Big Bang Nucleosynthesis: The Strong Nuclear Force meets the Weak Anthropic Principle

J. MacDonald and D.J. Mullan

Department of Physics and Astronomy, University of Delaware, DE 19716

(Dated: June 25, 2009)

Contrary to a common argument that a small increase in the strength of the strong force would lead to destruction of all hydrogen in the big bang due to binding of the diproton and the dineutron with a catastrophic impact on life as we know it, we show that provided the increase in strong force coupling constant is less than about 50% substantial amounts of hydrogen remain. The reason is that an increase in strong force strength leads to tighter binding of the deuteron, permitting nucleosynthesis to occur earlier in the big bang at higher temperature than in the standard big bang. Photodestruction of the less tightly bound diproton and dineutron delays their production to after the bulk of nucleosynthesis is complete. The decay of the diproton can, however, lead to relatively large abundances of deuterium.

PACS numbers: 26.35.+c,98.80.Bp

I. INTRODUCTION

The weak anthropic principle has often been used to infer limits on the range of the strong force strength or coupling parameters consistent with life as we know it. A common argument is that a small increase of the strong force strength will bind the dineutron and the diproton, leading to a large increase in the rate of the p+p and n+n reactions, so that big-bang nucleosynthesis (BBN) leads to all the protons being converted into isotopes of helium, leaving no hydrogen necessary for chemistry vital to life. For example, Dyson [1] writes "If a helium-2 nucleus could exist, the proton proton reaction would yield a helium-2 nucleus plus a photon, and the helium-2 nucleus would in turn spontaneously decay into a deuteron, a positron and a neutrino. As a consequence there would be no weak interaction hang-up, and essentially all of the hydrogen existing in the universe would have been burned to helium even before the first galaxies had started to condense." Barrow and Tipler [2] state on p322 of their book "If the strong interaction were a little stronger the diproton would be a stable bound state with catastrophic consequences all the hydrogen in the Universe would have been burnt to He2 during the early stages of the Big Bang and no hydrogen compounds or long-lived stable stars would exist today. If the diproton existed we would not!"

In this paper, we consider how BBN is altered by the existence of bound diproton and dineutron nuclei, taking into account some physical processes that so far have been overlooked. To relate the binding energies of the diproton, the dineutron and the deuteron to the relative strength of strong force, we use the same square well potential model as Barrow [2], who found that a 9% increase in the strong force coupling constant, $\alpha_s$, is sufficient to bind the dineutron and a 13% increase will bind the diproton. The needed increase in coupling constant to bind the diproton was confirmed by Pochet et al [4] for a more realistic nuclear potential. For small increases in $\alpha_s$, the diproton and dineutron binding energies are sufficiently small that photodestruction will prevent buildup of large amounts of these isotopes before freeze out occurs.

In section 2, we briefly review the physics of BBN relevant to our investigation of the effects of increased $\alpha_s$. In section 3 we describe how we determine the needed rates for reactions involving dineutrons and diprotons. Due to the electrostatic repulsion of the protons, there is a narrow range of strong force strength for which the dineutron is bound but the diproton is not. Nucleosynthesis in this regime is considered in section 4. In section 5, we consider the regime in which the diproton is also bound. Finally, in section 6 we give our conclusions.

II. BBN IN THE RADIATION DOMINATED ERA

In the standard hot big bang [5], nucleosynthesis takes place in the radiation dominated era that begins after electron pair annihilation is complete. At the beginning of this era the radiation and matter temperature is $\sim 4 \times 10^9$ K. Although the $p + n \rightarrow d + \gamma$ reaction is rapid, due to the relatively small binding energy of the deuteron, photodestruction prevents significant amounts of $^4$H being formed until the temperature has dropped to $\sim 10^9$ K. Further reactions continue, building up an appreciable amount of $^4$He and traces of other light elements, until freeze out occurs when the Universe is about 15 minutes old and has a temperature of $\sim 5 \times 10^8$ K. During the radiation era, the temperature varies with time, $t$, as

