Fermi National Accelerator Laboratory

FERMILAB-Conf-89/254-A
December 1989

Nuclear Physics and Cosmology

David N. Schramm

University of Chicago
5640 S. Ellis Avenue
Chicago, Illinois 60637
and
NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
Box 500
Batavia, Illinois 60510

ABSTRACT

Nuclear physics has provided one of the 2 critical observational tests of all Big Bang cosmology, namely Big Bang Nucleosynthesis. Furthermore, this same nuclear physics input enables a prediction to be made about one of the most fundamental physics questions of all, the number of elementary particle families. This paper reviews the standard Big Bang Nucleosynthesis arguments. The primordial He abundance is inferred from He-C and He-N and He-O correlations. The strengthened Li constraint as well as ^{2}D plus ^{3}He are used to limit the baryon density. This limit is the key argument behind the need for non-baryonic dark matter. The allowed number of neutrino families, N_ν, is delineated using the new neutron lifetime value of $\tau_n = 890 \pm 4s$ ($\tau_{1/2} = 10.3\ min$). The formal statistical result is $N_\nu = 2.6 \pm 0.3$ (1σ), providing a reasonable fit (1.3σ) to 3 families but making a fourth light ($m_\nu \lesssim 10MeV$) neutrino family exceedingly unlikely ($\gtrsim 4.7\sigma$) (barring significant systematic errors either in $D+^3He$, and Li and/or ^4He and/or τ_n). It is also shown that uncertainties induced by postulating a first-order quark-hadron phase transition do not seriously affect the conclusions.

Proceedings of talk delivered at the International Nuclear Physics Conference, Sao Paulo, Brazil, August 20-26, 1989

Nuclear physics in general and neutron lifetime measurements in particular, when coupled with cosmological arguments, have made a definitive prediction about a fundamental number in physics[1,2,3] the number of particle families; or to be more precise, the number of low mass ($m_\nu \lesssim 10MeV$) neutrino families. These predications about the number of neutrino families were one of the first examples of the particle cosmology interface, and are now beginning to be tested with accelerators. This paper reviews those arguments and shows the tightening of the argument as a result of the new more precise neutron lifetime measurements.

Furthermore, it is the nucleosynthetic arguments that are the crux of the arguments for non-baryonic dark matter. These points will be reviewed as well as the possibility that the arguments might be altered if the quark-hadron transition is a first-order phase transition.

The set at quantitative predictions and observations from Big Bang Nucleosynthesis is one of the two prime arguments favoring the Big Bang cosmological model. The other is the 3K background. Furthermore, the nucleosynthesis argument pushes our understanding to ~ 1 sec. after the start of time, whereas the 3K background is checking things relatively late, at $\sim 10^5$ years.

The power of Big Bang nucleosynthesis comes from the fact that essentially all of the physics input is well determined in the terrestrial laboratory. The appropriate temperatures, 0.1 to 1 MeV, are well explored in nuclear physics labs. Thus, what nuclei do under such conditions is not a matter of guesswork, but is precisely known. In fact, it is known for these temperatures far better than it is for the centers of stars like our sun. The center of the sun is only a little over 1 keV. Thus temperatures are below the energy where nuclear reaction rates yield significant results in laboratory experiments, and only the long times and higher densities available in stars enable anything to take place.

To calculate what happens in the Big Bang, all one has to do is follow what a gas of baryons with density ρ_b does as the universe expands and cools. As far as nuclear reactions are concerned, the only relevant region is from a little above 1 MeV down to a little below 100 keV. At higher temperatures, no complex nuclei other than single neutrons and protons can exist, and the ratio of neutrons to protrons, n/p, is just determined by $n/p = e^{-Q/T}$, where $Q = 1.3\ MeV$. is the neutron-proton mass difference. Equilibrium applies because the weak interaction rates are much faster than the expansion of the universe at temperatures much above $10^{10}K$. At temperatures much below 10^9K, the electrostatic repulsion of nuclei prevents nuclear reactions from proceeding as fast as the cosmological expansion separates the particles.

Because of the equilibrium existing for temperatures much above $10^{10}K$, we don't have to worry about what went on in the universe at higher temperatures. Thus, we can start our calculation at $\sim$ 10 MeV and not worry about speculative physics like the theory of everything (T.O.E.), or grand unifying theories (GUTs), as long as a gas of neutrons and protons exists in thermal equilibriuim by the time the universe has cooled to $\sim$ 10 MeV.

