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Heavy Neutral Leptons, Searches for

(A) Heavy Neutral Leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m<$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
$>$44.1	95	ALEXANDER	91F	OPAL	Dirac
$>$37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
$>$42.8	95	[1] ADEVA	90S	L3	Dirac
$>$34.8	95	[1] ADEVA	90S	L3	Majorana
$>$42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 >$ 6.2$\times$10^{-8} at $m_{L^0} = 20$ GeV and $>$ 5.1$\times$10^{-10} for $m_{L^0} = 40$ GeV.

Heavy Neutral Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \rightarrow \nu\gamma$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>101.3	95	ACHARD	01B	L3	Dirac coupling to e
>101.5	95	ACHARD	01B	L3	Dirac coupling to μ
> 90.3	95	ACHARD	01B	L3	Dirac coupling to τ
> 89.5	95	ACHARD	01B	L3	Majorana coupling to e
> 90.7	95	ACHARD	01B	L3	Majorana coupling to μ
> 80.5	95	ACHARD	01B	L3	Majorana coupling to τ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>$ 76.0	95	ABBIENDI	00I	OPAL	Majorana, coupling to e
$>$ 88.0	95	ABBIENDI	00I	OPAL	Dirac, coupling to e
$>$ 76.0	95	ABBIENDI	00I	OPAL	Majorana, coupling to μ
$>$ 88.1	95	ABBIENDI	00I	OPAL	Dirac, coupling to μ
$>$ 53.8	95	ABBIENDI	00I	OPAL	Majorana, coupling to τ
$>$ 71.1	95	ABBIENDI	00I	OPAL	Dirac, coupling to τ
$>$ 76.5	95	ABREU	99O	DLPH	Dirac coupling to e
$>$ 79.5	95	ABREU	99O	DLPH	Dirac coupling to μ
$>$ 60.5	95	ABREU	99O	DLPH	Dirac coupling to τ
$>$ 63	95	[2,3] BUSKULIC	96S	ALEP	Dirac
$>$ 54.3	95	[2,4] BUSKULIC	96S	ALEP	Majorana

[2] BUSKULIC 96S requires the decay length of the heavy lepton to be < 1 cm, limiting the square of the mixing angle $|U_{\ell j}|^2$ to 10^{-10}.

[3] BUSKULIC 96S limit for mixing with τ. Mass is > 63.6 GeV for mixing with e or μ.

[4] BUSKULIC 96S limit for mixing with τ. Mass is > 55.2 GeV for mixing with e or μ.

Astrophysical Limits on Neutrino MASS for $m_\nu > 1$ GeV

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 60–115		[5] FARGION	95	ASTR	Dirac
none 9.2–2000		[6] GARCIA	95	COSM	Nucleosynthesis
none 26–4700		[6] BECK	94	COSM	Dirac
none 6 – hundreds		[7,8] MORI	92B	KAM2	Dirac neutrino
none 24 – hundreds		[7,8] MORI	92B	KAM2	Majorana neutrino
none 10–2400	90	[9] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[10] ENQVIST	89	COSM	
none 12–1400		[6] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[6,7] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[6] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[5] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.

[6] These results assume that neutrinos make up dark matter in the galactic halo.

[7] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.

[8] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.

[9] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.

[10] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Other Bounds from Nuclear and Particle Decays

Limits on $|U_{ex}|^2$ as Function of m_{ν_x}

Peak and kink search tests

Limits on $|U_{ex}|^2$ as function of m_{ν_j}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1 × 10^{-7}	90	[11] BRITTON	92B	CNTR	50 MeV $< m_{\nu_x} < 130$ MeV

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

$<5 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=20 MeV
$<5 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=40 MeV
$<3 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=60 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=80 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=100 MeV
$<5 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=60 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=80 MeV
$<3 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=100 MeV
$<1 \times 10^{-6}$	90	AZUELOS	86	CNTR	m_{ν_x}=120 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	90	[12] BRYMAN	83B	CNTR	m_{ν_x}=5 MeV
$<1.5 \times 10^{-6}$	90	BRYMAN	83B	CNTR	m_{ν_x}=53 MeV
$<1 \times 10^{-5}$	90	BRYMAN	83B	CNTR	m_{ν_x}=70 MeV
$<1 \times 10^{-4}$	90	BRYMAN	83B	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	68	[13] SHROCK	81	THEO	m_{ν_x}=10 MeV
$<5 \times 10^{-6}$	68	[13] SHROCK	81	THEO	m_{ν_x}=60 MeV
$<1 \times 10^{-5}$	68	[14] SHROCK	80	THEO	m_{ν_x}=80 MeV
$<3 \times 10^{-6}$	68	[14] SHROCK	80	THEO	m_{ν_x}=160 MeV

[11] BRITTON 92B is from a search for additional peaks in the e^+ spectrum from $\pi^+ \to e^+ \nu_e$ decay at TRIUMF. See also BRITTON 92.

