Fermi National Accelerator Laboratory

FERMILAB-Conf-92/20-A
January 1992

QUARK MATTER AND COSMOLOGY *

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ABSTRACT

The possible implications of the quark-hadron transition for cosmology are explored. Possible surviving signatures are discussed. In particular, the possibility of generating a dark matter candidate such as strange nuggets or planetary mass black holes is noted. Much discussion is devoted to the possible role of the transition for cosmological nucleosynthesis. It is emphasized that even an optimized first order phase transition will not significantly alter the nucleosynthesis constraints on the cosmological baryon density nor on neutrino counting. However, it is noted that Be and B observations in old stars may eventually be able to be a signature of a cosmologically significant quark-hadron transition. It is pointed out that the critical point in this regard is whether the observed B/Be ratio can be produced by spallation processes or requires cosmological input. Spallation cannot produce a B/Be ratio below 7.6. A supporting signature would be Be and B ratios to oxygen that greatly exceed galactic values. At present, all data is still consistent with a spallagenic origin.

* Prepared for Proceedings of Quark Matter 91, Gatlinburg, Tennessee, November 1991

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

INTRODUCTION

The study of the cosmological quark-hadron transition is complementary to the study of the heavy ion quark-hadron transition. In extreme relativistic heavy ion studies, the dimensionless entropy per baryon can range from 10 to 100. In the Big Bang, the entropy per baryon is about 10^{10}. In cosmology, as in heavy ion studies, the central question is what possible signatures exist to reveal something about the nature of the transition. To produce signatures in cosmology requires some piece of surviving "debris" from the epoch of the transition. Possible candidates for debris are:

(1) surviving relics that could serve as cold dark matter;

(2) density fluctuations that could effect cosmological nucleosynthesis and the light element abundances.

Because the horizon mass at the time ($\sim 10^{-4}$ to 10^{-6}sec) of the quark-hadron transition is less than a solar mass, fluctuations produced in the transition are unlikely to affect directly anything larger than solar mass size systems. Thus, extreme fluctuations might produce planetary size nuggets or even black holes, but not galaxy or cluster size objects or seeds. However, fluctuations of this size can affect cosmological nucleosynthesis. Nucleosynthesis is affected by events at one second when the horizon mass is only a few thousand solar masses. Thus, quark-hadron effects that persist until 1 second can affect nucleosynthesis.

In this paper we will briefly describe possible dark matter relics from the quark-hadron transition and then turn our attention to cosmological nucleosynthesis where most of the current activity has taken placed. We will note that despite preliminary statements to the contrary, even the most optimistic parameter choices do not seem to allow significant variations from the standard homogeneous Big Bang Nucleosynthesis conclusions regarding the density of baryons in the universe and the limits on the number of neutrino flavors. Nevertheless, we will note that observations of Be and B in old, Population II stars may potentially become a signature for a cosmologically significant quark-hadron transition. However, despite claims to the contrary, the present observations may be explained by spallation processes in the early history of the Galaxy and thus not require any cosmological input.

Before turning to a specific discussion of these potential signatures, let us note that all signatures require the quark-hadron transition to be a true first-order phase transition or require significant instability growth to generate significant density variations. We are well aware from the other work presented at this meeting that lattice gauge calculations appear to show that the realistic transition with two light quarks is second order. In fact, it may not even be a phase transition at all but rather a transition more analogous to the ionization and recombination of hydrogen. However, we argue here that independent cosmological signatures of significant density inhomogeneities would nonetheless be dramatically important.

In all of our discussion we will be utilizing the basic Big Bang cosmological model. Since the popular press sometimes presents misleading headlines implying *doubts* about the Big Bang, it is important to note here that the real concerns referred to in these articles are really in regard to observations related to models of galaxy and structure formation. The basic hot Big Bang model itself is in fantastic shape[10] with high accuracy confirmations from COBE and, as we will discuss, nucleosynthesis. However, there is admittedly no fully developed model for galaxy and structure formation that fits all of the observations. (But, of course, there is also no fully developed first principles model for star formation either.) That we might not really know exactly how to make galaxies and large-scale structure in no way casts doubt on the hot, dense early universe which we call the Big Bang. (We also have trouble predicting earthquakes and tornadoes, but that hasn't meant that we throw out the concept of a spherical Earth.)

QUARK NUGGETS AND PLANETARY MASS BLACK HOLES

The possibility of producing some sort of remnant at the quark-hadron transition that could serve as cosmological dark matter and circumvent the Big Bang Nucleosyntheis bounds [1,2,3] on baryon density has been around almost as long as the dark matter problem itself.

