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The Effect of He4 Fusion on Primordial Deuterium

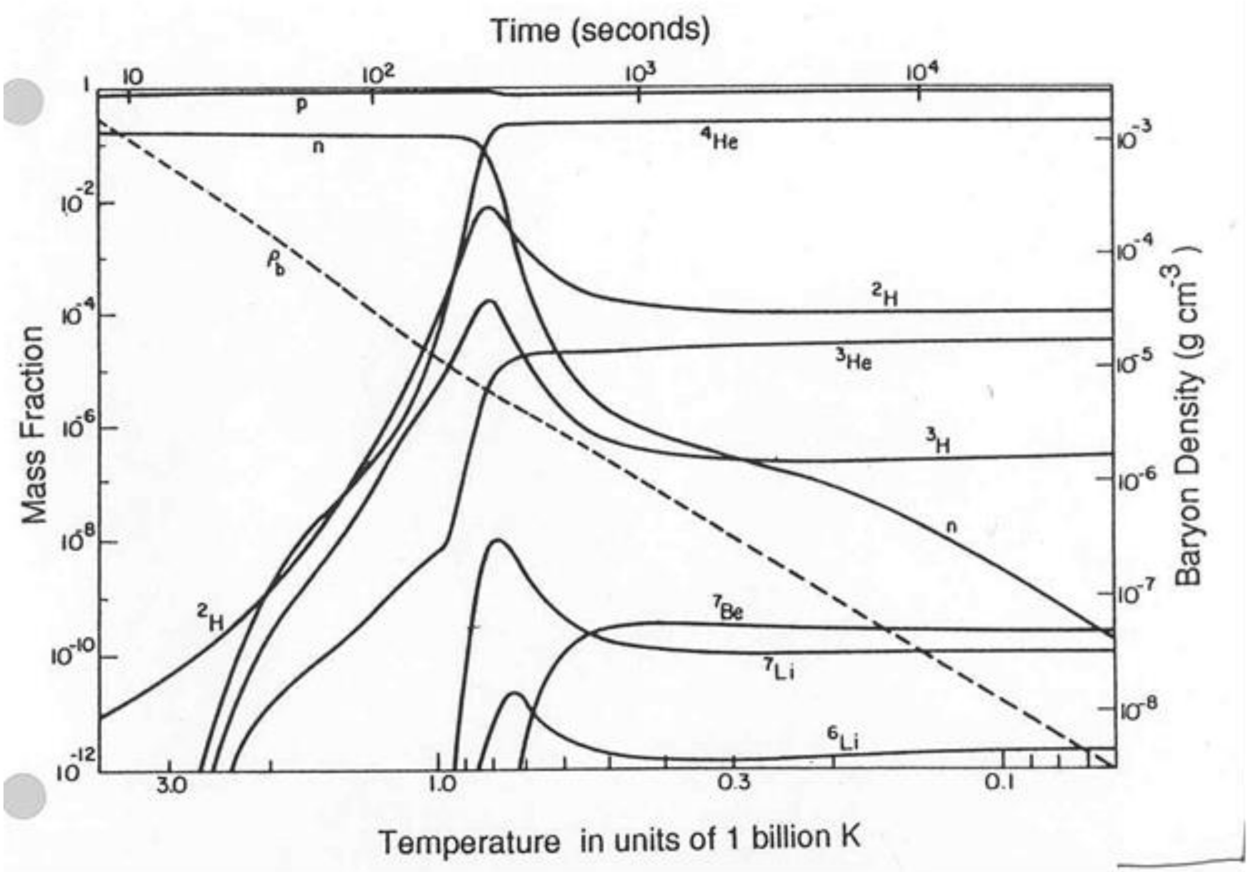
Abstract

It is well known that approximately 23% to 25% of nucleons found throughout space are in the form of Helium 4 atoms. The distribution uniformity indicates that these atoms were formed in the very early universe. In addition, trace amounts of Deuterium, Lithium 3 and Beryllium 7 are also uniformly distributed. These elements are evidence of a process known as primordial nucleosynthesis that has been well studied and documented by G. Gamow, H. Bethe and A. Sakarov.

The author explored a cosmology expansion curve called R1+R3 based on values found in a model of the proton [5][7]. The expansion curve is similar to the concordance model [4] with WMAP parameters [3]. Temperature histories that include He4 fusion energy all increase to temperatures that photo-disintegrates deuterium leading to potential difficulties explaining measured residual fractions. The first goal of the work below is to determine when residual primordial deuterium originated.

The R1+R3 expansion model starts at a kinetic energy of 9.8 MeV/particle, has omega baryons (protons) =0.5, omega dark matter =0.5 and dark energy =0. The associated temperature history decreases initially but as He4 fusion occurs, the temperature increases before finally decreasing to 2.73 K due to expansion. Surprisingly, literature was found [8][9] that does not account for fusion energy of He4. In addition, there are claims [4][6] that residual deuterium is a sensitive test that rules out cosmologies that contain more than 0.04 baryon fraction. The view that conventional mass is only 4% of the observed universe, with the remainder "missing" is becoming widely accepted. The second goal of this work is to investigate the claim that a low photon/baryon ratio is required to match measured residual deuterium.