After the weak interaction drops out of equilibrium, a little above $10^{10}K$, the ratio of neutrons to protons changes more slowly due to free neutrons decaying to protons, and similar transformations of neutrons to protons via interactions with the ambient leptons. By the time the universe reaches 10^9K (0.1 MeV), the ratio is slightly below 1/7. For temperatures above 10^9K, no significant abundance of complex nuclei can exist due to the continued existence of gammas with greater than MeV energies. Note that the high photon to baryon ratio in the universe ($\sim 10^{10}$) enables significant population of the high energy Boltzman tail until $T \lesssim 0.1\ MeV$. Once the temperature drops to about 10^9K, nuclei can survive and neutron capture on protons yields ^2D. The ^2D rapidly adds neutrons and protons, making ^3T and ^3He. These, in turn, add neutrons and protons to produce ^4He, or ^3T and ^3He and also collide to yield ^4He. Since ^4He is the most tightly bound nucleus in the region, the flow of reactions converts almost all the neutrons that exist of 10^9K into ^4He. The flow essentially stops there because there are no stable nuclei at either mass-5 or mass-8. Since the baryon density at Big Bang Nucleosynthesis is relatively low (much less than 1 g/cm^3), only reactions involving two-particle collisions occur. It can be seen that combining the most abundant nuclei, protons, and ^4He via two body interactions always lead to unstable mass-5. Even when one combines ^4He with rarer nuclei like ^3T or ^3He, we still only get to mass-7, which when hit by a proton, the most abundant nucleus around, yields mass-8. (A loophole around the mass-8 gap can be found if $n/p > 1$ so that excess neutrons exist, but for the standard case $n/p < 1$.) Eventually, ^3T radioactively decays to ^3He, and any mass-7 made, radioactively decays to ^7Li. Thus, Big Bang Nucleosynthesis makes ^4He with traces of ^2D, ^3He, and ^7Li. (Also, all the protons left over that did not capture neutrons remain as hydrogen.) All other chemical elements are made later in stars and in related processes. (Stars jump the mass-5 and -8 instability by having gravity compress the matter to sufficient densities and have much longer times available so that three-body collisions can occur.) A n/p ratio of $\sim$ 1/7 yeilds a ^4He primordial mass fraction,

$$Y_p = \frac{2n/p}{n/p+1} \approx \frac{1}{4}$$

The only parameter we can easily vary in such calculations is the density of the gas that corresponds to a given temperature. From the thermodynamics of an expanding universe we know that $\rho_b \propto T^3$; thus, we can relate the baryon density at $10^{11}K$ to the baryon density today, when the temperature is about 3 K. The problem is, we don't know today's ρ_b, so the calculation is carried out for a range in ρ_b. Another aspect of the density is that the cosmological expansion rate depends on the total mass-energy density associated with a given temperature. For cosmological temperatures much above $10^4 K$, the energy density of radiation exceeds the mass-energy density of the baryon gas. Thus, during Big Bang nucleosynthesis, we need the radiation density as well as the baryon density. The baryon density determines the density of the nuclei and thus their interaction rates, and the radiation density controls the expansion rate of the universe at those times. The density of radiation is just proportional to the number of types of radiation. Thus, the density of radiation is not a free parameter if we know how many types of relativistic particles exist when Big Bang nucleosynthesis occurred.

Assuming that the allowed relativistic particles at 1 MeV are photons, e, μ, and τ neutrinos (and their antiparticles) and electrons (and positrons), we have calculated the Big Bang Nucleosynthetic yields for a range in present ρ_b, going from less than that observed in galaxies to greater than that allowed by the observed large-scale dynamics of the universe. The ^4He yield is almost independent of the baryon density, with a very slight rise in the density due to the ability of nuclei to hold together at slightly higher temperatures and at higher densities, thus enabling nucleosynthesis to start slightly earlier, when the baryon to photon ratio is higher. No matter what assumptions one makes about the baryon density, it is clear that ^4He is predicted by Big Bang Nucleosynthesis to be around 25% of the mass of the universe. This was first noted by Hoyle and Taylor[4] and later found by Peebles[5] and by Wagoner *et al.*[6]. The current results do not differ in any qualitative way from Wagoner *et al.* (see Figure 1).

