(1954).

[7]T. Bates, in *Modern Aspects of the Vitreous State*, edited by J. D. MacKenzie (Butterworths, London, 1962), Vol. 1.

[8]For one sharp level, Eq. (1) takes the form $R=1+\rho^2F(\epsilon)$. Curves on Fig. 2(c) are of this form. Adding contributions from two levels and maintaining the form of Eq. (1) requires subtraction of 1.

[9]$\Delta\omega>0$ implies that $|V|^2\rho(\omega)$ peaks below $\omega(R)$, i.e., for $\omega<\omega(R)$.

[10]M. Blume and R. E. Watson, Proc. Roy. Soc. London, Ser. A 271, 565 (1963).

Helium Synthesis, Neutrino Flavors, and Cosmological Implications

F. W. Stecker
Laboratory for High Energy Astrophysics, National Aeronautics and Space Administration Goddard Space Flight Center, Greenbelt, Maryland 20771
(Received 10 December 1979)

The problem of the production of helium in the big bang is reexamined in the light of several recent astrophysical observations. These data, and theoretical particle-physics considerations, lead to some important inconsistencies in the standard big-bang model and suggest that a more complicated picture is needed. Thus, recent constraints on the number of neutrino flavors, as well as constraints on the mean density (openness) of the universe, need not be valid.

PACS numbers: 98.80.Ft, 95.30.Cq, 98.80.Bp

It has recently been claimed that the "standard" big-bang scenerio for cosmological helium production imposes a stringent limit on the number of neutrino flavors.[1] Recent astronomical evidence and theoretical particle-physics considerations discussed here suggest, however, that inconsistencies of a serious nature may be present within the standard scenerio and that, until the cosmological questions have been resolved, it may be more useful to adhere to the conventional view that physics imposes constraints on cosmology rather than vice versa.

It is useful to assume that the observed helium abundance by weight Y in a source consists of universal "primordial" contribution Y_p and a contribution ΔY from ordinary stellar nucleosynthesis. Stellar evolution theory suggests that $\Delta Y>0$ and that, furthermore, $\Delta Y\propto Z$, the abundance of heavier elements not made in the big bang. Thus $Y_p\leq\min\{Y_{\rm obs}\}$, the set of reliable observed astronomical helium abundances. Reported values of Y in our own and other galaxies range from 0.228 to 0.342, a 50% variation within star systems having undergone differing rates of stellar nucleosynthesis.[2-4] Studies of helium abundances in H II regions of blue compact and irregular galaxies yield lower values of Y because, as their large gas-to-total-mass ratios and small dust-to-gas ratios and Z values indicate, they have experienced less star production and stellar evolution. Of these systems, the most highly and reliably studied are the nearby Large and Small Magellanic Clouds (LMC, SMC).[2,5] Recent measurements of such galaxies, correlating ΔY with Z have suggested as value for $Y_p=0.228\pm0.014$ (3 standard deviations). If the high-quality data from the Orion nebula (our own galaxy) and the LMC alone are used, a value $Y_p=0.218$ is obtained.[2] If one takes account of the fact that abundances as low as 0.228 have been reported for three galaxies,[3,4] by taking for one of them, IIZw40, the reported[4] $Z=0.0041$ and using the well-substantiated relation $\Delta Y\simeq 3Z$, a value for $Y_p=0.216$ would be obtained. Thus, we consider the conservative value[4] $Y_p=0.228$ to be an upper limit on Y_p (see Fig. 1).

Independent estimates of Y_p can be obtained from other astronomical quarters. Closer to home in our own galaxy, it should be noted that while the Orion region[4] has a value for Y of 0.280 ± 0.010, this region is young and has seen multiple generations of stellar nucleosynthesis. The oldest stars in our own galaxy have significantly lower Y values. Horizontal-branch stars in globular clusters are extremely poor in He, at least in their surface atmospheres[6] and, most recently, data from very old subdwarf stars[7] have indicated values of $Y=0.19\pm0.02$. Models of nucleosynthesis in the Sun require a very low initial abundance of He and heavier elements in order to attain consistency with the low observed solar-neutrino flux.[8] Such models again require that $Y \sim 0.1-0.2$. Finally, there is evidence that quasars (at least 3C273 and 3C48, which have been studied) are deficient in helium abundance relative to our galaxy by at least a factor of 2.[9] All of these data are consistent with the upper limit on Y_p used in Fig. 1.

