR 95B quotes this as the combined BARR 95B + BURKHARDT 87 result after rescaling BURKHARDT 87 to use same branching ratios and lifetimes as BARR 95B.

Semileptonic modes

$\Gamma(\pi^{\pm} e^{\mp} \nu_e)/\Gamma_{\text{total}}$ — Γ_8/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
7.04 ±0.08 OUR FIT					
7.04 ±0.08 OUR AVERAGE					
7.046±0.18±0.16		[1] BATLEY	07D	NA48	$K^0(\overline{K}^0)(t) \to \pi e \nu$
6.91 ±0.34±0.15	624	[2] ALOISIO	02	KLOE	Tagged K^0_S using $\phi \to K^0_L K^0_S$
• • • We use the following data for averages but not for fits. • • •					
7.05 ±0.09	13k	[3] AMBROSINO	06E	KLOE	Not fitted
• • • We do not use the following data for averages, fits, limits, etc. • • •					
7.2 ±1.4	75	AKHMETSHIN	99	CMD2	Tagged K^0_S using $\phi \to K^0_L K^0_S$

[1] Reconstructed from $K^0(\overline{K}^0)(t) \to \pi e \nu$ distributions using PDG values of B($K^0_L \to \pi e \nu$) = 0.4053 ± 0.0015, $\tau_L = (5.114 \pm 0.021) \times 10^{-8}$ s and $\tau_S = (0.8958 \pm 0.0005) \times 10^{-10}$ s.

[2] Uses the PDG 00 value for B($K^0_S \to \pi^+\pi^-$).

[3] Obtained by imposing Σ_i B($K^0_S \to i$) = 1, where i runs over all the four branching ratios $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi e \nu$, and $\pi \mu \nu$. Input value of B($K^0_S \to \pi^+\pi^-$) / B($K^0_S \to \pi^0\pi^0$) from AMBROSINO 06C is used. To derive $\Gamma(K^0_S \to \pi^+ \mu \nu)$ / $\Gamma(K^0_S \to \pi^+ e \nu)$, lepton universality is assumed, radiative corrections from ANDRE 07 are used, and phase space integrals are taken from KTeV, ALEXOPOULOS 04A. This branching fraction enters our fit via their $\Gamma(\pi^{\pm} e^{\mp} \nu_e)$ / $\Gamma(\pi^+\pi^-)$ branching ratio measurement.

$\Gamma(\pi^{\pm} \mu^{\mp} \nu_\mu)/\Gamma_{\text{total}}$ — Γ_9/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
4.56±0.20 OUR FIT					
4.56±0.11±0.17	7223	[1] BABUSCI	20	KLOE	direct measurement

[1] Value obtained by normalizing to the KLOE measurement B($K^0_S \to \pi^+\pi^-$) = (69.196 ± 0.051)%. Also comparison with the PDG 18 based derived value leads to a lepton flavor universality test $|V_{us}\ f_+(0)|^2_{K^0_S \to \pi \mu \nu} / |V_{us}\ f_+(0)|^2_{K^0_S \to \pi e \nu}$ = 0.975 ± 0.044.

$\Gamma(\pi^{\pm} e^{\mp} \nu_e)/\Gamma(\pi^+\pi^-)$ — Γ_8/Γ_2

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN
10.18±0.12 OUR FIT				
10.19±0.11±0.07	13k	AMBROSINO	06E	KLOE

CP violating (*CP*) and $\Delta S = 1$ weak neutral current (*S1*) modes

$\Gamma(3\pi^0)/\Gamma_{\text{total}}$ — Γ_{10}/Γ

Violates *CP* conservation.

