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BIG BANG PHOTOSYNTHESIS AND PREGALACTIC NUCLEOSYNTHESIS OF LIGHT ELEMENTS

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Abstract Two non-standard scenarios for pregalactic synthesis of the light elements (^{2}H, ^{3}He, ^{4}He and ^{7}Li) are developed. Big Bang photosynthesis occurs if energetic photons, produced by the decay of massive neutrinos or gravitinos, partially photodisintegrate ^{4}He (formed in the standard hot Big Bang) to produce ^{2}H and ^{3}He. In this case, primordial nucleosynthesis no longer constrains the baryon density of the Universe, or the number of neutrino species. Alternatively, one may dispense partially or completely with the hot Big Bang, and produce the light elements by bombardment of primordial gas, provided that ^{4}He is synthesized by a later generation of massive stars.

I. INTRODUCTION

The abundances of the light elements, in particular ^2H, ^4He and ^7Li, are widely considered to provide, along with the Hubble recession and the 3K background radiation, one of the three principal pillars of support for hot Big Bang cosmology. Indeed, particle physicists are using constraints on the expansion rate inferred from primordial nucleosynthesis to derive stronger limits on particle properties than have been obtained in accelerators. Examples include limits on the mass of the tau neutrino (Lindley 1979; Sarkar and Cooper 1984), on the mass and abundance of the gravitino (Fayet 1984, Ellis et al 1984), and on the number of neutrino species (Schramm and Steigman 1984). It is therefore important to explore alternative models of light element nucleosynthesis in order to establish the significance of such limits. If further motivation is needed, there is the opinion of some authors that the observed abundances disagree with standard Big Bang predictions (Vidal-Madjar 1983; Gautier and Owen 1983; Audouze 1984). Finally, inflationary models of the early Universe, which predict $\Omega = 1$, and observations of the dynamics of large-scale structure, which favor $\Omega = 0.1 - 0.2$, are both difficult to reconcile with primordial nucleosynthesis of ^2H and ^4He if baryons are the dominant species of matter. At the same time, primordial synthesis of ^7Li, as well as of the combination $^2H + {}^3He$, sets a lower limit on Ωh^2 of 0.01 ($h = H_0/100 \mathrm{kms}^{-1} \mathrm{Mpc}^{-1}$) which, if $h > 0.5$, contradicts the determination that the known forms of baryonic matter (predominantly in stars and gas) total $\Omega \simeq 0.01$ (Yang et al 1984). There is no good reason to assume that the Universe is so simple as to contain matter only in the familiar form of baryons; we should therefore carefully re-examine the nucleosynthetic constraints on Ω .

Our contribution to this goal is to explore an alternative to the standard model of Big Bang nucleosynthesis of the light elements. Since ^{4}He is generally thought to be an inevitable product of the Big Bang, we describe in section II a hypothesis which either leads to negligible primordial abundances of the other light elements, or, for certain choices of parameters, produces significant amounts of ^{2}H and ^{3}He independently of any constraints on the baryon to photon ratio. Several authors, including Lindley (1979) and Hut and White (1984), have considered the implications of a massive unstable neutrino decaying as $\nu \rightarrow \nu_e \gamma$, and producing photons energetic enough to cause photofission of ^{4}He. Recently, Sarkar and Cooper (1984) have considered the decay channel $\nu \rightarrow \nu_e e^+ e^-$, appropriate for neutrino masses greater than 2MeV, to set limits on the mass of the tau neutrino if primordial nucleosynthesis is not to be perturbed. However, there is a considerable range of the neutrino mass-lifetime parameter space in which ^{4}He may be partially or entirely destroyed.

Additional motivation for considering neutrino decay in the very early Universe comes from the resulting increase of n_γ / n_ν for the surviving stable neutrino species. If the determination by Lyubimov et al (1980) of an electron neutrino mass in excess of 20eV is confirmed (see also Boris et al 1983), then such an increase provides an attractive means of reducing the maximum free-streaming scale of the neutrinos, namely the comoving horizon scale at $kT \simeq m_\nu c^2$. This scale fixes the minimum coherence length scale of primordial fluctuations in a neutrino-dominated Universe, and, with the standard value of n_γ/n_ν, is too large to be reconciled with the observed galaxy distribution (Peebles 1982; White et al 1983).

