π^0

$I^G(J^{PC}) = 1^-(0^{-+})$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** (1988).

π^0 MASS

The value is calculated from $m_{\pi^\pm}$ and $(m_{\pi^\pm} - m_{\pi^0})$. See notes under the $\pi^\pm$ Mass Listings concerning recent revision of the charged pion mass.

VALUE (MeV)	*DOCUMENT ID*
134.9766±0.0006 OUR FIT	Error includes scale factor of 1.1.

$m_{\pi^\pm} - m_{\pi^0}$

Measurements with an error > 0.01 MeV have been omitted.

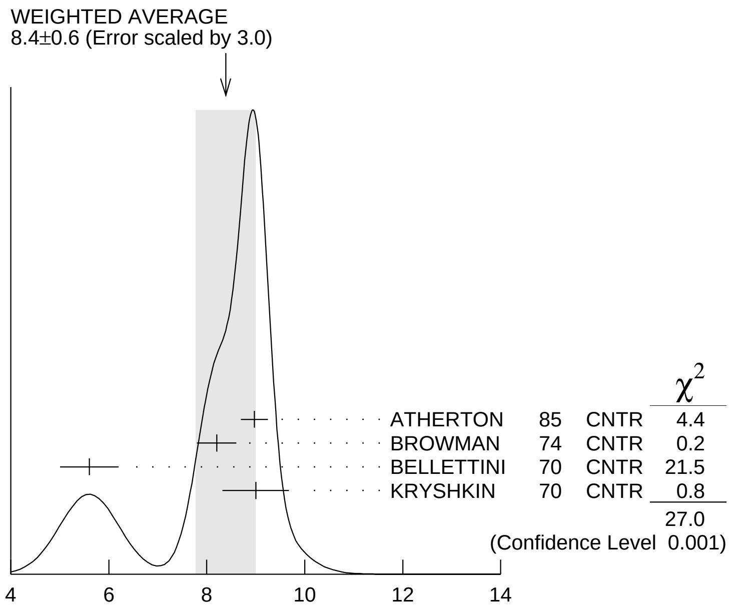
VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
4.5936 ±0.0005 OUR FIT				
4.5936 ±0.0005 OUR AVERAGE				
4.59364±0.00048	CRAWFORD	91	CNTR	$\pi^- p \to \pi^0 n$, n TOF
4.5930 ±0.0013	CRAWFORD	86	CNTR	$\pi^- p \to \pi^0 n$, n TOF
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.59366±0.00048	CRAWFORD	88B	CNTR	See CRAWFORD 91
4.6034 ±0.0052	VASILEVSKY	66	CNTR	
4.6056 ±0.0055	CZIRR	63	CNTR	

π^0 MEAN LIFE

Measurements with an error $> 1 \times 10^{-17}$ s have been omitted.

VALUE (10^{-17} s)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
8.4 ±0.6 OUR AVERAGE	Error includes scale factor of 3.0. See the ideogram below.				
8.97±0.22±0.17		ATHERTON	85	CNTR	
8.2 ±0.4		[1] BROWMAN	74	CNTR	Primakoff effect
5.6 ±0.6		BELLETTINI	70	CNTR	Primakoff effect
9 ±0.68		KRYSHKIN	70	CNTR	Primakoff effect
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.4 ±0.5 ±0.5	1182	[2] WILLIAMS	88	CBAL	$e^+ e^- \to e^+ e^- \pi^0$

[1] BROWMAN 74 gives a π^0 width $\Gamma = 8.02 \pm 0.42$ eV. The mean life is $\hbar/\Gamma$.
[2] WILLIAMS 88 gives $\Gamma(\gamma\gamma) = 7.7 \pm 0.5 \pm 0.5$ eV. We give here $\tau = \hbar/\Gamma$(total).