Two specific proposals were:

(1) planetary mass black holes[4]; and

(2) strange quark nuggets.[5,6,7]

In the first case it was noted that QCD-induced density fluctations at the quark-hadron transition could conceivably lead to black hole formation. Once the fluctuation was within its own Schwarzschild radius, then it could no longer evaporate and the fluctuation would survive. It was noted that the early universe is always near critical density, so fluctuations over the Schwarzschild criteria are not inconceivable. It was also noted that the larger the scale, R, of the fluctuation, the smaller the density required to achieve the Schwarzschild criteria.

$$\rho_s = \frac{3c^2}{8\pi G R^2} \tag{1}$$

The largest scale directly achievable is the horizon size at the time of the transition

$$R_H \sim \frac{3 \times 10^{10} cm}{T_{QH}^2(MeV)} \tag{2}$$

$T_{QH}^2(MeV)$ is the temperature of the quark-hadron transition in MeV. Thus, the maximum mass of black holes produced is a little below a solar mass. It is also worth noting the timescale for a small black hole to evaporate via the Hawking process,

$$t_{Hawking} \sim t_p(\frac{M}{M_p})^3, \tag{3}$$

where t_p is the Planck time, $\sim 10^{-43}$sec, and M_p is the Planck mass, $\sim 10^{19}$GeV. From this relationship it is clear that only black holes with $M \gtrsim 10^{15}g$ will survive for the present age of the universe. Thus, the quark-hadron transition could, in principle, produce survivable black holes with

$$10^{15}g \lesssim M \lesssim M_\odot, \tag{4}$$

hence, the term "planetary mass black holes." The mass fraction of the universe that could go into such holes is constrained from cosmological age arguments by the critical density of the universe, ρ_c. Since the density of black holes once formed scales like matter

($\propto T^3$), whereas the dominant density at the quark-hadron transition routinely scales like radiation ($\propto T^4$), models for black holes (or nugget formation) must be relatively inefficient to prevent present day densities from overly exceeding the critical values.[4] In particular,

$$\Omega_{BH} \equiv \frac{\rho_{BH}}{\rho_c} \sim 10^{-4} f_{BH} \, \frac{T_{QH}}{T_0} \lesssim 1 \tag{5}$$

where f_{BH} is the fraction of the universe at the quark-hadron transition going into black holes and T_O is the present background tempertature. Or, to be speciifc,

$$f_{BH} \lesssim 10^4 \frac{T_0}{T_{QH}}. \tag{6}$$

Putting in a limiting value of $T_{QH} \gtrsim 100 MeV$ yields

$$f_{BH} \lesssim 3 \times 10^{-8}. \tag{7}$$

In other words, if only a few parts in 10^8 of the matter at the quark-hadron transiton get within their own Schwarzschild radius, then there will be sufficient black holes produced to enable $\Omega = 1$ and solve the dark matter problem. The eventual clustering of these black holes was investigated by Freese *et al.*[8] and they do make excellent dark matter if they could be produced.

Another form of debris that could be generated at the quark-hadron transition is a strange quark nugget or "strangelet." This concept was first developed by Bodmer[5] who noted that another state of nuclear matter might exist due to the decreased Pauli exclusion effects if significant numbers of strange quarks were present instead of pure up and down quarks. Such a high density of strange quarks would be possible if the density is high enough to put the Fermi level above the strange quark mass. This point was further amplified by Witten[6] and the astrophysical consequences were reviewed by Alcock and Olinto.[7] Witten emphasized that nuggets of this strange quark material might be stable and serve as the dark matter. Again, the same arguments regarding the horizon size limit the upper mass bounds. The critical density argument of eq. (5) and eq. (6) also limits the efficiency of strangelet formation unless the strangelets evaporate, as Alcock and Olinto argue they will.

Since so much has been written elsewhere on strange matter, we won't say much more here other than to note that the production of either strange quark nuggets or planetary mass black holes requires significant density fluctuations of the type normally associated with extreme first order phase transitions. (For an early discussion of the potential role of the quark-hadron transition in cosmology, one might also read ref. 9 and the references therein.)

Let us now turn to Big Bang Nucleosynthesis which may provide us with a probe of the transition.

HOMOGENEOUS BIG BANG NUCLEOSYNTHESIS

Big Bang nucleosynthesis (BBN), along with the microwave background, is one of the two principle modern tests of the standard hot Big Bang model of the universe. Furthermore, these two tests have been symbiotically related since the early work of George

Gamow and his associates. Furthermore, just as the new COBE results have given renewed confidence in the $3K$ background argument, the LEP collider (along with the SLC) and the light element abundance measurements have given us renewed confidence in the BBN arguments. For a physicist it is worth noting that the microwave background probes events at temperatures $\sim 10^4 K$ and times of $\sim 10^5$ years, that is, the overlap of atomic physics with cosmology, whereas the light element abundances probe the universe at temperatures $\sim 10^{10} K$ and times of ~ 1 sec. Thus, it is the nucleosynthesis results that played the most significant role in leading to the nuclear-particle-cosmology merger that has taken place this past decade. Together, these two areas cover the blending of most of modern physics with cosmology and have led to the development of the field of physical cosmology as distinct from astronomical or mathematical cosmology which dominated cosmological studies 25 years ago.