Decaying gravitinos, predicted by current supersymmetric models (see e.g. Fayet 1984), provide another source of energetic photons capable of photofission of ^{4}He. Only the lightest supersymmetric particle, the photino, is expected to be stable. Phenomenological supergravity models contain gravitinos in the mass range 20GeV to 1TeV, with an estimated lifetime of order $m_{pl}^2/m_{3/2}^3$, or $\tau \simeq 10^8(100\text{GeV}/m_{3/2})^{-3}$sec, where m_{pl} is the Planck mass ($\simeq 10^{19}$GeV) and $m_{3/2}$ is the gravitino mass. Decay of gravitinos after cosmological nucleosynthesis produces energetic photons, but distortion of the microwave background provides a strong constraint on how late decay can occur.

If the standard primordial nucleosynthesis picture is no longer correct, then we should also consider pregalactic synthesis of all the light elements. In the absence of primordial ^{4}He, this leads to possible scenarios for ^{2}H synthesis, as we discuss in section III.

II NEUTRINO/GRAVITINO DECAYS AND LIGHT ELEMENT DESTRUCTION

Identifying the neutrino or gravitino lifetime with the cosmological epoch, and allowing the mass of the particle to be arbitrary, we find that four regimes are possible.

(a) The ^{4}He and ^{2}H abundances are unaffected by neutrino decay, in which case the standard Big Bang should account for light element abundances: the baryon density is low ($\Omega \simeq 0.07$), and there is a limit on the number of neutrino families ($N_\nu < 3$). This requires rather specific models of galactic evolution (Delbourgo-Salvador et al 1985) which allow ^{2}H astration by an order of magnitude.

(b) ^{4}He is not affected, but ^{2}H is destroyed. (This mimics a standard Big Bang with $\Omega \geq 0.01$). One then has to synthesize ^{2}H in a pregalactic environment. Spallation reactions, discussed by Epstein (1977) and Woltjer (1982), overproduce ^{6}Li and ^{7}Li by He + He forming ^{6}Li, ^{7}Li and ^{7}Be. Possible ways of avoiding this dilemma include ^{2}H production in accretion discs around black holes (Rees 1984, Aharonian and Sunyaev 1984) or postulating extremely large baryonic inhomogeneities in a uniform radiation field, identifying only the regions of low baryon density with the luminous regions of galaxies.

(c) ^{4}He is partially transformed into ^{2}H, and possibly also ^{3}He, by high energy gamma rays.

(d) Both ^{4}He and ^{2}H are destroyed, in which case one should consider the synthesis of ^{2}H, as well as ^{3}He, ^{4}He and ^{7}Li, in a pregalactic phase.

Option (a) has been extensively discussed in the literature, and option (b) seems highly contrived. We therefore focus now on options (c) and (d).

If massive neutrinos, or other particles, decay and produce high energy photons (either directly or indirectly), then a limit can be put on the lifetime of the particle by requiring that the light elements should not be destroyed by photonuclear reactions. The first estimate of this effect (Lindley 1979) contained a number of inaccuracies, and a revised calculation of the lifetime constraint has been recently carried out (Lindley 1984). The results of these calculations are used here to look at a slightly different effect, the creation of ^{2}H from the destruction of ^{4}He.