π^0 mean life (10^{-17} s)

π^0 DECAY MODES

For decay limits to particles which are not established, see the appropriate Search setions (A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	2γ		(98.798 ± 0.032) %	S=1.1
Γ_2	$e^+e^-\gamma$		(1.198 ± 0.032) %	S=1.1
Γ_3	γ positronium		$(1.82\pm0.29)\times10^{-9}$	
Γ_4	$e^+e^+e^-e^-$		$(3.14\pm0.30)\times10^{-5}$	
Γ_5	e^+e^-		$(6.2\pm0.5)\times10^{-8}$	
Γ_6	4γ		$< 2\times10^{-8}$	CL=90%
Γ_7	$\nu\overline{\nu}$		[a] $< 8.3\times10^{-7}$	CL=90%
Γ_8	$\nu_e\overline{\nu}_e$		$< 1.7\times10^{-6}$	CL=90%
Γ_9	$\nu_\mu\overline{\nu}_\mu$		$< 3.1\times10^{-6}$	CL=90%
Γ_{10}	$\nu_\tau\overline{\nu}_\tau$		$< 2.1\times10^{-6}$	CL=90%
Γ_{11}	$\gamma\nu\overline{\nu}$		$< 6\times10^{-4}$	CL=90%

Charge conjugation (C) or Lepton Family number (LF) violating modes

Γ_{12}	3γ	C	$< 3.1\times10^{-8}$	CL=90%
Γ_{13}	μ^+e^-		$< 3.8\times10^{-10}$	CL=90%
Γ_{14}	$\mu^+e^- + e^-\mu^+$	LF	$< 1.72\times10^{-8}$	CL=90%

[*a*] Astrophysical and cosmological arguments give limits of order 10^{-13}; see the Particle Listings below.

CONSTRAINED FIT INFORMATION

An overall fit to 2 branching ratios uses 4 measurements and one constraint to determine 3 parameters. The overall fit has a $\chi^2 =$ 1.9 for 2 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle \delta x_i \delta x_j \rangle / (\delta x_i \cdot \delta x_j)$, 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_4	−1	0
	x_1	x_2

π^0 BRANCHING RATIOS

$\Gamma(e^+ e^- \gamma)/\Gamma(2\gamma)$ — Γ_2/Γ_1

VALUE (%)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.213±0.033 OUR FIT	Error includes scale factor of 1.1.				
1.213±0.030 OUR AVERAGE					
1.25 ±0.04		SCHARDT	81	SPEC	$\pi^- p \rightarrow n \pi^0$
1.166±0.047	3071	[3] SAMIOS	61	HBC	$\pi^- p \rightarrow n \pi^0$
1.17 ±0.15	27	BUDAGOV	60	HBC	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.196		JOSEPH	60	THEO	QED calculation

[3] SAMIOS 61 value uses a Panofsky ratio = 1.62.

$\Gamma(\gamma \text{positronium})/\Gamma(2\gamma)$ — Γ_3/Γ_1

VALUE (units 10^{-9})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
1.84±0.29	277	AFANASYEV	90	CNTR	pC 70 GeV

$\Gamma(e^+ e^+ e^- e^-)/\Gamma(2\gamma)$ — Γ_4/Γ_1

VALUE (units 10^{-5})	*EVTS*	*DOCUMENT ID*		*TECN*
3.18±0.30 OUR FIT				
3.18±0.30	146	[4] SAMIOS	62B	HBC

[4] SAMIOS 62B value uses a Panofsky ratio = 1.62.

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

Experimental results are listed; branching ratios corrected for radiative effects are given in the footnotes. BERMAN 60 found $B(\pi^0 \to e^+e^-) \geq 4.69 \times 10^{-8}$ via an exact QED calculation.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
6.2 ±0.5 OUR AVERAGE						
6.09±0.40±0.24	275	[5] ALAVI-HARATI	99C	SPEC	0	$K^0_L \to 3\pi^0$ in flight
6.9 ±2.3 ±0.6	21	[6] DESHPANDE	93	SPEC		$K^+ \to \pi^+\pi^0$
7.6 $^{+2.9}_{-2.8}$ ±0.5	8	[7] MCFARLAND	93	SPEC		$K^0_L \to 3\pi^0$ in flight

[5] ALAVI-HARATI 99C quote result for $B[\pi^0 \to e^+e^-, (m_{e^+e^-}/m_{\pi^0})^2 > 0.95]$ to minimize radiative contributions from $\pi^0 \to e^+e^-\gamma$. After radiative corrections they obtain $(7.04 \pm 0.46 \pm 0.28) \times 10^{-8}$.

[6] The DESHPANDE 93 result with bremsstrahlung radiative corrections is $(8.0 \pm 2.6 \pm 0.6) \times 10^{-8}$.

[7] The MCFARLAND 93 result is for $B[\pi^0 \to e^+e^-, (m_{e^+e^-}/m_{\pi^0})^2 > 0.95]$. With radiative corrections it becomes $(8.8^{+4.5}_{-3.2} \pm 0.6) \times 10^{-8}$.