Before discussing possible quark-hadron variations on BBN, let us briefly discuss the standard homogeneous BBN results[11] shown in Figure 1. As far as the calculation itself goes, solving the reaction network is relatively simple by the standards of explosive nucleosynthesis calculations in supernovae (c.f. the 1965 calculation of Truran *et al.*,[12]) with the changes over the last 25 years being mainly in terms of more recent nuclear reaction rates as input, not as any great calculational insight (although the current Kawano/Walker code[11,13] is somewhat streamlined relative to the earlier Wagoner code[14,15]). With the possible exception of ^7Li yields, the reaction rate changes over the past 25 years have not had any major affect.[16,17] The one key improved input is a better neutron lifetime determination.[18]

BIG BANG NUCLEOSYNTHESIS

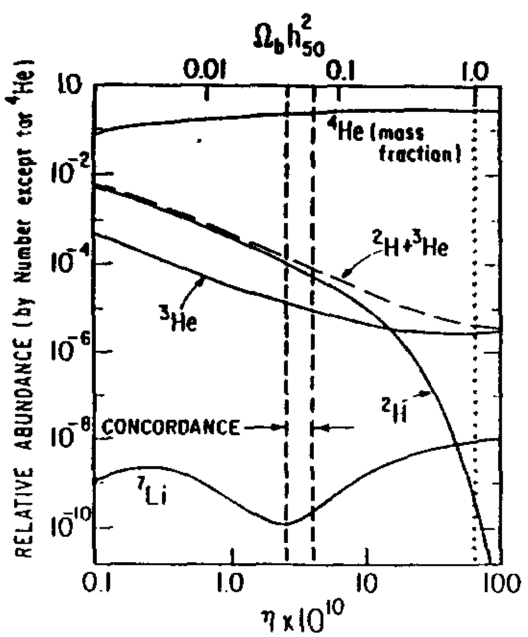


Figure 1. BBN abundances versus the baryon to photon ratio, η, or equivalently the fraction of the critical density, Ω_b. Based on calculation of reference 11.

With the exception of the effects of the quark-hadron transition to which we will return, the real excitement for BBN over the last 25 years has not really been in redoing the basic calculation. Instead, the true action is focused on understanding the evolution of the light element abundances and using that information to make powerful conclusions. In particular, in the 1960's, the main focus was on ^4He which is very insensitive to the baryon density. The agreement between BBN predictions and observations helped support the basic Big Bang model but gave no significant information at that time with regard to density. In fact, in the mid-1960's, the other light isotopes (which are, in principle, capable of giving density information) were generally assumed to have been made during the T-Tauri phase of stellar evolution,[19] and so, were not then taken to have cosmological significance. It was during the 1970's that BBN fully developed as a tool for probing the universe. This possibility was in part stimulated by Ryter *et al.*[20] who showed that the T-Tauri mechanism for light element synthesis failed. Furthermore, ^2H abundance determinations[21,22] improved significantly with solar wind measurements and the interstellar work from the Copernicus satellite. Reeves, Audouze, Fowler and Schramm[1] argued for cosmological ^2H and were able to place a constraint on the baryon density excluding a universe closed with baryons. Subsequently, the ^2H arguments were cemented when Epstein, Lattimer and Schramm[23] proved that no realistic astrophysical process other than the Big Bang could produce significant ^2H. It was also interesting that the baryon density implied by BBN was in good agreement with the density implied by the dark galactic halos.[24,25]

By the late 1970's, a complimentary argument to ^2H had also developed using ^3He. In particular, it was argued[26] that, unlike ^2H, ^3He was made in stars; thus, its abundance would increase with time. Since ^3He, like ^2H, monotonically decreased with cosmological baryon density, this argument could be used to place a lower limit on the baryon density[27] using ^3He measurements from solar wind or interstellar determinations.[28] Since the bulk of the ^2H was converted in stars to ^3He, the constraint was shown to be quite restrictive.[16] Support for this point[29] also comes from the observation of ^3He in horizontal branch stars which, as processed stars still having ^3He on their surface, indicates the survivability of ^3He and most recently Rood, Bania and Wilson found sufficient ^3He excess in planetary nebulae, verifying that ^3He is indeed produced in low mass stars.

It was interesting that the lower boundary from ^3He and the upper boundary from ^2H yielded the requirement that ^7Li be near its minimum of $^7Li/H \sim 10^{-10}$, which was verified by the Pop II Li measurements of Spite and Spite,[30] hence, yielding the situation emphasized by Yang *et al.*[16] that the light element abundances are consistent over nine orders of magnitude with BBN, but only if the cosmological baryon density is constrained to be around 6% of the critical value. It is this result that drives the search for non-baryonic dark matter. It is worth noting that ^7Li alone gives both an upper and a lower limit to Ω_b. However, while its derived upper limit is more than competitive with the ^2H limit, the ^7Li lower limit is not nearly as restictive as the $^2H+^3He$ limit. Claims that Big Bang Nucleosynthesis can yield Ω_b lower than 0.01 must necessarily neglect the $^3He+^2H$ limit.