$$T_9 = 13.8 \ t^{-1/2}$$

where $T_9$ is the temperature in units of $10^9$ K and $t$ is measured in s. The baryonic density in g cm$^{-3}$ is ap-
proximately given by
\[ \rho = 3.3\ 10^4 \eta T_g^3 \] (2)
where \( \eta \) is the ratio of the number of baryons to the number of photons. To explore the effects of bound diproton and dineutron on BBN, we have written a computer program that includes all the important reactions \[ [16] \] plus a few more relevant to universes in which the diproton and dineutron are stable. Because the binding energy of the deuteron is increased when \( \alpha_s \) is increased, nucleosynthesis can begin at higher temperatures than for standard BBN. We have modified equations (1) and (2) to include conditions in the leptonic era. We take \( T_g = 50 \) as the initial temperature. The initial abundances of neutrinos and protons are set to their equilibrium values, with all other abundances set to zero. The value of \( \eta \) is taken to be \( 4 \ 10^{-10} \), which gives for the standard big bang good agreement with observed light element abundances. As a test of our code, we have compared our standard big bang nucleosynthesis results with those obtained with the public bigbang code (which can be downloaded from [http://cococubed.asu.edu/code_pages/net_bigbang.shtml](http://cococubed.asu.edu/code_pages/net_bigbang.shtml)).

III. ADOPTED RATES FOR REACTIONS FOR REACTIONS INVOLVING DINEUTRONS AND DIPROTONS

The production of diprotons and dineutrons in the big bang will depend on the competition for neutrons and protons between the \( p + p \rightarrow pp + \gamma \) and \( n + n \rightarrow nn + \gamma \) reactions and the \( p + n \rightarrow d + \gamma \) reaction. To determine the rates of the \( p + p \rightarrow pp + \gamma \) and \( n + n \rightarrow nn + \gamma \) reactions, we make use of known results for the \( p + p \rightarrow d + e^+ + \nu \) reaction. We assume that the intrinsically nuclear part of the interaction potential is the same for all three reactions. To account for the difference in rates of the \( p + p \rightarrow d + e^+ + \nu \) reaction in which the intermediate state experiences a weak decay and the two reactions in which the intermediate state decays electromagnetically, we introduce a factor \( f_{w-e} \). Using the \( p + p \) S-factor \[ [8] \], a straightforward integration for the \( n + n \rightarrow nn + \gamma \) reaction gives for the reaction rate per particle in cm\(^3\) mol\(^{-1}\) s\(^{-1}\)
\[ N_A(\sigma v) = f_{w-e} 10^{-15}(1.78 + 1.80T_g + 1.99T_g^2)/T_g^{1/2} \] (3)
For the rate of the \( p + p \rightarrow pp + \gamma \) reaction, we simply multiply the \( p + p \rightarrow d + e^+ + \nu \) rate by \( f_{w-e} \).
\[ N_A(\sigma v) = f_{w-e} 10^{-15}(4.08 + 15.6T_g + 6.16T_g^2 + 0.588T_g^3 - 0.0465T_g^4)e^{-3.381/T_g^{1/3}}/T_g^{3/2} \] (4)
At first sight it might be thought that \( f_{w-e} \) could simply be obtained from consideration of the \( p + n \rightarrow d + \gamma \) reaction. However the comparison is complicated by the effects of nucleon spin on the nuclear interaction. The stability of the deuteron is a result of the nuclear force being stronger when the nucleons have parallel spin than when the spins are opposite. The Pauli exclusion principle requires that the nucleons in the diproton and dineutron have opposite spin. We can roughly estimate \( f_{w-e} \) by considering the nuclear S-factors for similar reactions. For example, comparing \( S_0 = 2.5 \ 10^{-4} \) KeV barn for \( d(p, \gamma)^3\)He with \( S_0 = 3.8 \ 10^{-22} \) KeV barn for \( p(p, \beta^+ \nu)d \) \[ [8] \] indicates that \( f_{w-e} \sim 10^{18} \). The nuclei in this reaction do not have the same spins as the nuclei in the reactions of interest. However a similar result is obtained by considering a reaction with the correct spins, \( ^{13}\)N\(+p \rightarrow ^{14}\)O\(+\gamma \). The non-resonant contribution to this reaction has \( S_0 \sim 3 \ 10^{-4} \) KeV barn \[ [8] \]. In figure 1, we plot the ratios \( \langle \sigma v \rangle_{np}/\langle \sigma v \rangle_{nn} \) and \( \langle \sigma v \rangle_{np}/\langle \sigma v \rangle_{pp} \) against \( T_g \) for the case in which a value of \( 10^{18} \) is adopted for \( f_{w-e} \). For the \( p + n \rightarrow d + \gamma \) reaction rate, we have used \[ [10] \]

