

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.

<u>VALUE (GeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
>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

¹ADEVA 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 $m_{L0} = 20$ GeV and $> 5.1 \times 10^{-10}$ for $m_{L0} = 40$ GeV.

———— Heavy Neutral Lepton MASS LIMITS ————

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

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

<u>VALUE (GeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
>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 —————

<u>VALUE (GeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● 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}

<u>VALUE</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
$<1 \times 10^{-7}$	90	¹¹ BRITTON	92B CNTR	$50 \text{ MeV} < m_{\nu_x} < 130 \text{ MeV}$

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

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

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

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

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

¹⁴Analysis of $(K^+ \rightarrow e^+ \nu_e)$ 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
< 4–20	90	700–3500	³⁸ mK	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 DRAGON 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	^3H	SPEC	$^{21}\text{HIDDEMANN}$	95
< 2	95	3	^3H	SPEC	$^{21}\text{HIDDEMANN}$	95
< 0.7	99	16.3–16.6	^3H	Prop chamber	$^{22}\text{KALBFLEISCH}$	93
< 2	95	13–40	^{35}S	Si(Li)	$^{23}\text{MORTARA}$	93
< 0.73	95	17	^{63}Ni	Mag spect	OHSIMA	93
< 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI	92
< 0.9–2.5	90	1200–6800	^{20}F	beta spectrum	$^{24}\text{DEUTSCH}$	90
< 8	90	80	^{35}S	Mag spect	$^{25}\text{APALIKOV}$	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	$^{26}\text{SCHRECK...}$	83
< 8	90	440	^{64}Cu	Mag spect	$^{26}\text{SCHRECK...}$	83
<100	90	0.1–3000		THEO	$^{27}\text{SHROCK}$	80
< 0.1	68	80		THEO	$^{28}\text{SHROCK}$	80

¹⁵ TRINCZEK 03 is a search for admixture of heavy neutrino to ν_e , in contrast to $\bar{\nu}_e$ 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 ~ 500 MeV, where the limit is about a factor of ~ 2 higher.

¹⁷ HOLZSCHUH 00 use an iron-free β spectrometer to measure the ^{35}S β 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 DRAGON 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}Ni β decay spectrum. An analysis of the spectrum in the energy range 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 $m_{\nu_x}=500$ keV, 1% for $m_{\nu_x}=550$ keV, 2% for $m_{\nu_x}=600$ 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 $m_{\bar{\nu}_1}$ state in the mass region 0.01–4 keV. For $m_{\nu_x} < 1$ 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 ^3H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{ex}|^2$ 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 $\bar{\nu}_e$ 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 $|U_{ex}|^2$ 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	$m_{\nu_x} = 4 \text{ MeV}$
$<4.5 \times 10^{-5}$	90	²⁹ BACK	03A CNTR	$m_{\nu_x} = 7 \text{ MeV}$
$<3.8 \times 10^{-5}$	90	²⁹ BACK	03A CNTR	$m_{\nu_x} = 10 \text{ MeV}$
$<1.5 \times 10^{-3}$	95	ACHARD	01 L3	$m_{\nu_x} = 80 \text{ GeV}$
$<2 \times 10^{-2}$	95	ACHARD	01 L3	$m_{\nu_x} = 175 \text{ GeV}$
<0.3	95	ACHARD	01 L3	$m_{\nu_x} = 200 \text{ GeV}$
$<4 \times 10^{-3}$	95	ACCIARRI	99K L3	$m_{\nu_x} = 80 \text{ GeV}$
$<5 \times 10^{-2}$	95	ACCIARRI	99K L3	$m_{\nu_x} = 175 \text{ GeV}$
$<2 \times 10^{-5}$	95	³⁰ ABREU	97I DLPH	$m_{\nu_x} = 6 \text{ GeV}$
$<3 \times 10^{-5}$	95	³⁰ ABREU	97I DLPH	$m_{\nu_x} = 50 \text{ GeV}$
$<1.8 \times 10^{-3}$	90	³¹ HAGNER	95 MWPC	$m_{\nu_h} = 1.5 \text{ MeV}$
$<2.5 \times 10^{-4}$	90	³¹ HAGNER	95 MWPC	$m_{\nu_h} = 4 \text{ MeV}$
$<4.2 \times 10^{-3}$	90	³¹ HAGNER	95 MWPC	$m_{\nu_h} = 9 \text{ MeV}$
$<1 \times 10^{-5}$	90	³² BARANOV	93	$m_{\nu_x} = 100 \text{ MeV}$
$<1 \times 10^{-6}$	90	³² BARANOV	93	$m_{\nu_x} = 200 \text{ MeV}$
$<3 \times 10^{-7}$	90	³² BARANOV	93	$m_{\nu_x} = 300 \text{ MeV}$
$<2 \times 10^{-7}$	90	³² BARANOV	93	$m_{\nu_x} = 400 \text{ MeV}$
$<6.2 \times 10^{-8}$	95	ADEVA	90S L3	$m_{\nu_x} = 20 \text{ GeV}$
$<5.1 \times 10^{-10}$	95	ADEVA	90S L3	$m_{\nu_x} = 40 \text{ GeV}$
all values ruled out	95	³³ BURCHAT	90 MRK2	$m_{\nu_x} < 19.6 \text{ GeV}$
$<1 \times 10^{-10}$	95	³³ BURCHAT	90 MRK2	$m_{\nu_x} = 22 \text{ GeV}$
$<1 \times 10^{-11}$	95	³³ BURCHAT	90 MRK2	$m_{\nu_x} = 41 \text{ GeV}$
all values ruled out	95	DECAMP	90F ALEP	$m_{\nu_x} = 25.0\text{--}42.7 \text{ GeV}$
$<1 \times 10^{-13}$	95	DECAMP	90F ALEP	$m_{\nu_x} = 42.7\text{--}45.7 \text{ GeV}$
$<5 \times 10^{-3}$	90	AKERLOF	88 HRS	$m_{\nu_x} = 1.8 \text{ GeV}$
$<2 \times 10^{-5}$	90	AKERLOF	88 HRS	$m_{\nu_x} = 4 \text{ GeV}$
$<3 \times 10^{-6}$	90	AKERLOF	88 HRS	$m_{\nu_x} = 6 \text{ GeV}$
$<1.2 \times 10^{-7}$	90	BERNARDI	88 CNTR	$m_{\nu_x} = 100 \text{ MeV}$
$<1 \times 10^{-8}$	90	BERNARDI	88 CNTR	$m_{\nu_x} = 200 \text{ MeV}$
$<2.4 \times 10^{-9}$	90	BERNARDI	88 CNTR	$m_{\nu_x} = 300 \text{ MeV}$

