Astrophysics and Cosmology Closing in on Neutrino Masses

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Massive neutrinos are expected in most grand unified theories that attempt to unify the strong and electroweak interactions. So far, heroic laboratory experiments have yielded only upper bounds on the masses of the elusive neutrinos. These bounds, however, are not very restrictive and cannot even exclude the possibility that the dark matter in the universe consists of neutrinos. The astrophysical and cosmological bounds on the masses of the muon and tau neutrinos, m_{ν_μ} and m_{ν_τ}, which already are much more restrictive than the laboratory bounds, and the laboratory bound on the mass of the electron neutrino, m_{ν_e}, can be improved significantly by future astrophysical and cosmological observations that perhaps will pin down the neutrino masses. Indeed, the recent results from the solar neutrino experiments combined with the seesaw mechanism for generating neutrino masses suggest that $m_{\nu_e} \sim 10^{-8}$ electron volts, $m_{\nu_\mu} \sim 10^{-3}$ electron volts, and $m_{\nu_\tau} \sim 10$ electron volts, which can be tested in the near future by solar neutrino and accelerator experiments.

THE EXISTENCE OF A NEUTRINO, A WEAKLY INTERACTING, spin 1/2, massless elementary particle, was proposed theoretically in 1932 by W. Pauli in order to conserve energy, momentum, and angular momentum in radioactive β decays of atomic nuclei. For a long time it was thought that the neutrino would be undetectable because of the weakness of its interaction with ordinary matter. However, after the development of the nuclear reactor in the 1940s, Reines and Cowan proposed that neutrinos from the huge neutrino fluxes emitted by the largest nuclear reactors could be detected in massive detectors shielded underground from cosmic rays, and in 1955 they finally succeeded in establishing the existence of the neutrino (*1*). Further studies have shown that the electron neutrino (ν_e) that is emitted in the β^+ decay of atomic nuclei is always left-handed and is different from its antiparticle, the antineutrino ($\bar{\nu}_e$), which is right-handed and is emitted in β^- decay; studies here also revealed that, in addition to carrying energy, momentum, and angular momentum (spin 1/2), the neutrino also carries a new charge, called "leptonic charge." The electron carries the same leptonic charge as the neutrino, whereas their antiparticles, the antineutrinos and positrons, carry the opposite leptonic charge. The total leptonic charge seems to be strictly conserved in nature.

The existence of a second type of neutrino, the muon neutrino (ν_μ), was discovered (*2*) in 1962 by Lederman, Schwartz, Steinberger, and their collaborators, and a third type, the tau neutrino (ν_τ), was inferred from the discovery of the tau in 1977 by Perl and collaborators and from the study of tau decays (*3*). (Although the data from the decay of the tau are strongly suggestive of the existence of the tau neutrino, direct evidence has yet to be presented.)

Subsequent experiments have shown that the three known charged leptons, the electron, the muon, and the tau, and their associated neutrinos, the ν_e, the ν_μ, and the ν_τ, respectively, seem to carry distinct types of lepton charges, called the electron, muon, and tau flavors, which are individually conserved. The experiments also showed that the three different lepton families have exactly the same electroweak interactions, which are accurately described by the standard Glashow-Salam-Weinberg electroweak theory (*4*). In fact, agreement between the theory and experiment was so impressive that Glashow, Salam, and Weinberg shared the 1979 Nobel prize in physics before the experimental discovery of the $W^\pm$ and Z^0 bosons, the mediators of the electroweak forces, that were predicted by the theory. The standard electroweak theory, however, does not restrict the number of lepton families. The number of neutrino flavors (that is, the number of lepton families) is of fundamental importance for understanding nature and for constructing a complete theory of particle physics. Countless experiments, which have searched for additional lepton families, have not discovered new ones but could not exclude the existence of additional generations of light neutrinos. However, a recent analysis based on 600,000 events from the CERN Large Electron Positron Collider (LEP) of Z^0 production in e^+e^- collisions, which was reported at the "Neutrino 90" meeting (*5*), showed (*6*) that there are only the three types of light neutrinos ($m_\nu << m_{Z^0}/2 \approx 45.6$ GeV), the ν_e, the ν_μ, and the ν_τ.

