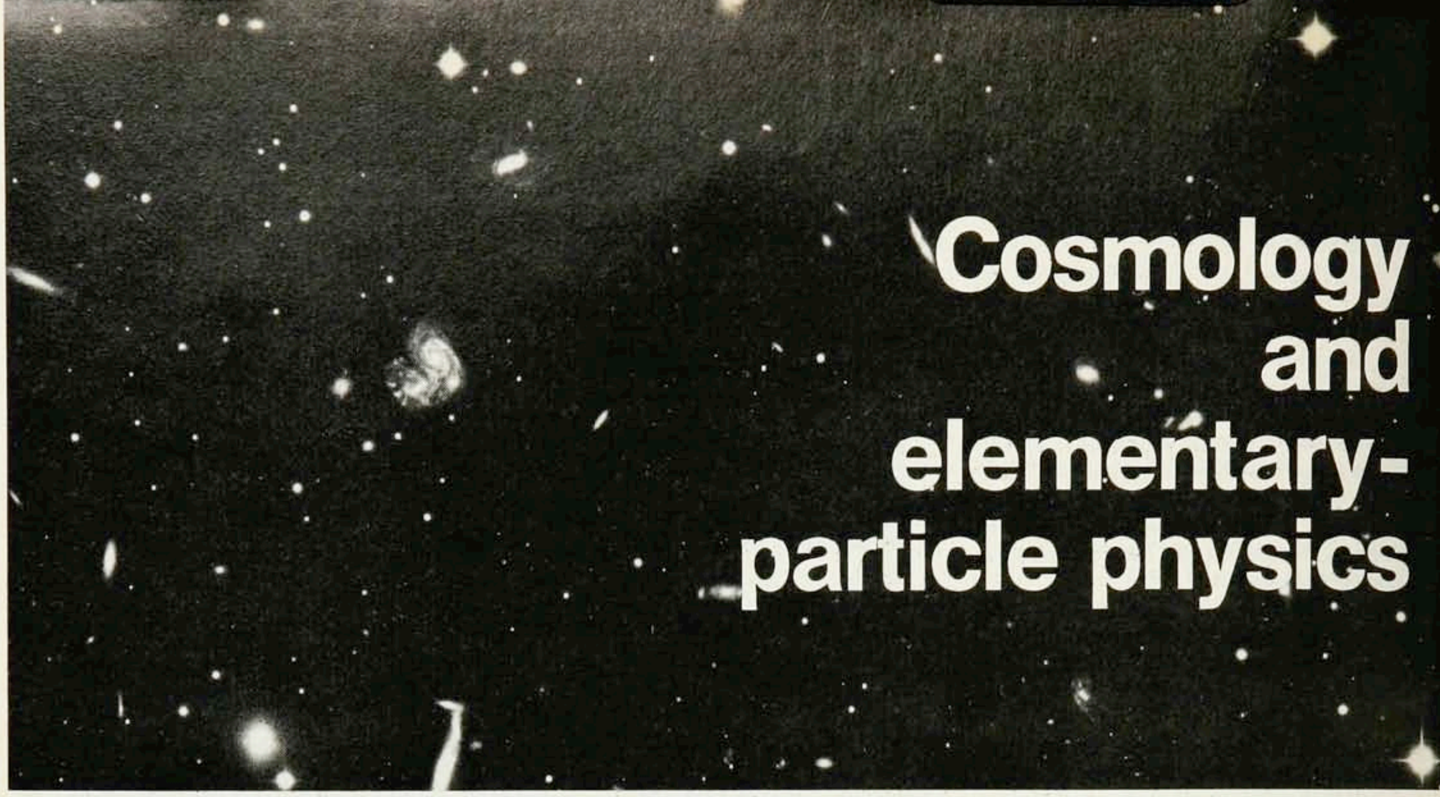

Cosmology and elementary-particle physics

Over the past decade or so, great progress has been made in two diverse areas of physics—cosmology and elementary-particle physics. In spite of the obvious differences of the two fields (figure 1), each has begun to illuminate the other, making interdisciplinary work involving them not only possible but even exciting. Thus, for example, the cosmological abundance of helium-4 fixes an upper limit of 8 on the number of quark varieties ("flavors") in models that have a symmetry between quarks and leptons. And developments in the grand unified theories of elementary processes may resolve the puzzle of why there are roughly a billion photons for every baryon in the universe. As our knowledge of the fundamental particles and their interactions increases, and as our determination of cosmological observables improves (or new observables are discovered) the close relationship of these two disciplines promises to continue to be an exciting one.

Recent developments

In cosmology, the hot big-bang model has become almost universally accepted. The discovery[1] of the 3-K microwave background by Arno Penzias and Robert W. Wilson in 1965 and the agreement of the predicted cosmological production of He^4 with the observed He^4 abundance are strong evidence for a hot big bang (reference 2 and references therein). In addition, the singularity theorems proven by Stephen Hawking, G.F.R. Ellis and Roger Penrose show that in General Relativity the existence of the 3-K background implies that the universe began from a hot big bang.[3]

In elementary-particle physics the following picture has evolved over the past fifteen years. All of the hadrons (baryons and mesons) are made of more fundamental point-like, spin-½ constituents—quarks. The leptons, on the other hand, are themselves fundamental point-like, spin-½ particles. The theories that describe the interactions of these fundamental particles are renormalizable gauge theories. In these theories there are also gauge particles, the photon being the most familiar, which mediate particle interactions, and the so-called Higgs particles, which have not been observed but are required by the theories. The theories are often denoted by the group-theoretic symbol for their fundamental internal symmetry. Thus, for example, the simplest gauge theory, quantum electrodynamics, is a U(1) theory and the quark theory of strong interactions is an SU(3) theory.

Some of these theories for the elementary interactions have recently been seen to fit into larger schemes. The most prominent success is the Weinberg–Salam $SU(2)\times U(1)$ gauge theory, which has unified the weak and electromagnetic interactions and is in good agreement with the experiments done to date. The original SU(3) models have been modified by giving the quarks "color" as well as the usual quantum numbers. The resulting theory, "quantum chromodynamics," has been very successful thus far in describing the strong interactions. Encouraged by the success of the $SU(2)\times U(1)$ theory and SU(3)-color theory, Howard Georgi and Sheldon Glashow,[4] as well as other theorists, have proposed grand unified theories to unify the strong, weak, and electromagnetic interactions. Supersymmetric theories that attempt to unify all the interactions including gravity are also being investigated. The agreement of the $SU(2)\times U(1)$ and SU(3)-color gauge theories with experiment is not less impressive than the concordance of the standard big-bang model with cosmological observations.

