Limit on Total ν MASS, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<180	SZALAY	74	COSM
<132	COWSIK	72	COSM
<280	MARX	72	COSM
<400	GERSHTEIN	66	COSM

Astrophysical and Cosmological Limits on ν MASSES

If neutrinos are present as dark matter in galactic halos, limits on neutrino masses have been computed based on neutrino degeneracy and Fermi statistics. The results depend strongly on assumptions. See the references.

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	SPERGEL	88B	COSM	
	KAWASAKI	86	COSM	
	KAWASAKI	86B	COSM	
	TAKAHARA	86	COSM	supernovae
	MADSEN	85	COSM	Some anisotropy
	MADSEN	84	COSM	Assume isotropy
	SARKAR	84	COSM	Decaying neutrinos
	FREESE	83	COSM	Degenerate ν
	LIN	83	COSM	
	PRIMACK	83	COSM	
	BOND	81	COSM	Adiabatic
	DAVIS	81	COSM	Adiabatic+decaying ν's
	SCHRAMM	81	COSM	Isothermal
	TREMAINE	79	COSM	Isothermal

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[1] OLIVE	82	COSM	Dirac ν
<200–2000	[1] OLIVE	82	COSM	Majorana ν

[1] Depending on interaction strength g_R where $g_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[2] OLIVE	82	COSM	g_R/G_F <0.1
>100	[2] OLIVE	82	COSM	g_R/G_F <0.01

[2] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >1.2 GeV (G_F/g_R).

REFERENCES FOR Neutrino Bounds from Astrophysics and Cosmology

SPERGEL	88B	PR D38 2014	+Weinberg, Gott	(PRIN)
KAWASAKI	86	PL B178 71	+Terasawa, Sato	(TOKY)
KAWASAKI	86B	PL 169B 280	+Sato	(TOKY)
TAKAHARA	86	PL B174 373	+Sato	(TOKY)
COWSIK	85	PL 151B 62		(TATA)
MADSEN	85	PRL 54 2720	+Epstein	(AARH, LANL)
FREESE	84	NP B233 167	+Schramm	(CHIC, FNAL)
MADSEN	84	APJ 282 11	+Epstein	(AARH, LANL)
SARKAR	84	PL 148B 347	+Cooper	(OXF, CERN)
SCHRAMM	84	PL 141B 337	+Steigman	(FNAL, BART)
FREESE	83	PR D27 1689	+Kolb, Turner	(CHIC, LANL)
LIN	83	APJ 266 L21	+Faber	(UCSC)
PRIMACK	83	Phil. 4th Workshop on Grand Unification		(UCSC)
Also	82	Nature 299 37	Blumenthal, Pagels, Primack	(UCSC, ROCK)
OLIVE	82	PR D25 213	+Turner	(CHIC, UCSB)
BERNSTEIN	81	PL 101B 39	+Feinberg	(STEV, COLU)
BOND	81	Nu Conf. Hawaii	+Szalay	(UCB, CHIC)
DAVIS	81	APJ 250 423	+Lecar, Pryor, Witten	(HARV, PRIN)
SCHRAMM	81	APJ 243 1	+Steigman	(CHIC, BART)
TREMAINE	79	PRL 42 407	+Gunn	(CIT, CAMB, CAIW)
VYSOTSKY	77	JETPL 26 188 Translated from ZETFP 26 200.	+Dolgov, Zeldovich	(ITEP)
SZALAY	76	AA 49 437	+Marx	(EOTV)
SZALAY	74	APAH 35 8	+Marx	(EOTV)
COWSIK	72	PRL 29 669	+McClelland	(UCB)
MARX	72	Nu Conf. Budapest	+Szalay	(EOTV)
GERSHTEIN	66	JETPL 4 120 Translated from ZETFP 4 189.	+Zeldovich	(KIAM)

QUARKS

NOTE ON QUARK MASSES

A. Introduction

This note discusses some of the theoretical issues involved in the determination of quark masses. Unlike the leptons, quarks are confined inside hadrons and are not observed as physical particles. Quark masses cannot be measured directly, but must be determined indirectly through their influence on hadron properties. As a result, the values of the quark masses depend on precisely how they are defined; there is no one definition that is the obvious choice. Though one often speaks loosely of quark masses as one would of the electron or muon mass, any careful statement of a quark mass value must make reference to a particular computational scheme that is used to extract the mass from observations. It is important to keep this scheme dependence in mind when using the quark mass values tabulated in the data listings.

The simplest way to define the mass of a quark is by making a fit of the hadron mass spectrum to a nonrelativistic quark model. The quark masses are defined as the values obtained from the fit. The resulting masses only make sense in the limited context of a particular quark model. They depend on the phenomenological potential used, and on how relativistic effects are modelled. The quark masses used in potential models also cannot be connected with the quark mass parameters in the QCD Lagrangian. Fortunately, there exist other definitions of the quark mass that have a more general significance, though they also depend on the method of calculation. The purpose of this review is to explain the most important such definitions and their interrelations.

B. Mass parameters and the QCD Lagrangian

The QCD Lagrangian for N_F quark flavors is

$$\mathcal{L} = \sum_{k=1}^{N_F} \overline{q}_k \left(i \not{D} - m_k \right) q_k - \tfrac{1}{4} G_{\mu\nu} G^{\mu\nu} \ , \tag{1}$$

where $\not{D} = \left(\partial_\mu - i g A_\mu \right) \gamma^\mu$ is the gauge covariant derivative, A_μ is the gluon field, $G_{\mu\nu}$ is the gluon field strength, m_k is the mass parameter of the k^{th} quark, and q_k is the quark Dirac field. The QCD Lagrangian Eq. (1) gives finite scattering amplitudes after renormalization, a procedure that invokes a subtraction scheme to render the amplitudes finite, and requires the introduction of a dimensionful scale parameter μ. The mass parameters in the QCD Lagrangian Eq. (1) depend on the renormalization scheme used to define the theory, and also on the scale parameter μ. The most commonly used renormalization scheme for QCD perturbation theory is the $\overline{\text{MS}}$ scheme.

The QCD Lagrangian has a chiral symmetry in the limit that the quark masses vanish. This symmetry is spontaneously broken by dynamical chiral symmetry breaking, and explicitly broken by the quark masses. The nonperturbative scale of