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PRIMORDIAL NUCLEOSYNTHESIS AND THE ABUNDANCE OF BERYLLIUM AND BORON *

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Abstract

The ability to now make measurements of Be and B as well as put constraints on ^{6}Li abundances in metal-poor stars has led to a detailed reexamination of Big Bang Nucleosynthesis in the $A \gtrsim 6$ regime. The nuclear reaction network has been significantly expanded with many new rates added. It is demonstrated that although a number of $A > 7$ reaction rates are poorly determined, even with extreme values chosen, the standard homogeneous model is unable to produce significant yields (Be/H and B/H $< 10^{-17}$ when $A \leq 7$ abundances fit) above $A = 7$ and the ^{7}Li/^{6}Li ratio always exceeds 500. We also preliminarily explore inhomogeneous models, such as those inspired by a first order quark-hadron phase transition, where regions with high neutron/proton ratios can allow some leakage up to $A > 7$. However models that fit the $A \leq 7$ abundances still seem to have difficulty in obtaining significant $A > 7$ yields.

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1. Introduction

Over the last quarter century the standard homogeneous model of Big Bang nucleosynthesis has proved spectacularly successful at predicting the primordial abundances of the light elements. In particular, Homogeneous Big Bang Nucleosynthesis (BBN) (see Walker et al. 1991 and references therein) successfully fits ^{1}H, ^{2}H, ^{3}H, ^{4}He, and ^{7}Li abundances in primordial objects (extremely low Z) over a dynamic range in abundance of almost ten orders of magnitude. The fit to these abundances has become the prime determinator of the cosmological density of baryons ($\Omega_b \sim 0.05$ where Ω_b is the fraction of the critical density in baryons). Also of significance has been BBN's prediction of the number of neutrino flavors (Steigman, Schramm & Gunn 1977, Yang et al. 1984, Walker et al. 1991) which has now been confirmed in accelerator experiments.

Because of the double particle instability gaps at $A = 5$ and $A = 8$ it was rapidly recognized that homogeneous BBN produces small amounts of $A = 7$ (^{7}Li/H$\sim 10^{-10}$) and no significant yields for $A > 7$. Recently observers have begun to be able to observe Be and B in extreme pop. II stars with low Z (Rebolo et al. 1988, Ryan et al. 1990, Gilmore, Edvardsson & Nissen 1991, Duncan, Lambert & Lemke 1992, Gilmore et al. 1992, Ryan et al. 1992) and have begun to put limits on ^{6}Li in similar objects (Andersen, Gustafsson & Lambert 1984, Spite & Spite 1982, Hobbs & Pilachowski 1988, Hobbs & Thornburn 1991). Data to date on Be and B are best understood as being due to cosmic ray spallation (Walker et al. 1992, Steigman & Walker 1992) and ^{6}Li is still undetected. However, because of the potential for new developments here, we have reexamined BBN yields with a particular focus on $A \geq 6$. While the basic conclusions of the earlier calculations remain unchanged, we did note that the networks used earlier were not particularly complete for $A \geq 6$. (This relative incompleteness had little or no effect on $A < 6$ yields.) Therefore we have extended the nuclear reaction network and included many links that were missing (or

poorly estimated) in earlier calculations. Where links in our new network are poorly known we have run the calculation with a range of values to assess the sensitvity to those links. We feel this present paper is the most thorough exploration of high $A(\geq 6)$ Homogeneous Big Bang Nucleosynthesis done to date.

A much discussed alternative to Homogeneous Big Bang Nucleosynthesis has been the first-order quark-hadron phase-transition inspired inhomogeneous model (Alcock, Fuller & Mathews 1987, Applegate, Hogan & Scherrer 1988, Turner 1988, Terasawa & Sato 1989, Kurki-Suonio et al. 1990). It had been proposed (Boyd & Kajino 1989, Malaney & Fowler 1989) that in such a model, the high n/p regions may allow leakage beyond the $A = 8$ gap and produce interesting amounts of Be and B. While Terasawa & Sato (1990) argued against such leakage, we noted that their network was not as complete as the one we have developed for the homogeneous case and that our more complete network may be needed to fully explore the situation. In addition, with our enhanced network, we are able to quantitatively compare the yields of the heavier elements in the homogeneous and inhomogeneous models.

Thus in this paper we will also do a preliminary exploration of high n/p conditions with a homogeneous calculation. (Since high n/p values only occur in the low density zones of inhomogeneous models, high baryon to photon results are less significant than the low baryon to photon results for our high n/p calculation.) In a future paper we will do a more complete exploration of inhomogeneous models using a full multizoned model with back diffusion as in Alcock, Fuller & Mathews (1987), Kurki-Suonio et al. (1990), Terasawa & Sato (1990). However, at present to get a feel for the full network and see the critical points in the calculation we felt this simpler exploration was necessary and illustrative of the network itself.

One point we emphasize is that the high A calculations cannot be used without making

sure that the low A abundances are fit. As Kurki-Suonio et al noted, the inhomogeneous calculations still require about the same Ω_b as the standard homogeneous BBN model. Thus any leakage up to high A must occur with standard Ω_b values if it is to be relevant.

2. The Reaction Network

Up until now, the emphasis in measuring astrophysically relevant nuclear reaction rates has generally been on those reactions involved in the production of elements up to Li. Of the yields for $A \leq 7$ only ^{7}Li has been found to be sensitive (Kawano et al. 1988, Krauss & Romanelli. 1990) to uncertainties in the measured reaction rates.

We have updated the reaction network in an attempt to resolve this question for $A \geq 6$. In table 1 we list the reactions that have been added (A) or updated (U) to the last version of the code (Walker et al. 1991) which itself is an updated version of Wagoner's code (Wagoner 1969), modified to evaluate neutron–proton weak interaction rates according to the prescription of Walker et al. (1991). The majority of the reaction rates used came from Caughlan and Fowler (1988). To this set we added reactions from Wagoner (1969), Lederer & Shirley (1978), Endt & Van der Leun (1978), Ajzenberg-Selove (1983), Tuli (1985), Malaney & Fowler (1989), Boyd & Kajino (1989), Wiescher, Steininger & Käppeler (1989), Wang, Vogelaar & Kavanagh (1991), Kawano et al. (1991), Brune, Kavanagh, Kellogg & Wang (1991), Barhoumi et al. (1991), Becchetti et al. (1992), Boyd et al. (1992a), and Boyd et al. (1992b). We also included reactions from Smith, Kawano & Malaney (1992) as given in Kawano (1992). In a number of cases (listed in table 1) we were unable to find any reliable figures for reactions in the relevant temperature range and made estimates (E). For a few reactions we have found more than one rate published recently and have tested for sensitivity (S) when these differed beyond stated errors. The complete network is shown in fig. 1. For the most part we used the most recently published rate, whenever more than one expression was available. For the reactions labelled S in table 1

we ran the code using the rates from each of the sources listed. For estimated rates or rates where experimental values differed outside of the published error bars we made tests of the sensitivity of our results by arbitrarily increasing and decreasing that particular rate by a factor of 1000 or by using the extreme experimental value to see the sensitivity of the result. The actual prefered reaction rates selected are shown in table 1, and the explicit rates used are given in Appendix 1.

In order to ensure that our network is sufficiently extensive, we have plotted flow diagrams (see figs. 2) for $\eta_{10} = 1.0$ for both the standard calculation, and for high n/p ($\eta_{10} = \eta \times 10^{10}$). These were produced by connecting the nuclide with the greatest increase in mass fraction, to that with the greatest decrease (omitting nuclides with $A \leq 4$) at each time step. This gives a pictorial representation of which links are most significant in producing any given nuclide. Fig. 2a shows that in the standard model, most of the flow proceeds along the central portion of the network, with the exception of the flow to ^{18}O. It was this ^{18}O that prompted us to add ^{16}C, ^{16}N, ^{17}N, ^{19}O, ^{20}O, ^{19}F, ^{20}F, ^{21}F and ^{21}Ne to our original network, however this made no difference to the yields of the light elements. Fig. 2b shows that for $n/p = 10$, even with the extended network, there is a significant flow on the neutron-rich side, particularly to ^{18}O and ^{19}O. Obviously, to accurately explore neutron-rich flows requires networks as rich as the one we use here. Previous explorations of $A > 7$ yields have not used such an extensive network.

3. The Results

The yields of the light elements are shown as functions of the baryon to photon ratio η, for a neutron mean-life of 889.6 sec. in figs. 3. Figure 3a shows the ^{4}He mass fraction as a function of the baryon to photon ratio, $\eta = n_B/n_\gamma$ and figure 3b shows the abundances of ^{2}H, ^{3}He, ^{6}Li and ^{7}Li. In particular, ^{7}Li is always greater than ^{6}Li by a factor of at least 500 (at $\eta_{10} = 0.01$), while for $\eta_{10} \sim 3$ (where calculations agree with observations)

the ^{7}Li/^{6}Li ratio is 4700.