The fact that the observed helium abundance in all objects is about 20-30% was certrainly a nice confirmation of these ideas. Since stars produce only a yield of 2% in all the heavy elements combined, stars cannot easily duplicate such a large yield. While the predicted Big Bang yields of the other light elements were also calculated in the 1960s, they were not considered important at that time, since it was assumed in the 1960s that these nuclei were made in more significant amounts in stars[7]. However, work[8] by our group in the U.S., as well as Reeves and Audouze and their collaborators in Paris, thoroughly established Big Bang Nucleosynthesis and enabled it to be a tool for probing the universe, as opposed to a consistency check. This was done by showing that other light-element abundances had major contributions from the Big Bang, and that the effects of stellar contributions, where relevant, could be removed by appropriate techniques to obtain constraints on the Big Bang yields for those isotopes. Thus, Big Bang predictions for all the four light isotopes are now very relevant.

STANDARD BIG BANG NUCLEOSYNTHESIS

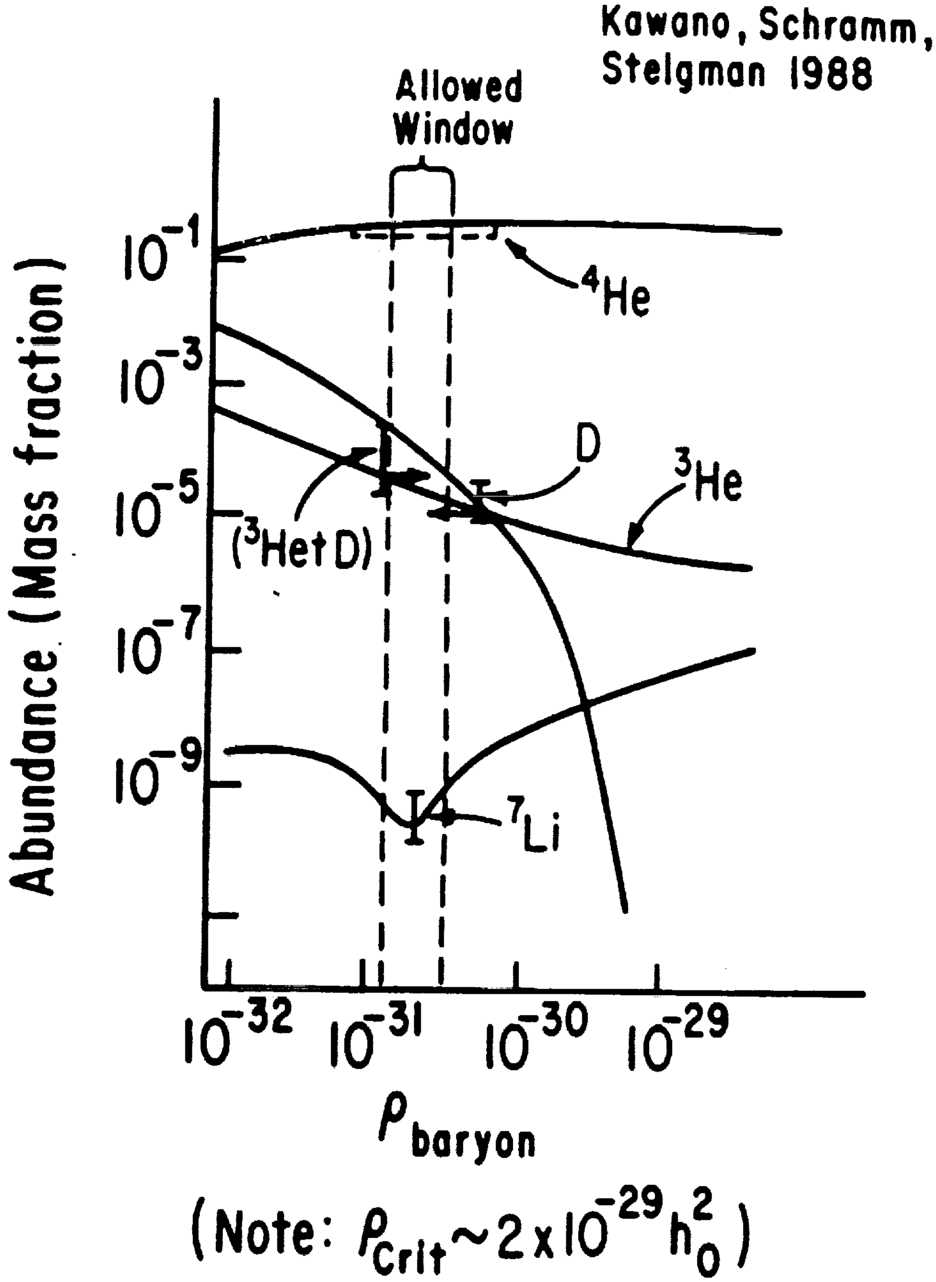

Figure 1. Big Bang Nucleosynthesis abundance yields versus baryon density for a homogeneous universe.