Conventional Primordial Nucleosynthesis



http://burro.astr.cwru.edu/Academics/Astr222/Cosmo/Early/nucleosynth_fig.jpg

The temperature in the graph above is about 3e9 K at 12 seconds. The kinetic energy associated with this temperature is 1.5*B*T=0.39 MeV, where B is Boltzmann's constant 8.62e-11 MeV/K. One can see from the smoothly decreasing temperature in the horizontal axis that as Helium 4 fuses, there is no increase in temperature. The energy associated with He4 fusion is 7.07*0.23=1.61 MeV. This amount of energy should increase the temperature to about 1.55e10 about 300 seconds into expansion. Appendix 1 contains a similar graph from a different source [9]. Again, the temperature does not increase with He4 fusion.

Temperature history for expansion models

The temperature curve for the above graph (call this the Astr222 temperature curve) can be simulated with the following information from Peebles [4] and other literature: Early expansion, according to some literature, is driven by photon and neutrino density and maintains the relationship kinetic energy (KE) = (2.7/t)^.5 with time t initial=0.002 seconds. This relationship defines a kinetic energy vs. time slope that is maintained until decoupling of matter and radiation at approximately 100K years into expansion. The temperature can be calculated from kinetic energy with T= (KE/(1.5*B). With these relationships, the temperature at 0.002 seconds is 2.5e11 K. Knowing the final temperature, expansion ratio z can be calculated since z=T/2.73 K.

Using z=2.5e11/2.7=1e11 and final radius 6.33e25, the initial radius=6.33e25/1e11=6e14 m. This initial radius does not quite agree with the concordance radius R=5.90e13*(t)^(2/3) but the difference does not affect the results. With z, the initial radius and slope the temperature at larger values of time can be determined. The simulated temperature curve in red below is the Astr222 curve that does not include energy from He4 fusion. Although it has a lower slope through part of the curve, the temperature decreases to the correct value 2.73 K at the end of expansion. The comparison curve is the author's R1+R3 model [7]. The initial kinetic energy (temperature) is about the same as the Astr222 curve but increases after He4 fusion. The higher slope associated with radius proportional to t^(2/3) after decoupling allows the curve to decrease uniformly to 2.73 K at the end of expansion.

