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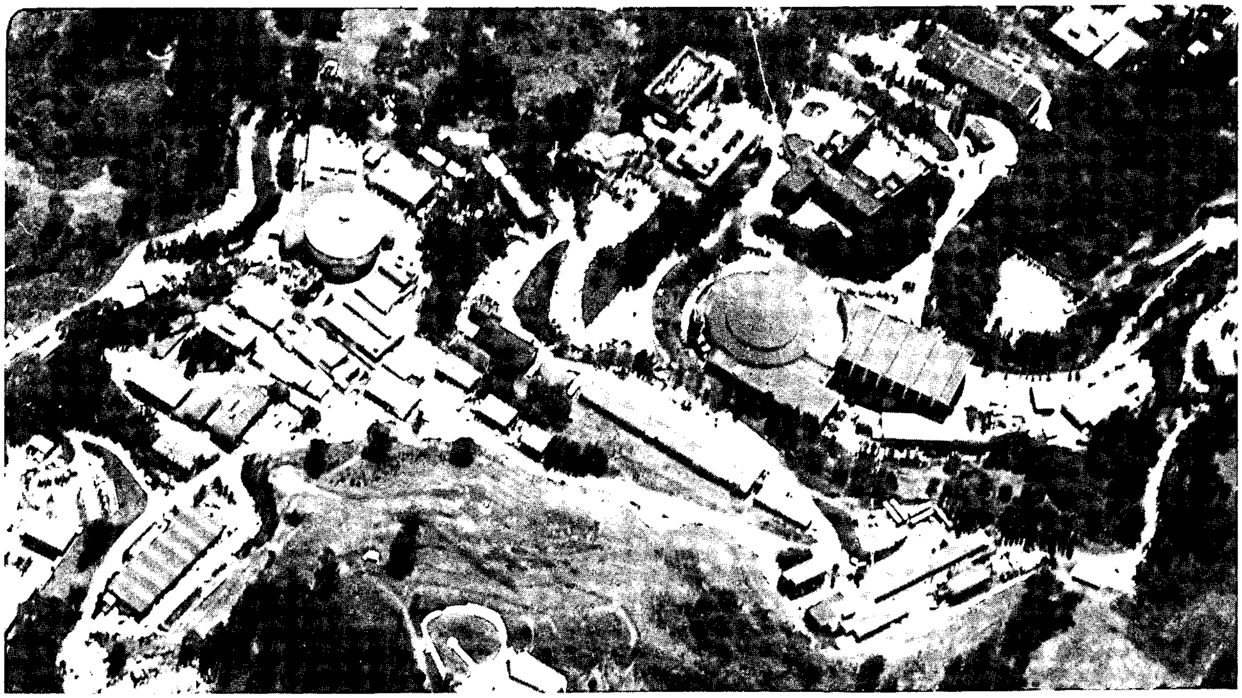

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# Primordial Nucleosynthesis During The keV Era *

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## Abstract

Energetic hadronic and electromagnetic showers in the keV era of the hot big bang are produced by the decays of long lived particles. These showers initiate a new phase of nucleosynthesis. The abundance ratios of $D$, $^3He$, $^6Li$ and $^7Li$ are given by fixed points of rate equations, which are determined by nuclear physics not by the nature of the decaying particle. The fixed points are independent of prior abundances, so that constraints from the MeV era of nucleosynthesis evaporate, except for a requirement that $^4He$ not be underproduced. For

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dances, so that constraints from the MeV era of nucleosynthesis evaporate, except for a requirement that $^4He$ not be underproduced. For

example, $\Omega_B = 1$ and many more than four neutrino species are both possible. Within the accuracy of our calculation (there are uncertainties of at least a factor of three), the abundances agree with those inferred from observations. Considerable $^6Li$ is produced and must be depleted in both population II halo stars and in the galactic disk. We predict $^6Li$, $^3He$ and $D$ abundances in primordial material which are higher than conventional nucleosynthesis.

In a recent paper[1] we gave a detailed analysis of how the decays of long-lived massive particles can lead to resynthesis of the light nuclei. In this talk we review the analytic derivation of these results and explore some of their consequences.

