Primordial Synthesis of Anomalous Nuclei

Duane A. Dicus
Center for Particle Theory, University of Texas, Austin, Texas 78712

and

Vigdor L. Teplitz[(a)]
Strategic Affairs Division, U. S. Arms Control & Disarmament Agency, Washington, D. C. 20451
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We calculate the abundances of anomalous light, $Z>1$ nuclei that would be produced by primordial nucleosynthesis if there exist new neutral, stable baryons.

Recently Dover, Gaisser, and Steigman[1] and Wolfram[1] considered astrophysical consequences of a new neutral, stable baryon, H^0. H^0 and $\bar{H}^0$, which occur in certain models,[2] would be present ($H^0/p \simeq 10^{-11}$, roughly independent of the H^0 mass[3]) at the time of cosmic nucleosynthesis and would be incorporated into nuclei. Middleton *et al.*[4] subsequently set a limit of 10^{-16} on the terrestrial abundance of anomalous isotopes of oxygen. The purpose of this note is to estimate abundances of anomalous isotopes within the standard model of big-bang nucleosynthesis[5]; we use for reactions of anomalous nuclei analogous reactions of normal nuclei.[6] We assume that the N-H^0 force is similar to the N-Λ force and that the pattern of stable H^0 nuclei and their reactions is the same as that of Λ hyperfragments.[7] H^0 will occur in the 1s shell; and, because it has $I=0$, it does not feel the one-pion-exchange potential. Stable H^0-nuclei binding energies could be calculated (up to certain unknown parameters) using the methods of Dover and Kahana.[8] Such calculations would be

TABLE I. Reactions used for, and results obtained from, numerical calculations. The calculations for $^6He^*$ are described in detail [(1)–(4)]; the other calculations are similar. We have for each H^0 nucleus investigated other chains of reactions that could determine its abundance; on the basis of the rates of Ref. 11 the reactions used here are the most important. For example, neutron-induced reactions are seldom important because the neutron abundance falls exponentially with decreasing T_9.[5] Usually this more than compensates for the fact that the rate does not have the exponential barrier of (2).

Element A_Z^*	Production Reaction	Analogue Production Reaction(s)	Depletion Reaction(s)	Analogue Depletion Reaction(s)	$\frac{A_{Z^*}}{^5He^*}$	$\frac{A_Z^*}{All_Z}\times 10^{10}$
$^6He^*$	$^5He^*(n,\gamma)^6He^*$	$^6Li(n,\gamma)^7Li$	(a) $^6He^*(p,d)^5He^*$ (b) $^6He^*(p,\gamma)^7Li^*$	$^7Li(p,^4He)^4He$ $^7Be(p,\gamma)^8B$ or $^6Li(p,\gamma)^7Be$	– 0.04	– 0.04
$^7Li^*$	$^5He^*(d,\gamma)^7Li^*$	$^4He(d,\gamma)^6Li$	$^7Li^*(p,^3He)^5He^*$	$^6Li(p,^3He)^4He$	10^{-11}	3×10^{-4}
$^8Li^*$	$^5He^*(^3H,\gamma)^8Li^*$	$^4He(^3H,\gamma)^7Li$	$^8Li^*(p,^4He)^5He^*$	$^7Li(p,^4He)^4He$	10^{-10}	3×10^{-3}
$^9Be^*$	$^5He^*(^4He,\gamma)^9Be^*$	Average of $^4He(d,\gamma)^6Li$ $^6Li(^4He,\gamma)^{10}B$ $^{12}C(^4He,\gamma)^{16}O$ $^{16}O(^4He,\gamma)^{20}Ne$	$^9Be^*(d,^4He)^7Li^*$ $^9Be^*(p,\gamma)^{10}B^*$	$^7Li(d,n)2^4He$ $^6Li(p,\gamma)^7Be$	10^{-6}	3×10^{4}
$^{11}B^*$	$^9Be^*(d,\gamma)^{11}B^*$	Same as for $^9Be^*$	$^{11}B^*(d,^8Be)^5He^*$ $^{11}B^*(d,^4He)^9Be^*$	$^7Li(d,n)2^4He$	10^{-13}	6×10^{-5}
$^7Li^*$	$^9Be^*(d,^4He)^7Li^*$	$^7Li(d,n)2^4He$	$^7Li^*(p,^3He)^5He^*$	$^6Li(p,^3He)^4He$	10^{-15}	3×10^{-8}
$^8Li^*$	$^9Be^*(^3H,^4He)^8Li^*$	$^7Li(^3H,2n)2^4He$	$^8Li^*(p,^4He)^5He^*$	$^7Li(p,^4He)^4He$	10^{-13}	3×10^{-6}