In the standard electroweak theory, neutrinos are usually assumed to be massless, although no established symmetry or experimental observation requires this. In fact, massive neutrinos are expected in most grand unified theories that attempt to unify the electroweak and strong interactions. The neutrinos are the only fundamental fermions in the standard model of particle physics whose masses are still unknown. Knowing their masses could be an important clue for the construction of a complete theory of particle physics. Neutrino masses also play a very important role in astrophysics and cosmology. For all these reasons, many experimental and theoretical efforts have been devoted to determining the masses of the three neutrinos. So far, all the laboratory experiments and the astrophysical and cosmological observations have succeeded only in establishing upper bounds on the neutrino masses. The best laboratory bounds, $m_{\nu_e} < 9.6$ eV (*7*), $m_{\nu_\mu} < 250$ keV (*8*), and $m_{\nu_\tau} < 35$ MeV (*9*), are not very restrictive, and it does not seem that these bounds can be improved significantly by laboratory experiments in the foreseeable future. The best astrophysical and cosmological bounds on m_{ν_e} are inferior to the laboratory bound, but the astrophysical and cosmo-

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Table 1. Present limits on neutrino masses. The astrophysical bound on the mass of ν_e follows from the measured spread in the arrival times of the neutrinos from SN1987A. The bounds on the masses of ν_μ and ν_τ were obtained from the neutrino cooling time of SN1987A and are valid only for Dirac neutrinos. The cosmological bounds on the neutrino masses were obtained from the observed energy density of the universe and apply only if their mean lifetime is longer than the age of the universe ($\tau \sim 13 \times 10^9$ years).

Mass	Laboratory	Astrophysics	Cosmology
m_{ν_e}	<9.6 eV	<16 eV	<40 eV
m_{ν_μ}	<250 keV	<15 keV	<40 eV
m_{ν_τ}	<35 MeV	<15 keV	<40 eV

logical bounds on m_{ν_μ} and m_{ν_τ} are already much more restrictive, as can be seen from Table 1. Moreover, there are good prospects for improving these bounds significantly by future cosmological and astrophysical observations, as indicated in Table 2. Furthermore, recent results from the solar neutrino experiments, when combined with the seesaw mechanism for generating neutrino masses (*10*), suggest that $m_{\nu_e} \sim 10^{-8}$ eV, $m_{\nu_\mu} \sim 10^{-3}$ eV, and $m_{\nu_\tau} \sim 10$ eV. The new generation of solar neutrino and neutrino oscillations experiments will be able to test these predictions in the near future and perhaps finally to pin down the precise values of the masses of the elusive neutrinos.

Bounds on the Electron Neutrino Mass

At present the laboratory bound on m_{ν_e} is more stringent than the astrophysical and cosmological bounds. But, as I shall explain below, the astrophysical bounds could be improved significantly in the future and may even yield a precise value for the mass of the ν_e.

A finite mass of ν_e affects the maximal energy that electrons can carry in nuclear β decay and their spectrum near this maximal energy (the end point). The present best bound on the mass of the electron neutrino, $m_{\nu_e} < 9.6$ eV, has been obtained by the Los Alamos group (*8*) from laboratory measurements of the end-point spectrum of electrons from tritium β decay. This limit could perhaps be somewhat improved if atomic tritium beams with intensities comparable to that of the molecular tritium beam are ever achieved (*8*).

The best astrophysical bound on m_{ν_e} was derived (*11*) from the neutrino observations of SN1987A by the Kamiokande collaboration (*12*) in Japan, the Irvine-Michigan-Brookhaven (IMB) collaboration (*13*) in the United States, and the Baksan group (*14*) in the U.S.S.R. The time of flight of neutrinos of energy $E >> m_\nu$ from a source at a distance D to Earth is

$$t_f \approx \frac{D}{c}\left(1 + \frac{1}{2}\frac{m_\nu^2}{E^2}\right) \tag{1}$$

where c is the speed of light. Thus, a nonzero neutrino mass results in different times of flight for different energies. From the observed spread in the arrival times of the neutrinos from SN1987A and their measured energies it was deduced (*11*) that $m_{\nu_e} < 16$ eV.

