TESTS OF CONSERVATION LAWS

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In keeping with the current interest in tests of conservation laws, we collect together a Table of experimental limits on all weak and electromagnetic decays, mass differences, and moments, and on a few reactions, whose observation would violate conservation laws. The Table is given only in the full *Review of Particle Physics*, not in the Particle Physics Booklet. For the benefit of Booklet readers, we include the best limits from the Table in the following text. Limits in this text are for CL=90% unless otherwise specified. The Table is in two parts: "Discrete Space-Time Symmetries," *i.e.*, C, P, T, CP, and CPT; and "Number Conservation Laws," *i.e.*, lepton, baryon, hadronic flavor, and charge conservation. The references for these data can be found in the the Particle Listings in the *Review*. A discussion of these tests follows.

CPT INVARIANCE

General principles of relativistic field theory require invariance under the combined transformation CPT. The simplest tests of CPT invariance are the equality of the masses and lifetimes of a particle and its antiparticle. The best test comes from the limit on the mass difference between K^0 and $\overline{K}^0$. Any such difference contributes to the CP-violating parameter ϵ. Assuming CPT invariance, ϕ_ϵ, the phase of ϵ should be very close to 44°. (See the "Note on CP Violation in K^0_L Decay" in the Particle Listings.) In contrast, if the entire source of CP violation in K^0 decays were a $K^0 - \overline{K}^0$ mass difference, ϕ_ϵ would be $44° + 90°$.

Assuming that there is no other source of CPT violation than this mass difference, it is possible to deduce that [1]

$$m_{\overline{K}^0} - m_{K^0} \approx \frac{2(m_{K^0_L} - m_{K^0_S})\,|\eta|\,(\frac{2}{3}\phi_{+-} + \frac{1}{3}\phi_{00} - \phi_0)}{\sin\phi_0} \ ,$$

where $\phi_0 = 43.5°$ with an uncertainty of less than 0.1°. Using our best values of the CP-violation parameters, we get $|(m_{\overline{K}^0} - m_{K^0})/m_{K^0}| \le 10^{-18}$. Limits can also be placed on specific CPT-violating decay amplitudes. Given the small value of $(1 - |\eta_{00}/\eta_{+-}|)$, the value of $\phi_{00} - \phi_{+-}$ provides a measure of

CPT violation in $K_L^0 \to 2\pi$ decay. Results from CERN [1] and Fermilab [2] indicate no CPT-violating effect.

CP AND T INVARIANCE

Given CPT invariance, CP violation and T violation are equivalent. So far the only evidence for CP or T violation comes from the measurements of η_{+-}, η_{00}, and the semileptonic decay charge asymmetry for K_L, *e.g.*, $|\eta_{+-}| = |A(K_L^0 \to \pi^+\pi^-)/A(K_S^0 \to \pi^+\pi^-)| = (2.285 \pm 0.019) \times 10^{-3}$ and $[\Gamma(K_L^0 \to \pi^- e^+ \nu) - \Gamma(K_L^0 \to \pi^+ e^- \overline{\nu})]/[\text{sum}] = (0.333 \pm 0.014)\%$. Other searches for CP or T violation divide into (a) those that involve weak interactions or parity violation, and (b) those that involve processes otherwise allowed by the strong or electromagnetic interactions. In class (a) the most sensitive are probably the searches for an electric dipole moment of the neutron, measured to be $< 1.0 \times 10^{-25}$ e cm, and the electron $(-0.18 \pm 0.16) \times 10^{-26}$ e cm. A nonzero value requires both P and T violation. Class (b) includes the search for C violation in η decay, believed to be an electromagnetic process, *e.g.*, as measured by $\Gamma(\eta \to \mu^+\mu^-\pi^0)/\Gamma(\eta \to \text{all}) < 5 \times 10^{-6}$, and searches for T violation in a number of nuclear and electromagnetic reactions.

CONSERVATION OF LEPTON NUMBERS

Present experimental evidence and the standard electroweak theory are consistent with the absolute conservation of three separate lepton numbers: electron number L_e, muon number L_μ, and tau number L_τ. Searches for violations are of the following types:

a) $\Delta L = 2$ for one type of lepton. The best limit comes from the search for neutrinoless double beta decay $(Z,A) \to (Z+2,A) + e^- + e^-$. The best laboratory limit is $t_{1/2} > 1.1 \times 10^{25}$ yr (CL=90%) for ^{76}Ge.

b) Conversion of one lepton type to another. For purely leptonic processes, the best limits are on $\mu \to e\gamma$ and $\mu \to 3e$, measured as $\Gamma(\mu \to e\gamma)/\Gamma(\mu \to \text{all}) < 5 \times 10^{-11}$ and $\Gamma(\mu \to 3e)/\Gamma(\mu \to \text{all}) < 1.0 \times 10^{-12}$. For semileptonic processes, the best limit comes from the coherent conversion process in a muonic atom, $\mu^- + (Z,A) \to e^- + (Z,A)$, measured as $\Gamma(\mu^-\text{Ti} \to e^-\text{Ti})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 4 \times 10^{-12}$. Of special interest is the case in which the hadronic flavor also changes, as in $K_L \to e\mu$ and $K^+ \to \pi^+ e^- \mu^+$, measured as $\Gamma(K_L \to e\mu)/\Gamma(K_L \to \text{all}) < 3.3 \times 10^{-11}$ and $\Gamma(K^+ \to \pi^+ e^- \mu^+)/\Gamma(K^+ \to \text{all}) < 2.1 \times 10^{-10}$. Limits on the conversion of τ into e or μ are found in τ decay and are much less stringent than those for $\mu \to e$ conversion, *e.g.*, $\Gamma(\tau \to \mu\gamma)/\Gamma(\tau \to \text{all}) < 3.0 \times 10^{-6}$ and $\Gamma(\tau \to e\gamma)/\Gamma(\tau \to \text{all}) < 2.7 \times 10^{-6}$.

c) Conversion of one type of lepton into another type of antilepton. The case most studied is $\mu^- + (Z, A) \to e^+ + (Z-2, A)$, the strongest limit being $\Gamma(\mu^-\text{Ti} \to e^+\text{Ca})/\Gamma(\mu^-\text{Ti} \to \text{all}) < 9 \times 10^{-11}$.

d) Relation to neutrino mass. If neutrinos have mass, then it is expected even in the standard electroweak theory that the lepton numbers are not separately conserved, as a consequence of lepton mixing analogous to Cabibbo quark mixing. However, in this case lepton-number-violating processes such as $\mu \to e\gamma$ are expected to have extremely small probability. For small neutrino masses, the lepton-number violation would be observed first in neutrino oscillations, which have been the subject of extensive experimental searches. For example, searches for $\overline{\nu}_e$ disappearance, which we label as $\overline{\nu}_e \not\to \overline{\nu}_e$, give measured limits $\Delta(m^2) < 9 \times 10^{-4}$ eV^2 for $\sin^2(2\theta) = 1$, and $\sin^2(2\theta) < 0.02$ for large $\Delta(m^2)$, where θ is the neutrino mixing angle. Possible evidence for mixing has come from two sources. The deficit in the solar neutrino flux compared with solar model calculations could be explained by oscillations with $\Delta(m^2) \leq 10^{-5}$ eV^2 causing the disappearance of ν_e. In addition underground detectors observing neutrinos produced by cosmic rays in the atmosphere have measured a ν_μ/ν_e ratio much less than expected and also a deficiency of upward going ν_μ compared to downward. This could be explained by oscillations leading to the disappearance of ν_μ with $\Delta(m^2)$ of the order 10^{-2}–10^{-3} eV^2.

