μ

$J = \frac{1}{2}$

μ MASS

The mass is known more precisely in u (atomic mass units) than in MeV (see the footnote to COHEN 87). The conversion from u to MeV, 1 u = 931.49432 ± 0.00028 MeV, involves the relatively poorly known electronic charge.

Where m_μ/m_e was measured, we have used the 1986 CODATA value for m_e = 0.51099906 ± 0.00000015 MeV.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.658389±0.000034	[1] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.65841 ±0.00033	[2] BELTRAMI	86	SPEC	−	Muonic atoms
105.658432±0.000064	[3] KLEMPT	82	CNTR	+	Incl. in MARIAM 82
105.658386±0.000044	[4] MARIAM	82	CNTR	+	
105.65856 ±0.00015	[5] CASPERSON	77	CNTR	+	
105.65836 ±0.00026	[6] CROWE	72	CNTR		
105.65865 ±0.00044	[7] CRANE	71	CNTR		

[1] The mass is known more precisely in u: $m = 0.113428913 \pm 0.000000017$ u. COHEN 87 makes use of the other entries below.

[2] BELTRAMI 86 gives $m_\mu/m_e = 206.76830(64)$.

[3] KLEMPT 82 gives $m_\mu/m_e = 206.76835(11)$.

[4] MARIAM 82 gives $m_\mu/m_e = 206.768259(62)$.

[5] CASPERSON 77 gives $m_\mu/m_e = 206.76859(29)$.

[6] CROWE 72 gives $m_\mu/m_e = 206.7682(5)$.

[7] CRANE 71 gives $m_\mu/m_e = 206.76878(85)$.

μ MEAN LIFE τ

Measurements with an error > 0.001×10^{-6} s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/ μ^-

$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

VALUE	*DOCUMENT ID*
(2±8) × 10^{-5} OUR EVALUATION	

μ MAGNETIC MOMENT ANOMALY

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

For reviews of theory and experiments, see HUGHES 85, KINOSHITA 84, COMBLEY 81, FARLEY 79, and CALMET 77.

VALUE (units 10^{-6})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1165.9230±0.0084	COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1165.910 ±0.011	[8] BAILEY	79	CNTR	+	Storage ring
1165.937 ±0.012	[8] BAILEY	79	CNTR	−	Storage ring
1165.923 ±0.0085	[8] BAILEY	79	CNTR	±	Storage ring
1165.922 ±0.009	[8] BAILEY	77	CNTR	±	Storage ring
1166.16 ±0.31	BAILEY	68	CNTR	±	Storage rings
1162.0 ±5.0	CHARPAK	62	CNTR	+	

[8] BAILEY 79 is final result. Includes BAILEY 77 data. We use μ/p magnetic moment ratio = 3.1833452 and recalculate the BAILEY 79 values. Third BAILEY 79 result is first two combined.

$(g_{\mu^+} - g_{\mu^-})\ /\ g_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-8})	*DOCUMENT ID*	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-19} ecm)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.7±3.4	[9] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[9] This is the combination of the two BAILEY 78 results given below.

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass. Measurements with an error > 0.00001 have been omitted.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.18334547±0.00000047	[10] COHEN	87	RVUE		1986 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

[10] COHEN 87 (1986 CODATA) value was fitted using their own selection of the following data. Because their value is from a multiparameter fit, correlations with other quantities may be important and one cannot arrive at this result by any average of these data alone.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode	Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$	$\approx$ 100%	
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$	[*a*] (1.4±0.4) %	
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$	[*b*] $(3.4\pm0.4)\times10^{-5}$	

Lepton Family number (*LF*) violating modes

Γ_4	$e^- \nu_e \overline{\nu}_\mu$	*LF*	[*c*] < 1.2	%	90%
Γ_5	$e^- \gamma$	*LF*	< 4.9	$\times 10^{-11}$	90%
Γ_6	$e^- e^+ e^-$	*LF*	< 1.0	$\times 10^{-12}$	90%
Γ_7	$e^- 2\gamma$	*LF*	< 7.2	$\times 10^{-11}$	90%

[*a*] This only includes events with the γ energy > 10 MeV. Since the $e^- \overline{\nu}_e \nu_\mu$ and $e^- \overline{\nu}_e \nu_\mu \gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

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

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

μ^- BRANCHING RATIOS

$\Gamma(e^- \overline{\nu}_e \nu_\mu \gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^- \overline{\nu}_e \nu_\mu e^+ e^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.4±0.2±0.3	7443	[11] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[12] CRITTENDEN	61	HLBC	+	$E(e^+ e^-)$>10 MeV
2	1	[13] GUREVICH	60	EMUL	+	
1.5±1.0	3	[14] LEE	59	HBC	+	

[11] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[12] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[13] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[14] In the three LEE 59 events, the sum of energies E(e^+) + E(e^-) + E(e^+) was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{\text{total}}$ — Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
< 0.012	90	FREEDMAN	93	CNTR	+	ν oscillation search
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.018	90	KRAKAUER	91B	CALO	+	
< 0.05	90	[15] BERGSMA	83	CALO		$\overline{\nu}_\mu e \rightarrow \mu^- \overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
−0.001±0.061		WILLIS	80	CNTR	+	
0.13 ±0.15		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[15] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \rightarrow \mu^- \overline{\nu}_e)/\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e)$, which is essentially equivalent to $\Gamma(e^- \nu_e \overline{\nu}_\mu)/\Gamma_{\text{total}}$ for small values like that quoted.