Of the reactions labelled S in table 1, the only rate whose variation has a significant effect on the results is ^{7}Li(t,n)^{9}Be. This sensitivity is shown in fig. 3c. Furthermore, variation in this reaction affects only ^{9}Be and ^{10}B. Yields of the lighter elements (H, He, Li) are unaffected by the variation in any of the rates S.

The double hump for ^{11}B is a result of the fact that it can be created directly (for low η) or through ^{11}C (high η) which then β-decays to ^{11}B. The highest yield for both ^{9}Bc and ^{10}B is given by the ^{7}Li(t,n)^{9}Be rate taken from Boyd & Kajino (1989). The lowest is from Malaney & Fowler (1989). Note that in no case is it possible to produce a ^{9}Be number density relative to hydrogen greater than about 10^{-14}. If we consider the observational limits on H, He and Li then η is constrained by $2.8 \lesssim \eta_{10} \lesssim 4.0$ (Walker et al. 1991). In this range ^{9}Be/H has a maximum yield of 6×10^{-18}, and ^{11}B/H a maximum of 8×10^{-17}.

For the reactions labelled E it was necessary to make estimates of the rates. Unfortunately the presence of resonances at nucleosynthesis energies can influence the reaction rate by many orders of magnitude. We have tried a number of approaches to this problem. Some of the reactions in question are given in Delano (1969). However, Delano parameterizes his rates for $1 \leq T_9 \leq 10$ and is not explicit about his estimation methods. Nor are they transparent from his rate expressions which are all fit to a standard form. The only theory he mentions is a statistical nuclear model which is only accurate for heavy nuclei with a large, even distribution of levels lying within nucleosynthesis energies.

To understand the possible effects of the unmeasured rates, one would ideally like to at least have upper bounds on them. Such limits are enormous, however, as resonances at the effective nucleosynthesis energy

$$E_{\rm eff} = [\pi\alpha Z_0 Z_1 kT(\mu c^2/2)^{1/2}]^{2/3} = 0.12204 Z_0^{2/3} Z_1^{2/3} \frac{A_0 A_1}{A_0 + A_1} T_9^{2/3}\ {\rm MeV} \qquad (1)$$

(where $\alpha \approx 1/137$, Z_0 and Z_1 are the charges of the incoming nuclei, and μ their reduced

mass) can enhance a reaction rate to many orders of magnitude larger than reactions that are nonresonant, or occur through the tail of a resonance. We have made estimates of the rates to compare with Delano's. To do this we assumed each reaction had two contributions, one nonresonant and one resonant. In both cases the reaction rates can be given by expressions of the form

$$\langle \sigma v \rangle_T = \lambda_0 T^{-n} \exp(-a/T^m) \tag{2}$$

where the constants λ_0, a, n and m differ for the two cases.

In the nonresonant case, the exponential part of the rate is determined by the nuclear masses and charges, so that it is only the preexponential factor which is unknown. We have estimated this factor (the unknown part of which is the cross section factor $S(0)$) using the method of Fowler & Hoyle (1964), and making conservative estimates of optical model parameters we have

$$\langle \bar{\sigma} v \rangle \approx \left(\frac{2}{\mu}\right)^{5/6} \left(\frac{2\hbar}{kT}\right)^{2/3} \frac{(2\pi e^2 Z_0 Z_1)^{4/3}}{(3V_0)^{1/2}} \exp(2x - \tau) \tag{3}$$

where $V_0 \approx 40$ MeV gives a good fit to known cross-sections,

$$x = 2\sqrt{2\mu Z_0 Z_1 e^2 R/\hbar^2}; \quad R = R_0(A_0^{1/3} + A_1^{1/3}); \quad R_0 = 1.44\text{fm} \tag{4}$$

and

$$\tau = 3E_{\text{eff}}/kT \tag{5}$$

Thus our rate is computed in an appropriate low-energy limit, but arises from an optical model which assumes a smoothly varying and large level density which we do not expect to be very accurate for the light nuclei we consider.

In the resonant case, we used a recent tabulation by Ajzenberg-Selove (1985, 1986, 1988) to locate levels and to find their widths. Knowing the resonant energy fixes the exponential term in the rate, and so again we are uncertain only in the preexponential factor. The unknown part here is the reduced width $(\omega\gamma)_r \sim \sigma_r E_r \Gamma_r$, in which the cross section at resonance, σ_r is unknown. For this we have assumed an arbitrary but generous value of 1 barn.

Using these estimates can have a significant effect on nuclear yields (although not for ^{9}Be or any of the lighter elements). In particular, $^{10}\mathrm{B}(\alpha,\gamma)^{14}\mathrm{N}$ and $^{11}\mathrm{B}(\alpha,\gamma)^{15}\mathrm{N}$ reduce the yields of ^{10}B and ^{11}B respectively by two or three orders of magnitude at $\eta_{10} = 3$, and while $^{11}\mathrm{C}(\alpha,\gamma)^{15}\mathrm{O}$ has no effect at $\eta_{10} = 3$, it removes ^{11}C almost completely above $\eta_{10} = 10$. We emphasize however, that these reaction rates are dominated by contributions from resonances near the entrance channel, and that we consider them to be extreme upper limits.

In order to find more reasonable limits we have also tried using Delano's expressions directly (with results identical to those obtained by omitting all reactions E) and estimating rates on the basis of "similar" reactions. For each reaction E, we used a rate which was higher than the rate of any reaction with a similar form (say all reactions X(n,p)Y for the case of $^{12}\mathrm{N(n,p)}^{12}\mathrm{C}$), and also higher than Delano's rate (where one was available) within the range $1 \leq T_9 \leq 10$, and than increased the result by a factor of 1000. The only reaction for which this had any effect on the results was $^9\mathrm{Li(d,n)}^{10}\mathrm{Be}$. Using 1000 times the rate for $^6\mathrm{Li(d,n)}^7\mathrm{Be}$ (Malaney & Fowler 1989) increases the yield of ^{10}B by up to a factor of 2 for $\eta_{10} \lesssim 0.1$. (For $\eta_{10} \gtrsim 0.1$ the effect is again insignificant.)

Clearly further experimental data would be helpful, however we believe (with a few special exceptions that will be mentioned later) that these reactions are likely to have little, if any, effect on the light element abundances.

The significance of the Be and B calculations has been made evident by recent observations in a number of low metallicity halo dwarf stars of these two elements. It is generally known that big bang nucleosynthesis is incapable of producing an observable amount of either of these two light elements. In fact, Be and B have generally been thought to have been produced by cosmic ray spallation. Indeed, in recent analyses, the observed Be and B have been argued to be explicable entirely in terms of cosmic ray spallation in the early galaxy, while maintaining consistency with big bang nucleosynthesis . (Spallation also produces ^{7}Li which thereby reduces the required production from big bang nucleosynthesis, but as emphasized by Olive & Schramm (1992) this reduction is still completely compatible with the other cosmological light element abundances). Furthermore, it has been speculated that inhomogeneous models may provide for enhanced Be and B abundances relative to the standard model. Here, we have found that the standard model production of Be and B is indeed negligible relative to the observations and in our exploration of high n/p we find that while Be and B yields are enhanced, they are still well below the observations.

4. Limits on Inhomogeneous Yields

To obtain an extreme upper limit on the yields produced by inhomogeneous nucleosynthesis, we show in figs. 4a,b the results of running the code with the initial neutron-proton ratio raised, for $\eta_{10} = 3.0$. (In these runs we have frozen the n/p ratio at the value given on the ordinate axis for temperatures down to $T_9 = 5$, below which the calculation is allowed to proceed as normal.) Raising n/p has the effect of increasing the yields of the light elements, however it is important to note that in an accurate calculation the large yields in the high n/p regions are diluted by the smaller yields in the low n/p regions as well as by interactions at the interface of the regions.

Note that increasing n/p ceases to cause significant effects for n/p$\gtrsim$ 3, and any realistic calculation with multizones (e.g. Kurki-Suonio et al. 1990) has been found to have much

back-diffusion, reducing the magnitude of any extremes. Fig. 4b shows that in our extreme cases ^{9}Be saturates at a yield of $\lesssim 10^{-12}$, however, note that ^{4}He is overproduced in all high n/p zones by a factor of ~ 4. Thus the minimum reduction must be at least a factor of 4, and as mentioned before, realistic multizone models will yield even greater reductions. In a future paper we will investigate more thoroughly the effects of our updated network on inhomogeneous nucleosynthesis, however from the current preliminary exploration it seems unlikely that the yields can be sufficient to produce the Be and B abundances observed in some Pop II stars (Ryan et al 1990, Gilmore, Edvardsson & Nissen 1991, Duncan, Lambert & Lemke 1992).