In particular, it was demonstrated in the early 1970s that contrary to the ideas of the 1960s, deuterium could not be made in any significant amount by *any* astrophysical process other than the Big Bang itself[9]. The Big Bang deuterium yield decreases rapidly with an increase in ρ_b. Since at high densities the deuterium gets more completely converted to heavier nuclei, this quantitatively means that the present density of baryons must be below $\sim 5 \cdot 10^{-31} g/cm^3$ in order for the Big Bang to have produced enough deuterium to explain the observed abundances. Similar though more complex arguments were also developed for ^3He, and most recently [10] for ^7Li, so that it can be said that only if the baryon density is between $2 \cdot 10^{-31}$ and $5 \cdot 10^{-31}$ g/cm^3 can all the observed light element abundances be consistent with the Big Bang yields. If the baryon density were outside of this range, a significant disagreement between the Big Bang predictions and the abundance observations would result. To put this in perspective, it should be noted that for this range in densities, the predicted abundances for the four separate species fall within a range from 25% to one part in $\sim 10^{10}$. (In fact, for lithium to get agreement requires an abundance just at 10^{-10}, and that is just what the latest observations show[10].)

The Big Bang yields all agree with only one freely adjustable parameter, ρ_b. Recent attempts to circumvent this argument[11], by having variable n/p ratios coupled with density inhomogeneities inspired by a first order quark-hadron phase transition fail in most cases to fit the Li and ^4He even when numerous additional parameters are added and fine-tuned. Figure 2 shows[12] that the observed abundance constraints yield such a robust solution that nucleosynthesis may constrain the quark-hadron phase transition more than the phase transition alters the cosmological conclusions. Even with the assumption of a first order quark-hadron phase transition, the density that fits all the abundances is still a few $10^{-31} g/cm^3$.

The loop holes to this conclusion require huge density contrasts ($\gtrsim 10^4$) during the transition and the dropping of the Lithium constraint, since high density models seem to overproduce Lithium. (The option that Li really started out high rather than at 10^{-10} runs contrary to other astrophysical arguments.) However, agreeing that the density constraint is robust does not detract from interest in the quark-hadron transition. Current research is focusing on what signatures might be possible to use cosmology to learn something about the nuclear physics.

The narrow range in cosmological baryon density for which agreement with abundance observations occurs is very interesting. Let us convert it into units of the critical cosmological density for the allowed range of Hubble expansion rates. From the Big Bang Nucleosynthesis constraints[8,10,13] the dimensionless baryon density, Ω_b, that fraction of the critical density that is in baryons, is less than 0.12 and greater than 0.03; that is,