[12] BRYMAN 83B obtain upper limits from both direct peak search and analysis of $\text{B}(\pi \to e\nu)/\text{B}(\pi \to \mu\nu)$. Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).

[13] Analysis of $(\pi^+ \to e^+ \nu_e)/(\pi^+ \to \mu^+ \nu_\mu)$ and $(K^+ \to e^+ \nu_e)/(K^+ \to \mu^+ \nu_\mu)$ decay ratios.

[14] Analysis of $(K^+ \to e^+ \nu_e)$ spectrum.

Kink search in nuclear β decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)) and in the 1998 edition (The European Physical Journal **C3** 1 (1998)). We list below only the best limits on $|U_{ex}|^2$ for each m_{ν_x}. See WIETFELDT 96 for a comprehensive review.

VALUE (units 10^{-3})	*CL%*	m_{ν_j} (keV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$<$ 4–20	90	700–3500	^{38m}K	Trap	[15] TRINCZEK	03
$<$ 9–116	95	1–0.1	^{187}Re	cryog.	[16] GALEAZZI	01
$<$ 1	95	10–90	^{35}S	Mag spect	[17] HOLZSCHUH	00
$<$ 4	95	14–17	^{241}Pu	Electrostatic spec	[18] DRAGOUN	99
$<$ 1	95	4–30	^{63}Ni	Mag spect	[19] HOLZSCHUH	99
$<$ 10–40	90	370–640	^{37}Ar	EC ion recoil	[20] HINDI	98
$<$ 10	95	1	^{3}H	SPEC	[21] HIDDEMANN	95

< 6	95	2	^{3}H	SPEC	[21] HIDDEMANN 95
< 2	95	3	^{3}H	SPEC	[21] HIDDEMANN 95
< 0.7	99	16.3–16.6	^{3}H	Prop chamber	[22] KALBFLEISCH 93
< 2	95	13–40	^{35}S	Si(Li)	[23] MORTARA 93
< 0.73	95	17	^{63}Ni	Mag spect	OHSHIMA 93
< 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI 92
< 0.9–2.5	90	1200–6800	^{20}F	beta spectrum	[24] DEUTSCH 90
< 8	90	80	^{35}S	Mag spect	[25] APALIKOV 85
< 1.5	90	60	^{35}S	Mag spect	APALIKOV 85
< 3.0	90	5–50		Mag spect	MARKEY 85
< 0.62	90	48	^{35}S	Si(Li)	OHI 85
< 0.90	90	30	^{35}S	Si(Li)	OHI 85
< 4	90	140	^{64}Cu	Mag spect	[26] SCHRECK... 83
< 8	90	440	^{64}Cu	Mag spect	[26] SCHRECK... 83
<100	90	0.1–3000		THEO	[27] SHROCK 80
< 0.1	68	80		THEO	[28] SHROCK 80

[15] TRINCZEK 03 is a search for admixture of heavy neutrino to ν_e, in contrast to $\overline{\nu}_e$ used in many other searches. Full kinematic reconstruction of the neutrino momentum by use of a magneto optical trap.

[16] GALEAZZI 01 use an cryogenic microcalorimeter to search for mass 50–1000 eV neutrino admixtures using the ^{187}Re beta spectrum with 2.4 keV endpoint. They derive limits for the admixture of heavy neutrinos, ranging from 9×10^{-3} for mass 1 keV to 0.116 for mass 100 eV. This is a significant improvement with respect to HIDDEMANN 95, especially for masses below $\sim$ 500 MeV, where the limit is about a factor of $\sim$ 2 higher.

[17] HOLZSCHUH 00 use an iron-free β spectrometer to measure the ^{35}Sβ decay spectrum. An analysis of the spectrum in the energy range 56–173 keV is used to derive limits for the admixture of heavy neutrinos. This extends the range of neutrino masses explored in HOLZSCHUH 99.