There is a natural interplay between cosmology and elementary-particle physics. At times close to the singularity the temperature and density of the universe were very large, and when kT is large compared to a particle's rest energy that particle species is roughly as abundant (to within statistical weight factors) as photons. Sufficiently close to the singularity, therefore, even particles that are far too massive to be produced by our largest accelerators were present in large numbers; so, as the saying goes, "The early universe is the poor man's high-energy physics laboratory." Furthermore, the subsequent evolution and the current state of the universe depend critically on the particles that were present in the early universe and on their interactions.

The "footprints" that remain today from the early universe include

- the 3-K microwave background
- the existence of clumps of matter—the galaxies and clusters of galaxies—in an otherwise homogeneous and isotropic universe
- the abundance of He^4 and several other light elements
- the matter-to-radiation or baryon–photon ratio.

The 3-K radiation reflects the state of the universe 10^5 years after the big bang when matter and radiation decoupled. This relic radiation is highly isotropic, and when the motion of our galaxy through the universe is taken into account the radiation displays no variation in its temperature over angular scales of degrees with instrumental sensitivities of millikelvins.[5]

The existence of galaxies and clusters

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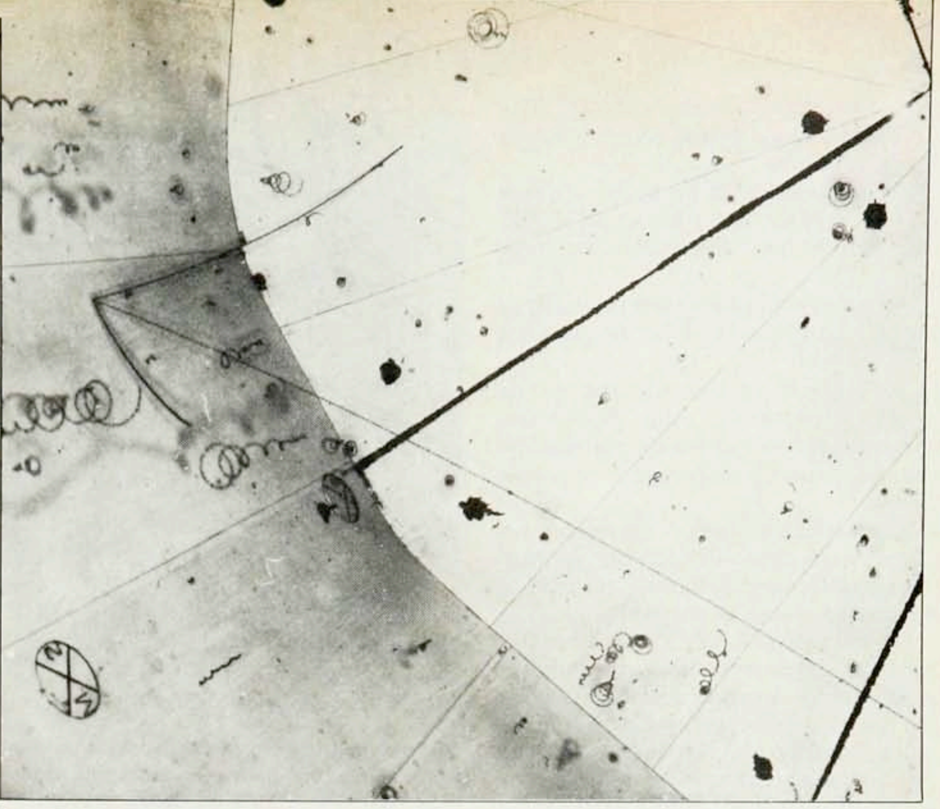
The early universe is the poor man's high-energy physics laboratory; knowledge about its state can be deduced from current observations and can illuminate our knowledge of the fundamental interactions.

Michael S. Turner and David N. Schramm



The very large and the very small. To illustrate the scales of phenomena that have recently been related by interdisciplinary work in cosmology and elementary—particle physics, we show (left) a section of a cluster of galaxies in the constellation Hercules, and (right) the tracks of an event produced by a neutrino in a bubble chamber. (Photos from Mount Wilson and Palomar Observatories and from Argonne National Laboratory) Figure 1

of galaxies implies the existence of small deviations from homogeneity and isotropy in the early universe. In the gravitational instability theory of galaxy formation, primordial density fluctuations begin to grow by their self-gravitational attraction after the matter and radiation decouple. The spatial distribution and mass spectrum of galaxies today possibly reflect the nature of the primordial fluctuations.

When the universe was about 3 minutes old, He^4, D, He^3, and Li^7 were synthesized from the primordial neutrons and protons. The mass fraction of He^4 produced (about $\frac{1}{4}$ by current estimates) is very sensitive to the expansion rate of the universe during these few minutes. The expansion rate depends upon the energy density of the universe, which in turn depends on the number of particle species present. Thus, the observed mass fraction of He^4 today can be used to gain knowledge about the types of particles present in the early universe. The amount of deuterium produced is very sensitive to the matter density during the epoch of nucleosynthesis and can be used to infer the matter density of the universe today.[6]

Photons are by far the most abundant particles in the universe, and almost all of them are in the 3-K cosmic background radiation, which has about 400 photons per cubic centimeter. There is very little antimatter in the universe—less than one part in 10^4, according to current observations.[7] The actual density of matter (the number of baryons) is still uncertain by a few orders of magnitude, but appears to be in the range of 10^{-8}–10^{-6} per cubic centimeter. The baryon–photon ratio is thus around $10^{-9\pm1}$. The reason for this particular value is a puzzle. It could merely be an initial condition, or the result of dissipative processes at some early state of the universe that produced a lot of photons. Or it could be due to more fundamental reasons, some of which we will discuss later.

