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PRIMORDIAL NUCLEOSYNTHESIS: THE EFFECTS OF INJECTING HADRONS*

M.H. Reno
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

The standard big bang nucleosynthesis model (BBN) successfully predicts the light element abundances.[1] By including extra exotic particles that decay into hadrons during the time of nucleosynthesis, the standard scenario is changed. Limits on the light element abundances therefore restrict the abundance of exotic particles as a function of their lifetime. The limits described here rely on work done with D. Seckel and are described in more detail in Ref. 2. The essential ingredient in our analysis is that the hadronic decay products interact with the ambient neutrons and protons during the nucleosynthesis era, inducing a net increase in the number of neutrons and therefore increase the ^{4}He, ^{3}He and deuterium (D) abundances.

The results presented below are for exotic particle X with lifetimes $\tau_X = 0.1 - 10^4$ sec. The standard nucleosynthesis parameters are set to: neutron lifetime, $\tau_n = 900$ sec, the number of neutrinos equals three, and the baryon-to-photon ratio, $\eta > 3 \cdot 10^{-10}$.

To describe the effect, consider X particles with mass of 100 GeV. In general, at least some of the time, X decays into p, $\bar{p}$, n, $\bar{n}$, mesons and short-lived baryons. For the moment, consider just the nucleon-anti-nucleon "injections" from X decays with $\tau_X = 1$ sec, that is, the temperature of the Universe of about 1 MeV. At this temperature, the Universe is radiation dominated, so injected nucleons thermalize from scattering with photons, and thermalization times are essentially instantaneous. The stopped antibaryons then annihilate with ambient neutrons and protons:

$$(n\bar{n}) + n \to n + \pi + \ \ldots \to n$$
$$(n\bar{n}) + p \to n + \ \ldots$$
$$(p\bar{p}) + n \to p + \ \ldots$$
$$(p\bar{p}) + p \to p + \ \ldots$$

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where the injected pairs are indicated by parentheses. Taking equal cross sections for nucleon-anti-nucleon annihilation, regardless of charge, the rate for $n \to p$ conversion and $p \to n$ conversion depends on the target particle densities. Because at $T < 1$ MeV, $n(n) < n(p)$ the rates $\Gamma(n \to p) < \Gamma(p \to n)$, so $(n/p) > (n/p)^o$, where the superscript indicates the ratio of number densities in the standard BBN scenario. As the density of X increases, for X decays in the allowed lifetime range, the neutron to proton ratio increases, eventually leading to an overproduction of ^{4}He, ^{3}He, and D.

To limit the X abundance, we assumed the primordial light element abundances[3] of Y, the relative ^{4}He abundance by mass, of $Y < 0.26$, and $X(\mathrm{D}) \geq 10^{-5}$ with $X(\mathrm{D}) + X(^3\mathrm{He}) \leq 10^{-4}$.

We use the Wagoner nucleosynthesis code[4] with appropriate modifications. In addition to including the energy and entropy density due to X and its decay, we add terms to the rate for n to p conversion and p to n conversion that depend on the $\bar{p}$, $\bar{n}$ and injected meson interaction rates with nucleons. They also depend on the particle multiplicities from the X decays.[5] We assume that injected hadrons are stopped before they interact with nucleons, and we neglect hadrons produced from annihilations of injected particles with ambient nucleons. Photofission of light elements is unimportant before 10^4 sec, because D is efficiently reformed, so we do not explicitly include photofission processes. Furthermore, we do not include ^{4}He fission induced by fast neutrons or antiparticles.

Fig. 1 shows our results for the limit on the X abundance scaled by the entropy density s and a factor F (which equals unity for a 100 GeV X particle which decays into 2 quarks and one lepton with a branching ratio of one) as a function of lifetime for $\eta = 3 \cdot 10^{-10}$ using just the ^{4}He limits. The D limits are included in Fig. 2 for $\eta = (3, 10) \cdot 10^{-10}$.

We can apply these results to the case of decaying gravitinos (Fig. 3) and decaying photinos in theories where R-parity is violated (Fig. 4). In Fig. 3, our results appear as the lower solid line. The work of Dominguez-Tenreiro[6] is in contradiction with ours at short lifetimes, even when we rescale our limits to account for different input parameters (dashed line). For decaying photinos, we can exclude a large region of $(m_{\tilde{\gamma}} - \tau_{\tilde{\gamma}})$ parameter space. The limits are dependent on $m_{\tilde{f}}$, the mass of the particle exchanged in $\tilde{\gamma} - \tilde{\gamma}$ annihilation.

We have also examined the case where there is a net baryon number in the final state of X decays, and we find that there are special circumstances in which $\Omega_B = 1$, however, they require that X always decay into a proton (plus the usual hadrons above). The consequences of cold dark matter annihations for the neutron-to-proton ratio and the light element abundances are also discussed in Ref. 2.

REFERENCES

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2. M. H. Reno and D. Seckel, *Phys. Rev.* **D38**, 3441 (1988).
3. For a review of the limits, see, e.g., J. Yang, M. S. Turner, G. Steigman, D. N. Schramm and K. A. Olive, *Ap. J.* **281**, 493 (1984);
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4. We have used L. Kawano's version of the Wagoner nucleosynthesis code. Details about the solution of the coupled differential equations appear in Ref. [1].
5. See Ref. [2] for details. The strong interaction cross sections come from low energy scattering experiments, and particle multiplicities are calculated in analogy with multiplicities in $e^+e^- \to 2$ jets.
6. R. Dominguez-Tenreiro, *Ap. J.* **313**, 523 (1987).