[18] DRAGOUN 99 analyze the β decay spectrum of ^{241}Pu in the energy range 0.2–9.2 keV to derive limits for the admixture of heavy neutrinos. It is not competitive with HOLZSCHUH 99.

[19] HOLZSCHUH 99 use an iron-free β spectrometer to measure the ^{63}Niβ decay spectrum. An analysis of the spectrum in the energy rage 33–67.8 keV is used to derive limits for the admixture of heavy neutrinos.

[20] HINDI 98 obtain a limit on heavy neutrino admixture from EC decay of ^{37}Ar by measuring the time-of-flight distribution of the recoiling ions in coincidence with x-rays or Auger electrons. The authors report upper limit for $|U_{ex}|^2$ of $\approx$ 3% for m_{ν_x}=500 keV, 1% for m_{ν_x}=550 keV, 2% for m_{ν_x}=600 keV, and 4% for m_x=650 keV. Their reported limits for $m_{\nu_x} \leq 450$ keV are inferior to the limits of SCHRECKENBACH 83.

[21] In the beta spectrum from tritium β decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For m_{ν_x} <1 keV, their upper limit on $|U_{ex}|^2$ becomes less

[22] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of ^{3}H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{e\,x}|^2$ as a function of m_{ν_x} in the range from 13.5 keV to 17.5 keV. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[23] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of ^{35}S and ^{14}C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."

[24] DEUTSCH 90 search for emission of heavy $\overline{\nu}_e$ in super-allowed beta decay of ^{20}F by spectral analysis of the electrons.

[25] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.

[26] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.

[27] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.

[28] Application of test to search for kinks in β decay Kurie plots.

Searches for Decays of Massive ν

Limits on $|U_{e\,x}|^2$ as function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.6 \times 10^{-4}$	90	[29] BACK	03A	CNTR	m_{ν_x} = 4 MeV
$<4.5 \times 10^{-5}$	90	[29] BACK	03A	CNTR	m_{ν_x} = 7 MeV
$<3.8 \times 10^{-5}$	90	[29] BACK	03A	CNTR	m_{ν_x} = 10 MeV
$<1.5 \times 10^{-3}$	95	ACHARD	01	L3	m_{ν_x}=80 GeV
$<2 \times 10^{-2}$	95	ACHARD	01	L3	m_{ν_x}=175 GeV
<0.3	95	ACHARD	01	L3	m_{ν_x}=200 GeV
$<4 \times 10^{-3}$	95	ACCIARRI	99K	L3	m_{ν_x}=80 GeV
$<5 \times 10^{-2}$	95	ACCIARRI	99K	L3	m_{ν_x}= 175 GeV
$<2 \times 10^{-5}$	95	[30] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[30] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<1.8 \times 10^{-3}$	90	[31] HAGNER	95	MWPC	m_{ν_h} = 1.5 MeV
$<2.5 \times 10^{-4}$	90	[31] HAGNER	95	MWPC	m_{ν_h} = 4 MeV
$<4.2 \times 10^{-3}$	90	[31] HAGNER	95	MWPC	m_{ν_h} = 9 MeV
$<1 \times 10^{-5}$	90	[32] BARANOV	93		m_{ν_x}=100 MeV
$<1 \times 10^{-6}$	90	[32] BARANOV	93		m_{ν_x}= 200 MeV
$<3 \times 10^{-7}$	90	[32] BARANOV	93		m_{ν_x}= 300 MeV
$<2 \times 10^{-7}$	90	[32] BARANOV	93		m_{ν_x}=400 MeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[33] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[33] BURCHAT	90	MRK2	m_{ν_x}= 22 GeV
$<1 \times 10^{-11}$	95	[33] BURCHAT	90	MRK2	m_{ν_x}= 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_x}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_x}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_x}=6 GeV
$<1.2 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_x}=100 MeV
$<1 \times 10^{-8}$	90	BERNARDI	88	CNTR	m_{ν_x}=200 MeV
$<2.4 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=300 MeV