Recent claims[31] that rotation-induced meridianal mixing could have caused significant depletion in the Pop II Li abundance can be turned around to argue exactly the opposite when the depletion predictions of the Li/H vs. surface temperature are compared with actual data. The actual data shows much less spread than such rotationally-induced depletion processes predict. Thus, the conclusion is that no such depletion occurred and the success of the standard BBN predictions stand.

The other development of the 70's for BBN was the explicit calculation of Steigman, Schramm and Gunn,[32] showing that the number of neutrino generations, N_ν, had to be small to avoid overproduction of ^4He. This will subsequently be referred to as the SSG limit. To put this in perspective, one should remember that the mid-1970's also saw the discovery of charm, bottom and tau, so that it almost seemed as if each new detector produced new particle discoveries, and yet, cosmology was arguing against this "conventional" wisdom. Over the years, the SSG limit on N_ν improved with ^4He abundance measurements, neutron lifetime measurements and with limits on the lower bound to the baryon density; hovering at $N_\nu \lesssim 4$ for most of the 1980's and dropping to slightly lower than 4 just before LEP and SLC turned on.[11,33,34] The recent verification of this cosmological prediction by the LEP and SLC results[35] where $N_\nu = 2.99 \pm 0.05$.

The power of homogeneous BBN comes from the fact that essentially all of the physics input is well determined in the terrestrial laboratory. The appropriate temperature regimes, 0.1 to $1MeV$, 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 $1keV$, thus, 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 $1MeV$ ($\sim 10^{10}K$) down to a little below $100keV$ ($\sim 10^9K$). At higher temperatures, no complex nuclei other than free single neutrons and protons can exist, and the ratio of neutrons to protons, n/p, is just determined by $n/p = e^{-Q/T}$, where $Q = (m_n - m_p)c^2 \sim 1.3MeV$. 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.

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 ($0.1MeV$), 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 energies greater than MeV. Note that the high photon to baryon ratio in the universe ($\sim 10^{10}$) enables significant population of the MeV high energy Boltzman tail until $T \lesssim 0.1\ MeV$.

Once the temperature drops to about 10^9K, sufficient abundances of nuclei can exist in statistical equilibrium through reactions such as $n + p \leftrightarrow {}^2H + \gamma$ and ${}^2H + p \leftrightarrow {}^3He + \gamma$ and ${}^2H + n \leftrightarrow {}^3H + \gamma$, which in turn react 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 at 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 (about 1% the density of terrestrial air) and the time-scale short ($t \lesssim 10^2 sec$), 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 leads to unstable mass-5. Even when one combines ^4He with rarer nuclei like ^3H or ^3He, we still get only to mass-7, which, when hit by a proton, the most abundant nucleus around, yields mass-8. (As we will discuss, 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, ^3H deccays radioactively to ^3He, and any mass-7 made radioactively decays to ^7Li. Thus, Big Bang Nucleosynthesis makes ^4He with traces of ^2H, ^3He, and ^7Li. (Also, all the protons left over that did not capture neutrons remain as hydrogen.) For standard homogeneous BBN, 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.) With the possible exception of ^7Li, the results are rather insensitive to the detailed nuclear reaction rates. This insensitivity was discussed in references 16 and 17.

INHOMOGENEOUS BIG BANG NUCLEOSYNTHESIS

As noted above, BBN yields all agree with observations using only one freely adjustable parameter, η, or equivalently, ρ_b. Thus, BBN can make strong statements regarding ρ_b if the observed light element abundances cannot be fit with any alternative theory. The most significant alternative that has been discussed involves quark-hadron transition inspired inhomogeneities.[36] While inhomogeneity models had been looked at previously (c.f. ref. 16) and were found to make little difference, the quark-hadron inspired models had the added ingredient of variations in n/p ratios.

The initial claim by Applegate *et al.*, followed by a similar argument from Alcock *et al.*, that $\Omega_b \sim 1$ might be possible, created tremendous interest. Their argument was that if the quark-hadron transition was a first-order phase transition, then it was possible that large inhomogeneities could develop at $T \gtrsim 100MeV$. The preferential diffusion of neutrons versus protons out of the high density regions could lead to Big Bang Nucleosynthesis occurring under conditions with both density inhomogeneities and variable neutron/proton ratios. In the first round of calculations, it was claimed that such conditions might allow $\Omega_b \sim 1$, while fitting the observed primordial abundances of $^4He, ^2H, ^3He$ with an overproduction of ^7Li. Since ^7Li is the most recent of the cosmological abundance constraints and has a different observed abundance in Pop I stars versus the traditionally more primitive Pop II stars,[30] some argued that perhaps some special depletion process might be going on to reduce the excess ^7Li.