\[ N_A(\sigma v) = 4.42 \ 10^4(1.0 + 3.75T_g + 1.93T_g^2 + 0.747T_g^3 + 0.0197T_g^4 + 3.00491 \ 10^{-6}T_g^5)/\]
\[ (1.0 + 5.47T_g + 5.62T_g^2 + 0.489T_g^3 + 7.47 \ 10^{-3}T_g^4) \] (5)
We see that at temperatures relevant to BBN, dineutron and diproton production will not be important unless \( f_{w-e} \gtrsim 10^{18} \). Because of the uncertainties involved in estimating \( f_{w-e} \), in the following we consider a range of \( f_{w-e} \) values.

The dineutron and diproton production will also depend on the rates of the reverse reactions \( pp + \gamma \rightarrow p + p \) and \( nn + \gamma \rightarrow n + n \). For small increases in the strength of the strong force coupling constant, the binding energies of dineutron and diproton will be of order \( kT \) during the nucleosynthesis phase of the big bang. Hence, the threshold value of \( E_p/kT \), where \( E_p \) is the photon energy, is not large compared to unity, and the usual approximation that the reverse rate is the forward rate multiplied by a factor
\[ \frac{\lambda}{N_A(\sigma v)} = 7.07 \ 10^9 T_g^{3/2} e^{-Q/kT} \] (6)
cannot be used indiscriminately. Although the rate of the \( nn + \gamma \rightarrow n + n \) reaction can be evaluated analytically in terms of Debye functions, we find it simpler to evaluate
FIG. 1: Dependence of the ratios \( \langle \sigma v \rangle_{np}/\langle \sigma v \rangle_{nn} \) and \( \langle \sigma v \rangle_{np}/\langle \sigma v \rangle_{pp} \) on temperature in units of \( 10^{9} \) K for \( f_{w-e} = 10^{18} \). This rate numerically, together with the \( pp + \gamma \rightarrow p + p \) reaction rate. For a binding energy \( Q = 150 \text{ keV} \), we find that the above approximation underestimates the reverse rate by only 13% at \( T_{9} = 4 \). We determine a correction to the approximate rate by multiplying it by a factor of form \( 1/(1 + a_{1}q + a_{2}q^{2} + a_{3}q^{3}) \) where \( q = e^{-Q/kT} \). The coefficients \( a_{1}, a_{2}, a_{3} \) are found by fitting to the numerical results. An important consequence of an increase in \( \alpha_{s} \) is that the binding energy of the deuteron will also be increased. This will reduce its photodestruction rate and allow \(^2\text{H} \) production to occur at higher temperature than in the standard big bang. We take this increase in the deuteron binding energy, \( Q_{d} \) into account in calculating the photodestruction rate of \(^2\text{H} \).

We now consider the rates of leptonic transformations between dineutrons, diprotons and deuterons. For small binding energies, we expect the time for dineutron decay to be comparable to that of the neutron. Similarly, since the proton is stable, the lifetime of the diproton is likely to be quite long. A comparison with the leptonic rates between \( n \) and \( p \) [11] indicates that the enhancements of the overall rates, including electron capture, at BBN temperatures will be modest and hence for simplicity we neglect these enhancements. To estimate the weak rates, we use the \( ft \) factors for the corresponding transitions in the beta decays of the analog nuclei \(^{14}\text{O} \) and \(^{14}\text{C} \).