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a step toward more precise anomalous cross sections; here, however, we assume that anomalous rates are similar, when corrected for barrier effects, to rates for analogous normal reactions. We note that a more detailed calculation is planned by others.[9]

Production of ^{5}He and lighter nuclei.*—Just as almost all neutrons end up in ^{4}He so will most H^0's end up in ^{5}He*. Following Dover, Gaisser, and Steigman,[1] we will assume $H^0/p \simeq 10^{-11}$ so that $^5He^*/^4He \simeq 10^{-10}$. We expect approximately the same 10^{-10} value for $^3H^*/^2H$, $^4H^*/^3H$, and $^4He^*/^3He$ as for $^5He^*/^4He$. We expect the ratio $^5He^*/^4He$ to be roughly constant with time[10] since the H^0 absorption reactions leading to ^{5}He* should have rates similar to n-absorption reactions leading to ^{4}He and, as shown by our calculations, most ^{5}He* once formed interacts no further while the ^{4}He abundance is, of course, constant for $T_9 < 0.8$ in the standard model.

^{6}He production.*—In "normal" nucleosynthesis the absence of a stable, mass-5 isotope suppresses heavy-element formation, since Li production then requires d or ^{3}H reactions, instead of a proton reaction, and these rates are suppressed by the small factors d/p and $^3H/p$. For anomalous nuclei the "gap" would occur at mass 6 but the existence of a stable, mass-6 hyperfragment, $^6_\Lambda$He, indicates the gap is filled by ^{6}He*. (The binding energy of $^6_\Lambda$He indicates that ^{6}He* is stable against β decay as well as strong decays.[7]) The reactions used to produce and to deplete ^{6}He* are given in the first row of Table I. In terms of these reactions the mass abundance of ^{6}He* ($Y_{^6He^*}$) is given by[5,11]

$$\frac{dY_{^6He^*}}{dt} = Y_{^5He^*} Y_n [v\sigma]_{^5He^*(n,\gamma)^6He^*} - Y_{^6He^*} Y_p ([v\sigma]_{^6He^*(p,d)^5He^*} + [v\sigma]_{^6He^*(p,\gamma)^7Li^*}), \tag{1}$$

where $[v\sigma]_{1(2,3)4}$ is related to the transition rate for nucleus 1 (to interact with 2) by[5,11] $1/\tau = [v\sigma]_{1(2,3)4} X_2/A_2$. The coefficients $[v\sigma]$ are tabulated by Fowler, Caughlan, and Zimmerman[11]; they are of the form

$$[v\sigma] = KhT_9^{3-2/3} \exp(-c/T_9^{1/3}), \tag{2}$$

where T_9 is the temperature of the universe in units of 10^9 K and hT_9^3 is the baryon (mass) density; c is a known coefficient determined by a WKB calculation of tunneling through the Coulomb barrier.[12] If Z_1 and Z_2 are the charges of nuclei 1 and 2 and A is the effective (reduced mass) atomic number, $A = A_1A_2/(A_1+A_2)$, then c equals $(Z_1^2Z_2^2A)^{1/3}$. K is determined from measured cross sections[11] and contains a factor[12]

$$\left(\frac{Z_1Z_2}{A}\right)^{1/3} \exp\left\{1.05[Z_1Z_2A(R_1+R_2)]^{1/2} - \frac{17.15\delta_{l,1}}{[Z_1Z_2A(R_1+R_2)]^{1/2}}\right\}, \tag{3}$$