Full details of the calculational procedure are given in Lindley (1984), but for clarity the fate of energetic photons is summarized here. Thermalisation of high energy photons proceeds by one of two routes: sufficiently energetic photons can scatter off thermal photons, creating electron-positron pairs, but below threshold for this process, photons lose energy by Compton scattering or pair-production in the presence of nuclei. The important difference is that photon-photon pair-production is much faster than the other processes because thermal photons are so much more numerous than electrons or nucleons. Photonuclear reactions occur as a small fraction of the total number of photon scatterings, and are negligible when photon-photon scattering dominates. In Lindley (1984), the formula $E_\gamma kT = (1/50)\mathrm{MeV}^2$ was used to determine the critical temperature kT below which photons of energy E_γ or less thermalise by electronic or nucleonic scattering, and above which they create pairs off the thermal photon background. For any destruction of ^{4}He (threshold = 20MeV) to occur, the temperature must be below 10^{-3}MeV. If, for instance, the decays produce 100MeV photons, it is not until the temperature has fallen to 2.1×10^{-4}MeV that double photon pair-production falls below threshold. In the intervening period, the initial photons produce pairs, which then undergo inverse Compton scattering to give a spectrum of secondary photons. Some of these photons will be above the ^{4}He threshold, but below the double photon threshold, and will therefore be capable of causing some photonuclear reactions. In Lindley (1984), this secondary spectrum is used to estimate the destruction rates of ^{4}He, ^{3}He and ^{2}H as functions of electron energy and cosmological temperature. In this calculation, photons behave like two electrons of half the energy, and so we can deal with decays leading either to photons or to electron-positron pairs. There will be differences between the effects of photons and electrons at a later time, when double photon pair-production has fallen below threshold, but any such differences are negligible because we are dealing with an exponentially decaying population of decay products, and the dominant contribution to the photodestruction rates is from the first particles to decay.

Having thus obtained the photodestruction rates, one can write down a simple reaction network which includes ^{4}He, ^{3}He, ^{3}H and ^{2}H. A small complication is that ^{3}H has a beta-decay to ^{3}He, which introduces time explicitly; all the photoreactions depend instead on the rate at which energetic photons are produced. As a simplification, it is quite reasonable for our purposes to treat ^{3}H as if it were ^{3}He, since the cross-section for either to produce ^2H by photodestruction is essentially the same. This gives a reaction network containing only three nuclei, and having no explicit time dependence (the reaction rates depend on the temperature, and therefore implicitly on time):

$$dN_4 = -\Sigma_4 N_4 dn_E/n_e$$

$$dN_3 = (-\Sigma_3 N_3 + f_{43}\Sigma_4 N_4) dn_E/n_e$$

$$dN_D = (-\Sigma_D N_D + f_{3D}\Sigma_3 N_3 + f_{4D}\Sigma_4 N_4) dn_E/n_e$$

where $N_{4,3,D}$ are the fractional abundances, by number, of ^4He, ^3He and ^2H, the Σ_A are the corresponding destruction rates, the f_{AB} are the branching ratios, n_E is the number per unit volume of energetic decay electrons and positrons, and n_e is the thermal electron density. For a given source of electrons, either direct decay or pair-production by decay photons, this network can be numerically integrated in a straightforward way. The values of all the reaction rates and ratios are calculated according to the description in Lindley (1984).

As examples, two possible sources of decay particles are considered. The first case is that of gravitinos, whose existence is envisaged in many phenomenological supersymmetry models (Fayet 1984). Since the gravitino probably does not decay until after cosmological nucleosynthesis, the effects of its presence and decay on light element abundances are potentially significant. In the standard Big Bang, one expects gravitinos to have essentially the same abundance as photons, and since they are massive they can easily dominate the density of the Universe at or before nucleosynthesis. Conventionally, one wishes to avoid this, and inflation may suppress the abundance of gravitinos to an acceptably low level (Nanopoulos, Olive and Srednicki 1984). To avoid disruption of light nuclei, Ellis, Kim and Nanopoulos (1984) have found a constraint on the maximum reheating temperature after inflation. A weaker constraint comes from requiring no distortion of the microwave background by decay products.