At first it appeared that if the lithium constraint could be surmounted, then the constraints of standard Big Bang Nucleosynthesis might disintegrate. (Although Audouze, Reeves and Schramm emphasized that the number of parameters needed to fit the light elements was somewhat larger for these non-standard models, nonetheless, a non-trivial loophole appeared to be forming.) To further stimulate the flow through the loophole, Malaney and Fowler showed that, in addition to looking at the diffusion of neutrons out of high density regions, one must also look at the subsequent effect of excess neutrons diffusing back into the high density regions as the nucleosynthesis goes to completion in the low density regions. (The initial calculations treated the two regions separately.) Malaney and Fowler argued that for certain phase transition parameter values (e.g. nucleation site separations $\sim 10m$ at the time of the transition), this back diffusion could destroy much of the excess lithium.

However, Kurki-Suonio, Matzner, Olive and Schramm,[37] the Tokyo group,[38] and the Livermore group[39] have recently argued that in their detailed diffusion models, the back diffusion not only affects ^7Li, but also the other light nuclei as well. They find that for $\Omega_b \sim 1$, ^4He is also overproduced (although it does go to a minimum for similar parameter values as does the lithium). One can understand why these models might tend to overproduce ^4He and ^7Li by remembering that in standard homogeneous Big Bang Nucleosynthesis, high baryon densities lead to excesses in these nuclei. As back diffusion evens out the effects of the initial fluctuation, the averaged result should approach the homogeneous value. Furthermore, it can be argued that any narrow range of parameters, such as those which yield relatively low lithium and helium, are unrealistic since in most realisitic phase transitions there are distributions of parameter values (distribution of nucleation sites, separations, density fluctuations, etc.). Therefore, narrow minima are washed out which would bring the ^7Li and ^4He values back up to their excessive levels for all parameter values with $\Omega \sim 1$. Furthermore, Freese and Adams[40] and Baym[41] have argued that the boundary between the two phases may be fractal-like rather than smooth. The large surface area of a fractal-like boundary would allow more interaction between the regions and minimize exotic effects.

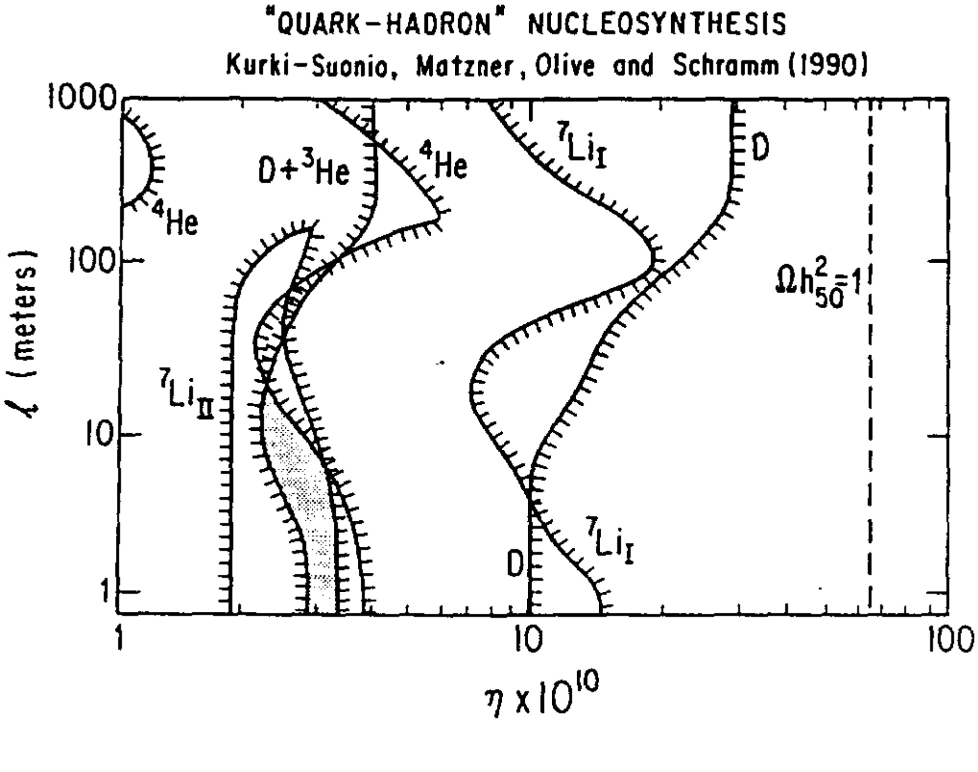


Figure 2. This shows the constraints on η of the various observed abundances in a first-order quark-hadron phase transition with nucleation sites separated by a distance l with density contrast $R \lesssim 10^3$. The Pop II lithium abundance used here is from the compilation of data given by Walker *et al.*[11] and is slightly more restrictive on η than that used in Figure 1 or used in the original Kurki-Suonio *et al.*[37] calculation from which this figure is derived. It should be noted that work by the Tokyo[38] group and by the Livermore group[39] confirms the conclusions on restricting Ω_b to values similar to the standard result even when $R \rightarrow \infty$.

