current. Therefore, the proposal made in Ref. 2, of abandoning the identification of the group generators with integrals of local currents, should be understood in the sense that one must renounce either the local commutativity of the transformed field, or its transformation law under the Poincaré group being the same as for the original field.

(c) One might argue about the necessity of working with interpolating fields; however, the Hall-Wightman theorem applies just as well to the asymptotic fields. Thus it is possible to find a unitary representation of the transformation $\mathcal{T}$ for the asymptotic ("in" or "out") fields if and only if the masses show the degeneracy imposed by exact symmetry under $\mathcal{T}$.

(d) It is possible to drop the hypothesis of a unique vacuum. This would allow for a "spontaneous breakdown" of an exact symmetry, as suggested by many authors.[6] However, in this case one is faced with the well-known problem of the massless particles,[7] unless one is prepared to renounce the idea that the symmetry is generated by conserved currents.[8]

We are grateful to Professor L. A. Radicati for useful discussions on this subject.

---

[1]B. W. Lee, Phys. Rev. Letters 14, 676 (1965); R. Dashen and M. Gell-Mann, Phys. Letters 17, 142 (1965).

[2]S. Coleman, Phys. Letters 19, 144 (1965).

[3]R. F. Streater and A. S. Wightman, PCT, Spin and Statistics, and All That (W. A. Benjamin, Inc., New York, 1964).

[4]S. Coleman, to be published.

[5]D. Hall and A. S. Wightman, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 31, No. 5 (1957). See also Ref. 3, pp. 162-167.

[6]Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345 (1961); M. Baker and S. L. Glashow, Phys. Rev. 128, 2462 (1962). For a discussion from the axiomatic point of view, see R. F. Streater, Proc. Roy. Soc. (London) A287, 510 (1965).

[7]R. F. Streater, Phys. Rev. Letters 15, 175 (1965).

[8]J. Łopuszański and H. Reeh, Phys. Rev. 140, B926 (1965).

PRIMEVAL HELIUM ABUNDANCE AND THE PRIMEVAL FIREBALL*

P. J. E. Peebles

Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 7 February 1966)

We have now a second point[1] on the spectrum of the microwave background,[2] and it is consistent with the idea[3] that this is black-body radiation, the primordial fireball left over from the "big bang." If this is confirmed by further observations at shorter wavelengths we will have learned the present temperature of the universe, and we will be able to trace back from this temperature to find something about the history of the universe. At an early stage in the expansion of the universe, thermal reactions would have produced deuterium and helium: This is the old big bang theory of the formation of the elements. The purpose of this note is to present the results of a recent calculation of the primeval element abundances issuing from the big bang. These depend on two observable quantities, the temperature of the fireball radiation and the mean mass density in the universe. The abundances are high enough that an observational test appears quite possible. The details of the calculation will be described elsewhere.

The computed helium and deuterium abundances are shown in Fig. 1. The best estimate for the mean mass density in the universe would be in the range 7×10^{-31} g/cm^3 (the estimated mass in galaxies[4]) to 2×10^{-29} g/cm^3 (the mass density required to close the universe). For this density range, if the present temperature of the fireball is 3°K,[1,2] the computed primeval helium abundance is 27 to 30% by mass. If the average mass density in the universe were a factor of 30 below the accepted estimate of the mass in galaxies, it would lead to a much lower primeval helium abundance.

It would be very interesting to compare the helium abundances in Fig. 1 with the composition of the oldest stars in our galaxy, but at present very little is known about the helium abundance in these stars. From the composition of solar cosmic rays and spectroscopic heavy-element abundances, and from solar models, the helium abundance in the sun is thought to be about 25% by mass,[5] and an abundance as high as 30% would not be excluded.