CONSERVATION OF HADRONIC FLAVORS

In strong and electromagnetic interactions, hadronic flavor is conserved, *i.e.* the conversion of a quark of one flavor (d, u, s, c, b, t) into a quark of another flavor is forbidden. In the Standard Model, the weak interactions violate these conservation laws in a manner described by the Cabibbo-Kobayashi-Maskawa mixing (see the section "Cabibbo-Kobayashi-Maskawa Mixing Matrix"). The way in which these conservation laws are violated is tested as follows:

a) $\Delta S = \Delta Q$ rule. In the semileptonic decay of strange particles, the strangeness change equals the change in charge of the hadrons. Tests come from limits on decay rates such as $\Gamma(\Sigma^+ \to ne^+\nu)/\Gamma(\Sigma^+ \to \text{all}) < 5 \times 10^{-6}$, and from a detailed analysis of $K_L \to \pi e\nu$, which yields the parameter x, measured to be $(\mathrm{Re}\,x, \mathrm{Im}\,x) = (0.006\pm0.018, -0.003\pm0.026)$. Corresponding rules are $\Delta C = \Delta Q$ and $\Delta B = \Delta Q$.

b) Change of flavor by two units. In the Standard Model this occurs only in second-order weak interactions. The classic example is $\Delta S = 2$ via $K^0 - \overline{K}^0$ mixing, which is directly measured by $m(K_S) - m(K_L) = (3.489 \pm 0.009) \times 10^{-12}$ MeV. There is now evidence for $B^0 - \overline{B}^0$ mixing ($\Delta B = 2$), with the corresponding mass difference between the eigenstates $(m_{B^0_{\mathrm{H}}} - m_{B^0_{\mathrm{L}}}) = (0.723 \pm 0.032)\Gamma_{B^0} = (3.05 \pm 0.12) \times 10^{-10}$ MeV, and for B^0_s–$\overline{B}^0_s$ mixing, with $(m_{B^0_{sH}} - m_{B^0_{sL}}) > 14\Gamma_{B^0_s}$ or $> 6 \times 10^{-9}$ MeV (CL=95%). No evidence exists for $D^0 - \overline{D}^0$ mixing, which is expected to be much smaller in the Standard Model.

c) Flavor-changing neutral currents. In the Standard Model the neutral-current interactions do not change flavor. The low rate $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K_L \to \text{all}) = (7.2 \pm 0.5) \times 10^{-9}$ puts limits on such interactions; the nonzero value for this rate is attributed to a combination of the weak and electromagnetic interactions. The best test should come from $K^+ \to \pi^+\nu\overline{\nu}$, which occurs in the Standard Model only as a second-order weak process with a branching fraction of (1 to 8)$\times10^{-10}$. Observation of one event has been reported [4], yielding $\Gamma(K^+ \to \pi^+\nu\overline{\nu})/\Gamma(K^+ \to \text{all}) = (4.2^{+9.7}_{-3.5}) \times 10^{-10}$. Limits for charm-changing or bottom-changing neutral currents are much less stringent: $\Gamma(D^0 \to \mu^+\mu^-)/\Gamma(D^0 \to \text{all}) < 4 \times 10^{-6}$ and $\Gamma(B^0 \to \mu^+\mu^-)/\Gamma(B^0 \to \text{all}) < 7 \times 10^{-7}$. One cannot isolate flavor-changing neutral current (FCNC) effects in non leptonic decays. For example, the FCNC transition $s \to d + (\overline{u} + u)$ is equivalent to the charged-current transition $s \to u + (\overline{u} + d)$. Tests for FCNC are therefore limited to hadron decays into lepton pairs. Such decays are expected only in second-order in the electroweak coupling in the Standard Model.

References

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TESTS OF DISCRETE SPACE-TIME SYMMETRIES

CHARGE CONJUGATION (C) INVARIANCE

$\Gamma(\pi^0 \to 3\gamma)/\Gamma_{\text{total}}$		$<3.1 \times 10^{-8}$, CL = 90%
η C-nonconserving decay parameters		
$\pi^+\pi^-\pi^0$ left-right asymmetry parameter		$(0.09 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ sextant asymmetry parameter		$(0.18 \pm 0.16) \times 10^{-2}$
$\pi^+\pi^-\pi^0$ quadrant asymmetry parameter		$(-0.17 \pm 0.17) \times 10^{-2}$
$\pi^+\pi^-\gamma$ left-right asymmetry parameter		$(0.9 \pm 0.4) \times 10^{-2}$
$\pi^+\pi^-\gamma$ parameter β (D-wave)		0.05 ± 0.06 (S = 1.5)
$\Gamma(\eta \to 3\gamma)/\Gamma_{\text{total}}$		$<5 \times 10^{-4}$, CL = 95%
$\Gamma(\eta \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\eta \to \pi^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	[a]	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\omega(782) \to \eta\pi^0)/\Gamma_{\text{total}}$		$<1 \times 10^{-3}$, CL = 90%
$\Gamma(\omega(782) \to 3\pi^0)/\Gamma_{\text{total}}$		$<3 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<1.3 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to \eta e^+ e^-)/\Gamma_{\text{total}}$	[a]	$<1.1 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to 3\gamma)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\pi^0)/\Gamma_{\text{total}}$	[a]	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\eta'(958) \to \mu^+\mu^-\eta)/\Gamma_{\text{total}}$	[a]	$<1.5 \times 10^{-5}$, CL = 90%

PARITY (P) INVARIANCE

e electric dipole moment	$(0.18 \pm 0.16) \times 10^{-26}$ $e\,$cm
μ electric dipole moment	$(3.7 \pm 3.4) \times 10^{-19}$ $e\,$cm
τ electric dipole moment (d_τ)	> -3.1 and $< 3.1 \times 10^{-16}$ $e\,$cm, CL = 95%
$\Gamma(\eta \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^+\pi^-)/\Gamma_{\text{total}}$	$<2 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \to \pi^0\pi^0)/\Gamma_{\text{total}}$	$<9 \times 10^{-4}$, CL = 90%
p electric dipole moment	$(-4 \pm 6) \times 10^{-23}$ $e\,$cm
n electric dipole moment	$<0.97 \times 10^{-25}$ $e\,$cm, CL = 90%
Λ electric dipole moment	$<1.5 \times 10^{-16}$ $e\,$cm, CL = 95%

TIME REVERSAL (T) INVARIANCE

Limits on e, μ, τ, p, n, and Λ electric dipole moments under Parity Invariance above are also tests of Time Reversal Invariance.

