REFERENCES FOR Limits on Number of Light Neutrino Types

ABREU	94	NP B418 403	+Adam, Adye, Agasi+	(DELPHI Collab.)
ACCIARRI	94	ZPHY C62 551	+Adam, Adriani, Aguilar-Benitez+	(L3 Collab.)
AKERS	94	ZPHY C61 19	+Alexander, Allison+	(OPAL Collab.)
BUSKULIC	94	ZPHY C62 539	+Casper, De Bonis, Decamp, Ghez, Goy+	(ALEPH Collab.)
BUSKULIC	93J	ZPHY C60 71	+Decamp, Goy, Lees, Minard+	(ALEPH Collab.)
BUSKULIC	93L	PL B313 520	+De Bonis, Decamp+	(ALEPH Collab.)
ADEVA	92	PL B275 209	+Adriani, Aguilar-Benitez+	(L3 Collab.)
ADRIANI	92E	PL B292 463	+Aguilar-Benitez, Ahlen, Akbari, Alcaraz+	(L3 Collab.)
DECAMP	92B	ZPHY C53 1	+Deschizeaux, Goy, Lees, Minard+	(ALEPH Collab.)
LEP	92	PL B276 247	+ALEPH, DELPHI, L3, OPAL	(LEP Collabs.)
ABREU	91F	NP B367 511	+Adam, Adami, Adye, Akesson+	(DELPHI Collab.)
ADEVA	91E	ZPHY C51 179	+Adriani, Aguilar-Benitez, Akbari, Alcaraz+	(L3 Collab.)
AKRAWY	91D	ZPHY C50 373	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
ALEXANDER	91F	ZPHY C52 175	+Allison, Allport, Anderson, Arcelli+	(OPAL Collab.)
WALKER	91	APJ 376 51	+Steigman, Schramm, Olive+	(HSCA, OSU, CHIC, MINN)
AARNIO	90	PL B241 425	+Abreu, Adam, Adami+	(DELPHI Collab.)
ABREU	90	PL B241 435	+Adam, Adami+	(DELPHI Collab.)
ADEVA	90D	PL B238 122	+Adriani, Aguilar-Benitez, Akbari+	(L3 Collab.)
ADEVA	90I	PL B249 341	+Adriani, Aguilar-Benitez, Akbari, Alcarez+	(L3 Collab.)
AKRAWY	90	PL B235 379	+Alexander, Allison, Allport, Anderson+	(OPAL Collab.)
AKRAWY	90E	PL B240 497	+Alexander, Allison, Allport+	(OPAL Collab.)
DECAMP	90B	PL B234 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90D	PL B235 399	+Deschizeaux, Lees, Minard, Crespo+	(ALEPH Collab.)
DECAMP	90P	ZPHY C48 365	+Deschizeaux, Goy, Lees+	(ALEPH Collab.)
DENEGRI	90	RMP 62 1	+Sadoulet, Spiro	(CERN, UCB, SACL)
OLIVE	90	PL B236 454	+Schramm, Steigman, Walker	(MINN, CHIC, OSU, HARV)
AARNIO	89	PL B231 539	+Abreu, Adam, Adrianos, Adye+	(DELPHI Collab.)
ABRAMS	89B	PRL 63 2173	+Adolphsen, Averill, Ballam, Barish+	(Mark II Collab.)
ELLIS	86	PL 167B 457	+Enqvist, Nanopoulos, Sarkar	(CERN, OXFTP)
STEIGMAN	86	PL B176 33	+Olive, Schramm, Turner	(BART, MINN+)
YANG	84	APJ 281 493	+Turner, Steigman, Schramm, Olive	(CHIC, BART)
OLIVE	81	APJ 246 557	+Schramm, Steigman, Turner, Yang+	(CHIC, BART)
OLIVE	81C	NP B180 497	+Schramm, Steigman	(EFI, BART)
STEIGMAN	79	PRL 43 239	+Olive, Schramm	(BART, EFI)
YANG	79	APJ 227 697	+Schramm, Steigman, Rood	(CHIC, YALE, VIRG)
STEIGMAN	77	PL 66B 202	+Schramm, Gunn	(YALE, CHIC, CIT)
PEEBLES	71	Physical Cosmology Princeton Univ. Press (1971)		(PRIN)
SHVARTSMAN	69	JETPL 9 184 Translated from ZETFP 9 315.		(MOSU)
HOYLE	64	Nature 203 1108	+Tayler	(CAMB)

Heavy Lepton Searches

NOTE ON HEAVY LEPTON SEARCHES

Data on the $\tau^{\pm}$ are listed in a separate section, following the e and μ listings. Data on excited leptons (e^*, μ^*, τ^*) appear in the section "Searches for Quark and Lepton Compositeness." Searches for fractionally charged heavy leptons are included in the section on "Free Quark Searches."