Here, we take a different philosophy, and a more positive approach. Allowing the gravitinos to have a thermal abundance, we ask whether gravitino dominated nucleosynthesis, followed by photoreactions induced by decay products, can lead to light element abundances that mimic the standard model. Provided that the mass of the gravitino is greater than about 50MeV, the Universe is dominated not by radiation, but by non-relativistic gravitinos, when the neutron-proton ratio freezes out. The expansion rate is speeded up sufficiently that the freeze-out temperature is increased from its usual value of about 0.8MeV, and the neutron-proton ratio is close to unity. If all the neutrons end up in ^{4}He nuclei, one has close to 100% ^{4}He. This may not be quite true if the increase in expansion rate is enough to decrease the efficiency of conventional nuclear reactions, but for our simple calculation we will assume that after nucleosynthesis, but before gravitino decay, there is nothing but ^{4}He. The initial condition for the photoreaction network is then $N_4 = 0.25$, the definition of N_4 being the number of ^{4}He nuclei divided by the total number of baryons. Figure 1 illustrates the conversion of ^{4}He to ^{3}He and ^{2}H as a function of gravitino lifetime. The predicted lifetime is $\tau \simeq 100 m_{3/2}^{-3}$sec (Ellis et al 1984), where the gravitino mass is in GeV. The range 20GeV to 1TeV is of interest in phenomenological supergravity models. If the lifetime is short, nothing happens, and if it is long, everything is destroyed. For intermediate lifetimes, which lead to interesting abundances of the lighter elements, it turns out that by the time ^{4}He destruction begins, a large fraction of the gravitinos ~~have~~ has already decayed, and only a part of the exponential tail of the gravitino distribution is responsible for the photoreactions. This also means that, when photoreactions are occurring, the Universe has returned to radiation domination. (We are assuming here that the decay products of the gravitino are effectively massless, so that their combined density is negligible throughout the radiation era. This can be achieved if the photino mass is small enough, or if the gravitinos decay only to very low mass particles such as axions or axinos, as in the model of Kim et al 1984)). Decay of the gravitinos heats up the Universe, and in these calculations it has been arranged that, after reheating, the baryon to photon ratio attains the standard value of 5×10^{-10}. (The Universe is therefore not only matter dominated, but tepid too, at nucleosynthesis). Figure 1 shows calculations of light element abundances as a function of gravitino lifetime. In the upper panel, the ^{4}He abundance was initially 100% by mass (0.25 by number) as we expect from matter dominated nucleosynthesis. For comparison, the lower panel shows a more conventional initial abundance of 24% (0.06). The remaining free parameter in the results is the gravitino mass, or alternatively the energy of the decay electrons. The curves in fig. 1 are for electron energies 50MeV and 200MeV; the lower energy electrons in fact cause more photofission than the higher energy ones, although the difference is small. This is because the photoreaction cross-sections have strong peaks at energies of some tens of MeV or less, and 50MeV electrons produce more inverse Compton photons than do 200MeV electrons at such energies. For electrons of much higher energy, such as would be produced by decays of gravitinos with mass around 100GeV, this trend is reversed, and the number of photoreactions induced per gravitino increases approximately in proportion to the mass (Lindley 1984). However, this is cancelled by demanding a specific final baryon to photon ratio after reheating, which requires a gravitino to baryon ratio decreasing with the mass. Consequently, we find that the results are independent of the gravitino mass, within the uncertainty of the calculations. In the results typified by fig. 1, there is a regime where more ^{3}He is produced than ^{2}H, because the threshold for burning ^{4}He to ^{3}He is lower than for ^{4}He to ^{2}H, so that production of ^{3}He begins earlier. The abundance of deuterium has a rather prominent peak, which may be partly due to numerical overshoot in the simple integration technique used. A deuterium abundance of more than 10^{-5} occurs over somewhat less than half an order of magnitude range in gravitino lifetime.

Our second example uses massive neutrinos as a source of electrons. In this case, the abundance of neutrinos relative to photons falls off as the mass increases, because freeze-out of neutrinos occurs at non-relativistic temperatures (Dicus et al 1978). If, as we expect, neutrinos of more than an MeV in mass decay to electron-positron pairs plus light neutrinos, then the typical electron energy will be one-third the neutrino mass. Figure 2a shows results for three different electron energies; the curves are qualitatively similar to those in fig. 1. In fig. 2b, we have plotted, as a function of neutrino mass, the lifetime for which an abundance of ^{2}H of 10^{-4} is produced. The abundance of neutrinos relative to thermal electrons depends on the baryon to photon ratio, and fig. 2b gives results for $n_B/n_\gamma = 5.10^{-10}$ and 5.10^{-9}. As the neutrino mass increases, the neutrino abundance decreases, and the sensitivity of the results to the lifetime is reduced (i.e. a wider range of lifetime allows $N(^2H) > 10^{-4}$.