μ decay parameters		
transverse e^+ polarization normal to plane of μ spin, e^+ momentum		0.007 ± 0.023
α'/A		$(0 \pm 4) \times 10^{-3}$
β'/A		$(2 \pm 6) \times 10^{-3}$
τ electric dipole moment (d_τ)		> -3.1 and $< 3.1 \times 10^{-16}$ $e$cm, CL = 95%
Im(ξ) in $K^{\pm}_{\mu 3}$ decay (from transverse μ pol.)		-0.017 ± 0.025
Im(ξ) in $K^{0}_{\mu 3}$ decay (from transverse μ pol.)		-0.007 ± 0.026
$n \rightarrow p e^- \nu$ decay parameters		
ϕ_{AV}, phase of g_A relative to g_V	[b]	$(180.07 \pm 0.18)^\circ$
triple correlation coefficient D		$(-0.5 \pm 1.4) \times 10^{-3}$
triple correlation coefficient D for $\Sigma^- \rightarrow n e^- \overline{\nu}_e$		0.11 ± 0.10

CP INVARIANCE

$\mathrm{Re}(d_\tau^W)$		$<0.56 \times 10^{-17}$ e cm, CL = 95%
$\mathrm{Im}(d_\tau^W)$		$<1.5 \times 10^{-17}$ e cm, CL = 95%
$\Gamma(\eta \rightarrow \pi^+\pi^-)/\Gamma_{\mathrm{total}}$		$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\eta'(958) \rightarrow \pi^+\pi^-)/\Gamma_{\mathrm{total}}$		$<2 \times 10^{-2}$, CL = 90%
$\Gamma(\eta'(958) \rightarrow \pi^0\pi^0)/\Gamma_{\mathrm{total}}$		$<9 \times 10^{-4}$, CL = 90%
$K^\pm \rightarrow \pi^\pm\pi^+\pi^-$ rate difference/average		(0.07 ± 0.12)%
$K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ rate difference/average		(0.0 ± 0.6)%
$K^\pm \rightarrow \pi^\pm\pi^0\gamma$ rate difference/average		(0.9 ± 3.3)%
$(g_{\tau^+} - g_{\tau^-})$ / $(g_{\tau^+} + g_{\tau^-})$ for $K^\pm \rightarrow \pi^\pm\pi^+\pi^-$		(-0.7 ± 0.5)%
CP-violation parameters in K_S^0 decay		
$\mathrm{Im}(\eta_{+-0}) = \mathrm{Im}(\mathrm{A}(K_S^0 \rightarrow \pi^+\pi^-\pi^0$, *CP*-violating) / $\mathrm{A}(K_L^0 \rightarrow \pi^+\pi^-\pi^0))$		-0.002 ± 0.008
$\mathrm{Im}(\eta_{000})^2 = \Gamma(K_S^0 \rightarrow 3\pi^0)$ / $\Gamma(K_L^0 \rightarrow 3\pi^0)$		<0.1, CL = 90%
charge asymmetry j for $K_L^0 \rightarrow \pi^+\pi^-\pi^0$		0.0011 ± 0.0008
$\lvert\epsilon'_{+-\gamma}\rvert/\epsilon$ for $K_L^0 \rightarrow \pi^+\pi^-\gamma$		<0.3, CL = 90%
$\Gamma(K_L^0 \rightarrow \pi^0\mu^+\mu^-)/\Gamma_{\mathrm{total}}$	[*c*]	$<5.1 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \rightarrow \pi^0 e^+ e^-)/\Gamma_{\mathrm{total}}$	[*c*]	$<4.3 \times 10^{-9}$, CL = 90%
$\Gamma(K_L^0 \rightarrow \pi^0\nu\overline{\nu})/\Gamma_{\mathrm{total}}$	[*d*]	$<5.8 \times 10^{-5}$, CL = 90%
$A_{CP}(K^+K^-\pi^\pm)$ in $D^\pm \rightarrow K^+K^-\pi^\pm$		-0.017 ± 0.027
$A_{CP}(K^\pm K^{*0})$ in $D^+ \rightarrow K^+\overline{K}^{*0}$ and $D^- \rightarrow K^-K^{*0}$		-0.02 ± 0.05
$A_{CP}(\phi\pi^\pm)$ in $D^\pm \rightarrow \phi\pi^\pm$		-0.014 ± 0.033
$A_{CP}(\pi^+\pi^-\pi^\pm)$ in $D^\pm \rightarrow \pi^+\pi^-\pi^\pm$		-0.02 ± 0.04
$A_{CP}(K^+K^-)$ in D^0, $\overline{D}^0 \rightarrow K^+K^-$		0.026 ± 0.035
$A_{CP}(\pi^+\pi^-)$ in D^0, $\overline{D}^0 \rightarrow \pi^+\pi^-$		-0.05 ± 0.08
$A_{CP}(K_S^0\phi)$ in D^0, $\overline{D}^0 \rightarrow K_S^0\phi$		-0.03 ± 0.09
$A_{CP}(K_S^0\pi^0)$ in D^0, $\overline{D}^0 \rightarrow K_S^0\pi^0$		-0.018 ± 0.030
$\lvert\mathrm{Re}(\epsilon_{B^0})\rvert$		0.002 ± 0.008
$[\alpha_-(\Lambda) + \alpha_+(\overline{\Lambda})]$ / $[\alpha_-(\Lambda) - \alpha_+(\overline{\Lambda})]$		-0.03 ± 0.06