$\Gamma(e^+e^-)/\Gamma(2\gamma)$ — Γ_5/Γ_1

VALUE (units 10^{-7})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<1.3	90		NIEBUHR	89	SPEC	$\pi^- p \to \pi^0 n$ at rest
<5.3	90		ZEPHAT	87	SPEC	$\pi^- p \to \pi^0 n$ 0.3 GeV/c
1.7 ±0.6 ±0.3		59	FRANK	83	SPEC	$\pi^- p \to n\pi^0$
1.8 ±0.6		58	MISCHKE	82	SPEC	See FRANK 83
2.23$^{+2.40}_{-1.10}$	90	8	FISCHER	78B	SPRK	$K^+ \to \pi^+\pi^0$

$\Gamma(4\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (units 10^{-8})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 2	90		MCDONOUGH	88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<160	90		BOLOTOV	86C	CALO	
<440	90	0	AUERBACH	80	CNTR	

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

The astrophysical and cosmological limits are many orders of magnitude lower, but we use the best laboratory limit for the Summary Tables.

VALUE (units 10^{-6})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.83	90		[8] ATIYA	91	B787	$K^+ \to \pi^+\nu\nu'$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 2.9 $\times 10^{-7}$			[9] LAM	91		Cosmological limit
< 3.2 $\times 10^{-7}$			[10] NATALE	91		SN 1987A
< 6.5	90		DORENBOS...	88	CHRM	Beam dump, prompt ν
<24	90	0	[8] HERCZEG	81	RVUE	$K^+ \to \pi^+\nu\nu'$

[8] This limit applies to all possible $\nu \nu'$ states as well as to other massless, weakly interacting states.

[9] LAM 91 considers the production of right-handed neutrinos produced from the cosmic thermal background at the temperature of about the pion mass through the reaction $\gamma\gamma \rightarrow \pi^0 \rightarrow \nu\overline{\nu}$.

[10] NATALE 91 considers the excess energy-loss rate from SN 1987A if the process $\gamma\gamma \rightarrow \pi^0 \rightarrow \nu\overline{\nu}$ occurs, permitted if the neutrinos have a right-handed component. As pointed out in LAM 91 (and confirmed by Natale), there is a factor 4 error in the NATALE 91 published result (0.8×10^{-7}).

$\Gamma(\nu_e \overline{\nu}_e)/\Gamma_{total}$ — Γ_8/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1.7	90	DORENBOS...	88	CHRM	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.1	90	[11] HOFFMAN	88	RVUE	Beam dump, prompt ν

[11] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\mu \overline{\nu}_\mu)/\Gamma_{total}$ — Γ_9/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<3.1	90	[12] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7.8	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[12] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\nu_\tau \overline{\nu}_\tau)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (units 10^{-6})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<2.1	90	[13] HOFFMAN	88	RVUE	Beam dump, prompt ν
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<4.1	90	DORENBOS...	88	CHRM	Beam dump, prompt ν

[13] HOFFMAN 88 analyzes data from a 400-GeV BEBC beam-dump experiment.

$\Gamma(\gamma \nu \overline{\nu})/\Gamma_{total}$ — Γ_{11}/Γ

Standard Model prediction is 6×10^{-18}.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<6 \times 10^{-4}$	90	ATIYA	92	CNTR	$K^+ \rightarrow \gamma\nu\overline{\nu}\pi^+$

$\Gamma(3\gamma)/\Gamma_{total}$ — Γ_{12}/Γ

Forbidden by *C* invariance.

VALUE (units 10^{-8})	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3.1	90		MCDONOUGH	88	CBOX	$\pi^- p$ at rest
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 38	90	0	HIGHLAND	80	CNTR	
<150	90	0	AUERBACH	78	CNTR	
<490	90	0	[14] DUCLOS	65	CNTR	
<490	90		[14] KUTIN	65	CNTR	

[14] These experiments give $B(3\gamma/2\gamma) < 5.0 \times 10^{-6}$.