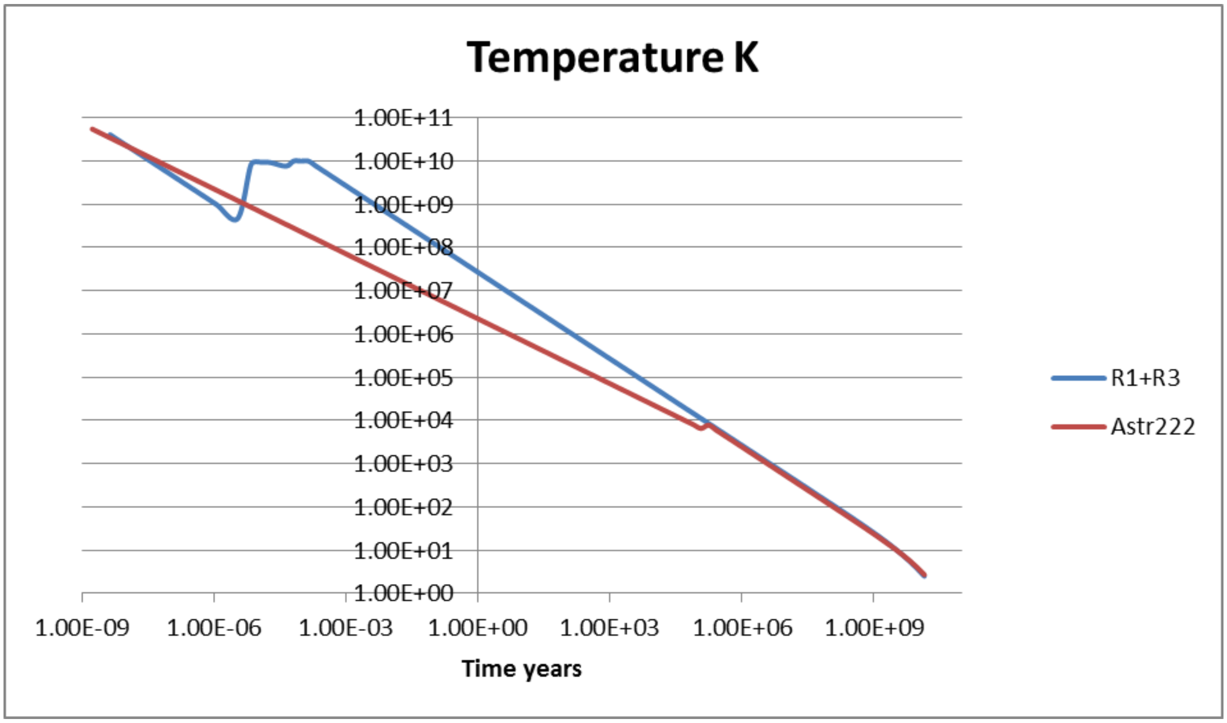


Photo-disintegration of Deuterium

Initial deuterium fraction is limited by photo-disintegration [4][6]. It is well known that deuterium readily fuses to He4 after the temperature falls to approximately 1e9 K. However when He4 fuses energy is released once again the temperature increases to levels that photo-disintegrates the remaining deuterium. This leads to difficulties explaining when the measured residual primordial deuterium originated.

The SAHA equation [4] is utilized to give the early deuterium fraction.

Ln SAHA=(D*N)/(p'*n')=-(25.82-Ln((Ob)*(T/1e10)^(3/2))-2.58/(T/1e10))

Example:

Temperature K		7.8750E+08
pt1=-25.82		-25.82
pt2=(Ln((0.044)*(7.87e8/1e10)^(1.5)))		-6.9358
pt3=(2.58/(7.87e8/1e10))		32.7619
total=(pt1+pt2+pt3)		0.0061
SAHA=exp(-0.0061)=1		1.006142403

Where: Ln stands for natural logarithm, D=deuterium, N=total number of nucleons, p’=protons, n’=neutrons, Ob is Omega baryons and T/1e10 is the temperature in degrees K divided by 1e10. SAHA=exp(Ln SAHA).

A more general SAHA equation is given below for variable critical density, baryon/photon ratio and Omega baryon.

Ln SAHA=Ln(rhoC*4/3*((1.67E-27^2)/(3.4E-27*photon/baryon*1.67E-27))^(3/2))+Ln((Ob)*(T/e10)^(3/2))+2.58/(T/1e10)

Example:

Temperature K					7.8750E+08
pt1=Ln(9.5E-24*4/3*((1.67E-27^2)/(3.4E-27*0.000000008*1.67E-27))^(3/2))					-25.82
pt2=Ln((0.044)*(7.87e8/1e10)^(3/2))					-6.94
pt3=2.58/(7.7e8/1e10)					32.76
total=(pt1+pt2+pt3)					0.00
SAHA=exp(0)=1					

Ref: clean273.xls

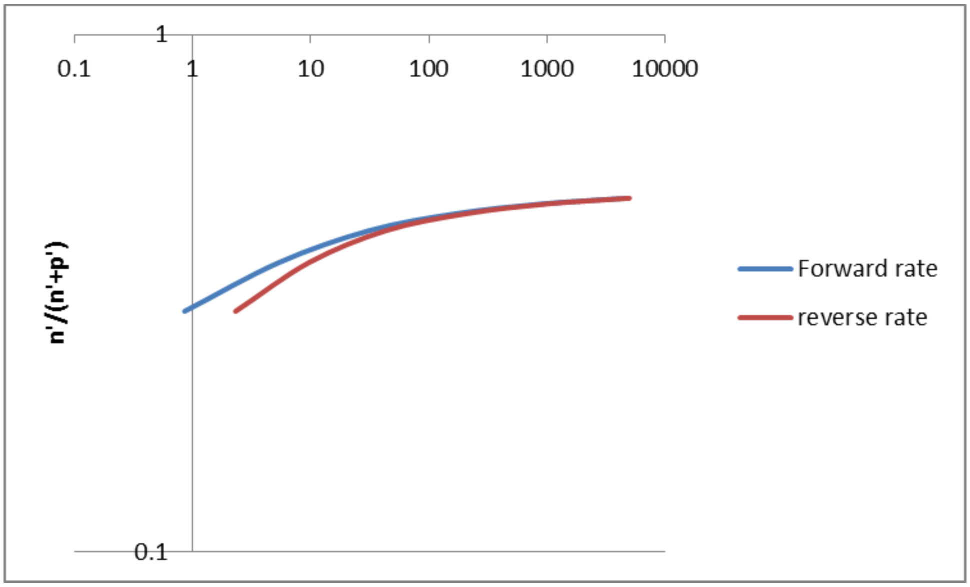
This reduces to the Ln SAHA above with rhoC=9.5e-24 and photon/baryon=8e-9.

