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# RADIATIVE ALPHA-CAPTURE RATES LEADING TO $A = 7$ NUCLEI: APPLICATIONS TO THE SOLAR NEUTRINO PROBLEM AND BIG BANG NUCLEOSYNTHESIS

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## ABSTRACT

Recent resonating group calculations provide a good description of the cross sections for the radiative capture reactions $^3He(\alpha, \gamma)^7Be$ and $^3H(\alpha, \gamma)^7Li$. We have reviewed the available experimental data for these reactions and extrapolated them to zero energy by normalizing to the resonating group results in a consistent way; recommended reaction rates as a function of temperature are obtained. From these $(\alpha, \gamma)$ rates and a survey of other nuclear reactions that influence the production of solar neutrinos, we conclude that remaining uncertainties in the nuclear reaction rates are not a likely explanation of the low observed detection rate in the $^{37}Cl$ solar neutrino detector. We also find that the reaction rates are sufficiently accurate to predict big bang production of $^7Li$ within $\pm 35\%$ at all relevant densities and to obtain both upper and lower bounds on the universal mass density from the observed $^7Li$ abundance.

*Subject headings:* neutrinos — nuclear reactions — nucleosynthesis — Sun: interior

## I. INTRODUCTION

Rates for the radiative capture of alpha particles by $^3He$ and $^3H$ are important in astrophysics. One application is to the solar neutrino problem: that only about one-third of the expected number of events is observed in a detector sensitive mainly to the high-energy neutrinos from decay of $^8B$ produced in the Sun (Davis, Harmer, and Hoffman 1968; Davis, Cleveland, and Rowley 1984). Since the solar production of $^8B$ neutrinos depends strongly on the rate of the $^3He(\alpha, \gamma)^7Be$ reaction, a new measurement of this cross section (Kräwinkel *et al.* 1982) that gave results nearly a factor of 2 smaller than previously found (Parker and Kavanagh 1963; Nagatani, Dwarakanath, and Ashery 1969) raised hopes that the origin of the solar neutrino problem might lie in poorly known nuclear reaction rates. Although subsequent experiments (Robertson *et al.* 1983; Osborne *et al.* 1982, 1984; Volk *et al.* 1983; Alexander *et al.* 1984) did not confirm this result, accurate estimates of the $^3He(\alpha, \gamma)^7Be$ rate remain important for understanding the solar neutrino problem.

Another important application concerns nucleosynthesis in the big bang expansion: production of primeval $^7Li$ is mediated by the $^3H(\alpha, \gamma)^7Li$ reaction at lower densities and by the $^3He(\alpha, \gamma)^7Be$ reaction followed by electron capture at higher densities. Recent measurements (Spite and Spite 1982*a*, *b*; Spite, Maillard, and Spite 1984) of the $^7Li$ abundance in very old stars may provide an estimate of the primeval abundance of $^7Li$ and permit its use, in conjunction with calculations of big bang nucleosynthesis, to provide an independent measurement (Spite and Spite 1982*a*, *b*; Yang *et al.* 1984; Austin and King 1977; Austin 1981) of the universal baryon density. Reliable values of the reaction rates for both of the radiative capture reactions discussed here, and for the $^7Li(p, \alpha)^4He$ reaction, which destroys $^7Li$, are necessary (Yang *et al.* 1984) for estimates of nucleosynthesis in the context of the standard big bang (Austin 1981; Wagoner 1973).

Experimental values of the reaction rates are based on extrapolation to low energy of the experimental data as represented by the $S$-factor:

$$S(E) = \sigma E e^{+2\pi\eta} . \quad (1)$$

Here $\sigma$ is the cross section and $\eta$ is the Sommerfeld parameter. The extrapolation is made by normalizing an assumed excitation function for $S$ to the data. For $^3H(\alpha, \gamma)^7Li$, $S$ has previously been assumed to be independent of energy, and for $^3He(\alpha, \gamma)^7Be$ the theoretical excitation function of Tombrello and Parker (1963) has been used. Although Tombrello and Parker's theory describes the energy dependence of the $S$-factor reasonably well, more detailed calculations (Kajino and Arima 1984*a*, *b*; Kajino 1985*a*, *b*, 1986; Walliser, Kanada, and Tang 1984; Langanke 1986) now give a reliable description of the data, both in shape and in magnitude, and it would seem a better strategy to fit the experimental results to these new calculations. It is the purpose of this paper to determine best values of these $(\alpha, \gamma)$ reaction rates in a form suitable for astrophysical calculations and to examine their implications for solar neutrino production and for $^7Li$ production in the big bang expansion.