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

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^- e^+ e^-)/\Gamma_{total}$ — Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[16] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[16] BERTL	85	SPEC	+	SINDRUM
<160	90	[16] BERTL	84	SPEC	+	SINDRUM
<130	90	[16] BOLTON	84	CNTR		LAMPF

[16] These experiments assume a constant matrix element.

$\Gamma(e^- 2\gamma)/\Gamma_{total}$ — Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[17] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[18] BOWMAN	78	CNTR		DEPOMMIER 77 data

[17] AZUELOS 83 uses the phase space distribution of BOWMAN 78.
[18] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \to e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- \, {}^{32}S \to e^- \, {}^{32}S) \,/\, \sigma(\mu^- \, {}^{32}S \to \nu_\mu \, {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-11}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-10}$	90	BADERT...	77	STRC	SIN

$\sigma(\mu^- \, \mathrm{Cu} \to e^- \, \mathrm{Cu}) \,/\, \sigma(\mu^- \, \mathrm{Cu} \to \mathrm{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-8}$	90	BRYMAN	72	SPEC

$\sigma(\mu^- \, \mathrm{Ti} \to e^- \, \mathrm{Ti}) \,/\, \sigma(\mu^- \, \mathrm{Ti} \to \mathrm{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-12}$	90	[19] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.6 \times 10^{-12}$	90	AHMAD	88	TPC	TRIUMF
$<1.6 \times 10^{-11}$	90	BRYMAN	85	TPC	TRIUMF

[19] DOHMEN 93 assumes $\mu^- \to e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^- \, \mathrm{Pb} \to e^- \, \mathrm{Pb}) \,/\, \sigma(\mu^- \, \mathrm{Pb} \to \mathrm{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.6 \times 10^{-11}$	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.9 \times 10^{-10}$	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \to e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^- \, {}^{32}S \to e^+ \, {}^{32}Si^*) \,/\, \sigma(\mu^- \, {}^{32}S \to \nu_\mu \, {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<9 \times 10^{-10}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-9}$	90	BADERT...	78	STRC	SIN

$\sigma(\mu^- \, ^{127}\mathrm{I} \rightarrow e^+ \, ^{127}\mathrm{Sb}^*) / \sigma(\mu^- \, ^{127}\mathrm{I} \rightarrow \text{anything})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3 × 10^{-10}	90	[20] ABELA	80	CNTR	Radiochemical tech.

[20] ABELA 80 is upper limit for $\mu^- \, e^+$ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^- \, \mathrm{Cu} \rightarrow e^+ \mathrm{Co}) / \sigma(\mu^- \, \mathrm{Cu} \rightarrow \nu_\mu \mathrm{Ni})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6 \times 10^{-8}$	90	BRYMAN	72	SPEC
$<2.2 \times 10^{-7}$	90	CONFORTO	62	OSPK

$\sigma(\mu^- \, \mathrm{Ti} \rightarrow e^+ \mathrm{Ca}) / \sigma(\mu^- \, \mathrm{Ti} \rightarrow \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.9 × 10^{-11}	90	[21] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.3 \times 10^{-12}$	90	[22] DOHMEN	93	SPEC	SINDRUM II
$<1.7 \times 10^{-10}$	90	[23] AHMAD	88	TPC	TRIUMF

[21] This DOHMEN 93 limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).
[22] This DOHMEN 93 limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.
[23] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C \, / \, G_F$

The effective Lagrangian for the $\mu^+ e^- \rightarrow \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2} \, G_C \, [\overline{\psi}_\mu \gamma_\lambda \, (1 - \gamma_5) \, \psi_e] \, [\overline{\psi}_\mu \gamma_\lambda \, (1 - \gamma_5) \, \psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C / G_F, where G_F is the Fermi coupling constant.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.13	90		GORDEEV	93	SPEC		JINR phasotron
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.14	90	1	[24] GORDEEV	94	SPEC	+	JINR phasotron
< 6.9	90		NI	93	CBOX		LAMPF
< 0.16	90		MATTHIAS	91	SPEC		LAMPF
< 0.29	90		HUBER	90B	CNTR		TRIUMF
< 0.88	90		HUBER	88	CNTR		See HUBER 90B
< 7.5	90		NI	87	CBOX		See NI 93
<20	95		BEER	86	CNTR		TRIUMF
<42	95		MARSHALL	82	CNTR		

[24] GORDEEV 94 quote limits on both $f = G_{M\overline{M}} / G_F$ and on the probability $W_{M\overline{M}} < 5.1 \times 10^{-7}$ (90% CL). Final results are based on the full data set.