In both these examples, with gravitinos or massive neutrinos, primordial nucleosynthesis no longer constrains the baryon to photon ratio, and therefore does not rule out the possibility of a dense, baryon-dominated Universe now. The standard limits on the number of neutrino families are also evaded.

III PREGALACTIC LIGHT ELEMENT SYNTHESIS

Destruction of all light elements by particle decay is a possibility we should also consider. More exotic processes for destroying light elements include primordial chaos or late production of entropy by pregalactic stars. Suppose now that only hydrogen survives to the pregalactic era. We must therefore devise a plausible scheme for synthesizing the light elements. In Audouze and Silk (1983), we described how an initial generation of helium-poor massive stars would have evolved (Ober and Falk 1984) to yield a helium mass fraction of about 20% (Bond, Carr and Arnett 1983). However, this takes a considerable time (10^7 yr or more), and we argued that cosmic rays would be produced before the stellar debris was efficiently mixed. These cosmic rays could be produced by post-main-sequence stellar winds, which are likely to provide an injection mechanism. The cosmic rays contain ^{4}He and possible traces of CNO, and interact with the essentially He- and metal-free intergalactic gas. Spallation reactions then yield ^{2}H and ^{7}Li. An alternative scheme, pointed out to us by D. D. Clayton (private communication) would require cosmic rays to be accelerated prior to the epoch of massive star formation. In this situation, cosmic ray protons would interact with the massive star ejecta, which are rich in ^{4}He and contain some CNO, presumably comparable to that in extreme population II (CNO/H $\simeq 10^{-5}$).

There are two barriers to surmount in constructing such schemes for ^{2}H synthesis. Excessive gamma-ray production via $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma$

is avoided if sufficient grammage is placed between us and the epoch of spallation. Provided that the ^2H is produced at a redshift > 100, the gamma radiation is absorbed by the hydrogen. The more severe problem is that of excessive Li production. While our schemes are devised to circumvent the $\alpha + \alpha \rightarrow {}^7Li + p$ channel, there can still be some CNO in either the cosmic rays, if produced by stellar injection, or in the intergalactic gas, via enrichment from stars.

The threshold for $^4He + p \rightarrow D$ is about 25MeV (Meyer 1972), and a flux of about $2.10^{-20} cm^{-2}$ in ^4He cosmic rays is required to impact on primordial H in order to produce $D/H \simeq 10^{-5}$. Overpopulation of ^7Li to an abundance exceeding $^7Li/H \simeq 10^{-10}$ is avoided only if $CNO/He < 10^{-5}$ in both cosmic rays and the intergalactic gas. Note that if ^7Li is indeed produced by this mechanism to an abundance level $^7Li/H \simeq 10^{-10}$ (Spite and Spite 1982), the other light elements are produced with precisely their <u>observed</u> abundances. As pointed out by Meneguzzi, Audouze and Reeves (1971), the amount of ^7Li synthesized by <u>galactic</u> cosmic rays is only 1.7 times that of ^6Li, i.e. about $1.2.10^{-10}$ relative to hydrogen. Hence the formation of ^6Li, ^9Be, ^{10}B and ^{11}B nuclei sets no further constraint on pregalactic CNO abundances.

An additional constraint arises from the $\alpha + \alpha \rightarrow {}^7Li + p$ spallation reaction, the cross-section for which is comparable to that for $He + H \rightarrow {}^2H$. To avoid exceeding $^7Li/H \simeq 10^{-5}$, the He/H ratio must be $< 10^{-5}$ in the intergalactic gas, if it is being bombarded by He-rich cosmic rays. Hence the cosmic ray He nuclei must react with H rather than be slowed down by ionization loss.

Suppose that cosmic rays are the sole source of He in the ambient medium. The condition for ^{7}Li to be less than 10^{-10}H is then, if σ is the spallation cross-section and σ_i is the ionization cross-section,

$$\frac{\sigma}{\sigma_i} > \frac{1}{2}\frac{(^2\mathrm{H/H})^2}{(^7\mathrm{Li/H})} \approx \frac{1}{2}$$

This is satisfied at energies > 300MeV per nucleon.