This best astrophysical bound on m_{ν_e} is inferior to the bound derived from tritium β decay. However, if neutrinos do not oscillate, it now seems that the only chance to measure m_{ν_e} below ~ 10 eV is by detecting neutrinos from the neutronization burst ($e^- p \rightarrow n\nu_e$) from a nearby ($D < 10$ kpc) gravitational stellar collapse (GSC). The burst can be detected by superlarge water Cerenkov detectors, such as the proposed Super Kamiokande detector, or by more sensitive underground massive detectors such as the heavy-water Cerenkov detector of the Sudbury Neutrino Observatory (SNO) that is under construction. In light-water detectors (H_2O) the ν_e is detected by the reaction $\nu_e + e^- \rightarrow \nu_e + e^-$. The electron recoils essentially in the direction of the incident ν_e and emits an ultraviolet Cerenkov light cone along the recoil direction. In heavy-water detectors (D_2O) the ν_e can also be detected by the reactions $\nu_e + D \rightarrow p + p + e^-$ and $\nu_e + D \rightarrow n + p + \nu_e$ (the neutrons are detected by the emission of a 2.23-MeV photon when they slow down and are captured by hydrogen). The expected duration of the neutronization burst (for massless neutrinos) is only a few milliseconds (*15*). If such a short neutronization burst from a galactic GSC will be observed with detectors whose effective neutrino energy threshold is ~ 7.5 MeV, then m_{ν_e} could be measured down to (*16*) ~ 0.5 eV.

Bounds on the Muon Neutrino and Tau Neutrino Masses

If the ν_μ and ν_τ are long-lived (that is, $\tau > t_0$, where t_0 is the observed age of the universe), then the best limits on their masses follow from cosmological observations. The observed energy density of the universe sets the present most stringent limit on m_{ν_μ} and m_{ν_τ}. The number density of relic neutrinos from the Big Bang is predicted by the standard cosmological model to be (*17*) $n_{\nu_i} \approx (3/11)n_\gamma$, where $n_\gamma \approx 20.4 \times T_\gamma^3 \approx 415$ cm^{-3} is the observed number density of relic photons (T_γ is the blackbody temperature of the cosmic microwave background). The neutrino energy density cannot exceed the total energy density, ρ, of the universe, that is, $\sum n_{\nu_i} m_{\nu_i} < \rho$, which can be rewritten as

$$\sum m_{\nu_i} < 94\Omega h^2 \text{ eV} \tag{2}$$

where $\Omega \equiv \rho/\rho_c$ is the energy density of the universe divided by its critical density $\rho_c \equiv 3H^2/8\pi G$, G is the gravitational constant, and h is the Hubble constant H in units of 100 km Mpc^{-1} s^{-1}. Observations yield $0.2 < \Omega < 1$ and $0.5 < h < 1$. The age of the universe (in 10^9 years) in the standard (Friedmann-Lemaitre) cosmology (*14*), is given by

$$t_0 = \frac{9.8}{h}\int_0^1 \frac{dx}{\sqrt{1 - \Omega + \Omega/x}} \tag{3}$$

which is limited by observations to 10×10^9 years $\leq t_0 \leq 20 \times 10^9$ years, then requires that $\Omega h^2 < 0.42$, which yields

$$m_{\nu_\mu}, m_{\nu_\tau} < 40 \text{ eV} \tag{4}$$

Better measurements of Ω (from gravitational lensing observations), of h (by the Hubble space telescope), and of t_0 may improve this

Table 2. Anticipated limits on neutrino masses. The anticipated laboratory limits are based on proposed improvements of current experiments. The astrophysical limits require the detection of the neutronization and thermal neutrino bursts from the birth of a nearby (galactic) neutron star in GSC. However, the rate of such events is currently estimated to be one event in 30 to 100 years. The cosmological bounds are based on expected improvements in the estimates of the Hubble parameter and the energy density of the universe from observations with the Hubble space telescope and large ground-based telescopes with adaptive optics.

Mass	Laboratory	Astrophysics	Cosmology
m_{ν_e}	<5 eV	<0.5 eV	<10 eV
m_{ν_μ}	<100 keV	<10 eV	<10 eV
m_{ν_τ}	<10 MeV	<10 eV	<10 eV

bound significantly. Observations already tend to indicate that $0.1 < \Omega < 0.2$, $0.75 < h < 1$, and 13×10^9 years $< t_0 < 16 \times 10^9$ years. Consequently, new cosmological observations may yield m_{ν_μ}, $m_{\nu_\tau} < 10$ eV.