Finally, there are two additional cosmological observables:

- the deceleration parameter, q_0
- the Hubble constant, H_0

The Hubble constant, which relates the redshift and distance of relatively nearby galaxies, is generally believed to be between 50 and 80 km/sec Mpc. However, q_0, which depends upon knowledge of the redshift and distance as well as the evolution of very distant objects, is very uncertain. In the standard big-bang model (zero cosmological constant) q_0 is related to the present density of the universe, ρ, by

$$q_0 = 4\pi G\rho/(3H_0^2)$$

Current indications are that the density is insufficient to close the universe (for which q_0 would have to be greater than $\frac{1}{2}$), but our inability to measure q_0 directly leaves the question unsettled. However, even our limited knowledge of q_0 allows us to place an upper limit on the present density of the universe. Particles that contribute to the present energy density of the universe are baryons, photons, neutrinos and possibly other undiscovered particles produced in the early universe. The limit on the energy density in turn places a limit on the types of yet undiscovered particles and their properties.

In the next sections we will discuss these ideas in more detail. In particular, we will consider the constraints on the number of particle species based on the observed He^4 abundance and on the present limits for the density of the universe. The former limits the number of quark flavors to eight or less in theories that postulate a correspondence between quarks and leptons. The latter give a stringent upper bound on neutrino masses. And, finally, we will discuss models for cosmological baryon production that may resolve the puzzle of why the baryon–photon ratio is $10^{-9\pm1}$.

Constraints from nucleosynthesis

One of the great triumphs of the big-bang theory is the explanation of the large abundance of helium-4 that we see today. This helium was produced, together with several other light elements, in a period of nucleosynthesis that occurred about three minutes after the singularity. The products of that nucleosynthesis, which are with us today, can thus be used to probe the state of the universe at that earlier time. In our discussion we shall use the so-called "standard model" of an expanding universe. It depends on the following assumptions:

- Special relativity is locally valid in all freely falling reference frames (the equivalence principle). This principle has been verified to a high degree of accuracy in a variety of experiments.
- The universe is isotropic and homoge-

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neous (the cosmological principle). The 3-K radiation and galaxy counts support this assumption.

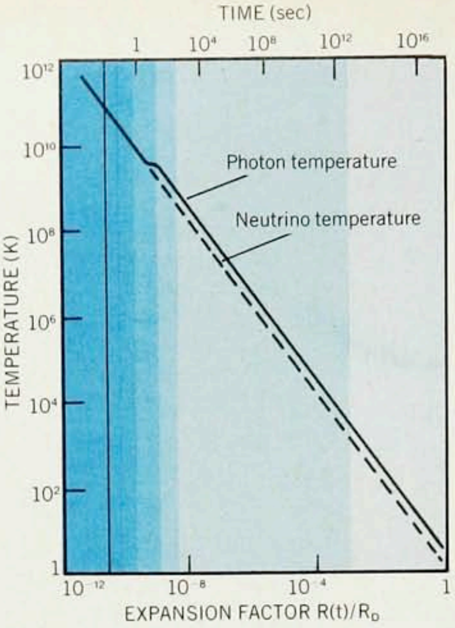
- The temperature of the universe was at one time greater than a few times 10^{10} K. This follows from the singularity theorems.[3]
- The universe is composed primarily of matter and contains negligible amounts of antimatter.[7]
- No particle species was degenerate (most importantly, the neutrinos). (Neutrino degeneracy severely affects He^4 abundance and is discussed in reference 2.)
- The expansion rate of the universe is given by the general relativistic formula (although General Relativity need not be the correct theory of gravity).

We can here give only a brief account of big-bang nucleosynthesis; reference 8 gives a more detailed account. During the epoch of nucleosynthesis, kT was much less than the rest energy of a baryon, so that there was only one baryon for about 10^9 photons. While each baryon contributed around 1000 MeV to the density and each photon contributed only a few MeV, the small number of baryons made their contribution negligible. Today, there is still only one baryon for 10^9 photons, but the average energy of a photon is only a thousandth of an electron volt; so the matter (baryon) density dominates the total observed energy density.

At a temperature of 10^{11} K (so that mean thermal energies are about 10 MeV), the particles present were: n, p, e^-, e^+, ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$, γ and possible other as yet undiscovered particles. These constituents were maintained in statistical equilibrium by the weak and electromagnetic interactions. The fact that the universe was in thermal equilibrium at 10^{11} K means that its future evolution is independent of its history before this temperature. At this temperature the ratio of neutrons to protons, essentially determined by a Boltzmann factor (more precisely, by the Saha equation), was close to unity.

As the universe expands and becomes cooler and less dense (see figure 2), collisions—and thus reactions—among particles become less frequent (see the box on page 44). At certain critical temperatures the reaction rates for certain interactions become less than what is needed to maintain thermal equilibrium for a class of particles. We are in such a non-equilibrium state now: The temperatures for matter and radiation are radically different. Such departures from equilibrium were also extremely important in the early universe.

When the temperature of the universe dropped to about 10^{10} K (mean thermal energy of about 1 MeV) the neutrinos ceased to be in equilibrium with the other particles. That is, neutrino interaction rates fell below the cosmological expan-



The thermal history of the universe in the standard big-bang model. The different shadings show the epochs at which very heavy neutrinos decouple, at which neutrinos and the neutron-proton ratio "freeze out," at which positrons and electrons annihilate (which heats the photons relative to neutrinos), at which nuclei form and at which atoms form. Today the photon temperature is 2.9 K, and the neutrino temperature is about 2 K. Figure 2

sion rate H (and never became greater than H again). Thereafter the neutrinos expanded freely, and maintained an equilibrium distribution corresponding to a temperature inversely proportional to $R(t)$.

At about the same temperature the weak reactions that maintained the equilibrium ratio of neutrons to protons were no longer effective ($\Gamma < H$) and the neutron–proton ratio "froze out" at the value corresponding to this temperature

$$n/p = \exp[(m_p - m_n)c^2/kT_f]$$

whose value was then about $1/6$. By the time of nucleosynthesis, neutron decays decreased it further, to a value of about $1/7$. The "freeze-out" temperature, T_f, and the time from "freeze-out" to nucleosynthesis will be very important.

Soon after, at a temperature of about 3×10^9 K, electrons and positrons could no longer remain abundant in thermal equilibrium, because typical photons (energy up to a few times kT) did not have enough energy to regenerate e^+e^- pairs while annihilations continued, decreasing their numbers. The e^+e^- annihilations heated the photons relative to the neutrinos, which had already decoupled from the rest of the universe, raising the photon temperature relative to the neutrino temperature by a factor of $(11/4)^{1/3}$, a ratio that should remain even today.