MUON DECAY PARAMETERS

(by W. Fetscher and H.-J. Gerber, ETH Zürich)

All measurements in direct muon decay, $\mu^- \rightarrow e^- + 2$ neutrals, and its inverse, $\nu_\mu + e^- \rightarrow \mu^- + \text{neutral}$, are successfully described by the "$V{-}A$ interaction," which is a particular case of a local, derivative-free, lepton-number-conserving, four-fermion interaction [1]. The matrix element is given below. The $V{-}A$ form and the nature of the neutrals (ν_μ and $\overline{\nu}_e$), and hence the doublet assignments $(\nu_e \, e^-)_L$ and $(\nu_\mu \, \mu^-)_L$, can be determined from experiments [2,3].

All results in direct muon decay (energy spectra, polarizations, and angular distributions) and in inverse muon decay (the reaction cross section) at energies well below $m_W c^2$ may be parametrized in terms of amplitudes $g^{\gamma}_{\varepsilon\mu}$ and the Fermi coupling constant G_F, using the matrix element

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T\\ \epsilon,\mu=R,L}} g^{\gamma}_{\epsilon\mu} \langle \overline{e}_\epsilon \,|\, \Gamma^\gamma \,|\, (\nu_e)_n \rangle \, \langle (\overline{\nu}_\mu)_m \,|\, \Gamma_\gamma \,|\, \mu_\mu \rangle \; . \tag{1}$$

We use the notation of Fetscher *et al.* [2], who in turn use the sign conventions and definitions of Scheck [4]. Here $\gamma = S, V, T$ indicate a scalar, vector, or tensor interaction; and ε, $\mu = R, L$ indicate a right- or left-handed chirality of the electron or muon. The chiralities n and m of the ν_e and $\overline{\nu}_\mu$ are then determined by the values of γ, ε, and μ. The particles are represented by fields of definite chirality [5].

As shown by Langacker and London [6], explicit lepton-number nonconservation still leads to a matrix element equivalent to Eq. (1). They conclude that it is not possible, even in principle, to test lepton-number conservation in (leptonic) muon decay if the final neutrinos are massless and are not observed.

The ten complex amplitudes $g^{\gamma}_{\varepsilon\mu}$ (g^T_{RR} and g^T_{LL} are identically zero) and G_F constitute 19 independent (real) parameters to be determined by experiment. The $V{-}A$ interaction corresponds to the single amplitude g^V_{LL} being unity and all the others being zero.

C. Jarlskog [7] has noted that certain experiments observing the decay electron are especially informative if they yield the $V{-}A$ values. Indeed, all (direct) muon decay experiments are compatible with an arbitrary mix of the scalar and vector amplitudes g^S_{LL} and g^V_{LL}—in the extreme, even with the purely scalar $g^S_{LL} = 2$, $g^V_{LL} = 0$. The decision in favor of $V{-}A$ comes from the quantitative observation of inverse muon decay, which would be forbidden for pure g^S_{LL} [2].

The differential decay probability to obtain an $e^\pm$ with (reduced) energy between x and $x + dx$, emitted in the direction $\widehat{z}$ at an angle between θ and $\theta + d\theta$ with respect to the muon polarization vector $\vec{P}_\mu$, and with its spin pointing in the arbitrary direction $\widehat{\zeta}$, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\; d\cos\theta} &= \frac{m_\mu}{4\pi^3}\, W^4_{e\mu}\, G_F^2 \sqrt{x^2 - x_0^2} \\ &\quad \times \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big) \\ &\quad \times [1 + \vec{P}_e(x,\theta)\cdot\widehat{\zeta}\,] \; .\end{aligned}$$