CP VIOLATION OBSERVED

K^0_L branching ratios		
charge asymmetry in $K^0_{\ell 3}$ decays		
$\delta(\mu) = [\Gamma(\pi^- \mu^+ \nu_\mu) - \Gamma(\pi^+ \mu^- \overline{\nu}_\mu)]/\text{sum}$		$(0.304 \pm 0.025)\%$
$\delta(e) = [\Gamma(\pi^- e^+ \nu_e) - \Gamma(\pi^+ e^- \overline{\nu}_e)]/\text{sum}$		$(0.333 \pm 0.014)\%$
parameters for $K^0_L \rightarrow 2\pi$ decay		
$\lvert\eta_{00}\rvert = \lvert A(K^0_L \rightarrow 2\pi^0) / A(K^0_S \rightarrow 2\pi^0)\rvert$		$(2.275 \pm 0.019) \times 10^{-3}$ (S = 1.1)
$\lvert\eta_{+-}\rvert = \lvert A(K^0_L \rightarrow \pi^+\pi^-) / A(K^0_S \rightarrow \pi^+\pi^-)\rvert$		$(2.285 \pm 0.019) \times 10^{-3}$
$\epsilon'/\epsilon \approx \text{Re}(\epsilon'/\epsilon) = (1-\lvert\eta_{00}/\eta_{+-}\rvert)/3$	[e]	$(1.5 \pm 0.8) \times 10^{-3}$ (S = 1.8)
ϕ_{+-}, phase of η_{+-}		$(43.5 \pm 0.6)^\circ$
ϕ_{00}, phase of η_{00}		$(43.4 \pm 1.0)^\circ$
parameters for $K^0_L \rightarrow \pi^+\pi^-\gamma$ decay		
$\lvert\eta_{+-\gamma}\rvert = \lvert A(K^0_L \rightarrow \pi^+\pi^-\gamma$, *CP* violating)$/A(K^0_S \rightarrow \pi^+\pi^-\gamma)\rvert$		$(2.35 \pm 0.07) \times 10^{-3}$
$\phi_{+-\gamma}$ = phase of $\eta_{+-\gamma}$		$(44 \pm 4)^\circ$
$\Gamma(K^0_L \rightarrow \pi^+\pi^-)/\Gamma_{\text{total}}$		$(2.067 \pm 0.035) \times 10^{-3}$ (S = 1.1)
$\Gamma(K^0_L \rightarrow \pi^0\pi^0)/\Gamma_{\text{total}}$		$(9.36 \pm 0.20) \times 10^{-4}$

CPT INVARIANCE

$(m_{W^+} - m_{W^-}) / m_{\text{average}}$		-0.002 ± 0.007
$(m_{e^+} - m_{e^-}) / m_{\text{average}}$		$<4 \times 10^{-8}$, CL = 90%
$\lvert q_{e^+} + q_{e^-} \rvert / e$		$<4 \times 10^{-8}$
$(g_{e^+} - g_{e^-}) / g_{\text{average}}$		$(-0.5 \pm 2.1) \times 10^{-12}$
$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$		$(2 \pm 8) \times 10^{-5}$
$(g_{\mu^+} - g_{\mu^-}) / g_{\text{average}}$		$(-2.6 \pm 1.6) \times 10^{-8}$
$(m_{\pi^+} - m_{\pi^-}) / m_{\text{average}}$		$(2 \pm 5) \times 10^{-4}$
$(\tau_{\pi^+} - \tau_{\pi^-}) / \tau_{\text{average}}$		$(6 \pm 7) \times 10^{-4}$
$(m_{K^+} - m_{K^-}) / m_{\text{average}}$		$(-0.6 \pm 1.8) \times 10^{-4}$
$(\tau_{K^+} - \tau_{K^-}) / \tau_{\text{average}}$		(0.11 ± 0.09)% (S = 1.2)
$K^\pm \rightarrow \mu^\pm \nu_\mu$ rate difference/average		(-0.5 ± 0.4)%
$K^\pm \rightarrow \pi^\pm \pi^0$ rate difference/average	[f]	(0.8 ± 1.2)%
$\lvert m_{K^0} - m_{\overline{K}^0} \rvert / m_{\text{average}}$	[g]	$<10^{-18}$
phase difference $\phi_{00} - \phi_{+-}$		$(-0.1 \pm 0.8)^\circ$
CPT-violation parameters in K^0 decay		
real part of Δ		0.018 ± 0.020
imaginary part of Δ		0.02 ± 0.04
$(\lvert \frac{q_{\overline{p}}}{m_{\overline{p}}} \rvert - \frac{q_p}{m_p}) / \lvert \frac{q}{m} \rvert_{\text{average}}$		$(1.5 \pm 1.1) \times 10^{-9}$
$\lvert q_p + q_{\overline{p}} \rvert / e$		$<2 \times 10^{-5}$
$(\mu_p + \mu_{\overline{p}}) / \lvert \mu \rvert_{\text{average}}$		$(-2.6 \pm 2.9) \times 10^{-3}$
$(m_n - m_{\overline{n}}) / m_{\text{average}}$		$(9 \pm 5) \times 10^{-5}$
$(m_\Lambda - m_{\overline{\Lambda}}) / m_\Lambda$		$(-1.0 \pm 0.9) \times 10^{-5}$
$(\tau_\Lambda - \tau_{\overline{\Lambda}}) / \tau_{\text{average}}$		0.04 ± 0.09
$(\mu_{\Sigma^+} + \mu_{\overline{\Sigma}^-}) / \lvert \mu \rvert_{\text{average}}$		0.014 ± 0.015
$(m_{\Xi^-} - m_{\overline{\Xi}^+}) / m_{\text{average}}$		$(1.1 \pm 2.7) \times 10^{-4}$
$(\tau_{\Xi^-} - \tau_{\overline{\Xi}^+}) / \tau_{\text{average}}$		0.02 ± 0.18
$(m_{\Omega^-} - m_{\overline{\Omega}^+}) / m_{\text{average}}$		$(0 \pm 5) \times 10^{-4}$

TESTS OF NUMBER CONSERVATION LAWS

LEPTON FAMILY NUMBER

Lepton family number conservation means separate conservation of each of L_e, L_μ, L_τ.