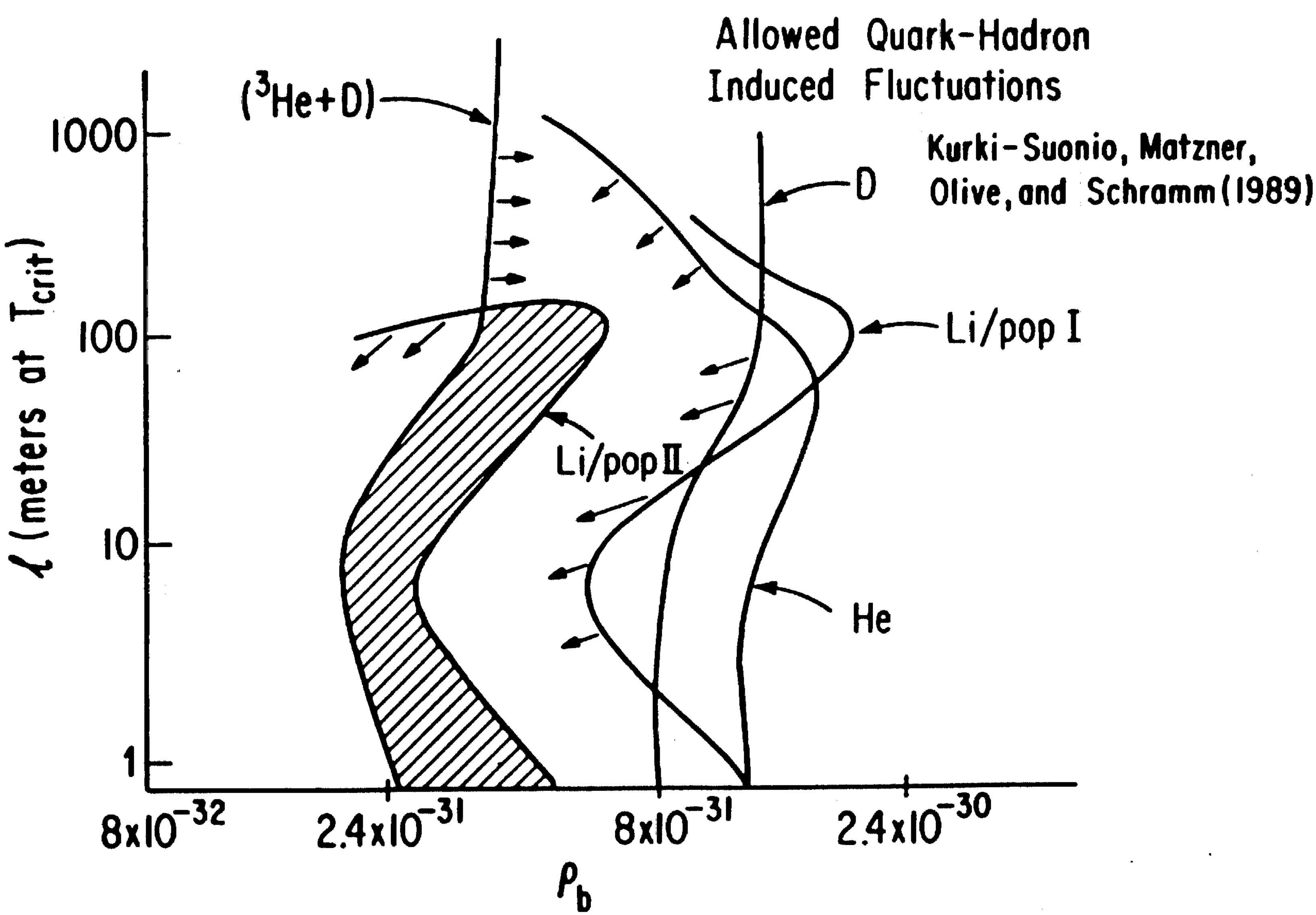

Figure 2 Allowed parameter space for quark-hadron induced fluctuations with nucleation sites separated by distance ℓ and average baryon.

the universe *cannot be closed with baryonic matter.* If the universe is truly at its critical density, then nonbaryonic matter is required. This agrument has led to one of the major areas of research at the particle-cosmology interface, namely, the search for nonbaryonic dark matter.

Another important conclusion regarding the allowed range in baryon density is that it is in very good agreement with the density implied from the dynamics of galaxies, *including their dark halos.* Baryonic dark halos could be "jupiters," brown drawfs, black holes, etc.). An early version of the baryonic density arguments, using only deuterium, was described over fifteen years ago[14]. As time has gone on, the argument has strengthened, and the fact remains that galaxy dynamics and nucleosynthesis agree at about 10% of the critical density. Thus, if the universe is indeed at its critical density, as many of us believe, it requires most matter not to be associated with galaxies and their halos, as well as to be nonbaryonic.

With the growing success of Big Bang Nucleosynthesis, the finer details of the results were put into focus. In particular, the ^4He yield was looked at in detail, since it is the most abundant of the nuclei, and thus in principle it is the one that observers should be able to measure to higher accurancy. In additiion, it is very sensitive to the n/p ratio. The more types of relativistic particles, the greater the energy density at a given temperatrure, and thus a faster cosmological expansion. A faster expansion yields the weak-interaction rates being exceeded by the cosmological expansion rate at an earlier, higher temperature; thus, the weak interaction drops out of equilibrium sooner, yielding a higher n/p ratio. It also yields less time between dropping out of equilibrium and nucleosynthesis at $10^9 K$, which gives less time for neutrons to change into protons, thus raising the n/p ratio. A higher n/p ratio yields more ^4He. Quark-hadron induced variations[11] in the standard model *also* yield higher ^4He for higher values of Ω_b, thus such variants still support the constraint on the number of relativistic species[12].

