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Cosmological Element Production

A record of the fireball phase of the universe may be contained in the abundances of some light nuclei.

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A potentially powerful line of attack is on the verge of revealing new insights into the structure and evolution of the universe. The method is essentially based on the fact that a record of the past history of the universe is contained in the abundances of the various elements which we observe today. Thus, for instance, the observation of certain lines in the spectra of the oldest stars in our galaxy may give us information about conditions in the universe when its density was over 10^{30} times the present value. This approach has become more quantitative mainly because of recent observations of background microwave radiation, improved determinations of abundances, and a better knowledge of rates of nuclear reactions. However, the interpretation of observed abundances in terms of production during a past high-density phase of the universe is strongly affected by the fact that most of the elements are believed to have been produced more recently within stars (*1*) or through other processes.

In this method of analyzing the past history of the universe, a given model of the universe is tested by comparing the amount of each element and isotope produced according to the model with the observed abundances in matter whose composition may not have been affected by subsequent processes. Other types of observational evidence allow one to limit the class of cosmological models which may be considered. The observational results which are of importance for this purpose are the following.

1) The distribution and red shifts of radio sources and clusters of galaxies appear to be isotropic to within ~ 30 percent (*2*). In addition, recent measurements of background microwave radiation at 3.2 centimeters (*3*) indicate its possible anisotropy to be $\lesssim$ 3 percent. It is expected that this limit will be further reduced in the near future.

2) The darkness of the night sky (Olber's paradox) (*4*) and the red shift of the spectral lines from distant galaxies imply that the universe is expanding. The measurements (*5*) indicate that at present

$$H_0 \equiv \left(\frac{1}{R}\frac{dR}{dt}\right)_0 \approx (10^{10}\ \text{yr})^{-1} \qquad (1)$$

$$0 \lesssim q_0 \equiv -\frac{1}{H_0^2}\left(\frac{1}{R}\frac{d^2R}{dt^2}\right)_0 < 3 \qquad (2)$$

where H_0 is the Hubble expansion constant and q_0 is the deceleration parameter. The scale factor R is proportional to the distance between clusters of galaxies, which are believed to be the smallest aggregates of visible matter whose motion is due solely to the universal expansion.

3) The present density of visible matter is $\sim 3 \times 10^{-31} - 3 \times 10^{-30}$ gram per cubic centimeter (*6*). However, other forms of matter, such as neutrinos or ionized intergalactic gas, may contribute significantly to the total density.

4) The microwave background radiation mentioned in observation 1 has also been detected at both 7.3 and 20.7 centimeters (*7*). All intensities lie very nearly on a 3°K black-body spectrum. In addition, measurements of the rotational structure of interstellar absorption bands of CN at 0.26 centimeter (*8*) are also consistent wiht a photon temperature of 3°K.

We shall further restrict our consideration of possible models by making three rather general assumptions.

1) The universe has emerged from a state of very high temperature and density. This is the hot "big bang," as first envisioned by Lemaître and Gamow (*9*). The detection of the 3°K photons provides support for this view, since it appears that the photons were probably thermalized during a higher-density phase of the universe, before the plasma recombined at 10^4 degrees Kelvin. (Subsequent reheating due to energy liberated in galaxy formation has presumably ionized any present-day intergalactic gas.) In particular, it is assumed that the temperature was once high enough ($T \gtrsim 10^{12}$ deg K in most models) to allow free neutrons to be present due to the equilibrium of the weak reactions:

$$\nu_e + n \rightleftarrows p + e^-,$$
$$e^+ + n \rightleftarrows p + \bar{\nu}_e,$$

and

$$n \rightleftarrows p + e^- + \bar{\nu}_e$$

In the case of an oscillating universe, such a temperature would also dissociate nuclei, and thus prevent a continual buildup of heavier elements from cycle to cycle through stellar nucleosynthesis.

2) The universe was fairly homogeneous during the early high-temperature stage. By homogeneity I mean that a cosmic time t can be chosen such that all locations in the universe are equivalent at a given time. As a result, all scalar quantities such as density, pressure, and temperature depend only on t. The observations of isotropy, plus the philosophical postulate that we are not occupying a unique location in the universe, lead to the conclusion that, at least within times not too far removed from the present epoch, the

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large-scale structure of the universe has been approximately homogeneous. It is usually assumed that the galaxies condensed out of an even more homogeneous medium. Additional evidence for homogeneity in the past comes from the fact that any initial large-scale inhomogeneities would be expected to grow, at least according to general relativity theory (*10*).

3) The measurements of the background radiation are due to primeval photons (*11*), not to photons produced as a result of processes such as (i) galaxy formation during later stages in the expansion of the universe (*12*) or (ii) a recent thermalization of starlight. The photons have cooled, due to the expansion, to their present temperature of 3°K. Combination of this temperature with estimates of the present baryon density yields the result that all fermions of nonzero rest mass have always been nondegenerate. However, there is no evidence suggesting that the neutrinos are nondegenerate.

Within these assumptions, we find that only three quantities are needed to specify the cosmological model during the phase when the elements are being produced. These are the entropy of the photons per gram of baryons, the number of electron-type neutrinos or antineutrinos per baryon, and the expansion rate of the matter. The effects of these factors on element production are illustrated in various specific models.

The observations of the abundance of helium constitute the most severe test of these big-bang theories of the universe. Recent observations of certain old stars indicate that their atmospheres contain much less helium than is usually found throughout our galaxy. If this does indeed indicate a very low primeval abundance of this element, we then reach the critical conclusion that the most widely accepted model of the universe must be abandoned.