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

²⁹ BACK 03A searched for heavy neutrinos emitted from ^8B 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 testLimits on $B(\pi \text{ (or } K) \rightarrow \mu\nu_x)$.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$<6.0 \times 10^{-10}$	95	37 ASTIER 02	NOMD	$\pi \rightarrow \mu X$ for $m_X=33.9$ MeV
		38 DAUM 00	CNTR	$\pi \rightarrow \mu X$ for $m_X=33.9$ MeV
		39 FORMAGGIO 00	CNTR	$\pi \rightarrow \mu X$ for $m_X=33.9$ MeV
<0.22	90	40 ASSAMAGAN 98	SILI	$m_{\nu_x} = 0.53$ MeV
<0.029	90	40 ASSAMAGAN 98	SILI	$m_{\nu_x} = 0.75$ MeV
<0.016	90	40 ASSAMAGAN 98	SILI	$m_{\nu_x} = 1.0$ MeV
$<4-6 \times 10^{-5}$		41 BRYMAN 96	CNTR	$m_{\nu_x} = 30-33.91$ MeV
$\sim 1 \times 10^{-16}$		42 ARMBRUSTER95	KARM	$m_{\nu_x} = 33.9$ MeV
$<4 \times 10^{-7}$	95	43 BILGER 95	LEPS	$m_{\bar{\nu}_x} = 33.9$ MeV
$<7 \times 10^{-8}$	95	43 BILGER 95	LEPS	$m_{\nu_x} = 33.9$ MeV
$<2.6 \times 10^{-8}$	95	43 DAUM 95B	TOF	$m_{\nu_x} = 33.9$ MeV
$<2 \times 10^{-2}$	90	DAUM 87		$m_{\nu_x} = 1$ MeV
$<1 \times 10^{-3}$	90	DAUM 87		$m_{\nu_x} = 2$ MeV
$<6 \times 10^{-5}$	90	DAUM 87		$3 \text{ MeV} < m_{\nu_x} < 19.5 \text{ MeV}$
$<3 \times 10^{-2}$	90	44 MINEHART 84		$m_{\nu_x} = 2$ MeV
$<1 \times 10^{-3}$	90	44 MINEHART 84		$m_{\nu_x} = 4$ MeV
$<3 \times 10^{-4}$	90	44 MINEHART 84		$m_{\nu_x} = 10$ GeV
$<5 \times 10^{-6}$	90	45 HAYANO 82		$m_{\nu_x} = 330$ MeV
$<1 \times 10^{-4}$	90	45 HAYANO 82		$m_{\nu_x} = 70$ MeV
$<9 \times 10^{-7}$	90	45 HAYANO 82		$m_{\nu_x} = 250$ MeV
$<1 \times 10^{-1}$	90	44 ABELA 81		$m_{\nu_x} = 4$ MeV
$<7 \times 10^{-5}$	90	44 ABELA 81		$m_{\nu_x} = 10.5$ MeV
$<2 \times 10^{-4}$	90	44 ABELA 81		$m_{\nu_x} = 11.5$ MeV
$<2 \times 10^{-5}$	90	44 ABELA 81		$m_{\nu_x} = 16-30$ 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 $B(\pi \rightarrow \mu X) \cdot B(X \rightarrow \nu e^+ e^-)$ 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 $B(\pi \rightarrow \mu Q^0) \cdot B(Q^0 \rightarrow \text{visible})$ 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 $^{12}\text{C}(\nu_e, e^-) ^{12}\text{N}$ and $^{12}\text{C}(\nu, \nu') ^{12}\text{C}^*$ 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. ● ● ●				
$< 1-10 \times 10^{-4}$		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 $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \bar{\nu}_x$ 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 $K \rightarrow \mu, \nu_\mu$ decay.

