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PRIMORDIAL NUCLEOSYNTHESIS REDUX *

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ABSTRACT

The latest nuclear reaction cross sections (including the most recent determinations of the neutron lifetime) are used to recalculate the abundance of deuterium, helium-3, helium-4 and lithium-7 within the framework of primordial nucleosynthesis in the standard (homogeneous and isotropic) hot, big bang model. The observational data leading to estimates of (or, bounds to) the primordial abundances of the light elements is reviewed with an emphasis on ^7Li and ^4He. A comparison between theory and observation reveals the consistency of the predictions of the standard model and leads to bounds to the nucleon-to-photon ratio: $2.8 \leq \eta_{10} \leq 4.0$ ($\eta_{10} \equiv 10^{10}\eta_B\ \eta_\gamma$) which constrains the baryon density parameter: $\Omega_B h_{50}^2 = 0.05 \pm 0.01$ (the Hubble parameter is $H_0 = 50 h_{50}$ kms$^{-1} Mpc^{-1}$). These bounds imply that the bulk of the baryons in the Universe are *dark* and, further, if $\Omega_{TOT} = 1$, would require that the Universe is dominated by non-baryonic matter. An upper bound to the primordial mass fraction of ^4He, $Y_p \leq 0.240$ constrains the number of light (equivalent) neutrinos to $N_\nu \leq 3.3$, in excellent agreement with the LEP and SLC collider results. Alternately, for $N_\nu = 3$ we bound the predicted primordial abundance of ^4He : $0.236 \leq Y_p \leq 0.243$ (for $882 \leq \tau_\nu \leq 896$ sec.).

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I. INTRODUCTION

It is well known that primordial nucleosynthesis provides a unique window on the early Universe. Along with measurements of the cosmic background radiation (CBR), it constitutes one of the two crucial quantitative tests of the Standard Big Bang Cosmological Model. Indeed, big bang nucleosynthesis (BBN) and the CBR, which have been related symbiotically since the early work of Gamow (1948) and Alpher and Herman (1949), provide complementary views of the early Universe. The synthesis of the light elements is determined by events occurring in the epoch from ~ 1 to $\sim 1,000$ seconds in the history of the Universe when temperatures varied from $\gtrsim 10^{10}$ K ($\gtrsim 1$ MeV) to $\lesssim 10^{9}$ K ($\lesssim 0.1$ MeV). Thus, the observed abundances offer a probe of the Universe at epochs far earlier than those probed by the CBR ($t \sim 10^5$ yr; $T \sim 10^4$ K (~ 1 eV)). Without BBN, those early epochs would be denied our scrutiny. Through a detailed comparison of the predicted abundances with the observational data, cosmological models may be tested and, constraints inferred on parameters of importance to cosmology (e.g., the universal density of baryons) and elementary particle physics (e.g., the number of species of light neutrinos).

The "standard", Big Bang model of cosmology is the simplest (i.e., it has the fewest adjustable parameters), based on the observed large scale isotropy and homogeneity of the Universe. Utilizing only the *known* particles (e.g., assuming three species of *light* neutrinos ν_e, ν_μ, ν_τ; $N_\nu = 3$) and assuming the correctness of General Relativity, the nucleosynthesis predictions of the standard model depend on only one parameter, the ratio, η, of nucleons to photons ($\eta \equiv n_B/n_\gamma$) (or, equivalently, the density of baryons, since n_γ is known from measurements of the CBR). The quantitative success of the standard model in accounting for the observed abundances of D, ^3He, ^4He and ^7Li, whose values span some nine orders of magnitude, has stimulated more detailed comparisons of predictions with data. Among the goals of such comparisons, key is that of testing in detail the consistency of the standard model (i.e., Is there a unique value of η such that the predicted abundances all agree with observations?). A related goal is to subject to the same detailed scrutiny alternate cosmological models (e.g., inhomogeneous nucleosynthesis), as well as variations on the standard model of particle physics (e.g., more species of light neutrinos and/or the existence of massive, unstable exotic particles).

Since Hayashi (1950) recognized the role of neutron-proton equilibration, the framework for Big Bang Nucleosynthesis calculations has not varied significantly. The work of Alpher, Follin and Herman (1953), Hoyle and Tayler (1964) and Zeldovich (1965) preceding the discovery of the 3K background, and Peebles (1966) and Wagoner, Fowler and Hoyle (1967), immediately following the discovery, and the more recent work in which some of us took part (Schramm and Wagoner 1977; Olive et al. 1981; Yang et al. 1984; Boesgaard and Steigman 1985; Kawano, Schramm and Steigman 1988) all do essentially the same basic calculation. As for the calculation itself, the reaction network is relatively simple by the standards of, for example, explosive nucleosynthesis calculations in supernovae. The changes over the last 25 years are mainly in the input of more recent nuclear reaction rates. This paper follows that trend by providing the most recent update to the input reaction rates.

With the exception of the effects of elementary particle assumptions to which we will return, the real excitement in BBN over the last 25 years has not been in redoing the calculation. Instead, the true action has been focused on understanding the evolution of the light element abundances and using that information to infer powerful conclusions. In particular, in the 1960s, the main focus was on ^4He which has the virtue (and the weakness!) of being very insensitive to the baryon density (η). The agreement between BBN predictions and observations provided support for the basic Big Bang model but did not significantly constrain the density. In fact, in the mid-1960s, the other light isotopes (which *are* capable of giving density information) were assumed to have been made during the T-Tauri phase of stellar evolution (Fowler, Greenstein and Hoyle 1962), and so, it was not appreciated that they too have cosmological significance. It was during the 1970s that BBN was developed fully as a tool for probing the Universe. This possibility was in part stimulated by Ryter et al. (1970) who showed that the T-Tauri mechanism for light element synthesis failed. Furthermore, deuterium abundance determinations improved significantly through solar wind measurements (Geiss and Reeves 1971; Black 1971) and the interstellar observations from the Copernicus satellite (Rogerson and York 1974). Reeves, Audouze, Fowler and Schramm (1973) argued for a cosmological origin of ^2H (and ^7Li) and were able to place a constraint on the baryon density excluding a universe closed by baryons alone.

Subsequently, the ^2H arguments were strengthened by Epstein, Lattimer and Schramm (1976) who showed that no realistic astrophysical process, other than the Big Bang, could produce cosmologically significant amounts of ^2H. It was also interesting that the baryon density implied by BBN was in good agreement with the density inferred from the dark galactic halos (Gott, Gunn, Schramm and Tinsley 1974).

By the late 1970s, a complementary argument (to ^2H) had developed, using ^3He. In particular, Rood, Steigman and Tinsley (1976) argued that unlike ^2H, ^3He *was* made in stars; thus, its abundance would increase with time. Since primordially synthesized ^3He, like ^2H, decreases monotonically with the cosmological baryon density (η), this argument could be utilized (Yang et al. 1984), in conjunction with measurements of ^3He in the solar wind (Black 1971; Geiss and Reeves 1971) or in the interstellar medium (Wilson, Rood and Bania 1983), to place a *lower* limit on the universal density of baryons. Since the bulk of the ^2H was converted in stars to ^3He, the constraint was quite restrictive (Yang et al. 1984).

It was interesting that the lower bound to η from ^3He and the upper bound to η from ^2H yielded the prediction that primordial ^7Li be near its minimum of $^7Li/H \sim 10^{-10}$, which was subsequently verified by the Pop II Li measurements of Spite and Spite (1982). This yielded the situation, emphasized by Yang et al. (1984), that the light element abundances are consistent with BBN over nine orders of magnitude *only* if the cosmological baryon density is constrained to be $\sim 5\%$ of the critical density.

The other development of the 70s for BBN was the explicit calculation of Steigman, Schramm and Gunn (1977; hereafter SSG), showing that the number of neutrino generations, N_ν, had to be small to avoid overproduction of ^4He. Earlier work had noted a dependence of the primordial ^4He abundance on the amount of the cosmological stress-energy in exotic particles (Hoyle and Tayler 1964; Shvartsman 1969; Peebles 1971), but had not explicitly calculated the quantity of interest to particle physics, N_ν. To put this in perspective, one should remember that the mid-1970s also saw the discovery of charm and bottom quarks and the tau lepton, so that is seemed as if each new accelerator experiment led to the discovery of new particles. And, yet, cosmology argued against this "conventional" wisdom. Over the years the SSG limit on N_ν has improved with better

^4He abundance determinations, neutron lifetime measurements and, with limits on the lower bound to the baryon density. For most of the 1980s, the SSG cosmological bound on N_ν hovered at $\lesssim 4$; just as LEP and SLC were accumulating data, N_ν dropped below 4 (Kawano and Schramm 1989; Steigman 1989a; Pagel 1989a; Olive et al. 1990).

Because of the obvious importance of BBN, it is clearly important to carry out, periodically, a re-evaluation using the latest reaction rates and latest abundance determinations. That is the purpose of this paper. In particular, many of the cross sections of relevance to the calculation of primordial nucleosynthesis have been reexamined. Of special importance for ^4He, the neutron lifetime has been measured in a series of modern, high accuracy experiments, leading to a slightly smaller (and, much more accurate) value than has been employed in previous calculations. On the observational side, lithium has been measured in large numbers of metal-poor (Pop II) stars, leading to increased confidence that the Pop II lithium abundance is an indicator of the primordial abundance (Spite and Spite 1982). Also, ^4He has been studied in many metal-poor extragalactic HII regions, leading to an improved estimate of the primordial abundance of ^4He. Furthermore, the LEP and SLC measurements of N_ν (Jarlskog 1990; Mark II 1989; L3 1989; ALEPH 1989; OPAL 1989; DELPHI 1989) provide laboratory tests of the standard cosmological model as well as of the standard model of particle physics.

It is this new laboratory and observational data that motivates our detailed reexamination of big bang nucleosynthesis. For the most part we will confine our attention to the predictions of BBN within the context of the standard model and, to the comparison of those predictions with the observations. We will, however, briefly comment on alternate scenarios (inhomogeneous models; decaying massive particles). We will also explore the sensitivity of the standard model to the number of light neutrino species to see by how much N_ν can differ from the "standard" value $N_\nu = 3$; the cosmological and accelerator constraints are, in fact, complementary (Schramm and Steigman 1984).

As a preview of our results, we note that we find that the standard model predictions for the abundances of the light elements *are* in agreement with observations for the baryon to photon ratio in the restricted range $2.8 \lesssim \eta_{10} \lesssim 4.0$. This corresponds to a baryon fraction of the critical density $\Omega_B h_{50}^2 = 0.05 \pm 0.01$, where $\Omega_B \equiv \rho_B/\rho_c$ and

$H_0 = 50h_{50}$ kms^{-1}Mpc^{-1}. Thus, the Universe fails to be "closed" by baryons by at least an order of magnitude. On the other hand, the lower bound to Ω_B suggests that most of the baryons in the Universe are "dark" (i.e., $\Omega_B \gtrsim \Omega_{LUM} \approx 0.007$). As for N_ν, the uncertainty in the upper bound to Y_p is the greatest source of uncertainty in the SSG upper bound to the number of light neutrino species; for $Y_p \leq 0.240$ we find $N_\nu \lesssim 3.3$. Alternately, for the allowed ranges of η and the neutron lifetime and, for the standard value $N_\nu = 3$, we predict that the primordial ^4He mass fraction lies in the range: $0.236 \leq Y_p \leq 0.243$.

In the next section we review the changes of relevance to BBN of the nuclear reaction rates and the neutron lifetime. Since the nuclear and weak reaction rate uncertainties are now much reduced, it is important to include finite temperature effects and radiative corrections in calculating the ^4He abundance (Dicus et al. 1982; Johansson, Peressuti and Skagerstam 1982; Saleem 1987). Then, we present the results of our calculations and emphasize any residual uncertainties. The observational data on D, ^3He, ^4He and ^7Li is reviewed and, for the latter two isotopes, updated. We try, as far as is possible, to derive from the data 95% Confidence Level (CL) ranges allowed for the primordial abundances (or, bounds thereof) of the light elements. Then, these 95% CL limits are compared with the predicted abundances to derive bounds on η and N_ν. These same 95% CL limits are also used to explore the consistency of alternate scenarios of BBN. Finally, we summarize our results.

II. NUCLEAR REACTION RATES

The calculation of the standard BBN production of D, ^3He, ^4He, and ^7Li proceeds in two distinct stages. The first involves the competition between the expansion rate of the Universe ($t^{-1} = 2H$, where $H^2 = \frac{8\pi}{3}G\rho$) and the rate of the weak interactions responsible for the interconversion of neutrons and protons ($ne^+ \leftrightarrow p\bar{\nu}_e$, $n\nu_e \leftrightarrow pe^-$ and $n \leftrightarrow pe^-\bar{\nu}_e$). The second stage involves the interplay between the expansion rate and the nuclear reactions that synthesize complex nuclei. For $T \gtrsim 1$ MeV, the $n \leftrightarrow p$ rates are greater than the expansion rate and the neutron-to-proton ratio traces its equilibrium value

$$(n/p) = \exp(-Q/T), \tag{1}$$

where $Q \equiv (m_n - m_p)c^2 = 1.293$ MeV. When the universe cools below ~ 1 MeV the $n \leftrightarrow p$ rates are less than H and (n/p) "freezes out", decreasing only slowly due to neutron-decay and residual $e^{\pm}$, ν_e, and $\bar{\nu}_e$ collisions until the onset of nucleolsynthesis. The high photon-to-baryon ratio, coupled with the relatively low binding energies per nucleon of the light nuclei, inhibits the buildup of significant abundances of more complex nuclei until $T \lesssim 100$ keV. In particular, the formation of the various light elements proceeds by a 2-body reaction network that flows through weakly bound nuclei such as deuterium. The equilibrium abundance of D does not become significant until $T \lesssim 100$ keV, at which point nearly all the available neutrons are quickly processed into the most tightly bound of the light nuclei, ^4He. A small amount of ^7Li is made by further reactions on ^4He – a point we address in more detail in section IV. The absence of stable nuclei at $A = 5$ and 8, coupled to the low densities of nuclei and nucleons (ensuring that 2-body reactions are dominant), and to a neutron/proton ratio less than unity make it difficult, in the standard model, to synthesize nuclei beyond mass-5. The small leakage to $^7Li/^7Be$ is prevented from extending beyond mass-8 by the rapid destruction of mass-7 nuclei by reactions with protons. Leakage to heavier nuclei *can* occur in regions of high neutron densities which aren't found in the standard model but which could be present in inhomogeneous models (Applegate et al. 1989; Terasawa and Sato 1989; Kawano, Fowler and Malaney 1990).

The calculated abundance of primordial ^4He is most sensitive to the ratio (n/p) at the onset of nucleosynthesis and therefore depends crucially on the weak interaction rate. The weak $n \leftrightarrow p$ rates, can be expressed in terms of the neutron decay rate τ_n^{-1} and thus, increasing (decreasing) τ_n raises (lowers) the "freeze-out" temperature and increases (decreases) the yield of ^4He. Prior to the very recent measurements of τ_n, the errors introduced in the overall normalization of the $n \leftrightarrow p$ rates due to the uncertainty in τ_n led to uncertainties in the primordial ^4He yield which were much greater than those introduced by approximating the temperature (T_γ) dependence of the tree-level $n \leftrightarrow p$ rates with analytic fits. The much improved accuracy of the τ_n measurements now requires a more careful evaluation of the $n \leftrightarrow p$ rates (Olive et al. 1990; hereafter OSSW). This was first discussed by Dicus et al. (1982) and we have adapted their prescription as follows: (1) The $n \leftrightarrow p$ rates are integrated numerically for each T_γ-step with an explicit calculation of the neutrino temperature required for the phase-space dependence and the appropriate Coulomb corrections to the tree-level interactions included, and (2) We verify at several values of (η, τ_n, N_ν) that the corrections to the primordial ^4He mass fraction, ΔY_p, due to the inclusion of radiative corrections, electron self-mass effects, and e^+e^- heating of ν_e, are less than 0.0001 in magnitude ($\Delta Y_p \leq \pm 0.0001$), whereas step (1) contributes $\Delta Y_p \simeq -0.0023$. To make a full exploration of parameter space possible, we turn off step (2) and conclude that for fixed τ_n the uncertainty in the predicted Y_p due to the weak interaction sector is ≤ 0.0002. Typically $Y_p \sim 0.24$ and so this amounts to better than 0.1% accuracy, whereas $2-\sigma$ variations in τ_n lead to $\sim 1\%$ uncertainties in the predicted Y_p. These latter changes are the same order as those found in going from an analytic fit to the $n \leftrightarrow p$ rates to the numerical evaluation of the Coulomb corrected tree-level rates.

The primordial yields of D, ^3He, and ^7Li are most sensitive to the competition between the nuclear reaction rates and the expansion rate H. Increasing the nucleon number density increases the temperature at which D has an appreciable equilibrium abundance, increases the efficiency of forming ^4He, and thus, decreases the primordial abundances of D and ^3He while increasing that of ^4He. Thus, $y_{2P} \equiv (D/H)_p$ and $y_{3P} \equiv (^3He/H)_p$ decrease with increasing η, while the ^4He mass fraction Y_p increases with η. The predicted ^{7}Li abundance has a similar coupling to the nuclear reaction rates, but it is slightly more complicated and we delay our discussion of its specific behavior for the moment. Obviously, the individual reaction rates for each link in the reaction network are crucial to the predicted yields of D, ^3He, and ^7Li. We have updated the standard reaction network (31 links up to and including nuclei of mass-7) using the most recent rate compilations of Caughlan and Fowler (CF). For the purposes of comparison we discuss our updated version relative to the network used by Kawano, Schramm, and Steigman (KSS). Except for $^4He(t,\gamma)$ and $^7Li(p,\alpha)$, the KSS network was based on the standard compilations of rates, up to and including Harris et al. (1983). The CF rates differ significantly from those used by KSS at only 5 links which we list below:

REACTION	(CF/KSS)	SOURCE
$D(d,n)^3He$	1.3	Krauss et al. 87; FCZ75
$D(d,p)T$	1.3	Krauss et al. 87; FCZ75
$^4He(t,\gamma)^7Li$	0.8	Langanke 86; Kajino 86; Schröder et al. 86
$^7Li(p,\alpha)^4He$	1.1	Rolfs and Kavanaugh 86
$^7Be(n,p)^7Li$	0.8	Koehler et al. 88; FCZ 75

For this comparison, the ratio of rates from CF and KSS are taken at a temperature characteristic of nucleosynthesis, 80 keV ($T_9 \equiv T_\gamma/10^9\text{K} = 0.9$). Following tradition, CF use the astrophysical S factor to parameterize the energy dependence of the cross section

$$\sigma(E) \equiv \frac{S(E)}{E} \exp\left[-\left(\frac{E_c}{E}\right)^{1/2}\right] \tag{2}$$

where E_c is the Coulomb barrier penetration factor and $S(E)$ is related to actual data by a Taylor series expansion about $E = 0$, $S(E) \simeq S(0) + \frac{dS}{dE}|_{E=0} \cdot E + \frac{1}{2}\frac{d^2S}{dE^2}|_{E=0} \cdot E^2$. Changes in the $D(d,n)$ and $D(d,p)$ reactions are based on the data of Krauss et al. (1987). For the $D(d,x)$ reactions, KSS use the compilation of Fowler, Caughlan, and Zimmerman (1975; FCZ75 in the table above). The CF rate for $^4He(t,\gamma)^7Li$ is based on the analysis of Langanke (1986) and Kajino (1986), both of which suggest a smaller $S(0)$ than that derived by KSS using the data of Schroeder et al.. (1986) alone. CF analyze the data of Rolfs and Kavanaugh (1986) on $^7Li(p,\alpha)^4He$ and find that, for applications to primordial nucleosynthesis, $S(E)$ is larger than KSS calculate from the same data.

The rate for $^7Be(n,p)^7Li$ used in KSS is based on the analysis of Bahcall and Fowler (1969; BF). BF used detailed balance to convert $^7Li(p,n)$ data (Gibbons and Macklin 1959) into $^7Be(n,p)$ cross sections which they then fit in the standard way (see eq. 2). Recently Koehler et al. (1988) have made direct measurements of $^7Be(n,p)$, from 25 MeV to 13.5 keV, which are ~ 10 times more precise and result in rates which are 60–80% of BF over the range $T_9 = [0.1, 1]$. The CF rate for $^7Be(n,p)$ reflects the new measurements and is therefore smaller than KSS which used BF.

Recently, Krauss and Romanelli (1990; KR) have studied the effects on the predicted yields of primordial nucleosynthesis of $\pm 2\sigma$ (where KR choose, from their analysis of the data, a "reasonable" $1-\sigma$ error for a reaction rate) variations in the weak $n \leftrightarrow p$ rates and in nine of the more important nuclear reaction rates. In this section we compare our network to theirs; we discuss the results of our calculations later. The reaction rates varied by KR and their adopted fractional $1-\sigma$ uncertainties are: $D(p,\gamma)$ (16%), $p(n,\gamma)$(10%), $D(d,n)$(10%), $D(d,p)$(10%), $T(d,n)$(10%), $^3He(\alpha,\gamma)$(6%), $^4He(t,\gamma)$(18%), $^7Li(p,\alpha)$(8%), and $^7Be(n,p)$(10%). Except for the last 3 reactions, the reference point of the KR variation is the KSS network. This difference makes comparison of the two networks difficult because the central values of the $D(d,n)$ and $D(d,p)$ rates have changed by more than $1-\sigma_{KR}$ based on the CF analysis of the Krauss et al. (1987) data. Excluding these 2 and the last 3, the KR network adopts the same central values as ours, fixed on CF. It also appears that the central values adopted by KR for $T(\alpha,\gamma)$, $^7Li(p,\alpha)$ and $^7Be(n,p)$ are consistent with those suggested by CF; i.e., the $T(\alpha,\gamma)$ rate is smaller than that used by KSS, $^7Li(p,\alpha)$ rate is larger, and $^7Be(n,p)$ is smaller.

Before presenting the results of our calculations, we turn to a brief discussion of the latest results on the neutron lifetime.

III. NEUTRON LIFETIME

From the previous discussion, it is clear that the nucleosynthetic yields and, in particular, the predicted abundances, depend on the competition between the expansion rate of the Universe and the weak interaction rate. Since the matrix element is the same for all $n \leftrightarrow p$ reactions, we can follow Wagoner (1973) and scale all variations in the weak-interaction rate to a variation in the neutron mean life. Prior to the measurement of Bondarenko et al. (1978) of $\tau_n = 877 \pm 8$ sec, the standard value was that of Christensen et al. (1972), $\tau_n = 918 \pm 14$. The effects on primordial nucleosynthesis of a possibly low neutron half-life was explored in detail by Olive et al. (1981) where limits on quantities such as $\eta(\Omega_B)$ and N_ν were given for $\tau_n = 918$ sec ($\tau_{1/2} = 10.61$ min) as well as $\tau_n = 877$ sec ($\tau_{1/2} = 10.13$ min) (the Bondarenko et al. (1978) value was later revised to the higher value of 881 ± 8 in Bondarenko et al. (1982)) and the even higher value found by Byrne et al. (1980) of $\tau_n = 937$ ($\tau_{1/2} = 10.82$ min). We note that this latter value has recently been withdrawn (PDG, 1990). Because of its large deviation from the other measurements, the

Bondarenko et al. (1978) measurement had generally not been included in "world averages" (cf. Review of Particle Properties, 1982). Only later, when recent measurements began to support lower values for τ_n, has the Bondarenko result been included. The 1984 and 1986 "world averages" by the Particle Data group gave $\tau_n = 898 \pm 16$ s ($\tau_{1/2} = 10.37$ min) and $\tau_n = 896 \pm 10$ s ($\tau_{1/2} = 10.35$ min) respectively. (The latter included the measurements of Kosvintsev et al. (1986) $\tau_n = 903 \pm 13$ and Last et al. (1988) $\tau_n = 876 \pm 21$.)

Recently, a very accurate measurement of the neutron lifetime has been reported by Mampe et al. (1989) who used a glass storage container coated by Fomblin oil. This container has a very low probability for leakage (2-3$\times10^{-5}$/bounce at room temperature) for ultra cold neutrons with kinetic energies $E_n \lesssim 10^{-7}$ eV. The measured mean lifetime in this experiment is $\tau_n = 887.6 \pm 3$ sec. Combining this result with the previous ones, removing the Byrne et al. (1982) result, replacing the Bondarenko et al. measurement with the recently revised value of $\tau_n = 891 \pm 9$ s (Spivak 1988) and, including the very recent results of Paul et al. (1989; $\tau_n = 887 \pm 10$ s) and Kossakowski et al. (1989; $\tau_n = 878 \pm 30$ s) leads to a new "world average" of $\tau_n = 888.6 \pm 3.5$ s.

For our calculations we have chosen the 95% CL range: $882 \leq \tau_n \leq 896$ s ($10.19 \leq \tau_{1/2} \leq 10.35$ min). Although we have not included the very recent results of Byrne et al. (1990), 893.6 ± 5.3 s, they are in good agreement with the value adopted here. Including this measurement, would raise the world average to 889.6 ± 2.9.