Factors Affecting Element Synthesis

In determining the element production in a given cosmological model, it is only necessary to consider what occurs after the temperature has dropped below $\sim 10^{11}$ deg K, since the electromagnetic, weak, and strong interactions are strong enough to keep all particles in statistical equilibrium above this temperature, making their properties independent of the previous history of the universe. (This temperature will vary somewhat among different models.) The particles present below this temperature will be neutrons, protons, nuclei, electrons, positrons, photons, and electron and muon neutrinos and antineutrinos. All heavier particles of each type, such as muons, pions, and hyperons, will have decayed by this time, since the temperature corresponds to an energy of ~ 10 million electron volts, well below the energy released in the decays. However, gravitons (*13*) or even scalarons (*14*) could also have been plentiful. There is reason to believe that the net baryon number is positive (*15*), resulting in baryon-antibaryon annihilations leaving essentially no antibaryons at this temperature. In addition, the photon flux prevents the neutrons and protons from combining until the photons have been cooled by the expansion to $\sim 10^{9}$ deg K, at which time nucleosynthesis can commence.

The abundance of a given nucleus, expressed in terms of its fraction of the total baryon mass density ρ_b, depends on the rates of the reactions which produce and destroy it, as well as on the time scale of the expansion. Knowledge of the relevant cross sections as a function of energy in the region of 100,000 electron volts allows us to express the reaction rates as functions of baryon density, temperature, and mass fractions of the colliding nuclei. During recent years much experimental and theoretical information on the cross sections of interest has become available, in work inspired to a large extent by the astrophysical studies of William A. Fowler and others, adding greatly to one's confidence in the nuclear-physics aspect of the problem.

The reactions of importance are illustrated in Fig. 1. Because of the high temperatures involved, both directions of a reaction must often be included.

Due to our assumption of homogeneity, the work-energy relation for

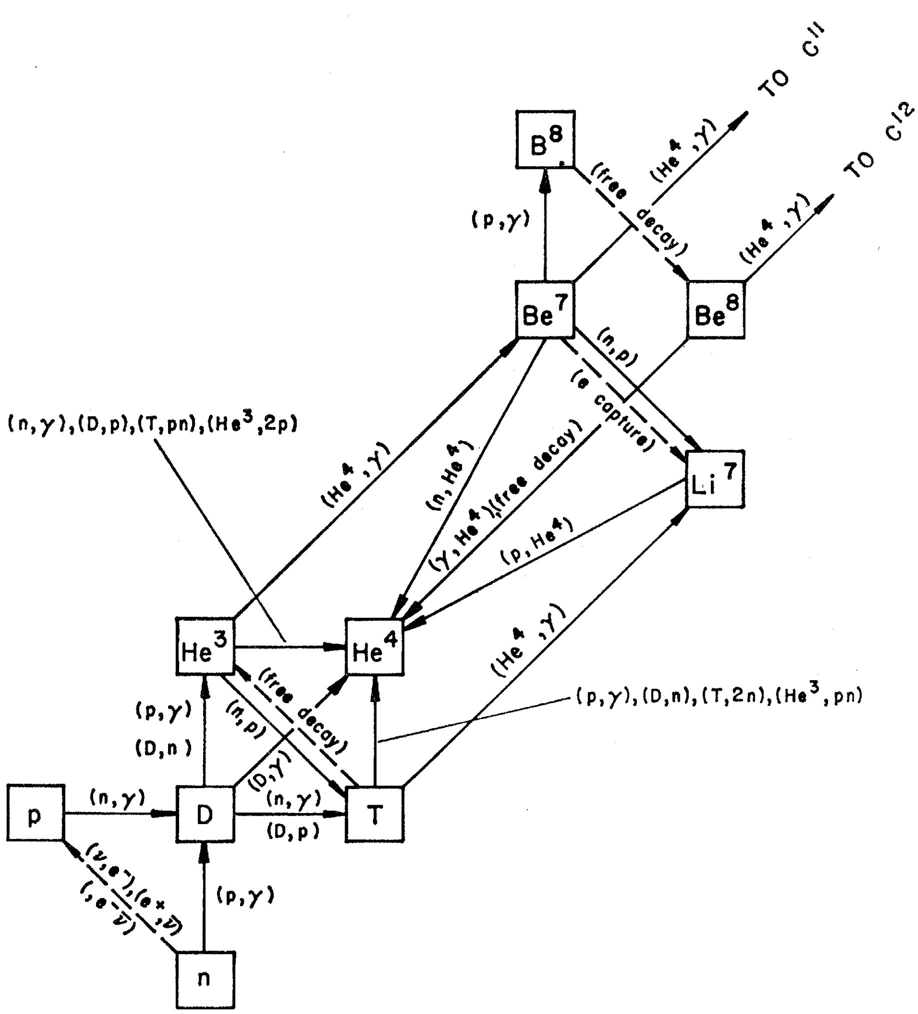


Fig. 1. Reactions of importance in big-bang nucleosynthesis. The exoergic directions are indicated, although rates are often rapid in both directions. The other incoming and outgoing particles, those not shown in squares, are indicated in parenthesis. Dashed arrows indicate the weak reactions. There are sometimes competing reactions leading from one nucleus to another.

a gas of total mass-energy density ρ and pressure p can be written

$$\frac{d}{dV}(\rho V) + \frac{p}{c^2} = 0 \qquad (3)$$

where V is an element of volume as measured by an observer moving with the matter. The baryon density decreases as V^{-1}, while the baryon pressure is negligible at these temperatures. In the case of the neutrinos, $\rho_\nu = 3p_\nu/c^2 \propto V^{-4/3}$, while their temperature T_ν and Fermi level Φ_ν decrease as $V^{-1/3}$ under isotropic expansion, since the neutrinos expand adiabatically in the temperature range of interest, having effectively ceased to interact with other particles. If the neutrinos are nondegenerate, then the density of each of the four types of neutrino is just 7/16 the density which photons would have at that temperature. (A factor ½ is due to the fact that neutrinos have only one spin state, while the remaining factor arises because they are fermions.)