When the temperature dropped to approximately 10^9 K, nucleosynthesis occurred very rapidly, because at this temperature the radiation is already cool enough that deuterium can be formed without being immediately photo-disintegrated, and the gas is still hot enough that two deuterium nuclei can overcome their Coulomb barrier to form He^4. Therefore, essentially all the neutrons form into deuterium, and all the deuterium combines into He^4. The resulting mass of helium is a fraction

$$Y = \frac{2\,n/p}{n/p + 1}$$

of the total mass of the universe. Small amounts of deuterium, He^3 and Li^7 were also synthesized at the same time. Nucleosynthesis beyond Li^7 is prevented by the lack of stable isotopes with atomic mass 5 or 8. This simplified picture is borne out by the very careful calculations done by Robert Wagoner, William Fowler and Fred Hoyle in 1967. An update of their results as a function of present baryon density (for a present photon temperature of 2.7 K) is shown in figure 3. It is interesting to note that the mass fraction of deuterium produced depends critically on the present baryon density.[6]

The fraction Y depends critically upon the neutron–proton ratio at the time of nucleosynthesis, which, in turn, depends upon the value of n/p at freeze-out and the time between freeze-out and nucleosynthesis during which neutrons are decaying. The neutron–proton ratio is held in equilibrium by weak interactions and freezes out when the reaction rate drops below the Hubble constant. At this time the Hubble constant (that is, the expansion rate) was approximately

$$H = (8\pi G\rho/3c^2)^{1/2}.$$

The major contribution to total energy density ρ came from the relativistic particles present; around freeze-out these were photons, electron–positron pairs and all the neutrinos:

$$\rho = \rho_e + \rho_\gamma + \rho_{\nu_\mu} + \rho_{\nu_e} + ? = K\,aT^4$$

The constant K is proportional to the number of species; photons contribute 1 to K and each neutrino species contributes $7/8$ to K. The value of K affects the amount of nucleosynthesis, so that, via K, isotope abundances in the universe constrain the number of relativistic-particle species that could have been present in the early universe. Specifically, the larger K is, the larger is the Hubble constant, so that not only does the universe expand faster, giving the neutrons less time to decay before condensing into deuterons, but also the neutron–proton ratio freezes out at a larger value. Both of these effects increase the value of n/p at the time of nucleosynthesis, and thus the fraction of He^4 in the universe.

Figure 4 shows how the primordial fraction of helium-4 depends on the present baryon density and the number of possible neutrino types (or, equivalently of any other light, stable particles).

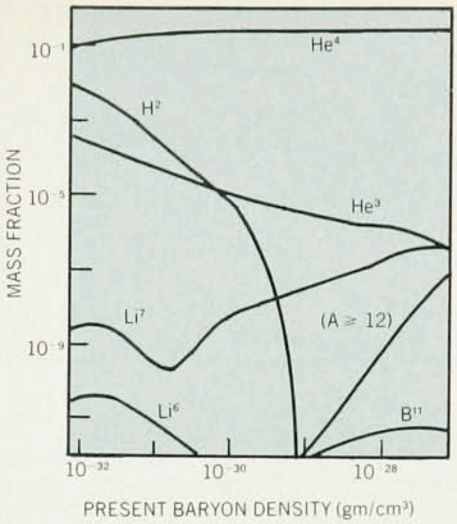
To make use of this information, we must know the fraction, Y, of helium-4 just after big-bang nucleosynthesis. This is a bit of a problem because He^4 is also made in stars; so stars forming now may be contaminated as by much as 6 percent "new helium." The best estimates for Y give a value of between 0.20 and 0.25 with 0.25 as an upper limit.[9] A very conservative upper limit, not correcting for He^4 produced in stars, would be 0.29. Present galactic dynamics suggests a lower limit on the present baryon density of about 2×10^{-31} gm/cm^3. An extreme lower limit on the baryon density of half this value and $Y \lesssim 0.25$ constrains the number of additional neutrino types (beyond ν_e and ν_μ) to 2. Almost certainly one of these neutrino types is the neutrino associated with the τ^- lepton. We can therefore conclude that there is at most one neutrino-like particle that is as yet unknown. Note also that these additional neutrino species necessarily restrict the baryon density of the universe toward lower values.

Standard models in elementary-particle physics have a correspondence between lepton pairs ("generations") and quark pairs. At present there is evidence for three generations: (u,d), (c,s) and (t,b) quarks, and (ν_e, e$^-$), (ν_μ, μ^-) and (ν_τ, τ^-) lepton pairs. (Not all pairs have been observed as yet; there is some evidence for the τ-neutrino, but none yet for the t-quark.) The evidence from the big bang thus implies that there can also only be one additional generation, making eight quark "flavors" in all, if $Y \lesssim 0.25$. If Y is as large as 0.29, there can be at most four new neutrino types, and, consequently, at most seven generations or fourteen quark flavors in total.

Other astrophysical constraints

In addition to limits obtained from our relatively good knowledge of the He^4 abundance, it is possible to use even our rather poor knowledge of q_0 and the corresponding upper limit on the present density of the universe to constrain the properties of hypothetical particles. For a model with zero cosmological constant and a Hubble constant of 50 km/sec Mpc, a deceleration parameter $q_0 < 2$ implies that the present density must be less than 2×10^{-29} gm/cm^3. For reference, the visible matter in galaxies (as determined from their rotation) provides a density of about 10^{-32} gm/cm^3 and as mentioned earlier the matter density inferred from galactic dynamics (virial theorem) is only about 2×10^{-31} gm/cm^3 (each uncertain by about a factor of 2).