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.26	90	590M	[1] BABUSCI	13C	KLOE	$\phi \to K^0_L K^0_S$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.2	90	37.8M	AMBROSINO	05B	KLOE	
< 7.4	90	4.9M	[2] LAI	05A	NA48	
<140	90	7M	ACHASOV	99D	SND	
<190	90	17300	[3] ANGELOPO...	98B	CPLR	
<370	90		BARMIN	83	HLBC	

[1] BABUSCI 13C uses 1.7 fb^{-1} of data of $\phi \rightarrow K^0_L K^0_S$ decays with K^0_L interaction in the calorimeter, collected from 2004 to 2005. No candidate events were found in the data with an expected background of $0.04^{+0.15}_{-0.03}$ events. Upper limit is obtained by normalizing to $K^0_S \rightarrow 2\pi^0$ decays.

[2] LAI 05A value is obtained from their bound on $|\eta_{000}|$ (not assuming CPT) and B($K^0_L \rightarrow 3\pi^0$) = 0.211 ± 0.003, and PDG 04 values for K^0_L and K^0_S lifetimes. If CPT is assumed then B($K^0_S \rightarrow 3\pi^0)_{CPT} < 2.3 \times 10^{-7}$ at 90% CL

[3] ANGELOPOULOS 98B is from Im(η_{000}) = −0.05 ± 0.12 ± 0.05, assuming Re(η_{000}) = Re(ϵ) = 1.635×10^{-3} and using the value B($K^0_L \rightarrow \pi^0\pi^0\pi^0$) = 0.2112 ± 0.0027.

$\Gamma(\mu^+\mu^-)/\Gamma_{\text{total}}$ — Γ_{11}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE	CL%	DOCUMENT ID		TECN
<2.1 × 10^{-10}	90	[1] AAIJ	20AE	LHCB
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<8 \times 10^{-10}$	90	[2] AAIJ	17BQ	LHCB
$<9 \times 10^{-9}$	90	[3] AAIJ	13G	LHCB
$<3.2 \times 10^{-7}$	90	GJESDAL	73	ASPK
$<7 \times 10^{-6}$	90	HYAMS	69B	OSPK

[1] AAIJ 20AE uses 8.6 fb^{-1} of LHCb data from 2011 to 2012 and 2016 to 2018. The result utilizes the normalization mode branching fraction B($K^0_S \rightarrow \pi^+\pi^-$) = (69.20 ± 0.05) × 10^{-2} from PDG 18. Supersedes AAIJ 17BQ.

[2] AAIJ 17BQ uses 3.0 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 and 8 TeV. The result utilizes the normalization mode branching fraction B($K^0_S \rightarrow \pi^+\pi^-$) = (69.20 ± 0.05) × 10^{-2} from PDG 16. Supersedes AAIJ 13G.

[3] AAIJ 13G uses 1.0 fb^{-1} of pp collisions at $\sqrt{s}$ = 7 TeV. They obtained B($K^0_S \rightarrow \mu^+\mu^-$) < 11×10^{-9} at 95% C.L.

$\Gamma(e^+e^-)/\Gamma_{\text{total}}$ — Γ_{12}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-7})	CL%	DOCUMENT ID		TECN	COMMENT
< 0.09	90	[1] AMBROSINO	09A	KLOE	$e^+e^- \rightarrow \phi \rightarrow K^0_S K^0_L$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.4	90	ANGELOPO...	97	CPLR	
< 28	90	BLICK	94	CNTR	Hyperon facility
<100	90	BARMIN	86	XEBC	

[1] AMBROSINO 09A reports < 0.09×10^{-7} from a measurement of [Γ($K^0_S \rightarrow e^+e^-$)/Γ_{total}] / [B($K^0_S \rightarrow \pi^+\pi^-$)] assuming B($K^0_S \rightarrow \pi^+\pi^-$) = (69.20 ± 0.05) × 10^{-2}.

$\Gamma(\pi^0 e^+e^-)/\Gamma_{\text{total}}$ — Γ_{13}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{3.0^{+1.5}_{-1.2} \pm 0.2}$		7	[1] BATLEY	03	NA48	m_{ee} >0.165 GeV

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

< 140	90		LAI	01	NA48
< 1100	90	0	BARR	93B	NA31
<45000	90		GIBBONS	88	E731

[1] BATLEY 03 extrapolate also to the full kinematical region using a constant form factor and a vector matrix element. The resulting branching ratio is $(5.8^{+2.9}_{-2.4}) \times 10^{-9}$.