Electromagnetic interactions are strong enough to keep the electrons and baryons in thermal equilibrium with the photons at a temperature T until the plasma recombines at $\sim 10^4$ deg K. Equation 3 serves to relate this temperature T to the volume V, once $\rho(T)$ and $p(T)$ are specified. One finds that, before the electron-positron pairs annihilate into the radiation field as the temperature drops from $\sim 6 \times 10^9$ to $\sim 10^9$ deg K, $T = T_\nu$, while afterward $T = 1.40\,T_\nu$ if the neutrinos are nondegenerate. While they are relativistic, the pairs have the same density per degree of freedom as the neutrinos. These properties of the particles usually assumed to be present are illustrated in Fig. 2. Note that, if the neutrinos are nondegenerate, the universe eventually becomes dominated by the baryon density.

Up to this point the discussion has been applicable to any cosmological model satisfying the three assumptions made. However, in order to calculate the abundances of the various nuclei, we require the further specification of three quantities within such a big-bang cosmology. These quantities are:

1) The entropy of the photons per gram of baryons after the electron-positron pairs have annihilated. Since the entropy of the photons, which is proportional to VT^3, remains constant except during pair annihilation, while the baryon density ρ_b varies as V^{-1}, we may write

$$\rho_b = hT_9^3 \text{ g cm}^{-3}, \qquad (4)$$

where the parameter h is inversely proportional to the entropy of the photons per gram of baryons, while T_9 is the photon temperature in units of 10^9 deg K. We shall consider that h lies in the range $10^{-6} \lesssim h \lesssim 10^{-2}$, which includes all the various estimates of the present baryon density.

2) The ratio of electron lepton number to baryon number, a ratio denoted by $L_{e\nu}$. If $|L_{e\nu}| \ll 10^3/h$, the electron neutrinos and antineutrinos will be nondegenerate. In this case, the neutrons and protons will be approximately equally abundant while they are kept in statistical equilibrium through the e, ν_e weak reactions. If $L_{e\nu} \gg 10^3/h$, the electron neutrinos will be degenerate; this will result in an equilibrium ratio of protons to neutrons much greater than unity, and will lead to very few neutrons' being available for element building. If $L_{e\nu} \ll -10^3/h$, the electron antineutrinos will be degenerate; this will lead to an excess of neutrons until the Fermi level has fallen below the energy released in the conversion of a neutron into a proton, ~ 1 million electron volts.

3) The expansion rate, $V^{-1}dV/dt$. This will depend upon the gravitational theory assumed, the nature of any anisotropy, and the types and amounts of particles present. For instance, the presence of a scalar field (*14*), gravitational radiation (*13*), magnetic fields, rotation, or degenerate neutrinos would all influence the expansion rate. Although most such effects (except for neutrino degeneracy) appear to be small today, they could have been important during the early element-building phase. However, the element abundances produced usually depend critically on the expansion rate only in the range $10^8 < T < 10^{10}$ deg K, and so it may be difficult to determine which of these factors were present, since what is of primary im-

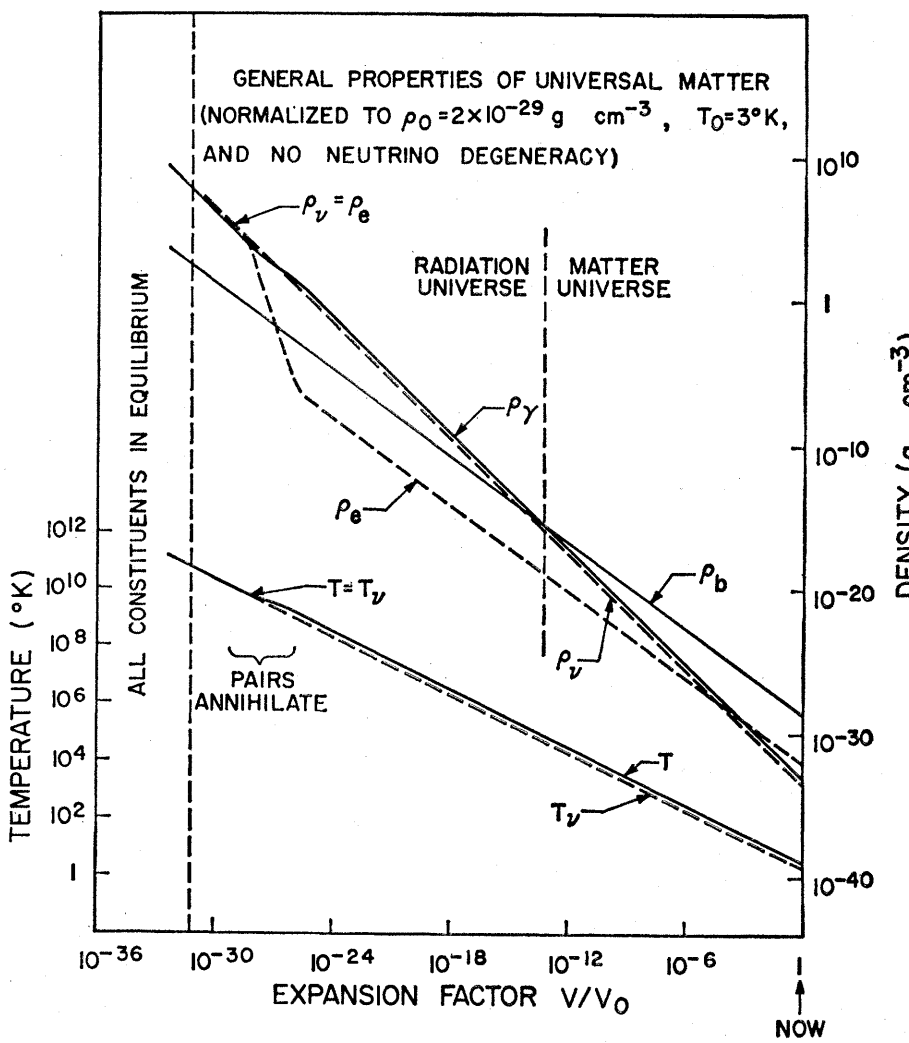


Fig. 2. Temperature and density of baryons, photons, electrons, and neutrinos during the universal expansion. The temperatures of the baryons and electrons no longer equal the photon temperature T below $\sim 10^4$ deg Kelvin. The effective neutrino temperature and density will be modified if the expansion was initially anisotropic.

portance is merely the magnitude of the rate near 10^9 deg K.