The primordial abundances of the light elements in standard cosmology depends on the baryonic (nucleon) number density in the universe, which can be used to estimate how much of the total energy density in the universe resides in baryonic matter. The most recent published comparison (*18*) between the primordial abundances of light elements predicted by the standard Big Bang model and those that were extracted from observations yields $0.010 < \Omega_b h^2 < 0.016 << \Omega h^2$, where Ω_b is the baryonic energy density in the universe divided by the critical density. It implies that most of the energy density of the universe consists of nonbaryonic dark matter. If this dark matter consists of massive neutrinos, then their masses must satisfy

$$5 \text{ eV} \leq \sum m_\nu \approx 94\Omega h^2 \text{ eV} \leq 40 \text{ eV} \tag{5}$$

while the best observational estimates, $\Omega \sim 0.2$ and $h \sim 0.75$, yield

$$\sum m_\nu \approx 10 \text{ eV} \tag{6}$$

Indirect evidence for such neutrino masses could perhaps be extracted from large-scale structure formation in the universe; from galaxy formation; from the dynamics of individual galaxies, groups, and rich clusters of galaxies; and from the amount and the distribution of dark matter at various scales.

If the mass of ν_μ or that of ν_τ, or both, are around 10 eV (that is, if most of the dark matter consists of neutrinos), then direct measurements of these masses will be possible only if the new generation of underground massive neutrino telescopes, which will be sensitive to all neutrino flavors, detects the neutrino burst from a neutron star formation in a nearby ($D < 10$ kpc) GSC. During the short cooling phase the protoneutron star radiates neutrinos of all three flavors. If neutrinos of different flavors have different masses, their times of flight to Earth will be different (see Eq. 1). The charged current reactions $\bar{\nu}_e + p \rightarrow e^+ + n$ in light water and $\bar{\nu}_e + D \rightarrow e^+ + 2n$ and $\nu_e + D \rightarrow e^- + 2p$ in heavy water can be used to isolate events induced by $\bar{\nu}_e$ and ν_e, respectively. The neutral current reactions, $\nu + e \rightarrow \nu + e$ in light water and in heavy water, and the reaction $\nu + D \rightarrow \nu + p + n$ in heavy water can be used to detect neutrinos of all flavors. The delay in arrival times due to mass will cause neutrinos of different flavors to group around different arrival times. This can be used to measure neutrino mass differences or to set new upper bounds on them. Monte Carlo simulations based on the expected neutrino fluxes and on the anticipated performances of the detectors (such as the light-water Cerenkov Super Kamiokande detector and the heavy-water SNO detector) indicate (*16*) that it will be possible to detect m_{ν_μ} or m_{ν_τ} in the range $10 \text{ eV} \leq m_\nu \leq 10$ keV from the measured arrival times, energy, and approximate flavor of the detected neutrinos, provided these neutrinos live long enough ($\gamma\tau > D/c \sim 10^{12}$ s) to survive their journey to Earth. However, the detectors used in these simulations will not be able to distinguish which mass belongs to ν_μ and which mass belongs to ν_τ.

The above cosmological bounds do not apply to unstable neutrinos with lifetimes shorter than the age of the universe. For Dirac neutrinos the present best bounds on the masses of unstable ν_μ and ν_τ were obtained (*19*) from the ~5-s neutrino cooling time of SN1987A measured by the Kamiokande II, IMB, and Baksan neutrino detectors (*12–14*). The gravitational binding energy released in the gravitational collapse of the stellar core of an evolved massive star into a neutron star is typically $3GM^2/5R \sim 3 \times 10^{53}$ ergs, where $M \approx 1.4M_\odot$ ($M_\odot$ is the solar mass) and $R \approx 10^6$ cm. This energy is first converted into thermal energy, mainly kinetic energy of nucleons in the protoneutron star for which the temperature is given by

$$T \approx \frac{2}{5}\frac{GMm_p}{R} \tag{7}$$

and then it is radiated away during a few seconds by neutrino emission from near the surface of the protoneutron star. The protoneutron star is highly opaque to neutrinos, and the relatively long cooling time reflects the long diffusion times of neutrinos to the surface of last scattering. However, if a left-handed (right-handed) Dirac neutrino (antineutrino) has a nonzero mass, $m_\nu > 0$, then it can flip its helicity in collisions inside the hot protoneutron star and become a sterile neutrino that escapes immediately outside (provided that $\gamma\tau > R/c \sim 10^{-4}$ s and neutrinos do not have properties inconsistent with the standard electroweak model such as magnetic moments larger by many orders of magnitude than those expected in the standard model). The protoneutron star loses energy per unit volume by the neutrino helicity flip escape mechanism at a rate given by