where the factors in the exponent are the energy-independent parts of the Coulomb and angular momentum barriers. R_1 and R_2 are the radii of the two nuclei. We estimate the coefficients K by choosing analog reactions whose initial nuclei have properties similar (e.g., the same isospin values) to the nuclei under consideration and then correcting the K values with use of (3). The analog reactions are also listed in Table I. Let K and c for the production (depletion) reaction have values K_2 and c_2 (K_1 and c_1). Then, using $t = 200/T_9^2$, we solve (1) for the quantity $F_{^6He^*} = {^6He^*}/{^5He^*}$, obtaining

$$F_{^6He^*}(T_9) = 1200hK_2c_2 \int_{\exp(-c_2/T_9^{1/3})}^{\exp(-c_2/T_0^{1/3})} \frac{dy}{\ln^2 y} Y_n(y) \exp\left\{-1200hK_1c_1 \int_{\exp(-c_1/T_9^{1/3})}^{y^{c_1/c_2}} \frac{dz}{\ln^2 z} Y_p(z)\right\}, \tag{4}$$

where we take the normal abundances, Y, from Wagoner[5] and T_0 is the largest value of T_9 for which ^{6}He* is zero. We evaluate (4) numerically. If the strong interaction $^6He^*(p,d)^5He^*$ is exoergic, as indicated by the corresponding hyperfragments, then it will dominate and no significant amount of ^{6}He* will build up. Our mathematical results in this case can be fit, for $T_9 < 0.8$, by $5.6 \times 10^{38} \exp(-88.6/T_9^{1/3})$. If, on the other hand, the strong reaction is not present, then a significant amount of ^{6}He* would exist, changing considerably our conclusions regarding Li* abundance. We list as case (b), in row 1 of the Table, the case that $^6He^*(p,d)^5He^*$ does not go.

^{7}Li production.*—The reactions and the result are shown in the second row of Table I. We take the total abundance of Li from Reeves.[13] The sixth row of Table I shows that the relatively large amount of ^{9}Be* (see below) does not signifi-

cantly add to the amount of ^{7}Li*. All this assumes case (a) of row one; no ^{6}He* production. If, contrary to the indications from hyperfragments, ^{6}He* is plentiful, case (b) of row one, then a large amount of ^{7}Li* is produced through ^{6}He*$(p,\gamma)^7$Li*. We find a final abundance in this case of ^{7}Li*/^{5}He* $\simeq 6\times10^{-6}$ or a ratio of ^{7}Li* to all Li of 2×10^{-8}. In this case Li would be a good element to search for H^0, but still not as good as Be.

^{8}Li production.*—This is shown in rows 3 and 7 of Table I. Unlike ^{7}Li* the amount of ^{8}Li* would not be radically changed by the presence of ^{6}He* since deuterium would be required to produce it via ^{6}He*$(d,\gamma)^8$Li*.

^{9}Be production.*—^{8}Be is unstable leaving the normal elements with a second mass gap at 8. $^9_\Lambda$Be is stable, however, and prevents a mass gap in anomalous nuclei at 9. Furthermore, the strong reaction which depletes ^{9}Be* requires the use of deuterium [^{9}Be*$(p,{}^3\text{He})^7$Li* is endoergic] and is thus suppressed. The observed abundance[13] of Be is about $10^{-10.7}$ and thus ^{9}Be*/^{5}He* is enhanced by a factor of $\sim 3\times10^4$ over ^{9}Be/^{4}He. This would appear to make Be the best light element to check for H^0 and $\bar{H}^0$.

Boron production.—Hyperfragment Λ-binding energies[7] imply that ^{10}B*, which is stable under strong interactions, should β decay to ^{10}Be*. This means the first possibility for a stable boron isotope is ^{11}B*. It may be that this one also β decays; we have found no binding energy data on $^{11}_\Lambda$C and $^{11}_\Lambda$Be with which to decide. Assuming ^{11}B* is stable, we have calculated its abundance as shown in the fifth row of Table I; ^{11}B*/^{5}He* is small.