IV. RESULTS

Figure 1a displays the abundance of ^7Li relative to that of H (by number) as a function of the baryon-to-photon ratio in units of 10^{-10}, $\eta_{10} \equiv 10^{10} n_B/n_\gamma$, for $882 \leq \tau_n \leq 896$ sec, for 3 (solid) and 4 (dashed) light neutrino species. Note that unlike D, ^3He, and ^4He, ^7Li is not a monotonic function of η – it has a minimum at $\eta_{10} \sim 3$. The ^7Li-trough is due to the competition between the production and destruction of mass-7 nuclei: $^4He(t,\gamma)^7Li \leftrightarrow {}^7Li(p,\alpha)^4He$, (yielding an abundance that decreases with increasing η) competes with $^3He(\alpha,\gamma)^7Be \leftrightarrow {}^7Be(e,\nu_e)^7Li$ (yielding an abundance that increases with increasing η). In addition, there is a mass-7 leak at high η where $^7Be(n,p)$ reactions convert ^7Be to the more fragile ^7Li which can be destroyed by $^7Li(p,\alpha)$. In Figure 1b we compare the ^7Li yield as a function of η_{10} for the current network based on CF (solid curve) to the pre-CF network of KSS (dashed curve). The net effect of using the CF results is to decrease the low-η ^7Li branch (the change is dominated by the decrease in $^4He(t,\alpha)\,^7Li$, and the increase in $^7Li(p,\alpha)\,^4He$), and to increase the high-η ^7Li branch (here changes in $D(d,n)^3He$ and $^7Be(n,p)^7Li$ dominate) relative to the KSS calculations. Relative to the central values of the KR code we would expect a slight low-η ^7Li increase (due to $D(d,p)^3H$) and a slight increase at high-η (due to $D(d,n)^3He$) due to the changes in the rates in going from KSS to CF. A direct comparison does show a very small increase in the extreme low-η ^7Li branch and the high-η ^7Li branch.

We pause here to comment on the residual uncertainties in the predicted ^7Li abundance due to uncertainties in the nuclear cross sections that constitute the big bang reaction network. KR have shown, using Monte Carlo techniques with $1-\sigma$ variations in the reaction rates, that the predicted abundance of ^7Li is uncertain by $\sim 40\%$ at the 2-σ level. Although the KR central values do not completely agree with ours, we estimate that our predicted abundance of ^7Li should also be accurate to 40% at the $2-\sigma$ level. This uncertainty is particularly important for the high-η branch since we will use the comparison of the observed primordial ^7Li abundance with the big bang ^7Li prediction to constrain the baryon-to-photon ratio from above.

In figure 2a we display the abundances of D, ^3He, and $D+\,^3He$ relative to H (by number) as a function of η_{10} for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ sec (the dashed line shows $D+\,^3He$ for $N_\nu = 4$ and $\tau_n = 889$ sec). In figure 2b we compare our new results ($N_\nu = 3$) with those of the KSS network. There is a very small decrease relative to KSS (and the central values of KR) due to the increases in $D(d,n)$ and $D(p,n)$. Over most of the range $1 \lesssim \eta_{10} \lesssim 10$, the predicted deuterium abundance is well fit by,

$$10^5 y_{2p} = 46\eta_{10}^{-5/3}. \tag{3}$$

We note that the thickness of the abundance curves reflects the adopted range of uncertainty in τ_n.

Figure 3a shows the primordial mass fraction of ^4He, Y_p, as a function of η_{10} for $N_\nu = 3$ and 4 and $\tau_n = 889 \pm 7$ secs. The dependence of Y_p on N_ν can be understood as follows. The Universe at the time of primordial nucleosynthesis is radiation dominated by photons, electron-positron pairs and light ($\lesssim$ MeV) neutrinos. Recall that the expansion rate $H \propto \rho^{1/2} \simeq (\rho_\gamma + \rho_e + \rho_\nu)^{1/2}$, so that increases in the number of light neutrinos leads to an increase in H. An increase in H means that $n \leftrightarrow p$ interactions freeze out earlier when (n/p) is larger, resulting in the increase of Y_p with N_ν. It is useful to fit the primordial ^4He yield to the free parameters of the model: η, τ_n, and N_ν. Over the range $3 \leq \eta_{10} \leq 10$, Y_p is well fit (to within ± 0.001) by

$$Y_p = 0.228 + 0.010 \ln \eta_{10} + 0.012(N_\nu - 3) + 0.185 \left(\frac{\tau_n - 889}{889} \right), \tag{4}$$

or, in terms of the neutron half-life (in minutes),

$$Y_p = 0.228 + 0.010 \ln \eta_{10} + 0.012(N_\nu - 3) + 0.017(\tau_{1/2} - 10.27). \tag{4'}$$

Notice that (for η_{10} and N_ν fixed), the 95% CL uncertainty in τ_n, ± 7 sec, contributes only $\lesssim \pm 0.0014$ ($\lesssim \pm 0.6\%$) to the uncertainty in Y_p. Alternately, if Y_p and η_{10} are fixed, the 95% CL uncertainty in τ_n contributes $\lesssim \pm 0.12$ ($\lesssim 4\%$) to the uncertainty in N_ν.

In Figure 3b we compare the KSS predictions (dashed curve) with our new results for $\tau_n = 889$ sec. and $N_\nu = 3$. The difference between our results and KSS for ^4He is due to two sets of changes. Our code integrates the weak rates numerically and includes an explicit calculation of the neutrino temperature (see our earlier discussion) rather than approximating these corrections to Y_p by uniformly reducing the numerical fit by the average amount found by Dicus et al. (1982). Our code also uses the updated (CF) reaction network rather than that used by KSS. In particular, the increases of the $D(d,n)$ and $D(d,p)$ rates increase the ^{4}He production. The total change due to both effects can be written $\Delta Y \equiv Y_{WSSOK} - Y_{KSS} = \Delta Y_{CF} + \Delta Y_{WEAK} \simeq 6 \times 10^{-4} + 5 \times 10^{-4} \simeq 1.1 \times 10^{-3}$. For comparison, note that the $2-\sigma$ uncertainty in τ_n leads to $\Delta Y = \pm 1.4 \times 10^{-3}$.

To reiterate, since the predicted primordial abundances of D, ^3He and ^7Li depend mainly on the nucleon abundance η, a comparison with the observed abundances of D, ^3He and ^7Li will lead to bounds on the allowed range of η. In contrast, the predicted ^4He mass fraction varies very slowly (only logarithmically) with η but, does depend on τ_n and

N_ν. Given the experimentally allowed (95% CL) range for τ_n, coupled with the range of η determined from D, ^3He and ^7Li, the observations of ^4He can be used to constrain N_ν. In anticipation of these comparisons we first turn to a discussion of the observations.

V. OBSERVATIONAL DATA

Crucial to testing the standard model, and to constraining non-standard models, are the abundances of the light elements derived from the observational data. Furthermore, to test the theoretical predictions requires that the *primordial* abundances be extracted from the observations. Thus, any intrinsic observational uncertainties will be compounded by the uncertainties due to galactic chemical evolution. In the following we collect and review the best current data and, to the extent possible, try to infer 95% CL ($\sim 2\sigma$) bounds to the primordial abundances of D, ^3He, ^4He, ^7Li. Whenever possible, we will rely on model independent bounds rather than claim a more stringent constraint which is model dependent.

Deuterium and Helium-3

At relatively low temperatures ($\sim 6 \times 10^5$K), deuterium is destroyed by (p,γ) reactions. Thus, any D which is cycled through stars will be completely burned away. Also, since D is so weakly bound, it is difficult to produce deuterium in significant quantities (i.e., comparable to the observed abundance) in any astrophysical environment (Epstein, Lattimer and Schramm 1976). As a result, a (virtually) model independent assumption is that the primordial deuterium abundance is no *smaller* than the present or, the presolar, D abundance. Therefore, we will concentrate on deriving a *lower bound* to the primordial D abundance.

The extensive data on atomic hydrogen in the interstellar medium (ISM) was reviewed by Boesgaard and Steigman (1985). Comparing the D and H column densities for some two dozen lines of sight in the local ISM ($\lesssim$ 1kpc), reveals a linear N_D vs. N_H relation which corresponds to $[D]_{ISM} = 7.2 \pm 0.2$ (here and below we use the notation $[X] = 12 + \log(N_X/N_H)$).

Since the presolar D abundance should represent a sample of the ISM 4.5 Gyr ago (when, it is reasonable to expect, less D would have been destroyed), we will bound the primordial D abundance with the presolar D abundance. However, since the Sun destroyed any initial deuterium during its pre-main sequence evolution, we must infer the presolar D abundance indirectly. Indeed, since presolar D is burned to ^3He via (p,γ) reactions, the solar ^3He abundance should have increased from its presolar value. Thus, we need to compare "old" and "new" samples of ^3He. The meteorites provide the sites for such a comparison. The smallest ^3He abundances are found in the carbonaceous chondrites (CC) which provide a sample of the most primitive solar system material. The $^3He/^4He$ ratio derived from this sample (Frick and Moniot 1977; Eberhardt 1978) is,

$$10^4(y_3/y_4)_{CC} = 1.52 \pm 0.04. \tag{5}$$

(Here and subsequently, we use the notation $y_X = N_X/N_H$.)

In contrast, higher $^3He/^4He$ ratios are found in gas rich meteorites (GRM) (Jeffrey and Anders 1970), lunar soil and breccias (Black 1972) and the solar wind (Geiss et al. 1970).

$$10^4(y_3/y_4)_{GRM} = 4.03 \pm 0.19. \tag{6}$$

Following Black (1971) and Geiss and Reeves (1972), we identify the CC ^3He abundance with the presolar ^3He abundance and, the GRM abundance with the *sum* of presolar D plus ^3He.

$$10^4(y_{23}/y_4)_\odot = 4.03 \pm 0.19, \tag{7a}$$

$$10^4(y_3/y_4)_\odot = 1.52 \pm 0.04. \tag{7b}$$

Therefore, we may infer the presolar D abundance,

$$10^4(y_2/y_4)_\odot = 2.51 \pm 0.23. \tag{8}$$

We still need to know the solar ^4He abundance ($y_{4\odot}$). The only direct observations are those of Heasley and Milkey (1978) who found in solar prominences: $y_{4\odot} = 0.10 \pm 0.025$; for a solar metallicity $Z_\odot = 0.02$, this corresponds to $Y_\odot = 0.28 \pm 0.05$ for the helium mass fraction. Recent solar models (Bahcall and Ulrich 1988; Turck-Chieze et al. 1988) are consistent with this value and suggest a smaller range, $y_{4\odot} = 0.10 \pm 0.01$ ($Y_\odot = 0.28 \pm 0.02$), which we shall adopt here. Thus, our "95%CL" ($\sim 2\sigma$) range for presolar D and ^3He are,

$$1.8 \leq 10^5 y_{2\odot} \leq 3.3, \tag{9a}$$

$$1.3 \leq 10^5 y_{3\odot} \leq 1.8, \tag{9b}$$

$$3.3 \leq 10^5 y_{23\odot} \leq 4.9. \tag{9c}$$

In particular, we will require that the primordial abundance of D satisfy,

$$y_{2P} \geq y_{2\odot} \gtrsim 1.8 \times 10^{-5} \tag{10}$$

Having bounded y_{2P} from *below* we turn to the question of an *upper* bound. Any primordial D should either reside in the ISM (if it has not been cycled through stars) or, have been destroyed. But, deuterium is burned to ^3He and *some* ^3He survives stellar processing (YTSSO). Therefore, although attempting to estimate how much D has been destroyed is model dependent, the evolution of D plus ^3He is less so. Dearborn, Schramm and Steigman (1986) have estimated the survival fraction of ^3He to be $g_3 \equiv N_{3f}/N_{23i} \approx 1/4 - 1/2$ and YTSSO utilized a simplified "one-cycle" approximation to galactic evolution to derive,

$$y_{23P} \leq y_{23\odot} + (g_3^{-1} - 1) y_{3\odot}. \tag{11}$$

The inequality arises, in part, because of the neglect of ^3He *production* in low mass stars (Iben 1967; Rood 1972). Using the upper bounds in (9b) and (9c) and taking $g_3 \geq 1/4$, we find $10^5 y_{23P} \lesssim 10$, consistent with the original bound of YTSSO.

However, we can be more realistic. In OSSW we replaced the "one-cycle" approximation with an "instantaneous recycling" approximation (IRA) which accounts for material that has been through more than one generation of stars. Again neglecting possible production of ^3He (and, possible infall), it can be shown that

$$X_p y_{23P} < A_\odot^{(g_3 - 1)} y_{23\odot} X_\odot, \tag{12}$$

where $A_\odot \equiv X_{2\odot}/X_{2P}$ is the deuterium "astration" factor. To avoid overproduction of the heavy elements requires (Pagel 1989a) $A_\odot \gtrsim 1/3$. To find an upper bound to $y_{23\odot} X_\odot$, note that $y_{4\odot}X_\odot = Y_\odot/4 \leq 0.075$, so that with $g_3 \geq 1/4$ and the upper bound on $(y_{23}/y_4)_\odot$ from (7a) we have,

$$X_P y_{23P} \leq 7.5 \times 10^{-5} \tag{13}$$

Note that for $Y_P \lesssim 0.25$ ($X_P \gtrsim 0.75$), (13) is consistent with the bound on y_{23P} derived from (11).

Lithium-7

The cosmological significance of ^7Li increased enormously with the discovery (Spite and Spite 1982a,b) of lithium in halo (Pop II) stars. This discovery has subsequently been confirmed by many observers who have detected lithium in several dozen, metal-poor Pop II stars. These Pop II stars, if sufficiently warm ($T \gtrsim 5500$K), have apparently not depleted their surface lithium (see Figure 4), in contrast to Pop I stars (e.g., the Sun) of similar temperatures. Thus, Spite and Spite (1982a,b) were led to suggest that these very old Pop II stars provide a fair sample of the lithium abundance present during the early evolution of the Galaxy. The higher Pop I lithium abundance then requires a production source(s) and Type II supernovae have recently been suggested (Dearborn et al. 1989; Woosley et al. 1989) as a possible site; an alternate source of lithium could be the super-Li rich red giants (Smith and Lambert 1989) if this material is ejected into the interstellar medium.

This most natural hypothesis (Primordial $\approx$ Pop II) finds support in the "Li-plateau". In Figure 4 we show $[Li] = 12 + \log(Li/H)$ as a function of T_{eff} for the most metal-poor Pop II stars ($[Fe/H] \leq -1.3$). For the 35 stars with $T_{eff} \geq 5500$K, *all* abundances lie in the range $1.84 \leq [Li] \leq 2.32$ with a mean value of $[Li] = 2.08$ and a $1-\sigma$ scatter about the mean of ± 0.12. This scatter is entirely consistent with the observational uncertainties which range from ± 0.1 to ± 0.2. Also shown in Figure 4 are those cooler ($T < 5500$ K) metal-poor stars which display the depletion pattern familiar from the Pop I stars. The "plateau" for the warmer stars is very narrow in comparison to the range in $[Li]$ for the cooler stars.

In Figure 5 we show the variation of $[Li]$ with $[Fe/H]$; note the separation between the "warm" ($T_{eff} > 5500$K) stars and the "cool" ($T_{eff} < 5500$K) stars. In choosing our sample, which is detailed in Table 1, we have restricted attention to the "extreme" Pop II stars (i.e., most metal-poor). As is well-known (e.g. Rebolo et al. 1988), as $[Fe/H]$ increases, the $[Li]$ vs. $[Fe/H]$ relation shows increasing dispersion (see Figure 6). That $[Li]$ increases with $[Fe/H]$ can be understood as a consequence of lithium production during the course of galactic evolution. That $[Li]$ also decreases with $[Fe/H]$ is most likely due to stellar destruction of lithium occurring in warmer stars as the metallicity increases. To obtain a good sample of the oldest stars, in which both these effects are absent or, at least, minimized, we restrict our attention to the most metal-poor Pop II stars ($[Fe/H] \leq -1.3$). Our sample (with the exception of our cool stars) is almost the same as the "Group A" stars of Deliyannis et al. (1989) who require: $[Fe/H] \leq -1.3$, $V_{LSR} \geq 160\mathrm{kms}^{-1}$ and $T_{eff} \geq 5500$K.

That the plateau is so narrow (i.e., its dispersion is consistent with observational uncertainty) supports the original claim of Spite and Spite (1982a,b) that the lithium observed in the hotter Pop II dwarfs is a measure of the primordial abundance. For the 35 stars with $T_{eff} \geq 5500$ K, the weighted (by the quoted uncertainties for $[Li]$ in each observation) mean value is,

$$\langle [Li] \rangle = 2.08 \pm 0.07 \tag{14}$$

where the dispersion is the 2σ error in the mean.

There still remains the question whether the observed lithium in these (Pop II) stars provides a fair sample of the lithium abundance in the nearly primordial gas out of which these stars formed. That is, could lithium have been depleted during the evolution of even the w rmer ($T \gtrsim 5500$ K), extreme Pop II ($[Fe/H] \leq -1.3$) stars? Although Vauclair (1988) suggests that depletion could be important, detailed calculations of Deliyannis et al. (1989) suggest otherwise. From their standard main sequence isochrones which yield the best fit to the data, Deliyannis et al. (1989) conclude that the plateau stars are essentially undepleted in lithium and, they derive an upper limit (2σ) of $[Li] \leq 2.21$. Although their non-standard isochrones which allow diffusion yield poorer, but acceptable, fits to the lithium data, Deliyannis et al. (1989) still conclude that very little lithium depletion is allowed: $[Li] \leq 2.36(2\sigma)$. Including the non-standard diffusion models, Deliyannis et al. (1989) find for the 95% CL range of the pre-Pop II lithium abundance,

$$2.04 \leq [Li] \leq 2.36. \tag{15}$$

Since, however, the "best fit" isochrones of Deliyannis et al. (1989) are consistent with very little lithium depletion, we adopt here the observationally determined "plateau" value for the bound to the primordial abundance. In subsequent comparisons we will take for the "95% CL" upper bound,

$$[Li] \leq 2.15. \tag{16}$$

Helium-4

Finally, we turn to the most abundant (after hydrogen) element to emerge from the early universe. The abundance of ^4He has been determined from observations of young stars, old stars, planetary nebulae and galactic and extragalactic HII regions (cf. Boesgaard and Steigman 1985). Since helium is so abundant, it can be observed throughout the universe and, its abundance can be determined more accurately than that of any of the other light elements. However, since (many) stars generate their energy by burning hydrogen to helium, the primordial abundance of ^4He has been contaminated by the debris of galactic evolution. Therefore, to better approach the uncontaminated primordial abundance, it is best to restrict attention to helium observations in metal-poor environments. That means concentrating on extragalactic HII regions.

Helium is observed in HII regions via its recombination radiation. For detailed discussions of the observational techniques – and their uncertainties – see Davidson and Kinman (1985), Davidson et al. (1989) and Pagel and Simonson (1989). Here, we only comment on two of the potential problems. Since helium is revealed via its recombination radiation, neutral helium is invisible. Thus, it is necessary either to use a theoretical model of the HII region to estimate the HeI contribution or, as is more common, to restrict attention to hotter, higher excitation HII regions and to neglect the HeI contribution. It is not always easy to estimate the uncertainty associated with this neglect and, indeed, Dinnerstein and Shields (1986) have shown that, under special circumstances, it could be substantial. Another difficulty in deriving accurate helium abundance estimates is that, for high temperature and density HII regions, collisional excitation may compete with radiative transitions in determining the populations of excited states in ionized helium (Ferland 1986). To correct for this effect it is necessary to determine the electron density (and temperature), which is not always easy to do (Pagel 1988). Further, the initial estimate of this effect (Ferland 1986) was too large by ~50% to a factor of 2 (Pequignot, Baluteau and Gruenwald 1988; Berrington and Kingston 1987; Clegg 1987). Although the correction is typically only a few percent, the uncertainty in the correction is of comparable size.

In Table 2 we list the abundances of ^4He, C, N O derived from observations of the most metal-poor extragalactic HII regions. This table is largely taken from Pagel's (1988) compilation, updated by the newer data of Pagel and Simonson (1989). Pagel's data set contains 33 metal-poor extragalactic HII regions, including those studied by Kunth and Sargent (1983). Pagel (1988) reanalyzed the original data, starting from the spectral line strengths and using a common set of atomic data. To Pagel's data set we have added three additional HII regions: IZW18, NGC5471 and CG1116+51; IZW18 is the most metal-poor HII region yet observed. Further, for the oxygen and nitrogen abundances in the SMC we adopted the results of DSS (1985) and PPT-P(1986). We also included the DSS (1985) value for O/H in NGC2363. The helium mass fractions (Y) have, in general, been corrected by Pagel (1988) for collisional excitation but, Pagel has assumed that the possible neutral helium contribution can be ignored. Also, in using the $^4He/H$ ratios to infer Y, the heavy element mass fraction, Z, has been ignored. In Figures 7-10 we plot Y as a function of the oxygen, nitrogen and carbon abundances and of the N/O ratio.

Even for these low-metal abundance HII regions it is still necessary to correct for the evolution of ^4He. Peimbert and Torres-Peimbert (1974) originally suggested correlating Y with O/H and, until very recently, this has remained the most frequent approach to deriving the primordial helium mass fraction. The helium/oxygen data set is, indeed, strongly correlated; for the 36 data points the linear correlation coefficient is $r = 0.55$ which would have a probability , $P < 0.001$, if they were drawn from an uncorrelated parent population (Bevington 1969). A linear fit to the data in Table 2 (using the errors listed in the Table) which minimizes χ^2 yields,

$$Y = 0.226 \pm 0.005 + (1.6 \pm 0.4) \times 10^2(O/H). \tag{17}$$

This fit has a reduced χ^2 of 0.57.

However, despite the small value of the reduced χ^2, it is our opinion that some of the error estimates in Table 2 may be unrealistically small and, could give excess weight to a handful of HII regions. As an example, doubling the error estimate (for Y) for T1214–277 increases the intercept in (17) to 0.228±0.005 and, excluding this HII region entirely results in $Y_p = 0.229 \pm 0.005$. Recently, Davidson et al. (1989) have paid special attention to estimating errors in their very careful study of IZw18. Because of their conservative error estimate, $\sigma_Y = \pm 0.016$, this most metal poor HII region has relatively little weight in our linear Y vs. O/H fit. To attempt to correct for this possible inequity, we have also analyzed the data by assigning an equal uncertainty, which we have arbitrarily chosen to be $\sigma_Y = \pm 0.009$, to all entries in Table 2. With this prescription we now find (for $0.14 \leq 10^4(O/H) \leq 2.15$),

$$Y = 0.229 \pm 0.004 + (1.3 \pm 0.3) \times 10^2(O/H). \tag{18}$$

The reduced χ^2 of this fit is 0.95.

An alternate approach to Y_p would be to restrict attention to the most metal-poor of the HII regions. The mean of the ^4He mass fraction for these objects would then provide an upper bound to the primordial abundance: $Y_p \leq \langle Y \rangle$. For example, for the 20 HII regions with $10^4(O/H) \leq 1.0$, $\langle Y \rangle = 0.237 \pm 0.009$; for the 10 HII regions with $10^4(O/H) \leq 0.8$, $\langle Y \rangle = 0.236 \pm 0.009$.

Although a *linear* Y vs. O/H relation is simplest (fewest adjustable parameters), it is far from clear that it is "physical" (Steigman, Gallagher and Schramm 1989). The reason is that oxygen is produced only by massive stars ($\gtrsim 12M_\odot$) while ^4He is contributed by all stars ($\gtrsim 2M_\odot$). Since nitrogen and carbon are produced in intermediate mass stars, it might be expected that N and/or C would correlate better with helium (Pagel et al. 1986;

Steigman, Gallagher and Schramm, 1989). Indeed, the Y versus N/H data set has a linear correlation coefficient $r = 0.63$ (very highly correlated; $P \lesssim 10^{-4}$). The linear fit (with $\sigma_Y = \pm 0.009$) which minimizes χ^2 yields

$$Y = 0.231 \pm 0.003 + (2.8 \pm 0.7) \times 10^3 (N/H). \tag{19}$$

The reduced χ^2 of this fit is 0.81. If instead of equal errors in Y we had used the quoted errors (Table 2), we would have found

$$Y = 0.230 \pm 0.004 + (3.0 \pm 0.7) \times 10^3 (N/H). \tag{20}$$

For this latter fit the reduced χ^2 is 0.41.

For the 20 HII regions with $10^6(N/H) \leq 3.4$, the mean helium abundance is $\langle Y \rangle = 0.239 \pm 0.010$; for the 10 HII regions with $10^6(N/H) \leq 2.4$, $\langle Y \rangle = 0.234 \pm 0.009$.

To test the robustness of the Y versus N/H correlation we have divided the data into 9 overlapping bins (in N/H), each containing 8 HII regions. We have then chosen the second and third lowest values of Y in each bin and compared Y versus $\langle N/H \rangle$, the average nitrogen abundance for that bin. For the second-ranked correlation we find $r = 0.97$ and $\Delta Y / \Delta \langle N/H \rangle = 3.3 \times 10^3$, in agreement with eqs. (19) and (20). For the third-ranked correlation, $r = 0.93$ and $\Delta Y / \Delta \langle N/H \rangle = 2.9 \times 10^3$. These comparisons suggest that the correlations found earlier are not an artifact of a systematic bias in the data (B.J.T. Jones, Private Communication; Hawkins 1980).

There are only six extragalactic HII regions with carbon abundances determined. Further, since UV and optical observations (made with different telescopes, detectors, etc.) are required to derive the carbon abundance, carbon abundances are quite uncertain. Nonetheless, since it would be very valuable to correlate Y with C/H (Steigman, Gallagher and Schramm 1989), we show the existing data in Figure 9. This data set has a correlation coefficient $r = 0.75$. A linear fit to the data (with $\sigma_Y = 0.009$) yields (for $0.6 \leq 10^5(C/H) \leq 6.3$)

$$Y = 0.230 \pm 0.007 + (3.1 \pm 2.2) \times 10^2 (C/H). \tag{21}$$

The reduced χ^2 of this fit is 0.47.

We have also looked for a possible correlation of Y with N/O. In Figure 10, Y is plotted versus N/O. The data has a correlation coefficient of $r = 0.43$ ($P \approx 0.01$) and, a two parameter fit, with a reduced χ^2 of 1.03; is: $Y = 0.227 \pm 0.005 + (0.42 \pm 0.12)N/O$. Finally, for general information, we show in Figure 11, the N/O ratio versus O/H; this comparison has a correlation coefficient of only $r = 0.14$.