In the standard calculation we allowed for photons, electrons, and the three known neutrino species (and their antiparticles). However, by doing the calculation for additional species of neutrinos we can see when ^4He yields exceed observational limits while still yielding a density consistent with the ρ_b bounds from ^2D, ^3He, and now ^7Li. (The new ^7Li value gives approximately the same constraint on ρ_b as the others, thus strengthening the conclusion.) The bound on ^4He comes from observations of helium in many different objects in the universe. However, since ^4He is not only produced in the Big Bang but in stars as well, it is important to estimate what part of the helium in some astronomical object is primordial–from the Big Bang–and what part is due to stellar production after the Big Bang. To do this we[15] have found that the carbon content of the object can be used to track the addtional helium. Carbon is made in the same mass stars that also produce ^4He; thus, as the carbon abundance increases, so must the helium. Other heavy elements, such as oxygen, have been tried for this extrapolation, but these tend not to focus their production as well on the same type of stars as those that also produce helium. However, it is interesting that at low heavy element content the extrapolation to the primordial value using carbon,[15] oxygen[15] or even nitrogen[16] yields approximately the same answer, ~ 0.232, for primordial helium. A reasonable estimate of the uncertainty is a 1σ error of 0.004 which would make $Y_p \lesssim 0.245$ a 3σ upper limit, as contrasted with the extreme upper limit of $Y_p \lesssim 0.255$ used by Yang et al[8]. In fact, if anything, our estimates are on the high side due to possible systematic errors (e.g., collisional excitation of helium lines) yielding slight overestimates[16] for Y_p.

Prior to the 1989 Grenoble meeting on slow neutron physics, it used to be said that the other major uncertainty in the prediction was the neutron lifetime. However, the new value of Mampe et al. $\tau_n = 890 \pm 4s(\tau_{1/2} = 10.3\ min)$ is quite consistent with the standard particle data table value of $896 \pm 10s(\tau_{1/2} = 10.35\ min)$ which is consistent with the precise G_A/G_V measurements from PERKEO [18] and others also reported at the Grenoble Workshop. Thus the old ranges of $10.4 \pm 0.2\ min$ used for the half life in calculations[3,8] seem to have converged towards the lower side. The convergence means that instead of broad bands for each neutrino flavour we obtain[10] relatively narrow bands (see Figure 3). The vertical line at a baryon-to-photon ratio $3 \cdot 10^{-10}$ is the lower bound from ^3He plus ^2D. (^7Li gives a slightly weaker bound[10]). The lower horizontal line is the best fit Y_p *of* 0.232; the upper horizontal line is the 3σ upper limit. Note that, barring systematic errors, $N_\nu = 4$ appears excluded, which would imply that all the fundamental families may have already been discovered.

We can study the sensitivity of our conclusions from the following equation:

$$N_\nu \approx 2.6 - 10\frac{\Delta\tau}{\tau} + 17\frac{\Delta Y_p}{Y_p}$$

for $\tau = 890s$ and $Y_p = 0.232$ (assuming the limiting value for the sum of D and ^3He is 10^{-4} relative to H). Plugging in the uncertainties with an rms analysis yields $1\sigma \sim 0.3$ thus formally $N_\nu \approx 2.6 \pm 0.3$ which fits 3 families reasonably well ($\sim 1.3\sigma$) but probably excludes ($\gtrsim 4.7\sigma$) a fourth unless systematic errors are involved. While systematic errors may have dominated the uncertainties in the past, the bounds on such excursions are coming into control. As mentioned before, current trends in Y_p would imply, if anything, a downward rather than upward shift if a systematic error occurred. (Note that $Y_p < 0.235$ is inconsistent with $N_\nu = 3$ which would require $m_{\nu_\tau} \gtrsim 10MeV$ and $Y_p < 0.22$ is even inconsistent with $N_\nu = 2$.) For the $^3He + D$ bound, the fact that Li backs it up seems