5. Conclusions

We have shown that even with our extended reaction network, the standard homogeneous model of primordial nucleosynthesis is unable to produce significant yields of Be and B. In addition, it appears that inhomogeneous nucleosynthesis is unlikely to produce much greater yields, even though there are uncertainties in some reactions.

Finally, we feel it would be useful to have further data on those nuclear reaction rates marked S and E in table 1. In particular, ^{7}Li(t,n)^{9}Be, ^{8}Li(p,γ)^{9}Be and ^{9}Li(p,n)^{9}Be may have a measurable effect on ^{9}Be production. ^{10}B$(\alpha,\gamma)^{14}$N, ^{11}B$(\alpha,\gamma)^{15}$N and ^{11}C$(\alpha,\gamma)^{15}$O may also be critical in the production of the heavier elements.

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Appendix 1—Reaction Rates

We present below the rates, in Fortran notation, used for reactions introduced or updated since Walker et al (1991). The notation is the usual one, used in astrophysical reaction rate tabulations, in which T9ab = $T_9^{a/b}$, T9Mab = $T_9^{-a/b}$ and the expressions represent values for $F \equiv N_A\langle\sigma v\rangle$, where N_A is Avogadro's number, σ the cross-section, v relative velocity, and the thermal average is taken over a Boltzmann distribution.

$^{3}\mathrm{H} + \mathrm{e} \rightarrow {}^{3}\mathrm{He}$
F = 1.78E-9

$^{8}\mathrm{Li} \rightarrow \mathrm{e} + 2^{4}\mathrm{He}$
F = 8.27E-1

$^{11}\mathrm{Be} \rightarrow \mathrm{e} + {}^{11}\mathrm{B}$
F = 0.0502

$^{8}\mathrm{B} + \mathrm{e} \rightarrow 2^{4}\mathrm{He}$
F = 9.00E-1

$^{12}\mathrm{B} \rightarrow \mathrm{e} + {}^{12}\mathrm{C}$
F = 3.43E+1

$^{11}\mathrm{C} + \mathrm{e} \rightarrow {}^{11}\mathrm{B}$
F = 5.67E-4

$^{14}\mathrm{O} + \mathrm{e} \rightarrow {}^{14}\mathrm{N}$
F = 9.82E-3

$^{15}\mathrm{O} + \mathrm{e} \rightarrow {}^{15}\mathrm{N}$
F = 5.67E-3

$^{17}\mathrm{F} + \mathrm{e} \rightarrow {}^{17}\mathrm{O}$
F = 0.0107

$^{18}\mathrm{F} + \mathrm{e} \rightarrow {}^{18}\mathrm{O}$
F = 1.052E-4

$^{18}\mathrm{Ne} + \mathrm{e} \rightarrow {}^{18}\mathrm{F}$
F = 0.4146

$^1H + p \rightarrow e^+\nu + {}^2H$

```
    IF (T9 .LE. 3.)  THEN
    F = 4.01E-15*T9M23*EXP(-3.380/T913)
    * (1.+.123*T913+1.09*T923+.938*T9)
    ELSE
    F = 1.16E-15
    END IF
```

$^1H + e + p \rightarrow \nu + {}^2H$

```
    IF (T9 .LE. 3.)  THEN
    F = 1.36E-20*T9M76*EXP(-3.380/T913)
    * (1.-.729*T913+9.82*T923)
    ELSE
    F = 7.38E-12
    END IF
```

$^3He + e \rightarrow \nu + {}^3H$

```
    IF (T9 .LE. 3.)  THEN
    F = 7.71E-12*T932*EXP(-.2158/T9)
    * (1.+6.48*T9+7.48*T9**2+2.91*T9**3)
    ELSE
    F = 6.20E-9
    END IF
```

$^3He + p \rightarrow e^+\nu + {}^4He$

```
    IF (T9 .LE. 3.)  THEN
    F = 8.78E-13*T9M23*EXP(-6.141/T913)
    ELSE
    F = 5.97E-15
    END IF
```

$^7Be + e \rightarrow \nu\gamma + {}^7Li$

```
    IF (T9 .LE. 3.)  THEN
    F = 1.34E-10/T912 * (1.-.537*T913+3.86*T923
    + .0027*EXP(2.515E-3/T9)/T9)
    ELSE
    F = 6.39E-10
    END IF
```

$^6He \rightarrow e + {}^6Li$

```
    F = 0.859
```

$^9Li \rightarrow e + {}^9Be$

```
    F = 0.9846
```

$^9Li \rightarrow en + 2^4He$

```
    F = 2.9538
```

^{10}Be(p,γ)^{11}B

```
    F = 2.45E+6*T9M23*EXP(-10.39/T913)
```

^{16}O(p,γ)^{17}F

```
    F = 1.50E+8/(T923*(1.+2.13*(1.-EXP(-0.728*T923))))
    *EXP(-16.692/T913)
```

^{17}O(p,γ)^{18}F

```
    T9A = T9/(1.+2.69*T9)
    F = 7.97E+7*T9A**(5./6.)*T9M32*EXP(-16.712/T9A**(1./3.))
    + 1.51E+8*T9M23*EXP(-16.712/T913)*(1.+0.025*T913
    - 0.051*T923-8.82E-3*T9) + 1.56E+5*EXP(-6.272/T9)/T9
    + 1.31*T9M32*EXP(-1.961/T9)
```

^{4}He(nn,γ)^{6}He

```
    F = 4.04E-12/T9**2 * EXP(-9.585/T9)*(1.+.138*T9)
```

^{7}Li(n,γ)^{8}Li

```
    F = 3.144E+3 + 4.26E+3*T9M32*EXP(-2.576/T9)
```

^{8}Li(n,γ)^{9}Li

```
    F = 4.294E+4 + 6.047E+4*T9M32*EXP(-2.866/T9)
```

^{9}Be(n,γ)^{10}Be

```
    F = 1.26E+3
```

^{10}Be(n,γ)^{11}Be

```
    F = 1.32
```

^{11}B(n,γ)^{12}B

```
    F = 7.29E+2+T9M32*(2.25E+3*EXP(-0.221/T9)
    +3.26E+4*EXP(-4.514/T9)+1.96E+4*EXP(-10.804/T9)
    +3.90E+4*EXP(-13.323/T9)+5.86E+4*EXP(-18.916/T9))
```

^{16}O(n,γ)^{17}O

```
    F = 2.36E+1*(1.+4.45*T9)+9.66E+4*T9M32*EXP(-4.75/T9)
```

^{17}O(n,γ)^{18}O

```
    F = 3.11*(1.+100.*T9)
```

^{14}N(n,p)^{14}C

```
    F = 2.39E+5*(1.+.361*T912+.502*T9)
    + 1.112E+8*EXP(-4.983/T9)/T912
```

^{14}O(n,p)^{14}N

```
    F = 2.02E+8*(1.+.658*T912+.379*T9)
```

$^{17}F(n,p)^{17}O$

```
      F = 1.80E+8
```

$^{18}F(n,p)^{18}O$

```
      F = 1.80E+8
```

$^{11}Be(p,n)^{11}B$

```
      F = 1.71E+11*T9M23*EXP(-10.42/T913)
```

$^{12}C(\alpha,\gamma)^{16}O$

```
      F = 1.04E+8*EXP(-32.120/T913-(T9/3.496)**2)
      / (T9*(1.+.0489*T9M23))**2
      + 1.76E+8*EXP(-32.120/T913)/(T9*(1.+.2654*T9M23))**2
      + 1.25E+3*T9M32*EXP(-27.499/T9)
      + 1.43E-2*T9**5*EXP(-15.541/T9)
```

$^{14}C(\alpha,\gamma)^{18}O$

```
      F = 3.375E+8*EXP(-32.513/T913)/T9**2
      + 1.528E+9*T9M23*EXP(-32.513/T913-(T9/2.662)**2)
      * (1.+0.0128*T913-0.869*T923
      - 0.0779*T9+0.321*T943+0.0732*T953)
      + 9.29E-8*T9M32*EXP(-2.048/T9)
      + 2.77E+3*EXP(-9.876/T9)/T9**(4./5.)
```

$^{14}N(\alpha,\gamma)^{18}F$

```
      F = 7.78E+9*T9M23*EXP(-36.031/T913-(T9/0.881)**2)
      * (1.+0.012*T913+1.45*T923+0.117*T9+1.97*T943+0.406*T953)
      + 2.36E-10*T9M32*EXP(-2.798/T9)+2.03*T9M32*EXP(-5.054/T9)
      + 1.15E+4*T9M32*EXP(-12.310/T9)
```

$^{14}O(\alpha,\gamma)^{18}Ne$

```
      F = 9.47E+8*T9M23*EXP(-39.388/T913-(T9/.717)**2)
      * (1.+.011*T913+1.974*T923+.146*T9+3.036*T943+.572*T953)
      + 1.16E-1*T9M32*EXP(-11.733/T9)
      + 3.39E+1*T9M32*EXP(-22.609/T9)
      + 9.10E-3*T9**5*EXP(-12.159/T9)
```