$$d\epsilon/dt \approx n\sigma_{\text{flip}}c\epsilon_\nu \tag{8}$$

where n is the nucleon number density, ϵ_ν is the neutrino energy density, and $\sigma_{\text{flip}} \approx G_F^2\, m_\nu^2/\pi$ is the helicity flip cross section off a neutron (calculated from the standard electroweak theory for Z^0 exchange). The typical cooling time of the protoneutron star via the helicity flip mechanism is then given approximately by

$$\Delta t \approx \frac{\epsilon}{d\epsilon/dt} \approx \frac{3\pi T}{2cG_F m_\nu^2 \epsilon_\nu} \tag{9}$$

where the neutrino energy density per flavor is $\epsilon_\nu = (7/8)aT^4$. Because the release of the gravitational binding energy from SN1987A lasted longer than 5 s, it follows from Eqs. 7 through 9 that, if $\gamma\tau_i > R/c \sim 10^{-4}$ s, then $m_\nu < 5$ keV for Dirac neutrinos. However, if the uncertainties in the various parameters and approximations are taken into consideration, then a more conservative bound is obtained (*20*),

$$m_{\nu_\mu}, m_{\nu_\tau} < 15 \text{ keV} \tag{10}$$

The argument put forth in the previous paragraph and the last bound do not apply to Majorana neutrinos (for Majorana neutrinos the helicity flip transforms the left-handed Majorana neutrinos into the right-handed antineutrinos, which have normal electroweak interactions and therefore cannot escape directly). However, neutrino masses larger than ~250 keV have a noticeable effect on the primordial abundances of the light elements predicted by the standard Big Bang model, especially on the abundance of primordial ^{4}He. Primordial nucleosynthesis takes place only when the rate of photodissociation of D by background radiation photons becomes slower than the rate of nuclear fusion of D. This happens when the universe cools to a temperature $T \sim 70$ keV. The expansion rate of the early universe determines the neutron-to-proton ratio at neutrino decoupling ($T \sim 0.7$ MeV) and also the number of these neutrons that survive β decay until nucleosynthesis ($T \sim 70$ keV) to end up in ^{4}He. If neutrinos become nonrelativistic before nucleosynthesis, that is, if $m_\nu > 3.15T \sim 250$ keV, then the energy density of the universe, and consequently the expansion rate of the universe, $\tau_{ex}^{-1} \approx (8\pi G\rho/3)$, which determines the neutron-to-proton ratio when nucleosynthesis begins, depends on the neutrino masses. This dependence can be used to rule out both Majorana and Dirac neutrino masses in the range (*21*) 0.5 MeV $< m_\nu < 10$ MeV, if the observed primordial mass fraction of ^{4}He is less than 24%.

Neutrino Masses from Neutrino Oscillations

Finally, if lepton flavors are not strictly conserved and if the neutrino mass eigenstates are admixtures of neutrino flavor eigenstates, for example,

$$\begin{aligned} |\nu_1> &= \cos\theta\,|\nu_e> + \sin\theta\,|\nu_\mu> \\ |\nu_2> &= -\sin\theta\,|\nu_{esbx}> + \cos\theta\,|\nu_\mu> \end{aligned} \tag{11}$$

(where θ is the mixing angle), then the neutrino flavor will oscillate as a function of time or distance traveled by the neutrino (*22*). The probabilities for flavor retention and flavor conversion after a neutrino with $E_\nu >> m_\mu$ has traveled a distance D are given, respectively, by

$$P(\nu_e \leftrightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{\pi D}{L_V}\right) \tag{12}$$

and

$$P(\nu_e \leftrightarrow \nu_\mu) = \sin^2 2\theta \sin^2\left(\frac{\pi D}{L_V}\right) \tag{13}$$

where the oscillation length (in centimeters), L_V, is given by

$$L_V \equiv \frac{4\pi E_\nu}{\Delta m^2} \approx 248\,\frac{E_\nu}{\Delta m^2} \tag{14}$$

where E_ν is in megaelectron volts squared and Δm^2 is in electron volts.