Consider a particle $X$ of mass $m_X$ anywhere from a few GeV to hundreds of TeV and lifetime[2] $\tau_X$ between $10^4 - 10^6$ sec. When the $X$ decays the universe is a hot plasma of photons, electrons, protons and light nuclei at a temperature of several keV. The interactions of the decay products of the $X$ with the background plasma cause electromagnetic[3] and baryonic showers.[1] The high energy photons of the electromagnetic shower are removed by pair production off the abundant thermal photons $\gamma\gamma \rightarrow e^+e^-$. This produces[3] a sharp upper cutoff to the photon spectrum given by

$$E_{max} \simeq \frac{m_e^2}{25T} \ln \frac{\eta}{5.10^{-10}} \tag{1}$$

$\eta = n_B/n_\gamma$ is the baryon to photon number density ratio. As the universe cools, $E_{max}$ increases so that successively more and more tightly bound nuclear species become vulnerable to photodissociation. The resulting photon spectrum per $X$-decay is given by[1]

$$\xi_{\gamma^*}(E) = \begin{matrix} \frac{M_X}{2E_{max}^{1/2}} & \frac{1}{E^{3/2}} & E < E_{max} \\ 0 & & E > E_{max} \end{matrix} \quad . \tag{2}$$

These photons interact predominantly with electrons except for an occasional photodissociation of a light nucleus.

Baryonic showers occur when the $X$ decays into an energetic baryon.[1] An energetic baryon, whether a neutron <u>or</u> a proton, loses very little energy to the plasma of photons and electrons as long as its kinetic energy exceeds a GeV[1]. Therefore, it slows down by sequentially colliding and sharing its energy with several protons

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and nuclei and exciting them to large kinetic energies. These "heated" protons and nuclei collide with each other and undergo a new phase of nucleosynthesis resulting in the production of $\xi_i$ nuclei of type $i$ per baryonic $X$ decay. These $\xi_i$'s were calculated in reference [1].

We proceed with an approximate analytic treatment of simplified rate equations for the nuclear abundances. This treatment stresses the physics of the abundance evolution, and gives results which are in excellent agreement with the numerical solutions of the complete rate equations given in reference [1].

Taking $\tau_X$ small enough so that the $^4He$ reduction occurs predominantly by baryo destruction rather than photodestruction[4]

$$\dot{f}_4 = +f_X^o \Gamma_X e^{-\Gamma_X t} r_B^* \xi_4 \tag{3}$$

where $\xi_4$ is negative, $r_B^*$ is the effective branching ratio of $X$ to final states containing baryons as precisely defined in ref. [1], $\Gamma_X = \tau_X^{-1}$, $f_A$ is the number density of $A$ divided by the thermal photon number density and $f_A^o$ is the initial abundance. The fractional destruction of $^4He$ therefore determines[1] $\frac{f_X^o}{f_B} r_B^*$,

$$\frac{f_X^o}{f_B} r_B^* \simeq 1.15.10^{-3} - \frac{(Y-.24)}{40} + 2.2.10^{-4} \ln \Omega_B h_o^2 + 7.10^{-4}(N_{100} - 3.36). \tag{4}$$

where $N_T$ is the effective number of degrees of freedom contributing to $\rho$ at temperature $T$ keV:

$$\rho(T) = \frac{\pi^2}{30} N_T T^4. \tag{5}$$

$\Omega_B h_o^2$ and $N_{100}$ appear because they determine the amount of $^4He$ produced during the conventional nucleosynthesis era, $Y$ is the final value of the primordial $^4He$ mass fraction.

The equations for the abundances of $D, ^3He, ^6Li$, and $^7Li$ have a common feature: the dominant production occurs inside the hadronic showers and involves the relevant $\xi_i$, and the dominant destruction is by photodissociation.

$$\dot{f}_i = f_X^o \Gamma_X e^{-\Gamma_X t} r_B^* \xi_i - n_i \int_{Q_i}^{E_{max}(t)} f_{\gamma^*}(E) \sigma_{\gamma i}(E) dE \tag{6}$$

where $Q_i$ is the binding energy, $n_i$ the number density and $\sigma_{\gamma i}$ the photodissociation cross-section of the nuclear species $i$, $E_{max}(t)$ is given by (1), together with the time temperature relation

$$\frac{t}{sec} = \frac{2.4}{\sqrt{N_T}} \left(\frac{MeV}{T}\right)^2. \tag{7}$$

The non-thermal photon spectrum is given by its fixed point value,[1]

$$f_{\gamma^*}(E) = \frac{\xi_{\gamma^*}(E) f_X^o \Gamma_X e^{-\Gamma_X t}}{n_e \sigma_c(E)}. \tag{8}$$

where $\sigma_c(E)$ is the Compton scattering cross-section averaged over non-forward angles, and $\xi_{\gamma^*}(E)$ is given in equation (2).