I next discuss element production in certain specific cosmologies—namely, isotropic general relativistic universes with (i) nondegenerate and (ii) degenerate neutrinos; (iii) anisotropic general relativistic universes with nondegenerate neutrinos; and (iv) isotropic nondegenerate universes with a scalar field. In addition, I present the general features of the results expected in any homogeneous big-bang cosmology.

Isotropic general relativistic universes with nondegenerate neutrinos. If one assumes that general relativity provides a correct description of the gravitational interaction back to early times in the expansion of the universe, and that this universe has been isotropic as well as homogeneous, then one arrives at the most popular dynamical model. Indeed, the pioneering studies of element production by Gamow, Alpher, Bethe, Herman, Fermi, Turkevich, Hayashi, and others (*16*) were all based upon this very simple and possibly philosophically pleasing framework. Gamow originally envisioned the initial matter as pure neutrons, but Hayashi pointed out that the weak interactions require as many protons as neutrons in the hot primordial material if there is no degeneracy, as these early workers assumed to be the case. Recently, Hoyle and Tayler (*17*), Peebles (*18*), and Wagoner, Fowler, and Hoyle (*19*) have calculated in more detail the abundances of various elements expected from this model.

The expansion rate during the early phases of such a universe is given (*4*) by

$$\frac{1}{V}\frac{dV}{dt} = (24\pi\ G\ \rho)^{\frac{1}{2}}\ \text{sec}^{-1}, \qquad (5)$$

where G is the gravitational constant and ρ is the total mass density. Above $\sim 6 \times 10^9$ deg K, where photons, pairs, and neutrinos are roughly all equally abundant and at the same temperature, one has $\rho = 38\ T_9{}^4$ grams per cubic centimeter, so that Eq. 5 becomes

$$\frac{1}{V}\frac{dV}{dt} = 0.014\ T_9{}^2\ \text{sec}^{-1}. \qquad (6)$$

After the pairs annihilate, the coefficient becomes 0.008. The baryons make a negligible contribution to the total density until the temperature has dropped to, at most, $\sim 10^6$ deg K.

The neutrons and protons drop out of equilibrium at a temperature of $\sim 10^{10}$ deg K, the neutron-proton ratio decreasing slowly thereafter until the element-building phase begins, at $\sim 10^9$ deg K. The details of the buildup during this phase (*19*) are presented in Fig. 3 for a universe in which $h = 3.6 \times 10^{-5}$. This parameter is the only degree of freedom which distinguishes between various models of this class.

The first step in the production of nuclei is the formation of deuterium when its photodissociation lessens. Synthesis of heavier nuclei can then proceed rapidly, but the lack of stable nuclei of masses 5 and 8 prevents appreciable buildup of nuclei heavier than helium. Most of the neutrons are converted into He^4, so that the n/p ratio of $\sim 1/6$ at 10^{10} deg K results in $2n/(n+p) \approx 20$ to 30 percent He^4 at $\sim 10^9$ deg K. The effect of the Coulomb barrier causes the reaction rates of the charged particles to decrease sharply with decrease in temperature. The neutron reaction rates also decrease rapidly because of the depletion of neutrons. This causes the abundances to reach their final values by $T \approx 10^8$ deg K.

In Fig. 4 are shown the final abundances of all nuclei produced in this type of universe as a function of the parameter h (*19*). Since h can be expressed in terms of the present-day density, and since general relativity (without the cosmological constant) provides the relation

$$q_0 = 2.7 \times 10^{28}\rho_0 \qquad (7)$$

between the deceleration parameter and the density [with $H_0 = 100$ km (sec megaparsec)$^{-1}$], these quantities are also used as the parameter.

Note the important result that this range of h values does not allow the density to be high enough during element building for the reactions $He^4 + Be^7 \rightarrow C^{11} + \gamma$ and $3He^4 \rightarrow C^{12} + \gamma$ to produce significant quantities of nuclei heavier than mass 7. The deuterium abundance decreases sharply as h is increased, due to the increased effectiveness of the reaction $p + D \rightarrow He^3 + \gamma$, while the He^3 decreases, due to the fact that He^3 and tritium are more easily converted into He^4 at the higher densities. The increase in Li^7 at low densities is due to its depletion by $p + Li^7 \rightarrow He^4 + He^4$ being less at these densities, while its increase at higher densities is due to the increasing effectiveness of the reaction $He^3 + He^4 \rightarrow Be^7 + \gamma$, followed by $Be^7 \rightarrow Li^7$.

Isotropic general relativistic universes with degenerate neutrinos. Let us now consider the possibility that the universe is filled with enough electron neutrinos or antineutrinos to induce degeneracy (*20*). If Φ_ν is their Fermi level, and if they are completely degenerate ($|\Phi_\nu/kT_\nu| \gg 1$), their resulting mass density is

$$\rho_\nu = \frac{\Phi_\nu{}^4}{8\pi^2c^5\hbar^3} = 2920\ \Phi_\nu{}^4\ (\text{Mev})\ \text{g cm}^{-3}. \qquad (8)$$

Since we shall assume the same dynamical model as in case 1, we see that, in order that the neutrino density be within the upper limit $\rho \lesssim 10^{-28}$ gram per cubic centimeter set by the deceleration of distant galaxies, the Fermi level at present can be at most 10^{-2} electron volt. This is well within the upper limit of 2 electron volts imposed by measurements indicating a lack of proton-neutrino interactions in the very-high-energy cosmic rays (*21*). The quantity which determines the element production is Φ_ν/kT (T is the photon temperature), which remains constant except during pair annihilation.