$<2.1 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=400 MeV
$<2 \times 10^{-2}$	68	[34] OBERAUER	87		m_{ν_x}=1.5 MeV
$<8 \times 10^{-4}$	68	[34] OBERAUER	87		m_{ν_x}=4.0 MeV
$<8 \times 10^{-3}$	90	BADIER	86	CNTR	m_{ν_x}=400 MeV
$<8 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_x}=1.7 GeV
$<8 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=100 MeV
$<4 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_x}=400 MeV
$<3 \times 10^{-5}$	90	DORENBOS...	86	CNTR	m_{ν_x}=150 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_x}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	m_{ν_x}=1.6 GeV
$<7 \times 10^{-7}$	90	[35] COOPER-...	85	HLBC	m_{ν_x}=0.4 GeV
$<8 \times 10^{-8}$	90	[35] COOPER-...	85	HLBC	m_{ν_x}=1.5 GeV
$<1 \times 10^{-2}$	90	[36] BERGSMA	83B	CNTR	m_{ν_x}=10 MeV
$<1 \times 10^{-5}$	90	[36] BERGSMA	83B	CNTR	m_{ν_x}=110 MeV
$<6 \times 10^{-7}$	90	[36] BERGSMA	83B	CNTR	m_{ν_x}=410 MeV
$<1 \times 10^{-5}$	90	GRONAU	83		m_{ν_x}=160 MeV
$<1 \times 10^{-6}$	90	GRONAU	83		m_{ν_x}=480 MeV

[29] BACK 03A searched for heavy neutrinos emitted from ^{8}B decay in the Sun using the decay $\nu_h \rightarrow \nu_e e^+ e^-$ in the Counting Test Facility (the prototype of the Borexino detector) and obtained limits on heavy neutrino admixture for the ν_h mass range 1.1–12 MeV.

[30] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[31] HAGNER 95 obtain limits on heavy neutrino admixture from the decay $\nu_h \rightarrow \nu_e e^+ e^-$ at a nuclear reactor for the ν_h mass range 2–9 MeV.

[32] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[33] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[34] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' e e$ decay mode using reactor (anti)neutrinos.

[35] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since $m_{\nu_3} < 70$ MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[36] BERGSMA 83B also quote limits on $|U_{e3}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Limits on Coupling of μ to ν_x as Function of m_{ν_x}

Peak search test

Limits on B(π (or K) $\to$ $\mu\nu_x$).

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[37] ASTIER	02	NOMD	$\pi \to \mu X$ for m_X=33.9 MeV
$<6.0 \times 10^{-10}$	95	[38] DAUM	00	CNTR	$\pi \to \mu X$ for m_X=33.9 MeV
		[39] FORMAGGIO	00	CNTR	$\pi \to \mu X$ for m_X=33.9 MeV
<0.22	90	[40] ASSAMAGAN	98	SILI	m_{ν_x}= 0.53 MeV
<0.029	90	[40] ASSAMAGAN	98	SILI	m_{ν_x}= 0.75 MeV
<0.016	90	[40] ASSAMAGAN	98	SILI	m_{ν_x}= 1.0 MeV
$<$ 4–6 $\times 10^{-5}$		[41] BRYMAN	96	CNTR	m_{ν_x} = 30–33.91 MeV
$\sim 1 \times 10^{-16}$		[42] ARMBRUSTER	95	KARM	m_{ν_x} = 33.9 MeV
$<4 \times 10^{-7}$	95	[43] BILGER	95	LEPS	$m_{\overline{\nu}_x}$ = 33.9 MeV
$<7 \times 10^{-8}$	95	[43] BILGER	95	LEPS	m_{ν_x} = 33.9 MeV
$<2.6 \times 10^{-8}$	95	[43] DAUM	95B	TOF	m_{ν_x} = 33.9 MeV
$<2 \times 10^{-2}$	90	DAUM	87		m_{ν_x}=1 MeV
$<1 \times 10^{-3}$	90	DAUM	87		m_{ν_x}=2 MeV
$<6 \times 10^{-5}$	90	DAUM	87		3 MeV $< m_{\nu_x} <$ 19.5 MeV
$<3 \times 10^{-2}$	90	[44] MINEHART	84		m_{ν_x}=2 MeV
$<1 \times 10^{-3}$	90	[44] MINEHART	84		m_{ν_x}=4 MeV
$<3 \times 10^{-4}$	90	[44] MINEHART	84		m_{ν_x}=10 GeV
$<5 \times 10^{-6}$	90	[45] HAYANO	82		m_{ν_x}=330 MeV
$<1 \times 10^{-4}$	90	[45] HAYANO	82		m_{ν_x}=70 MeV
$<9 \times 10^{-7}$	90	[45] HAYANO	82		m_{ν_x}=250 MeV
$<1 \times 10^{-1}$	90	[44] ABELA	81		m_{ν_x}=4 MeV
$<7 \times 10^{-5}$	90	[44] ABELA	81		m_{ν_x}=10.5 MeV
$<2 \times 10^{-4}$	90	[44] ABELA	81		m_{ν_x}=11.5 MeV
$<2 \times 10^{-5}$	90	[44] ABELA	81		m_{ν_x}=16–30 MeV