Two other observations bear on the He-production problem. The first comes from x-ray studies of the intergalactic gas in galaxy clusters where iron abundances averaging about half the local value (and in some cases approaching the solar value) have been observed in the intergalactic medium.[10] This may indicate that a significant active period characterized by a high rate of stellar nucleosynthesis and gas ejection occurred at an early stage in the galactic or protogalactic era in the evolution of the universe. Suggestions of this sort have been made in the past[11] and they may be lent support with the recent advent of far-infrared measurements near the peak of the cosmic background blackbody-radiation spectrum.[12] These recent data indicate an excess radiation density at present of 1.14 eV/cm^3 above that expected from a 2.7-K blackbody spectrum, a value far in excess of that expected within the standard scenario.[13] Under the hypothesis that a significant far-infrared background arises from dust reradiation which is superimposed on the 2.7-K

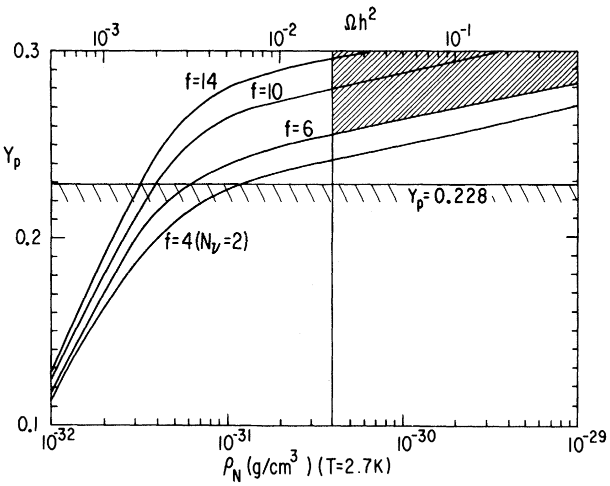

FIG. 1. Helium abundance Y_p from big-band nucleosynthesis vs present mean nucleon density ρ_N for quark flavor numbers f (Ref. 1). The null intersection of the independent data sets indicated by the cross-hatched area and upper-limit line $Y_p = 0.228$ shows the basic inconsistency in the standard scenario.

background, fits to the observations may be obtained.[14] Such models require that the excess radiation orginate at a redshift $z_n \sim 10-15$. If the energy originated in He synthesis, which releases an energy of 7 MeV/nucleon, the number ratio of He to H which would have been produced is

$$R_{\mathrm{He/H}} = 5\times 10^{-4}\Omega^{-1}h^{-2}(1+z_n), \qquad (1)$$

where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} (1 Mpc = 1 megaparsec) and Ω is the fraction of the closure density in the standard big-bang model. The value of h is in the range 0.5–1 with more recent results[15] tending to favor a value near 1. It follows from Eq. (1) that the values of Y produced at redshift z_n under these assumptions are too high (0.8–0.9) for $\Omega h^2 = 0.01$, and are only negligible (0.02–0.03) for $\Omega h^2 \simeq 1$. However, the latter case, while giving only a small contribution to the observed value of Y, is inconsistent with the standard big-bang nucleosynthesis model, since this model requires $\Omega h^2 \ll 1$. Another contradiction with the standard model is then implied by recent analyses of the dynamics of galaxy clustering[16] which yields values for Ω in the range 0.2–0.7.

The above discussion leads to the conclusion that we may consider the value $Y_p \simeq 0.23$ to be an upper limit on big-bang nucleosynthesis (Fig. 1), with other data giving even lower values for Y_p and with the x-ray and infrared data suggesting the additional possibility that even only a small portion of this may be left over from the first three minutes of the big bang. We now turn to the important implications of this conclusion.

Figure 1, based on the calculations in Ref. 1, shows the values of Y_p obtained under various assumptions regarding the number of flavors of neutrinos with masses below 1 MeV. We know, of course, that there are at least two flavors, ν_e and ν_μ, presumably of zero mass since present evidence is consistent with the absence of right-handed neutrinos. Although there is at present only an upper limit of ~250 MeV on the mass of the ν_τ associated with the decay of the newly discovered τ lepton, it is generally considered that $(\nu_\tau, \tau)_L$ and the $(t, b)_L$ quarks make up Weinberg-Salam SU(2) doublets which fit grand-unification-theory SU(5) multiplets, e.g., $\overline{5} = (\nu_\tau, \tau | \overline{b})_L$, in which case the symmetry breaking caused by the Higgs sector will leave the ν_τ with a zero mass as is the case with the other neutrinos. Thus, in Fig. 1, we can consider the curve $f = 6$, corresponding to six quark flavors and three neutrino flavors $(\nu_e, \nu_\mu, \nu_\tau)$ to define a lower bound on Y_p

as predicted by the standard model. In the figure, the vertical line at $\Omega h^2 = 0.02$ ($\rho_N = 4\times 10^{-31}$ g/cm^3) indicates, as per the dynamical and observational arguments outlined earlier,[17] a conservative lower limit obtained by taking $\Omega \geq 0.08$ and $h^2 \geq 0.25$. The allowed region in the figure is indicated by the crosshatching. This obviously conflicts with the upper limit $Y_p = 0.228$ discussed above. Thus it appears that a reexamination of the orthodox He-synthesis picture is in order.