$^{11}B(\alpha,p)^{14}C$

```
      F = 8.403E+15*(1.+0.022*T913+5.712*T923+0.642*T9
      +15.982*T943+4.062*T953)
      *EXP(-31.914/T913-(T9/0.3432)**2)
      +4.944E+6*T9**(3./5.)*EXP(-11.26/T9)+T9M32
      *(5.44E-3*EXP(-2.868/T9)+2.419E+2*EXP(-5.147/T9)
      +4.899E+2*EXP(-5.157/T9))
```

$^{11}C(\alpha,p)^{14}N$

```
      T9A = T9/(1.+4.78E-2*T9+7.56E-3*T953/(1.+4.78E-2*T9)**(2./3.))
      F = 7.15E+15*T9A56*T9M32*EXP(-31.883/T9A13)
```

$^{14}O(\alpha,p)^{17}F$

```
F = 1.68E+13*T9M23*EXP(-39.388/T913-(T9/0.717)**2)
* (1.+0.011*T913+13.117*T923+0.971*T9+85.295*T943
+ 16.061*T953)
+ 3.31E+4*T9M32*EXP(-11.733/T9)+1.79E+7*T9M32
* EXP(-22.609/T9)
+ 9.E+3*T9**(11./3.)*EXP(-12.517/T9)
```

$^{7}Li(p,\alpha\gamma)^{4}He$

```
T9A=T9/(1.+.759*T9)
F = 1.096E+9*T9M23*EXP(-8.472/(T913))
-4.830E+8*(T9A**(5./6.))*T9M32*EXP(-8.472/(T9A**.333333333))
+1.06E+10*T9M32*EXP(-30.442/T9)
+1.56E+5*T9M23*EXP(-8.472/T913-(T9/1.696)**2)
*(1.+.049*T913+2.498*T923+.860*T9+3.518*T943+3.080*T953)
+1.55E+6*T9M32*EXP(-4.478/T9)
```

$^{10}Be(p,\alpha)^{7}Li$

```
F = 2.45E+11*T9M32*EXP(-10.39/T913)
```

$^{11}Be(p,\alpha)^{8}Li$

```
F = 8.57E+10*T9M23*EXP(-10.42/T913)
```

$^{11}B(p,\alpha)2^{4}He$

```
F = 2.20E+12*T9M23*EXP(-12.095/T913-(T9/1.644)**2)
*(1.+.034*T913+.140*T923+.034*T9+.190*T943+.116*T953)
+4.03E+6*EXP(-1.734/T9)*T9M32
+6.73E+9*EXP(-6.262/T9)*T9M32
+3.88E+9*EXP(-14.154/T9)/T9
```

$^{17}O(p,\alpha)^{14}N$

```
F = 1.53E+7*T9M23*EXP(-16.712/T913-(T9/0.565)**2)
* (1.+0.025*T913+5.39*T923+0.940*T9+13.5*T943+5.98*T953)
+ 2.92E+6*T9*EXP(-4.247/T9)
+ 0.1*(4.81E+10*T9*EXP(-16.712/T913-(T9/0.04)**2)
+ 5.05E-5*T9M32*EXP(-0.723/T9)
+ 1.31E+1*T9M32*EXP(-1.961/T9))
```

$^{18}O(p,\alpha)^{15}N$

```
F = 3.63E+11*T9M23*EXP(-16.729/T913-(T9/1.361)**2)
* (1.+0.025*T913+1.88*T923+0.327*T9+4.66*T943+2.06*T953)
+ 9.9E-14*T9M32*EXP(-0.231/T9)+2.66E+4*T9M32*EXP(-1.67/T9)
+2.41E+9*T9M32*EXP(-7.638/T9)+1.46E+9*EXP(-8.31/T9)/T9
```

$^{18}F(p,\alpha)^{15}O$

```
F = 9.52E+12*T9M23*EXP(-18.1/T913)
```

$^{8}Li(\alpha,n)^{11}B$

```
      F = T9M32*(5.505E+6*EXP(-4.410/T9)
      +4.596E+8*EXP(-6.847/T9))
      +1.E+13*T9M23*EXP(-19.45/T913)*(2.02*T913
      +17.71*T923+17.65*T9+3.57*T943)
```

$^{10}Be(\alpha,n)^{13}C$

```
      F = 3.64E+14*T9M23*EXP(-24.12/T913)
```

$^{11}Be(\alpha,n)^{14}C$

```
      F = 4.51E+14*T9M23*EXP(-24.33/T913)
```

$^{10}B(\alpha,n)^{13}N$

```
      F = 1.20E+13*T9M23*EXP(-27.989/T913-(T9/9.589)**2)
```

$^{11}B(\alpha,n)^{14}N$

```
      F = 2.468E+15*(1.+7.519*T913+1.361*T923-14.972*T9
      -11.61*T943+18.145*T953)*EXP(-18.145/T913
      -(T9/0.7207)**2)
      +1.459E+7*T9**(3./5.)*EXP(-11.26/T9)+T9M32
      *(1.79*EXP(-2.868/T9)+1.678E+3*EXP(-5.147/T9)
      +5.358E+3*EXP(-5.157/T9))
```

$^{13}C(\alpha,n)^{16}O$

```
      F = 6.77E+15*T9M23*EXP(-32.329/T913-(T9/1.284)**2)
      * (1.+.013*T913+2.04*T923+.184*T9)
      + 3.82E+5*T9M32*EXP(-9.373/T9)
      + 1.41E+6*T9M32*EXP(-11.873/T9)
      + 2.00E+9*T9M32*EXP(-20.409/T9)
      + 2.92E+9*T9M32*EXP(-29.283/T9)
```

$^{17}O(n,\alpha)^{14}C$

```
      F = 3.11E+4*(1.+100.*T9)+2.12E+16*T9M23
      * EXP(-32.51/T913+21.11/T9-(2.33/T9)**2.51)/2.03
```

$^{17}F(n,\alpha)^{14}N$

```
      F = 7.76E+9*(1.-1.15*T912+0.365*T9)*EXP(-(T9/2.798)**2)
      + 4.85E+10*T9M32*EXP(-15.766/T9)
```

$^{18}F(n,\alpha)^{15}N$

```
      F = 6.28E+8*(1.-0.641*T912+0.108*T9)
```

$^{2}H(d,\gamma)^{4}He$

```
      F = 4.84E+1*T9M23*EXP(-4.258/T913)
      * (1.+.098*T913-.203*T923-.139*T9+.106*T943+.185*T953)
```

^{6}Li(d,n)^{7}Be

```
F = 1.48E+12*T9M23*EXP(-10.135/T913)
```

^{8}Li(d,n)^{9}Be

```
F = 3.22E+11*T9M23*EXP(-10.357/T913)
```

^{14}C(d,n)^{15}N

```
F = 4.27E+13*T9M23*EXP(-16.939/T913)
```

^{6}Li(d,p)^{7}Li

```
F = 1.48E+12*T9M23*EXP(-10.135/T913)
```

^{7}Li(d,p)^{8}Li

```
F = 8.31E+8*T9M32*EXP(-6.998/T9)
```

^{9}Be(p,d)2^{4}He

```
F = 2.11E+11*T9M23*EXP(-10.359/T913 - (T9/.520)**2)
*(1.+.040*T913+1.09*T923+.307*T9+3.21*T943+2.30*T953)
+ 5.79E+8*EXP(-3.046/T9)/T9
+ 8.50E+8*EXP(-5.800/T9)/T934
```

^{3}H(t,2n)^{4}He

```
F = 1.67E+9*T9M23*EXP(-4.872/T913)
* (1.+.086*T913-.455*T923-.272*T9+.148*T943+.225*T953)
```

^{7}Li(t,nnα)^{4}He

```
F = 8.81E+11*T9M23*EXP(-11.333/T913)
```

^{7}Li(t,n)^{9}Be

```
F = 1.46E+11*T9M23*EXP(-11.333/T913)
```

^{9}Be(t,n)^{11}B

```
F = 3.80E+12*T9M23*EXP(-14.02/T913)
+ 1.25E+8*T9M32*EXP(-4.43/T9)
```

^{3}He(t,d)^{4}He

```
T9A = T9 / (1.+.128*T9)
F = 5.46E+9*T9A56*T9M32*EXP(-7.733/T9A13)
```

^{1}H(pn,p)^{2}H

```
F = 1.42E-2*T9M32*EXP(-3.720/T913)
* (1.+.784*T913+.346*T923+.690*T9)
```

^{7}Be(^{3}He,ppα)^{4}He

```
F = 6.11E+13*T9M23*EXP(-21.793/T913)
```

$^{14}C(n,\gamma)^{15}C$

```
F = 1.08E+8*3.0E-5*T9
```

$^{13}N(\alpha,p)^{16}O$

```
T9A = T9/(1.+7.76E-2*T9+2.64E-2*T953/(1.+7.76E-2*T9)**(2./3.))
F = 3.23E+17*T9A56*T9M32*EXP(-35.829/T9A13)
```