Consider the effect on today's density of a massive stable neutral lepton L^0; that is, a particle that couples with the same strength as a neutrino but is not massless. The existence of such a particle was suggested by the SU(3)×U(1) gauge theory of the weak and electromagnetic interactions proposed to explain the seemingly



The mass fraction of light nuclei produced in the standard big-bang model as a function of present baryon density. We assume a present photon temperature of 2.7 K. Note the relative insensitivity of the He^4 fraction and the extreme sensitivity of the H^2 fraction to the present baryon density. Nucleosynthesis of nuclei with $A \geq 12$ is negligible. (From ref. 2.) Figure 3

troublesome (for SU(2)×U(1)) trimuon events seen by the Fermilab–Harvard–Pennsylvania–Rutgers–Wisconsin neutrino experiment. There now exist simple explanations of these events within the standard SU(2)×U(1) theory; however, this hypothetical particle will still serve as a good example of the nature and power of cosmological density constraints. If such a particle's mass were less than 1 MeV/c^2, then, in the early universe for temperatures above 10^{10} K ($kT > 1$ MeV), it would have been as abundant as any other neutrino. Because this particle only couples to other particles via the weak interaction, it, like the standard neutrinos, would decouple at a temperature of approximately 10^{10} K. When kT dropped below $m_L c^2$, these leptons, which should have dwindled in number by annihilations, would instead remain abundant because their annihilation rate fell below the expansion rate at about 10^{10} K. Because of the freezing-out of its interactions, the L^0 would be about as abundant today as the standard neutrinos (and photons), with a number density of about 100/cm^3. Since each L^0 contributes $m_L c^2$ to the energy density, the contribution of such a lepton would exceed the upper limit on the present energy density[10] if m_L were greater than about 50 eV/c^2.

R. Cowsik and J. McClelland first discussed these cosmological arguments in reference to the usual neutrinos, ν_e and ν_μ. The current upper limits on their masses set by laboratory experiments are 0.65 MeV/c^2 for ν_μ and 60 eV/c^2 for ν_e. Particularly in the case of the μ-neutrino the cosmological limit (< 50 eV/c^2) is a much better one than the laboratory limit. Interestingly enough, should the mass of the electron or muon neutrino turn out to be around 40 eV/c^2 or so, the neutrino background would contribute enough mass to close the universe. This extra mass is not forbidden by our earlier arguments based on the D and He^4 abundances, as they only limit the present baryon density.

For a stable neutral lepton with a mass greater than 1 MeV/c^2 the situation is a bit different. (It was first treated by Ben Lee and Steven Weinberg.) As all particles that couple to other matter via the weak interactions, it would have frozen out (decoupled) when the temperature dropped below 10^{10} K (kT around 1 MeV). But since $m_L c^2$ is larger than kT at this point, L–$\bar{\text{L}}$ annihilations would have substantially reduced the number of these leptons before the temperature had dropped enough for them to be decoupled.

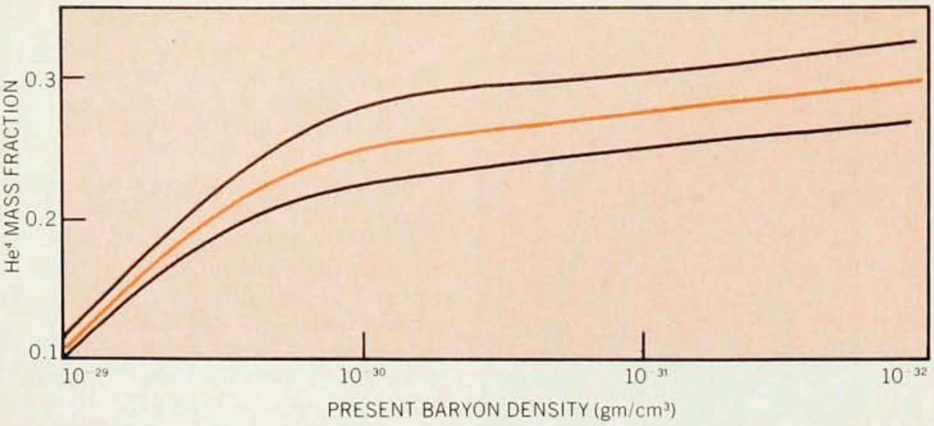
So for a neutral lepton of mass greater than 1 MeV/c^2, although each particle present today contributes more than a light lepton, their reduced abundance lowers their total contribution to the present density of the universe. The curve peaks, as one might naively expect, at about 1 MeV/c^2; the contribution of very heavy leptons is suppressed by their small numbers today, and the contributions of very light leptons is suppressed by their small mass.

As can be seen in figure 4, m_L in the range from about 50 eV/c^2 to about 2 GeV/c^2 is not allowed by current cosmological observations ($q_0 < 2$). It is interesting to note that the current upper limit on the mass of the τ-neutrino is 250 MeV/c^2. If the τ-neutrino exists and is stable, then these cosmological considerations constrain its mass to be less than 50 eV/c^2.

The origin of baryons

In the previous two sections we have primarily discussed how cosmology has been used to put constraints on particle-physics theories. In this section we will discuss how recent ideas in particle physics may resolve the cosmological puzzle of why the ratio of baryons to photons is 10^{-9} (within a factor of ten). The recent developments in grand unified theories of particle interactions may explain the origin of baryons in the universe. The motivation for these theories, which unify the weak, electromagnetic and strong interactions, comes from the striking success of the SU(2)×U(1) gauge theory of weak and electromagnetic interactions and the SU(3)-color gauge theory of strong interactions.

A common feature of all the grand unified theories is that baryon number is no longer absolutely conserved. Qualitatively this is easy to understand: Putting quarks and leptons on equal footing in multiplets generated by the theory requires symmetry operations (gauge transformations) that turn quarks into leptons. In these theories there are also "gauge particles" that mediate the inter-



The mass fraction of He^4 produced in the big bang as a function of present baryon density and numbers of new neutrino types (in addition to ν_e and ν_μ). The colored curve is drawn for two additional neutrinos. With a present baryon density $\geqslant 10^{-31}$ g/cm^3 and $Y < 0.25$ there can be at most two additional neutrino types. (From reference 9.) Figure 4

actions corresponding to the symmetry operations. (Analogously, protons are turned into neutrons and *vice versa* by symmetry operations of an SU(2) theory—"rotations" in isospin. The corresponding gauge particle is the W boson.)

That baryon number might not be absolutely conserved is not too surprising. Black holes, for example, do not conserve baryon number because, unlike charge or mass, baryon number has no long range force coupled to it. To see this, consider the following example: Construct a black hole from charged baryons. An observer outside can determine the charge, mass, and angular momentum of the black hole, but nothing else. That is, if one were to try to account for all the charge and baryon number in the universe the black hole would contribute a charge equal to the total charge of the baryons that created it, but the black hole would not contribute to the baryon number of the universe. A hole made of baryons or equally charged antibaryons appears the same to an outside observer and therefore the baryon number that went into the hole is lost forever.