Peak Search in Muon Capture

Limits on $|U_{\mu x}|^2$ 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	$m_{\nu_x} = 45$ MeV
$< 7 \times 10^{-3}$	DEUTSCH 83	$m_{\nu_x} = 70$ MeV
$< 1 \times 10^{-1}$	DEUTSCH 83	$m_{\nu_x} = 85$ MeV

Searches for Decays of Massive ν

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. ● ● ●				
$<5 \times 10^{-7}$	90	52 VAITAITIS	99 CCFR	$m_{\nu_X}=0.28$ GeV
$<8 \times 10^{-8}$	90	52 VAITAITIS	99 CCFR	$m_{\nu_X}=0.37$ GeV
$<5 \times 10^{-7}$	90	52 VAITAITIS	99 CCFR	$m_{\nu_X}=0.50$ GeV
$<6 \times 10^{-8}$	90	52 VAITAITIS	99 CCFR	$m_{\nu_X}=1.50$ GeV
$<2 \times 10^{-5}$	95	53 ABREU	97I DLPH	$m_{\nu_X}=6$ GeV
$<3 \times 10^{-5}$	95	53 ABREU	97I DLPH	$m_{\nu_X}=50$ GeV
$<3 \times 10^{-6}$	90	GALLAS	95 CNTR	$m_{\nu_X}=1$ GeV
$<3 \times 10^{-5}$	90	54 VILAIN	95C CHM2	$m_{\nu_X}=2$ GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S L3	$m_{\nu_X}=20$ GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S L3	$m_{\nu_X}=40$ GeV
all values ruled out	95	55 BURCHAT	90 MRK2	$m_{\nu_X} < 19.6$ GeV
$<1 \times 10^{-10}$	95	55 BURCHAT	90 MRK2	$m_{\nu_X}=22$ GeV
$<1 \times 10^{-11}$	95	55 BURCHAT	90 MRK2	$m_{\nu_X}=41$ GeV
all values ruled out	95	DECAMP	90F ALEP	$m_{\nu_X}=25.0-42.7$ GeV
$<1 \times 10^{-13}$	95	DECAMP	90F ALEP	$m_{\nu_X}=42.7-45.7$ GeV
$<5 \times 10^{-3}$	90	AKERLOF	88 HRS	$m_{\nu_X}=1.8$ GeV
$<2 \times 10^{-5}$	90	AKERLOF	88 HRS	$m_{\nu_X}=4$ GeV
$<3 \times 10^{-6}$	90	AKERLOF	88 HRS	$m_{\nu_X}=6$ GeV
$<1 \times 10^{-7}$	90	BERNARDI	88 CNTR	$m_{\nu_X}=200$ MeV
$<3 \times 10^{-9}$	90	BERNARDI	88 CNTR	$m_{\nu_X}=300$ MeV
$<4 \times 10^{-4}$	90	56 MISHRA	87 CNTR	$m_{\nu_X}=1.5$ GeV
$<4 \times 10^{-3}$	90	56 MISHRA	87 CNTR	$m_{\nu_X}=2.5$ GeV
$<0.9 \times 10^{-2}$	90	56 MISHRA	87 CNTR	$m_{\nu_X}=5$ GeV
<0.1	90	56 MISHRA	87 CNTR	$m_{\nu_X}=10$ GeV
$<8 \times 10^{-4}$	90	BADIER	86 CNTR	$m_{\nu_X}=600$ MeV
$<1.2 \times 10^{-5}$	90	BADIER	86 CNTR	$m_{\nu_X}=1.7$ GeV
$<3 \times 10^{-8}$	90	BERNARDI	86 CNTR	$m_{\nu_X}=200$ MeV
$<6 \times 10^{-9}$	90	BERNARDI	86 CNTR	$m_{\nu_X}=350$ MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86 CNTR	$m_{\nu_X}=500$ MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86 CNTR	$m_{\nu_X}=1600$ MeV
$<0.8 \times 10^{-5}$	90	57 COOPER-...	85 HLBC	$m_{\nu_X}=0.4$ GeV
$<1.0 \times 10^{-7}$	90	57 COOPER-...	85 HLBC	$m_{\nu_X}=1.5$ GeV