$^{4}He(2\alpha,\gamma)^{12}C$

```
F = 2.79E-8*T9M32*T9M32*EXP(-4.4027/T9)
```

$^{8}Li(p,n\alpha)^{4}He$

```
F = 1.031E+10*T9M23*EXP(-8.429/T913)
+6.79E+5*T9M32*EXP(-1.02/T9)
+3.28E+8*T9M32*EXP(-7.024/T9)
+1.13E+9*T9**(-0.433)*EXP(-3.982/T9)
```

$^{15}N(p,\alpha)^{12}C$

```
F = 1.08E+12*T9M23*EXP(-15.251/T913-(T9/.522)**2)
*(1.+.027*T913+2.62*T923+.501*T9+5.36*T943+2.60*T953)
+1.19E+8*T9M32*EXP(-3.676/T9)
+5.41E+8*EXP(-8.926/T9)/T912
+4.72E+7*T9M32*EXP(-7.721/T9)
+2.20E+8*T9M32*EXP(-11.418/T9)
```

$^{18}O(n,\gamma)^{19}O$

```
F = 21.2
```

$^{20}O \rightarrow e + \bar{\nu} + {}^{20}F$

```
F = 0.737
```

$^{21}F \rightarrow e + \bar{\nu} + {}^{21}Ne$

```
F = 0.234
```

The remaining reactions are estimated as follows.

$^{8}Li(p,\gamma)^{9}Be$

```
F = 6.27E+8*T9M23*EXP(-8.5/T913)*(1.+0.049*T913)
```

$^{9}Li(p,\alpha)^{6}He$

```
F = 1.03E+11*T9M23*EXP(-8.533*T9M13)
```

$^{9}Li(d,n)^{10}Be$

```
F = 2.86E+11*T9M23*EXP(-10.41*T913)
```

$^{12}N(n,d)^{11}C$

```
F = 1.32E+5
```

^{10}Be$(\alpha,\gamma)^{14}$C

```
F = 5.82E+14*T9M23*EX(-24.12/T913)
+ 8.30E+7*T9M32*EX(-1.161/T9)
+ 1.01E+8*T9M32*EX(-6.731/T9)
```

^{11}B$(\alpha,\gamma)^{15}$N

```
F = 4.3E+15*T9M23*EXP(-6.082/T913)
+ 6.8E+7*T9M32*EXP(-1.242/T9)
+ 7.5E+7*T9M32*EXP(-2.832/T9)
```

^{12}N$(n,p)^{12}$C

```
F = 1.0E+12
```

^{8}Li$(d,p)^{9}$Li

```
F = 2.58E+11*T9M23*EX(-10.34/T913)
+ 1.24E+8*T9M32*EXP(-2.95/T9)
```

^{9}Li$(p,n)^{9}$Be

```
F = 1.03E+11*T9M23*EXP(-8.533/T913)
```

^{9}Li$(\alpha,n)^{12}$B

```
F = 8.82E+15*T9M23*EXP(-19.70/T913)
```

^{9}Li$(p,\gamma)^{10}$Be

```
F = 1.03E+11*T9M23*EXP(-8.533/T913)
+ 3.1E+5*T9M32*EXP(-11.61/T9)
```

^{13}N$(n,\gamma)^{14}$N

```
F = 1.32E+5
+ 1.25E+6*T9M23*EXP(-0.16/T9)
+ 1.32E+7*T9M23*EXP(-1.39/T9)
```

^{10}B$(\alpha,\gamma)^{14}$N

```
F = 5.82E+14*T9M23*EXP(-27.98/T913)
+ 8.22E+7 *T9M32*EXP(-1.718/T9)
+ 2.99E+10*T9M32*EXP(-1.485/T9)
```

^{11}C$(\alpha,\gamma)^{15}$O

```
F = 2.05E+16*T9M23*EXP(-31.88/T913)
+ 1.27E+8*T9M32*EXP(-0.928/T9)
+ 1.34E+8*T9M32*EXP(-3.017/T9)
+ 1.35E+8*T9M32*EXP(-3.365/T9)
```

^{8}B$(\alpha,\gamma)^{12}$N

```
F = 8.67E+8*T9M23*EXP(-8.08/T913)
* (1.+0.052*T913-0.448*T923-0.165*T9+0.144*T943+0.134*T953)
```

$^{19}O(n,\gamma)^{20}O$

```
F = 1.3E+5
```

$^{17}N(\alpha,p)^{20}O$

```
F = 3.3E+14*T9M23*EXP(-36.51/T913)
```

$^{16}C(\alpha,\gamma)^{20}O$

```
F = 5.6E+16*T9M13*EXP(-32.82/T913)
```

$^{20}F(n,\gamma)^{21}F$

```
F = 1.3E+5
```

$^{21}F(p,\alpha)^{18}O$

```
F = 1.6E+13*T9M23*EXP(-18.10/T9)
```

$^{17}N(\alpha,\gamma)^{21}F$

```
F = 3.3E+14*T9M23*EXP(-36.51/T913)
```

Table 1. Reactions changed since Walker et al (1991).

Reaction	Notes	Refs
$^{3}H + e \rightarrow {}^{3}He$	U	T85
$^{8}Li \rightarrow e + 2^{4}He$	U	T85
$^{11}Be \rightarrow e + {}^{11}B$	A	T85
$^{8}B + e \rightarrow 2^{4}He$	U	T85
$^{12}B \rightarrow e + {}^{12}C$	U	T85
$^{11}C + e \rightarrow {}^{11}B$	U	T85
$^{14}O + e \rightarrow {}^{14}N$	U	T85
$^{15}O + e \rightarrow {}^{15}N$	U	T85
$^{17}F + e \rightarrow {}^{17}O$	A	T85
$^{18}F + e \rightarrow {}^{18}O$	A	T85
$^{18}Ne + e \rightarrow {}^{18}F$	A	T85
$^{1}H + p \rightarrow e^{+}\nu + {}^{2}H$	A	CF88
$^{1}H + e + p \rightarrow \nu + {}^{2}H$	A	CF88
$^{3}He + e \rightarrow \nu + {}^{3}H$	A	CF88
$^{3}He + p \rightarrow e^{+}\nu + {}^{4}He$	A	CF88
$^{7}Be + e \rightarrow \nu\gamma + {}^{7}Li$	A	CF88
$^{6}He \rightarrow e + {}^{6}Li$	A	T85
$^{9}Li \rightarrow e + {}^{9}Be$	A	LS78
$^{9}Li \rightarrow en + 2^{4}He$	A	LS78
$^{10}Be(p,\gamma)^{11}B$	A	W69
$^{16}O(p,\gamma)^{17}F$	A	CF88
$^{17}O(p,\gamma)^{18}F$	A	CF88
$^{4}He(nn,\gamma)^{6}He$	A	CF88
$^{7}Li(n,\gamma)^{8}Li$	U	WSK89
$^{8}Li(n,\gamma)^{9}Li$	A	MF89
$^{9}Be(n,\gamma)^{10}Be$	A	W69
$^{10}Be(n,\gamma)^{11}Be$	A	W69
$^{11}B(n,\gamma)^{12}B$	US	MF89
$^{16}O(n,\gamma)^{17}O$	A	W69
$^{17}O(n,\gamma)^{18}O$	A	W69
$^{14}N(n,p)^{14}C$	U	CF88
$^{14}O(n,p)^{14}N$	A	CF88
$^{17}F(n,p)^{17}O$	A	W69
$^{18}F(n,p)^{18}O$	A	W69
$^{11}Be(p,n)^{11}B$	A	W69

Table 1 (continued). Reactions changed since Walker et al (1991).