Baryon nonconservation is even more apparent when the black hole evaporates by radiating a thermal spectrum of particles, a process predicted by Hawking. The hole created from charged baryons will radiate a net charge equal to the charge that initially went into it; however, it will radiate almost equal numbers of baryons and antibaryons. Both in the creation of a black hole and its eventual evaporation, charge, angular momentum, and energy are all conserved, but baryon number can be greatly changed.

In the simplest of the grand unified theories, SU(5), there are the six usual quark flavors (u, d, c, s, t, b), the six usual leptons (ν_e, e^-, ν_μ, μ^-, ν_τ, τ^-) and twenty-four gauge particles: the photon; the weak interactions' bosons W^+, W^-, Z^0; eight gluons for the strong interations, and twelve new superheavy gauge particles, which mediate baryon nonconservation. There are also Higgs bosons, which are associated with the broken symmetry that generates masses for these particles; in addition to the Higgs particles of earlier theories, whose masses are on the order of 200 GeV/c^2 and which generate masses for the quarks, leptons, and weak bosons, there are superheavy Higgs bosons, whose mass is on the order of 10^{15} GeV/c^2 and which generate masses for the superheavy gauge particles. These superheavy Higgs particles can also mediate baryon nonconservation.

At present energies (hundreds of GeV) baryon nonconserving processes are almost negligible (*almost*, but not quite—a point we will return to later) and are effectively a point interaction with an interaction constant that is about 10^{-24} times the Fermi constant for the weak interactions. Normally, then, these processes are extremely weak. However, at energies approaching mc^2 for the superheavy bosons, the processes will be roughly as strong as all the other interac-

Thermodynamics of the expanding universe

The expansion of the universe can be described in terms of the time evolution of $R(t)$, the scale factor of the universe, which, for a closed universe, is like the radius. At $t = 0$ (the big bang) $R = 0$, and as R increases the universe expands. The rate at which R increases is usually measured by the Hubble "constant" at that epoch

$$H(t) = \dot{R}(t)/R(t)$$

and the deceleration of $R(t)$ is given in terms of the parameter

$$q = -\ddot{R}/H^2R$$

The Hubble constant, or expansion rate, has dimensions of (time)$^{-1}$, and the reciprocal of the Hubble constant, $H(t)^{-1}$, is approximately the time it takes the universe to double in size and is also roughly the age, t, of the universe.

The size of the universe, the distance between two galaxies (or between any two particles separated by "cosmological" distances), and the wavelength of a non-interacting photon all scale as $R(t)$. As the universe expands it is like an adiabatic container with expanding walls, and because of Wien's displacement law for thermal radiation, the temperature of the radiation in the universe scales as

$$T \propto \lambda^{-1} \propto R(t)^{-1}$$

The corresponding energy density is proportional to $R(t)^{-4}$. For an ideal nonrelativistic gas, by contrast, the adiabatic expansion gives

$$T \propto R(t)^{-2}$$

Another, more relevant example, is the ratio of neutrons to protons: In thermal equilibrium, that ratio is determined by a Boltzmann factor (involving their mass difference), and as the temperature changes, weak interactions (β decay and related reactions) must act to change the ratio if equilibrium is to be maintained. Unless the interactions that can maintain thermal equilibrium are occurring rapidly, different constituents of the universe can acquire different temperatures.

Therefore, for the various particles to adjust to the changing temperature the relevant interactions must happen on a time scale short compared with H^{-1}; that is the reaction rate, Γ, must be larger than H. For a two-body reaction the rate is proportional to the density, the relative speed, and the interaction cross section of the particles

$$\Gamma \sim \sigma n v$$

Thus, as the universe expands (decreasing the mean density), the reaction rates for the interacting particles decrease, ultimately decoupling particles from the general thermal equilibrium.

When the thermal energy is larger than the rest-mass energy of a particle, $kT > mc^2$, particle–antiparticle pairs are freely created by thermal interactions. Particles for which mc^2 is less than kT are thus as abundant as photons and, because they are highly relativistic, contribute to the thermodynamics of the universe in the same way as photons. In particular, for example, the density will scale as

$$\rho \propto T^4 \propto R^{-4}$$

For lower temperatures, $kT < mc^2$, particle–antiparticle annihilations are not balanced by pair-production from thermal photons, because the photons are not energetic enough. The particle species will then be less abundant than photons.

tions. Energies of the order of 10^{15} GeV occur in the very early universe when the temperature was of order 10^{28} K. In the standard model this corresponds to a time of 10^{-35} sec after the singularity. Since the baryon nonconserving interactions are strong at very early times, it seems reasonable that a universe, even if it started with zero net baryon number, might evolve a net baryon number. However, two additional ingredients are necessary:

- particle–antiparticle asymmetry, or, equivalently, nonconservation of CP (which is actually observed in the K^0–$\overline{K}^0$ system)
- departure from thermal equilibrium at some point in the early universe.

If the first condition is not met, baryons and antibaryons are generated at equal rates by baryon nonconserving processes: There is no "arrow" to direct the system to one side or the other. Several authors have shown[11] that if CPT is a good symmetry, then regardless of other violated conservation laws, a system in equilibrium that has a baryon number of zero will maintain it.

The exciting and amazing new result, first discussed by M. Yoshimura, is that if the grand unified theories correctly describe the interactions in the very early universe ($T \gtrsim 10^{28}$ K), an initially baryon-symmetrical state can acquire a slight baryon excess. Much later, when the baryons and antibaryons annihilate ($T \sim 10^{12}$ K), this excess leaves the one baryon per $10^{9\pm1}$ photons we see today. If, on the other hand baryon number is absolutely conserved, so that an initially baryon-symmetrical universe would remain symmetrical (contrary to the apparent lack of antimatter in the universe), the near completeness of baryon–antibaryon annihilations would leave a baryon–photon ratio[7] of only 10^{-18}.