Here $W_{e\mu} = \max(E_e) = (m_\mu^2 + m_e^2)/2m_\mu$ is the maximum $e^\pm$ energy, $x = E_e/W_{e\mu}$ is the reduced energy, and $x_0 = m_e/W_{e\mu} = 9.67 \times 10^{-3}$. The quantity $P_\mu = |\vec{P}_\mu| \cdot \widehat{\zeta}$ has the significance of the direction in which a perfect polarization-sensitive electron detector would be most sensitive. The isotropic part of the spectrum, $F_{IS}(x)$, the anisotropic part, $F_{AS}(x)$, and the electron polarization, $\vec{P}_e(x,\theta)$, depend on bilinear combinations—called decay parameters—of the coupling constants $g^\gamma_{\varepsilon\mu}$. Neglecting possible nonzero neutrino masses, we have, in terms of the decay parameters ρ, η, ξ, δ, etc.,

$$F_{IS}(x) = x(1-x) + \tfrac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta\, x_0(1-x)$$

$$F_{AS}(x) = \tfrac{1}{3}\xi\sqrt{x^2 - x_0^2}$$
$$\times \left[1 - x + \tfrac{2}{3}\delta\Big(4x - 3 - (\sqrt{1-x_0^2} - 1)\Big)\right]$$

$$\vec{P}_e(x,\theta) = P_{T_1}\,\widehat{x} + P_{T_2}\,\widehat{y} + P_L\,\widehat{z}\ .$$

Here $\widehat{x}$, $\widehat{y}$, and $\widehat{z}$ are orthogonal unit vectors defined as follows:

$\widehat{z}$	is along the e momentum
$\widehat{y} = [\widehat{z} \times \vec{P}_\mu]/\lvert[\widehat{z} \times \vec{P}_\mu]\rvert$	is transverse to the e momentum and perpendicular to the "decay plane"
$\widehat{x} = \widehat{y} \times \widehat{z}$	is transverse to the e momentum and in the "decay plane."

The components of $\vec{P}_e$ then are given by

$$P_{T_1}(x,\theta) = P_\mu \sin\theta\, F_{T_1}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big)$$

$$P_{T_2}(x,\theta) = P_\mu \sin\theta\, F_{T_2}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big)$$

$$P_L(x,\theta) = \pm F_{IP}(x) + P_\mu \cos\theta$$
$$\times\, F_{AP}(x) \Big/ \Big(F_{IS}(x) \pm P_\mu \cos\theta\, F_{AS}(x)\Big)\ ,$$

where

$$F_{T_1}(x) = \tfrac{1}{12}\Big\{-2\Big[\xi'' + 12(\rho - \tfrac{3}{4})\Big](1-x)x_0$$
$$- 3\eta(x^2 - x_0^2) + \eta''(-3x^2 + 4x - x_0^2)\Big\}$$

$$F_{T_2}(x) = \tfrac{1}{3}\sqrt{x^2 - x_0^2}\left\{3\frac{\alpha'}{A}(1-x) + 2\frac{\beta'}{A}\sqrt{1-x_0^2}\right\}$$

$$F_{IP}(x) = \tfrac{1}{54}\sqrt{x^2 - x_0^2}\left\{9\xi'\Big(-2x + 2 + \sqrt{1-x_0^2}\Big)\right.$$

$$+ 4\xi(\delta - \tfrac{3}{4})\Big(4x - 4 + \sqrt{1-x_0^2}\Big)\Big\}$$

$$F_{AP}(x) = \tfrac{1}{6}\Big\{\xi''(2x^2 - x - x_0^2) + 4(\rho - \tfrac{3}{4})(4x^2 - 3x - x_0^2) + 2\eta''(1-x)x_0\Big\} \ .$$

For the experimental values of the decay parameters ρ, ξ, ξ', ξ'', δ, η, η'', α/A, β/A, α'/A, β'/A, which are not all independent, see the Data Listings below. Experiments in the past have also been analyzed using the parameters a, b, c, a', b', c', α/A, β/A, α'/A, β'/A (and $\eta = (\alpha - 2\beta)/2A$), as defined by Kinoshita and Sirlin [8]. They serve as a model-independent summary of all possible measurements on the decay electron (see Listings below). The relations between the two sets of parameters are

$$\rho - \frac{3}{4} = \frac{3}{4}(-a + 2c)/A \ ,$$

$$\eta = (\alpha - 2\beta)/A \ ,$$

$$\eta'' = (3\alpha + 2\beta)/A \ ,$$

$$\delta - \frac{3}{4} = \frac{9}{4}\cdot\frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A} \ ,$$

$$1 - \xi\frac{\delta}{\rho} = 4\frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A} \ ,$$

$$1 - \xi' = [(a + a') + 4(b + b') + 6(c + c')]/A \ ,$$

$$1 - \xi'' = (-2a + 20c)/A \ ,$$

where

$$A = a + 4b + 6c \ .$$

The relations to the coupling constants are:

$$a = 16(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 + |g^S_{LR} + 6g^T_{LR}|^2 \ ,$$

$$a' = 16(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 - |g^S_{LR} + 6g^T_{LR}|^2 \ ,$$

$$\alpha = 8\,\mathrm{Re}\left[g^V_{RL}(g^S_{LR} + 6g^T_{LR})^* + g^V_{LR}(g^S_{RL} + 6g^T_{RL})^*\right] \ ,$$