FIGURE CAPTIONS

1. Maximum values of $y_X F$ for $\eta = 3 \cdot 10^{-10}$ assuming that X decays into a final state with no net baryon number. The limits coming from just $\pi^\pm$, K^-, K_L, $p\bar{p}$ or $n\bar{n}$ are shown separately. The factor F is defined by $F = (N_{quarks} B_{hadronic})/2 \cdot \langle n_{ch}(E_{quark})\rangle \, / \, \langle n_{ch}(E = 33 \text{ GeV})\rangle$, and $y_X = n(X)/s$ for entropy density s. The charged particle multiplicity n_{ch} as a function of the quark energy is used to scale the particle multiplicities of hadrons in X decay final states.
2. Maximum values of $y_X F$ for $\eta = 3 \cdot 10^{-10}$ (solid line) and $\eta = 10^{-9}$ (dashed line) for final states with no net baryon number. The limits come from $Y \leq 0.26$ and $X(D) + X(^3He) \leq 10^{-4}$.
3. Maximum gravitino abundance $y_{\tilde{G}}$ versus lifetime. The bold line shows our result, and the other solid line indicates the limits from Dominguez-Tenreiro[6]. The dotted line is a rescaling of our limits to compare with the Dominguez-Tenreiro limits.
4. Mass versus lifetime for a decaying photino when $m_{\tilde{f}} = 50,\ 100,\ 250$ GeV.

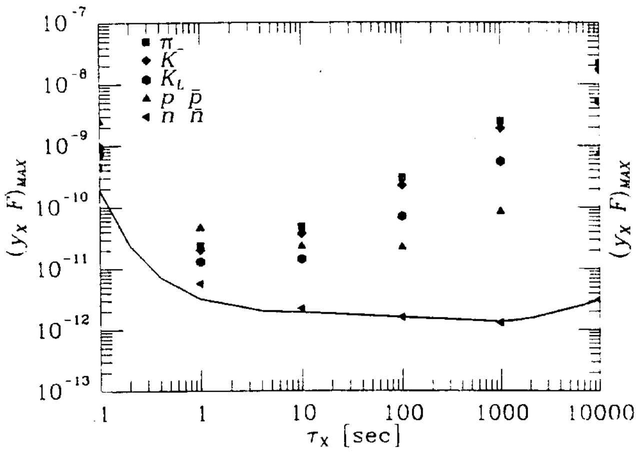

Figure 1.

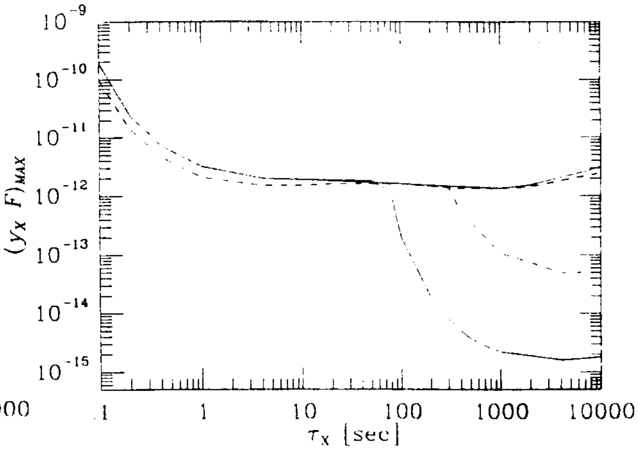

Figure 2.

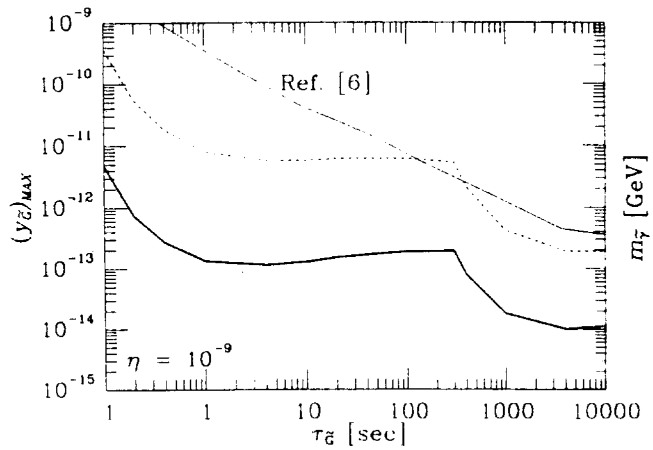

Figure 3.

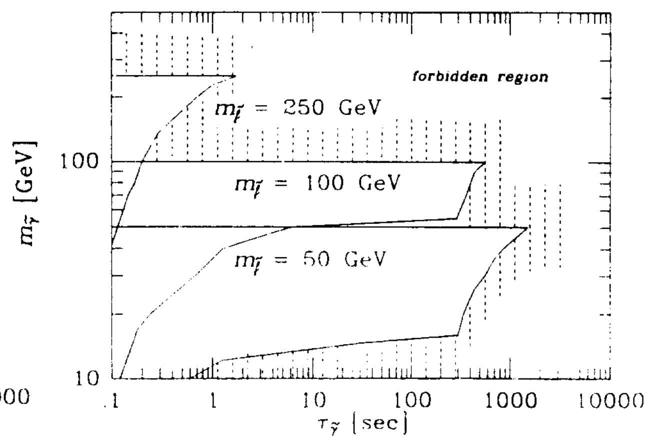

Figure 4.