Figure 2 shows the updated results of Kurki-Suonio *et al.*[37] for varying spacing l with the constraints from the different light element abundances. Notice that the Li and even the ^4He constraint do not allow $\Omega_b \sim 1$. Note also that with the Pop II ^7Li constraint, the results for Ω_b are quite similar to the standard model with a slight excess in Ω_b possible if l is tuned to ~ 10. Thus, even an optimally tuned first order quark-hadron transition is not able to alter the basic conclusions of homogeneous BBN regarding Ω_b. (It also cannot significantly change the N_ν argument.) In fact, the main role that a quark-hadron option has played for BBN is to show how robust the standard model results are.

BORON, BERYLLIUM AND A QUARK-HADRON SIGNATURE

While quark-hadron inspired variations have not been able to alter the basic conclusions of BBN, an important question remains, namely, is there an observable signature that could differentiate quark-hadron inspired variations from the homogeneous model? On the theoretical side, this point has been debatable. Several authors[42,43,44] have argued that because of the high n/p region in the inhomogeneous models, leakage beyond the mass 5 and 8 instability gaps can occur and traces of ^{9}Be, ^{10}B, ^{11}B and maybe even r-process elements can be produced. Thus, detection of nuclei beyond ^{7}Li in primative objects may be a signature. However, Tarasawa and Sato[38] have argued that such leakage is negligible. Because of this debate as well as the recent experimental results, we have started theoretically examing this question ourselves. However, before discussing our results, let us first comment on some recent observations of Be and B in primitive Pop II stars.

In particular, there has been much recent attention given to reports[45,46] of beryllium lines being observed in extreme Pop II stars. For one very metal poor Pop II star, HD 140283, boron was also observed.[47] The observations yielded

$$\frac{Be}{H} \sim 10^{-12.9 \pm 0.3} \tag{8}$$

which represents a combination of the two Be/H measurements with Gilmore *et al.*[45] obtaining a factor of ~ 2 higher Be/H than Ryan *et al.*[46] The boron was measured using the Hubble Space Telescope where a value was obtained[47] of

$$\frac{B}{H} \sim 10^{-12.1 \pm 0.1}. \tag{9}$$

The resulting boron to beryllium ratio is

$$\frac{B}{Be} \sim 5^{+4}_{-2}. \tag{10}$$

This particular star has its iron abundance depleted relative to the standard Pop I (present galactic disk) iron abundance by a factor of about $10^{-2.6}$, and its oxygen is depleted relative to Pop I by about $10^{-2.1}$. The high oxygen to iron in extreme Pop II stars is well understood [48] as due to heavy element production in massive Type II supernova producing high oxygen to iron whereas later Pop I abundances also get a significant admixture of low-mass, slow-to-explode, Type I supernova ejecta where iron is dominant over oxygen. Because oxygen is chiefly made in Type II supernova, whereas iron has at least two significant sources, we feel it is mandatory to use oxygen as a measure of the Type II supernova contribution to such stars. In this regard, it is important to note that the Be/O for these stars is, within experimental errors, the same as Be/O for those high surface temperature Pop I stars whose convective zones are not deep enough to destroy their original Be. Thus, contrary to some initial claims, the Be/H observation alone is not sufficient to require cosmological origin, only a scaling with oxygen of the same process that produced Be in the Pop I stars.

The presumed process that produced Be and B in Pop I stars (as well as the ^{6}Li), is thought to be cosmic ray spallation.[49] For Be and B, such spallation comes from the breakup of heavy nuclei such as CNO and Ne, Mg, Si, S, Ca and Fe by protons and alphas. As noted by Epstein *et al.*,[50,24] for lithium one must also include alpha plus alpha fusion processes as well. This latter point was well noted by Steigman and Walker[51] who emphasized that Be and B spallation production on Pop II abundances would imply a significant enhancement of lithium from alpha-alpha relative to the reduced production of Be and B from depleted heavy nuclei. While the ^{6}Li so produced would be destroyed at the base of the convective zones in the stars observed,[52,31] the ^{7}Li would survive and might result in observable variations in the Spite and Spite[30] Pop II lithium plateau.

Perhaps most critical to any spallation origin is the resultant B/Be ratio. Steigman and Walker[51] calculate that a Pop I composition of targets hit by the current observed cosmic ray energy spectrum, $E^{-2.6}$, yields B/Be $\sim$ 17. However, it is also known, from actual measurements, that the cosmic rays themselves[53] show $\frac{\mathrm{B}}{\mathrm{Be}} \sim 14$ with a carbon to oxygen ratio exceeding unity (Pop I has C/O $\lesssim 0.5$). Since spallation off carbon favors B relative to Be (mass 11 requires only a single nucleon ejected from mass 12), whereas oxygen being farther from either shows less favoritism, we feel the cosmic ray observations are actually an upper limit on what B/Be ratio one might expect in Pop I cosmic rays. However, of more concern here is the lower limit on B/Be achievable by a spallation process.[54] Reference 54 addresses this point in detail, but for our present concerns, we merely note that cosmic ray spectra that are flatter than $E^{-2.6}$ will be less favorable towards boron production. This is because the ^{11}B production threshold is below that for ^{9}Be. Thus, steeper spectra favor B relative to Be, whereas flatter specta remove the role of the threshold effects and yield relatively higher Be. Furthermore, Pop II composition has a lower C/O ratio than does Pop I. Like iron, carbon is not a pure Type II supernova product. Thus, spallation on pure Type II ejecta would have targets of oxygen, neon, magnesium, silicon, etc., but less carbon and nitrogen than Pop I.