To summarize, our linear fits of Y (with $\sigma_Y = 0.009$) and O, N, C have led to these estimates of the primordial helium abundance,

$$O: \qquad Y_p = 0.229 \pm 0.004, \tag{22a}$$

$$N: \qquad Y_p = 0.231 \pm 0.003, \tag{22b}$$

$$C: \qquad Y_p = 0.230 \pm 0.007. \tag{22c}$$

The above are all consistent with $Y_p = 0.23 \pm 0.01$. The real question is, what is the true uncertainty in this estimate? Can we determine the third decimal place in the bounds to Y_p? A corollary question is, what should we take as the "95%CL" upper limit to the primordial abundance of helium? Until the many possible systematic effects (ionization corrections, collisional excitation corrections, non-linear detectors, etc.) are sorted out, these questions are difficult to answer quantitatively, especially if we want Y_p to 3 significant figures. In subsequent comparisons with the predicted abundance, we will choose the upper bound $Y_p \leq 0.240$, keeping in mind that the uncertainty in this upper bound may be of the order of ± 0.005.

VI. COMPARISON WITH THE STANDARD MODEL

We are now in a position to confront the predictions of the standard model ($N_\nu = 3$, $882 \leq \tau_n \leq 896$) with the observational data. Initially, we will examine D, ^3He and ^7Li to see if there is a range of baryon densities (i.e., η values) for which the predictions are in concordance with our adopted 95%CL bounds to the primordial abundances. Then, we will turn to ^4He where a comparison between theory and observations will permit us to bound the effective number of light neutrinos N_ν.

The meteoritic data has provided a lower bound to the deuterium abundance in the presolar nebula ($y_{2\odot} \geq 1.8 \times 10^{-5}$) which, since D is only destroyed, bounds the primordial abundance from below ($y_{2p} \geq y_{2\odot}$). To satisfy this bound (see Fig. 2) requires that,

$$D: \qquad \eta_{10} \leq 6.8. \tag{23}$$

The same meteoritic data, coupled to estimates of the ^3He survival fraction (Dearborn et al. 1986), permitted us to place an upper bound on the sum of the primordial abundances of D plus ^3He ($10^5 y_{23p} \leq 10$; $10^5 X_p y_{23p} \leq 7.5$). This bound is satisfied (see Fig. 2) for,

$$D + {^3He}: \qquad \eta_{10} \geq 2.8. \tag{24}$$

Next, we turn to ^7Li. From our discussion of the observations of Pop II stars, we have adopted a 95% CL upper limit: $[Li]_p \leq 2.15$. This limit is, indeed, consistent (see Fig. 1) with the abundances predicted for η in the range allowed by the D and ^3He abundances ($2.8 \leq \eta_{10} \leq 6.8$). However the lithium constraint by itself selects a somewhat different range for η. For CF (see Fig. 1b), $[Li] \leq 2.15$ is satisfied when,

$$Li(CF): \quad 1.9 \leq \eta_{10} \leq 3.3. \tag{25}$$

If, however, we allow for the 40% residual uncertainty in lithium production, this range extends to

$$1.6 \leq \eta_{10} \leq 4.0. \tag{26}$$

Until the residual uncertainties in the predicted lithium abundance are reduced further, we will adopt $1.6 \leq \eta_{10} \leq 4.0$ as the ("95%CL") range consistent with the Pop II lithium abundances.

Thus, combining the constraints from D, ^3He and ^7Li, we find that the predictions of the standard model are consistent with the observationally inferred primordial abundances (or, bounds thereof) for a very limited range of nucleon densities,

$$D,\ {^3He},\ {^7Li}: \qquad 2.8 \leq \eta_{10} \leq 4.0. \tag{27}$$

For our comparison with ^4He, we will restrict our attention to this concordant range.

For the standard model ($N_\nu = 3$, $882 \le \tau_n \le 896$) with η in the above range, the predicted ^4He primordial mass fraction lies in the range (see Fig. 3)

$$0.236 \le Y_p^{BBN} \le 0.243. \tag{28}$$

In our discussion of the data we noted that the observations were consistent with $Y_p^{OBS} = 0.23 \pm 0.01$. Clearly, there is complete agreement between theory and observations is complete. The standard model successfully accounts for the observed abundances of *all* the light elements.

Can we use the ^4He data to bound the nucleon density? In principle yes but, the logarithmic dependence of Y_p on η (see eq. 4) requires a highly accurate upper bound to the ^4He abundance since,

$$\Delta\eta_{10} \approx 100\eta_{10}\Delta Y_p. \tag{29}$$

Since $N_\nu \ge 3$ (assuming $m_{\nu\tau} \lesssim$ few MeV; the inequality is because BBN is sensitive to particles which could be undetected at SLC and LEP) and $\tau_n \ge 882$, we see from eq. 4,

$$Y_p \ge 0.227 + 0.010 \ln \eta_{10}, \tag{30}$$

so that, for $Y_p \le 0.240$ we find $\eta_{10} \le 4$. If, however, we chose for the observational upper bound to the primordial helium abundance $Y_p \le 0.245(0.235)$, this bound on the nucleon density changes to $\eta_{10} \le 6(2)$.

The above results are displayed in Figures 12 and 13 where the predicted abundances of all the light elements are shown (for $N_\nu = 3$, $\tau_n = 889 \pm 7$ sec.) along with the bands allowed by the observations. The range $2.8 \le \eta_{10} \le 4.0$ is consistent with all the data (for values of τ_n toward the *high* end of the allowed range, consistency with ^4He requires that η be near the *low* end of its range). In the next section we will explore the consequences of this concordance and probe the viability of models which deviate from the standard model.

VII. DISCUSSION

In this section we consider the consequences, for particle physics and cosmology, of the consistency of the standard model. Then, we will examine alternate models for cosmological nucleosynthesis and test their consistency by comparing their predictions with the observational data.

The Standard Model

Since the nucleon-to-photon ratio is (virtually) unaltered from the epoch of primordial nucleosynthesis to the present, the bounds (eq. 27) on η translate into bounds on the current density of baryons

$$n_B = \eta n_\gamma = 20.3 T^3 \eta (\mathrm{cm}^{-3}), \tag{31}$$

where T is in $^\circ K$. Comparing the baryon mass density ($\rho_B = M_N n_B$) to the critical mass density ($\rho_c = 3H_0^2/8\pi G$) yields

$$\Omega_B h_{50}^2 = 0.015 T_{2.75}^3 \eta_{10}, \tag{32}$$

where $\Omega_B = \rho_B/\rho_c$, the present value of the Hubble parameter is $H_0 = 50 h_{50} \mathrm{kms}^{-1} Mpc^{-1}$ and, the present cosmic background radiation temperature is $T = 2.75 T_{2.75}$K. Palazzi et al. (1989) find that all recent data at $\lambda \geq 1$ mm are consistent with $T = 2.78 \pm 0.01$ K. The new results from COBE (Mather et al. 1990), $T = 2.735 \pm 0.06$ K, have large residual uncertainties. They are, however, entirely consistent with the conclusions of Gush et al. (1990) who find: $T = 2.736 \pm 0.017$. The 95% CL range consistent with a weighted average of these data is: $2.75 \leq T \leq 2.79$ K. For T in this range,

$$0.015\eta_{10} \leq \Omega_B h_{50}^2 \leq 0.016\eta_{10}. \tag{33}$$

For our allowed range of nucleon densities ($2.8 \leq \eta_{10} \leq 4.0$), we obtain

$$0.04 \leq \Omega_B h_{50}^2 \leq 0.06. \tag{34}$$

The uncertainty in the true value of the Hubble parameter prevents us from deriving an accurate estimate of Ω_B. It is not excluded that H_0 could be as low as $\sim 40 \mathrm{kms}^{-1} Mpc^{-1}$ (Sandage 1988; Steigman 1989b; Wheeler 1989). For $h_{50} \geq 0.8$, we bound Ω_B from *above*,

$$\Omega_B \leq 0.10. \tag{35}$$

At the other extreme, if we were to adopt $H_0 \leq 100\text{kms}^{-1}\text{Mpc}^{-1}$, we would derive a *lower* bound,

$$\Omega_B \geq 0.01. \tag{36}$$

However, within the context of the standard model (i.e., zero cosmological constant), a Hubble parameter as large as $100\text{kms}^{-1}Mpc^{-1}$ is almost certainly excluded since it corresponds to a "young" Universe; $t_0 \leq H_0^{-1} \lesssim 9.8$Gyr for $H_0 = 100$. Indeed, if we adopt the popular assumption ("naturalness/inflation") that $\Omega_{TOT} = 1$, then $t_0 = (2/3)H_0^{-1} \approx 13h_{50}^{-1}$Gyr. For, $t_0 \gtrsim 10(13)$Gyr, the Hubble parameter is then bounded from above by $h_{50} \lesssim 1.3(1.0)$ and

$$\Omega_B \gtrsim 0.02(0.04). \tag{37}$$

It is clear from the above that the Universe fails to be "closed" by baryons by at least a factor of 10. If, indeed, $\Omega_{TOT} = 1$, non-baryonic matter is required. However, our lower bounds to Ω_B strongly suggest that most of the nucleons in the Universe are "dark". For example, if the mass-to-light ratio inferred from the *luminous* matter in galaxies (Faber and Gallagher 1979; Pagel 1989b) is typical of the matter throughout the Universe,

$$\Omega_{LUM} \lesssim 0.007. \tag{38}$$

Comparing (34) and (38) reveals that most of the nucleons in the Universe are dark.

$$\Omega_B/\Omega_{LUM} \gtrsim 6h_{50}^{-2}. \tag{39}$$

Is non-baryonic matter *required* ? Here, the answer is less clear. The data on rich clusters and large scale flows suggest $\Omega_{TOT} \gtrsim 0.2 \pm 0.1$. It is very suggestive but, we think, not yet mandatory that the Universe is dominated by non-baryonic dark matter.

Another constraint which emerges from the consistency of the standard model is the upper bound on N_ν. In Figure 14 we show in detail the predicted Y_p vs. η relation for $882 \leq \tau_n \leq 896$s. Y_p is shown for the standard model ($N_\nu = 3.0$) and, for $N_\nu = 3.3$. Also indicated is the "95%CL" range of η_{10}; the dashed line corresponds to the constraint

$Y_p \leq 0.240$. A more detailed comparison between theory and observation reveals the bounds,

$$Y_p \leq 0.240; \qquad N_\nu \leq 3.3, \tag{40}$$

Notice that (cf. eq. 4), for fixed Y_p and η_{10}, the uncertainty in the bound to N_ν due to the uncertainty in the neutron lifetime is $\delta N_\nu = 0.017\delta\tau_n \approx \pm 0.12$. The BBN bounds to N_ν are clearly sensitive to the precise value of the upper bound to Y_p derived from the observations; it would be very valuable to reduce the *uncertainty* in this upper bound. The upper bound to N_ν also depends on the *lower* bound to η. This constraint on η was derived from the requirement that ^3He not be overproduced when primordial D is burned in stars. Detailed modeling of the galactic evolution of D and ^3He would be very useful (Steigman and Tosi 1990). For example, if we were to employ the stronger constraint ($YTSSO$), $10^5 y_{23p} \leq 6$, then $\eta_{10} \geq 4$ and, $Y_p > 0.240$. This would lower our upper bound to $N_\nu \leq 3.0$.

Although the current SSG bound (eq. 40) on N_ν is consistent with the new accelerator limits, $N_\nu = 3.10 \pm 0.09$ (ALEPH 1989; DELPHI 1989; L3 1989; OPAL 1989; Mark II 1989; Jarlskog 1990), it is worth noting that the cosmological and accelerator bounds are complementary (Schramm and Steigman 1984). Any light ($\lesssim$ 1MeV) particles, regardless of their coupling to the Z^0 are counted cosmologically. In contrast, the accelerator tests count even very massive particles ($\lesssim m_{Z^0}/2$), *but* only if they couple with full (nearly full) strength to the Z^0. For example, in many extensions of the standard particle physics model there are, in addition to the usual, three, left-handed neutrinos (ν_e, ν_μ, ν_τ), three right-handed neutrinos which couple to a new, heavier Z' gauge boson. Our bound, $N_\nu \leq 3.3$, then restricts the Z' to be very heavy: $m_{Z'} \gtrsim 2$ TeV. This bound from BBN (which, however, is model dependent) exceeds the current accelerator limits (CDF) on $M_{Z'}$ of $\gtrsim$ 400 GeV.

Alternately, our bound $N_\nu \leq 3.3$ can be used to constrain the properties (or existence!) of any new, superweakly interacting particles (Steigman, Olive and Schramm 1979; Olive, Schramm and Steigman 1981). To see this recall that the "usual" weakly interacting particles (coupling with full strength to the Z° and/or $W^\pm$) decouple at a temperature of a few MeV. A more weakly interacting particle will decouple earlier, at a higher temperature. If the decoupling temperature, T_D is sufficiently high ($\gtrsim 100$ MeV), these superweak particles will – by the epoch of nucleosynthesis – be diluted by the entropy produced in the decay and/or annihilation of heavy particle species (muons, pions, etc.; see Steigman, Olive and Schramm 1979). In Figure 15 we show the bound on N – the equivalent number of (two-component) light neutrinos – as a function of the decoupling temperature. Significant entropy production – and, hence, dilution – is associated with the quark-hadron transition. The two curves in Fig. 15 show N vs. T_D for two possible quark-hadron transition temperatures.

Finally, we note that if the tau-neutrino should prove very massive (e.g., $m_{\nu_\tau} \gtrsim$ 20 MeV), it would not contribute to N_ν and, the "standard" model would have $N_\nu = 2$. However, if $m_{\nu_\tau} \sim 10$ MeV, the tau neutrino could actually have a greater effect on the universal expansion rate at the epoch of nucleosynthesis and, the "effective" N_ν would, in this case, exceed 3 (Kolb and Scherrer 1982).

In YTSSO and in Boesgaard and Steigman (1985), the relic abundances of the light elements were used to constrain and/or exclude non-standard cosmologies. Here we will consider two recent proposals: Inhomogeneous Nucleosynthesis (Applegate, Hogan and Scherrer 1987; Alcock, Fuller and Mathews 1987) and nucleosynthesis initiated by the decay of a massive particle (Dimopoulos et al. 1988).

Inhomogeneous Nucleosynthesis

When the early Universe cooled below ~200 MeV the quark-hadron transition occurred. If this (or, the related chiral symmetry breaking) is a first-order phase transition, the result might be a Universe with large baryon inhomogeneities (Witten 1980; Crawford and Schramm 1982; Kapusta and Olive 1988). At early times ($T \gtrsim 1$ MeV) neutrons and protons interconvert rapidly. However, for lower temperatures, neutrons and protons have "frozen-out" and, since neutrons interact more weakly than protons with the $e^{\pm}$ plasma, neutrons can diffuse much further than protons resulting in an inhomogeneous neutron-to-proton ratio. The result will be high density, proton rich regions, separated by low density, neutron rich regions. Nucleosynthesis in these regions is very different from that in the "standard" model and, initially, led to the hope that an $\Omega_B = 1$ universe might be reconciled with the observed abundances of the light elements (Appelgate, Hogan and Scherrer 1987; Alcock, Fuller and Mathews 1987). This hope has proved illusory (Kurki-Suonio et al. 1990). The problem is that nucleosynthesis begins earlier in the high density regions, depleting them of free neutrons. The resulting neutron gradient drives a back diffusion of neutrons (Malaney and Fowler 1988) leading to the overproduction of ^4He (Terasawa and Sato 1990; Kurki-Suonio and Matzner 1990). An associated problem is that mass-7 is produced in the high density, proton rich regions (as ^7Be) and in the low density, neutron rich regions (as ^7Li), resulting in overproduction of primordial ^7Li as well. The overproduction of ^4He and ^7Li has been further verified in the recent calculations of Mathews et al. (1990). Calculations which include back diffusion of neutrons suggest that the allowed range of nucleon-to-photon ratios is increased, in the inhomogeneous case, by at most a factor of two over that for the "standard" model.

Decaying Particles

The existence of a massive particle whose density dominates that of the relativistic particles present during BBN speeds up the universal expansion resulting in abundances inconsistent with those observed. In particular, ^4He is overproduced. However, if, when this hypothetical massive particle later decays, its hadronic decay products break up the previously synthesized nuclei and initiate a new round of nucleosynthesis, it may be possible to reproduce the observed abundances, even if $\Omega_B = 1$. This scenario has been investigated by Dimopoulos et al. (1988) who find that the uncertainties in the relevant nuclear reaction rates are sufficiently large that it is very difficult to make absolute abundance predictions. As a result, this exotic scenario may not be easy to rule out (or in!). However, Dimopoulos et al. (1988) argue that they can predict abundance ratios ($^3He/D$, $^6Li/^7Li$) with greater certainty; this may well prove to be the Achilles Heel of this model. In this scenario, more ^3He than D is produced, and more ^6Li than ^7Li is produced. The absence of detectable ^6Li (Pilachowski et al. 1989), argues against this scenario. Although the fact that ^6Li is burned away in stars at a lower temperature than is ^7Li, makes the interpretation of the data complicated, Brown and Schramm (1989) argue that the stars observed by Pilachowski et al. (1989) should not have destroyed ^6Li if it were present when they formed. Perhaps more serious is the predicted high $^3He/D$ ratio (Dimopoulos et al. 1988). In the course of galactic chemical evolution deuterium is destroyed when interstellar gas is cycled through stars. In contrast, ^3He is produced by low mass stars (Iben 1967) and, not all the initial ^3He (^3He plus D) is burned away in stars (Dearborn et al. 1986). The result is that the ratio $^3He/D$ is expected to *increase* with time. For the solar system, $(y_3/y_2)_\odot \approx 0.6$, $(X_3/X_2)_\odot \approx 0.9$ arguing strongly that primordial D should exceed primordial ^3He. Although the absence of firm predictions makes the decaying massive particle scenario a difficult target, the apparent problem with these isotope ratios renders this model an unlikely alternative to the standard model.

VIII. SUMMARY AND CONCLUSIONS

We have updated the BBN computer code to take account of new laboratory data and, to follow more accurately the weak interactions crucial to a precise prediction of the ^4He abundance. Of particular importance has been the recent, high precision determinations of the neutron lifetime (Mampe et al. 1989; Paul et al. 1989; Kossakowski 1989; Byrne et al. 1990). The new "World Average" of $\tau_n = 889 \pm 7$ sec (95% CL) is significantly lower than the earlier values used by YTSSO ($\tau_n = 918 \pm 17$ sec; $\tau_{1/2} = 10.6 \pm 0.2$ min.) and leads to (with all other parameters held fixed) a *reduction* of $\Delta Y_p \sim 0.006$ in the predicted ^4He mass fraction.

We reviewed the observational data, with particular attention paid to ^7Li and ^4He. The accumulating observations of ^7Li in metal poor Pop II stars, especially the warmer ($\gtrsim$ 5500 K) stars, leads to an accurate determination of the ^7Li abundance $[Li] = 2.08 \pm 0.07$. When compared with the predictions of BBN in the standard model (with allowance for the uncertainties) we bound the baryon density: $1.6 \leq \eta_{10} \leq 4.0$. We note here that the solar system or Pop I values of $[Li] \gtrsim 3.0 - 3.3$ would require either very large or very small values of η which would be inconsistent with the observed abundances of D, ^3He and (for high η) ^4He.

The lower bound to the primordial abundance of deuterium, $y_{2p} \gtrsim y_{2\odot} \gtrsim 1.8 \times 10^{-5}$, leads to an upper bound on the nucleon density, $\eta_{10} \leq 6.8$, which is consistent with, but weaker than that already determined by the Pop II lithium data. Of crucial importance to the BBN bound on N_ν is the determination of a *lower* bound to η. Using the solar system abundances of D and ^3He, along with twc simple, complementary models for the galactic evolution of D plus ^3He (the two models yield the same bound to the primordial abundance), we bound $D + {}^3He$ from above: $y_{23p} \lesssim 1.0 \times 10^{-4}$, which leads to $\eta_{10} \geq 2.8$ (for which $[Li]_p \gtrsim 2.0$ in agreement with the Pop II data).

Our bounds on the baryon density, $2.8 \leq \eta_{10} \leq 4.0$, then lead to constraints of importance to cosmology and elementary particle physics. For a cosmic background radiation temperature $2.75 \leq T_\gamma \leq 2.79$ K, the fraction of the critical density contributed by baryons is: $\Omega_B = (0.05 \pm 0.01)h_{50}^{-2}$. For $H_0 \gtrsim 40$ kms$^{-1}Mpc^{-1}$ (Sandage 1988; Steigman 1989b; Wheeler 1989), $\Omega_B \lesssim 0.10$ and the Universe fails, by a wide margin, to be "closed" by baryons. On the other hand, using the age of the Universe to constrain H_0 (in the absence of a cosmological constant), $t_0 \gtrsim 10(13)$ Gyr $\Rightarrow H_0 \lesssim 65(50)$ kms$^{-1}Mpc^{-1}$, and a lower bound to the nucleon density is found: $\Omega_B \gtrsim 0.02(0.04)$. Comparison of this lower bound with estimates of the density of luminous matter in the Universe suggests that most of the nucleons in the Universe are "dark" (i.e., $\Omega_B/\Omega_{LUM} \gtrsim 6h_{50}^{-2}$).

For the standard model ($N_\nu = 3$) with $882 \leq \tau_n \leq 896$ sec and $2.8 \leq \eta_{10} \leq 4.0$, we predict that primordial abundance of helium-4 should lie in the range: $0.236 \leq Y_p \leq 0.243$. This prediction is consistent with our analysis of the metal-poor HII region data which suggests that $Y_p = 0.23 \pm 0.01$. This consistency permits us to derive a reduced SSG upper bound to the number of equivalent, light neutrino species; for $Y_p \leq 0.240$ we find $N_\nu \leq 3.3$. We note that if our lower bound on η were increased from $\eta_{10} = 2.8$ to $\eta_{10} = 4.0$, the "window" on N_ν would be closed (for $Y_p \leq 0.240$). Alternately, if the observational bound on Y_p were reduced below 0.236, the standard model would require $N_\nu < 3$ (Is ν_τ really light?). Thus, BBN is truly a falsifiable theory.

Primordial nucleosynthesis provides the only probe of the early evolution of the Universe accessible to observational tests. The standard, hot big bang model has passed those tests with flying colors leading to significant constraints of importance to cosmology and high energy physics. The robustness of the standard model in accounting – with only one free parameter, the nucleon abundance – for the observed abundances of D, ^3He, ^4He and ^7Li which span some nine orders of magnitude, is impressive. Alternate cosmologies (e.g. inhomogeneous, decaying massive particles) with more free parameters to vary, fail to achieve consistency with the data.

The current successes of standard BBN should not be a cause for complacency. Further observations of lithium in Pop II stars, coupled with the modeling of the evolution of such stars would be of value in further constraining the range allowed for the primordial abundance of lithium. Models of the chemical evolution of the Galaxy which could lead to more restrictive bounds on the pregalactic abundances of deuterium and helium-3 would also be of great value. Such improvements in the estimates of the primordial abundances of D, ^3He and ^7Li would provide ongoing checks of the consistency of the standard model; if, indeed, the standard model is correct, these improved bounds would help us "zero in" on the true nucleon abundance η. The primordial abundance of helium-4 is crucial to the consistency of standard BBN. Very careful, detailed studies of selected, extragalactic HII regions could be of great value in helping us get a handle on possible systematic errors (ionization corrections, collisional excitations, etc.). A firm and accurate (i.e., to the third significant figure) upper bound to Y_p could provide the key test of the standard model.

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Table 1

Lithium in Metal-Poor Halo Stars

Star	$T_{eff}(K)$	$[Fe/H]$	$[Li]$	Reference*
G64–12	6267	−3.5	2.19	HP, RBM, SSPC
LP608–62	6250	−2.7	2.20	HD
HD84937	6226	−2.1	2.11	SS, HD, B
HD74000	6223	−1.8	2.16	$\overline{SS}$
BD3°740	6190	−2.9	2.12	HP, RMB
BD72°94	6160	−1.8	2.22	RMB
BD34°2476	6119	−2.3	2.14	SS, HP
BD20°3603	6019	−2.3	2.10	SS, HD
BD26°2606	5980	< −2.2	2.24	RMB
BD42°2667	5960	−1.7	2.12	RMB
BD−10°388	5950	−2.2	2.18	RMB
HD16031	5929	−2.2	2.03	SMS
BD21°607	5929	−1.6	1.98	SMS
BD26°3578	5914	−2.4	1.84	SMS, HD
BD9°352	5870	−2.2	2.12	RMB
HD108177	5869	−1.9	2.00	$\overline{SS}$
HD166913	5861	−1.8	2.17	$\overline{SS}$
HD160617	5861	−1.6	2.20	$\overline{SS}$
BD17°4708	5850	−1.9	1.94	HD, RMB
BD59°2723	5830	−1.6	1.95	RMB
HD94028	5827	−1.7	2.10	SS, HD
BD2°3375	5820	< −2.5	2.00	RMB
HD201891	5818	−1.3	1.98	SS, HD, RMB
HD194598	5808	−1.6	2.00	SS
HD134169	5797	−1.6	2.21	SS, HD
BD2°4651	5794	−2.3	1.92	SMS
HD19445	5789	−2.1	2.07	SS, HD, RMB
HD219617	5784	−1.4	2.18	SS, HD, RMB
BD29°2091	5670	−2.1	2.10	RMB
BD4°4551	5670	−1.7	1.88	RMB
HD189558	5662	−1.3	2.04	SMS
BD23°3912	5658	−1.5	2.36	SMS, RMB
G238–30	5600	−3.0	1.84	HP
HD140283	5591	−2.4	2.06	SS, HD, RMB
HD132475	5550	−1.6	2.05	RMB
HD64090	5363	−1.8	1.16	$\overline{SS}$, HD, RMB
HD188510	5297	−1.8	1.43	SS
BD66°268	5240	< −2.5	<1.1	RMB
HD211998	5200	−1.5	1.04	SS
BD−0°4470	5200	−1.4	1.02	SMS
HD128279	5180	−2.3	<1.0	DDK
BD38°4955	5080	−2.5	<0.8	RMB
HD103095	5070	−1.4	<0.45	SS, HD
HD25329	4842	−1.8	<0	SMS
HD122563	4400	−2.7	< −0.4	HD

* References: B ≡ Boesgaard (1985); BRM ≡ Beckman, Rebolo, Molaro (1986); DDK ≡ Deliyannis, Demarque, Kawaler (1989); HD ≡ Hobbs and Duncan (1987); HP ≡ Hobbs and Pilachowski (1988); RMB ≡ Rebolo, Molaro and Beckman (1988). SMS ≡ Spite, Maillard, Spite (1984). SS ≡ Spite and Spite (1982); $\overline{SS}$ ≡ Spite and Spite (1986); SSPC ≡ Spite, Spite, Peterson and Chaffee (1989).