Neutrino degeneracy affects element production in two ways. First, the increased density increases the expansion rate, allowing less time for the nuclear reactions to take place. This is the only way in which muon neutrino or antineutrino degeneracy would affect the problem. Second, the reaction rates governing the interconversion of neutrons and protons are altered. As mentioned above, electron neutrino degeneracy results in a preponderance of protons, while electron antineutrino degeneracy allows the neutrons to remain dominant until the Fermi level has decreased to the level where they can decay, ~ 1 million electron volts.

Two parameters, h and $(\Phi_\nu/kT)_0$ (the subscript refers to the value after pair annihilation), determine the element abundances in these universes. These are related to the more fundamental electron lepton-baryon ratio $L_{e\nu}$ in the case of complete degeneracy by the formula

$$L_{e\nu} = 2.33 \times 10^3 \frac{(\Phi_\nu/kT)_0{}^3}{h}. \qquad (9)$$

In Fig. 5 are plotted the results for universes having a representative value of h, 10^{-4}, but containing various numbers of neutrinos (+) or antineutrinos (−) per baryon. The amount necessary to produce a closed universe (corresponding to $q_0 = 1$) is indicated on the graph for the antineutrinos. The muon neutrino number has been set equal to the electron neutrino number for definiteness. The major effect of electron neutrino degeneracy is a sharp drop in the production of He^4 and Li^7, followed by declines in the other abundances as fewer and fewer neutrons are available for synthesis. In the case of antineutrino degeneracy, an almost pure helium universe results from mild degeneracy, corresponding to roughly equal numbers of neutrons and protons being present at the time when the nuclear reactions can begin producing He^4. For higher densities of antineutrinos, the protons are produced at lower temperatures, so that the charged-particle reactions have increasing difficulty in building up the heavier nuclei. Finally, even the abundance of deuterium is reduced, due to the lower densities and faster expansion rates which obtain when it can be produced.

Anisotropic general relativistic universes with nondegenerate neutrinos. The lack of any evidence for anisotropy at present does not rule out the possibility that a highly anisotropic situation might have existed during element synthesis. In fact, there are known solutions of the field equations of general relativity which have the property of smoothing out initial anisotropies as the universe expands (*22, 23*). Furthermore, it has been pointed out by Thorne and others (*22, 24*) that there are reasons for believing that, if the galactic magnetic fields which are observed today existed before galaxy formation, then a general relativistic universe would have been very anisotropic in its early stages.

The effect of anisotropy on element production occurs through modification of the expansion rate. In the general case, $V^{-1}dV/dt \equiv \Theta$ is determined (*25*) by an equation of the form (neglecting neutrinos)

$$\frac{d\Theta}{dt} + \frac{1}{3}\Theta^2 = 2(\omega^2 - \sigma^2) + \text{div}\, A - 4\pi G\,(\rho + 3p/c^2), \qquad (10)$$

where ω is a term due to the rotation of the matter, σ is its shear, and div A is the four-dimensional divergence of the acceleration. For our purposes it is sufficient to note that any shearing motion acts like an attractive agent, while the rotation acts as a repulsion. The sign of div A is not fixed in general, but this term does vanish in the absence of pressure or rotation (*26*). Thus we see that the expansion rate may be both faster or slower than in the isotropic situation.

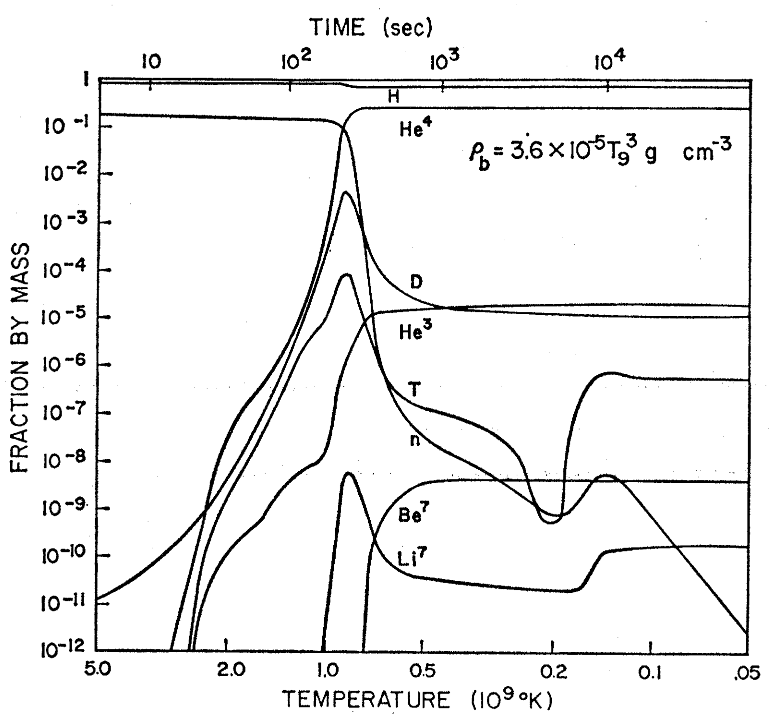
Some calculations of element production have been carried out for certain models in which two spatial directions are equivalent (*22, 27*). In these models the initial expansion rate is proportional to T^3, rather than to T^2 as in the isotropic case. The constant of proportionality depends on the type of anisotropy but increases with the amount.

Isotropic nondegenerate universes with a scalar field. The attempt to more fully incorporate Mach's principle (*28*) into a theory of gravitation led Brans and Dicke (*14*), following Dirac and Jordan (*29*), to introduce a scalar field, whose value is determined by the distribution of nonrelativistic matter throughout the universe. In one form of the theory, the field ψ takes the place of the gravitational "constant," and its value is roughly

$$\psi \sim G^{-1} \sim \frac{M}{Rc^2}, \qquad (11)$$

where M is the rest mass contained within the "radius" R of the observable universe. This field is very "stiff," having effectively $p = c^2\rho$. The expansion rate is increased during element synthesis, due to the additional energy density this field provides.