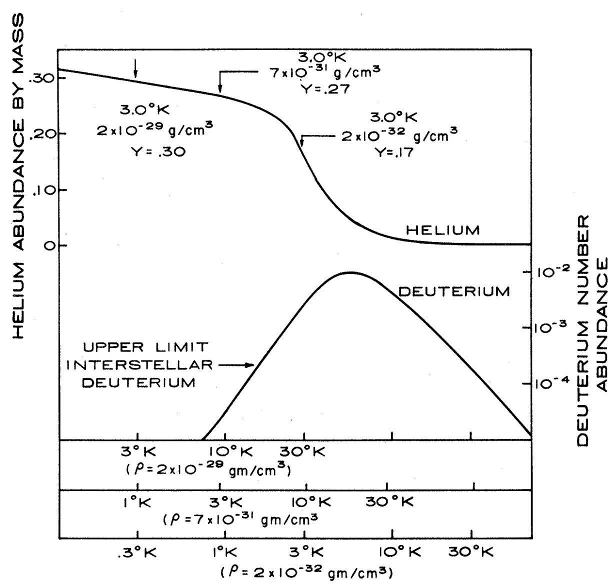

FIG. 1. Helium and deuterium production in the early universe. The abundances are given as functions of the temperature of the primordial black-body radiation in the present universe. The three scales for the radiation temperature correspond to three different assumptions about the mean mass density in the present universe.

An important question here is whether the solar helium abundance could be accounted for by production in earlier generations of stars. It has been emphasized that the present rate of hydrogen burning in the galaxy is not enough to produce this much helium over the lifetime of the galaxy, possibly indicating a high primordial helium abundance.[6] Also, the rapidly evolving massive stars which would have produced the elements in the solar system actually may produce less helium than heavier elements,[7,8] implying a helium production less than the heavy-element abundance, roughly 2% by mass. On the other hand, we know from the rapid increase of heavy elements through the population-II stars that the early galaxy was much more active than it is now, and stellar evolution theory is not well enough established to exclude a high rate of helium production in massive stars in the young galaxy. The high initial helium abundance required by the theory therefore remains quite possible, but it appears that a definite test of the theory must await improved observational evidence.

The deuterium abundance shown in Fig. 1 can exceed the upper limit on the abundance of interstellar deuterium,[9] but deuterium would have been burned out of the hydrogen in the cycling of material through stars. Since we thus can imagine deuterium being produced or destroyed in the galaxy, with the present state of knowledge the deuterium abundance cannot provide a very clear test either for or against the theory. The computed He^3/He^4 abundance ratio is somewhat less than the abundance ratio found in primordial gas in meteorites, so apparently it should be assumed that some He^3 was produced in the galaxy. There appear to be no reactions capable of producing appreciable amounts of elements heavier than helium.

The abundances in Fig. 1 were obtained with two basic assumptions; that general relativity is valid, and that the universe may be treated as homogeneous and isotropic. It has been pointed out[10] that if we relaxed the condition of isotropy, and allowed a homogeneous shear motion, the expansion time scale in the early universe could be decreased almost at will. This is an important point, but there is a general difficulty with the idea that the early universe may have been highly anisotropic, or irregular. We know from galaxy counts and red-shift observations that the universe is, in the large, homogeneous and isotropic about us out to a red shift of perhaps $Z=0.2$. Assuming that the new microwave background is the primordial fireball, we have also a measure of isotropy at a much larger distance. If the early universe were highly anisotropic it would require a very special choice of the free parameters of the solution to assure a nearly isotropic universe now. Given the freedom of starting with a highly anisotropic universe it is difficult to believe that these parameters would have been just such as to present us now with an isotropic universe. More generally, if we introduced any appreciable perturbation to the expansion time scale or density distribution in the early universe, we must expect that the perturbations would only grow worse with time. There do exist solutions in which the perturbations grow smaller, but, just as in conventional perturbation problems, we would never expect to observe a decaying perturbation when a growing perturbation exists, because it would require so very special initial conditions.