Variation of parameters.—It is difficult to quantify the uncertainty introduced into the numerical results by the range of choices for an analogue reaction or by deviation of the true reaction rate from any analog-deduced value. An illustrative, extreme example is that of ^{5}He*$({}^4\text{He},\gamma)^9$Be* for which no analog can have similar doubly magic A values. For K, from (3), one obtains from the analog reactions of Table I, $K=2\times10^4$, $(3.5-1)\times10^5$, $(2-300)\times10^4$, and 6×10^3 for ^{4}He, ^{6}Li, ^{12}C, and ^{16}O, respectively; the ranges for ^{6}Li and ^{12}C correspond to extra variation[11] in the rates beyond (2) over the temperature range $T_9=0.85$ to $T_9=0.0$. We used, for this case, $K=7\times10^4$; the final value for ^{9}Be* scales roughly linearly with K. In other cases where we made choices between different analog reactions, we chose the one which maximized the Li* abundance and minimized the Be* abundance. The calculations above were performed with $m_{H^0}=m_n$. The value of m_{H^0} enters the calculation only through the mass number A which enters the reaction rate only through c in (2) and through K from (3). The effect of changing A tends to cancel between the temperature-dependent term in (2) and the temperature-independent terms in (3). We have checked numerically that as m_{H^0} varies from 0 to ∞ the ^{9}Be* and Li* abundances vary by less than a factor of 2. We have, in the calculations above, assumed the baryon density factor h to be 10^{-5}. The maximum h allowed by the deuterium abundance is 3×10^{-5}. Varying h, in the calculation of ^{9}Be*, from this upper limit down to 10^{-6} indicates that the anomalous abundance is almost directly proportional to h. Thus, ^{9}Be*/^{5}He* could be increased by a factor of 3 or decreased by as much as 10. The other anomalous abundances should change in much the same way. The K values are sensitive to the radii in (3). We have taken normal radii from Preston[14] and assumed the radius of each anomalous nucleus, ^AZ*, is equal to the radius of the normal nucleus, ^{A-1}Z. We estimate that changing the radii of the anomalous particles by 20% will not change the abundances by more than a factor of 3. In view of these uncertainties, and the larger uncertainty in the abundances of the normal nuclei,[13] a reasonable error to assign to the values in the final column of Table I would seem to us to be a factor of 10 in each direction.

Given an H^0 abundance $H^0/p=10^{-11}$ at the time of cosmic nucleosynthesis primordial He*/He (all primordial He* isotopes/ all He) should be 10^{-10} while Li*/Li and B*/B should be much less —probably $3\times10^{-13\pm1}$ and $6\times10^{-15\pm1}$, respectively. Primordial Be*/Be is considerably larger, $3\times10^{-6\pm1}$. Uncertainties from our choice of single dominant reactions over retention of the complete network and from our use of analogous reactions to establish rates could, perhaps, change these results beyond the normal $10^{\pm1}$ quoted but would be unlikely to reverse the factor of 10^7 by which Be is favored over Li or B. We therefore recommend that further searches for H^0's be directed to beryllium.

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[(a)]Permanent address after June 30, 1980: Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061.

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[2]See, for example, F. Wilczek and A. Zee, Phys. Rev. D 16, 860 (1977), and reference cited therein and in Ref. 1.

[3]We use particle symbols for particle number densities and denote nuclei containing an H^0 or $\bar{H}^0$ by $^AZ*$, where A is the total baryon number and Z is the atomic symbol.

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[9]E. W. Kolb and G. Steigman have informed us of a calculation in progress by C. Dover, W. Fowler, E. Kolb, and G. Steigman.

[10]Dr. Kolb has informed us of an interesting analogous result from the calculation of Ref. 9: If the mass gap in normal nuclei at $A=5$ is "artificially closed" the full network of nuclear reactions of Ref. 5 then leads to a "^{5}He"/^{4}He ratio that varies by less than a factor of 2 over the time of nucleosynthesis.

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ERRATUM

ANOMALOUS CONDUCTION-ELECTRON POLARIZATION IN SUPERCONDUCTING YRh_4B_4. P. K. Tse, A. T. Aldred, and F. Y. Fradin [Phys. Rev. Lett. 43, 1825 (1979)].

On page 1826, second column, the third line is a repeat of the second line, second column on page 1825 of our paper. Instead, the line on page 1826 should read "transition in the magnetically doped alloys. There . . . ."