Table 2

HII Region Abundances*

HII Region	$10^6 O/H$	$10^7 N/H$	$10^6 C/H$	Y
IZw 18	14 ± 2	4 ± 1	5.5 ± 4	$.234 \pm .016$
Tol 65	33 ± 4	5 ± 1		$.224 \pm .014$
T1214–227	40 ± 3	10 ± 7		$.224 \pm .008$
CG1116 + 51	48 ± 6	9 ± 4		$.251 \pm .018$
T1304 – 353	49 ± 6	20 ± 7		$.233 \pm .014$
POX 186	52 ± 8	24 ± 7		$.244 \pm .013$
C1543 + 091	57 ± 5	21 ± 7		$.240 \pm .012$
UM 461	66 ± 5	17 ± 5		$.233 \pm .007$
POX 120	70 ± 5	32 ± 4		$.247 \pm .013$
POX 105	73 ± 15	30 ± 3		$.228 \pm .014$
NGC 2363	85 ± 8	28 ± 3	24 ± 4	$.230 \pm .014$
SMC	87 ± 13	26 ± 5	14 ± 4	$.242 \pm .007$
POX 4	89 ± 5	34 ± 3		$.237 \pm .006$
T1304 – 386	92 ± 6	60 ± 4		$.253 \pm .009$
POX 139	95 ± 9	32 ± 3		$.255 \pm .011$
C1148 – 2020	96 ± 8	34 ± 3		$.240 \pm .007$
POX 4NW	98 ± 12	17 ± 4		$.228 \pm .017$
F 30	99 ± 7	44 ± 3		$.237 \pm .016$
POX 108	102 ± 8	52 ± 7		$.233 \pm .009$
NGC 4861	104 ± 10	16 ± 7	19 ± 10	$.230 \pm .015$
CS0341 – 4045E	110 ± 10	27 ± 8		$.244 \pm .018$
NGC 5471	112 ± 14	52 ± 15	38 ± 30	$.242 \pm .007$
UM 439	114 ± 8	38 ± 6		$.225 \pm .020$
Tol 35	128 ± 13	34 ± 4		$.257 \pm .016$
IIZw 40	128 ± 9	71 ± 4		$.251 \pm .009$
IIZw 40	130 ± 6	76 ± 8		$.251 \pm .009$
NGC 5253A	137 ± 15	110 ± 15		$.262 \pm .007$
IIZw 70	140 ± 15	41 ± 5		$.246 \pm .020$
Tol 35	141 ± 12	55 ± 4		$.257 \pm .011$
T0633 – 415	144 ± 2	59 ± 8		$.248 \pm .009$
POX 36	156 ± 15	43 ± 4		$.239 \pm .018$
NGC 6822V	158 ± 20	40 ± 10		$.244 \pm .012$
NGC 6822X	180 ± 20	30 ± 10		$.253 \pm .012$
Tol 3	185 ± 14	77 ± 5		$.250 \pm .010$
Tol 3	193 ± 18	73 ± 8		$.250 \pm .013$
LMC	215 ± 15	80 ± 20	63 ± 16	$.252 \pm .009$

* The data in this table was obtained from Davidson et al. (1989), Dinnerstein and Shields (1986), Dufour et al. (1982), Dufour et al. (1988), Pagel et al. (1986), Pagel (1988), Pagel and Simonson (1989), Peimbert and Torres-Peimbert (1976), Peimbert et al. (1986), Rosa and Mathis (1989), Torres-Peimbert et al. (1989).

Figure Captions

Fig. 1a The predicted abundance (ratio, by number, to hydrogen) of ^7Li as a function of the baryon-to-photon ratio ($\eta_{10} = 10^{10}\eta$) for $N_\nu = 3$ (solid curve) and 4 (dashed curve). The width of the $N_\nu = 3$ curve corresponds to the 95% CL range of the neutron lifetime ($882 \leq \tau_n \leq 896$ sec.). The $N_\nu = 4$ dashed line is for $\tau_n = 889$ sec.

Fig. 1b The predicted abundance (ratio, by number, to hydrogen) of ^7Li as a function of the baryon-to-photon ratio ($\eta_{10} = 10^{10}\eta$) for $N_\nu = 3$ and $\tau_n = 889$ sec. The solid curve is this work and the dash-dot curve is the KSS result.

Fig. 2a The predicted abundances (ratios, by number, to hydrogen) of D, ^3He and their sum as a function of η. The dashed curve is the sum $D + {}^3He$ for $N_\nu = 4$. The thickness of the solid $N_\nu = 3$ curves correspond to the 95% CL range of the neutron lifetime ($882 \leq \tau_n \leq 896$ sec.); the $N_\nu = 4$ dashed curve is for $\tau_n = 889$ sec.

Fig. 2b As in Fig. 1b, but for D, ^3He and their sum.

Fig. 3a The primordial mass fraction of ^4He, Y_p, as a function of η. The thickness of the two bands $N_\nu = 3$ and 4 represent the 95% CL range of the neutron lifetime.

Fig. 3b As in Fig. 1b, but for the primordial mass fraction of ^4He, Y_p.

Fig. 4 The ^7Li abundance ($[Li] = 12 + \log(Li/H)$) in the most metal-poor ($[Fe/H] \leq -1.3$) Pop II stars as a function of T_{eff}. The filled diamonds are upper limits to Li. The crosshair shows the resprentative errors in $[Li]$ and T_{eff}.

Fig. 5 The ^7Li abundance $[Li]$ as a function of $[Fe/H]$ for all stars with $[Fe/H] \leq -1.3$. The squares are the warmer (≥ 5500 K) and the circles are the cooler ($\leq 5400K$)

stars. The filled circles are for upper limits to Li; the filled squares are for upper limits to Fe; the filled diamonds are for upper limits to Li and Fe.

Fig. 6 The ^7Li abundance $[Li]$ as a function of $[Fe/H]$ for all stars with $T_{eff} \geq 5500$ K (cf. Rebolo et al. 1988). The filled symbols are for upper limits to Li.

Fig. 7 The ^4He mass fraction, Y, observed in extragalactic HII regions versus the observed oxygen abundance (see Table 2).

Fig. 8 The ^4He mass fraction, Y, observed in extragalactic HII regions versus the observed nitrogen abundance (see Table 2).

Fig. 9 The ^4He mass fraction, Y, observed in extragalactic HII regions versus the observed carbon abundance (see Table 2).

Fig. 10 The ^4He mass fraction, Y, observed in extragalactic HII regions versus the observed ratio of nitrogen to oxygen.

Fig. 11 The ratio N/O versus O/H.

Fig. 12 The predicted abundances (by number) of D, $D + {}^3He$ and ^7Li and the ^4He mass fraction as a function of η for $N_\nu = 3$ and $\tau_n = 889$ sec. for $0.1 \leq \eta_{10} \leq 100$. The vertical band delimits the range of η consistent with the observations.

Fig. 13 The predicted abundances (by number) of $D, {}^3He$, $D + {}^3He$ and ^7Li and the ^4He mass fraction as a function of η for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ sec. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.

Fig. 14 The shaded bands are the predicted ^4He mass fractions versus η for the neutron lifetime in the range $882 \leq \tau_n \leq 896$ sec and $N_\nu = 3.0$ and 3.3. The dashed line is the upper bound $Y_p = 0.240$. The vertical band is the 95% CL range in η derived from the D, ^3He and ^7Li data.

Fig. 15 The bound on the equivalent number of two component light neutrinos as a function of the decoupling temperature T_d. The two curves are for quark-hadron transition temperatures of 150 and 400 MeV.