Element production in the big bang is based on the idea[11] that if we can trace the expansion of the universe back to a temperature well above

10^{10} °K (1 MeV), we find that the thermal pair-production reactions flood space with electron and neutrino pairs, and these leptons react with nucleons, the most important reactions being

$$p+e^- \leftrightarrow n+\nu, \quad (1)$$

$$p+\bar{\nu} \leftrightarrow n+e^+. \quad (2)$$

The resulting neutron abundance was first computed in detail by Alpher, Follin, and Herman.[12]

The neutrons can react with protons to form deuterium, but photodissociation keeps the abundance very low until the temperature has dropped to about 10^9 °K. The amount of element formation thus depends on the nucleon density in the universe when the temperature has dropped to 10^9 °K. On the plateau at the left-hand side of the helium abundance curve in Fig. 1, almost all the neutrons which survive to the time nuclear burning becomes possible react to form deuterium, which burns to helium. The helium abundance increases slowly with decreasing temperature because fewer neutrons decay before nuclear reactions commence. For a high primordial fireball temperature the nucleon density would be low when nuclear burning could begin, so little deuterium or helium would be produced. The deuterium abundance is maximum at the shoulder of the helium curve: In a hotter universe little deuterium is produced, and in a colder universe a good deal of deuterium is produced but most of it burns to helium.

The rate of expansion of the universe depends on the energy density and pressure of the electromagnetic radiation, electron pairs, and the two kinds of neutrinos. It may be assumed that these all are in thermal equilibrium in the early universe, but when the electron pairs recombine, at 10^{10} °K, the energy goes into radiation, and the radiation temperature ends up higher than the neutrino temperature by the factor $(11/4)^{1/3}$.

The reaction rates for (1) and (2) were obtained from the $V-A$ theory, neglecting electromagnetic corrections, and the coupling constants taken from a recent review.[13] The electron density was computed using the free-particle approximation. The half-life for neutron decay was taken to be 11.7 min, with no correction for partial degeneracy of the electrons and neutrinos because by the time any appreciable number of neutrons can decay the partial degeneracy extends to an energy well less than the decay energy. For the same reason we can neglect the three-body reaction which is the reverse of neutron decay. From a numerical integration taking account of (1), (2), and neutron decay, the neutron abundance was found to be consistent within 5% with the previous calculation of Alpher, Follin, and Herman.[12]

The important nuclear reactions are[14] $n+p \rightarrow d+\gamma$, $d+d \rightarrow He^3+n$, $d+d \rightarrow t+p$, $He^3+n \rightarrow t+p$, and $t+d \rightarrow He^4+n$. There are many other possible reactions, but for conditions of interest none would appreciably affect the final deuterium abundance. In some cases the He^3 abundance would be lowered if we took account of other He^3-burning reactions. With regard to the He^4 abundance, we know quite generally that it is a question of how completely the nuclei can relax to thermal equilibrium. The introduction of any new nuclear reactions could only increase the relaxation rate, and so increase the final abundance of helium (or heavier elements).

The experimentally determined reaction cross sections were fitted to simple formulas, the cross section taken to be inversely proportional to velocity for the neutron-capture reactions and a formula of the Gamow type assumed for the charged-particle reactions, and the results numerically integrated against a Maxwell velocity distribution to obtain the reaction rates. The six differential equations for the abundances, taking account of reactions (1) and (2), neutron decay, the above mentioned nuclear reactions, and the reverse of each of these reactions, were numerically integrated from an initial temperature of 10^{12} °K, through the completion of nuclear burning. The results of a typical integration are shown in Fig. 2.