The major \(^{14}\text{O} \) decay channel is to an excited \( J^{\pi} = 0^{+} \) state \( 2.313 \text{ MeV} \) above the ground state of \(^{14}\text{N} \) (99.3%, log \( ft \) = 3.4825). This is analogous to diproton decay to the spin singlet state of \(^2\text{H} \). There are also decays to the \( 1^{+} \) ground state (log \( ft \) = 7.279) and to a \( 1^{+} \) excited state at 3.948 MeV (log \( ft \) = 3.131). We have calculated the Fermi integrals with the relativistic form of the Fermi factor for the two higher energy decay channels which correspond to those of the diproton. For the diproton decay channel corresponding to the dominant \(^{14}\text{O} \) decay, we find that an accurate approximation to the decay time scale is

\[
\log t_{1/2} = 3.490 - 5 \log E_{+}
\]
where the maximum positron kinetic energy measured in MeV is, in terms of binding energies,

$$E_+ = Q_{nn} - Q_{pp} - (m_n - m_p) - m_e = Q_{nn} - Q_{pp} - 1.8043.$$  \hspace{1cm} (10)

For the decay to the ground state

$$\log t_{1/2} = 7.287 - 5 \log E_+$$  \hspace{1cm} (11)

where now

$$E_+ = Q_D - Q_{pp} - (m_n - m_p) - m_e = Q_D - Q_{pp} - 1.8043.$$  \hspace{1cm} (12)

The analog of the dineutron, $^{14}$C, decays only to the ground state of $^{14}$N with half-life $t_{1/2} = 1.8 \times 10^{11}$ s ($\log ft = 9.040$). We find that the half-life for the corresponding dineutron decay is approximately related to the maximum electron kinetic energy in MeV by

$$t_{1/2} = (63/E_-)^5$$  \hspace{1cm} (13)

where

$$E_- = Q_D - Q_{nn} - (m_n - m_p - m_e) = Q_D - Q_{nn} - 0.7823.$$  \hspace{1cm} (14)

Since we expect the dineutron will also have a decay channel to the $0^+$ excited state of $^2$H (which will exist if the dineutron is bound), we use for this channel the $ft$ factor for the corresponding transition in $^{14}$O. The energy difference between the dineutron and the $^2$H singlet state will always be about the difference in mass of the neutron and proton, 1.3 MeV, and the $f$-factor will then be about 1.8, which gives $t_{1/2} = 1.5 \times 10^3$ s. Combining the rates for the two decay channels gives

$$\lambda_{nn} = 4.62 \times 10^{-4} + (E_-/58.5)^5.$$  \hspace{1cm} (15)

The resulting decay time scales, $\lambda^{-1}$, are plotted against $G$ in figure 3.

Finally, we need to also consider additional reactions that arise when the diproton and dineutron are bound. The most rapid reactions are likely to be $pp + n \rightarrow d + p$ and $nn + p \rightarrow d + n$. Due to the complexity of calculating reaction rates even for few nucleon systems (see for example Marcucci et al. \cite{12}), we settle for estimating when these two reactions are likely to be important by comparing the results of calculations in which these reactions are completely neglected with the results of calculations in which they are assumed to be instantaneous.

**IV. THE $n+n \rightarrow nn$ REACTION REGIME**

Due to the electrostatic repulsion of the protons, there is a narrow range of strong force strength for which the dineutron is bound but the diproton is not. According to the square well potential model, this range is $1.043 < G < 1.063$. The dineutron binding energy in this regime is $Q_{nn} = 0 - 14$ KeV. The relevant new reactions for BBN are $n+n \rightarrow nn + \gamma$, $nn + \gamma \rightarrow n+n$ and $nn \rightarrow d + e^- + \bar{\nu}$.

In figure 4, we show for $G = 1.06$ how the final mass fractions of $^1$H, $^4$He and the dineutron depend on $f_{w-e}$ when only the $n + n \rightarrow nn + \gamma$ reaction is included. We see that there is no significant production of dineutrons unless $f_{w-e} \gtrsim 10^{15}$. Also the H abundance increases with $f_{w-e}$ because the $n + n \rightarrow nn + \gamma$ reaction removes the neutrons before the $n + p \rightarrow d + e^+ + \nu$ reaction can take place.

In figure 5, we show the final dineutron abundance when the $nn + \gamma \rightarrow n + n$ reaction is also included for different values of $G$. Dineutron production is small unless its binding energy is comparable to that of the deuteron. Otherwise, the neutrons are removed by proton capture before significant amounts of dineutron can be produced. For values of $G$ large enough to give the dineutron a binding energy greater than 2 MeV, the diproton would certainly be bound.