$$\alpha' = 8\,\mathrm{Im}\left[-g^V_{LR}(g^S_{RL} + 6g^T_{RL})^* - g^V_{RL}(g^S_{LR} + 6g^T_{LR})^*\right] \ ,$$

$$b = 4(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2 \ ,$$

$$b' = 4(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2 \ ,$$

$$\beta = -4\,\mathrm{Re}\left[g^V_{RR}(g^S_{LL})^* + g^V_{LL}(g^S_{RR})^*\right] \ ,$$

$$\beta' = 4\,\mathrm{Im}\left[g^V_{RR}(g^S_{LL})^* - g^V_{LL}(g^S_{RR})^*\right] \ ,$$

$$c = \tfrac{1}{2}\left[|g^S_{RL} - 2g^T_{RL}|^2 + |g^S_{LR} - 2g^T_{LR}|^2\right] \ ,$$

$$c' = \tfrac{1}{2}\left[|g^S_{RL} - 2g^T_{RL}|^2 - |g^S_{LR} - 2g^T_{LR}|^2\right] \ .$$

If also the electron mass is neglected, the energy and angular distribution of the electron in the rest frame of a polarized muon ($\mu^\mp$) is given by the Michel spectrum:

$$d^2\Gamma \sim \left\{3(1-x) + \frac{2\rho}{3}(4x-3) \right.$$
$$\left. \mp\xi\,\cos\theta[1 - x + \frac{2\delta}{3}(4x-3)]\right\} x^2 dx\, d(\cos\theta) \ .$$

Here θ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. For pure V–A coupling, we obtain $\rho = \xi\delta = 3/4$, $\xi = 1$, and the differential decay rate is

$$d^2\Gamma = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[3 - 2x \pm \cos\theta(1-2x)\right] x^2 dx\, d(\cos\theta) \ .$$

Here the coefficient in front of the square bracket is the total decay rate.

In order to determine the amplitudes $g^\gamma_{\varepsilon\mu}$ uniquely from experiment, Fetscher *et al.* [2] introduced four probabilities $Q_{\varepsilon\mu}(\varepsilon, \mu = R, L)$ for the decay of a μ-handed muon into an ε-handed electron and showed that there exist upper bounds on Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound on Q_{LL}. These probabilities are given in terms of the $g^\gamma_{\varepsilon\mu}$'s by

$$Q_{\varepsilon\mu} = \frac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1 - \delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2 \ , \qquad (2)$$

where $\delta_{\varepsilon\mu} = 1$ for $\varepsilon = \mu$ and $\delta_{\varepsilon\mu} = 0$ for $\varepsilon \neq \mu$. They are related to the parameters a, b, c, a', b', and c' by

$$Q_{RR} = 2(b + b')/A \ ,$$

$$Q_{LR} = [(a - a') + 6(c - c')]/2A \ ,$$

$$Q_{RL} = [(a + a') + 6(c + c')]/2A \ ,$$

$$Q_{LL} = 2(b - b')/A \ ,$$

with $A = 16$. In the pure V–A theory, $Q_{LL} = 1$ and the others are zero.

Since the upper bounds on Q_{RR}, Q_{LR}, and Q_{RL} are found to be small, and since the helicity of the ν_μ in pion decay is known from experiment [9,10] to very high precision to be -1 [11], the cross section S of *inverse* muon decay, normalized to the V–A value, yields [2]

$$|g^S_{LL}|^2 \leq 4(1-S) \tag{3}$$

and

$$|g^V_{LL}|^2 = S \ . \tag{4}$$

Thus the Standard Model assumption of a pure V–A leptonic charged weak interaction for e and μ is confirmed (within errors) by experiments at energies far below the mass of the $W^\pm$: Eq. (4) gives a lower limit for V–A, and Eqs. (2) and (3) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR}+Q_{RL} = (1-\xi')/2$ and $Q_{RR}+Q_{LR} = \frac{1}{2}(1+\xi/3-16\xi\delta/9)$. Table 1 gives the current experimental limits on the magnitudes of the $g^\gamma_{\varepsilon\mu}$'s.

Table 1. Ninety-percent confidence level experimental limits for the coupling constants $g^\gamma_{\varepsilon\mu}$. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 12, and the others are from Ref. 13. The experimental uncertainty on the muon polarization in pion decay is included.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.55$	$\lvert g^V_{LL}\rvert > 0.96$	$\lvert g^T_{LL}\rvert \equiv 0$

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 14), are given by Burkard *et al.* [15].