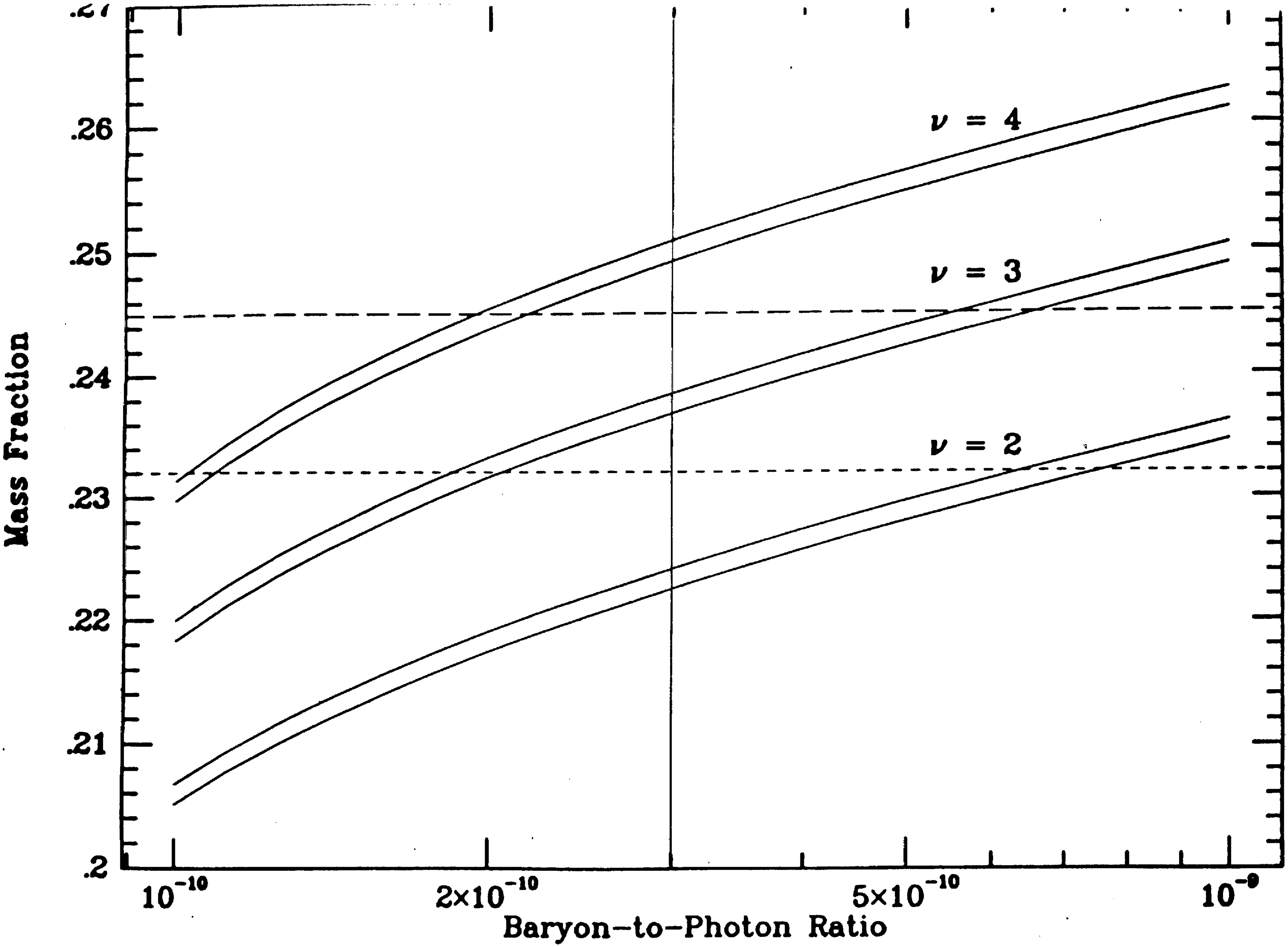

Figure 3. Helium mass fraction versus the cosmological baryon-to-photon ratio. The vertical line is the lower bound on this ratio from considerations of ${}^2D$ and ${}^3He$ (see Yang et al.) (Using ${}^7Li$ as a constraint would move the vertical line only slightly to the left.) The lower horizontal line is the current best fit zero metalicity extrapolation of 0.232. The 3σ upper bound of 0.245 is also shown. The width of the lines for $N_\nu = 2, 3$ and 4 is due to $\tau_n = 890 \pm 4s$. Note that $N_\nu = 4$ appears to be excluded barring a systematic error upward in Y_p which would be contrary to current systematic trends.

to make significant excursions difficult since such excursions would require simultaneous systematic shifts in D,^3He and ^7Li. While quoting a statistical error may be misleading compared to merely stating a limit that incorporates possible systematics, as we have done in the past, our errors none-the-less convey the increasing difficulties for the existence of a 4th light neutrino.