The $n+n \rightarrow nn + \gamma$ reaction could lead to significant production of $^2$H if the dineutron leptonic decay occurs more quickly than its photodestruction. In figure 6, we show how the final mass fraction of $^1$H depends on the time scale of the $nn \rightarrow d + e^- + \bar{\nu}$ reaction for $G = 1.06$. In order to have significant dineutron production to occur, we have set $f_{w-e} = 10^{20}$. We see that, if fast enough, the leptonic decay increases the hydrogen abundance. This is because the set of reactions

$$n + n \rightarrow nn + \gamma$$

$$nn \rightarrow d + e^- + \bar{\nu}$$

$$d + \gamma \rightarrow n + p$$

will always be about the difference in mass of the neutron and proton.

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{figure3.png}
\caption{Dependence of the dineutron and diproton beta decay life times in seconds on the relative strong charge $G$.}
\end{figure}
FIG. 4: Final mass fractions of $^1$H (solid line), $^4$He (long dash line) and dineutron (short dash line) when only the $n+n \rightarrow nn$ reaction is included.

FIG. 5: Final abundance of dineutron for $G$ values from bottom to top of 1.25, 1.50, 1.75 and 2.00.

FIG. 6: Dependence of hydrogen final abundance for $G = 1.06$ on dineutron life time (in s).

conversion a neutron into a proton. For this to happen, the dineutron decay must occur on a time scale of $10^{-12}$ s or less, which is much less than the estimate above, $\tau_{nn} \sim 10^3$ s. Hence it is unlikely that this set of reactions is important.

Finally we consider the effects of the $nn + p \rightarrow d + n$ reaction. To gauge the importance of this reaction, we assume that it is instantaneous. The final mass fractions of $^1$H, $^4$He are shown in figure 7, again for $G = 1.06$. We see that this reaction leads to small reductions in the H abundance for $f_{w-e} > 10^{19}$. Hence this reaction does not have a major effect on BBN when only the dineutron is bound.

To summarize the results presented in this section, we find that for values of the strong force coupling constant at which the dineutron is bound and the diproton is unbound, there are no catastrophic impacts on BBN.

V. THE p+p $\rightarrow$ pp REGIME

For $G > 1.065$ both the diproton and the dineutron are bound. Increased $G$ also binds the deuteron more tightly, allowing it to be formed earlier in the big bang at higher temperatures, where the less tightly bound diproton and dineutron are easily destroyed by energetic photons. We first consider only the effects of increased $G$ on deuteron binding by setting $f_{w-e} = 0$. Figure 8 shows how the final hydrogen and helium abundances depend on $G$. In the standard big bang $^2$H production begins when the temperature has dropped to about $10^9$ K. For $G \gtrsim 1.2$, $Q_d$ is high enough that $^2$H production begins in the leptonic era. The final $^1$H abundance is then approximately the difference in the equilibrium proton and neutron abundances at the temperature at which photodestruction of $^2$H becomes unimportant.

When $f_{w-e} > 0$, if diproton production occurs it does so long after the primordial neutrons have been consumed
FIG. 7: $^1$H and $^4$He mass fractions when the $nn + p \rightarrow d + n$ reaction is included.

FIG. 8: Dependence of the final abundances of H (solid line) and $^4$He (broken line) on $G$ in the absence of production of dineutrons and diprotons.

in the reactions that lead to $^4$He. Hence essentially no dineutrons are produced. The amount of additional $^4$He produced depends on the temperature at which diproton production occurs. If the diproton is lightly bound the temperature will be too low for further nuclear processing except for the decay to $^2$H. If the diproton is tightly bound the temperature can be high enough for further nuclear processing to $^4$He. In either case diproton production does further reduce the hydrogen abundance.

The second phase of $^4$He production occurs only if

$$f_{w-e} \gtrsim \frac{10^{14}}{(G - 1.113)^{13/3}}$$

A typical situation is shown in figure 9. Here $G = 1.3$ and $f_{w-e} = 10^{18}$. Initially weak interactions convert neutrons to protons. When the Universe is 2 s old the temperature is $8 \times 10^9$ K, which for $Q_d = 16$ MeV is low enough for $^2$H production to occur. The $^2$H is quickly converted to $^4$He, so that by age 10 s, this initial phase of nucleosynthesis has finished. A second phase of nucleosynthesis occurs at age 500 s, when the temperature, $T = 6 \times 10^8$ K, is low enough for production of diprotons, which have a binding energy of 1.8 MeV. The beta decay life time of the diproton is 100 s, and hence diprotons decay to $^2$H before significant cooling by expansion occurs. The temperature is sufficiently high that the $^2$H is converted to $^4$He. If the diproton binding energy was lower, then diproton production would occur at lower temperature and only $^2$H would be made in the second phase of nucleosynthesis. Note the small amount of neutrons released in the second phase of nucleosynthesis. These are produced by the reaction sequence $d + d \rightarrow t + p$, followed by $t + t \rightarrow ^4He + n + n$.