Detection of neutrino oscillations can provide information on neutrino mixings and mass differences. Searches for neutrino oscillations using accelerator neutrinos and reactor neutrions have not yet provided any confirmed evidence for neutrino oscillations. This has been used to exclude mass-squared differences $\Delta m^2 \equiv m_2^2 - m_1^2$ as small as ~ 0.1 eV^2 for large mixings ($\sin\theta > 0.1$). Future oscillation experiments with reactor neutrinos and with neutrino beams from accelerators aimed at distant underground neutrino detectors will explore (*23*) mass-squared differences as small as 10^{-4} eV^2. Solar neutrino experiments can be used to explore the Mikheyev-Smirnov-Wolfenstein matter-enhanced oscillations (*24*) (the MSW effect) for mass differences in the range 10^{-7} eV$^2 < \Delta m^2 < 10^{-4}$ eV^2, whereas detecting the flavor content of the neutrinos from a galactic supernova explosion will constrain mass differences in a much wider range, 10^{-8} eV$^2 < \Delta m^2 < 10^6$ eV^2. In fact, the recent results reported from the Kamiokande II solar neutrino experiment (*25*) [~46% of the flux predicted by the standard solar model (*11*)], from the Homestake solar neutrino experiment (*26*) [~27% of the flux predicted by the standard solar model (*11*)], and from the Soviet-American gallium experiment (*27*) (no detected solar neutrino flux) are compatible with the MSW effect [the Rosen-Gelb solution (*28*)] provided that

$$\Delta m^2 \sim 10^{-6}\ \text{eV}^2 \text{ and } \sin^2 2\theta \sim 4 \times 10^{-2} \tag{15}$$

and provided that the time variation in the solar neutrino flux seen by the Homestake chlorine experiment is due to statistical fluctuations (*29*). A convincing demonstration that the MSW effect with the above mass difference is indeed the correct solution to the solar neutrino problem will be provided if the missing solar neutrinos will be detected as ν_μ or μ_τ, perhaps by the underground SNO heavy-water detector that is under construction.

Moreover, the seesaw mechanism, which is the only scheme presently known for naturally generating small, nonvanishing, neutrino masses, relates the masses of the neutrinos to corresponding Dirac fermions (*10*). If one identifies (*30*) the latter with the "up quarks," then

$$m_{\nu_e}:m_{\nu_\mu}:m_{\nu_\tau} \approx m_u^2:m_c^2:m_t^2 \approx 0.005^2:1.5^2:135^2 \tag{16}$$

where I have used a recent estimate for the mass of the top quark (*6*), $m_t = (135 \pm 20)$ GeV (m_c is the mass of the charm quark). Adopting the value $\Delta m^2 \approx 10^{-6}$ eV^2 suggested by the MSW solution to the solar neutrino problem, we then find

$$m_{\nu_e} \sim 10^{-8}\ \text{eV};\ m_{\nu_\mu} \sim 10^{-3}\ \text{eV};\ m_{\nu_\tau} \sim 10\ \text{eV} \tag{17}$$

Summary and Conclusions

The elusive neutrinos are the only fundamental fermions in the impressively successful standard particle physics model whose masses are still unknown. The present best upper bound, 9.6 eV, on the mass of ν_e could be improved slightly by measurements of the end-point spectrum of β decay of atomic tritium. However, it does not seem that the present laboratory bounds on the masses of ν_μ and ν_τ can be improved significantly in the foreseeable future by laboratory experiments, if neutrinos are unmixed. The observed energy density of the universe provides the presently best upper bound, 40 eV, on the masses of stable ν_μ and ν_τ. This bound is likely to be improved to ~10 eV in the near future by more precise determinations of the Hubble constant and the energy density of the universe from observations with the Hubble space telescope and ground-based large telescopes with adaptive optics. If the mass of ν_e is between ~ 0.5 and 10 eV, it could be measured by the new generation of massive underground solar and supernova neutrino telescopes that are under construction, from the dispersion in arrival times of neutrinos from the neutronization burst that precedes the birth of a nearby neutron star. Moreover, the arrival times of the neutrinos from the thermal burst that follows the neutronization burst can be used to measure the masses of ν_μ and ν_τ, if they are larger than ~10 eV. However, the current best estimate for the birth-rate of neutron stars in our galaxy, about 1 per 56 years, is quite discouraging, but no other way has been found for measuring neutrino masses in this mass range.