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

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 0.38	90	0	APPEL	00	SPEC	$K^+ \to \pi^+ \mu^+ e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<16	90		LEE	90	SPEC	$K^+ \to \pi^+ \mu^+ e^-$
<78	90		CAMPAGNARI	88	SPEC	See LEE 90

$[\Gamma(\mu^+ e^-) + \Gamma(e^- \mu^+)]/\Gamma_{total}$ — Γ_{14}/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-9})	CL%	DOCUMENT ID		TECN	COMMENT
< 17.2	90	KROLAK	94	E799	In $K^0_L \to 3\pi^0$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<140		HERCZEG	84	RVUE	$K^+ \to \pi^+ \mu e$
< 2 $\times 10^{-6}$		HERCZEG	84	THEO	$\mu^- \to e^-$ conversion
< 70	90	BRYMAN	82	RVUE	$K^+ \to \pi^+ \mu e$

π^0 ELECTROMAGNETIC FORM FACTOR

The amplitude for the process $\pi^0 \to e^+ e^- \gamma$ contains a form factor F(x) at the $\pi^0\gamma\gamma$ vertex, where $x = [m_{e^+ e^-}/m_{\pi^0}]^2$. The parameter a in the linear expansion F(x) = 1 + ax is listed below.

All the measurements except that of BEHREND 91 are in the time-like region of momentum transfer.

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.032 ±0.004 OUR AVERAGE					
+0.026 ±0.024 ±0.048	7548	FARZANPAY	92	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.025 ±0.014 ±0.026	54k	MEIJERDREES	92B	SPEC	$\pi^- p \to \pi^0 n$ at rest
+0.0326 ±0.0026 ±0.0026	127	[15] BEHREND	91	CELL	$e^+ e^- \to e^+ e^- \pi^0$
−0.11 ±0.03 ±0.08	32k	FONVIEILLE	89	SPEC	Radiation corr.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.12 $^{+0.05}_{-0.04}$		[16] TUPPER	83	THEO	FISCHER 78 data
+0.10 ±0.03	31k	[17] FISCHER	78	SPEC	Radiation corr.
+0.01 ±0.11	2200	DEVONS	69	OSPK	No radiation corr.
−0.15 ±0.10	7676	KOBRAK	61	HBC	No radiation corr.
−0.24 ±0.16	3071	SAMIOS	61	HBC	No radiation corr.

[15] BEHREND 91 estimates that their systematic error is of the same order of magnitude as their statistical error, and so we have included a systematic error of this magnitude. The value of a is obtained by extrapolation from the region of large space-like momentum transfer assuming vector dominance.

[16] TUPPER 83 is a theoretical analysis of FISCHER 78 including 2-photon exchange in the corrections.

[17] The FISCHER 78 error is statistical only. The result without radiation corrections is +0.05 ± 0.03.

π^0 REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1988 edition Physics Letters **B204** (1988).