The dependence of the final value of $X_H$ on $G$ is shown in Figure 10 for different values of $f_{w-e}$, ranging from $10^{15}$ to $10^{23}$. The value of $f_{w-e}$ at which $X_H$ is significantly reduced decreases with increasing $G$, due to the
tightly binding of diproton reducing its rate of photodestruction. Figure 11 shows how the final value of the $^2\text{H}$ abundance depends on $G$ for the same range of $f_{w-e}$. Clearly a major difference from standard BBN is in the amount of $^2\text{H}$ that can be produced when the diproton is bound. To understand why consider the specific case $G = 1.2$. The binding energy of $^2\text{H}$ is then about 10 MeV which means that it can be produced very early on in the big bang. Subsequent reactions reduce the $^2\text{H}$ abundance by making $^3\text{He}$ and $^4\text{He}$. Most of the $^4\text{He}$ is produced very quickly (90% is produced by $t = 8\text{ s}$). On the other hand, the binding energy of the diproton is relatively small, 0.7 MeV. Hence the temperature must drop to about $1.4 \times 10^9\text{ K}$ before significant production can begin. This occurs at $t = 100\text{ s}$. The diproton beta-decay life time is about $10^3\text{ s}$. Hence the diproton abundance increases during the first few thousand seconds, and then it decays to $^2\text{H}$. The temperature ($< 3 \times 10^8\text{ K}$) is now too low for further reactions involving destruction of $^2\text{H}$. Hence, depending on the value of $f_{w-e}$, significant amounts of $^2\text{H}$ can be produced.

Figure 12 shows the dependence of the final $^4\text{He}$ abundance on $G$ for a range of $f_{w-e}$ values. It can be seen that there are many combinations of $G$ and $f_{w-e}$ for which complete conversion to $^4\text{He}$ does not occur.

For $f_{w-e} = 10^{18}$ the final $\text{H}$ abundance is greater than 10% of the standard value for $G < 1.5$. Hence significant amounts of $\text{H}$ remain even when the strong force coupling constant is 50% greater than the current value. In general, the final $\text{H}$ abundance is greater than 0.075 provided $f_{w-e} < 6 \times 10^{15}/(G - 1.065)^6$. 

FIG. 10: Dependence of the final hydrogen abundance on $G$ for different values of $f_{w-e}$ ranging from $10^{15}$ at top to $10^{23}$ at bottom.

FIG. 11: Dependence of the final $^2\text{H}$ abundance on $G$ for different values of $f_{w-e}$. The thin line is for $f_{w-e} = 0$. The thick lines are for $f_{w-e}$ ranging from $10^{15}$ (bottom) to $10^{23}$ (top).

FIG. 12: Dependence of the final $^4\text{He}$ abundance on $G$ for different values of $f_{w-e}$ ranging from $10^{16}$ (bottom) to $10^{23}$ (top).
We now consider inclusion of $pp + n \to d + p$ and $nn + p \to d + n$ as instantaneous reactions. In general these reactions have small effects on the final abundances, primarily because most of the neutrons have been depleted by the $p + n$ reaction before the temperature has dropped sufficiently for diproton and dineutron production to occur. A small amount of neutrons are produced during the second phase of nucleosynthesis by the $p + p \to pp + \gamma$, $pp \to d + e^+ + \nu$, $d + d \to t + p$, $t + t \to ^4He + n + n$ sequence of reactions. These neutrons can then react by $n + pp \to d + p$. The net result is a small increase in the final H abundance. Also since the $n + pp \to d + p$ reaction is assumed instantaneous, $^2H$ is produced earlier than by diproton decay alone. Provided the temperature is high enough, this leads to a decrease in the final $^2H$ abundance.