$\Gamma(\pi^0\mu^+\mu^-)/\Gamma_{total}$ — Γ_{14}/Γ

Test for $\Delta S = 1$ weak neutral current. Allowed by first-order weak interaction combined with electromagnetic interaction.

VALUE (units 10^{-9})	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{2.9^{+1.5}_{-1.2}\pm0.2}$	6	[1] BATLEY	04A	NA48	NA48/1 K^0_S beam

[1] Background estimate is $0.22^{+0.18}_{-0.11}$ events. Branching ratio assumes a vector matrix element and unit form factor.

K^0_S FORM FACTORS

For discussion, see note on $K_{\ell 3}$ form factors in the $K^\pm$ section of the Particle Listings above. Because the semileptonic branching fraction is smaller in K^0_S than K^0_L by the ratio of the mean lives, the K^0_S semileptonic form factor has so far been measured only in the K_{e3} mode using the linear expansion $f_+(t) = f_+(0)\ (1 + \lambda_+ t\ /m^2_{\pi^+})$, which gives the vector form factor $f_+(t)$ relative to its value at $t = 0$.

λ_+ (LINEAR ENERGY DEPENDENCE OF f_+ IN K^0_{e3} DECAY)

VALUE (units 10^{-2})	EVTS	DOCUMENT ID		TECN
3.39±0.41	15k	AMBROSINO	06E	KLOE

CP VIOLATION IN $K_S \to 3\pi$

Written 1996 by T. Nakada (Paul Scherrer Institute) and L. Wolfenstein (Carnegie-Mellon University).

The possible final states for the decay $K^0 \to \pi^+\pi^-\pi^0$ have isospin $I = 0$, 1, 2, and 3. The $I = 0$ and $I = 2$ states have $CP = +1$ and K_S can decay into them without violating CP symmetry, but they are expected to be strongly suppressed by centrifugal barrier effects. The $I = 1$ and $I = 3$ states, which have no centrifugal barrier, have $CP = -1$ so that the K_S decay to these requires CP violation.

In order to see CP violation in $K_S \to \pi^+\pi^-\pi^0$, it is necessary to observe the interference between K_S and K_L decay, which determines the amplitude ratio

$$\eta_{+-0} = \frac{A(K_S \to \pi^+\pi^-\pi^0)}{A(K_L \to \pi^+\pi^-\pi^0)} \ . \tag{1}$$

If η_{+-0} is obtained from an integration over the whole Dalitz plot, there is no contribution from the $I = 0$ and $I = 2$ final states and a nonzero value of η_{+-0} is entirely due to CP violation.

Only $I = 1$ and $I = 3$ states, which are $CP = -1$, are allowed for $K^0 \to \pi^0\pi^0\pi^0$ decays and the decay of K_S into $3\pi^0$ is an unambiguous sign of CP violation. Similarly to η_{+-0}, η_{000} is defined as

$$\eta_{000} = \frac{A(K_S \to \pi^0\pi^0\pi^0)}{A(K_L \to \pi^0\pi^0\pi^0)} \ . \tag{2}$$

If one assumes that CPT invariance holds and that there are no transitions to $I = 3$ (or to nonsymmetric $I = 1$ states), it can be shown that

$$\begin{aligned} \eta_{+-0} &= \eta_{000} \\ &= \epsilon + i\frac{\text{Im } a_1}{\text{Re } a_1} \ . \end{aligned} \tag{3}$$

With the Wu-Yang phase convention, a_1 is the weak decay amplitude for K^0 into $I = 1$ final states; ϵ is determined from CP violation in $K_L \to 2\pi$ decays. The real parts of η_{+-0} and η_{000} are equal to $\text{Re}(\epsilon)$. Since currently-known upper limits on $|\eta_{+-0}|$ and $|\eta_{000}|$ are much larger than $|\epsilon|$, they can be interpreted as upper limits on $\text{Im}(\eta_{+-0})$ and $\text{Im}(\eta_{000})$ and so as limits on the CP-violating phase of the decay amplitude a_1.