Such high energy cosmic rays drive up the energetic requirements of the model, but not to an unacceptably high level. The required cosmic ray energy density is $2.10^{-8}(E/300\mathrm{MeV})(10^6\mathrm{yr}/t_{cr})\mathrm{erg\ cm}^{-3}$, t_{cr} being the cosmic ray lifetime. To minimize the energy requirements, we identify t_{cr} with the cosmological epoch. The injection rate will determine the effective lifetime, and the stellar lifetime will exceed the expansion time of the Universe at $z > 100$. The ratio of cosmic ray energy density to that in the cosmic background radiation is $3(1+z)^{-5/2}(E/300\mathrm{MeV})^{1/2}$. A more appropriate ratio is to the energy released in nuclear burning by the pregalactic stars. If an efficiency ξ is attained, then the ratio of cosmic ray energy required to produce ^{2}H relative to nuclear energy release (for which $\xi \simeq 0.01$) is $0.2(E/300\mathrm{MeV})^{1/2}\,\Omega_*^{-1}\,(1+z)^{-3/2}(0.01/\xi)$, where Ω_* is the mass fraction (relative to the closure density) processed through massive stars. At $z \simeq 100$, the cosmic ray energy input only amounts to 10^{-4} of the total stellar nuclear energy release involved in synthesizing the ^{4}He.

IV SUMMARY

Two alternative models to the standard Big Bang nucleosynthesis scheme have been presented here. In one model, ^{4}He is first produced during the Big Bang, and is partially transformed into ^{2}H and ^{3}He by photons coming from the decay products of gravitinos or massive neutrinos. The ^{7}Li observed in old galactic halo stars can be synthesized subsequently by cosmic ray bombardment of the same interstellar matter that is responsible for the formation of the ^{6}Li, ^{9}Be, ^{10}B and ^{11}B known to be produced during the early phase of galactic evolution.

Decays of massive gravitinos or neutrinos may yield appreciable abundances of ^{3}He and ^{2}H without destroying all of the primordial ^{4}He. This means that the ratios of pregalactic light element abundances no longer simply depend on the baryon to photon ratio of the Universe, but may reflect a history of exotic particle decays during the first 10^7 seconds of the expansion. At later times, there would be unacceptable distortions of the cosmic background radiation were particle decays still occurring at a sufficiently great rate. The dark matter in a Universe with Ω =1 could, for example, consist entirely of baryons, provided we assume the presence of a neutrino or gravitino within the mass-lifetime constraints indicated by figures 1 and 2. Moreover, the ^{4}He abundance can no longer be used to restrict the number of neutrino species, once we allow the possibility of ^{4}He destruction.

In an alternative scenario, we envisage that either there is no light element production during the first minutes of the Big Bang, or else that there was total destruction of them by, for example, excessive gravitino domination or decays in the very early Universe. During the pregalactic era, the absence of ^{4}He allows cosmic ray spallation to produce substantial amounts of ^{2}H without overproducing ^{7}Li. The observed ^{4}He is then a by-product of stellar nucleosynthesis by the first generation of massive stars.

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FIGURE CAPTIONS

Figure 1 Effect of decaying gravitinos on light element abundances. Initial abundances were 0.25 ^{4}He by number (100% by mass) for the upper panel, and 0.06 (24% by mass) for the lower panel, with no ^{3}He or ^{2}H in either case. Massive gravitinos rapidly produce electron-positron pairs, which then cause photodissociation through inverse Compton photons. The two sets of curves are for 50MeV and 200MeV electrons. Abundances are plotted against gravitino lifetime.

Figure 2 Effect of massive unstable neutrinos on light element abundances. The upper panel shows the resulting abundances for three different neutrino masses, as a function of lifetime, from an initial ^{4}He abundance of 0.07 by number (28% by mass). The lower panel shows the region in mass-lifetime parameter space in which an abundance of ^{2}H greater than 10^{-4} is synthesized.