If equations (6) reach their fixed points ($\dot{f}_i = 0$) the abundances of $D$. $^3He$, $^6Li$, and $^7Li$, after the keV era nucleosynthesis, are given by

$$\frac{f_i}{f_B} \simeq 30 \xi_i Q_i^{1/2} E_{max}^{1/2}(t_{fi}) \frac{r_B^*}{M_X}. \tag{9}$$

We have taken $\sigma_{\gamma i}(E)/\sigma_c(E) = 1/30$. At the freeze–out time $t_{fi}$, the photodissociation rate for species $i$ drops below the expansion rate of the universe and the baryoproduction of species $i$ is negligable because sufficient $X$'s have decayed. In practice this occurs while the equations are at their fixed points. In order that the abundances reach the fixed point values of equation (9), $E_{max}(t_{fi}) > Q_i$, which translates into a condition on $\tau_X$

$$\tau_X \left(\frac{N_1}{3.36}\right)^{1/2} \gtrsim 4 \cdot 10^5 sec \tag{10a}$$

where we take 1 keV to be the characteristic temperature for the keV era of nucleosynthesis.

The constraint that little $^4He$ is photodissociated,[4] in particular that the resulting $^3He$ production is negligible, gives

$$\tau_X \left(\frac{N_1}{3.36}\right)^{1/2} \lesssim 8 \cdot 10^5 sec \tag{10b}$$

The fixed point result of equation (9) is of great importance. The keV era nucleosynthesis erases any previous abundance of $D, ^3He, ^6Li$ and $^7Li$. Furthermore the ratios

$$D : {}^3He : {}^6Li : {}^7Li \simeq 1 : 1 : 10^{-5} : 10^{-6} \tag{11}$$

are given predominantly by the ratios of $\xi_i$ since the remaining $i$ dependence is weak.[1] The absolute value of these abundances determines $M_X/r_B^*$:

$$\frac{M_X}{r_B^*} \simeq (2-10) \cdot 10^4 GeV. \tag{12}$$

The abundances (9) were obtained from a simple analytic approximation; they agree well with a more detailed numerical calculation.[1] However, the $\xi_i$ have not been computed numerically, and contain uncertainties arising from a lack of nuclear cross-section data. The detailed calculation of the $\xi_i$ in reference 1 could easily be off by a factor of 3. This would affect the results (11) and (12).

Consider the processes leading to $\xi_i$. For a given $X$ mass it is first necessary to estimate the average number of $\bar{p}p$ or $\bar{n}n$ pairs per $X$ decay and their spectra. For certain values of $M_X$ $e^+e^-$ data is available, but an extrapolation is required for most masses. Fortunately, within our uncertainties this only affects the magnitudes of all the $\xi_i$ and not their ratios. For $\xi_2$ and $\xi_3$ the number of $D$, $^3H$ or $^3He$ produced in a $N^4He$ collision is computed ($N$ represents a primary $n, \bar{n}, p$ or $\bar{p}$). Next one must find out what fraction of these $D$, $^3H$ or $^3He$ are destroyed before they are slowed to thermal equilibrium. Finally the process must be iterated: high energy $p$ and $n$ undergo many nuclear scatterings before they thermalize.

Calculations of $\xi_6$ and $\xi_7$ are much lengthier. The dominant production mechanisms are $^3H^* \, ^4He \rightarrow \, ^6Li \, n$ and $^4He^* \, ^4He \rightarrow \, ^7Li \, p, \, ^7Be \, n$. To calculate these one must know the spectra of $^3H^*$ and $^4He^*$ produced in high energy $N^4He$ collisions. One must then compute the fraction of $^3H^*$ and $^4He^*$ which produce $^6Li$ and $^7Li$. A major uncertainty here is that, as far as we know, the $^3H$ and $^4He$ spectra and the $^6Li$ and $^7Li$ production cross-sections for these processes have not been measured for all energies and scattering angles of interest to us. Hence there are uncertainties in the ratio $\xi_6/\xi_7$ as well as in the ratios of $\xi_6$ or $\xi_7$ to $\xi_2$ or $\xi_3$. However, it is clear why $\xi_6$ and $\xi_7$ are much smaller than $\xi_2$ and $\xi_3$: there are extra stages in the processes of building up $^6Li$ and $^7Li$ and the probability of each stage occurring is small because there are many other possible reactions which do not produce $^6Li$ or $^7Li$.