It is nice to hear that particle accelerators are beginning to probe to the cosmological level of sensitivity, and that soon we will know whether or not cosmological theory is able to make reliable predictions about fundamental physics. (It is also intriguing that the recent supernova, 1987a, can set a limit[19] of $\lesssim 7$ families, or otherwise the $\bar{\nu}_e$ flux would be too diluted to be detectable. Thus we have an independent indication that the number of neutrino families is small.) Or, to turn the argument around, perhaps LEP and SLC provide us with indirect checks of neutron lifetime measurements via determinations of N_ν. Recent reports from SLC[21] put an upper limit (95% conf.) on N_ν of 3.9 in amazing agreement with the cosmological prediction.

ACKNOWLEDGMENT

I would like to thank Gary Steigman, Keith Olive, Michael Turner, Rocky Kolb and Larry Kawano for many discussions. I would also like to thank Stuart Freedman and Walter Mampe for discussions on τ_n. This work was supported in part by NSF AST 88-22595 and NASA NAGW 1321 at the University of Chicago and by DOE and NASA NAGW 1340 at Fermilab.

REFERENCES

[1] G. Steigman, D. Schramm and J. Gunn. (1977) *Phys. Lett.* **B66**, 202.

[2] D. Schramm. (1987) *Ann. New York Academy of Sciences* **518,** 92.

[3] G. Steigman, K. Olive, D. Schramm and M. Turner. (1986) *Phys. Lett. B* **176,** 33.

[4] F. Hoyle, and R. Taylor. (1964) *Nature* **203**, 1108.

[5] P.J.E. Peebles. (1966) *Phys. Rev. Lett.* **16**, 410.

[6] R. Wagoner, W. Fowler and F. Hoyle. (1967) *Astrophys. J.* **148**, 3.

[7] W. Fowler, J. Greenstein and F. Hoyle. (1962) *Geophys. J.R.A.S.* **6**, 148. (However, see C. Ryter, H. Reeves, E. Gradsztajn and J. Audouze. (1970) *Astron. and Astrophys.* **8**, 389 where above paper is questioned.)

[8] J. Yang, M. Turner, G. Steigman, D. Schramm and K. Olive. (1984) *Astrophys. J* **281**, 493 (and references therein).

[9] R. Epstein, J. Lattimer and D. Schramm. (1976) *Nature* **263**, 198. (See also earlier arguments of H. Reeves, J. Audouze, W. Fowler and D.N. Schramm. (1973) *Astrophys. J.* **179,** 909).

[10] L. Kawano, D. Schramm and G. Steigman. (1988) *Astrophys. J.* **327**, 750. (See also L. Krauss et al. (1989) *Yale University preprint.*)

[11] R. Scherrer, J. Applegate and C. Hogan. (1987) *Phys. Rev.* **D35**, 1151.
C. Alcock, G. Guller and G.J. Mathews. (1987) *Astrophys. J.* **320**, 439.
W.A. Fowler and R. Malaney. (1988) *Astrophys. J.* **333**, 14.

[12] H. Kurki-Suonio, R. Matzner, K. Olive and D. Schramm. (1989) *Astrophys. J.*, in press.
H. Reeves, K. Sato and M. Tarasawa. (1989) Univ. of Tokyo preprint.

[13] K. Freese and D. Schramm. (1984) *Nucl. Phys.* **B233**, 167.

[14] J. Gott, J. Gunn, D. Schramm and B. Tinsley. (1974) *Astrophys. J.* **194**, 543.

[15] G. Steigman, J. Gallagher III and D. Schramm. (1989) *Comments on Astrophysics* **XIV**, 97-106.

[16] B. Pagel. (1987) in *Proc. 1987 Rencontres de Moriond, Astrophysics.* ed. T. Thran.

[17] W. Mampe, P. Ageron, J. Bates, J. Pendebury and A. Steyerl. (1989) *Proc. Grenoble Workshop on Slow Neutrons.*

[18] H. Abele, M. Arnould, H. A. Borel, J. Dohner, D. Dubbers, S. Freedman, J. Last and I. Reichert. (1989) *Proc. Grenoble Workshop on Slow Neutrons.*

[19] D. Schramm and L. Kawano. (1989) *Proc. Grenoble Workshop on Slow Neutrons.*

[20] D. Schramm. (1987) in *Proc. 1987 Rencontres de Moriond, Astrophysics*, ed. T. Thran.

[21] J. Dorfani. (1989) *Madrid Meeting of European Physical Society.*