$\Gamma(Z \to e^{\pm}\mu^{\mp})/\Gamma_{\text{total}}$	[h]	$<1.7 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to e^{\pm}\tau^{\mp})/\Gamma_{\text{total}}$	[h]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^{\pm}\tau^{\mp})/\Gamma_{\text{total}}$	[h]	$<1.2 \times 10^{-5}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^-\,{}^{32}\text{S} \to e^-\,{}^{32}\text{S})$ / $\sigma(\mu^-\,{}^{32}\text{S} \to \nu_\mu\,{}^{32}\text{P}^*)$		$<7 \times 10^{-11}$, CL = 90%
$\sigma(\mu^-\,\text{Ti} \to e^-\,\text{Ti})$ / $\sigma(\mu^-\,\text{Ti} \to \text{capture})$		$<4.3 \times 10^{-12}$, CL = 90%
$\sigma(\mu^-\,\text{Pb} \to e^-\,\text{Pb})$ / $\sigma(\mu^-\,\text{Pb} \to \text{capture})$		$<4.6 \times 10^{-11}$, CL = 90%
limit on muonium $\to$ antimuonium conversion $R_g = G_C\,/\,G_F$		<0.018, CL = 90%
$\Gamma(\mu^- \to e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\text{total}}$	[i]	$<1.2 \times 10^{-2}$, CL = 90%
$\Gamma(\mu^- \to e^-\gamma)/\Gamma_{\text{total}}$		$<4.9 \times 10^{-11}$, CL = 90%
$\Gamma(\mu^- \to e^-e^+e^-)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-12}$, CL = 90%
$\Gamma(\mu^- \to e^-2\gamma)/\Gamma_{\text{total}}$		$<7.2 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^-\gamma)/\Gamma_{\text{total}}$		$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\gamma)/\Gamma_{\text{total}}$		$<3.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\pi^0)/\Gamma_{\text{total}}$		$<3.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\pi^0)/\Gamma_{\text{total}}$		$<4.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-K^0)/\Gamma_{\text{total}}$		$<1.3 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to \mu^-K^0)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-3}$, CL = 90%
$\Gamma(\tau^- \to e^-\eta)/\Gamma_{\text{total}}$		$<8.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\eta)/\Gamma_{\text{total}}$		$<9.6 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\rho^0)/\Gamma_{\text{total}}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\rho^0)/\Gamma_{\text{total}}$		$<6.3 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-K^*(892)^0)/\Gamma_{\text{total}}$		$<5.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-K^*(892)^0)/\Gamma_{\text{total}}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\overline{K}^*(892)^0)/\Gamma_{\text{total}}$		$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\overline{K}^*(892)^0)/\Gamma_{\text{total}}$		$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\phi)/\Gamma_{\text{total}}$		$<6.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^-\phi)/\Gamma_{\text{total}}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-e^+e^-)/\Gamma_{\text{total}}$		$<2.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^-\mu^+\mu^-)/\Gamma_{\text{total}}$		$<1.8 \times 10^{-6}$, CL = 90%

$\Gamma(\tau^- \to e^+ \mu^- \mu^-)/\Gamma_{total}$	$<1.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- e^+ e^-)/\Gamma_{total}$	$<1.7 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ e^- e^-)/\Gamma_{total}$	$<1.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \mu^+ \mu^-)/\Gamma_{total}$	$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ \pi^-)/\Gamma_{total}$	$<2.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ \pi^-)/\Gamma_{total}$	$<8.2 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^+ K^-)/\Gamma_{total}$	$<6.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^- K^+)/\Gamma_{total}$	$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to e^- K^+ K^-)/\Gamma_{total}$	$<6.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^+ K^-)/\Gamma_{total}$	$<7.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^- K^+)/\Gamma_{total}$	$<7.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- K^+ K^-)/\Gamma_{total}$	$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0 \pi^0)/\Gamma_{total}$	$<6.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0 \pi^0)/\Gamma_{total}$	$<1.4 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \eta \eta)/\Gamma_{total}$	$<3.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \eta \eta)/\Gamma_{total}$	$<6.0 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \pi^0 \eta)/\Gamma_{total}$	$<2.4 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \mu^- \pi^0 \eta)/\Gamma_{total}$	$<2.2 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to e^- \text{light boson})/\Gamma_{total}$	$<2.7 \times 10^{-3}$, CL = 95%
$\Gamma(\tau^- \to \mu^- \text{light boson})/\Gamma_{total}$	$<5 \times 10^{-3}$, CL = 95%

ν oscillations. (For other lepton mixing effects in particle decays, see the Particle Listings.)

$\overline{\nu}_e \not\to \overline{\nu}_e$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	$<9 \times 10^{-4}$ eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	<0.02, CL = 90%
$\nu_e \to \nu_\tau$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	<9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	<0.25, CL = 90%
$\overline{\nu}_e \to \overline{\nu}_\tau$	
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	<0.7, CL = 90%
$\nu_\mu \to \nu_e$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	<0.09 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	$<3.0 \times 10^{-3}$, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_e$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	<0.14 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	<0.004, CL = 95%
$\nu_\mu(\overline{\nu}_\mu) \to \nu_e(\overline{\nu}_e)$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	<0.075 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	$<1.8 \times 10^{-3}$, CL = 90%
$\nu_\mu \to \nu_\tau$	
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$	<0.9 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$	<0.004, CL = 90%
$\overline{\nu}_\mu \to \overline{\nu}_\tau$	

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<2.2 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<4.4 \times 10^{-2}$, CL = 90%
$\nu_\mu (\overline{\nu}_\mu) \rightarrow \nu_\tau (\overline{\nu}_\tau)$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<1.5 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<8 \times 10^{-3}$, CL = 90%
$\nu_e \not\rightarrow \nu_e$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.17 eV^2, CL = 90%
$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$		$<7 \times 10^{-2}$, CL = 90%
$\nu_\mu \not\rightarrow \nu_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.23 or >1500 eV^2
$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2	[*j*]	<0.02, CL = 90%
$\overline{\nu}_\mu \not\rightarrow \overline{\nu}_\mu$		
$\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<7 or >1200 eV^2
$\sin^2(2\theta)$ for 190 eV^2 $<$ $\Delta(m^2)$ $<$ 320 eV^2	[*k*]	<0.02, CL = 90%
$\Gamma(\pi^+ \rightarrow \mu^+ \nu_e)/\Gamma_{\rm total}$	[*l*]	$<8.0 \times 10^{-3}$, CL = 90%
$\Gamma(\pi^+ \rightarrow \mu^- e^+ e^+ \nu)/\Gamma_{\rm total}$		$<1.6 \times 10^{-6}$, CL = 90%
$\Gamma(\pi^0 \rightarrow \mu^+ e^- + e^- \mu^+)/\Gamma_{\rm total}$		$<1.72 \times 10^{-8}$, CL = 90%
$\Gamma(\eta \rightarrow \mu^+ e^- + \mu^- e^+)/\Gamma_{\rm total}$		$<6 \times 10^{-6}$, CL = 90%
$\Gamma(K^+ \rightarrow \mu^- \nu e^+ e^+)/\Gamma_{\rm total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \rightarrow \mu^+ \nu_e)/\Gamma_{\rm total}$	[*l*]	$<4 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^+ \mu^+ e^-)/\Gamma_{\rm total}$		$<2.1 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^+ \mu^- e^+)/\Gamma_{\rm total}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \rightarrow e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<3.3 \times 10^{-11}$, CL = 90%
$\Gamma(K^0_L \rightarrow e^\pm e^\pm \mu^\mp \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<6.1 \times 10^{-9}$, CL = 90%
$\Gamma(D^+ \rightarrow \pi^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \rightarrow \pi^+ e^- \mu^+)/\Gamma_{\rm total}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \rightarrow K^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \rightarrow K^+ e^- \mu^+)/\Gamma_{\rm total}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \rightarrow \mu^\pm e^\mp)/\Gamma_{\rm total}$	[*h*]	$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \rightarrow \pi^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<8.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \rightarrow \eta e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \rightarrow \rho^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<4.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \rightarrow \omega e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \rightarrow \phi e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<3.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \rightarrow \overline{K}^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \rightarrow \overline{K}^*(892)^0 e^\pm \mu^\mp)/\Gamma_{\rm total}$	[*h*]	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \rightarrow \pi^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow \pi^+ e^- \mu^+)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow K^+ e^+ \mu^-)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow K^+ e^- \mu^+)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow \pi^- e^+ \mu^+)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \rightarrow K^- e^+ \mu^+)/\Gamma_{\rm total}$		$<6.4 \times 10^{-3}$, CL = 90%