If the universe contains gravitational radiation, or perhaps a new kind of neutrino field, the time scale for expansion is reduced. This increases the neutron abundance coming out of the bang, and so raises the level of the plateau on the left-hand side of the helium-abundance curve in Fig. 1. If we introduce new radiation energy density equivalent to a new kind of (two-component) neutrino field, the resulting helium abundance by mass is increased from 0.30 to 0.32. The additional radiation also moves the shoulder of the curve to the left, the radiation temperature at the shoulder varying inversely as the sixth root of the total energy density in the form of primeval radia-

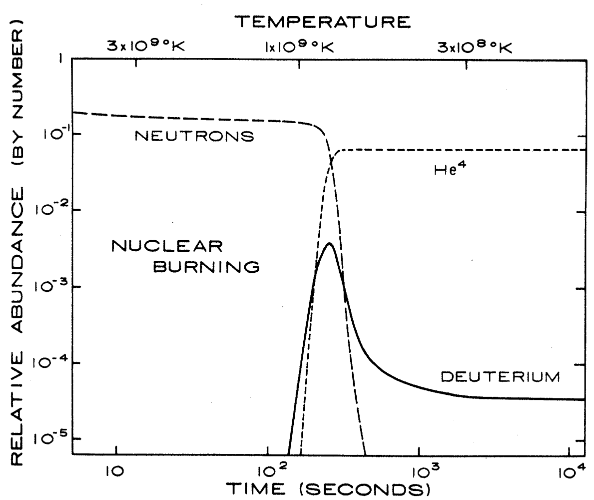

FIG. 2. Abundances of the elements versus time. It is assumed here that the present primordial fireball radiation temperature is 3.5°K and the present mean mass density in the universe is 7×10^{-31} g/cm^3.

tion and neutrinos. Assuming that the nucleon mass density now is at least 7×10^{-31} g/cm^3, with the addition of an amount of radiation consistent with the limits implied by the acceleration parameter the first effect is more important, and the primeval helium abundance is increased.

For a reasonable value of the mean mass density in the universe we have concluded that the theory requires a large primeval helium abundance, and if this agrees with observation it must be considered a remarkably stringent test of general relativity. On the other hand, if the primeval helium abundance is found to be low, and the presence of the 3°K primordial fireball confirmed, we believe that the result will be difficult to explain on the basis of conventional general relativity.

It is a pleasure to acknowledge fruitful discussions of this problem with R. H. Dicke, D. T. Wilkinson, P. G. Roll, and R. J. Tayler.

---

*This research was supported in part by the National Science Foundation and the Office of Naval Research of the U. S. Navy.

[1]P. G. Roll, and D. T. Wilkinson, Phys. Rev. Letters 16, 405 (1966).

[2]A. A. Penzias and R. W. Wilson, Astrophys. J. 142, 420 (1965).

[3]R. H. Dicke, P. J. Peebles, P. G. Roll, and D. T. Wilkinson, Astrophys. J. 142, 414 (1965).

[4]J. H. Oort, Onzieme Conseil de I'Institut International de Physique Solvay, La Structure et l'Evolution de l'Univers (Editions Stoops, Brussels, 1958), p. 163; S. van den Bergh, Z. Astrophys. 53, 219 (1961).

[5]J. Gaustad, Astrophys. J. 139, 406 (1964).

[6]F. Hoyle and R. J. Tayler, Nature 203, 1108 (1964).

[7]C. Hayashi, in Origin of the Solar System: Proceedings of a Conference held at the Goddard Institute for Space Studies, New York, 1963, edited by R. Jastrow and A. G. W. Cameron (Academic Press, Inc., New York, 1963).

[8]J. W. Truran, C. J. Hansen, and A. G. W. Cameron, to be published.

[9]R. L. Adgie, Paris Symposium on Radio Astronomy, edited by R. Bracewell (Stanford University Press, Stanford, California, 1958), p. 352.

[10]R. Kantowski and R. Sachs, to be published.

[11]C. Hayashi, Progr. Theoret. Phys. (Kyoto) 5, 224 (1950).

[12]R. A. Alpher, J. W. Follin, and R. C. Herman, Phys. Rev. 92, 1347 (1953).

[13]G. Källén, Elementary Particle Physics, (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1964), p. 353.

[14]E. Fermi and A. Turkevich, in work described by R. A. Alpher and R. C. Herman, Rev. Mod. Phys. 22, 193 (1950).