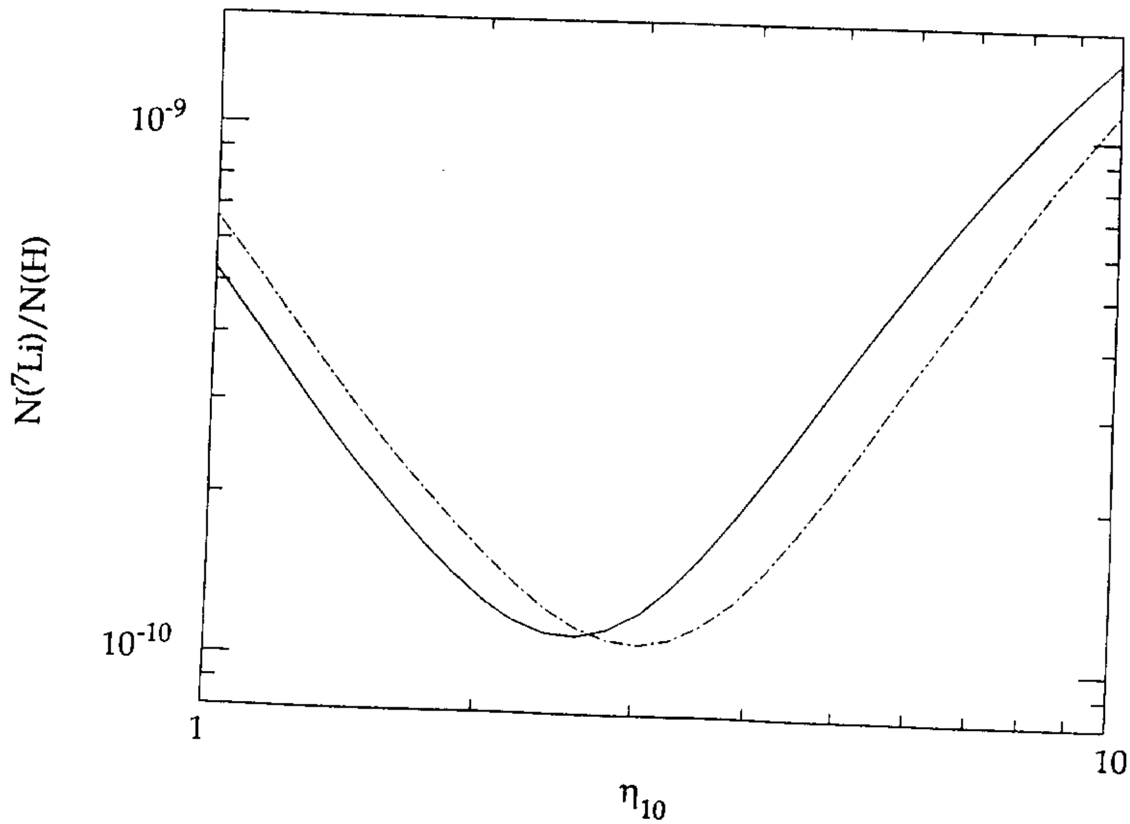


Fig. 4b

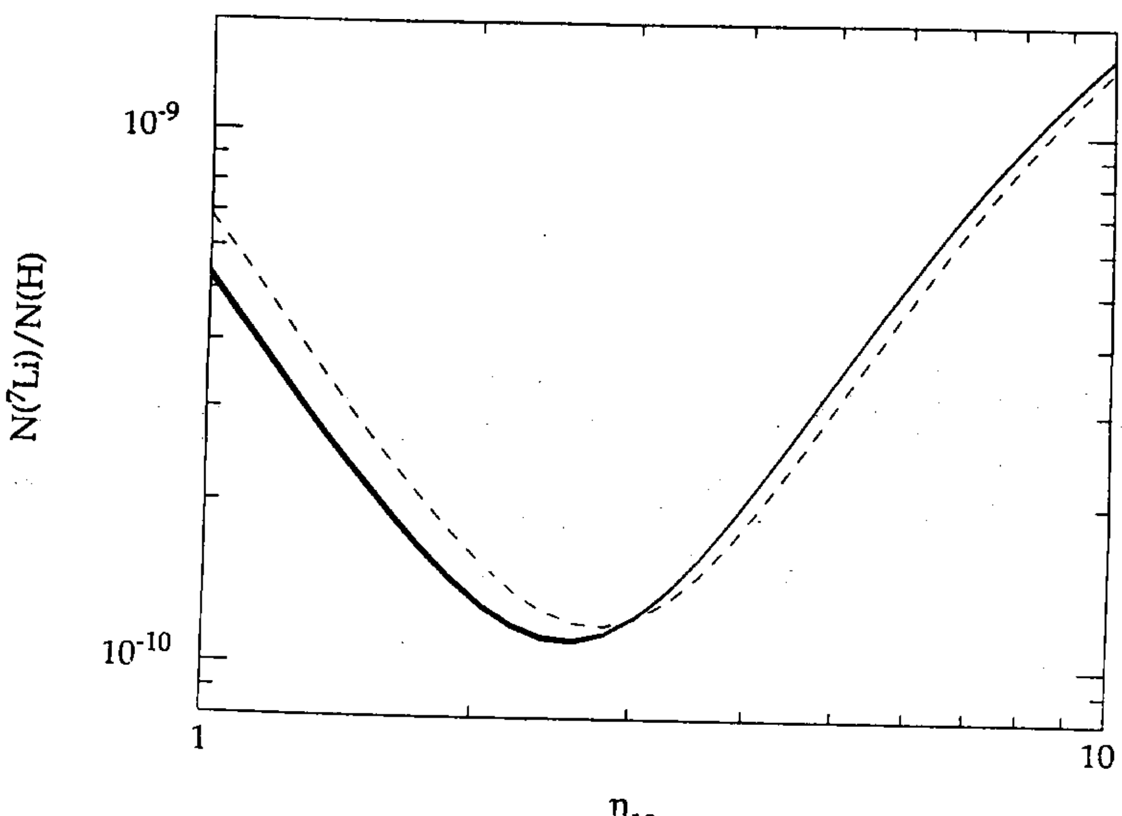


Fig. 4c

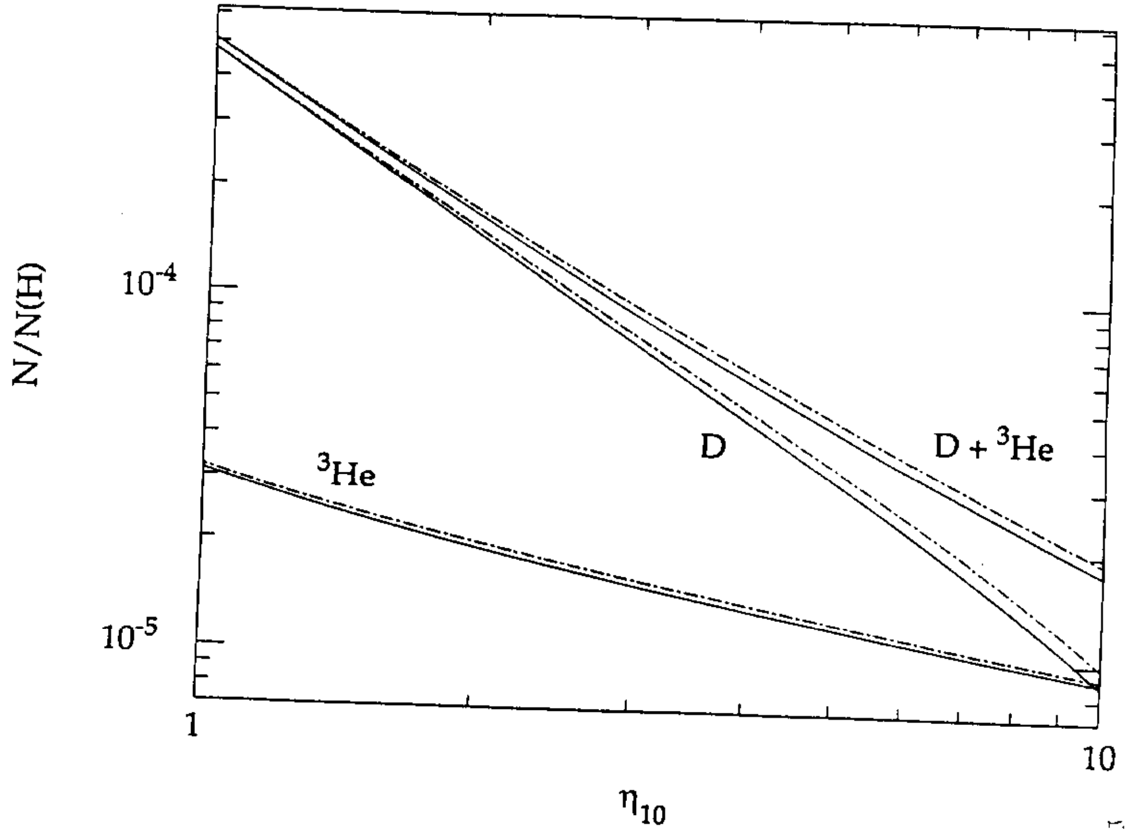


Fig. 2b

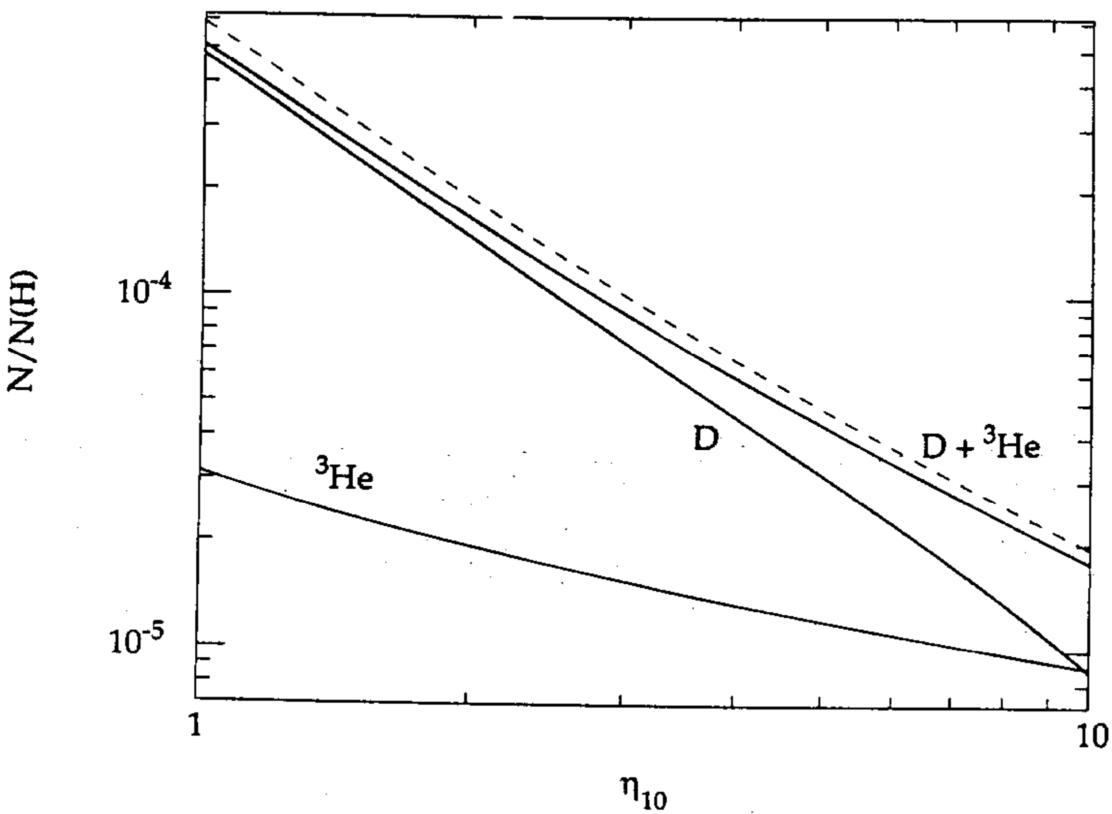


Fig. 2c

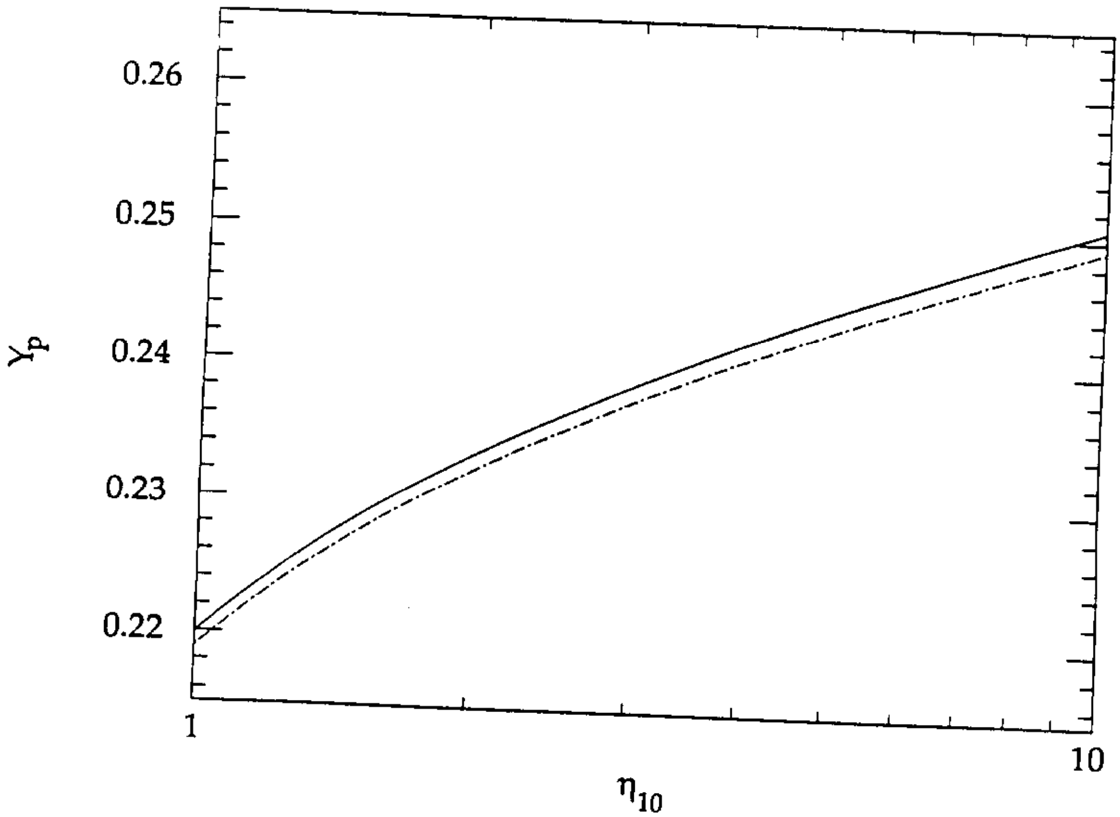

0.26
0.25
0.24
0.23
0.22
Y_p
1
10
η_{10}

Fig. 3b

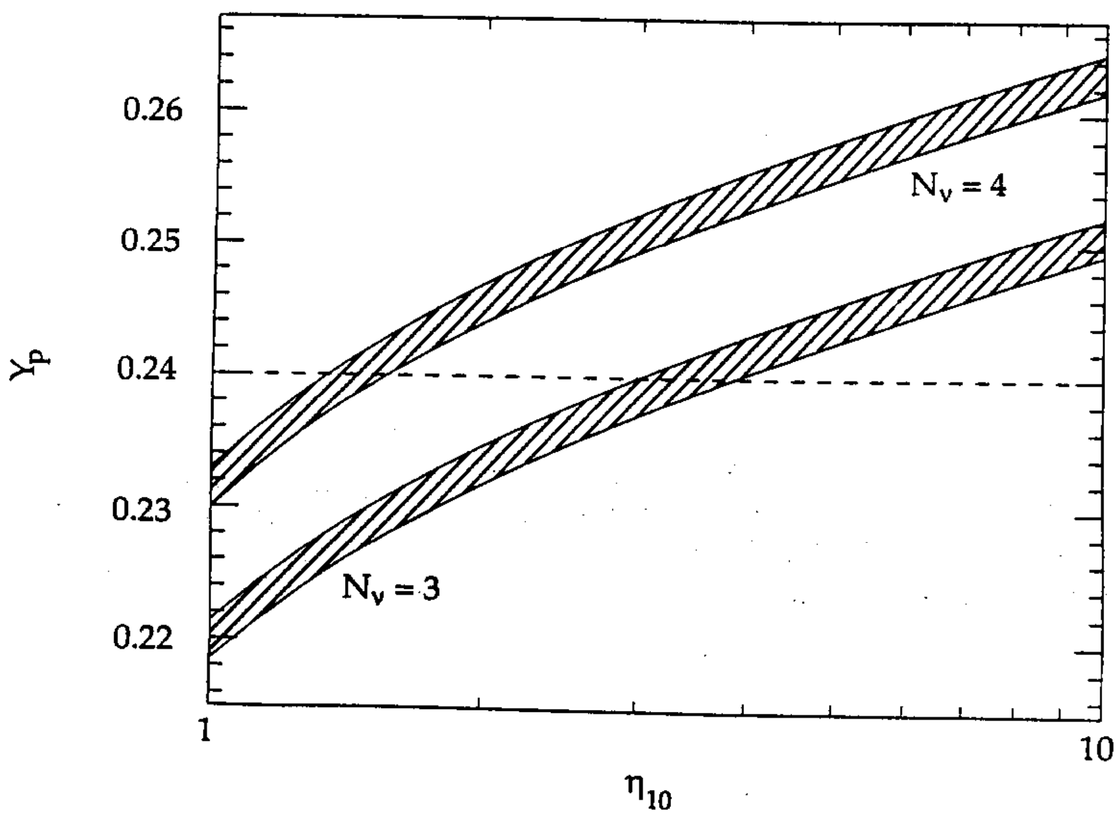
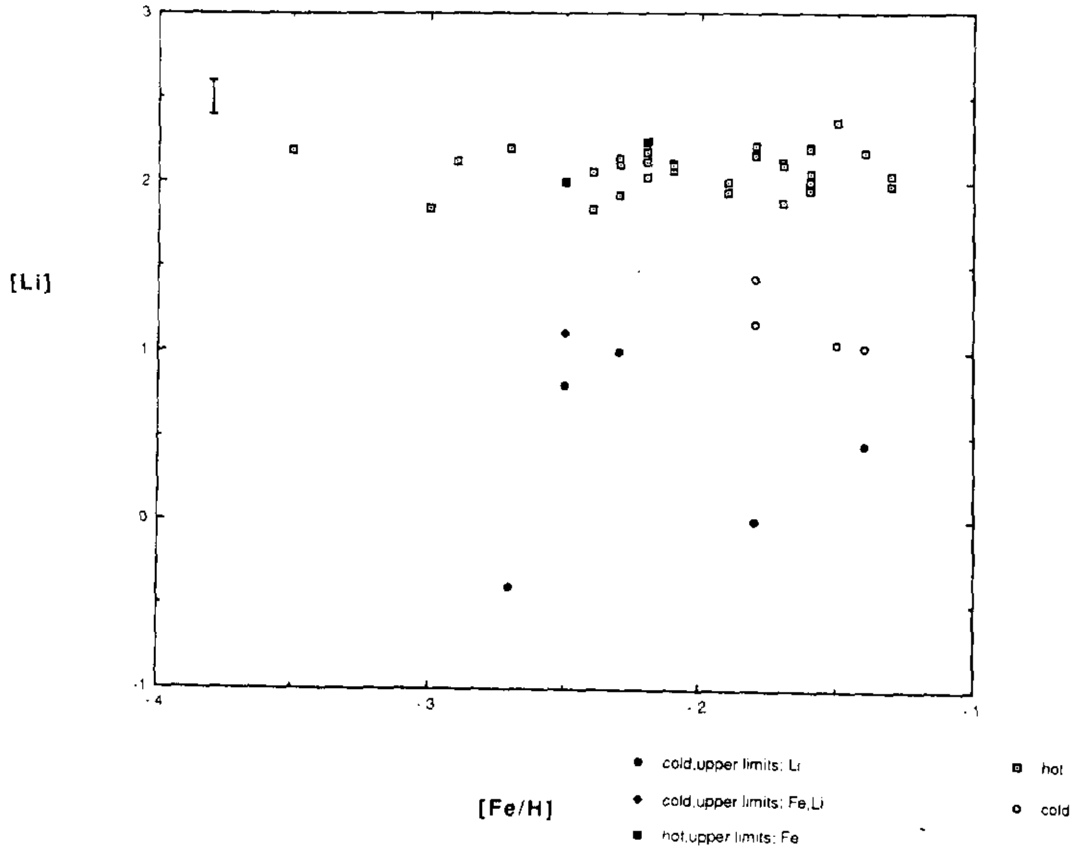
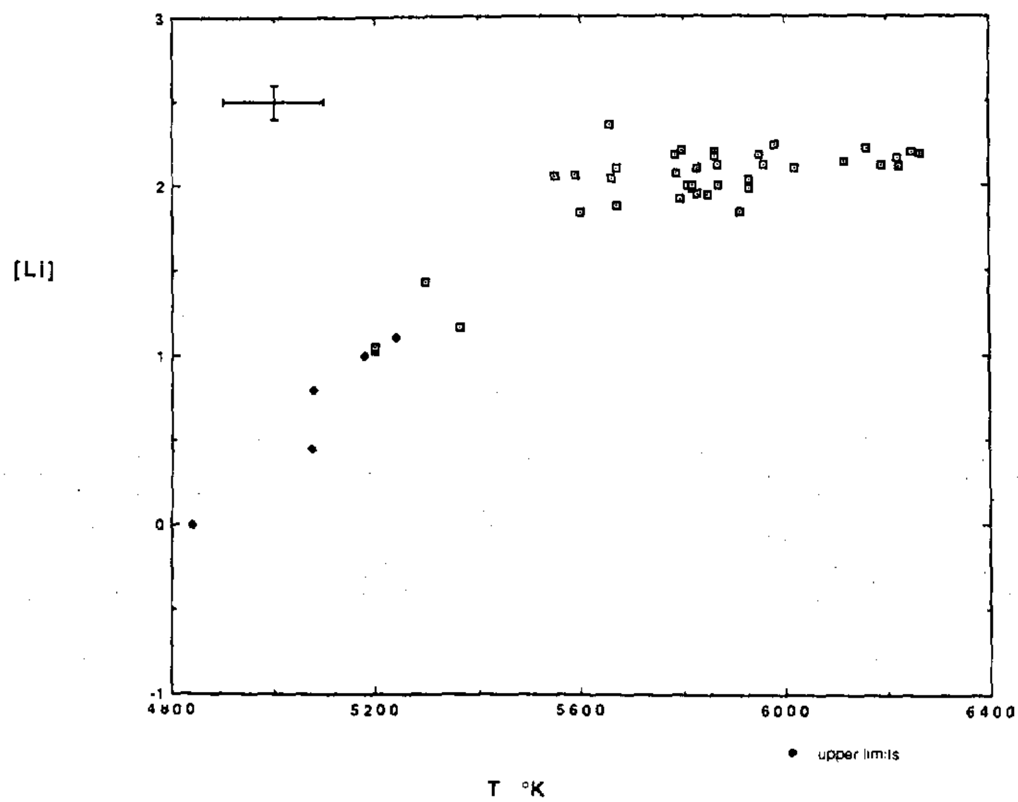

0.26
0.25
0.24
0.23
0.22
Y_p
$N_\nu = 4$
$N_\nu = 3$
1
10
η_{10}

Fig. 3a



[Li]
[Fe/H]
3
2
1
0
-1
-4
-3
-2
-1
cold,upper limits: Li
cold,upper limits: Fe,Li
hot,upper limits: Fe
hot
cold

Fig. 3



[Li]
T °K
3
2
1
0
-1
4800
5200
5600
6000
6400
upper limits

Fig. 4

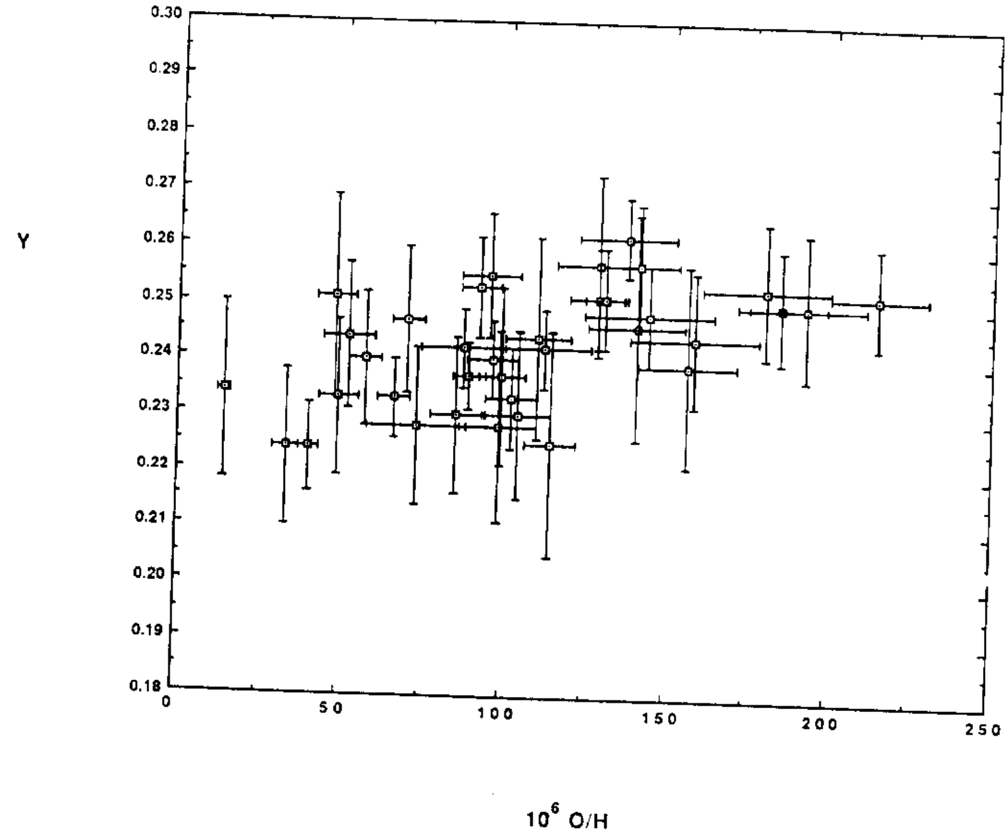


Fig. 5

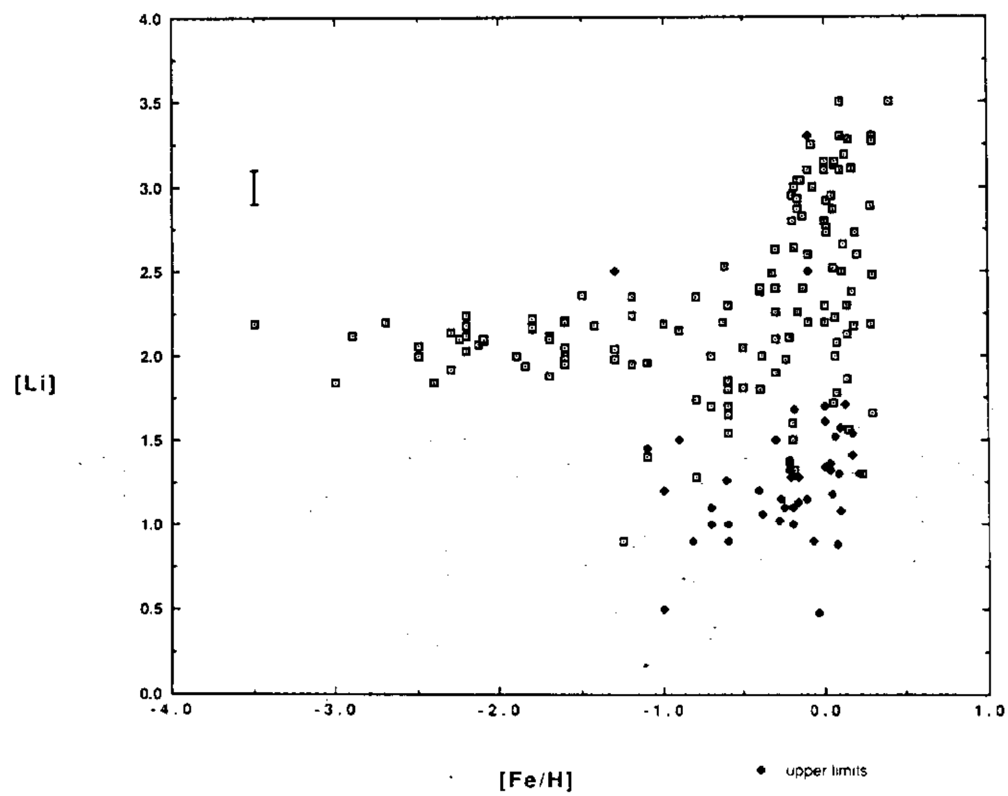


Fig. 6

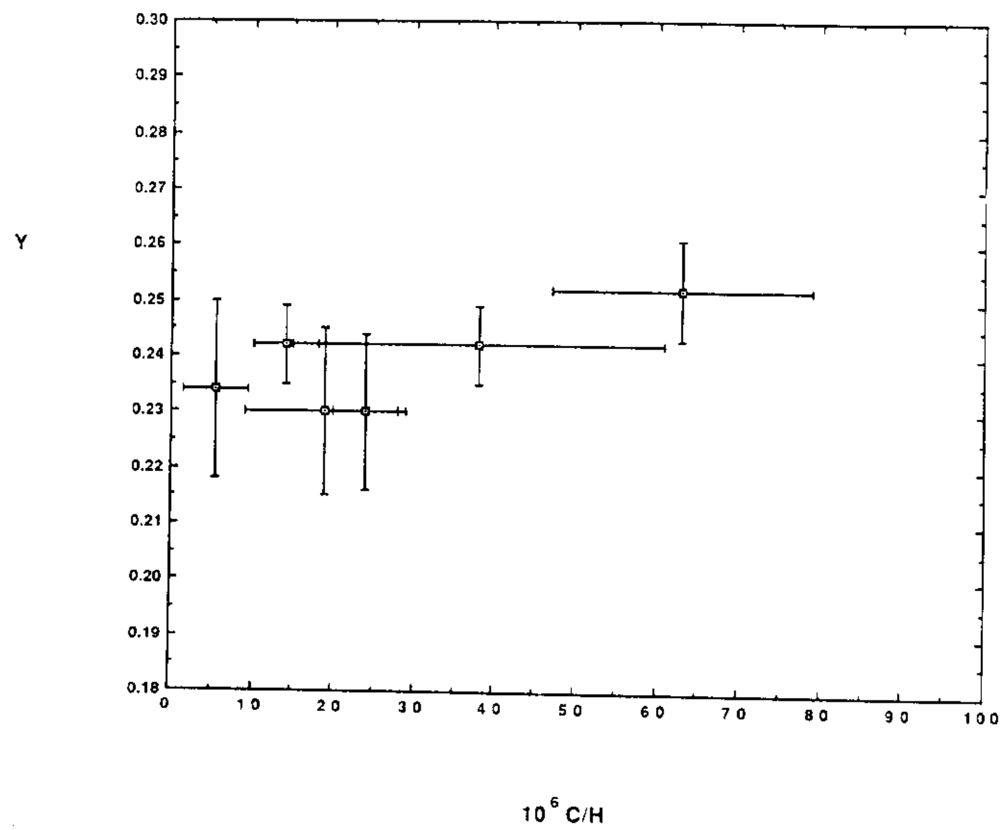

Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0
10
20
30
40
50
60
70
80
90
100
10^6 C/H

Fig. 2

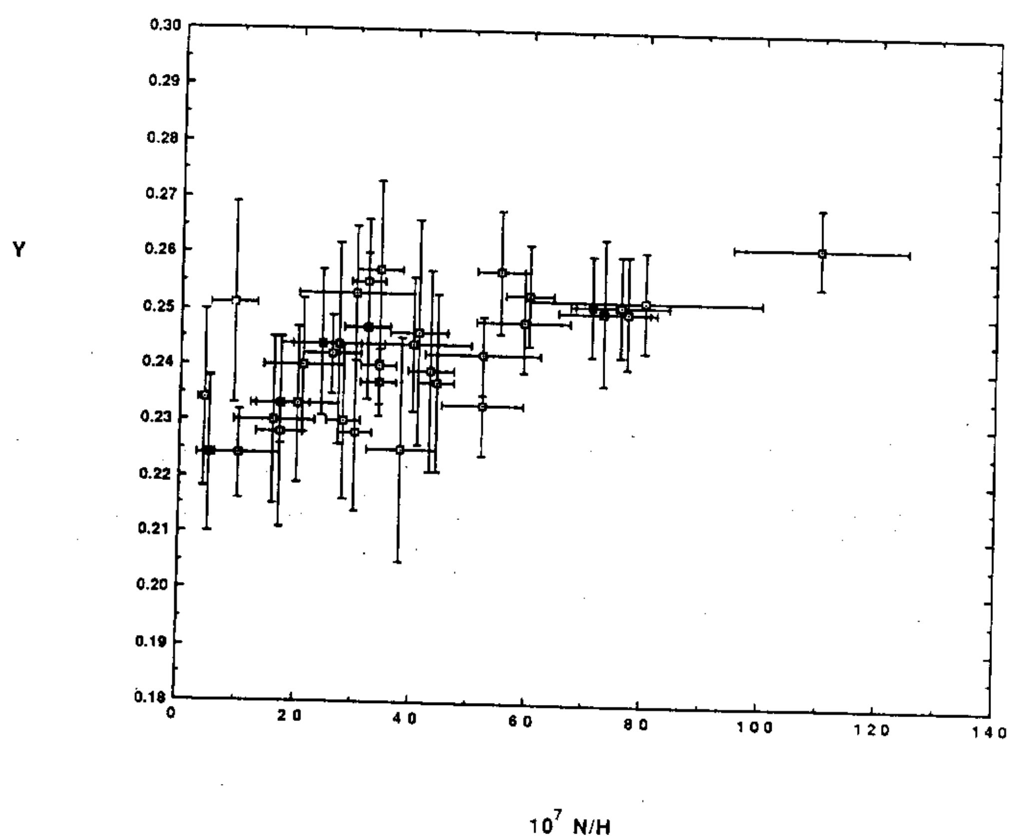
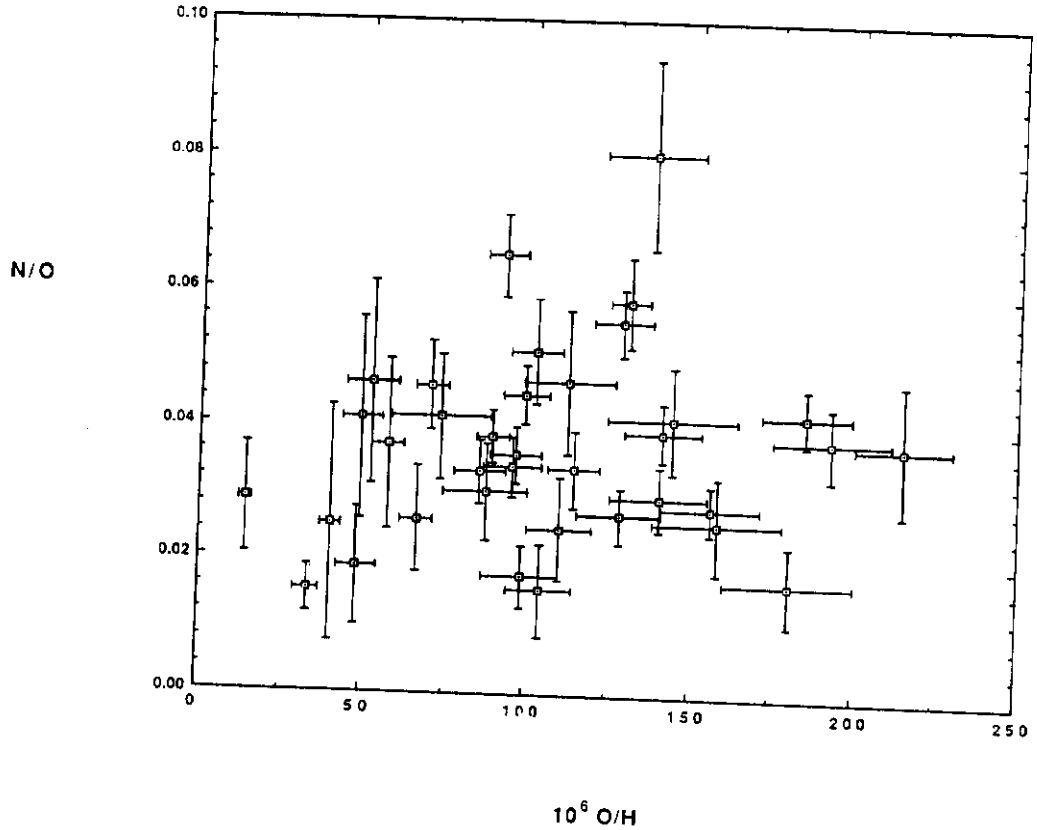
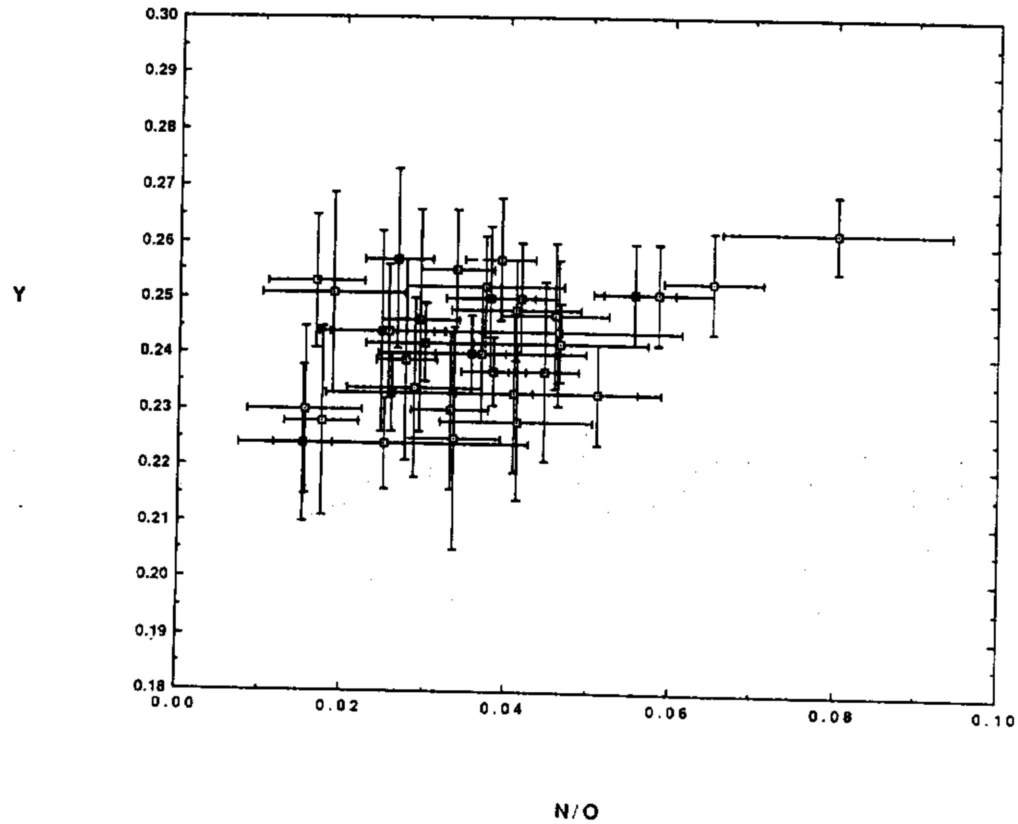

Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0
20
40
60
80
100
120
140
10^7 N/H

Fig. 3



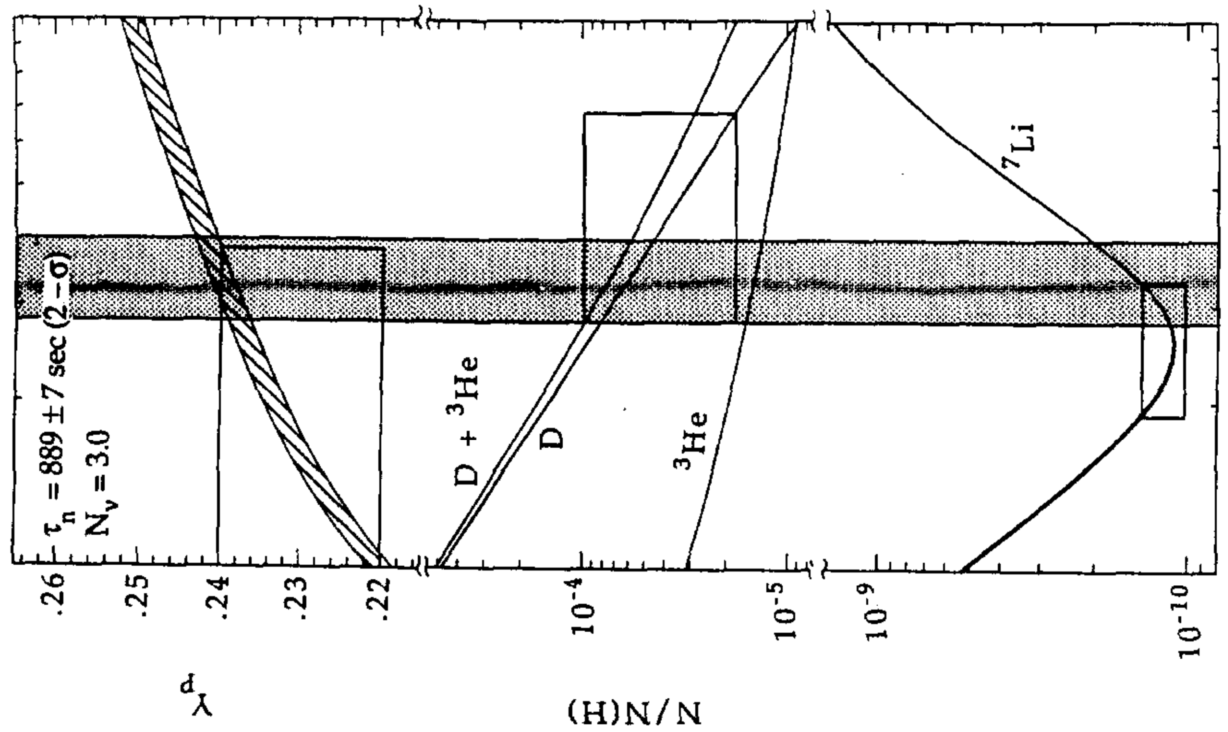
N/O
0.10
0.08
0.06
0.04
0.02
0.00
0
50
100
150
200
250
10^6 O/H