It may appear that one way out of the difficulty is to postulate a nonnucleonic dynamical mass density from hypothetical stable neutral heavy leptons extant in the universe.[18] Such particles may not be detectable by other means.[19] However, the motivation for considering the existence of heavy neutrinos,[20] namely, the consideration of a SU(3)⊗U(1) theory of electroweak interactions,[21] has now disappeared as it has become evident that the minimal SU(2)⊗U(1) model of Weinberg and Salam provides the best explanation of experimental results.[22] It has also been suggested that light neutrinos could make up the missing mass needed to explain galaxy dynamics.[23] This hypothesis has been recently advocated,[24] but other recent calculations claim inconsistencies which argue against it, particularly for large neutrino-mass densities and smaller values of h, which are needed in order to "solve" the helium problem with this scenario.[25]

I therefore conclude that if one wishes to explain *all of the cosmological data*—viz., the dynamical studies of the mean mass density in the universe, the low values of Y observed in less-evolved galaxies, the variation of Y from one galaxy to another, and the possible evidence of high-redshift nucleosynthesis—the simplest big-bang model for helium production may be untenable. Bearing this in mind, together with the consideration (Fig. 1) that the three-neutrino (or even the *two*-neutrino) case may be inconsistent with the data, the cosmological arguments to discourage consideration of the possibility of additional undiscovered neutrino flavors appear unjustified. In judging theories with more than six quark flavors, physics considerations should thus outweigh arguments based on the standard cosmological scenario. In this regard, it should be noted that recent work[26] has indicated that the use of renormalization-group methods in the SU(5) grand unification scheme, twelve quark flavors are required to explain the mass ratio of the b quark and τ lepton, i.e., m_{T}/m_τ. (This is still consistent with the requirements of asymptotic freedom.)

One is still left with the problem of replacing the orthodox helium-synthesis model with a different (and clearly more complicated) model. One possible scenario will be suggested here. Let us assume that the standard big-bang nucleosynthesis does take place as in Fig. 1. Then with $f \geq 6$ and $\Omega h^2 \geq 0.02$, too much He is produced. Also considering that significant protogalactic nucleosynthesis may take place, we must then propose a means for destroying either some or all of the He made in the big bang. Within the context of standard cosmology, no effective destruction mechanism suggests itself. However, in the context of the baryon-antibaryon domain model, a model which we have argued follows from the concepts of spontaneous symmetry breaking of grand unified gauge theories and causality,[27] an effective destruction mechanism exists. This mechanism is photodisintegration of He by radiation produced by N-$\bar{N}$ annihilation in the early big bang.[28] Subsequent protogalactic and galactic nucleosynthesis might then play an important role in He production.[11, 14]

Since the standard big-bang He-synthesis model, when considered with the other data summarized above, leads to too much helium production, any nonminimal scenario which provides a consistent picture of He synthesis will invalidate previous arguments constraining both the number of neutrino flavors and the mean density (or openness) of the universe.[29]

The author would like to thank Sheldon Glashow for discussions which suggested and motivated this paper and David Layzer, Jim Peebles, and Robert Shrock for helpful discussions regarding various aspects of this work.

[1]G. Steigman, D. N. Schramm, and J. Gunn, Phys. Lett. 66B, 202 (1977); J. Yang, D. N. Schramm, G. Steigman, and R. T. Rood, Astrophys. J. 227, 697 (1979).

[2]M. Peimbert and S. Torrez-Peimbert, Astrophys. J. 193, 327 (1974).

[3]E. M. Burbidge and G. R. Burbidge, in *Proceedings of the Symposium on H II Regions and Related Topics, Mittelberg, Germany,* edited by T. L. Wilson and D. Downes, Lecture Notes in Physics (Springer, Berlin, 1975), and references therein.

[4]J. Lequeux, M. Peimbert, J. F. Rayo, A. Serrano, and S. Torres-Peimbert, Astron. Astrophys. 80, 155 (1979).