The following section contains information on searches for heavy leptons of other types.

Several types of heavy leptons (that is, non-strongly-interacting fermions other than e and μ) have been proposed. In the Full Listings, following a historical practice specific to this area, we distinguish four types [1]. Each has a corresponding antiparticle with opposite charge and lepton number. For convenience we omit writing the antiparticles in the following descriptions. The four types are:

Sequential leptons (L^-, ν_L). Such a pair has often been assumed to have its own separately strictly conserved lepton number $n_L = +1$. Such a conservation law means that the radiative decays

$$\left.\begin{array}{l} L^- \to e^-\gamma \\ L^- \to \mu^-\gamma \\ L^- \to \tau^-\gamma \end{array}\right\} \quad \text{are forbidden ,}$$

while the weak decays (assuming m_{L^-} sufficiently large)

$$\left.\begin{array}{l} L^- \to \nu_L e^- \overline{\nu}_e \\ L^- \to \nu_L \mu^- \overline{\nu}_\mu \\ L^- \to \nu_L \tau^- \overline{\nu}_\mu \\ L^- \to \nu_L \; hadrons \end{array}\right\} \quad \text{are allowed .}$$

There could be an increasing mass sequence of such pairs. It is frequently assumed that the neutrinos are massless (a natural concomitant of the L number conservation law).

Decay rates are assumed to be calculable from conventional weak interaction theory. For example, for an L^- mass between 1 GeV and 3 GeV, the branching fraction to each of the two leptonic modes above should be roughly 10% to 20%. For an L^- mass above 1 GeV, the mean life should be $\lesssim 10^{-12}$ second.

Paraleptons (e_P^+, e_P^0), (μ_P^+, μ_P^0), (τ_P^+, τ_P^0). The lepton number of (e_P^+, e_P^0) is the same as that of (ν_e, e^-), and similarly for the other paraleptons. Radiative decays are again forbidden, and decays similar to those allowed for L^- are allowed here, *e.g.*,

$$\mu_P^+ \to \nu_\mu e^+ \nu_e$$

$$\mu_P^+ \to \nu_\mu \mu^+ \nu_\mu$$

$$\mu_P^+ \to \nu_\mu \; hadrons \; .$$

However, the lightest member is not stable as is the case for sequential leptons, so that bizarre decay schemes such as

$$e_P^+ \to e_P^0 \mu^+ \nu_\mu$$
$$\hookrightarrow e^- e^+ \nu_e$$

(assuming $m_{e_P^0} < m_{e_P^+}$) are allowed. Occasional searches have been made for doubly-charged paraleptons.

Before the discovery of the Z boson, heavy leptons of this type were proposed in unified gauge theories of weak and electromagnetic interactions to cancel unphysical high-energy behavior in such processes as $e^+e^- \to W^+W^-$ [2]. The theoretical motivation disappeared with the discovery of neutral currents and confirmation of the standard electroweak theory. However, from a purely phenomenological viewpoint, it is still of interest to search for paraleptons.

Ortholeptons $(e_O^-, \mu_O^-, \tau_O^-)$. These are defined as having the same lepton numbers as the corresponding regular leptons. The quantum numbers of an ortholepton are thus essentially equivalent to those of an excited lepton. Historically, the emphasis in the excited leptons has been on the radiative decay mode, and the connection with compositeness, whereas the ortholepton denotation has been a more general category. Reflecting this, we list limits on excited leptons in the section on compositeness. Ortholeptons may or may not have associated neutral leptons. Both radiative decays and regular weak decays similar to those of sequential leptons can occur.

Long-lived penetrating particles. Heavy leptons could have long mean lives under certain circumstances. For example, if $m_{\nu_L} > m_{L^-}$, then L^-, the sequential lepton, would only be able to decay via lepton mixing and could have a relatively long lifetime.

Perl's review [3] gives further details.