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See also P. Vilain *et al.*, Phys. Lett. **B364**, 121 (1995).
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μ DECAY PARAMETERS

ρ PARAMETER

($V{-}A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[25] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[25] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[25] PEOPLES	66	ASPK	+	20–53 MeV e^+

[25] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

($V{-}A$) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[26] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−0.012±0.015±0.003	5.3M	[27] BURKARD	85B	CNTR	+	9–53 MeV e^+
0.011±0.081±0.026	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
−0.7 ±0.5	170k	[28] FRYBERGER	68	ASPK	+	25–53 MeV e^+
−0.7 ±0.6	280k	[28] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.05 ±0.5	800k	[28] PEOPLES	66	ASPK	+	20–53 MeV e^+
−2.0 ±0.9	9213	[29] PLANO	60	HBC	+	Whole spectrum

[26] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[27] $\alpha = \alpha' = 0$ assumed.
[28] ρ constrained = 0.75.
[29] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

($V{-}A$) theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[30] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[31] VOSSLER	69			
0.752 ±0.009	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.782 ±0.031		KRUGER	61			
0.78 ±0.05	8354	PLANO	60	HBC	+	Whole spectrum

[30] BALKE 88 uses $\rho = 0.752 \pm 0.003$.
[31] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

$|(\xi$ PARAMETER$)\times(\mu$ LONGITUDINAL POLARIZATION$)|$

$(V-A)$ theory predicts $\xi = 1$, longitudinal polarization = 1.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
1.0013±0.0030±0.0053		[32] IMAZATO	92	SPEC	+	$K^+ \rightarrow \mu^+ \nu_\mu$
0.975 ±0.015		AKHMANOV	68	EMUL		140 kG
0.975 ±0.030	66k	GUREVICH	64	EMUL		See AKHMANOV 68
0.903 ±0.027		[33] ALI-ZADE	61	EMUL	+	27 kG
0.93 ±0.06	8354	PLANO	60	HBC	+	8.8 kG
0.97 ±0.05	9k	BARDON	59	CNTR		Bromoform target

[32] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.

[33] Depolarization by medium not known sufficiently well.

$\xi \times (\mu$ LONGITUDINAL POLARIZATION$) \times \delta / \rho$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99682	90	[34] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[35] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[34] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.

[35] STOKER 85 find $(\xi P_\mu \delta/\rho)$ >0.9955 and >0.9966, where the first limit is from new μ spin-rotation data and the second is from combination with CARR 83 data. In $V-A$ theory, $(\delta/\rho) = 1.0$.

ξ' = LONGITUDINAL POLARIZATION OF e^+

$(V-A)$ theory predicts the longitudinal polarization $= \pm1$ for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998±0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
0.89 ±0.28	29k	SCHWARTZ	67	OSPK	−	Moller scattering
0.94 ±0.38		BLOOM	64	CNTR	+	Brems. transmiss.
1.04 ±0.18		DUCLOS	64	CNTR	+	Bhabha scattering
1.05 ±0.30		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[36] BURKARD	85	CNTR	+	Bhabha + annihil

[36] BURKARD 85 measure $(\xi''-\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.016±0.021±0.01	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[37] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
15 ±50 ±14	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[37] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
− 0.2± 4.3		[38] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
−47 ±50 ±14	5.3M	[39] BURKARD	85B	CNTR	+	9–53 MeV e^+

[38] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[39] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.9± 6.2		[40] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2 ±17 ±6	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
1.5± 6.3		[41] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
17 ±17 ±6	5.3M	[42] BURKARD	85B	CNTR	+	9–53 MeV e^+

[41] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[42] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[43] BURKARD	85B	FIT

[43] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3±4.1	[44] BURKARD	85B	FIT

[44] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[45] BURKARD	85B	FIT

[45] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[46] BURKARD	85B	FIT

[46] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID	TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •		
3.5±2.0	[47] BURKARD 85B	FIT

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\overline{\eta}$ PARAMETER

$(V{-}A)$ theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	DOCUMENT ID	TECN	CHG	COMMENT
0.02 ±0.08 OUR AVERAGE				
−0.014±0.090	EICHENBER... 84	ELEC	+	ρ free
+0.09 ±0.14	BOGART 67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
−0.035±0.098	EICHENBER... 84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