APPEL	00	PRL 85 2450	R. Appel *et al.*	(BNL 865 Collab.)
Also	97	Thesis, Yale Univ.	D.R. Bergman	
Also	97	Thesis, Univ. Zurich	S. Pislak	
ALAVI-HARATI	99C	PRL 83 922	A. Alavi-Harati *et al.*	(KTeV Collab.)
KROLAK	94	PL B320 407	P. Krolak *et al.*	(EFI, UCLA, COLO, ELMT+)
DESHPANDE	93	PRL 71 27	A. Deshpande *et al.*	(BNL E851 Collab.)
MCFARLAND	93	PRL 71 31	K.S. McFarland *et al.*	(EFI, UCLA, COLO+)
ATIYA	92	PRL 69 733	M.S. Atiya *et al.*	(BNL, LANL, PRIN+)
FARZANPAY	92	PL B278 413	F. Farzanpay *et al.*	(ORST, TRIU, BRCO+)
MEIJERDREES	92B	PR D45 1439	R. Meijer Drees *et al.*	
ATIYA	91	PRL 66 2189	M.S. Atiya *et al.*	(BNL, LANL, PRIN+)
BEHREND	91	ZPHY C49 401	H.J. Behrend *et al.*	(CELLO Collab.)
CRAWFORD	91	PR D43 46	J.F. Crawford *et al.*	(VILL, VIRG)
LAM	91	PR D44 3345	W.P. Lam, K.W. Ng	(AST)
NATALE	91	PL B258 227	A.A. Natale	(SPIFT)
AFANASYEV	90	PL B236 116	L.G. Afanasyev *et al.*	(JINR, MOSU, SERP)
Also	90B	SJNP 51 664	L.G. Afanasyev *et al.*	(JINR)
		Translated from YAF 51 1040.		
LEE	90	PRL 64 165	A.M. Lee *et al.*	(BNL, FNAL, VILL, WASH+)
FONVIEILLE	89	PL B233 65	H. Fonvieille *et al.*	(CLER, LYON, SACL)
NIEBUHR	89	PR D40 2796	C. Niebuhr *et al.*	(SINDRUM Collab.)
CAMPAGNARI	88	PRL 61 2062	C. Campagnari *et al.*	(BNL, FNAL, PSI+)
CRAWFORD	88B	PL B213 391	J.F. Crawford *et al.*	(PSI, VIRG)
DORENBOS...	88	ZPHY C40 497	J. Dorenbosch *et al.*	(CHARM Collab.)
HOFFMAN	88	PL B208 149	C.M. Hoffman	(LANL)
MCDONOUGH	88	PR D38 2121	J.M. McDonough *et al.*	(TEMP, LANL, CHIC)
PDG	88	PL B204	G.P. Yost *et al.*	(LBL+)
WILLIAMS	88	PR D38 1365	D.A. Williams *et al.*	(Crystal Ball Collab.)
ZEPHAT	87	JPG 13 1375	A.G. Zephat *et al.*	(OMICRON Collab.)
BOLOTOV	86C	JETPL 43 520	V.N. Bolotov *et al.*	(INRM)
		Translated from ZETFP 43 405.		
CRAWFORD	86	PRL 56 1043	J.F. Crawford *et al.*	(SIN, VIRG)
ATHERTON	85	PL 158B 81	H.W. Atherton *et al.*	(CERN, ISU, LUND+)
HERCZEG	84	PR D29 1954	P. Herczeg, C.M. Hoffman	(LANL)
FRANK	83	PR D28 423	J.S. Frank *et al.*	(LANL, ARZS)
TUPPER	83	PR D28 2905	G.B. Tupper, T.R. Grose, M.A. Samuel	(OKSU)
BRYMAN	82	PR D26 2538	D.A. Bryman	(TRIU)
MISCHKE	82	PRL 48 1153	R.E. Mischke *et al.*	(LANL, ARZS)
HERCZEG	81	PL 100B 347	P. Herczeg, C.M. Hoffman	(LANL)
SCHARDT	81	PR D23 639	M.A. Schardt *et al.*	(ARZS, LANL)
AUERBACH	80	PL 90B 317	L.B. Auerbach *et al.*	(TEMP, LASL)
HIGHLAND	80	PRL 44 628	V.L. Highland *et al.*	(TEMP, LASL)
AUERBACH	78	PRL 41 275	L.B. Auerbach *et al.*	(TEMP, LASL)
FISCHER	78	PL 73B 359	J. Fischer *et al.*	(GEVA, SACL)
FISCHER	78B	PL 73B 364	J. Fischer *et al.*	(GEVA, SACL)
BROWMAN	74	PRL 33 1400	A. Browman *et al.*	(CORN, BING)
BELLETTINI	70	NC 66A 243	G. Bellettini *et al.*	(PISA, BONN)
KRYSHKIN	70	JETP 30 1037	V.I. Kryshkin, A.G. Sterligov, Y.P. Usov	(TMSK)
		Translated from ZETF 57 1917.		
DEVONS	69	PR 184 1356	S. Devons *et al.*	(COLU, ROMA)
VASILEVSKY	66	PL 23 281	I.M. Vasilevsky *et al.*	(JINR)
DUCLOS	65	PL 19 253	J. Duclos *et al.*	(CERN, HEID)
KUTIN	65	JETPL 2 243	V.M. Kutjin, V.I. Petrukhin, Y.D. Prokoshkin	(JINR)
		Translated from unknown journal.		
CZIRR	63	PR 130 341	J.B. Czirr	(LRL)
SAMIOS	62B	PR 126 1844	N.P. Samios *et al.*	(COLU, BNL)
KOBRAK	61	NC 20 1115	H. Kobrak	(EFI)
SAMIOS	61	PR 121 275	N.P. Samios	(COLU, BNL)
BERMAN	60	NC XVIII 1192	S. Berman, D. Geffen	
BUDAGOV	60	JETP 11 755	Y.A. Budagov *et al.*	(JINR)
		Translated from ZETF 38 1047.		
JOSEPH	60	NC 16 997	D.W. Joseph	(EFI)