⁵²VAITAITIS 99 search for $L_{\mu}^0 \rightarrow \mu X$. See paper for rather complicated limit as function of m_{ν_X} .

⁵³ABREU 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_T 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_T 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.

Limits on $|U_{Tx}|^2$ 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 CHR	$m_{\nu_x}=45$ MeV
$<1.4 \times 10^{-4}$	90	⁵⁸ ORLOFF	02 CHR	$m_{\nu_x}=180$ MeV
<0.025	90	ASTIER	01	$m_{\nu_x}=45$ MeV
<0.002	90	ASTIER	01	$m_{\nu_x}=140$ MeV
$<2 \times 10^{-5}$	95	⁵⁹ ABREU	97i DLP	$m_{\nu_x}=6$ GeV
$<3 \times 10^{-5}$	95	⁵⁹ ABREU	97i DLP	$m_{\nu_x}=50$ GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90s L3	$m_{\nu_x}=20$ GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90s L3	$m_{\nu_x}=40$ 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	$m_{\nu_x} = 22$ GeV
$<1 \times 10^{-11}$	95	⁶⁰ BURCHAT	90 MRK2	$m_{\nu_x} = 41$ GeV
all values ruled out	95	DECAMP	90F ALEP	$m_{\nu_x} = 25.0-42.7$ GeV
$<1 \times 10^{-13}$	95	DECAMP	90F ALEP	$m_{\nu_x} = 42.7-45.7$ GeV
$<5 \times 10^{-2}$	80	AKERLOF	88 HRS	$m_{\nu_x}=2.5$ GeV
$<9 \times 10^{-5}$	80	AKERLOF	88 HRS	$m_{\nu_x}=4.5$ 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 $a = e, \mu$ 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	$m_{\nu_x}=10$ GeV
$<2 \times 10^{-3}$	68	SHROCK	81B THEO	$m_{\nu_x}=40$ MeV
$<4 \times 10^{-2}$	68	SHROCK	81B THEO	$m_{\nu_x}=70$ 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	$m_{\nu_j} = 80$ MeV
$<3 \times 10^{-6}$	90	⁶¹ BARANOV	93	$m_{\nu_j} = 160$ MeV
$<6 \times 10^{-7}$	90	⁶¹ BARANOV	93	$m_{\nu_j} = 240$ MeV
$<2 \times 10^{-7}$	90	⁶¹ BARANOV	93	$m_{\nu_j} = 320$ MeV
$<9 \times 10^{-5}$	90	BERNARDI	86 CNTR	$m_{\nu_j} = 25$ MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86 CNTR	$m_{\nu_j} = 100$ MeV
$<3 \times 10^{-8}$	90	BERNARDI	86 CNTR	$m_{\nu_j} = 200$ MeV
$<6 \times 10^{-9}$	90	BERNARDI	86 CNTR	$m_{\nu_j} = 350$ MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B CNTR	$m_{\nu_j} = 10$ MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B CNTR	$m_{\nu_j} = 140$ MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B CNTR	$m_{\nu_j} = 370$ MeV

⁶¹BARANOV 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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