HONECKER 96 PRL 76 200 +Dohmen, Haan, Junker+ (SINDRUM II Collab.)
GORDEEV 94 JETPL 59 589 +Kiselev, Aleshin+ (PNPI, JINR)
Translated from ZETFP 59 565.
DOHMEN 93 PL B317 631 +Groth, Heer+ (PSI SINDRUM-II Collab.)
FREEDMAN 93 PR D47 811 +Fujikawa, Napolitano, Nelson+ (LAMPF E645 Collab.)
GORDEEV 93 JETPL 57 270 +Savchenko, Abazov+ (PNPI, JINR)
Translated from ZETFP 57 262.
NI 93 PR D48 1976 +Arnold, Chmely+ (LAMPF Crystal-Box Collab.)
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
BARANOV 91 SJNP 53 802 +Vanko, Glazov, Evtukhovich+ (JINR)
Translated from YAF 53 1302.
KRAKAUER 91B PL B263 534 +Talaga, Allen, Chen, Doe+ (UMD, UCI, LANL)
MATTHIAS 91 PRL 66 2716 +Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
Also 91B PRL 67 932 erratum Matthias, Ahn+ (YALE, HEIDP, WILL, GSI, VILL, BNL)
HUBER 90B PR D41 2709 + (WYOM, VICT, ARIZ, ROCH, TRIU, SFRA, BRCO)
AHMAD 88 PR D38 2102 +Azuelos+ (TRIU, VICT, VPI, BRCO, MONT, CNRC)
Also 87 PRL 59 970 Ahmad+ (TRIU, VPI, VICT, BRCO, MONT, CNRC)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BELLGARDT 88 NP B299 1 +Otter, Eichler+ (SINDRUM Collab.)
BOLTON 88 PR D38 2077 +Cooper, Frank, Hallin+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 56 2461 Bolton, Bowman, Cooper+ (LANL, STAN, CHIC, TEMP)
Also 86 PRL 57 3241 Grosnick, Wright, Bolton+ (CHIC, LANL, STAN, TEMP)
HUBER 88 PRL 61 2189 +Beer+ (WYOM, VICT, ARIZ, ROCH, TRIU, BRCO)
BELTRAMI 87 PL B194 326 +Burkard, Von Dincklage+ (ETH, SIN, MANZ)
COHEN 87 RMP 59 1121 +Taylor (RISC, NBS)
NI 87 PRL 59 2716 +Arnold, Chmely+ (YALE, LANL, WILL, MISS, HEIDP)
BEER 86 PRL 57 671 +Marshall, Mason+ (VICT, TRIU, WYOM)
BELTRAMI 86 NP A451 679 +Aas, Beer, Dechambrier, Goudsmit+ (ETH, FRIB)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
BERTL 85 NP B260 1 +Egli, Eichler+ (SINDRUM Collab.)
BRYMAN 85 PRL 55 465 + (TRIU, CNRC, BRCO, LANL, CHIC, CARL+)
BURKARD 85 PL 150B 242 +Corriveau, Egger+ (ETH, SIN, MANZ)
BURKARD 85B PL 160B 343 +Corriveau, Egger+ (ETH, SIN, MANZ)
Also 81B PR D24 2004 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
Also 83B PL 129B 260 Corriveau, Egger, Fetscher+ (ETH, SIN, MANZ)
HUGHES 85 CNPP 14 341 +Kinoshita (YALE, CORN)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
BARDIN 84 PL 137B 135 +Duclos, Magnon+ (SACL, CERN, BGNA, FIRZ)
BERTL 84 PL 140B 299 +Eichler, Felawka+ (SINDRUM Collab.)
BOLTON 84 PRL 53 1415 +Bowman, Carlini+ (LANL, CHIC, STAN, TEMP)
EICHENBER... 84 NP A412 523 Eichenberger, Engfer, VanderSchaff (ZURI)
GIOVANETTI 84 PR D29 343 +Dey, Eckhause, Hart+ (WILL)
KINOSHITA 84 PRL 52 717 +Nizic, Okamoto (CORN)
AZUELOS 83 PRL 51 164 +Depommier, Leroy, Martin+ (MONT, TRIU, BRCO)
Also 77 PRL 39 1113 Depommier+ (MONT, BRCO, TRIU, VICT, MELB)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
KINNISON 82 PR D25 2846 +Anderson, Matis, Wright+ (EFI, STAN, LANL)
Also 79 PRL 42 556 Bowman, Cooper, Hamm+ (LASL, EFI, STAN)
KLEMPT 82 PR D25 652 +Schulze, Wolf, Camani, Gygax+ (MANZ, ETH)
MARIAM 82 PRL 49 993 +Beer, Bolton, Egan, Gardner+ (YALE, HEIDH, BERN)
MARSHALL 82 PR D25 1174 +Warren, Oram, Kiefl (BRCO)
COMBLEY 81 PRPL 68 93 +Farley, Picasso (SHEF, RMCS, CERN)
NEMETHY 81 CNPP 10 147 +Hughes (LBL, YALE)
ABELA 80 PL 95B 318 +Backenstoss, Simons, Wuest+ (BASL, KARLK, KARLE)
BADERT... 80 LNC 28 401 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
Also 82 NP A377 406 Badertscher, Borer, Czapek, Flueckiger+ (BERN)
JONKER 80 PL 93B 203 +Panman, Udo, Allaby+ (CHARM Collab.)
SCHAAF 80 NP A340 249 +Engfer, Povel, Dey+ (ZURI, ETH, SIN)
Also 77 PL 72B 183 Povel, Dey, Walter, Pfeiffer+ (ZURI, ETH, SIN)
WILLIS 80 PRL 44 522 +Hughes+ (YALE, LBL, LASL, SACL, SIN, CNRC+)
Also 80B PRL 45 1370 Willis+ (YALE, LBL, LASL, SACL, SIN, CNRC+)