Reaction	Notes	Refs
$^{12}C(\alpha,\gamma)^{16}O$	U	CF88
$^{14}C(\alpha,\gamma)^{18}O$	A	CF88
$^{14}N(\alpha,\gamma)^{18}F$	A	CF88
$^{14}O(\alpha,\gamma)^{18}Ne$	A	CF88
$^{11}B(\alpha,p)^{14}C$	US	CF88
$^{11}C(\alpha,p)^{14}N$	U	CF88
$^{14}O(\alpha,p)^{17}F$	A	CF88
$^{7}Li(p,\alpha\gamma)^{4}He$	A	CF88
$^{10}Be(p,\alpha)^{7}Li$	A	W69
$^{11}Be(p,\alpha)^{8}Li$	A	W69
$^{11}B(p,\alpha)2^{4}He$	U	CF88
$^{17}O(p,\alpha)^{14}N$	A	CF88
$^{18}O(p,\alpha)^{15}N$	A	CF88
$^{18}F(p,\alpha)^{15}O$	A	W69
$^{8}Li(\alpha,n)^{11}B$	US	MF89
$^{10}Be(\alpha,n)^{13}C$	A	W69
$^{11}Be(\alpha,n)^{14}C$	A	W69
$^{10}B(\alpha,n)^{13}N$	U	CF88
$^{11}B(\alpha,n)^{14}N$	US	CF88
$^{13}C(\alpha,n)^{16}O$	U	CF88
$^{17}O(n,\alpha)^{14}C$	A	W69
$^{17}F(n,\alpha)^{14}N$	A	CF88
$^{18}F(n,\alpha)^{15}N$	A	CF88
$^{2}H(d,\gamma)^{4}He$	A	CF88
$^{6}Li(d,n)^{7}Be$	A	MF89
$^{8}Li(d,n)^{9}Be$	A	MF89
$^{14}C(d,n)^{15}N$	A	KFKM91
$^{6}Li(d,p)^{7}Li$	A	MF89
$^{7}Li(d,p)^{8}Li$	A	MF89
$^{9}Be(p,d)2^{4}He$	U	CF88
$^{3}H(t,2n)^{4}He$	A	CF88
$^{7}Li(t,nn\alpha)^{4}He$	A	CF88
$^{7}Li(t,n)^{9}Be$	AS	MF89
$^{9}Be(t,n)^{11}B$	A	BK89
$^{3}He(t,d)^{4}He$	A	CF88

Table 1 (continued). Reactions changed since Walker et al (1991).

Reaction	Notes	Refs
$^{1}H(pn,p)^{2}H$	A	CF88
$^{7}Be(^{3}He,pp\alpha)^{4}He$	A	CF88
$^{14}C(n,\gamma)^{15}C$	A	KFKM91
$^{13}N(\alpha,p)^{16}O$	U	CF88
$^{4}He(2\alpha,\gamma)^{12}C$	U	CF88
$^{8}Li(p,n\alpha)^{4}He$	U	BBL92
$^{15}N(p,\alpha)^{12}C$	U	CF88
$^{18}O(n,\gamma)^{19}O$	A	AS83
$^{20}O \rightarrow e + \bar{\nu} + ^{20}F$	A	AS83
$^{21}F \rightarrow e + \bar{\nu} + ^{21}Ne$	A	EV78
$^{8}Li(p,\gamma)^{9}Be$	E	
$^{9}Li(p,\alpha)^{6}He$	E	
$^{9}Li(d,n)^{10}Be$	E	
$^{12}N(n,d)^{11}C$	E	
$^{10}Be(\alpha,\gamma)^{14}C$	E	
$^{11}B(\alpha,\gamma)^{15}N$	E	
$^{12}N(n,p)^{12}C$	E	
$^{8}Li(d,p)^{9}Li$	E	
$^{9}Li(p,n)^{9}Be$	E	
$^{9}Li(\alpha,n)^{12}B$	E	
$^{9}Li(p,\gamma)^{10}Be$	E	
$^{13}N(n,\gamma)^{14}N$	E	
$^{10}B(\alpha,\gamma)^{14}N$	E	
$^{11}C(\alpha,\gamma)^{15}O$	E	
$^{8}B(\alpha,\gamma)^{12}N$	E	
$^{19}O(n,\gamma)^{20}O$	E	
$^{17}N(\alpha,p)^{20}O$	E	
$^{16}C(\alpha,\gamma)^{20}O$	E	
$^{20}F(n,\gamma)^{21}F$	E	
$^{21}F(p,\alpha)^{18}O$	E	
$^{17}N(\alpha,\gamma)^{21}F$	E	

In the notes column, U refers to a reaction whose rate has been updated since Walker et al (1991); A, to a reaction which has been added; S, to a reaction with several recent measurements; and E, to a reaction which has been estimated.

The references give the most recent rate measurements and refer to: T85—Tuli (1985), CF88—Caughlan and Fowler (1988), LS78—Lederer and Shirley (1978), EV78—Endt and Van der Leun (1978), AS83—Ajzenberg-Selove (1983), W69—Wagoner (1969), WSK89—Wiescher et al (1989), MF89—Malaney and Fowler (1989), KFKM91—Kawano et al (1991), BK89—Boyd and Kajino (1989), BBL92—Becchetti et al (1992)

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Figure Captions

1. The reaction network used in the code. Estimated reactions are shown with dashed lines.

2a. Flow diagram for the standard model, with $\eta_{10} = 3.0$ (Flows to/from nuclides with $A \leq 4$ are neglected).

2b. Flow diagram for the high n/p calculation, with n/p = 10 and $\eta_{10} = 3.0$ (Flows to/from nuclides with $A \leq 4$ are neglected).

3a. ^{4}He mass fraction (Y_p) as a function of baryon to photon ratio ($\eta = n_b/n_\gamma$). Neutron lifetime is 889.6 sec.

3b. Yields (number density relative to hydrogen) of ^{2}H, ^{3}He, ^{6}Li and ^{7}Li as functions of baryon to photon ratio ($\eta = n_b/n_\gamma$). Neutron lifetime is 889.6 sec.

3c. Yields (number density relative to hydrogen) of ^{9}Be, ^{10}B and ^{11}B as functions of baryon to photon ratio. The bands for ^{9}Be and ^{10}B are a result of the variation in the ^{7}Li(t,n)^{9}Be rate. The maximum yields for ^{9}Be, ^{10}B, ^{11}B within the range $2.8 \leq \eta_{10} \leq 4.0$ are 6×10^{-18}, 2×10^{-19}, 5×10^{-17} respectively. Within $0.01 \leq \eta_{10} \leq 100$, maximum yields are 1×10^{-14}, 5×10^{-19}, 2×10^{-14} respectively.

4a. ^{4}He mass fraction (Y_p) as a function of neutron to proton ratio, for $\eta_{10} = 3.0$.

4b. Yields as a function of neutron to proton ratio, for $\eta_{10} = 3.0$.

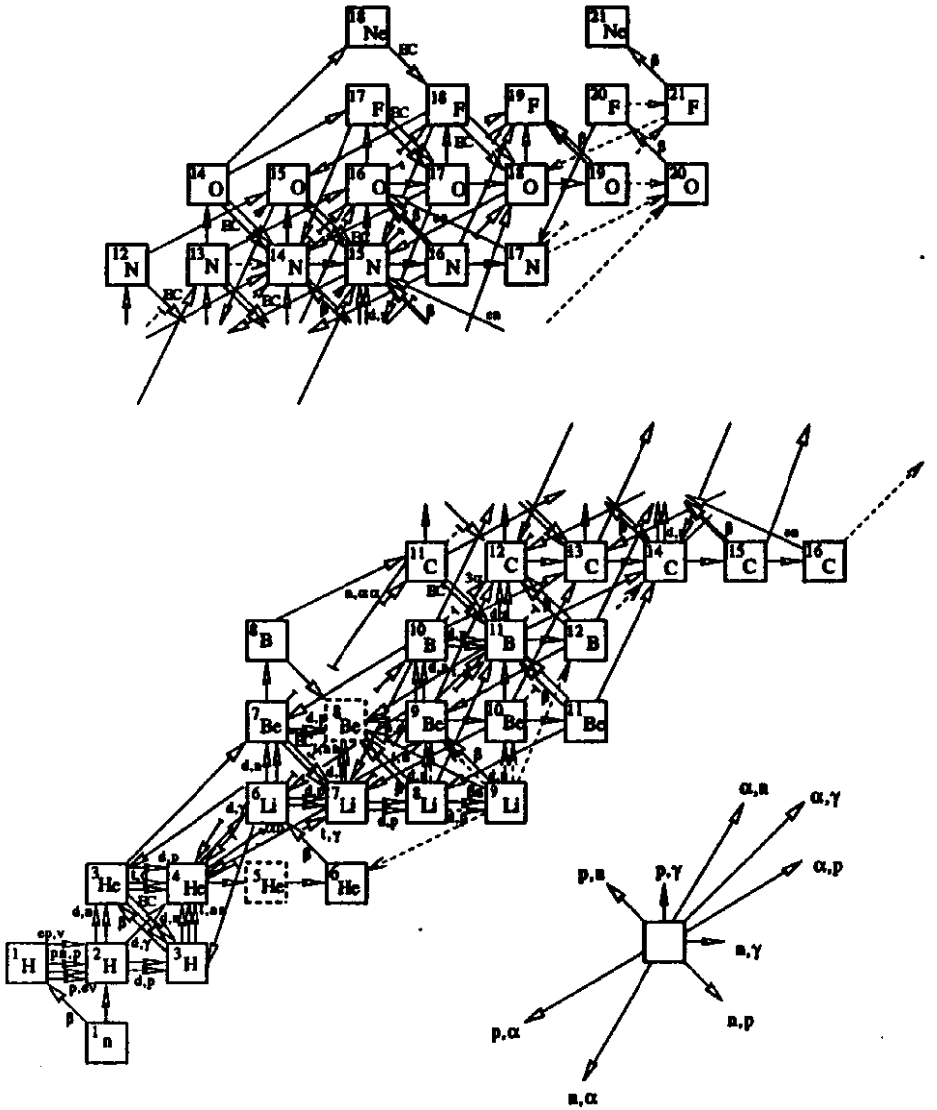
18 Ne
21 Ne
17 F
18 F
19 F
20 F
21 F
14 O
15 O
16 O
17 O
18 O
19 O
20 O
12 N
13 N
14 N
15 N
16 N
17 N
11 C
12 C
13 C
14 C
15 C
16 C
8 B
10 B
11 B
12 B
7 Be
9 Be
10 Be
11 Be
6 Li
7 Li
8 Li
9 Li
3 He
4 He
5 He
6 He
1 H
2 H
3 H
1 n
α,n
α,γ
α,p
p,n
p,γ
n,γ
n,p
p,α
n,α