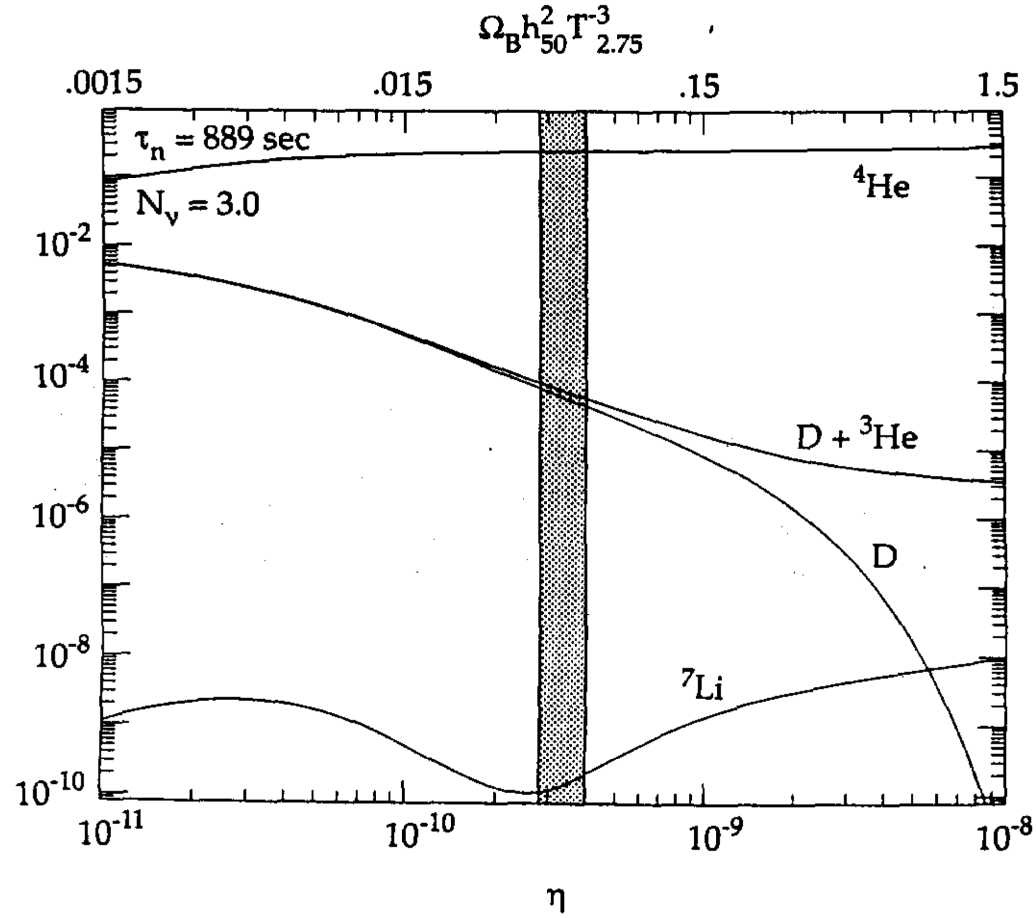
Fig. 11



Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.00
0.02
0.04
0.06
0.08
0.10
N/O

Fig. 12


τn = 889 ± 7 sec (2-σ)
Nν = 3.0
D + 3He
D
3He
7Li
η10
Yp
N/N(H)
.26
.25
.24
.23
.22
10-4
10-5
10-9
10-10
1
10


ΩBh250T-32.75
.0015
.015
.15
1.5
τn = 889 sec
Nν = 3.0
4He
D + 3He
D
7Li
10-2
10-4
10-6
10-8
10-10
10-11
10-10
10-9
10-8
η