$\Gamma(B^0 \rightarrow e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[*h*]	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \rightarrow e^\pm \tau^\mp)/\Gamma_{\text{total}}$	[*h*]	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \rightarrow \mu^\pm \tau^\mp)/\Gamma_{\text{total}}$	[*h*]	$<8.3 \times 10^{-4}$, CL = 90%
$\Gamma(B \rightarrow e^\pm \mu^\mp s)/\Gamma_{\text{total}}$		$<2.2 \times 10^{-5}$, CL = 90%
$\Gamma(B_s^0 \rightarrow e^\pm \mu^\mp)/\Gamma_{\text{total}}$	[*h*]	$<4.1 \times 10^{-5}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

limit on $\mu^- \rightarrow e^+$ conversion		
$\sigma(\mu^- \, ^{32}\text{S} \rightarrow e^+ \, ^{32}\text{Si}^*)$ / $\sigma(\mu^- \, ^{32}\text{S} \rightarrow \nu_\mu \, ^{32}\text{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, ^{127}\text{I} \rightarrow e^+ \, ^{127}\text{Sb}^*)$ / $\sigma(\mu^- \, ^{127}\text{I} \rightarrow \text{anything})$		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, \text{Ti} \rightarrow e^+ \, \text{Ca})$ / $\sigma(\mu^- \, \text{Ti} \rightarrow \text{capture})$		$<8.9 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \rightarrow \pi^- \gamma)/\Gamma_{\text{total}}$		$<2.8 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \rightarrow \pi^- \pi^0)/\Gamma_{\text{total}}$		$<3.7 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \rightarrow e^+ \pi^- \pi^-)/\Gamma_{\text{total}}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow \mu^+ \pi^- \pi^-)/\Gamma_{\text{total}}$		$<3.4 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow e^+ \pi^- K^-)/\Gamma_{\text{total}}$		$<2.1 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow e^+ K^- K^-)/\Gamma_{\text{total}}$		$<3.8 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow \mu^+ \pi^- K^-)/\Gamma_{\text{total}}$		$<7.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow \mu^+ K^- K^-)/\Gamma_{\text{total}}$		$<6.0 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \rightarrow \overline{p} \gamma)/\Gamma_{\text{total}}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \rightarrow \overline{p} \pi^0)/\Gamma_{\text{total}}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \rightarrow \overline{p} \eta)/\Gamma_{\text{total}}$		$<1.30 \times 10^{-3}$, CL = 90%
$\nu_e \rightarrow (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.14 eV^2, CL = 90%
$\alpha^2 \sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.032, CL = 90%
$\nu_\mu \rightarrow (\overline{\nu}_e)_L$		
$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$		<0.16 eV^2, CL = 90%
$\alpha^2 \sin^2(2\theta)$ for "Large" $\Delta(m^2)$		<0.001, CL = 90%
$\Gamma(\pi^+ \rightarrow \mu^+ \overline{\nu}_e)/\Gamma_{\text{total}}$	[*l*]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^- \mu^+ e^+)/\Gamma_{\text{total}}$		$<7 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^- e^+ e^+)/\Gamma_{\text{total}}$		$<1.0 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^- \mu^+ \mu^+)/\Gamma_{\text{total}}$	[*l*]	$<1.5 \times 10^{-4}$, CL = 90%
$\Gamma(K^+ \rightarrow \mu^+ \overline{\nu}_e)/\Gamma_{\text{total}}$	[*l*]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \rightarrow \pi^0 e^+ \overline{\nu}_e)/\Gamma_{\text{total}}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \rightarrow \pi^- e^+ e^+)/\Gamma_{\text{total}}$		$<1.1 \times 10^{-4}$, CL = 90%

$\Gamma(D^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<8.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+ \mu^+)/\Gamma_{total}$		$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to \rho^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<1.2 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- e^+ \mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<4.3 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^- \mu^+ \mu^+)/\Gamma_{total}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- \mu^+ \mu^+)/\Gamma_{total}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^- \mu^+ \mu^+)/\Gamma_{total}$		$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(\Xi^- \to p \mu^- \mu^-)/\Gamma_{total}$		$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^- \mu^+ \mu^+)/\Gamma_{total}$		$<7.0 \times 10^{-4}$, CL = 90%

BARYON NUMBER

$\Gamma(\tau^- \to \overline{p} \gamma)/\Gamma_{total}$		$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \pi^0)/\Gamma_{total}$		$<6.6 \times 10^{-4}$, CL = 90%
$\Gamma(\tau^- \to \overline{p} \eta)/\Gamma_{total}$		$<1.30 \times 10^{-3}$, CL = 90%
p mean life		$>1.6 \times 10^{25}$ years

A few examples of proton or bound neutron decay follow. For limits on many other nucleon decay channels, see the Baryon Summary Table.

$\tau(N \to e^+ \pi)$		$>$ 130 (n), $>$ 550 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+ \pi)$		$>$ 100 (n), $>$ 270 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to e^+ K)$		$>$ 1.3 (n), $>$ 150 (p) $\times 10^{30}$ years, CL = 90%
$\tau(N \to \mu^+ K)$		$>$ 1.1 (n), $>$ 120 (p) $\times 10^{30}$ years, CL = 90%
limit on $n\overline{n}$ oscillations (bound n)	[m]	$>1.2 \times 10^{8}$ s, CL = 90%
limit on $n\overline{n}$ oscillations (free n)		$>0.86 \times 10^{8}$ s, CL = 90%

ELECTRIC CHARGE (Q)

e mean life / branching fraction	[n]	$>4.3 \times 10^{23}$ yr, CL = 68%
$\Gamma(n \to p \nu_e \overline{\nu}_e)/\Gamma_{total}$		$<8 \times 10^{-27}$, CL = 68%

$\Delta S = \Delta Q$ RULE

Allowed in second-order weak interactions.