Figure 13 summarizes the results of this section. The thicker of the solid lines is the contour on which the final H mass fraction is 0.075. The thinner solid line is the contour for final H mass fraction equal to 0.375, which is approximately half the standard BBN value. The broken lines are contours on which the final $^2H$ mass fraction is 0.001. The thin solid line is the second $^4He$ production phase boundary. Below and to the left of this line the second phase does not occur.

VI. CONCLUSIONS

We have addressed some aspects of the effects of larger than standard values for the strong force coupling constant on nucleosynthesis during the hot big bang. For relative strong charge $G > 1.065$, both the diproton and dineutron are bound. We have estimated the beta-decay time scales from the $ft$ factors for the analog nuclei $^{14}O$ and $^{14}C$. Assuming that the rate of the reaction $p + p \to pp + \gamma$ can be parameterized by multiplying the rate of the reaction $p + p \to d + e^+ + \nu$ by a factor $f_{w-e}$, and that the rate of the reaction $n + n \to nn + \gamma$ is then related to that for the reaction $p + p \to pp + \gamma$ by neglecting the Coulomb repulsion, we find that significant amounts of H remain provided $f_{w-e} < 6 \times 10^{15}/(G - 1.065)^6$. By comparing similar reactions, we estimate that $f_{w-e} \sim 10^{18}$, which gives a corresponding limit of $G < 1.5$. The primary reason for the survival of hydrogen is that the diproton and dineutron are always less tightly bound than the deuteron, which is a consequence of the spin-dependent part of the nuclear force. Photodestruction reactions prevent buildup of diprotons and dineutrons before the neutrons are depleted by deuteron formation. Diprotons can be formed once the temperature has dropped sufficiently. These diprotons are converted to deuterons mainly by beta decay with possibly a contribution from the $pp + n \to d + p$ reaction. This can lead to much a larger $^2H$ abundance than in the standard BBN.

Our main result is that the existence of bound diproton and dineutron nuclei does not necessarily lead to complete conversion of hydrogen to helium in the big bang. Instead there are parameter ranges for which significant amounts of hydrogen remain. We estimate for reasonable values of the factor by which the $p + p \to pp + \gamma$ rate is enhanced relative to the $p + p \to d + e^+ + \nu$ rate, the final hydrogen abundance is greater than 50% of the standard BBN value for increases in the strong force coupling constant less than about 50%. Anthropic limits on the strong force strength from BBN are indeed weak.

Acknowledgments

We thank Stuart Pittel, David Seckel and Stephen Barr for enlightening discussions. This research was supported in part by a grant from the Mount Cuba Astronomical Foundation.

[1] F. J. Dyson, Scientific American 225, 50 (1971).
[2] J. D. Barrow and F. J. Tipler, The anthropic cosmological
principle (1986).
[3] J. D. Barrow, Phys. Rev. D 35, 1805 (1987).
[4] T. Pochet, J. M. Pearson, G. Beaudet, and H. Reeves, Astronomy and Astrophysics 243, 1 (1991).
[5] E. R. Harrison, Annual Review of Astronomy and Astrophysics 11, 155 (1973).
[6] P. J. E. Peebles, Astrophys. J. 146, 542 (1966).
[7] R. V. Wagoner, W. A. Fowler, and F. Hoyle, Astrophys. J. 148, 3 (1967).
[8] C. Angulo, M. Arnould, M. Rayet, P. Descouvemont, D. Baye, C. Leclercq-Willain, A. Coc, S. Barhoumi, P. Aguer, C. Rolfs, et al., Nuclear Physics A 656, 3 (1999).
[9] D. D. Clayton, Principles of stellar evolution and nucleosynthesis (1968).
[10] S. Ando, R. H. Cyburt, S. W. Hong, and C. H. Hyun, Phys. Rev. C 74, 025809 (2006), arXiv:nucl-th/0511074.
[11] T. Oda, M. Hino, K. Muto, M. Takahara, and K. Sato, Atomic Data and Nuclear Data Tables 56, 231 (1994).
[12] L. E. Marcucci, K. M. Nollett, R. Schiavilla, and R. B. Wiringa, Nuclear Physics A 777, 111 (2006), arXiv:nucl-th/0402078.