Many different scenarios have been suggested for the actual details of baryon generation.[11] We shall briefly describe the decay scenario suggested by Weinberg and Frank Wilczek. Suppose that baryon nonconservation is mediated by a very heavy boson (X boson), which might be either a Higgs or gauge boson. We denote its mass by m_x and its coupling strength by α_x (if it is a gauge boson α_x is approximately 10^{-2}, and if it is a Higgs boson α_x is around 10^{-5}). The quantities of interest during the evolution of the universe are the expansion rate, H, the rate for baryon nonconserving collisions, Γ_c, and the rate for X decay and inverse decay, Γ_x.

At some very early time the universe is a very hot ($T \sim 10^{32}$ K) baryon-symmetrical soup containing all the fundamental particles (quarks, leptons, gauge and Higgs bosons) in thermal equilibrium. As the temperature of the universe drops, kT eventually falls below m_xc^2. From this point forward the *equilibrium* abundance of X bosons is (roughly) a Boltzmann factor, $\exp(-m_xc^2/kT)$, less than that of the relativistic particles (such as the photon). However, the X bosons can diminish in number and assume this equilibrium distribution only if they either annihilate or decay at a rate greater than H. When kT is less than m_xc^2 the annihilation rate is a factor of α_x less than the decay rate; so the decay rate, at least, must be greater than H to maintain thermal equilibrium. The subsequent evolution of the universe thus depends on the relative values of α_x and m_x.

If m_x is less than about $\alpha_x 10^{20}$ GeV/c^2 then Γ_x is greater than H for kT less than m_xc^2, as shown in figure 6, and the X bosons can maintain a thermal distribution until they are no longer present. In this case no departures from equilibrium occur in the period of interest and no baryon excess is generated.

If, on the other hand, m_x is larger than about α_x 10^{20} GeV/c^2, neither annihilations nor decays will be effective for maintaining an equilibrium distribution of X and $\overline{X}$ when kT drops below m_xc^2, because the rates for both processes will be smaller than H at that time. The X bosons will thus remain as abundant as photons and will be far from equilibrium until the decay rate becomes larger than the expansion rate of the universe. Once Γ_x does become larger than H, that is, once the X lifetime becomes shorter than the age of the universe, the X and $\overline{X}$ bosons can freely decay, because their decay products are no longer energetic enough to regenerate them (because $kT < m_xc^2$), as shown in figure 7. In this case a baryon excess may arise.

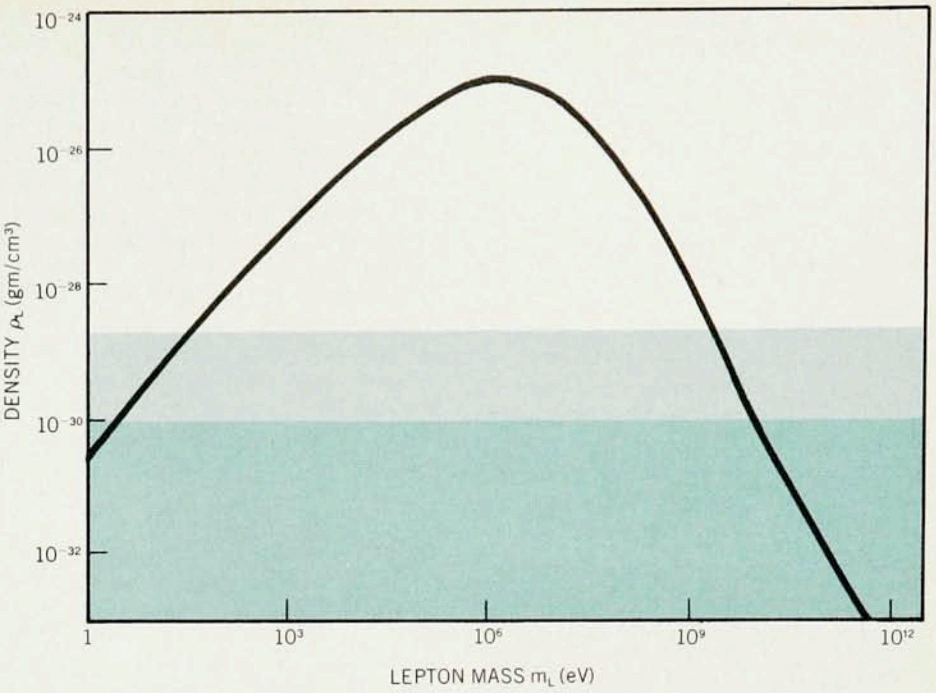
To produce a baryon excess from the non-equilibrium distribution, Weinberg suggested the following mechanism: Suppose the X and $\overline{X}$ bosons can decay in two different ways, into states with two different baryon numbers B_1 and B_2 (with a fraction r decaying into state 1 and $1-r$ into state 2). The $\overline{X}$ decays into the anti-states, with baryon numbers $-B_1$, and $-B_2$, with fractions $\bar{r}$ and $1-\bar{r}$. If CP is not conserved, the branching ratios r and $\bar{r}$ need not be equal. The net baryon number generated from X and $\overline{X}$ decays is then

$$\Delta B = (r - \bar{r})\,(B_1 - B_2)$$

which depends on the size of the particle–antiparticle asymmetry of the theory.

The baryon excess survives because the only other processes that could affect it, baryon nonconserving collisions, are ineffective—Γ_c is smaller than H.

Most of the photons around today represent the results of particle–antiparticle annihilations, which had not taken place at the time the baryon excess was generated. To obtain a value for the current baryon–photon ratio from the computed baryon excess, one can use the entropy of the universe instead of the number of photons. The entropy of the universe is, roughly, proportional to the total number of relativistic particles in the universe. Right now, most of the particles are photons in the 3-K cosmic background; so the entropy is proportional to the number of photons. Assuming that little entropy was generated between the time the baryon excess was produced and