Freeze-out Mechanism

Initially the number of neutrons is controlled by a Boltzmann relationship: n’/N=exp(-1.293/Ke) where Ke is in MeV and p’=N-n’. As the kinetic energy falls with expansion, neutrons become less prevalent until a condition known as freeze-out occurs. At this condition, temperature reduction due to expansion is high compared to the reaction rates and the reaction favoring protons stops progressing. The relative forward and reverse reactions determine the balance of neutrons and protons as early expansion occurs. An excerpt from Pebbles [4] Table 6.2 pg. 185 is included below:

T(10^10 K)		lam t	lamb t		n'/(n'+p')
22.5		4700	5000		0.483
13.1		900	1010		0.471
7.6		170	208		0.451
4.45		31	43		0.418
2.59		5.4	9.7		0.363
1.51		0.85	2.3		0.292

A plot of the above data is shown below. When n’/(n’+p’) takes on the approximate value 0.4, freeze-out has occurred because the forward reaction (lam t) cannot keep up with the reverse reaction rate (lamb t). This keeps more protons from forming from this mechanism fixing the ratio 0.4.



Decay mechanism

There is another mechanism that forms protons. The neutrons decay to protons with the relationship:

n'/N=(EXP(-0.693*t/866)) where t is time and 866 sec is the decay half time.

Determine D and He4

He4 formation can be calculated by applying the freeze-out mechanism to determine n’/N, then applying decay to n’/N. Determine p’/N as the subtraction p’=N-n’. For example, at t=40.7 seconds and n’/(n’+p’)=0.4

n'/N=EXP(-0.693*40.7/866)*0.4=0.387

p’/N=1-.387=0.613

As temperature decreases, the SAHA ratio (DN)/(p’n’) =1.0. At this condition, literature states that the deuterium D rapidly converts to He4.

With SAHA=1, D/N=1*p’n’=0.387*0.613=0.237. Rapid conversion to He4 results in He4 fraction= 0.237.

> Note regarding the meaning of He4 fraction: The fraction 0.24 He4 means that 24% of N nucleons (neutrons and protons) have converted to He4. This also means that fraction

0.24 of initial nucleons have converted to D. These are number fractions of the total. The fact that D contains one proton and one neutron and He4 contains 2 neutrons and 2 protons does not enter the calculations. Simply, 24% of all nucleons have been converted to a new form.

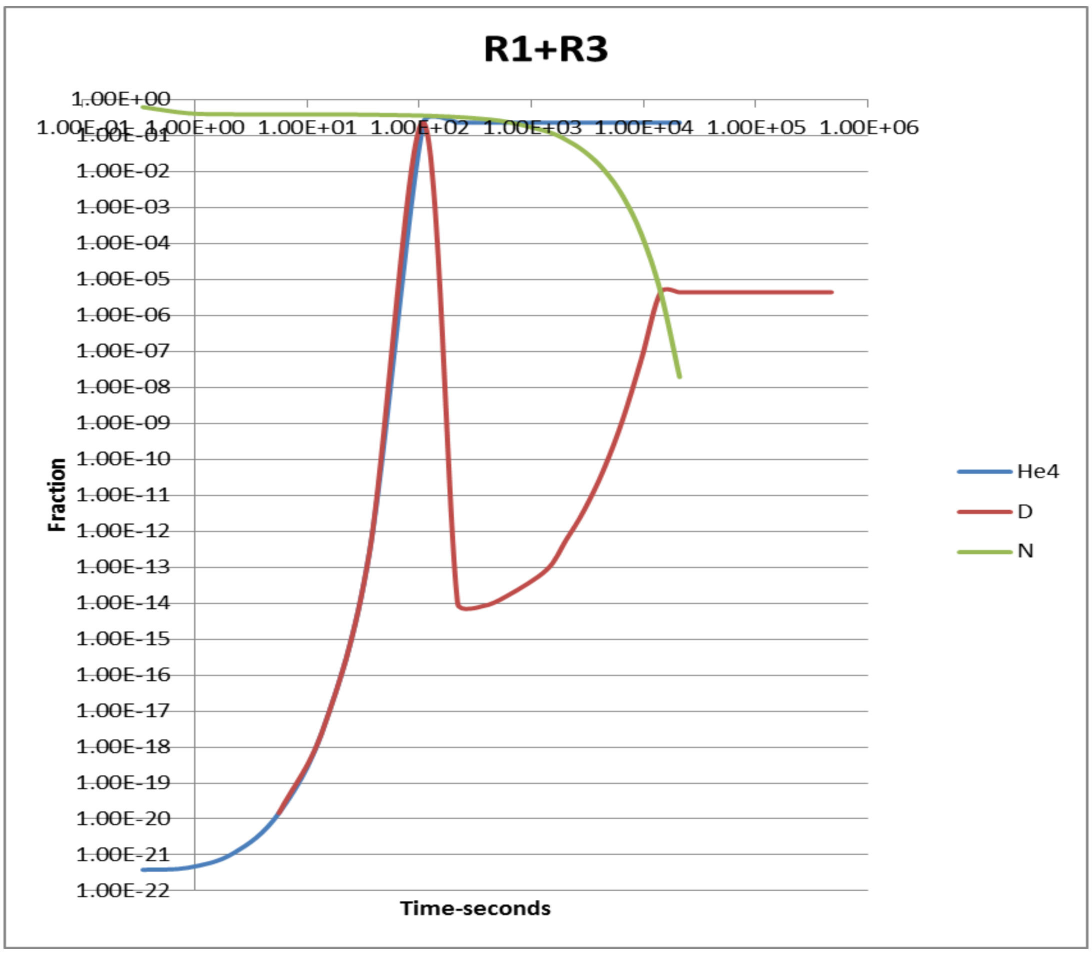
The author's R1+R3 expansion will be used as an example.