Fig. 1

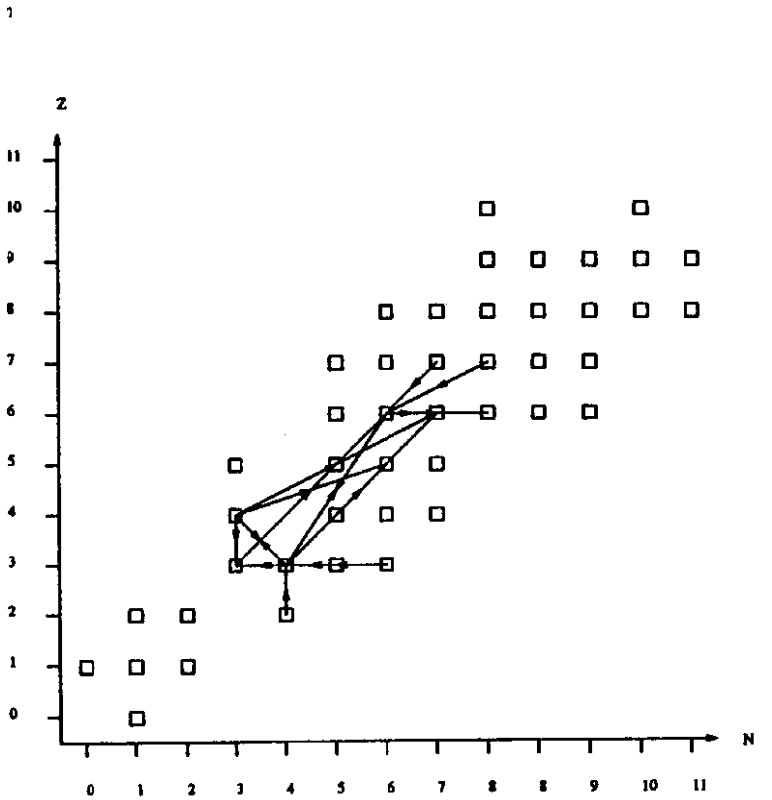
Z
N
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 2a

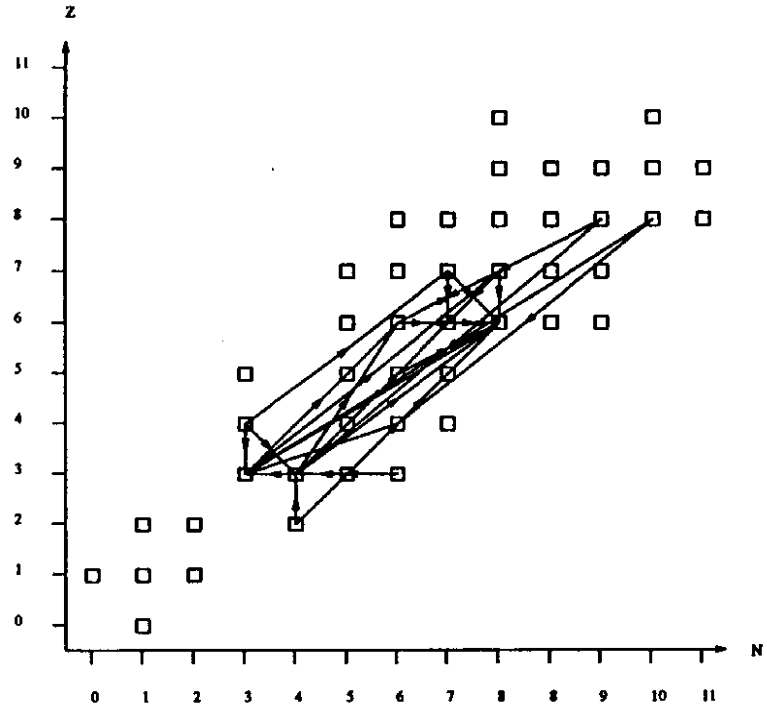
Z
N
0
1
2
3
4
5
6
7
8
9
10
11

Fig. 2b

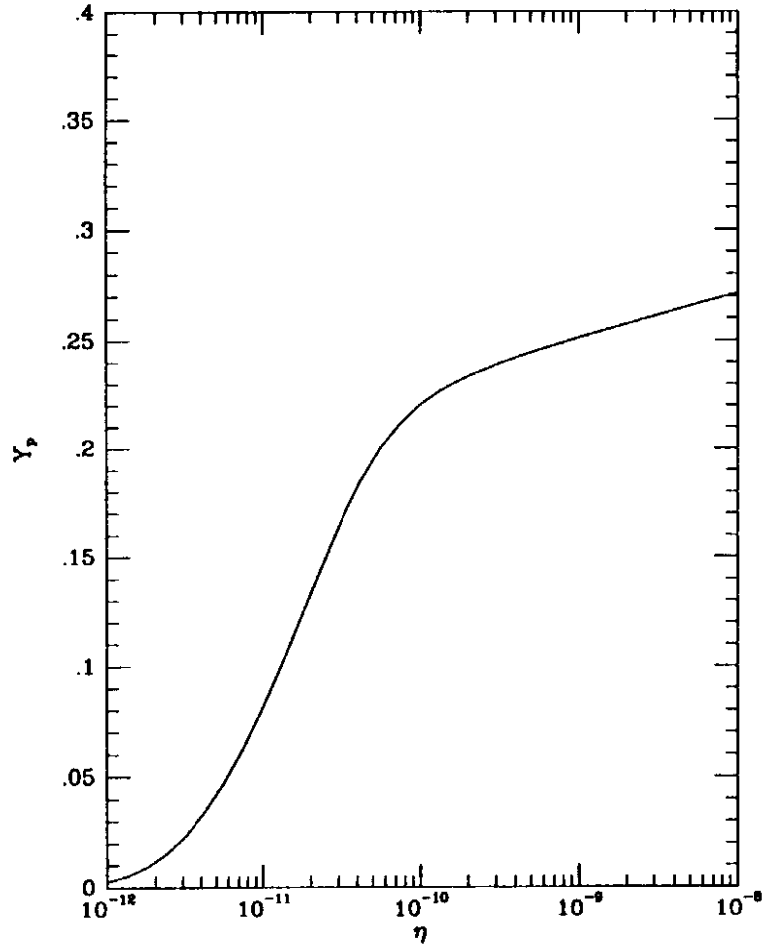
Y_p
η
.4
.35
.3
.25
.2
.15
.1
.05
0
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}

Fig. 3a

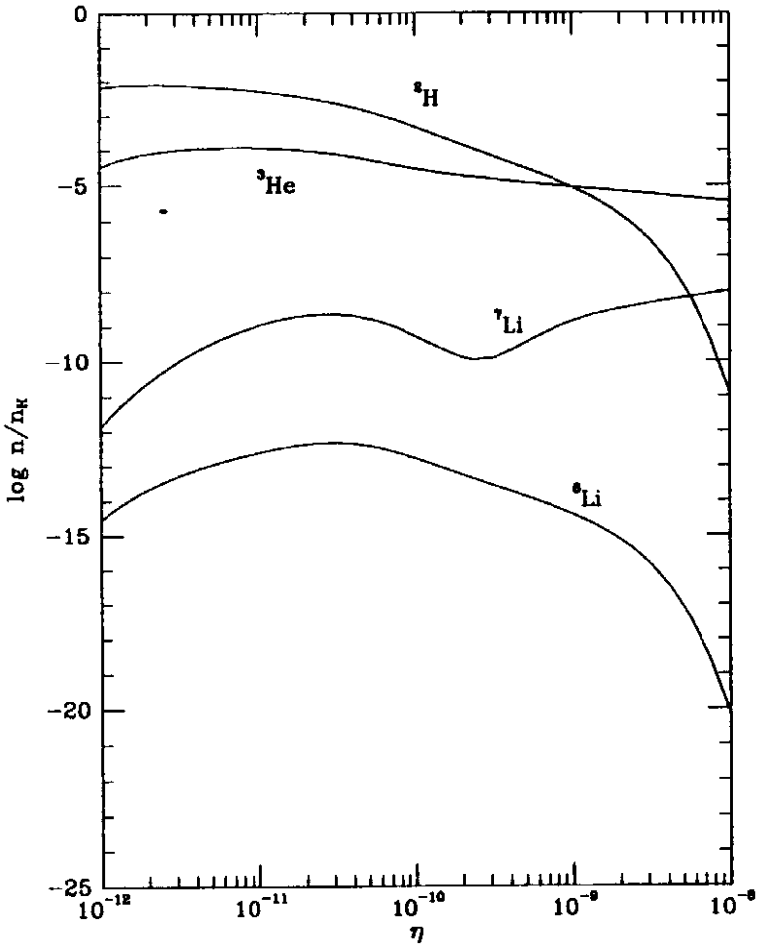
0
−5
−10
−15
−20
−25
log n/n_H
²H
³He
⁷Li
⁶Li
10⁻¹²
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
η