Our scenario leads to significant primordial $^6Li$ production, typically $f_6/f_7 \simeq 10$. Is this a problem? Since $f_6/f_7$ ratios $\leq \cdot 1$ are seen in both population II halo stars[5] and in the galactic disk[6] substantial $^6Li$ depletion must occur in both cases. For the halo stars this is probable, the rate for $^6Li$ destruction is about a hundred times that for $^7Li$ destruction at any point in the convective zone of the star. Hence even if the $^7Li$ depletion is very small, a large $^6Li$ depletion can occur.

Depletion of $^6Li$ in the the galactic disk seems to require significant stellar processing of the disk material. One then expects that if stellar processing depletes

$^6Li$ by a factor 1–A (the astration factor), $D$ will also be changed by $1-A$; and $^3He$ by $1-(1-g)A$ (where $g$ is expected to be between 1/4 and a 1/2)[7]. Hence we should choose our $X$ parameters, $M_X/r_B^*$ and $\tau_X$, such that our primordially produced $^6Li$, $D$ and $^3He$ are all overabundant. For example for $M_X/r_B^* = 3.10^4$ GeV and $\tau_X = 6.10^5$ sec. we find primordial abundances of $1.5 \times 10^{-10}$ for $^7Li$, $2 \times 10^{-9}$ for $^6Li$, $2.5 \times 10^{-4}$ for $^3He$ and $9 \times 10^{-5}$ for $D$, all relative to $H$. The $^7Li$ abundance agrees well with the population II stars, and, as in the standard scenario, essentially all the $^7Li$ observed in the disk ($10^{-9}$ abundance) must be produced during the evolution of the galaxy. If the astration factor $A = .9$ (90% of disk material processed), then the disk abundances are $2 \times 10^{-10}$ for $^6Li$, $1 \times 10^{-4}$ for $^3He$ (using $g = 1/3$) and $9 \times 10^{-6}$ for $D$.

These numbers agree well with observations. This is highly significant: it may have been that the abundance ratio predictions were off by many orders of magnitude. However, this success must be qualified. Until we have better data on the $N^4He \rightarrow ^4He$, $^3H$ and $^3H \, ^4He \rightarrow ^6Li \, n$ reactions, we cannot have confidence in our values of $\xi_6$ and $\xi_7$. Our present uncertainties are at least a factor of 3. The ranges quoted for $\tau_X$ and $M_X/r_B^*$ in (10) and (12) assume a factor of 3 uncertainty. When these uncertainties are resolved, these allowed ranges may increase or they may disappear altogether. Our present central values for the $\xi_i$ require about 90% stellar processing in the disk. With more accurate values for the $\xi_i$ this may also change substantially; for example lower $^6Li$ could mean that 50% or less astration is needed. Fifty percent stellar processing is required in the standard scenario to explain the observed abundances of heavy elements. Some authors claim that these abundances are consistent with over 90% processing.

Our theory of nucleosynthesis has several implications for both particle physics and cosmology. In sharp contrast to the standard theory, it works for a very broad range of $N_{100}$, $N_1$ and $\eta$ (or $\Omega_B h_0^2$). This implies that we can afford to allow major changes to the structure of the theory at 100 keV or 1 keV or its baryon to photon density without reaching a contradiction with the observed light element abundances.

Our theory gives us the freedom to explore new avenues in both cosmology and particle physics. Ordinary nucleosynthesis conflicts with any physics that creates a $^4He$ overabundance, whereas our theory is consistent with any such excess. The first application of these ideas[1] was to show that it is possible to have a completely baryonic $\Omega = \Omega_B = 1$ universe. In fact it is possible to have a universe with any proportion of weakly interacting and baryonic dark matter in the allowed range $0.03 < \Omega_B h_o^2 < 1.1$.[8] A second application is that we now have the freedom to have more than three light neutrino species (i.e., $N_1 = N_{100} = N_\nu$).

To conclude, we have discovered that within the accuracy of our calculations a late decaying particle satisfying (4), (10) and (12) can account for the observed light nuclear abundances. The $D : {}^3He : {}^6Li : {}^7Li$ ratio is determined by fixed point behavior, which erases prior abundances and yields predictions which depend only on nuclear physics. The $D : {}^3He : {}^7Li$ ratios are successful. We predict that primordial material should have higher ${}^6Li$, ${}^3He$ and $D$ abundances than would be expected with standard nucleosgnthesis. This appears to be a viable possibility which needs further investigation.

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