If neutrinos are mixed and oscillate, then reactor, accelerator, solar, and supernova neutrinos can be used together with the new generation of neutrino detectors to explore a wide range of neutrino masses and mixings that has not yet been eliminated by previous neutrino oscillations experiments. In particular, the recently reported results from the Homestake, Kamiokande, and Baksan solar neutrino experiments, if correct, imply nonconservation of lepton flavor, whose simple manifestation is neutrino oscillations. Indeed, all three solar neutrino experiments can be well explained by matter-enhanced neutrino oscillations (the MSW effect). Then the seesaw mechanism for generating neutrino masses suggests the following neutrino masses: $m_{\nu_e} \sim 10^{-8}$ eV, $m_{\nu_\mu} \sim 10^{-3}$ eV, and $m_{\nu_\tau} \sim 10$ eV. Appearance of the missing solar neutrinos as ν_μ or ν_τ in the new generation of solar neutrino experiments and detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in experiments at accelerators (*31*) can be used to test the above MSW-seesaw predictions for the neutrino masses and, perhaps, finally to pin down the masses of the elusive neutrinos.

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A View of Interphase Chromosomes

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Metaphase chromosomes are dynamically modified in interphase. This review focuses on how these structures can be modified, and explores the functional mechanisms and significance of these changes. Current analyses of genes often focus on relatively short stretches of DNA and consider chromatin conformations that incorporate only a few kilobases of DNA. In interphase nuclei, however, orderly transcription and replication can involve highly folded chromosomal domains containing hundreds of kilobases of DNA. Specific "junk" DNA sequences within selected chromosome domains may participate in more complex levels of chromosome folding, and may index different genetic compartments for orderly transcription and replication. Three-dimensional chromosome positions within the nucleus may also contribute to phenotypic expression. Entire chromosomes are maintained as discrete, reasonably compact entities in the nucleus, and heterochromatic coiled domains of several thousand kilobases can acquire unique three-dimensional positions in differentiated cell types. Some aspects of neoplasia may relate to alterations in chromosome structure at several higher levels of organization.

EUKARYOTIC DNA EXPRESSES AND REPRODUCES ITSELF only in the context of an interphase nucleus. It is therefore biologically most meaningful to understand chromosome organization in this state. Until recently, however, only very general features of euchromatic DNA (extended chromatin) and heterochromatic DNA (more condensed chromatin) could be distinguished in interphase nuclei, and each type of chromatin appeared ultrastructurally homogeneous. Furthermore, nuclear chromatin patterns bore no obvious relation to individual mitotic chromosomes, the recognizable genomic structures studied for over 100 years. For this reason the chromatin of mitotic chromosomes was often considered to be randomly and diffusely dispersed throughout the interphase nucleus. Recent advances in molecular biology combined with high-resolution in situ hybridization have made it possible to visualize individual genes (*1, 2*), selected chromosome domains (*3–8*), and entire single chromosomes (*9, 10*) in interphase nuclei. As will be discussed below, these and other studies demonstrate that (i) even in genetically active regions chromatin can be highly folded and confined to discrete, spatially limited nuclear domains; (ii) whole individual chromosomes are organized as finite morphological entities in interphase; and (iii) at least some chromosomal domains are nonrandomly arranged in a cell type–specific manner.

The term chromatin is imprecise because it does not identify specific levels of folding or address functional regions that can encompass hundreds of kilobases of DNA. In this article the term chromatin is used to designate the lower levels of folding, where nucleosome fibers (DNA wrapped around histones) are wound into 30-nm-wide solenoid fibers (*11*). Each full turn of the solenoid accounts for only ~1.2 kb of DNA, which is less than the sequence length of many transcriptional open reading frames. Functional single genes span 30 kb to more than 1 megabase (Mb) of linear DNA. The most fundamental higher structural level of chromosome folding considered below encompasses small functional genetic units of ~30 kb (a loop domain). Additional higher levels of folding correspond to (i) larger transcriptional and replication units that define band-like chromosome domains (of 0.3 to >3 Mb) and (ii) constitutive heterochromatic coiled domains of ~9 Mb. The highest and most complex level of genome organization manifests itself as the massive regions of dense heterochromatin and more extended euchromatin that morphologically characterize each interphase nucleus. A uniformly heterochromatic region within the nucleus can include coil size domains from several different chromosomes (*6, 7*).

How are these structural domains distinguished in molecular

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