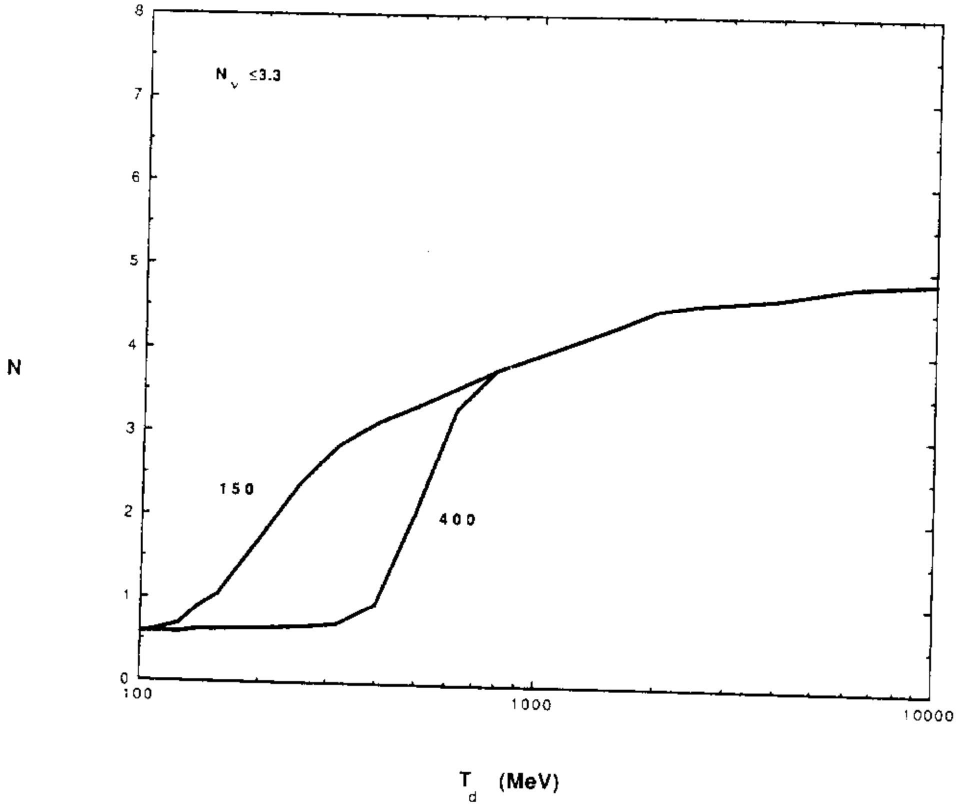

N
$N_\nu \le 3.3$
150
400
T_d (MeV)
100
1000
10000
0
1
2
3
4
5
6
7
8

Fig. 15

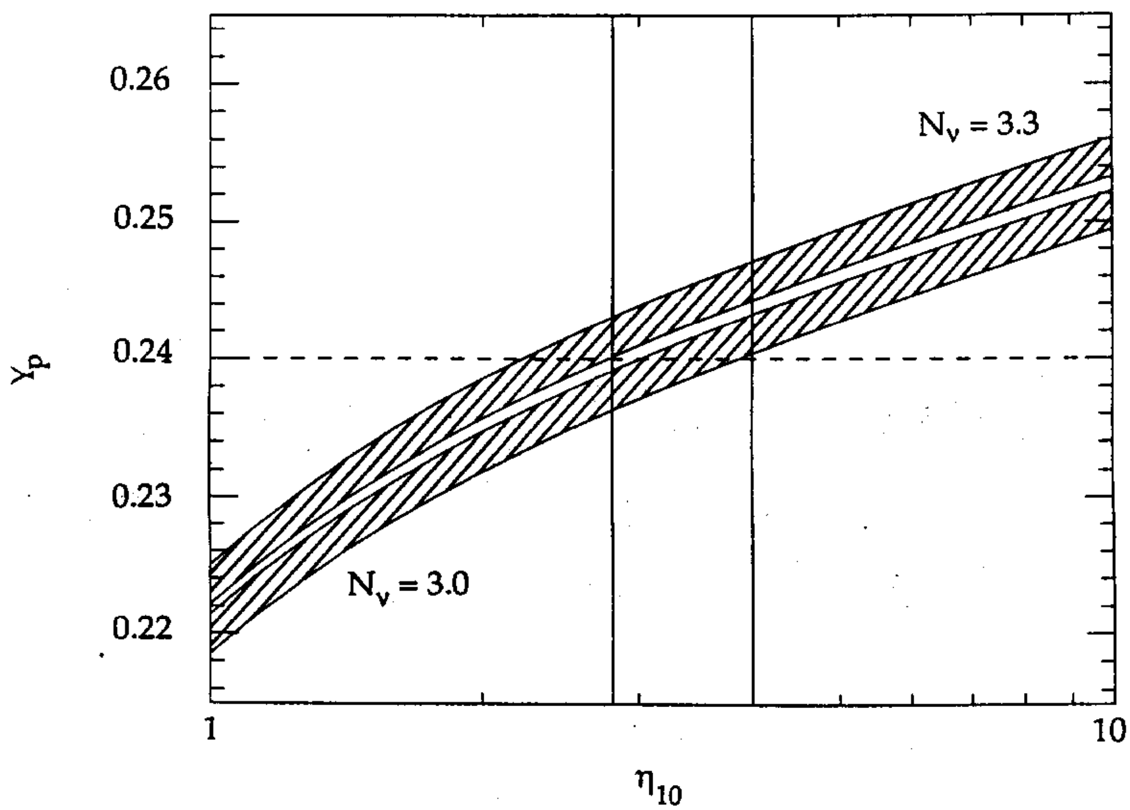

Y_p
η_{10}
$N_\nu = 3.3$
$N_\nu = 3.0$
0.26
0.25
0.24
0.23
0.22
1
10

Fig. 14

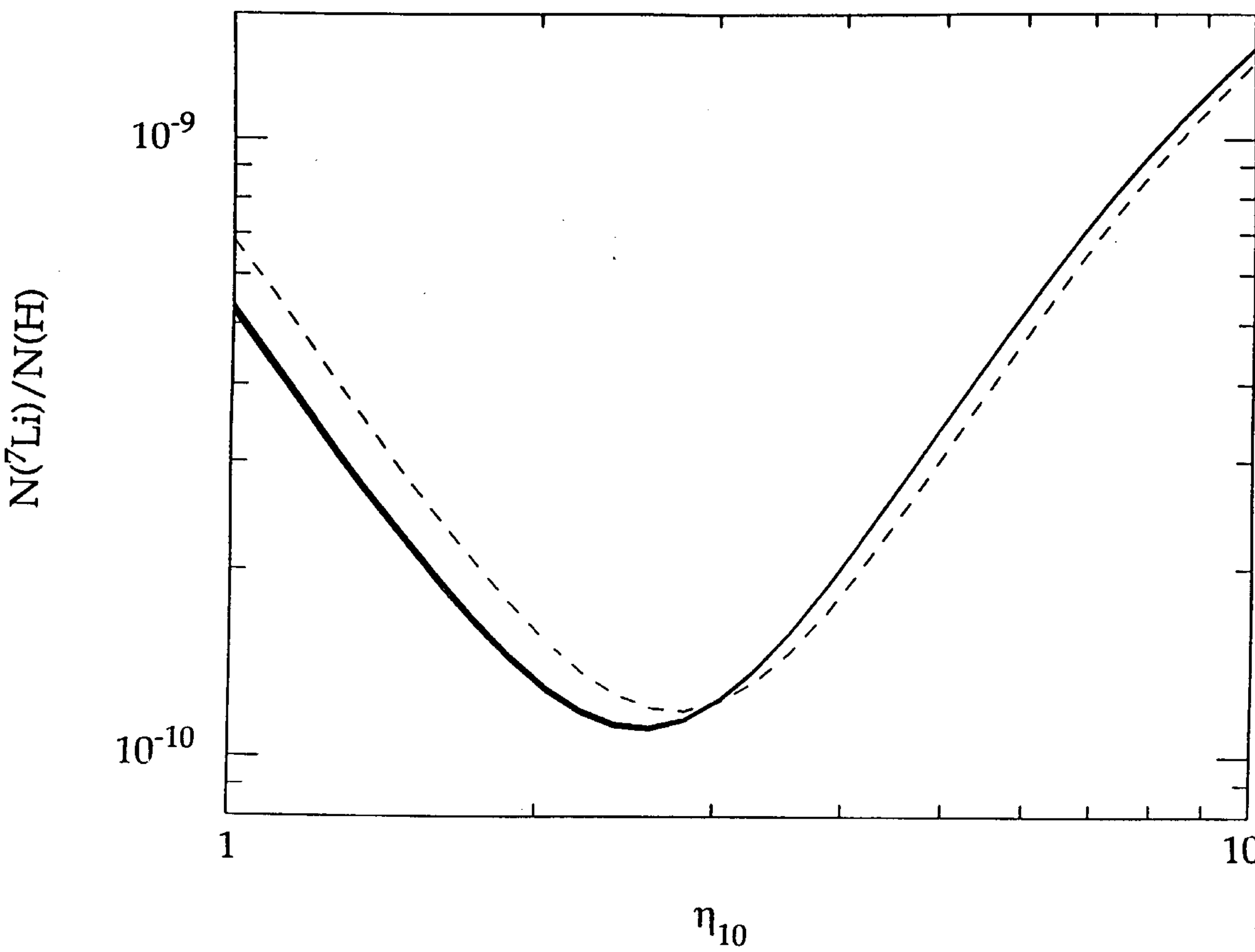


Fig. 1e

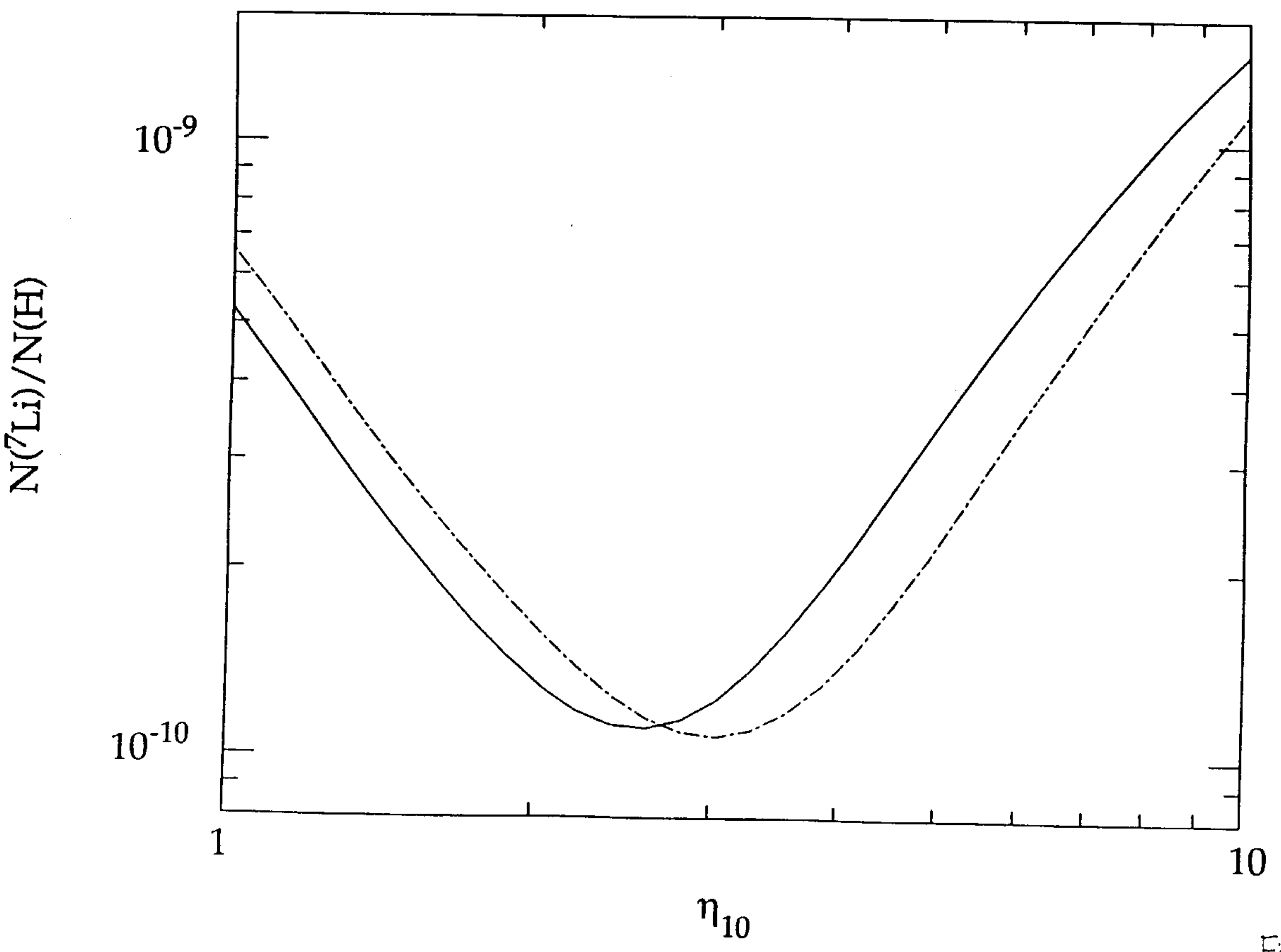


Fig. 1b

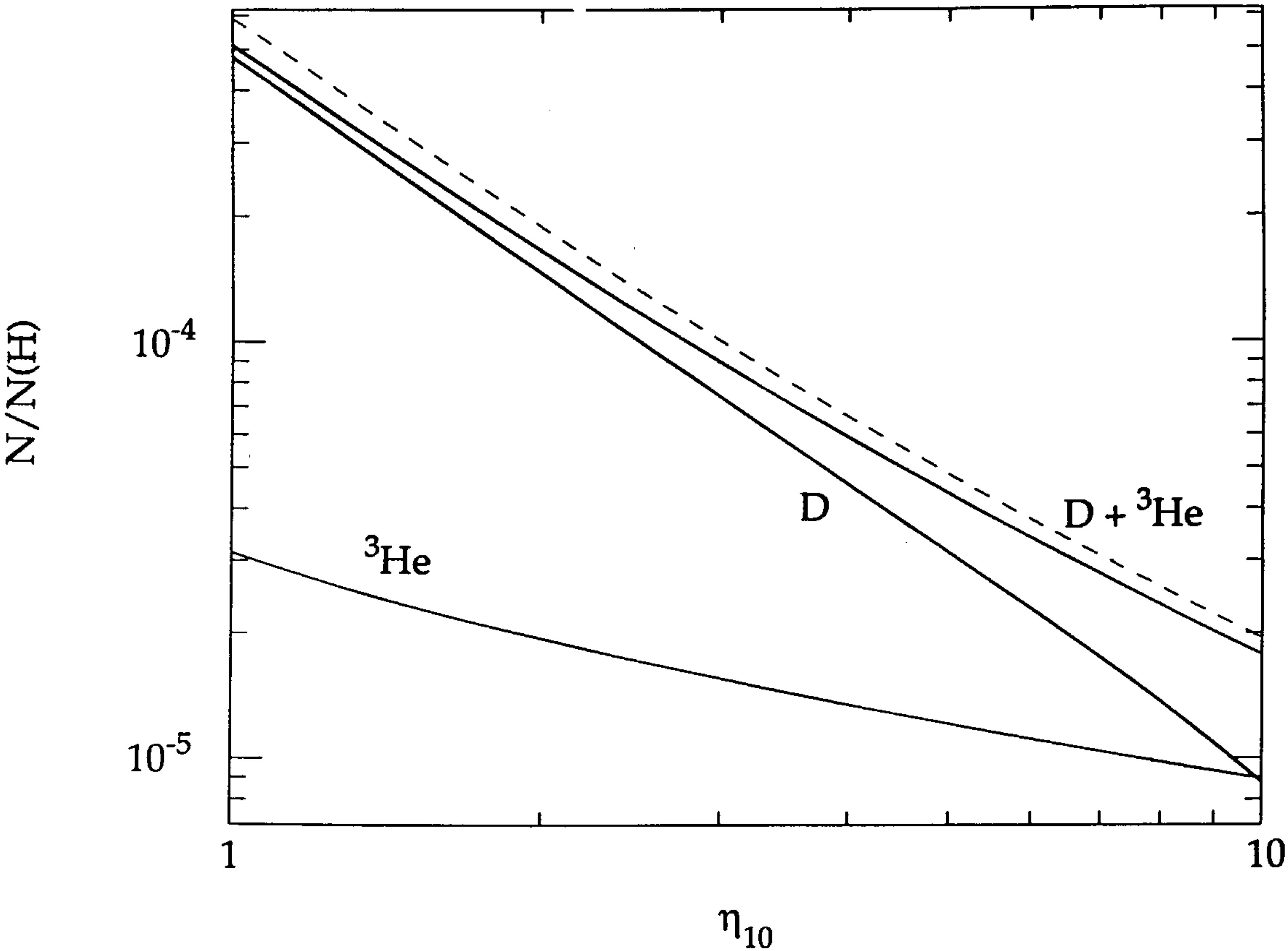


Fig. 2a

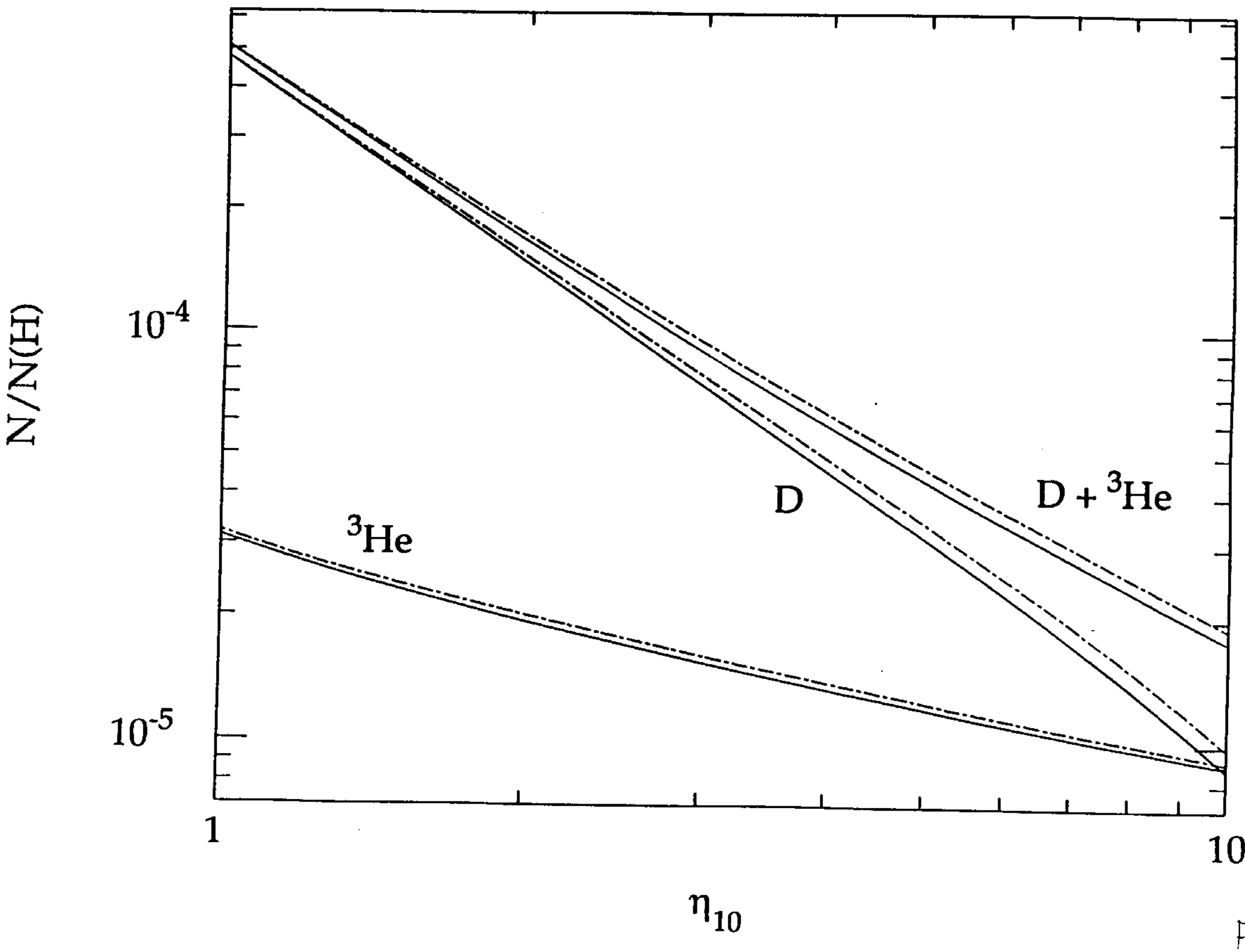


Fig. 2b

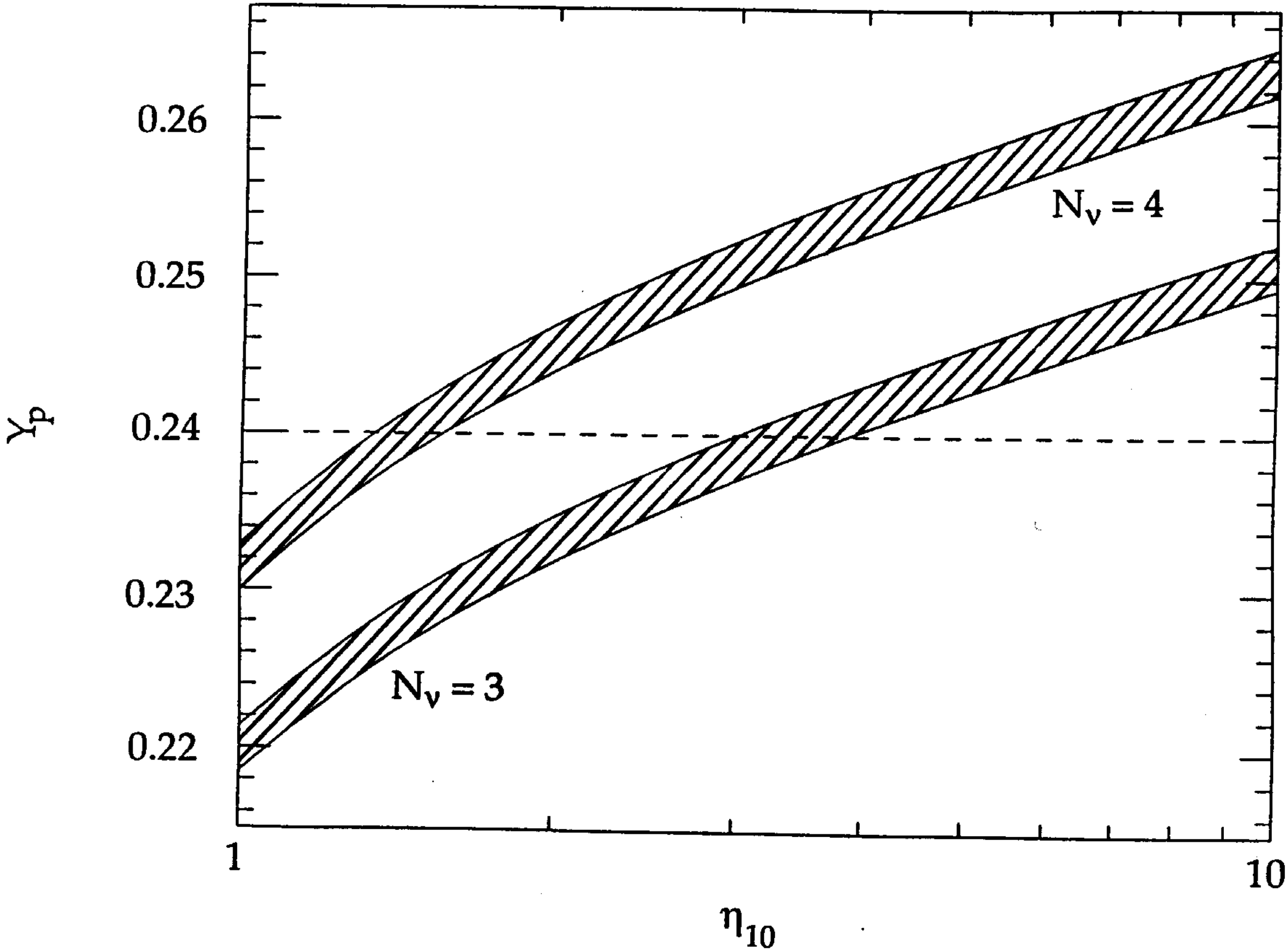


Fig. 3a

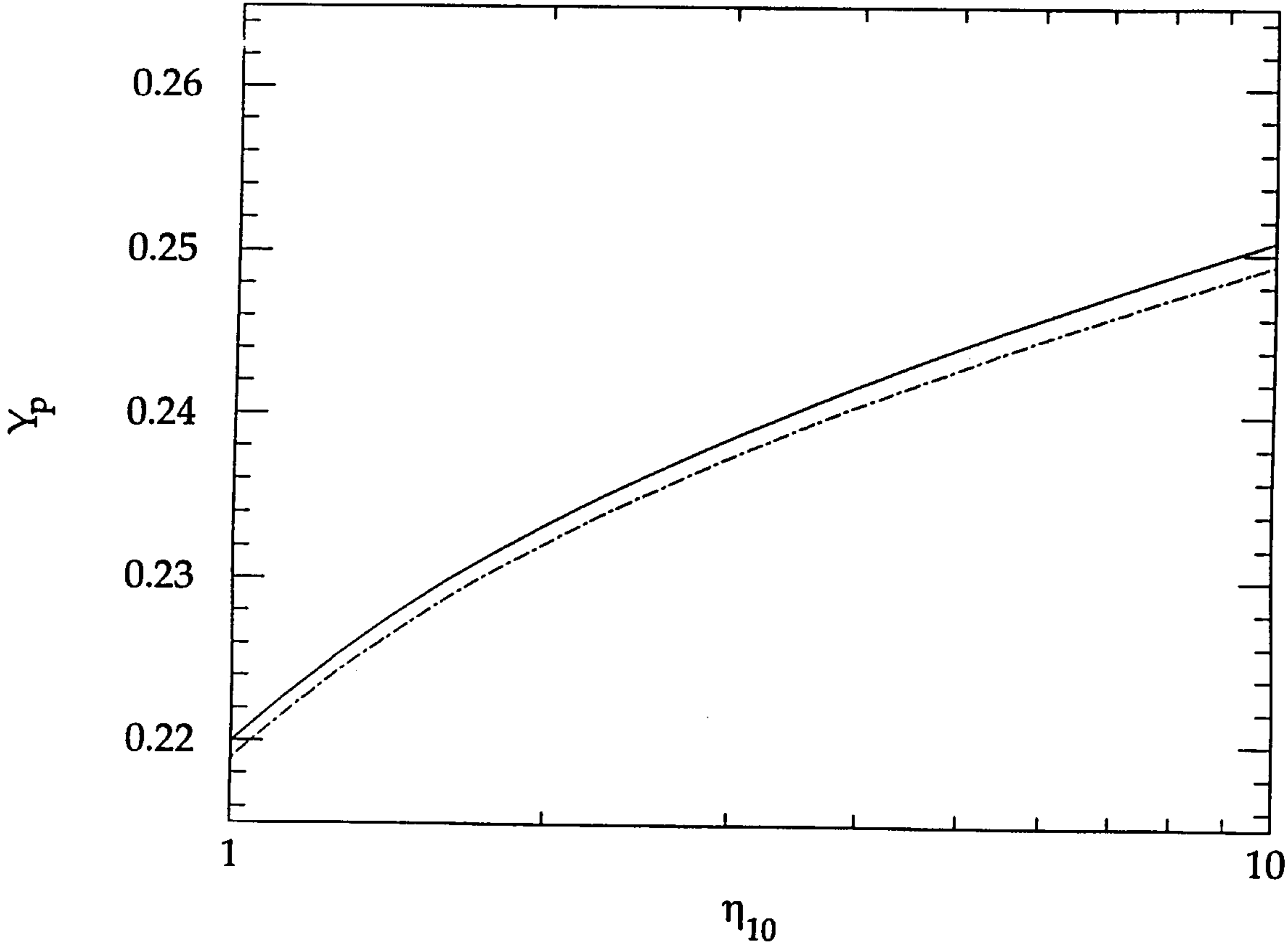


Fig.3b

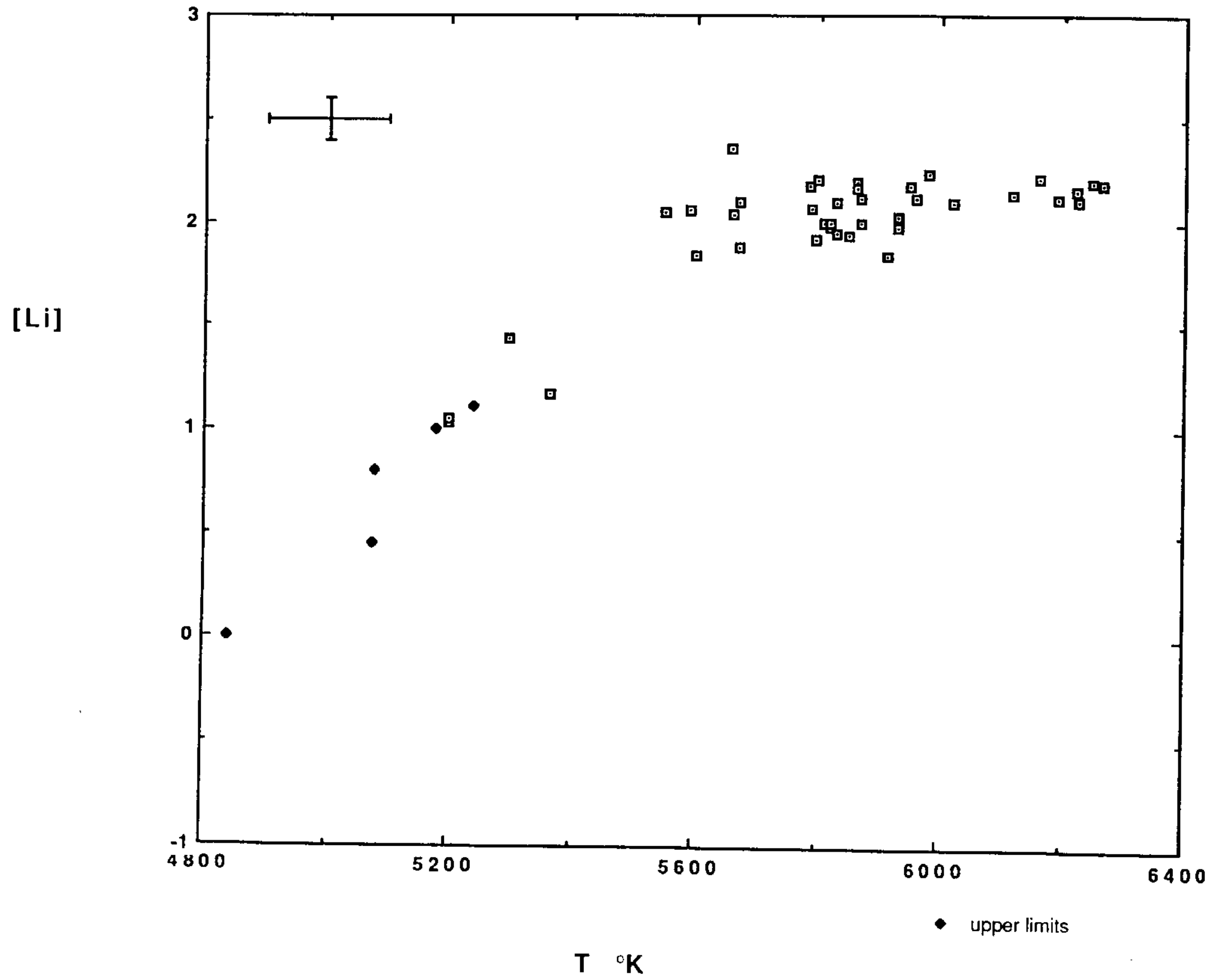


Fig. 4

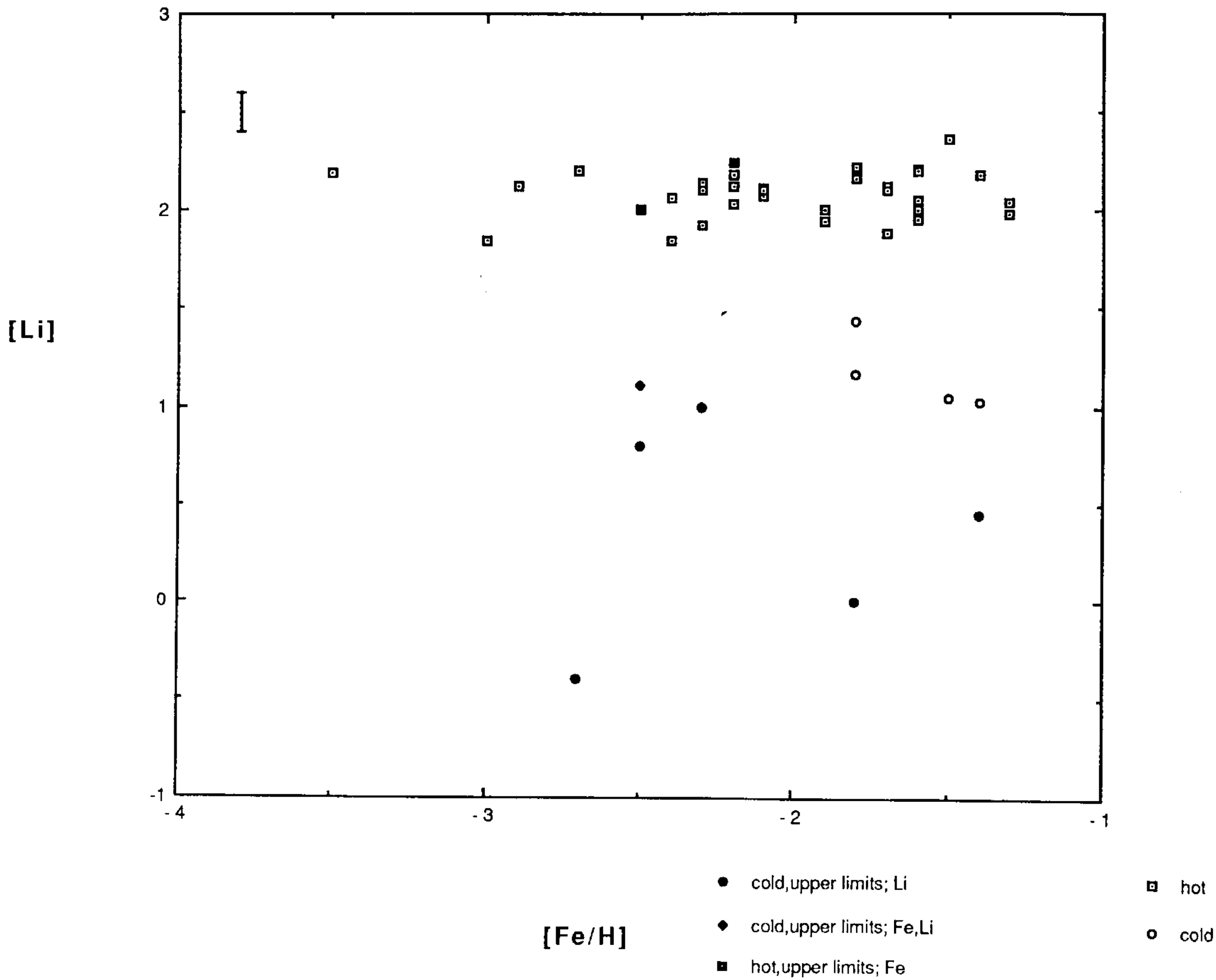

3
2
1
0
-1
[Li]
-4
-3
-2
-1
[Fe/H]
cold,upper limits; Li
cold,upper limits; Fe,Li
hot,upper limits; Fe
hot
cold

Fig. 5

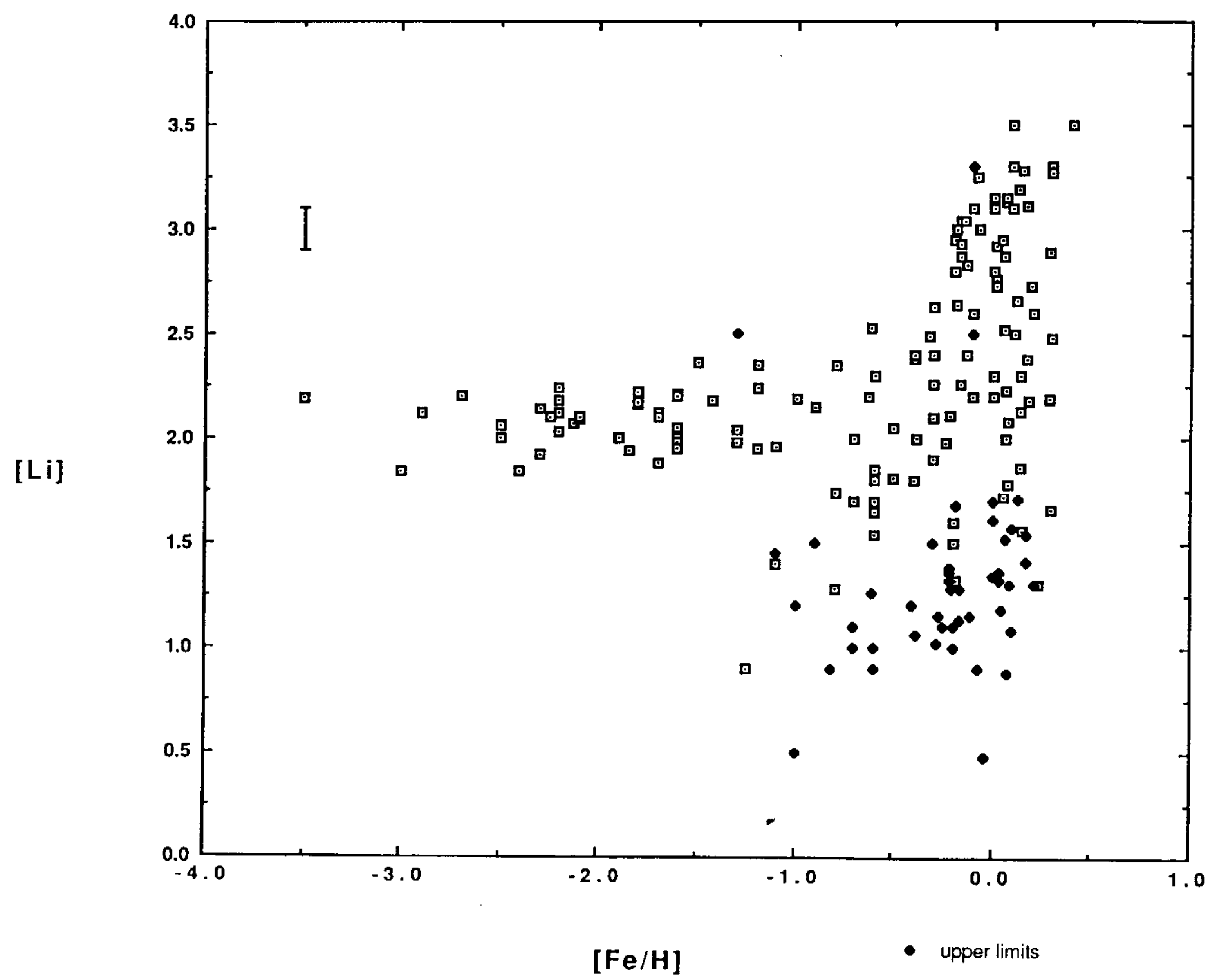


Fig. 6

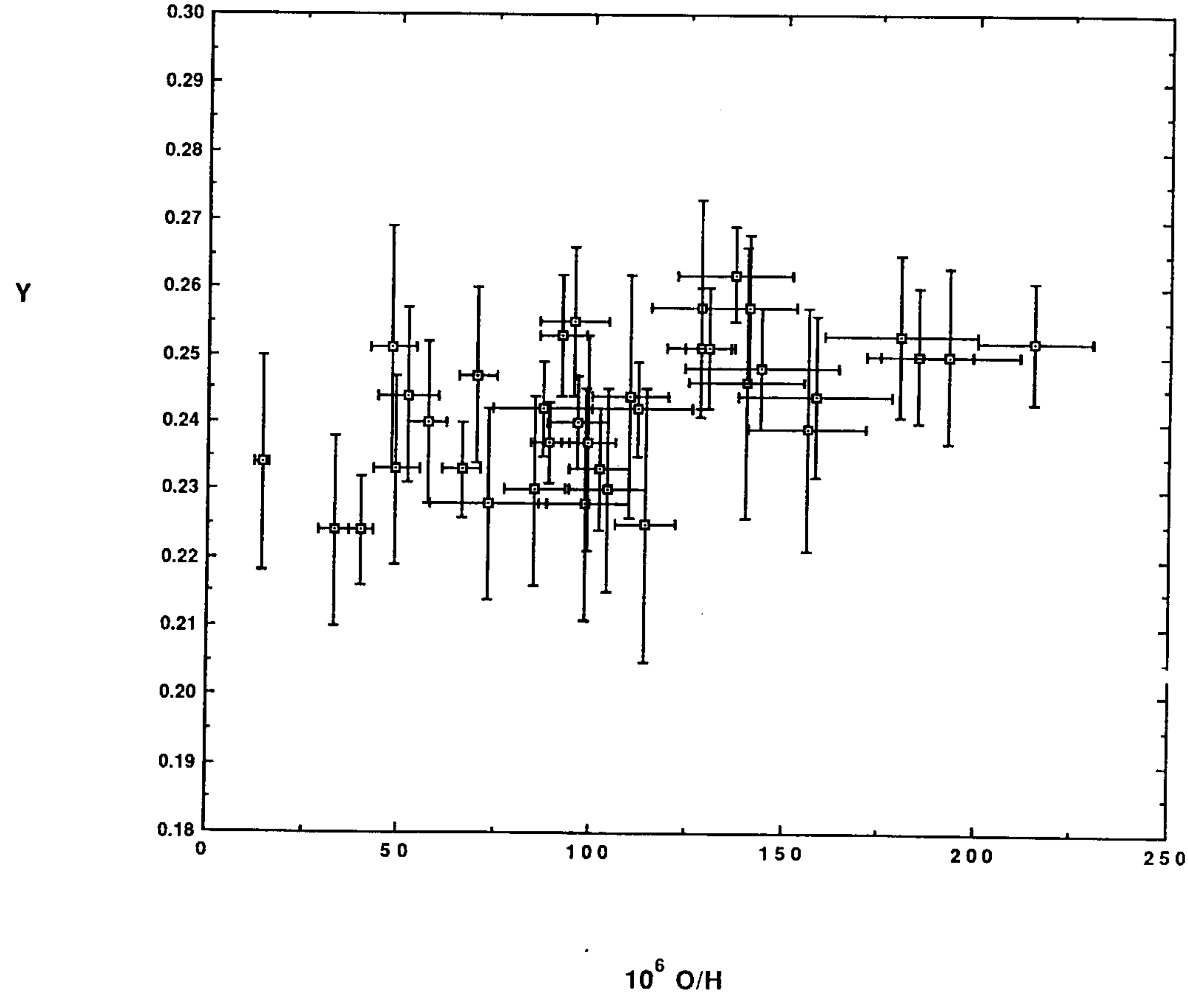
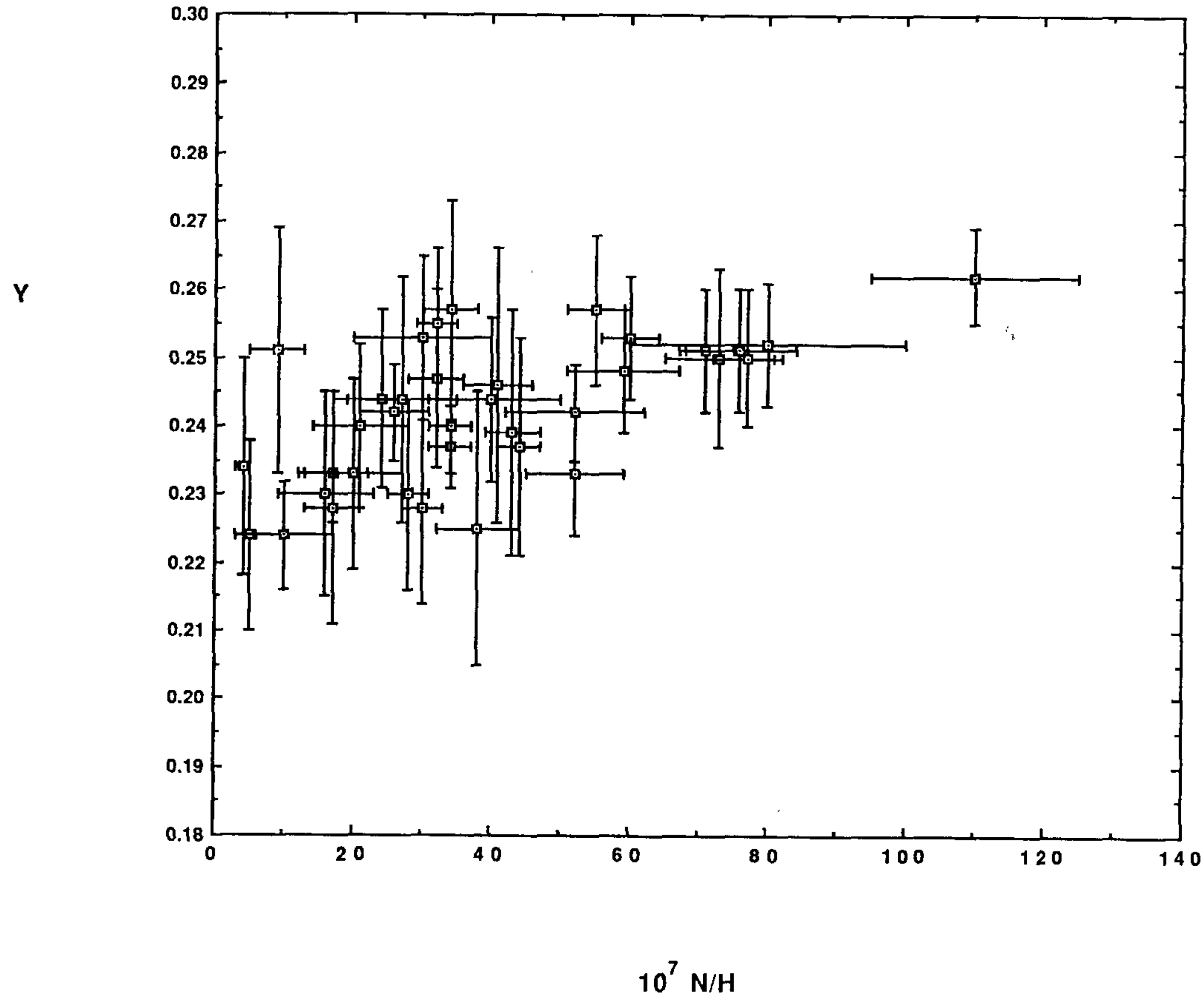

Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0
50
100
150
200
250
10^6 O/H

Fig. 7


Y
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0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
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0.19
0.18
0
20
40
60
80
100
120
140
10^7 N/H