Fig. 3b

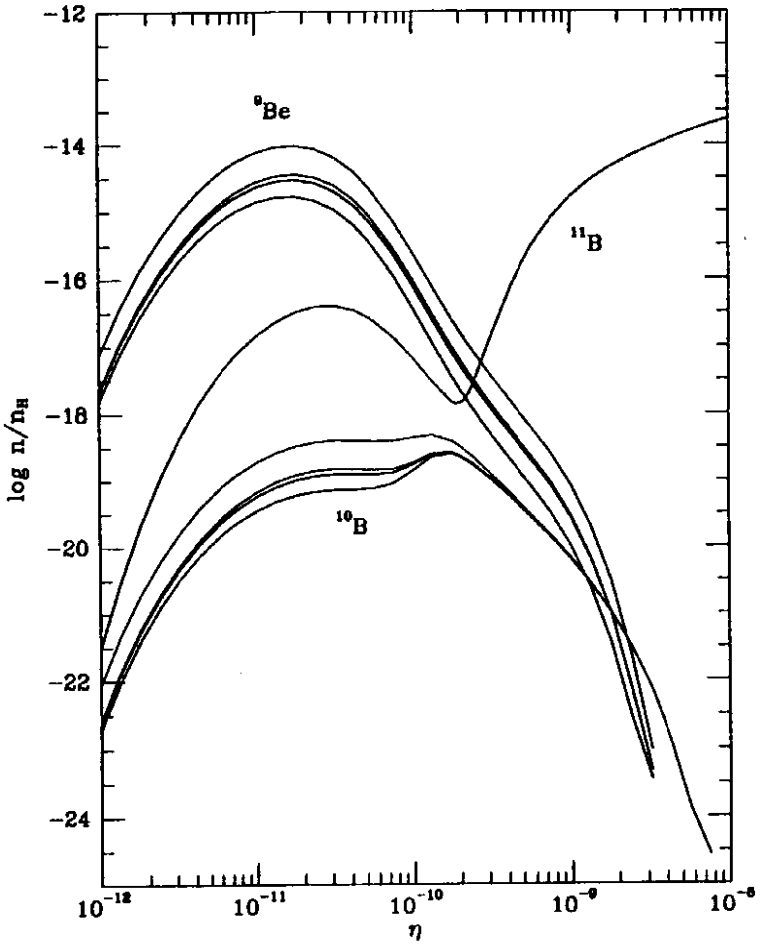
−12
−14
−16
−18
−20
−22
−24
log n/n_H
⁹Be
¹¹B
¹⁰B
10⁻¹²
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
η

Fig. 3c

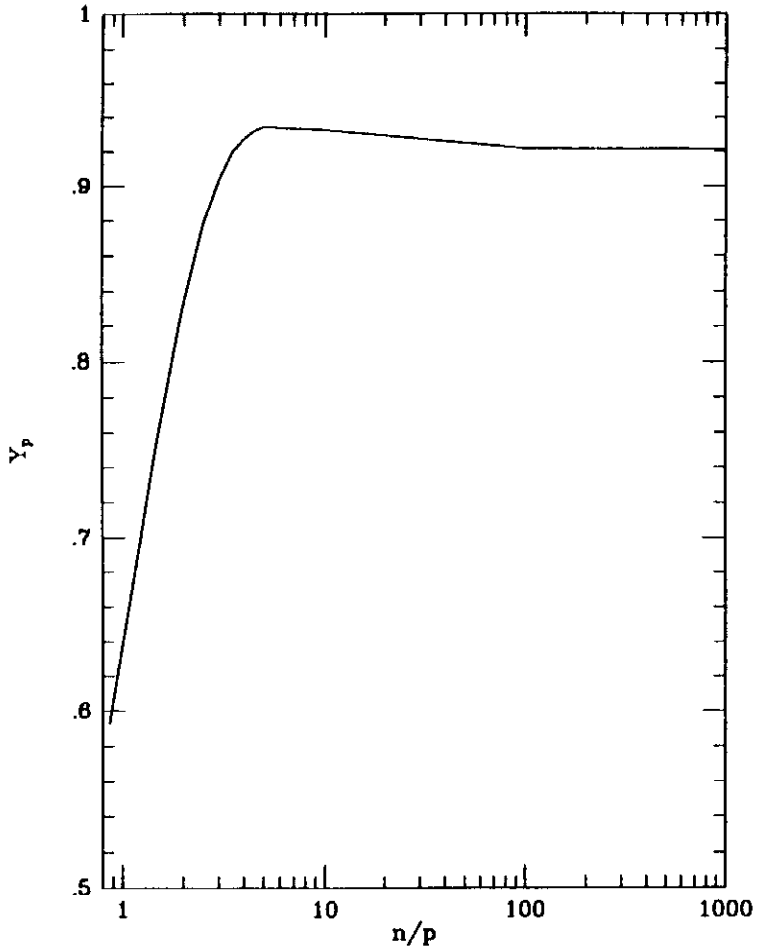
1
.9
.8
.7
.6
.5
Y_p
1
10
100
1000
n/p

Fig. 4a

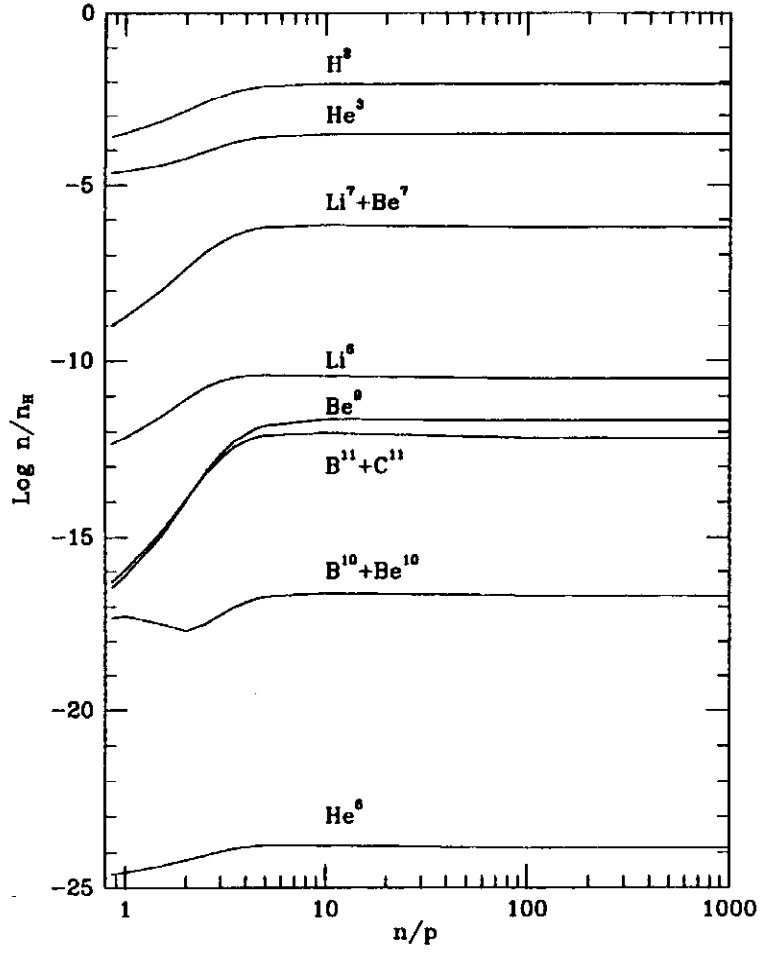
0
-5
-10
-15
-20
-25
Log n/n_H
H^2
He^3
Li^7+Be^7
Li^6
Be^9
$B^{11}+C^{11}$
$B^{10}+Be^{10}$
He^6
1
10
100
1000
n/p

Fig. 4b