CP-VIOLATION PARAMETERS IN K_S^0 DECAY

$A_S = [\,\Gamma(K_S^0 \to \pi^- e^+ \nu_e) - \Gamma(K_S^0 \to \pi^+ e^- \overline{\nu}_e)\,] / \text{SUM}$

Such asymmetry violates CP. If CPT is assumed then $A_S = 2\,\text{Re}(\epsilon)$.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN
$-3.8\pm5.0\pm2.6$	83k	[1] ANASTASI	18A	KLOE
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.5\pm9.6\pm2.9$	13k	AMBROSINO	06E	KLOE

[1] ANASTASI 18A result is a combination of the new measurement and AMBROSINO 06E. The new ANASTASI 18A measurement using data collected from 2004–2005, which corresponds to an integrated luminosity of 1.63 fb^{-1} is $A_S = (-4.9 \pm 5.7 \pm 2.6) \times 10^{-3}$.

PARAMETERS FOR $K_S^0 \to 3\pi$ DECAY

$\text{Im}(\eta_{+-0})^2 = \Gamma(K_S^0 \to \pi^+\pi^-\pi^0, CP\text{-violating}) / \Gamma(K_L^0 \to \pi^+\pi^-\pi^0)$

CPT assumed valid (i.e. $\text{Re}(\eta_{+-0}) \simeq 0$).

VALUE	CL%	EVTS	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.23	90	601	[1] BARMIN	85	HLBC
<0.12	90	384	METCALF	72	ASPK

[1] BARMIN 85 find $\text{Re}(\eta_{+-0}) = (0.05 \pm 0.17)$ and $\text{Im}(\eta_{+-0}) = (0.15 \pm 0.33)$. Includes events of BALDO-CEOLIN 75.

$\text{Im}(\eta_{+-0}) = \text{Im}(A(K_S^0 \to \pi^+\pi^-\pi^0, CP\text{-violating}) / A(K_L^0 \to \pi^+\pi^-\pi^0))$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$-0.002\pm0.009^{+0.002}_{-0.001}$	500k	[1] ADLER	97B	CPLR	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$-0.002\pm0.018\pm0.003$	137k	[2] ADLER	96D	CPLR	Sup. by ADLER 97B
$-0.015\pm0.017\pm0.025$	272k	[3] ZOU	94	SPEC	

[1] ADLER 97B also find $\text{Re}(\eta_{+-0}) = -0.002 \pm 0.007^{+0.004}_{-0.001}$. See also ANGELOPOULOS 98C.

[2] The ADLER 96D fit also yields $\text{Re}(\eta_{+-0}) = 0.006 \pm 0.013 \pm 0.001$ with a correlation $+0.66$ between real and imaginary parts. Their results correspond to $|\eta_{+-0}| < 0.037$ with 90% CL.

[3] ZOU 94 use theoretical constraint $\text{Re}(\eta_{+-0}) = \text{Re}(\epsilon) = 0.0016$. Without this constraint they find $\text{Im}(\eta_{+-0}) = 0.019 \pm 0.061$ and $\text{Re}(\eta_{+-0}) = 0.019 \pm 0.027$.

$\text{Im}(\eta_{000})^2 = \Gamma(K_S^0 \to 3\pi^0) / \Gamma(K_L^0 \to 3\pi^0)$

CPT assumed valid (i.e. $\text{Re}(\eta_{000}) \simeq 0$). This limit determines branching ratio $\Gamma(3\pi^0)/\Gamma_{\text{total}}$ above.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<0.1	90	632	[1] BARMIN	83	HLBC	
<0.28	90		[2] GJESDAL	74B	SPEC	Indirect meas.