In cases 3 and 4 we have seen



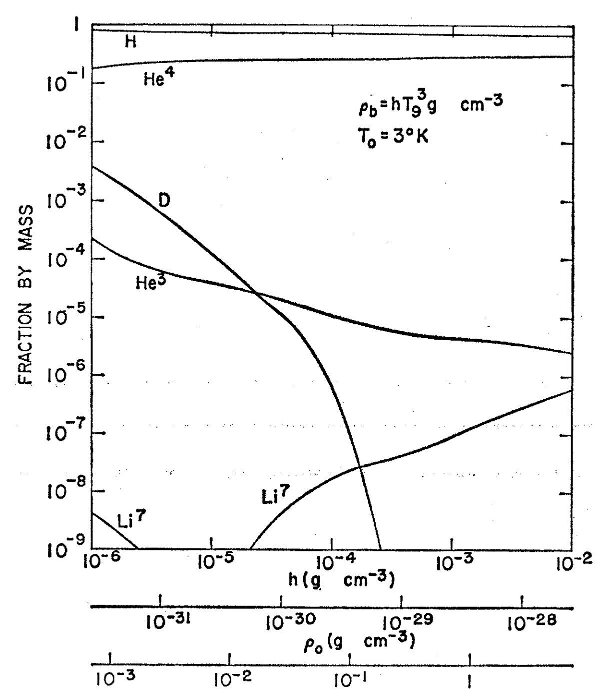


Fig. 3 (left). Evolution of nuclear abundances during the expansion of a typical general-relativistic, isotropic, nondegenerate universe. The ρ_b, T_9^3 relation refers to the period after pair annihilation ($T_9 \lesssim 1$). Fig. 4 (right). Abundances produced in general-relativistic, isotropic, nondegenerate universes as a function of photon entropy per gram of baryons ($\propto h^{-1}$). The range of present densities and deceleration parameters, if the photon temperature is 3°K, is also indicated. The ρ_b, T_9^3 relation refers to the period after pair annihilation.

examples of the way in which the expansion rate can be modified by various factors. However, it appears reasonable to assume that any such factors would still produce an expansion rate of the approximate form

$$\frac{1}{V}\frac{dV}{dt} = a\,T_9{}^b\ \mathrm{sec}^{-1}, \tag{12}$$

where a and b are roughly constant in the temperature range of interest, $0.1 \lesssim T_9 \lesssim 10$. In the examples I have discussed, $a \gtrsim 10^{-2}\ \mathrm{sec}^{-1}$, the value for an isotropic, general relativistic, nondegenerate universe, while $b = 2$ and 3.

In Fig. 6 are shown the abundances produced in nondegenerate universes having the typical value of $h = 10^{-4}$, and the expansion rate given by Eq. 12, for a range of values of a, and with $b = 2$ and 3 (*30*). Most reasonable models would be expected to have values of b near these. We see that very slow expansion rates produce few nuclei, since most of the neutrons have time to decay before element synthesis begins. As the expansion rate is increased, production rises, due to the increased availability of neutrons. As the rate is increased still further, however, there is insufficient time to build as much He^4 and Li^7, but deuterium and He^3 continue to rise, since they are no longer consumed in forming the heavier nuclei. Finally, for sufficiently rapid expansions, He^3 and, finally, deuterium cannot be formed.

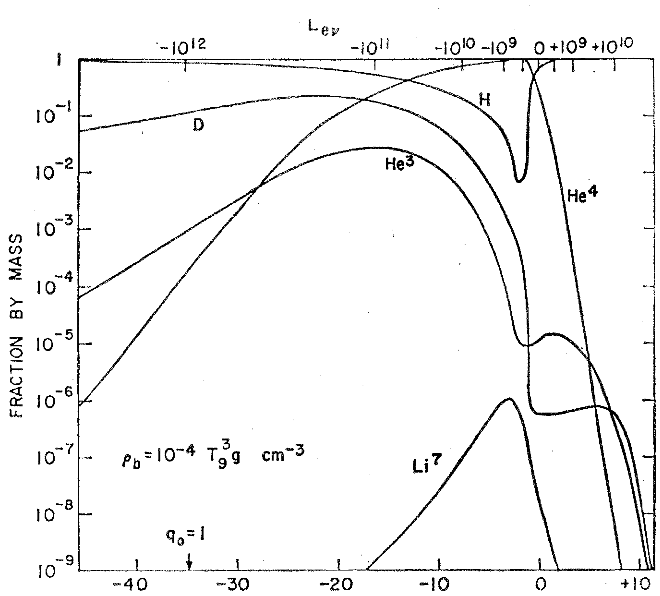
Figures 4, 5, and 6 illustrate how each of the three basic factors (h, $L_{e\nu}$, and $V^{-1}dV/dt$) in *any* homogeneous big-bang cosmological model separately affects element production. Let us now compare these predictions with what can be inferred from the observations.

The observational data of most interest are listed in Table 1. In addition to the abundances of nuclei produced in a big bang, abundances of some other nuclei are included. Since we are interested in the composition of the universe before galaxy formation commenced, the most informative observations are observations of matter which has been least altered by processes such as stellar synthesis, spallation, and chemical fractionation.

Thus far deuterium has been observed only within the solar system. This is not surprising, since the displacement of the spectral lines from those of hydrogen is not easily detected in stellar spectra. That the D/H mass ratios found in two quite different constituents of the solar system should agree so well is interesting, although these are average values. However, it must be emphasized that this amount may have been due to processes occurring during the formation of the solar system (*31*). The best hope at present for obtaining the abundance of primordial deuterium appears to be through the search by radio astronomers for the interstellar 91.6 centimeter hyperfine line, produced by the spin-flip transition in the ground state, which has a lifetime of $\sim 7 \times 10^8$ years. Since deuterium is rapidly consumed during stellar nucleosynthesis, and since production due to cosmic-ray collisions with helium should be negligible, one might expect that any interstellar deuterium would be mostly primeval, although possibly less abundant than it was originally. It may be seen that the upper limit (*32*) is just below the solar-system value.