[5]B. Bok, Annu. Rev. Astron. Astrophys. 4, 95 (1966); J. Borgman, R. J. van Duinen and J. Koorneef, Astron.

Astrophys. 40, 461 (1975); S. C. B. Gascoigne, Mon. Not. Roy. Astron. Soc. 166, 25P (1974); R. X. McGee and J. A. Milton, Aust. J. Phys. 19, 343 (1966); J. V. Hindmann, Aust. J. Phys. 20, 147 (1967).

[6]J. L. Greenstein and G. Münch, Astrophys. J. 146, 618 (1966); E. B. Newell, Astrophys. J. 159, 443 (1970).

[7]B. W. Carney, Astrophys. J. 233, 877 (1979).

[8]J. N. Bahcall, W. F. Huebner, N. H. Magee, A. L. Mertz, and P. K. Ulrich, Astrophys. J. 184, 1 (1973); M. J. Newman and R. J. Talbot, Nature (London) 262, 559 (1976); I. Iben, Jr., and J. Mahaffy, Astrophys. J. 209, L39 (1976); G. R. Isaak, Nature (London) 283, 644 (1980).

[9]D. E. Osterbrock and R. A. R. Parker, Astrophys. J. 143, 268 (1966); J. N. Bahcall and B.-Z. Kozlovsky, Astrophys. J. 158, 529 (1969).

[10]R. F. Mushotzky, P. J. Serlemitsos, B. W. Smith, E. A. Boldt, and S. S. Holt, Astrophys. J. 225, 21 (1978); R. F. Mushotzky, in Proceedings of the NATO X-Ray Astronomy Institute, Erice, July 1979 (to be published); see also NASA Report No. TM 80559 (unpublished).

[11]D. Layzer and R. Hively, Astrophys. J. 179, 361 (1973); M. Rees, Nature (London) 275, 35 (1978), and references therein.

[12]D. P. Woody and P. L. Richards, Phys. Rev. Lett. 42, 925 (1979).

[13]F. W. Stecker, J. L. Puget, and G. G. Fazio, Astrophys. J. 214, L51 (1977).

[14]J. L. Puget and J. Heyvaerts, to be published.

[15]G. de Vaucoulers and G. Bollinger, Astrophys. J. 233, 433 (1979); M. Aaronson, J. Mould, J. Huchra, W. T. Sullivan, III, R. A. Schommer, and G. D. Bothun, Astrophys. J. (to be published).

[16]P. J. E. Peebles, Astronom. J. 84, 730 (1979); J. Silk and M. L. Wilson, Astrophys. J. 233, 769 (1979); Aaronson *et al.*, Ref. 15.

[17]While Peebles and Aaronson *et al.* (Ref. 15) give a value for Ω of 0.2 to 0.7, we choose as a more conservative value for lower-limit purposes, $\Omega = 0.08$, based on the work of J. R. Gott, III, and E. L. Turner, Astrophys. J. 209, 1 (1976).

[18]G. Steigman, C. L. Sarazin, H. Quintana, and J. Faulkner, Astronom. J. 83, 1050 (1978).

[19]F. W. Stecker, Astrophys. J. 223, 1032 (1978).

[20]B. W. Lee and S. Weinberg, Phys. Rev. Lett. 39, 165 (1977).

[21]B. W. Lee and R. E. Shrock, Phys. Rev. D 17, 2410 (1978).

[22]C. Prescott *et al.*, Phys. Lett. 77B, 347 (1978).

[23]R. Cowsik and J. McClellend, Astrophys. J. 180, 7 (1973).

[24]P. J. E. Peebles, in 1979 Les Houches Summer School lecture notes (unpublished).

[25]S. Tremaine and J. E. Gunn, Phys. Rev. Lett. 42, 407 (1979).

[26]P. H. Frampton, S. Nandi, and J. J. Scanio, Phys. Lett. 85B, 225 (1979).

[27]R. W. Brown and F. W. Stecker, Phys. Rev. Lett. 43, 315 (1979); see also F. W. Stecker, Nature (London) 273, 493 (1978); F. W. Stecker and R. W. Brown, in Proceedings of the Neutrino—79 International Symposium, Bergen, Norway, June 1979 (to be published).

[28]F. Combes, O. Fassi-Fehri, and B. Leroy, Astrophys. Space Sci. 37, 151 (1975).

[29]Other speculated constraints based on the standard model, e.g., those on superweak particles [G. Steigman, K. A. Olive, and D. N. Schramm, Phys. Rev. Lett. 43, 239 (1979)] would also not be valid.