The values [7] for the SAHA equation are: Critical density 2.6e-24 gm/cm^3, Omega baryon (Ob) =0.5 and variable photon/baryon ratio based on:

Baryon number density=0.5*exp(180)/Volume

Photon number density=8*PI()/(H*C)^3*(1.5*B*T)^3

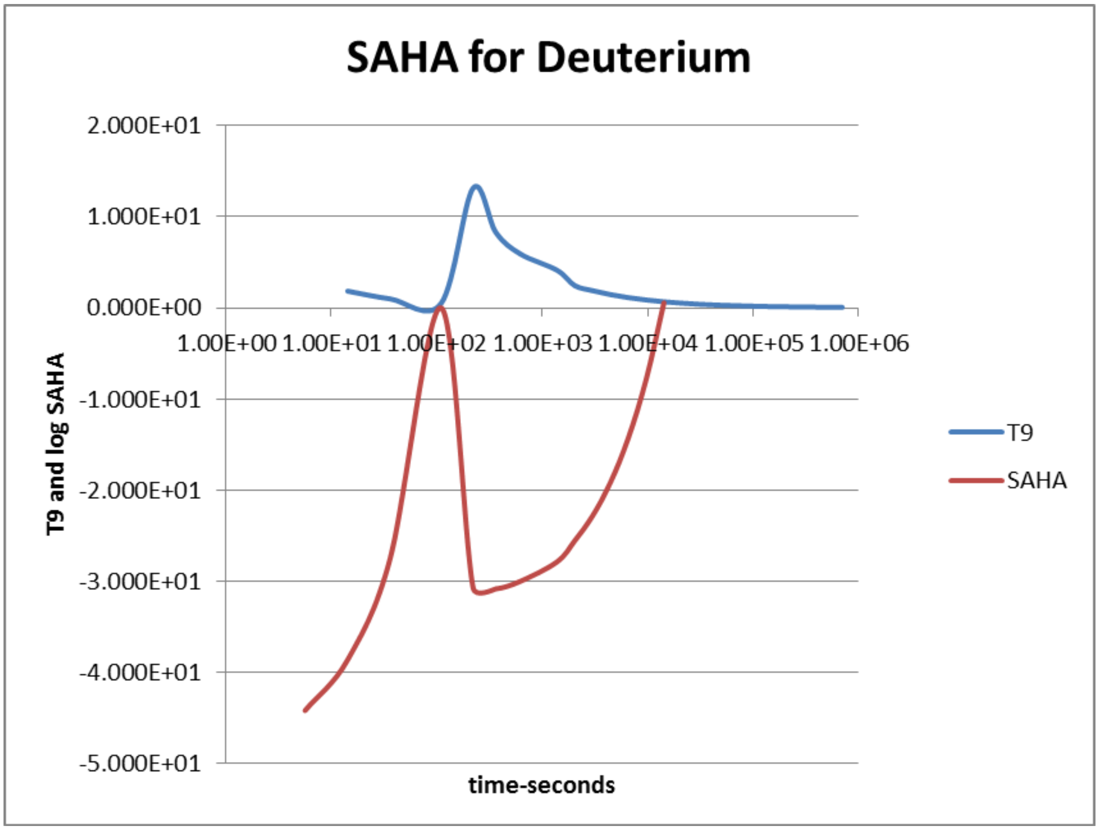
Initially the kinetic energy is 9.8 mev and temperature falls directly with expansion ratio z. The resulting graph of Helium and D fractions (the vertical axis) as a function of time in seconds (the horizontal axis) follows:



Helium4 abundance is shown in blue and increases to 0.24. Neutrons decay and are shown in green. Deuterium, shown in red, is photo-disintegrated and almost completely destroyed when the temperature increases due to He4 fusion. However, when the temperature decreases following fusion, the D fraction recovers somewhat. After the SAHA value becomes positive (maximum = 1.0), the D fraction becomes fixed.