BAILEY	79	NP B150 1		(CERN, DARE, MANZ)
FARLEY	79	ARNPS 29 243	+Picasso	(RMCS, CERN)
BADERT...	78	PL 79B 371	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
BAILEY	78	JPG 4 345		(DARE, BERN, SHEF, MANZ, RMCS, CERN, BIRM)
Also	79	NP B150 1	Bailey	(CERN, DARE, MANZ)
BLIETSCHAU	78	NP B133 205	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BOWMAN	78	PRL 41 442	+Cheng, Li, Matis	(LASL, IAS, CMU, EFI)
CAMANI	78	PL 77B 326	+Gygax, Klempt, Schenck, Schulze+	(ETH, MANZ)
BADERT...	77	PRL 39 1385	Badertscher, Borer, Czapek, Flueckiger+	(BERN)
BAILEY	77	PL 67B 225	+	(CERN Muon Storage Ring Collab.)
Also	77C	PL 68B 191	Bailey+	(CERN, DARE, BERN, SHEF, MANZ+)
Also	75	PL 55B 420	Bailey+	(CERN Muon Storage Ring Collab., BIRM)
CALMET	77	RMP 49 21	+Narison, Perrottet+	(CPPM)
CASPERSON	77	PRL 38 956	+Crane+	(BERN, HEIDH, LASL, WYOM, YALE)
DEPOMMIER	77	PRL 39 1113	+	(MONT, BRCO, TRIU, VICT, MELB)
BALANDIN	74	JETP 40 811	+Grebenyuk, Zinov, Konin, Ponomarev	(JINR)
		Translated from ZETF 67 1631.		
COHEN	73	JPCRD 2 663	+Taylor	(RISC, NBS)
DUCLOS	73	PL 47B 491	+Magnon, Picard	(SACL)
EICHTEN	73	PL 46B 281	+Deden, Hasert, Krenz+	(Gargamelle Collab.)
BRYMAN	72	PRL 28 1469	+Blecher, Gotow, Powers	(VPI)
CROWE	72	PR D5 2145	+Hague, Rothberg, Schenck+	(LBL, WASH)
CRANE	71	PRL 27 474	+Casperson, Crane, Egan, Hughes+	(YALE)
DERENZO	69	PR 181 1854		(EFI)
VOSSLER	69	NC 63A 423		(EFI)
AKHMANOV	68	SJNP 6 230	+Gurevich, Dobretsov, Makarina+	(KIAE)
		Translated from YAF 6 316.		
BAILEY	68	PL 28B 287	+Bartl, VonBochmann, Brown, Farley+	(CERN)
Also	72	NC 9A 369	Bailey, Bartl, VonBochmann, Brown+	(CERN)
FRYBERGER	68	PR 166 1379		(EFI)
BOGART	67	PR 156 1405	+Dicapua, Nemethy, Strelzoff	(COLU)
SCHWARTZ	67	PR 162 1306		(EFI)
SHERWOOD	67	PR 156 1475		(EFI)
PEOPLES	66	Nevis 147 unpub.		(COLU)
BLOOM	64	PL 8 87	+Dick, Feuvrais, Henry, Macq, Spighel	(CERN)
DUCLOS	64	PL 9 62	+Heintze, DeRujula, Soergel	(CERN)
GUREVICH	64	PL 11 185	+Makarina+	(KIAE)
BUHLER	63	PL 7 368	+Cabibbo, Fidecaro, Massam, Muller+	(CERN)
MEYER	63	PR 132 2693	+Anderson, Bleser, Lederman+	(COLU)
CHARPAK	62	PL 1 16	+Farley, Garwin+	(CERN)
CONFORTO	62	NC 26 261	+Conversi, Dilella+	(INFN, ROMA, CERN)
ALI-ZADE	61	JETP 13 313	+Gurevich, Nikolski	
		Translated from ZETF 40 452.		
CRITTENDEN	61	PR 121 1823	+Walker, Ballam	(WISC, MSU)
KRUGER	61	UCRL 9322 unpub.		(LRL)
GUREVICH	60	JETP 10 225	+Nikolski, Surkova	(ITEP)
		Translated from ZETF 37 318.		
PLANO	60	PR 119 1400		(COLU)
ASHKIN	59	NC 14 1266	+Fazzini, Fidecaro, Lipman, Merrison+	(CERN)
BARDON	59	PRL 2 56	+Berley, Lederman	(COLU)
LEE	59	PRL 3 55	+Samios	(COLU)