$\Gamma(K^+ \to \pi^+\pi^+ e^- \overline{\nu}_e)/\Gamma_{total}$	$<1.2 \times 10^{-8}$, CL = 90%
$\Gamma(K^+ \to \pi^+\pi^+ \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<3.0 \times 10^{-6}$, CL = 95%
$x = \mathrm{A}(\overline{K}^0 \to \pi^- \ell^+ \nu)/\mathrm{A}(K^0 \to \pi^- \ell^+ \nu) = \mathrm{A}(\Delta S{=}-\Delta Q)/\mathrm{A}(\Delta S{=}\Delta Q)$	
real part of x	0.006 ± 0.018 (S = 1.3)
imaginary part of x	-0.003 ± 0.026 (S = 1.2)
$\Gamma(\Sigma^+ \to n\ell^+\nu)/\Gamma(\Sigma^- \to n\ell^-\overline{\nu})$	<0.043
$\Gamma(\Sigma^+ \to n e^+ \nu_e)/\Gamma_{total}$	$<5 \times 10^{-6}$, CL = 90%
$\Gamma(\Sigma^+ \to n \mu^+ \nu_\mu)/\Gamma_{total}$	$<3.0 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^- e^+ \nu_e)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^0 \to \Sigma^- \mu^+ \nu_\mu)/\Gamma_{total}$	$<9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ FORBIDDEN

Allowed in second-order weak interactions.

$\Gamma(\Xi^0 \to p\pi^-)/\Gamma_{total}$	$<4 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^0 \to p e^- \overline{\nu}_e)/\Gamma_{total}$	$<1.3 \times 10^{-3}$
$\Gamma(\Xi^0 \to p \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<1.3 \times 10^{-3}$
$\Gamma(\Xi^- \to n\pi^-)/\Gamma_{total}$	$<1.9 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to n e^- \overline{\nu}_e)/\Gamma_{total}$	$<3.2 \times 10^{-3}$, CL = 90%
$\Gamma(\Xi^- \to n \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<1.5 \times 10^{-2}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^-\pi^-)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^- e^- \overline{\nu}_e)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Xi^- \to p\pi^- \mu^- \overline{\nu}_\mu)/\Gamma_{total}$	$<4 \times 10^{-4}$, CL = 90%
$\Gamma(\Omega^- \to \Lambda\pi^-)/\Gamma_{total}$	$<1.9 \times 10^{-4}$, CL = 90%

$\Delta S = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$m_{K_L^0} - m_{K_S^0}$	$(0.5301 \pm 0.0014) \times 10^{10}\ \hbar\ \mathrm{s}^{-1}$
$m_{K_L^0} - m_{K_S^0}$	$(3.489 \pm 0.009) \times 10^{-12}$ MeV

$\Delta C = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

$\lvert m_{D^0_1} - m_{D^0_2} \rvert$	[o]	$<24 \times 10^{10}$ $\hbar$ s^{-1}, CL = 90%
$\lvert \Gamma_{D^0_1} - \Gamma_{D^0_2} \rvert / \Gamma_{D^0}$ mean life difference/average	[o]	<0.20, CL = 90%
$\Gamma(K^+ \ell^- \overline{\nu}_\ell (\text{via } \overline{D}^0)) / \Gamma(K^- \ell^+ \nu_\ell)$		<0.005, CL = 90%
$\Gamma(K^+ \pi^-$ or $K^+ \pi^- \pi^+ \pi^-$ (via $\overline{D}^0$))/$\Gamma(K^- \pi^+$ or $K^- \pi^+ \pi^+ \pi^-)$	[p]	< 0.0085 (or < 0.0037), CL = 90%
$\Gamma(D^0 \rightarrow K^+ \ell^- \overline{\nu}_\ell (\text{via } \overline{D}^0))/\Gamma_{\text{total}}$		$<1.7 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \rightarrow K^+ \pi^-$ or $K^+ \pi^- \pi^+ \pi^-$ (via $\overline{D}^0$))/Γ_{total}		$<1.0 \times 10^{-3}$, CL = 90%

$\Delta B = 2$ VIA MIXING

Allowed in second-order weak interactions, e.g. mixing.

χ_d	0.172 ± 0.010
$\Delta m_{B^0} = m_{B^0_H} - m_{B^0_L}$	$(0.464 \pm 0.018) \times 10^{12}$ $\hbar$ s^{-1}
$x_d = \Delta m_{B^0} / \Gamma_{B^0}$	0.723 ± 0.032
χ_B at high energy	0.118 ± 0.006
$\Delta m_{B^0_s} = m_{B^0_{sH}} - m_{B^0_{sL}}$	$>9.1 \times 10^{12}$ $\hbar$ s^{-1}, CL = 95%
$x_s = \Delta m_{B^0_s} / \Gamma_{B^0_s}$	>14.0, CL = 95%
χ_s	>0.4975, CL = 95%

$\Delta S = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(K^+ \rightarrow \pi^+ e^+ e^-)/\Gamma_{\text{total}}$	$(2.74 \pm 0.23) \times 10^{-7}$
$\Gamma(K^+ \rightarrow \pi^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$	$(5.0 \pm 1.0) \times 10^{-8}$
$\Gamma(K^+ \rightarrow \pi^+ \nu \overline{\nu})/\Gamma_{\text{total}}$	$(4.2^{+9.7}_{-3.5}) \times 10^{-10}$
$\Gamma(K^0_S \rightarrow \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<3.2 \times 10^{-7}$, CL = 90%
$\Gamma(K^0_S \rightarrow e^+ e^-)/\Gamma_{\text{total}}$	$<1.4 \times 10^{-7}$, CL = 90%
$\Gamma(K^0_S \rightarrow \pi^0 e^+ e^-)/\Gamma_{\text{total}}$	$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(K^0_L \rightarrow \mu^+ \mu^-)/\Gamma_{\text{total}}$	$(7.2 \pm 0.5) \times 10^{-9}$ (S = 1.4)
$\Gamma(K^0_L \rightarrow \mu^+ \mu^- \gamma)/\Gamma_{\text{total}}$	$(3.25 \pm 0.28) \times 10^{-7}$
$\Gamma(K^0_L \rightarrow e^+ e^-)/\Gamma_{\text{total}}$	$<4.1 \times 10^{-11}$, CL = 90%
$\Gamma(K^0_L \rightarrow e^+ e^- \gamma)/\Gamma_{\text{total}}$	$(9.1 \pm 0.5) \times 10^{-6}$

$\Gamma(K^0_L \to e^+ e^- \gamma\gamma)/\Gamma_{\rm total}$	[q]	$(6.5 \pm 1.2) \times 10^{-7}$
$\Gamma(K^0_L \to \pi^+ \pi^- e^+ e^-)/\Gamma_{\rm total}$	[q]	$<4.6 \times 10^{-7}$, CL = 90%
$\Gamma(K^0_L \to \mu^+ \mu^- e^+ e^-)/\Gamma_{\rm total}$		$(2.9^{+6.7}_{-2.4}) \times 10^{-9}$
$\Gamma(K^0_L \to e^+ e^- e^+ e^-)/\Gamma_{\rm total}$		$(4.1 \pm 0.8) \times 10^{-8}$ (S = 1.2)
$\Gamma(K^0_L \to \pi^0 \mu^+ \mu^-)/\Gamma_{\rm total}$		$<5.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to \pi^0 e^+ e^-)/\Gamma_{\rm total}$		$<4.3 \times 10^{-9}$, CL = 90%
$\Gamma(K^0_L \to \pi^0 \nu\overline{\nu})/\Gamma_{\rm total}$		$<5.8 \times 10^{-5}$, CL = 90%
$\Gamma(\Sigma^+ \to p e^+ e^-)/\Gamma_{\rm total}$		$<7 \times 10^{-6}$