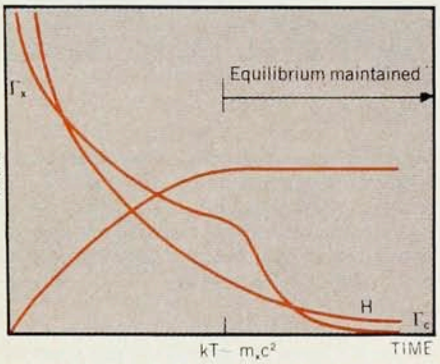
The contribution of a massive stable neutral lepton to the present density of the universe as a function of its mass. For an upper limit on the density of the universe of 2×10^{-29} g/cm^3 (light color) m_L must be less than about 50 eV/c^2 or greater than about 2 GeV/c^2. The upper limit can be improved to about 10 GeV/c^2 by noting that these leptons would have clumped into galaxies just as the baryons did; galactic dynamics would then constrain their average contribution to the mass density to be less than 10^{-30} g/cm^3 (dark color). (From reference 10.) Figure 5 now, we can conclude that the baryon–entropy ratio is constant and proportional to

$$n_B/n_\gamma$$

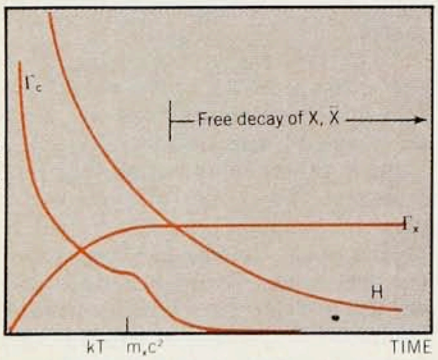
now, and to

$$N_x \Delta B/N$$

then, where N_x is the number of possible X states (including different helicities) and N is the total number of possible particle states. The ratio $N_x\ \Delta B/N$ is in the range 10^{-10} to 10^{-8} for reasonable values of parameters for the grand unified theory. Of course, the details must be worked out to see if this is just a numerical coincidence or whether the baryons in our universe could have actually been produced this way. But if the general idea of cosmological baryon generation is correct, then there is a deep connection between puzzles from elementary-particle physics and from cosmology: the puzzle of the observed small CP violation in the K_o–$\bar{K}_o$ system and the puzzles of the very large photon–baryon ratio and the dominance of matter over antimatter in the universe.



The evolution of the important rates in cosmological baryon generation for m_x smaller than $\alpha_x\ 10^{20}$ GeV/c^2. The temperature is proportional to (time)$^{-1/2}$. The expansion rate, H, in this radiation-dominated epoch is proportional to $\rho^{1/2}$ or T^{-2}. The X-decay and inverse-decay rate is Γ_x; for early times Γ_x is small because the X is very relativistic and time dilation extends its lifetime. The rate for baryon nonconserving collisions is Γ_c. The annihilation rate is always less than or equal to Γ_c. When kT drops below $m_x c^2$, X decays are effective in reducing the number of X bosons. Thus the X and $\bar{X}$ maintain an equilibrium distribution, no departures from equilibrium occur and no baryon excess is generated. Figure 6



Rates for large m_x. The curves are as in figure 6, except that m_x is larger than $\alpha_x\ 10^{20}$ GeV/c^2. In this case when kT drops below $m_x c^2$, X decays and annihilations are not effective in maintaining thermal equilibrium, and the X bosons have a highly non-equilibrium distribution until Γ_x becomes greater than H. At this point the X (and $\bar{X}$) bosons freely decay and generate a baryon excess (for $r \neq \bar{r}$) that cannot be destroyed since Γ_c is less than H. Figure 7

We mentioned earlier that the effects of baryon nonconservation at present energies are *almost* negligible. If baryon number is not absolutely conserved, then the lightest baryon, the proton, is no longer stable, and has a lifetime given by

$$\tau_p \sim (h/c^2)\alpha_x^{-2}\,(m_x^4/m_p^5)$$

In the SU(5) theory τ_p is estimated to be 10^{31}–10^{33} years. Such a number may seem inaccessible to measurement; however, that is not the case. If the lifetime of the proton were 10^{16} years (a factor of 10^6 longer than the age of the universe) the nucleon decays in a person's body would provide a yearly dose of roughly 50 rad over the entire body—the effects of which would certainly be noticeable. To explore lifetimes longer than 10^{30} years, one needs large numbers of nucleons (10^{32} or more) well isolated from all background sources. Such experiments exist: neutrino detectors in deep mines. Frederick Reines and his coworkers have used their South African mine experiment to set[12] the best lower limit to date of 10^{29} yrs. Ken Lande and his collaborators hope to reach sensitivity levels of 10^{31} yrs with their Homestake experiment some time this year. Groups led by Carlo Rubbia and David Cline and by Reines and Lawrence Sulak hope to build experiments at the 10^{33} yr sensitivity level within a few years. These experiments are extremely important; a positive result from a proton decay experiment would be strong evidence for the grand unification ideas and for the cosmological generation of baryons. In addition, if the universe is open, as it appears to be, then it will eventually (10^{32} years) be devoid of matter (baryons).

Cosmological generation of baryons has some important astrophysical implications. In all but one of the scenarios suggested the baryon–entropy ratio is determined only by the parameters of the grand unified theory. Therefore, independent of any primordial temperature fluctuations, the baryon–entropy ratio will be constant throughout the universe (unless the fluctuations were so large that some parts of the universe were never hot enough to have had the superheavy X bosons). Such a uniformity would clearly have profound effects on galaxy formation and galaxy clustering. It would, for example, permit only adiabatic fluctuations in the early universe. The evolution of galaxies from such fluctuations differs from that expected from isothermal fluctuations, in which the radiation temperature remains uniform.

The baryon–photon ratio can be turned upside-down and viewed as a photon or entropy to baryon ratio of $10^{9\pm1}$ indicating an apparent large entropy per baryon. Some years ago, Charles Misner suggested an alternate explanation of the ratio based on this idea. He proposed that the universe may have started with cold baryons and a very chaotic geometry (rather than the isotropic and homogeneous geometry it has today) and that the large entropy–baryon ratio of $10^{9\pm1}$ and the isotropy and homogeneity were produced naturally through dissipation. However, Penrose and others have argued that the amount of entropy per baryon that could have been produced by a chaotic geometry being smoothed by dissipation is more like 10^{40}. They conclude that our apparently large entropy per baryon is in fact very small, and this should indicate that the initial geometry was very close to being isotropic and homogeneous.

However, if the grand unification ideas are correct, the baryon–entropy ratio cannot be used as a "footprint" of the initial geometry because it could easily have been raised from near 0 to the present $10^{-9\pm1}$ by cosmological baryon generation. Our relatively small entropy–baryon ratio (compared to 10^{40}) therefore cannot be used to infer that the universe has been isotropic and homogeneous *ab initio*. In fact, the initial geometry could have been quite chaotic.

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