[37] ASTIER 02 search for anomalous pion decay into a 33.9 MeV neutral particle. No evidence was found and the sensitivity to the branching ratio B($\pi \to \mu X$)·B($X \to \nu e^+ e^-$) is as low as 3.7×10^{-15}, depending on the X lifetime.

[38] DAUM 00 search for anomalous pion decay into a 33.9 MeV neutral particle that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration.

[39] FORMAGGIO 00 search for anomalous pion decay into a 33.9 MeV neutral particle Q^0 that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration. In the E815 (NuTeV) experiment at Fermilab no evidence was found, with sensitivity for the pion branching ratio B($\pi \to \mu Q^0$)·B($Q^0 \to$ visible) as low as 10^{-13}.

[40] ASSAMAGAN 98 obtain a limit on heavy neutrino admixture from π^+ decay essentially at rest, by measuring with good resolution the momentum distribution of the muons. However, the search uses an ad hoc shape correction. The authors report upper limit for

$|U_{\mu x}|^2$ of 0.22 for $m_\nu = 0.53$ MeV, 0.029 for $m_\nu = 0.75$ MeV, and 0.016 for $m_\nu = 1.0$ MeV at 90%CL.

[41] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay.

[42] ARMBRUSTER 95 study the reactions ^{12}C(ν_e,e^-) ^{12}N and ^{12}C(ν,ν') ^{12}C* induced by neutrinos from π^+ and μ^+ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where ν_x is a neutral weakly interacting particle with mass ≈ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.

[43] From experiments of π^+ and π^- decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).

[44] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[45] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

Peak search test

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1–10×10^{-4}		[46] BRYMAN	96	CNTR	$m_{\nu_x} = 30$–33.91 MeV
$<2 \times 10^{-5}$	95	[47] ASANO	81		$m_{\nu_x}=70$ MeV
$<3 \times 10^{-6}$	95	[47] ASANO	81		$m_{\nu_x}=210$ MeV
$<3 \times 10^{-6}$	95	[47] ASANO	81		$m_{\nu_x}=230$ MeV
$<6 \times 10^{-6}$	95	[48] ASANO	81		$m_{\nu_x}=240$ MeV
$<5 \times 10^{-7}$	95	[48] ASANO	81		$m_{\nu_x}=280$ MeV
$<6 \times 10^{-6}$	95	[48] ASANO	81		$m_{\nu_x}=300$ MeV
$<1 \times 10^{-2}$	95	CALAPRICE	81		$m_{\nu_x}=7$ MeV
$<3 \times 10^{-3}$	95	[49] CALAPRICE	81		$m_{\nu_x}=33$ MeV
$<1 \times 10^{-4}$	68	[50] SHROCK	81	THEO	$m_{\nu_x}=13$ MeV
$<3 \times 10^{-5}$	68	[50] SHROCK	81	THEO	$m_{\nu_x}=33$ MeV
$<6 \times 10^{-3}$	68	[51] SHROCK	81	THEO	$m_{\nu_x}=80$ MeV
$<5 \times 10^{-3}$	68	[51] SHROCK	81	THEO	$m_{\nu_x}=120$ MeV

[46] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay. They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise

[47] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[48] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.

[49] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

[50] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.

[51] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu$, ν_μ decay.

Peak Search in Muon Capture

Limits on $\lvert U_{\mu x}\rvert^2$ as function of m_{ν_x}

VALUE	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=45 MeV
$<7 \times 10^{-3}$	DEUTSCH	83	m_{ν_x}=70 MeV
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=85 MeV