Late D formation

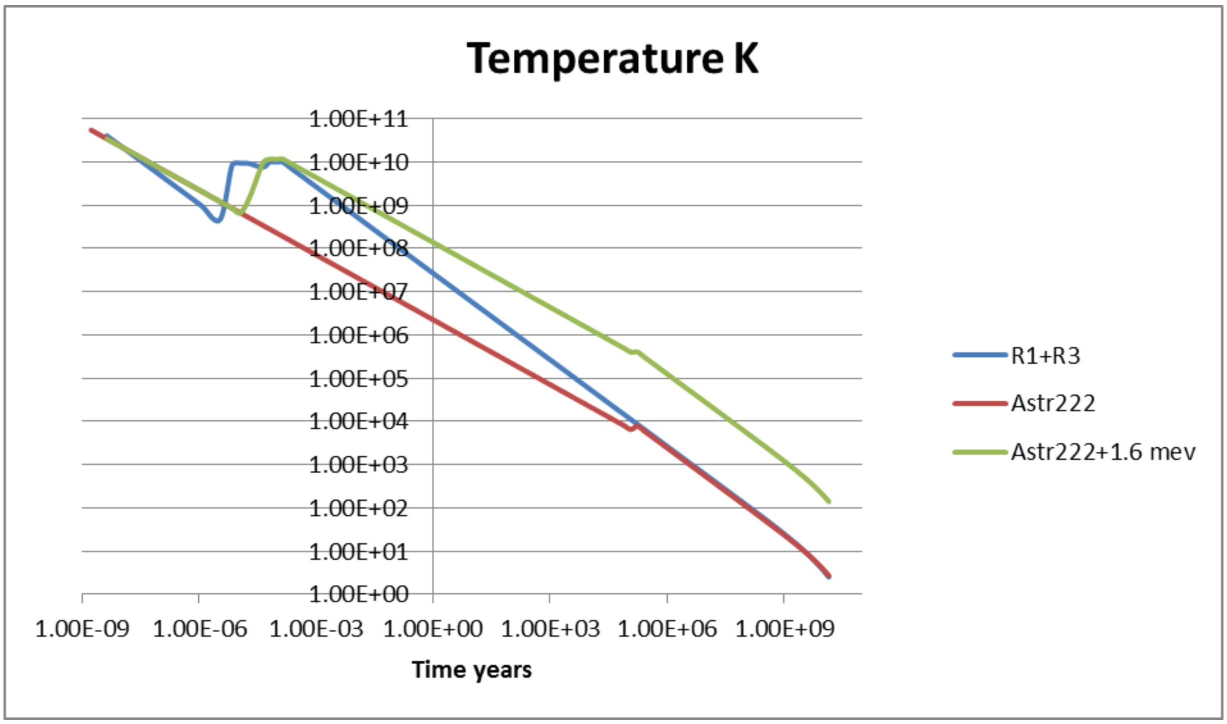
The above results may answer the question, "where does the measured residual deuterium originate?" Fusion in stars is from hydrogen. The hydrogen contributes protons that must be converted to neutrons by energetic electrons. This is quite a different situation than exists for the first few minutes following primordial He4 formation. In this environment there were still a large fraction of neutrons that had not decayed. A graph of the SAHA criteria [4] for deuterium formation is shown below. The SAHA criteria used is the natural logarithm of the SAHA value. As the SAHA criteria increased to 0, He4 fused and T9 (the temperature divided by 1e9 K) increased. With the addition of fusion energy, the SAHA criteria became negative again and caused photo-disintegration of deuterium. The temperature finally fell due to expansion and the SAHA criteria rose to 0 where deuterium was again formed. It is this deuterium that we measure uniformly throughout space at an abundance fraction of 1e-5.



The rich neutron environment fuses to deuterium when photo-disintegration is allowed again. The same equations apply as before, i.e. the SAHA equation gives the fraction of deuterium. The above plot shows this in red above and agrees substantially with the deuterium residual abundance we measure.