Fig. 8

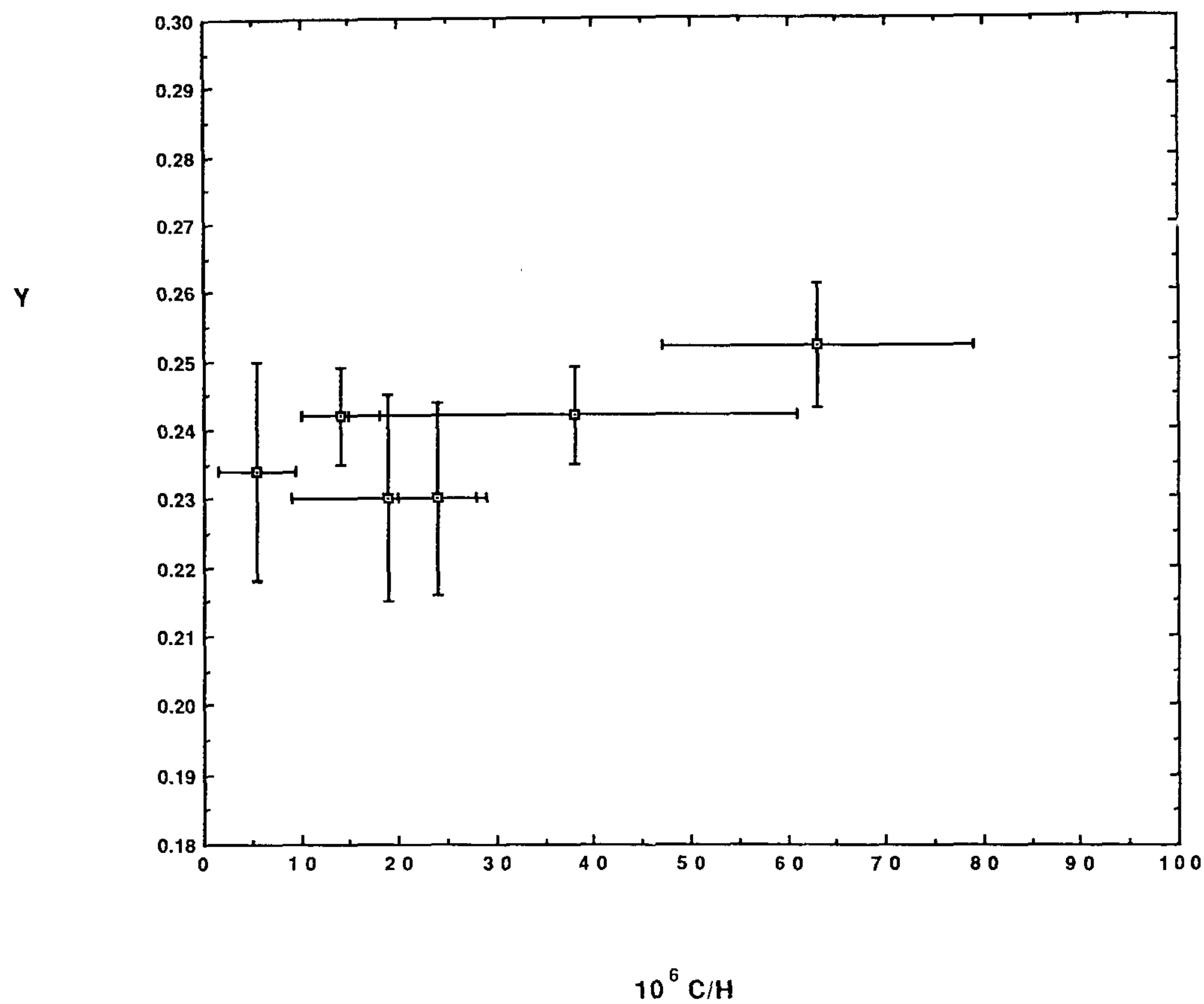

Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0
10
20
30
40
50
60
70
80
90
100
10^6 C/H

Fig. 9

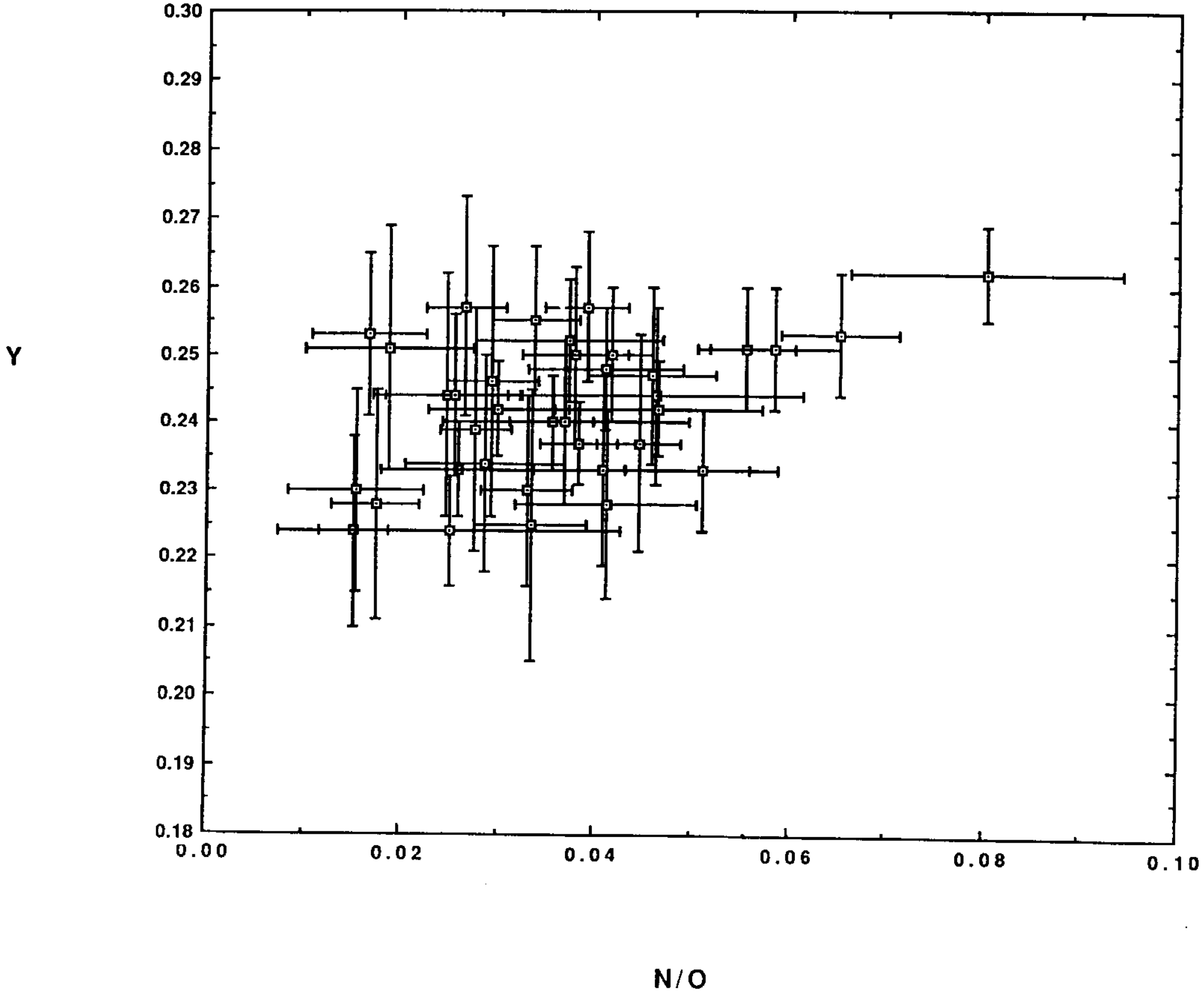

Y
0.30
0.29
0.28
0.27
0.26
0.25
0.24
0.23
0.22
0.21
0.20
0.19
0.18
0.00
0.02
0.04
0.06
0.08
0.10
N/O

Fig. 10

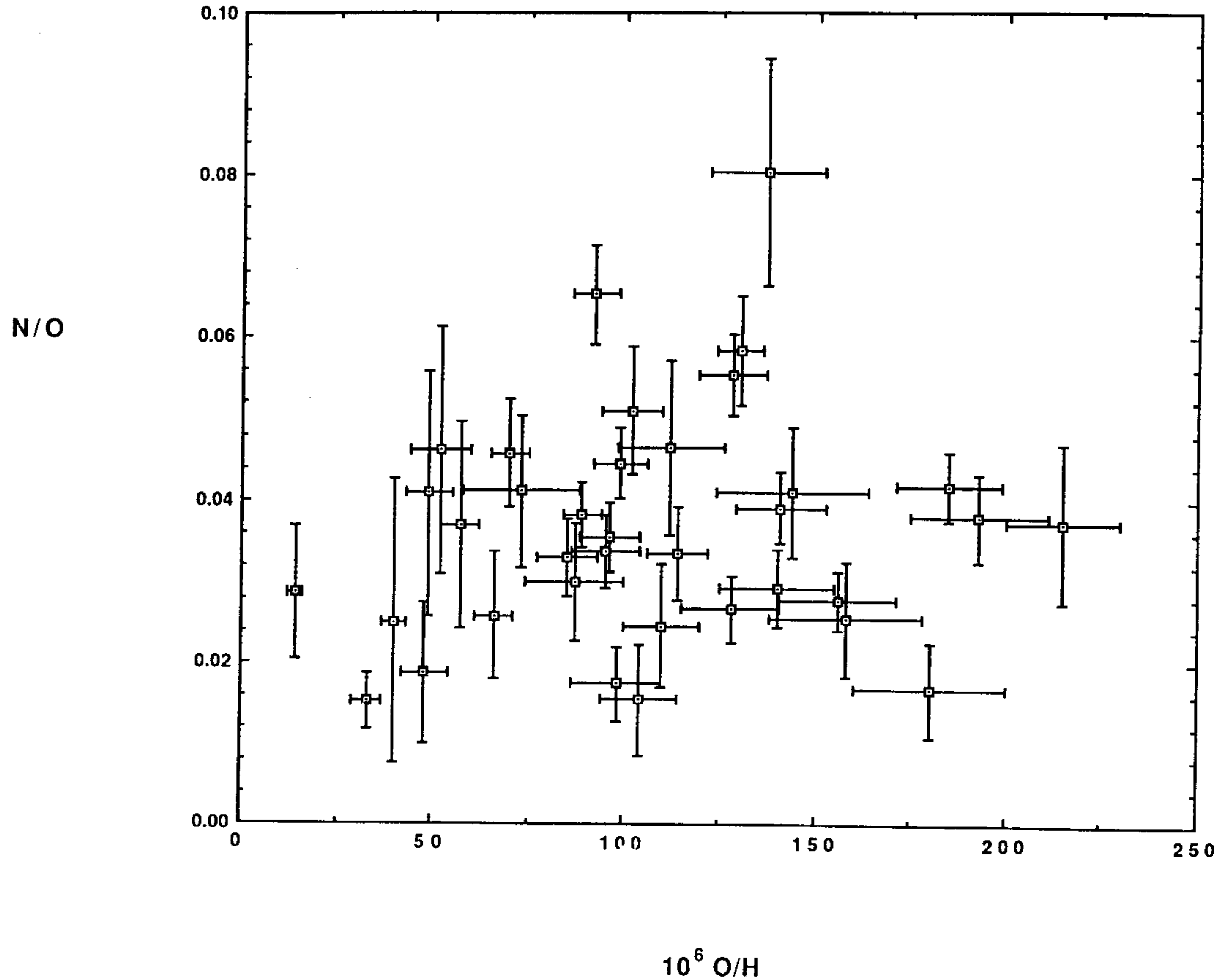
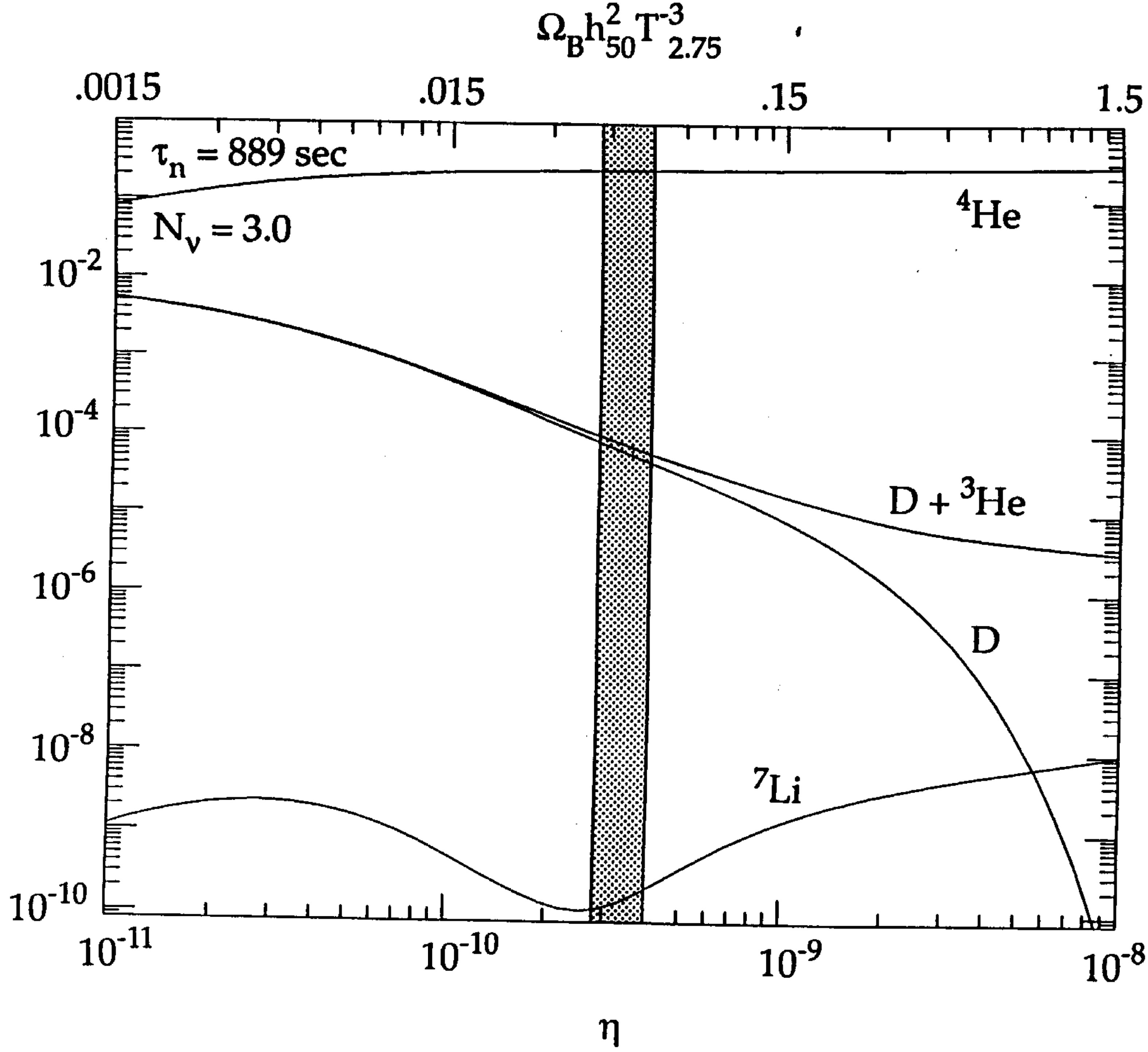
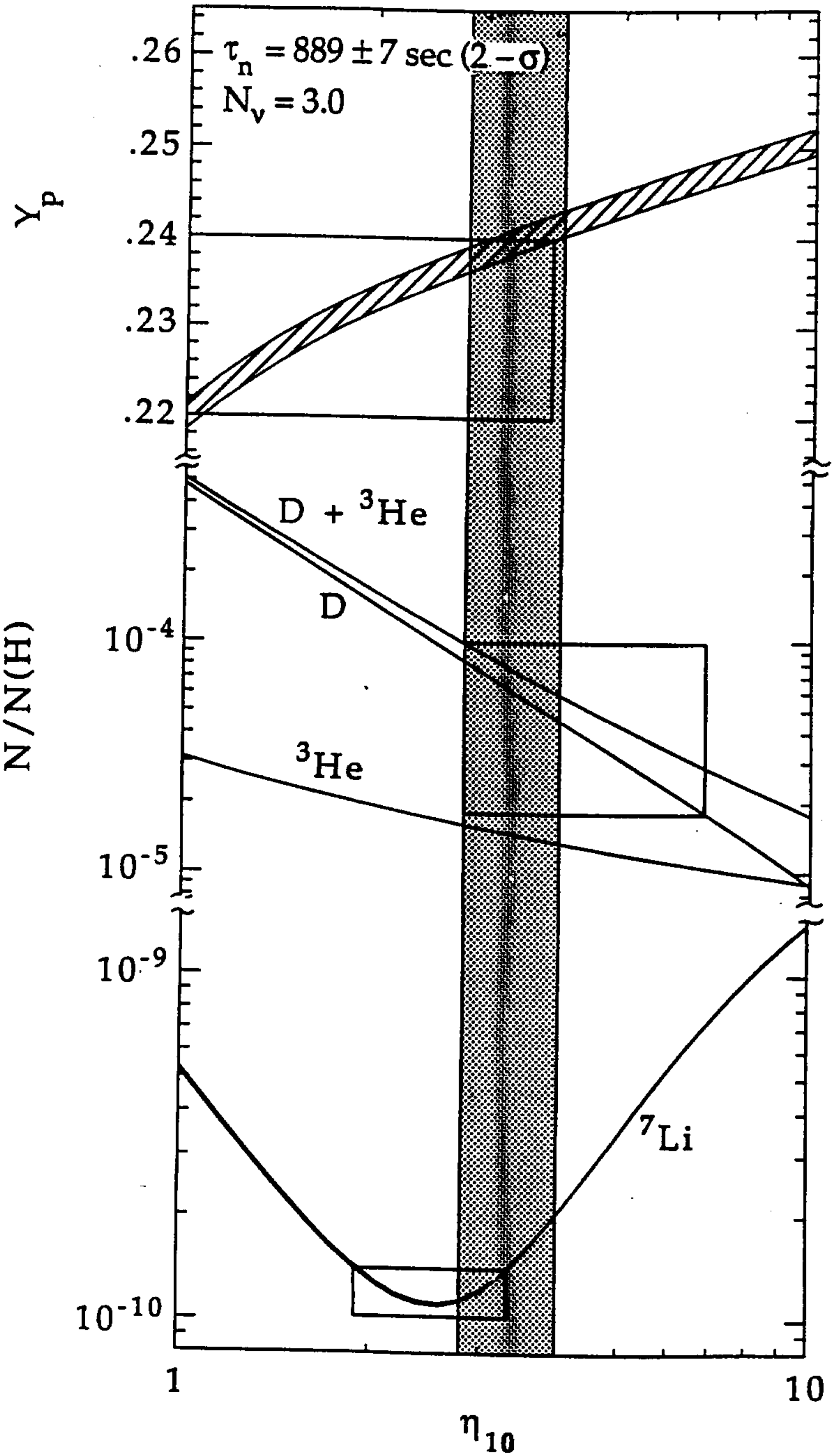


Fig. 11



Ω_B h²_50 T⁻³_2.75
.0015
.015
.15
1.5
τ_n = 889 sec
N_ν = 3.0
⁴He
D + ³He
D
⁷Li
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
η

Fig. 12



$\tau_n = 889 \pm 7$ sec (2 − σ)
$N_\nu = 3.0$
Y_p
.26
.25
.24
.23
.22
D + ^{3}He
D
10^{-4}
N/N(H)
^{3}He
10^{-5}
10^{-9}
^{7}Li
10^{-10}
1
10
η_{10}

Fig. 13

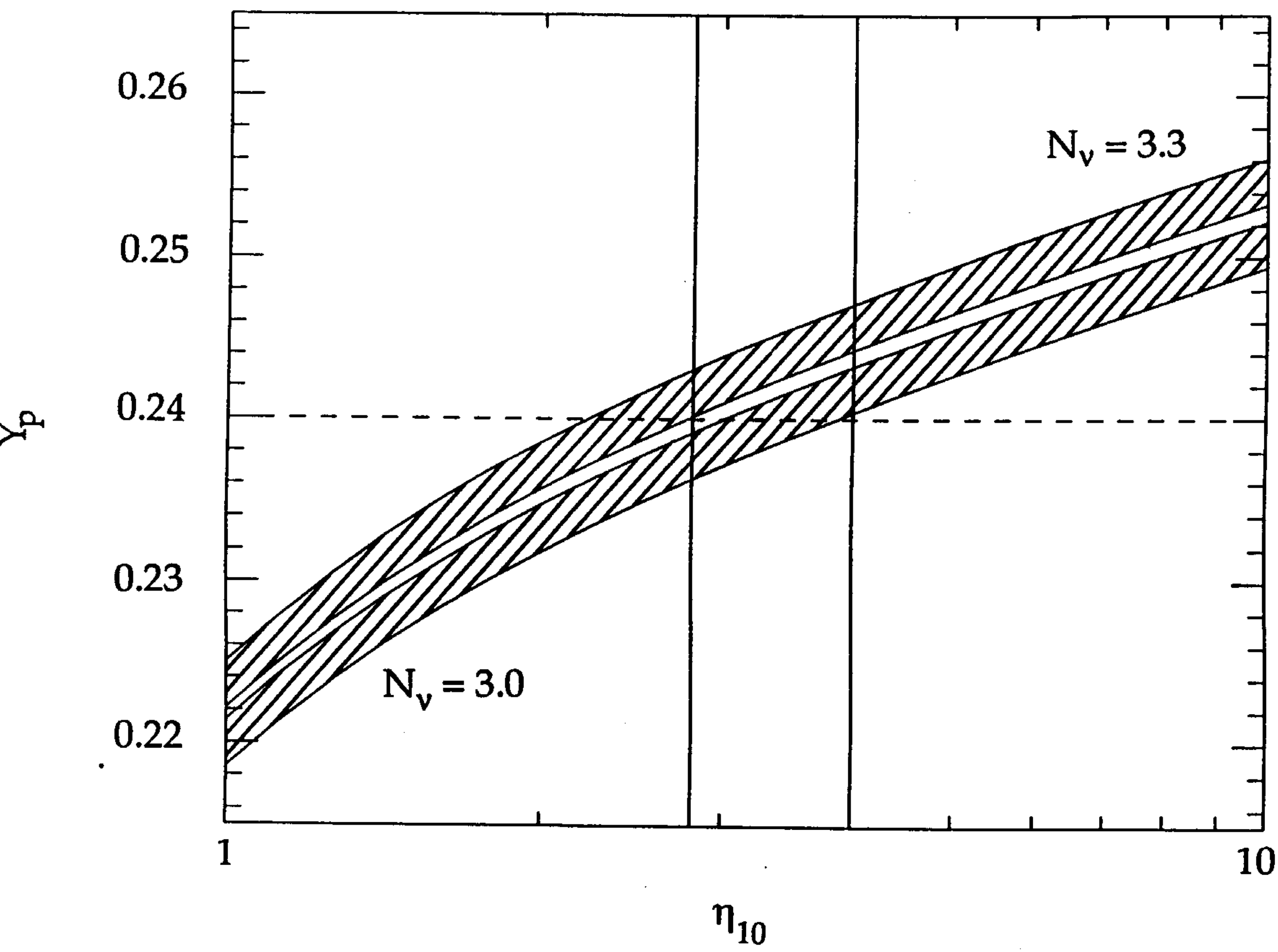


Fig. 14

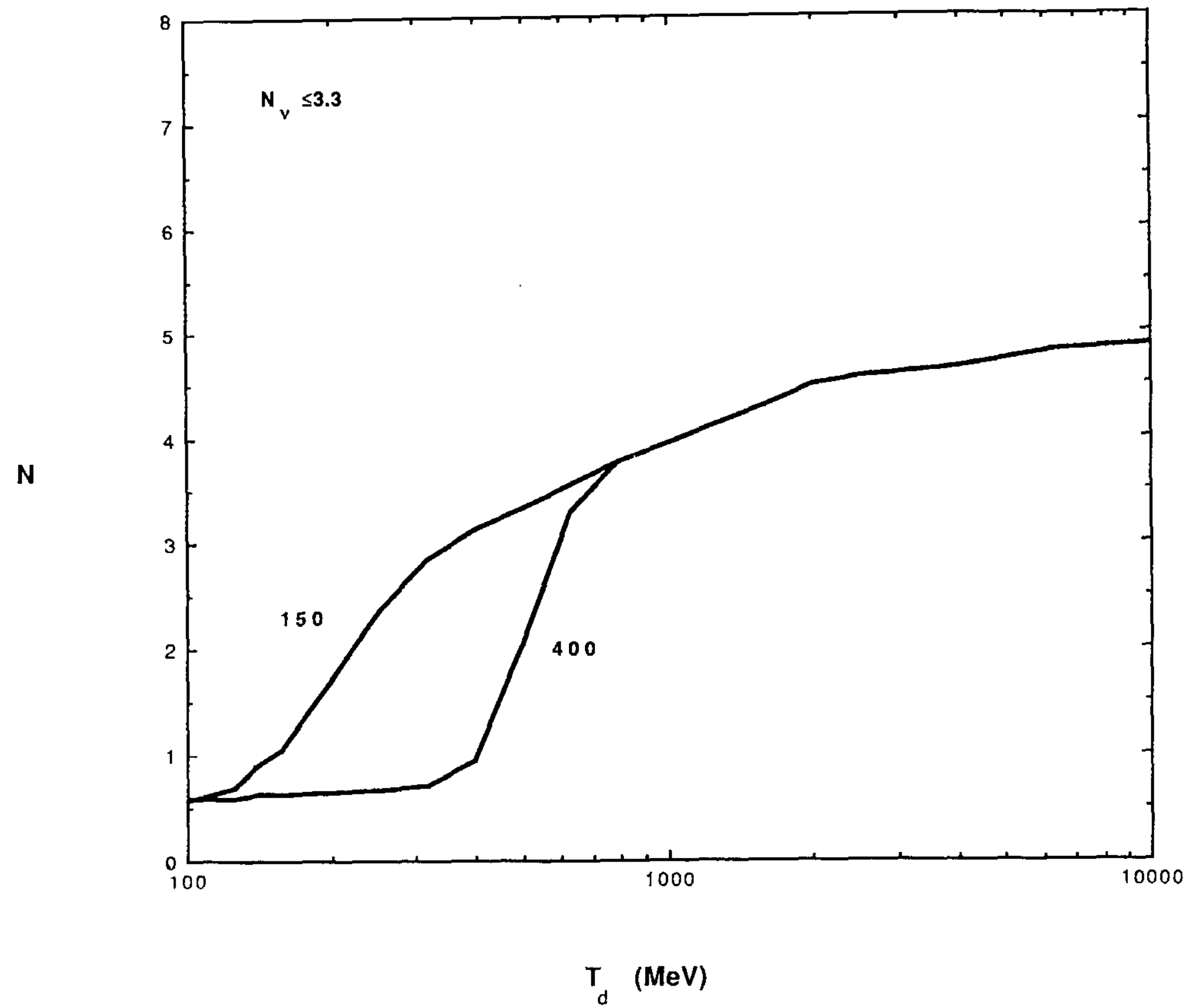


Fig. 15