Searches for Decays of Massive ν

Limits on $\lvert U_{\mu x}\rvert^2$ as function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-7}$	90	[52] VAITAITIS	99	CCFR	m_{ν_x}=0.28 GeV
$<8 \times 10^{-8}$	90	[52] VAITAITIS	99	CCFR	m_{ν_x}=0.37 GeV
$<5 \times 10^{-7}$	90	[52] VAITAITIS	99	CCFR	m_{ν_x}= 0.50 GeV
$<6 \times 10^{-8}$	90	[52] VAITAITIS	99	CCFR	m_{ν_x}= 1.50 GeV
$<2 \times 10^{-5}$	95	[53] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[53] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<3 \times 10^{-6}$	90	GALLAS	95	CNTR	m_{ν_x} = 1 GeV
$<3 \times 10^{-5}$	90	[54] VILAIN	95C	CHM2	m_{ν_x} = 2 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[55] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[55] BURCHAT	90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[55] BURCHAT	90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_x}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_x}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_x}=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_x}=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=300 MeV
$<4 \times 10^{-4}$	90	[56] MISHRA	87	CNTR	m_{ν_x}=1.5 GeV
$<4 \times 10^{-3}$	90	[56] MISHRA	87	CNTR	m_{ν_x}=2.5 GeV
$<0.9 \times 10^{-2}$	90	[56] MISHRA	87	CNTR	m_{ν_x}=5 GeV
<0.1	90	[56] MISHRA	87	CNTR	m_{ν_x}=10 GeV
$<8 \times 10^{-4}$	90	BADIER	86	CNTR	m_{ν_x}=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_x}=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_x}=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_x}=500 MeV

$<1 \times 10^{-7}$	90	DORENBOS... 86	CNTR	m_{ν_x}=1600 MeV
$<0.8 \times 10^{-5}$	90	[57] COOPER-... 85	HLBC	m_{ν_x}=0.4 GeV
$<1.0 \times 10^{-7}$	90	[57] COOPER-... 85	HLBC	m_{ν_x}=1.5 GeV

[52] VAITAITIS 99 search for $L^0_\mu \rightarrow \mu X$. See paper for rather complicated limit as function of m_{ν_x}.

[53] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[54] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.

[55] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[56] See also limits on $|U_{3x}|$ from WENDT 87.

[57] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{\tau x}|^2$ as a Function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1 \times 10^{-2}$	90	[58] ORLOFF 02	CHRM	m_{ν_x}=45 MeV
$<1.4 \times 10^{-4}$	90	[58] ORLOFF 02	CHRM	m_{ν_x}=180 MeV
<0.025	90	ASTIER 01		m_{ν_x}=45 MeV
<0.002	90	ASTIER 01		m_{ν_x}=140 MeV
$<2 \times 10^{-5}$	95	[59] ABREU 97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[59] ABREU 97I	DLPH	m_{ν_x}=50 GeV
$<6.2 \times 10^{-8}$	95	ADEVA 90S	L3	m_{ν_x}=20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA 90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[60] BURCHAT 90	MRK2	$m_{\nu_x} <$ 19.6 GeV
$<1 \times 10^{-10}$	95	[60] BURCHAT 90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[60] BURCHAT 90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP 90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP 90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF 88	HRS	m_{ν_x}=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF 88	HRS	m_{ν_x}=4.5 GeV

[58] ORLOFF 02 use the negative result of a search for neutral particles decaying into two electrons performed by CHARM to get these limits for a mostly isosinglet heavy neutrino.

[59] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.

[60] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{ax}|^2$

Where $a = e$, μ from ρ parameter in μ decay.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1 \times 10^{-2}$	68	SHROCK 81B	THEO	m_{ν_x}=10 GeV
$<2 \times 10^{-3}$	68	SHROCK 81B	THEO	m_{ν_x}=40 MeV
$<4 \times 10^{-2}$	68	SHROCK 81B	THEO	m_{ν_x}=70 MeV

Limits on $|U_{1j} \times U_{2j}|$ as Function of m_{ν_j}

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3 \times 10^{-5}$	90	[61] BARANOV 93		m_{ν_j}= 80 MeV
$<3 \times 10^{-6}$	90	[61] BARANOV 93		m_{ν_j}= 160 MeV
$<6 \times 10^{-7}$	90	[61] BARANOV 93		m_{ν_j}= 240 MeV
$<2 \times 10^{-7}$	90	[61] BARANOV 93		m_{ν_j}= 320 MeV
$<9 \times 10^{-5}$	90	BERNARDI 86	CNTR	m_{ν_j}=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI 86	CNTR	m_{ν_j}=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI 86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA 83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA 83B	CNTR	m_{ν_j}=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA 83B	CNTR	m_{ν_j}=370 MeV

[61] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

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