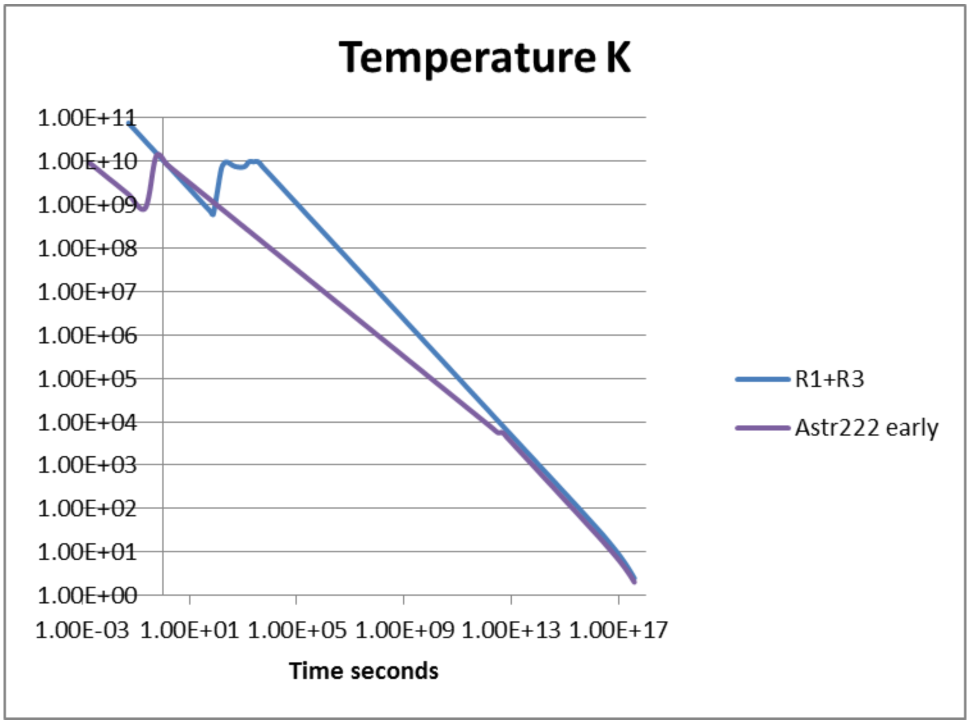
The author analyzed the effect of Omega mass and photon/baron ration on the abundance of He4 and deuterium. The SAHA equation yields the value 1.0 at a slightly different time with different SAHA parameters but this has neither an effect on the temperature value nor an effect on abundance calculations. There is no reason to believe that the photon/baryon fraction demands a maximum baryon fraction 0.04.

Analysis of Alternate Temperature Histories

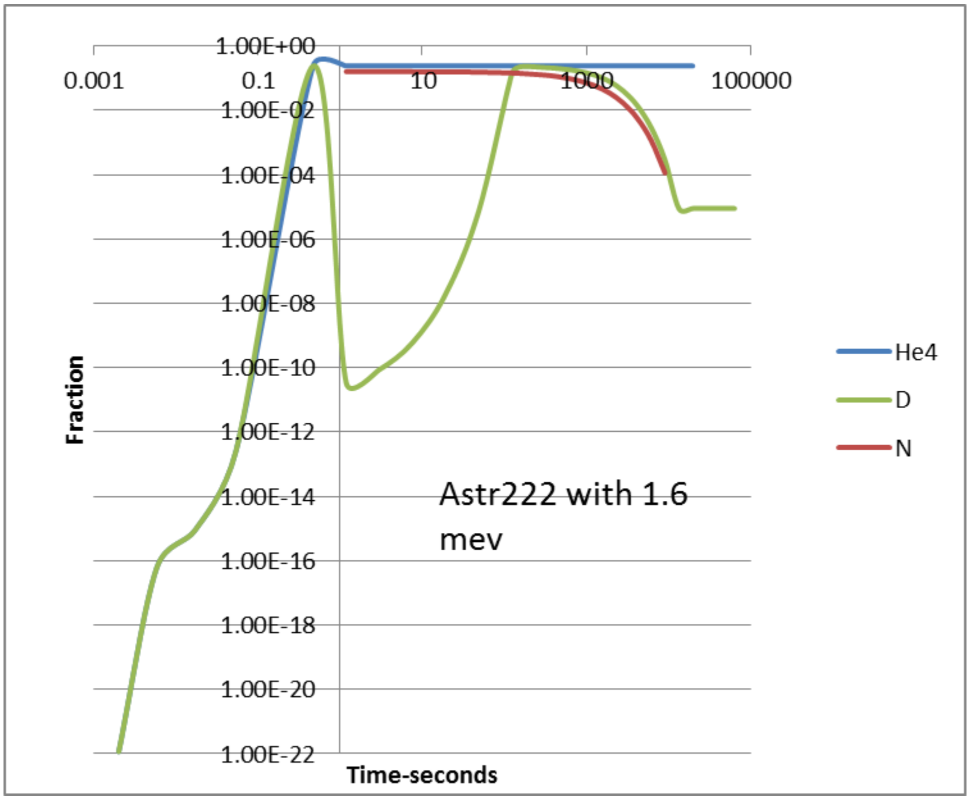


The author's R1+R3 expansion model described above is dark blue and the Astr222 curve without fusion energy is shown in red. An attempt was made to include the He4 fusion energy in the Astr222 expansion history. The temperature curve shown in green is about the same temperature as R1+R3 at the beginning. When fusion occurs, the temperature increases. After the increase, it once again decreases and follows the lower slope until decoupling of matter and radiation occurs. At about 100 thousand years, it follows the t^(2/3) slope but at the end, the temperature is 200 K, well above the accepted temperature of 2.73K.

This lead to a further attempt to use the lower slope relationship: The curve below starts at a lower temperature of about 1e9 K where He4 fusion starts. For this alternative, fusion occurs at 0.1 seconds, the low slope can be maintained and the temperature at the end is 2.73 K.