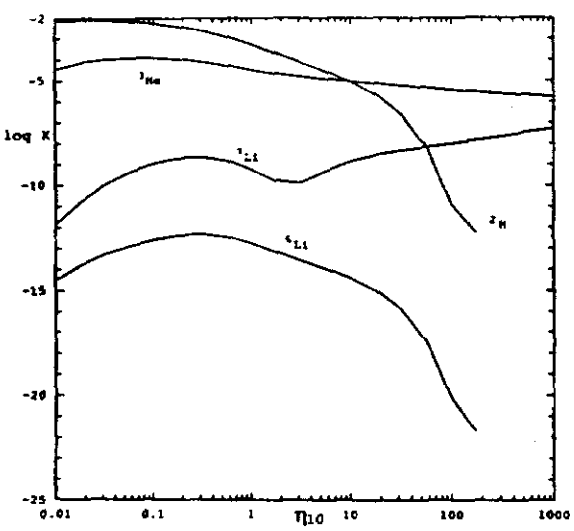
We have carried out spallation calculations for flat spectra on such material. The cross sections we used for the spallation calculations are a combination of all measured cross section data[55] and our semi-empirical estimates (see Appendix I). For comparison, we also used the semi-empirical cross sections of Silberberg and Tsao. The resultant ratio is

$$\frac{\mathrm{B}}{\mathrm{Be}} \simeq 7.6 \qquad (11)$$

(from our semi-empirical cross sections), and $\frac{\mathrm{B}}{\mathrm{Be}} \simeq 8.6x$ (Silberberg and Tsao). In other words, optimizing Be yields can still not get a B/Be ratio below 7.6. Since this is still within one sigma of the observations on HD 140283, it is obvious that the present observations are still quite consistent with spallation. This point is discussed thoroughly by Walker *et al.*[54]

It is important to note that if spallation processes do indeed produce the observed Be and B in Pop II stars, then the cosmic ray flux must be stronger than it is in the present Galaxy. Remember that the present Pop I abundance of Be and B and ^{6}Li can be explained by the present cosmic ray flux hitting the Pop I CNO abundances[19,1] integrated over the lifetime of the Galactic disk prior to the formation of the observed stars. However, for these Pop II stars, the CNO and heavier element abundances are down and the stars presumably formed relatively early, before the disk formed. While some Galactic evolution models[57] expect this pre-disk formation epoch to be several Gyr long, it is nonetheless shorter than the age of the disk. (If the pre-disk time is merely the massive star stellar evolution time scale, then it can be very short.) The shorter time scale thus requires a consumately higher flux if the ratios to oxygen observed in Pop I are to be retained in the Pop II objects. Of course, many galactic evolution models[57] predict higher early supernova rates which produce just such a higher cosmic ray flux, so consistent models do exist.

From the above, we, at present, see no cause to invoke anything other than spallation; however, if the uncertainties in the B/Be ratio are decreased and the ratio remains below 7.6, then spallation would fail. Furthermore, if Be/O and B/O are found to exceed significantly the ratio observed for higher oxygen abundances, then we would have to conclude that there is primordial cosmological production of Be and B.



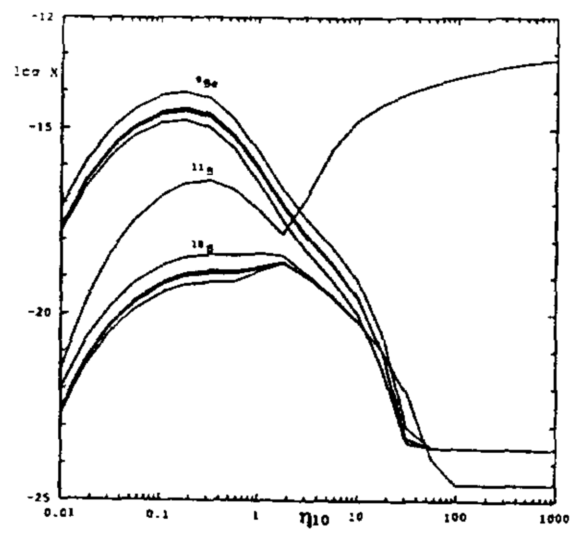


Figure 3A. The standard homogeneous BBN yields showing ^{2}H, ^{3}He, ^{6}Li and ^{7}Li for 6 orders of magnitude in η_b/η_γ. Note that ^{6}Li is always negligible relative to ^{7}Li.