$\Delta C = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(D^+ \to \pi^+ e^+ e^-)/\Gamma_{\rm total}$	$<6.6 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \pi^+ \mu^+ \mu^-)/\Gamma_{\rm total}$	$<1.8 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to \rho^+ \mu^+ \mu^-)/\Gamma_{\rm total}$	$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to e^+ e^-)/\Gamma_{\rm total}$	$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \mu^+ \mu^-)/\Gamma_{\rm total}$	$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^0 \to \pi^0 e^+ e^-)/\Gamma_{\rm total}$	$<4.5 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^0 \mu^+ \mu^-)/\Gamma_{\rm total}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta e^+ e^-)/\Gamma_{\rm total}$	$<1.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \eta \mu^+ \mu^-)/\Gamma_{\rm total}$	$<5.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 e^+ e^-)/\Gamma_{\rm total}$	$<1.0 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \rho^0 \mu^+ \mu^-)/\Gamma_{\rm total}$	$<2.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega e^+ e^-)/\Gamma_{\rm total}$	$<1.8 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \omega \mu^+ \mu^-)/\Gamma_{\rm total}$	$<8.3 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \phi e^+ e^-)/\Gamma_{\rm total}$	$<5.2 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \phi \mu^+ \mu^-)/\Gamma_{\rm total}$	$<4.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to \pi^+ \pi^- \pi^0 \mu^+ \mu^-)/\Gamma_{\rm total}$	$<8.1 \times 10^{-4}$, CL = 90%
$\Gamma(D^+_s \to K^+ \mu^+ \mu^-)/\Gamma_{\rm total}$	$<5.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^+_s \to K^*(892)^+ \mu^+ \mu^-)/\Gamma_{\rm total}$	$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(\Lambda^+_c \to p \mu^+ \mu^-)/\Gamma_{\rm total}$	$<3.4 \times 10^{-4}$, CL = 90%

$\Delta B = 1$ WEAK NEUTRAL CURRENT FORBIDDEN

Allowed by higher-order electroweak interactions.

$\Gamma(B^+ \to \pi^+ e^+ e^-)/\Gamma_{\text{total}}$	$<3.9 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<9.1 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to K^+ e^+ e^-)/\Gamma_{\text{total}}$	$<6 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \to K^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^+ e^+ e^-)/\Gamma_{\text{total}}$	$<6.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^+ \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<1.2 \times 10^{-3}$, CL = 90%
$\Gamma(B^0 \to \gamma\gamma)/\Gamma_{\text{total}}$	$<3.9 \times 10^{-5}$, CL = 90%
$\Gamma(B^0 \to e^+ e^-)/\Gamma_{\text{total}}$	$<5.9 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<6.8 \times 10^{-7}$, CL = 90%
$\Gamma(B^0 \to K^0 e^+ e^-)/\Gamma_{\text{total}}$	$<3.0 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<3.6 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^*(892)^0 e^+ e^-)/\Gamma_{\text{total}}$	$<2.9 \times 10^{-4}$, CL = 90%
$\Gamma(B^0 \to K^*(892)^0 \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<2.3 \times 10^{-5}$, CL = 90%
$\Gamma(B^0 \to K^*(892)^0 \nu\overline{\nu})/\Gamma_{\text{total}}$	$<1.0 \times 10^{-3}$, CL = 90%
$\Gamma(B \to e^+ e^- s)/\Gamma_{\text{total}}$	$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(B \to \mu^+ \mu^- s)/\Gamma_{\text{total}}$	$<5.8 \times 10^{-5}$, CL = 90%
$\Gamma(\overline{b} \to \mu^+ \mu^- \text{anything})/\Gamma_{\text{total}}$	$<3.2 \times 10^{-4}$, CL = 90%
$\Gamma(B_s^0 \to \mu^+ \mu^-)/\Gamma_{\text{total}}$	$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(B_s^0 \to e^+ e^-)/\Gamma_{\text{total}}$	$<5.4 \times 10^{-5}$, CL = 90%
$\Gamma(B_s^0 \to \phi\nu\overline{\nu})/\Gamma_{\text{total}}$	$<5.4 \times 10^{-3}$, CL = 90%

NOTES

[*a*] C parity forbids this to occur as a single-photon process.

[*b*] Time-reversal invariance requires this to be 0° or 180°.

[*c*] Allowed by higher-order electroweak interactions.

[*d*] Violates CP in leading order. Test of direct CP violation since the indirect CP-violating and CP-conserving contributions are expected to be suppressed.

[*e*] ϵ'/ϵ is derived from $\left|\eta_{00}/\eta_{+-}\right|$ measurements using theoretical input on phases.

[*f*] Neglecting photon channels. See, *e.g.*, A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).

[*g*] Derived from measured values of ϕ_{+-}, ϕ_{00}, $\left|\eta\right|$, $\left|m_{K_L^0} - m_{K_S^0}\right|$, and $\tau_{K_S^0}$, as described in the introduction to "Tests of Conservation Laws."

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

[*i*] A test of additive vs. multiplicative lepton family number conservation.

[*j*] $\Delta(m^2) = 100$ eV^2.

[*k*] 190 eV^2 $< \Delta(m^2) <$ 320 eV^2.

[*l*] Derived from an analysis of neutrino-oscillation experiments.

[*m*] There is some controversy about whether nuclear physics and model dependence complicate the analysis for bound neutrons (from which the best limit comes). The second limit here is from reactor experiments with free neutrons.

[*n*] This is the best "electron disappearance" limit. The best limit for the mode $e^- \rightarrow \nu\gamma$ is $> 2.35 \times 10^{25}$ yr (CL=68%).

[*o*] The D_1^0-D_2^0 limits are inferred from the D^0-$\overline{D}^0$ mixing ratio $\Gamma(K^+\ell^-\overline{\nu}_\ell(\text{via } \overline{D}^0))$ / $\Gamma(K^-\ell^+\nu_\ell)$.

[*p*] The larger limit (from E791) allows interference between the doubly Cabibbo-suppressed and mixing amplitudes; the smaller limit (from E691) doesn't. See the papers for details.

[*q*] See the K_L^0 Particle Listings for the energy limits used in this measurement.