The graph below includes He4 fusion for the “Astr222 early” temperature curve. It shows that the lower slope portion of the curve is feasible and gives a residual deuterium level consistent with the measured value 1e-5. The curve below utilized rhoC=2.6e-24 gm/cm^3 and Ob=0.5. Again, the baryon/photon number ratio was variable depending on temperature. The baryon density was 0.5*exp(180)/volume.



The above graph shows fractions associated with the "Astr222 early" curve with 1.6 MeV He4 fusion energy included. Although the calculations show reasonable results, the author notes that it is not part of the literature. Some sources indicate that expansion of plasma follows the low slope until decoupling but sources vary on this section of the curve. WMAP analysis [3] gives parameters that apparently apply uniformly throughout the expansion curve and the slope is the higher R=5.89e13*t^(5/3) relationship for this expansion component.

Conclusions

Primordial fusion of He4 releases a significant amount of energy and must be included when determining temperature curves associated with expansion. After formation of He4, the temperature rises and photo-disintegrates the deuterium. Subsequently, the temperature decreases and deuterium is once again produced. The author's calculations for the deuterium abundance with the R1+R3 model agree with measured values.

Reference 7 concludes that Omega baryons=0.5*exp(180). Simulations of observed primordial nucleosynthesis are substantially consistent with this value and there is no reason to believe that a low baryon/photon number density limits Omega baryons to 0.04 as literature suggests.

References:

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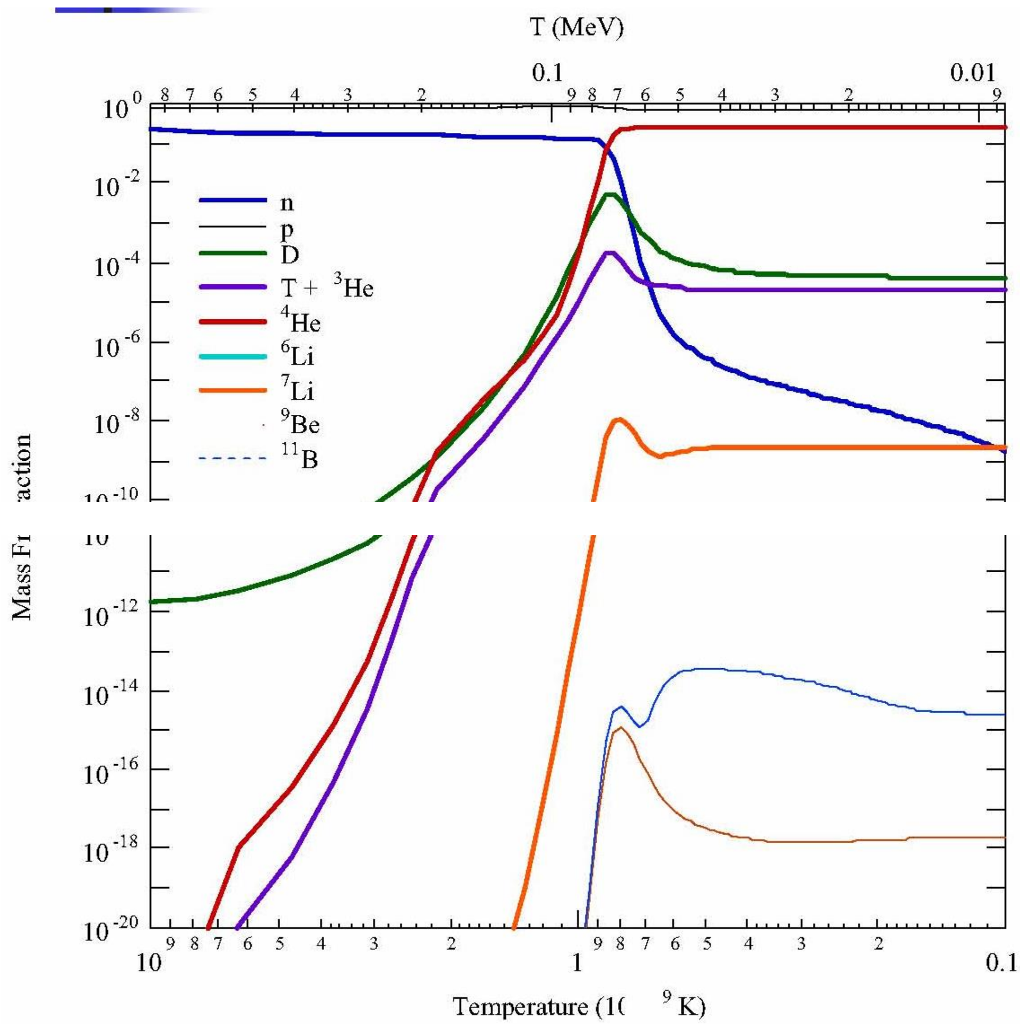

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