The best determination of an He^3 abundance comes from the He^3/He^4 ratio in a special class of gas-rich meteorites (*33*) in which, it is thought, remnants of a primitive solar wind have become trapped. The question is, how representative is this solar wind of primordial material? In addition to being produced from He^4 through spallation, He^3 could have been produced within stars by the reaction $p + D \rightarrow He^3 + \gamma$, either from some initial deuterium or through the p-p chain in the late stages of stellar evolution (*34*).

The nucleus whose abundance determination involves the fewest uncertainties is He^4. This is due to the fact that, because of its very large binding energy, He^4 is the most abundant nucleus synthesized, under most conditions. Therefore its fractional production or depletion due to processes other than universal or stellar nucleosynthesis is expected to be small. In addition, it appears that the present rate of hydrogen burning may have been able to produce



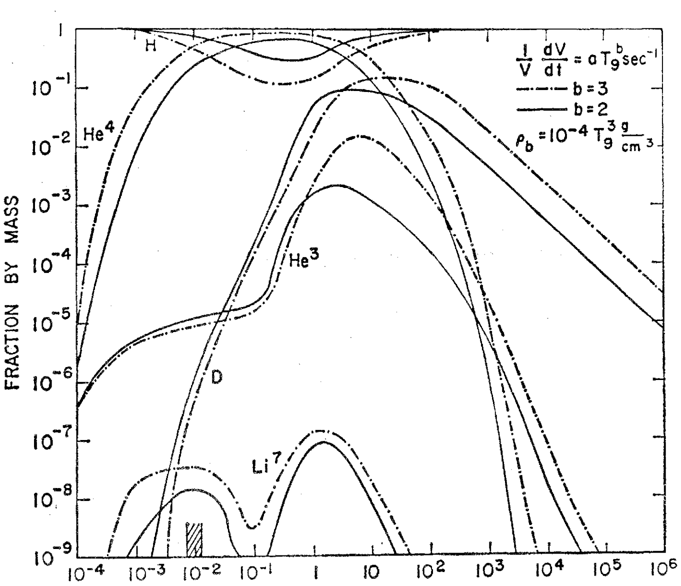


Fig. 5 (left). Abundances produced in typical ($h = 10^{-4}$) general-relativistic, isotropic universes containing various numbers of electron neutrinos (+) or antineutrinos (−) per baryon, $L_{e\nu}$. The present-day ratio of neutrino Fermi level to photon energy is also indicated, along with the value (for antineutrinos) necessary to produce a closed universe. The ρ_b, $T_9{}^3$ relation refers to the period after pair annihilation. Fig. 6 (right). Abundances produced in typical ($h = 10^{-4}$) nondegenerate universes having various expansion rates during element production. The range of a during the expansion of the general-relativistic, isotropic model (for which $b = 2$) is indicated. The ρ_b, $T_9{}^3$ relation refers to the period after pair annihilation.

a mass fraction of only about 0.03 during the lifetime of the Galaxy (*17*), although conditions may have been more violent during the formation of the Galaxy. Solar cosmic rays and evolution calculations (*35*) indicate a mass fraction of 0.27 for the sun, and for B stars helium abundances up to 0.4 have been observed (*36*), while gaseous nebulas in our galaxy and other galaxies in the local group yield abundances in this range (*37*). However, lower abundances have recently been indicated in quasars (*38*), while some blue halo stars appear to be deficient in helium by a factor of ~100 (*39*).

Table 1. Observed abundances of elements and isotopes.

Element, or isotope ratio	Where observed	Mass fraction
D/H	Ocean	3×10^{-4}
D/H	Meteorites	3×10^{-4}
D/H	Interstellar gas	$< 1.5 \times 10^{-4}$
He^3/He^4	Meteorites	2×10^{-4}
He	Hot stars	0.4
He	Gaseous nebulas	0.27–0.43
He	Sun	0.27
He	Quasars	$\lesssim 0.1$?
He	Blue halo stars	$\sim 4 \times 10^{-3}$
Li	Meteorites	1×10^{-8}
Li^6/Li^7	Earth	0.1
Be	Meteorites	1×10^{-9}
B	Meteorites	6×10^{-9}
C	Sun	4×10^{-3}
N	Sun	8×10^{-4}
O	Sun	8×10^{-3}
Mg and heavier elements	Sun, meteorites	2×10^{-3}

Since lithium is easily destroyed by proton reactions, and since it can be produced by spallation reactions on carbon, nitrogen, and so on, it is not surprising that its abundance varies greatly among stars. The best value for its abundance appears to be that obtained from meteorites.

In the remainder of Table 1 are listed some elements which are not produced in a big bang. As in the case of Li^7, the nuclei of Li^6, Be^9, B^{10}, and B^{11} can be destroyed in deep convective stellar atmospheres or produced by spallation, and so meteoritic or terrestrial data are used. The abundances given for carbon, nitrogen, oxygen, and heavier metals are those for the sun, but these elements are as much as ~ 100 times less abundant in some old stars.

In comparing these abundances with the calculated results of a big-bang universe, the first fact to be realized is that none of the three factors mentioned allows significant production of nuclei other than deuterium, He^3, He^4, and Li^7. The densities are too low in the relevant temperature range. It is therefore safe to say that stellar nucleosynthesis, such as outlined in the work of the Burbidges, Fowler, and Hoyle (*1*), has produced many of the heavier elements. However, the hypothesis that a massive star or stars exploded during the formation of the Galaxy may be required to account for the small abundances of heavy elements seen in the oldest stars (*19*). In fact, the massive star may have been the Galaxy itself in the process of birth, as Ambartsumian (*40*) and others have suggested.