[1] BARMIN 83 find $\text{Re}(\eta_{000}) = (-0.08\pm0.18)$ and $\text{Im}(\eta_{000}) = (-0.05\pm0.27)$. Assuming CPT invariance they obtain the limit quoted above.

[2] GJESDAL 74B uses $K2\pi$, $K_{\mu3}$, and K_{e3} decay results, unitarity, and CPT. Calculates $|(\eta_{000})| = 0.26 \pm 0.20$. We convert to upper limit.

$\mathrm{Im}(\eta_{000}) = \mathrm{Im}(A(K^0_S \to \pi^0\pi^0\pi^0)/A(K^0_L \to \pi^0\pi^0\pi^0))$

$K^0_S \to \pi^0\pi^0\pi^0$ violates *CP* conservation, in contrast to $K^0_S \to \pi^+\pi^-\pi^0$ which has a *CP*-conserving part.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
−0.001±0.016 OUR AVERAGE					
0.000±0.009±0.013	4.9M	[1] LAI	05A	NA48	Assumes *CPT*
−0.05 ±0.12 ±0.05	17300	[2] ANGELOPO...	98B	CPLR	Assumes *CPT*

[1] LAI 05A assumes $\mathrm{Re}(\eta_{000})=\mathrm{Re}(\epsilon)=1.66 \times 10^{-3}$. The equivalent limit is $|\eta_{000}|_{CPT}$ <0.025 at 90% CL Without assuming *CPT* invariance, they obtain $\mathrm{Re}(\eta_{000})=-0.002 \pm 0.011 \pm 0.015$ and $\mathrm{Im}(\eta_{000})=-0.003 \pm 0.013 \pm 0.017$ with a statistical correlation coefficient of 0.77 and an overall correlation coefficient of 0.57 between imaginary and real part. The equivalent limit is $|\eta_{000}|$ <0.045 at 90% CL

[2] ANGELOPOULOS 98B assumes $\mathrm{Re}(\eta_{000}) = \mathrm{Re}(\epsilon) = 1.635 \times 10^{-3}$. Without assuming *CPT* invariance, they obtain $\mathrm{Re}(\eta_{000}) = 0.18 \pm 0.14 \pm 0.06$ and $\mathrm{Im}(\eta_{000}) = 0.15 \pm 0.20 \pm 0.03$.

$|\eta_{000}| = |A(K^0_S \to 3\pi^0)/A(K^0_L \to 3\pi^0)|$

A non-zero value violates CP invariance.

VALUE	CL%	EVTS	DOCUMENT ID		TECN
<0.0088	90	590M	BABUSCI	13C	KLOE
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.018	90	37.8M	AMBROSINO	05B	KLOE
<0.045	90	4.9M	LAI	05A	NA48

DECAY-PLANE ASYMMETRY IN $\pi^+\pi^-e^+e^-$ DECAYS

This is the *CP*-violating asymmetry

$$A= \frac{N_{\sin\phi\cos\phi>0.0}-N_{\sin\phi\cos\phi<0.0}}{N_{\sin\phi\cos\phi>0.0}+N_{\sin\phi\cos\phi<0.0}}$$

where ϕ is the angle between the e^+e^- and $\pi^+\pi^-$ planes in the K^0_S rest frame.

CP asymmetry *A* in $K^0_S \to \pi^+\pi^-e^+e^-$

VALUE (%)	DOCUMENT ID		TECN	COMMENT
−0.4±0.8 OUR AVERAGE				
−0.4±0.8	[1] BATLEY	11	NA48	2002 data
−1.1±4.1	LAI	03C	NA48	1998+1999 data
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.5±4.0±1.6	LAI	03C	NA48	1999 data

[1] The result is used to set the limit $A < 1.5\%$ at 90% C.L.

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