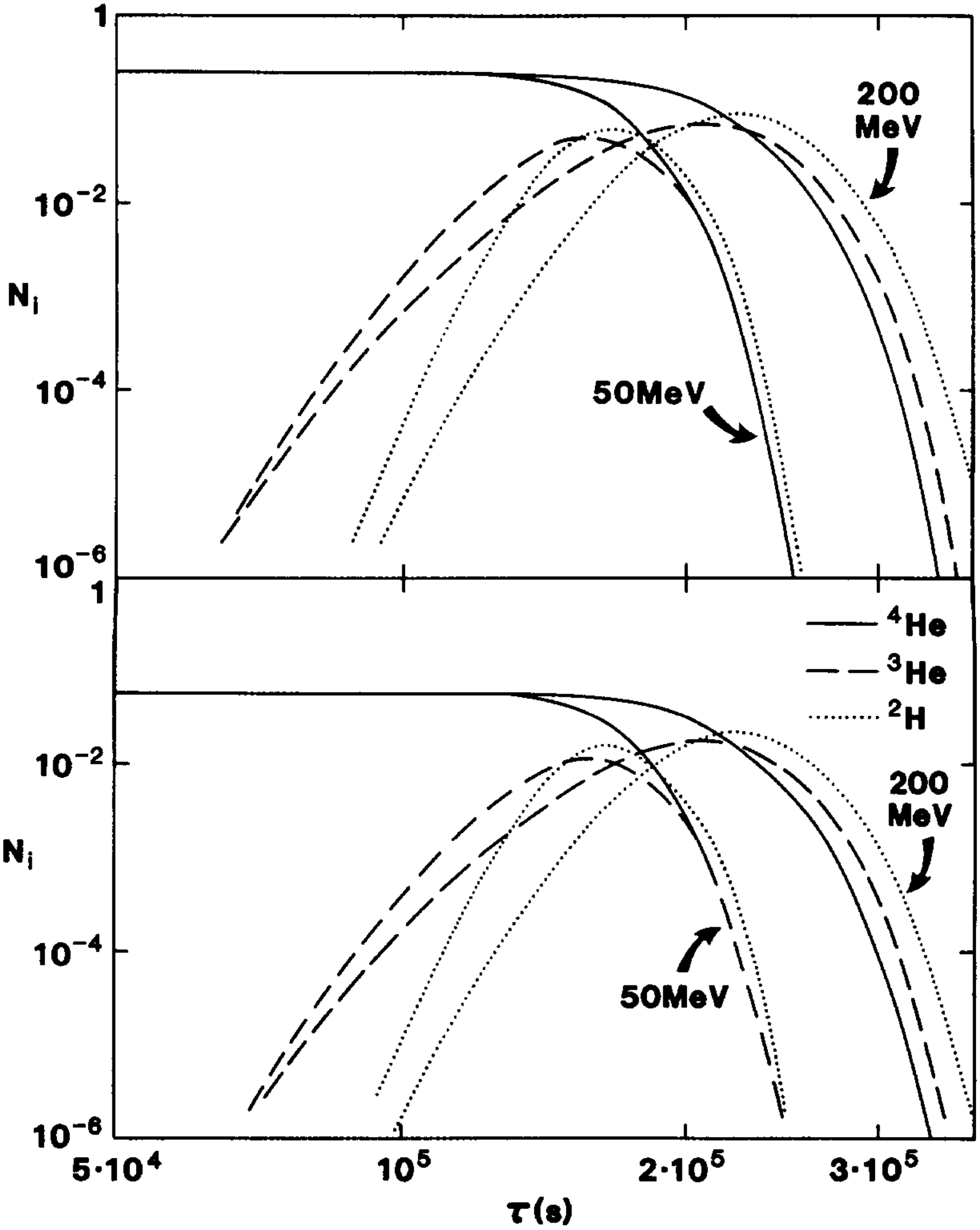
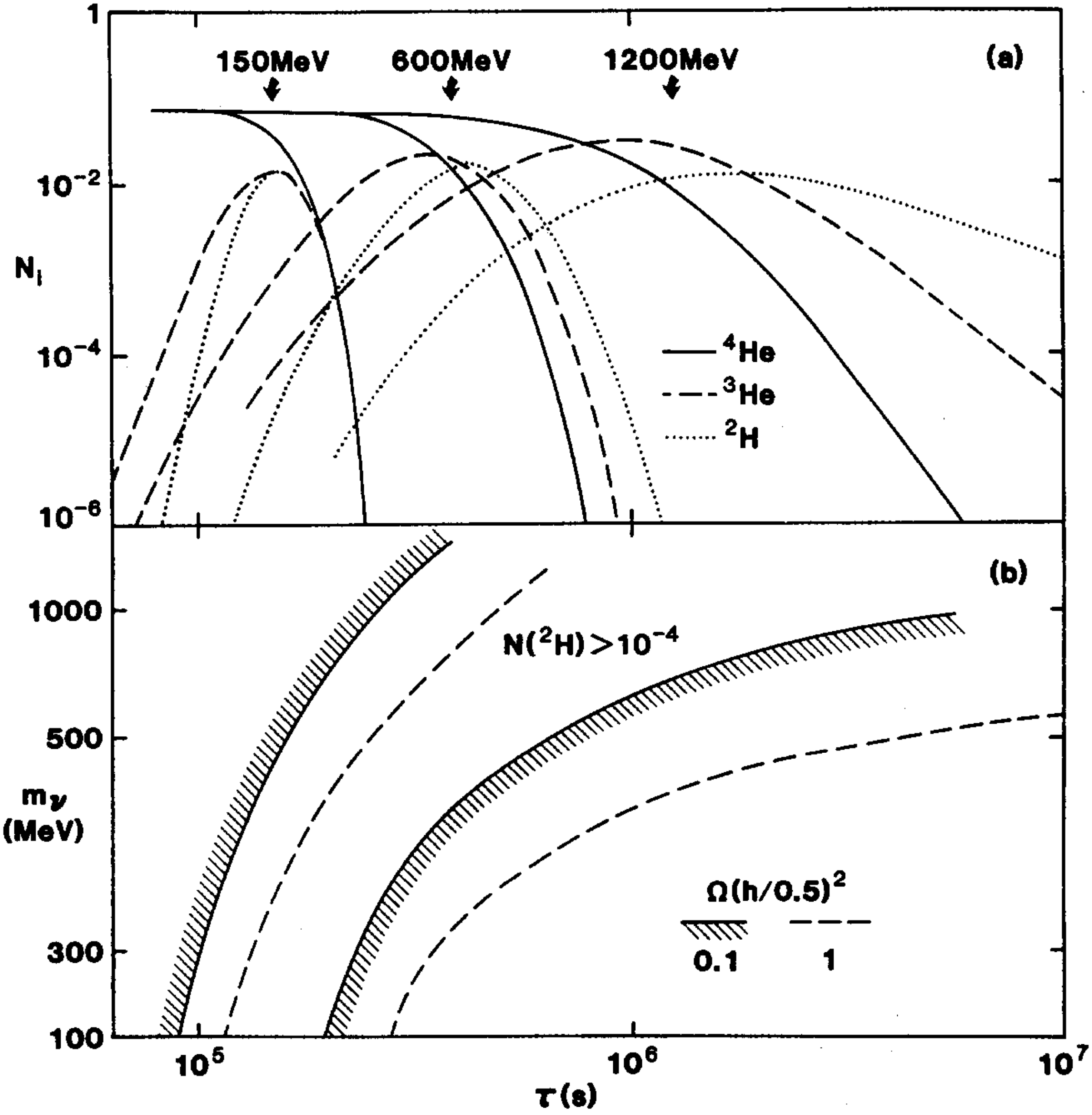

1
10^{-2}
10^{-4}
10^{-6}
N_i
200 MeV
50MeV
^{4}He
^{3}He
^{2}H
$5\cdot10^4$
10^5
$2\cdot10^5$
$3\cdot10^5$
τ(s)

FIGURE 1



1
150MeV
600MeV
1200MeV
(a)
10^{-2}
N_i
10^{-4}
10^{-6}
^{4}He
^{3}He
^{2}H
(b)
1000
$N(^2H)>10^{-4}$
500
m_ν (MeV)
300
100
$\Omega(h/0.5)^2$
0.1
1
10^5
10^6
10^7
τ(s)

FIGURE 2