However, the production of Li^6, beryllium, and boron can be due to neither universal nor stellar synthesis. The most probable mechanism is spallation reactions of protons on carbon, nitrogen, and oxygen, due to particle acceleration in stellar atmospheres. This conclusion is supported by the observation that the Li^6/Li^7 ratio observed in many stars having high abundances of lithium (*41*) is that expected from spallation. This leads to the important question of whether the deuterium, He^3, and Li^7 observed could have also been produced in this way. From what is known about the relevant cross sections and expected fluxes, it appears possible that the observed He^3 and lithium could have been produced along with the beryllium and boron. Production of the deuterium appears to require more elaborate processes, however.

A further remark is necessary. Study of the gas and stars in our galaxy indicates that much of the material of the solar system has passed through a previous generation of stars (*42*). Therefore, any primordial deuterium, He^3, or Li^7 now present in the solar system would have existed originally in greater abundance. It is difficult to determine this depletion factor, however.

Thus, theoretical and observational uncertainties hinder us at present from determining with confidence the composition of the primordial gas from which the Galaxy formed. Some upper limits can be set, however. Clearly needed are improved observations of abundances in the oldest stars and further attempts to detect elements in interstellar and even intergalactic regions. In interpreting the observations of old stars, the possibilities of accretion, spallation, and mixing with deep layers must be considered.

Remembering these uncertainties, let us now evaluate the results of the various cosmologies. Since He^4 is the critical nucleus, the discussion centers upon its abundance. Deuterium is probably the next most critical nucleus.

We consider first the abundances produced in a general relativistic, nondegenerate, and isotropic universe, given in Fig. 4. The most notable feature is the fact that the He^4 production varies only from 20 to 30 percent over the entire range of permissible values of h. The solar value falls in this range, and, indeed, the choice $h = 7 \times 10^{-6}$ produces the solar-system abundances of deuterium, He^3, and He^4, within the errors of observation and interpretation. A slightly higher value of h would be required to produce the observed solar-system abundance of Li^7. The present density of such a universe would be 2×10^{-31} gram per cubic centimeter, a density agreeing roughly with that of visible matter.

Although such a universe agrees with many of the observations, the abundance determinations of helium in some objects other than the sun cast serious doubt on its validity. The range of higher helium abundances indicates that processes within the Galaxy may have produced the helium, while the presence of the helium-poor halo stars also suggests that there was little, if any, helium present before the Galaxy formed. The observations of very low helium abundance are especially important, since He^4 is not easily destroyed. We therefore conclude that, if surface processes have not depleted the helium in these halo stars, and if our initial assumptions are valid, then at least one of the following statements must be true:

1) The universe was highly anisotropic in the past.

2) The correct theory of gravitation is not general relativity.

3) Most of the mass of the universe was not in the form of known particles during element building.

4) The universe contains degenerate neutrinos.

Of the two possibilities which could lead to a reduction in helium production, let us first investigate the effect of the expansion rate, illustrated in Fig. 6. It may be seen that both slower and faster rates can reduce the helium abundance by any amount. However, the faster rates are the more probable because almost all other known reasonable models produce a fast rate of expansion. An important point, however, is the fact that requiring that the deuterium abundance be less than the interstellar upper limit requires very fast expansion rates, and results in the production of essentially nothing but deuterium in this case. Of course, the small amount of helium observed could be due to production in short-lived massive stars which formed and exploded before any of the now-observable stars had condensed. This hypothesis is supported somewhat by the fact that no star has ever been observed to contain no heavy elements.

When we turn to the other possibility, illustrated in Fig. 5, it appears that a reduction in helium abundance due to antineutrino degeneracy ($L_{\nu\nu} \ll -10^7$) results in production of too much deuterium to agree with observations. Choosing other values of h could not lower it sufficiently unless all but ~ 1 percent of the deuterium had been cycled through stars, while increasing the number of antineutrinos would result in a deceleration parameter larger than the observed upper limit. On the other hand, the presence of degenerate electron neutrinos could drastically reduce the abundances of He^4, while leaving those of deuterium and He^3 virtually unchanged. For instance, a universe in which, today, $\rho_b \approx 3 \times 10^{-31}$ gram per cubic centimeter and $L_{e\nu} \approx 2 \times 10^9$ would produce the present solar-system abundances of deuterium and He^3 (but not Li^7) and the abundance of He^4 seen in the halo stars. Of course, higher values of $L_{e\nu}$ which virtually eliminate element production are also consistent with the observations. A possibility for reconciling the slightly disturbing discrepancy between the observed density of visible matter and the density required to produce the observed deceleration of galaxies (a density which, however, is poorly known) is the presence of such neutrinos. The amount required to reconcile the discrepancy ($10^{11} \lesssim L_{e\nu} \lesssim 10^{13}$) would produce such a pure hydrogen universe. It should be mentioned that other cosmologies not contained within our initial assumptions, such as a steady-state universe (*4*) or a universe which began from temperatures $\lesssim 10^{11}$ deg K, would also allow no synthesis.

The presence of more electron leptons than antileptons in the universe would not be too surprising, in view of the fact that there is some evidence that the net baryon number is positive. This positive net number suggests the possibility that baryons were created during an extremely high density phase ($\rho \gtrsim 10^{49}$ grams per cubic centimeter), in which one might expect gravitational effects on particle structure to be important (*43*). If the net lepton number was established in the same process, many more leptons than baryons would have had to be created in order for the present-day abundance of helium to be less than 20 percent. Since the creation mechanism itself is completely unknown, this does not seem to be a particularly unlikely possibility.

Summary

Two recent observations appear to have provided critical information about the past history of the universe. The thermal character of the microwave background radiation suggests that the universe has expanded from a state of high temperature and density, and places constraints on such a big-bang cosmology. The observations of very weak helium lines in the spectra of certain stars in the halo of our galaxy are possibly due to a low primeval abundance of this element. However, the simplest model of a big-bang cosmology leads to much higher helium abundances, such as are observed in the solar system and in many stars. The production of helium can be reduced either by altering the early expansion rate or by introducing degenerate electron neutrinos. Observations of interstellar and intergalactic deuterium and He^4, and possibly even He^3 and Li^7, are needed to test the various models.

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