Figure 3B. The standard homogeneous BBN yields for ^{9}Be, ^{10}B and ^{11}B. The various curves for ^{9}Be and ^{10}B represent different cross section assumptions. The ^{11}B yield is double humped due to production both directly as ^{11}B and also as ^{11}C which beta decays to ^{11}B.

Figures 3A and 3B show the trace element yields in a standard homogeneous BBN calculation with Figure 3A showing ^{2}H, ^{3}He, ^{6}Li and ^{7}Li, and Figure 3B showing the ^{9}Be, ^{10}B and ^{11}B yields. This work is part of an extensive study of $A \geq 6$ BBN by Thomas *et al.*,[58] using a more extensive reaction network than previously used. Note, in particular, that ^{9}Be/H yields are always less than 10^{-14} regardless of $\eta = n_b/n_\gamma$. (Also note that for the standard model, B/Be $\gg$ 10 unless $\eta \lesssim 3 \times 10^{-10}$.) In other words, homogeneous BBN can not yield Be/H consistent with the Pop II stellar observations. To explore preliminarily the alternative of inhomogeneous models, we have taken our extensive network and looked at high n/p ratios. For regions with $n/p > 3$, we can obtain Be/H $\sim 10^{-13}$. However, any realistic model will have a significant dilution of this material with low n/p regions. Thus, we tentatively view the achievement of such high values as somewhat problematic, as do Tarasawa and Sato.[38] We will continue to explore a full inhomogeneous model which includes regions of extremely high n/p to see how robust any leakage to $A > 7$ truly is. Such an exploration is just beginning.

If some Be and B can be shown to be cosmological, it will have great implications for Big Bang Nucleosynthesis. If simple inhomogeneities are unable to produce it, then more exotic ones will be required. The source of such inhomogeneities is either the quark-hadron transition or some other activity around that same cosmological epoch (no earlier than the electro-weak transition) so that density variations are retained. Of course, whatever these variations might be, they must not alter the spectacular agreement for A $\leq$ 7 abundances for N_ν.

CONCLUSION

We have seen that the quark-hadron transition may play a cosmological role only if significant density variations occur. At present, the trend is against such variations. However, if cosmological Be or B are found, then there is a signature for significant density variations. Such variations could even lead to planetary msass black holes or quark nuggets that could serve as the dark matter of the universe.

ACKNOWLEDGEMENTS

We would like to thank our recent collaborators, Gary Steigman, Keith Olive, Michael Turner, Rocky Kolb, Grant Mathews, George Fuller and Terry Walker for many useful discussions. We would also like to thank Doug Duncan, Lew Hobbs and Don York for valuable discussion regarding the astronomical observations and John Simpson, Mark Wiedenbeck and John Wefel regarding spallation cross sections and cosmic ray observations. This work was supported in part by NSF Grant AST 90-22629, by NASA Grant NAGW-1321 and by DoE Grant DE-FG02-91-ER40606 at the University of Chicago, and by the DoE and NASA Grant NAGW-2381 at the NASA/Fermilab Astrophysics Center.

APPENDIX I

Semi-Empirical Cross Sections

Estimating spallation yields has been carried out by semi-empirical fitting formulae of Rudstam and of Silberberg and Tsao.[56] We note here that a simplified estimate of the yields can be made by observing that once one looks at high energies above resonances and single particle and alpha particle effects, the products can be any particle stable nucleus with the yields almost uniformaly spread. If we wish the yield of product, A_p, from target A_t, when hit by a proton (or alpha), let us estimate that when A_t breaks up, it has $\sim A_t^2$

combinations of nucleon products. Since the total cross section σ is $\propto A_t^{2/3}$, then the yield to any given A_p is $\sim A_t^{2/3}/A_t^2 \sim A_t^{-4/3}$.

This dependence fits the observed data[55] quite well. As mentioned above, we also note that at high energy the relative yields for $A_t \gg A_p$ will just be the ratios of the number of particle stable nuclei with each A_p. (For A_t only slightly above A_p, single particle and alpha particle effects become dominant). In the case of B/Be yields, the ratio of particle-stable nuclei is ~ 3.9. Thus, we have used this ratio in estimating the relative yields for unmeasured targets with $A_t \gtrsim 20$. The yields of each A_t are weighted by the $A_t^{-4/3}$ cross section. Thus, higher A_t contribute less to any given A_p. Whenever the cross section is measured, the measured value is, of course, used in place of our estimate. Since all oxygen to B and Be yields have been measured, we can start our procedure at $A \geq 20$. When summed over the Cameron[59] relative abundances for alpha particle nuclei from oxygen to titanium, as might be appropriate for a Type II supernova, the above procedure with measured and estimated cross sections yields, the resultant ratio B/Be is 7.6 compared to a B/Be ratio of 8.6 using the Silberberg and Tsao[56] fitting formula. We view this ratio as a lower limit on the yield.

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