In § II we discuss the recent theoretical calculations of Kajino and Arima (1984*a*) and the results of fitting them to the experimental data. Values of the reaction rates as a function of temperature are then compared to the earlier results. In § III we consider the solar neutrino problem. Following a survey of the reaction rates to which solar neutrino production is sensitive, recommended rates for these reactions are presented. These new rates lead to a significantly more accurate prediction of solar neutrino production and to a decrease in the



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predicted event rate in the $^{37}$Cl detector. But the observed rate is smaller than the calculation by a factor of 3–4, so the problem persists. In § IV we consider big bang nucleosynthesis of $^7$Li and the other light elements. After a review of the important reaction rates we find that $^7$Li production can be predicted reliably. Comparing this prediction with new measurements of the $^7$Li abundance in very old stars yields *both upper and lower bounds* on the universal baryon density. Predictions for the ratio of the $^7$Li and deuterium abundances, when compared with the data for this ratio, yield an upper limit on the density which may be less dependent on stellar processing. In § V, we summarize the results.

## II. THEORY

The theoretical calculations discussed here are based on the resonating group method (RGM), which accounts for the important alpha-particle–like correlation among nucleons in light nuclei; in addition, the bound states and scattering states of clusters are treated in a uniform way. The power and the technique of the RGM are demonstrated by Ikeda and Tamagaki (1977) and Ikeda *et al.* (1980).

The RGM wave function of the $A = 7$ system contains the internal wave functions of the two clusters $\phi_\alpha$ and $\phi_\tau$ describing $^4$He and $^3$He or $^3$H, and the intercluster relative wave function $\chi$. Its form is

$$\langle \xi_\alpha \xi_\tau \boldsymbol{r} | \Psi \rangle = A[\phi_\alpha(\xi_\alpha)\phi_\tau(\xi_\tau)\chi(\boldsymbol{r})] . \tag{2}$$

Here $\xi_\alpha$ and $\xi_\tau$ are the internal coordinates of the $\alpha$ cluster and the $A = 3$ cluster, $\boldsymbol{r}$ is the intercluster distance, and the antisymmetrizer $A$ handles the antisymmetrization of all coordinates. The unknown function $\chi(\boldsymbol{r})$ is obtained by the variational requirement

$$\delta\langle \Psi | H | \Psi \rangle / \langle \Psi | \Psi \rangle = 0 , \tag{3}$$

which leads to the integro-differential RGM equation of motion for $\chi$. After removing the center-of-mass energy, the Hamiltonian is translationally invariant with the form

$$H = \sum_{i=1}^{7} t_i - T_{\mathrm{CM}} + \sum_{i<j} V_{ij} , \tag{4}$$

where $t_i$ is the kinetic energy, $T_{\mathrm{CM}}$ is the center-of-mass energy, and $V_{ij}$ is the two-body interaction.

The internal wave functions $\phi_\alpha$ and $\phi_\tau$ are chosen to satisfy the variational stability condition (Kajino and Arima 1984*a*) with respect to the harmonic oscillator parameter. Although the resulting difference between the oscillator parameters for the two-cluster wave functions makes the calculation difficult, the stability condition is essential in reducing couplings with other channels.

Given these calculational methods, the chief remaining ambiguity is in the choice of the two-body interaction. In order to assess the importance of this ambiguity several different effective interactions have been used in constructing the cluster wave functions (eq. [2]), and almost all existing data on the binding energies, magnetic and electric properties of the $A = 7$ systems have been compared with the calculated results. This comparison indicates that the modified Hasegawa-Nagata (HN) force (Tanabe, Tohsaki, and Tamagaki 1975) is the best of those tried; it is used in the following calculations. Once the wave functions are constructed systematically for both the bound and scattering channels with the use of this interaction, there is no serious remaining uncertainty in the RGM that is expected to affect the calculated value of the *S*-factor. Details are given in Kajino and Arima (1984*a*) and Kajino (1985*a*, *b*, 1986).

The calculated *S*-factors of the $^3$He($\alpha$, $\gamma$)$^7$Be and $^3$H($\alpha$, $\gamma$)$^7$Li reactions for the HN force are shown in Figure 1; they describe

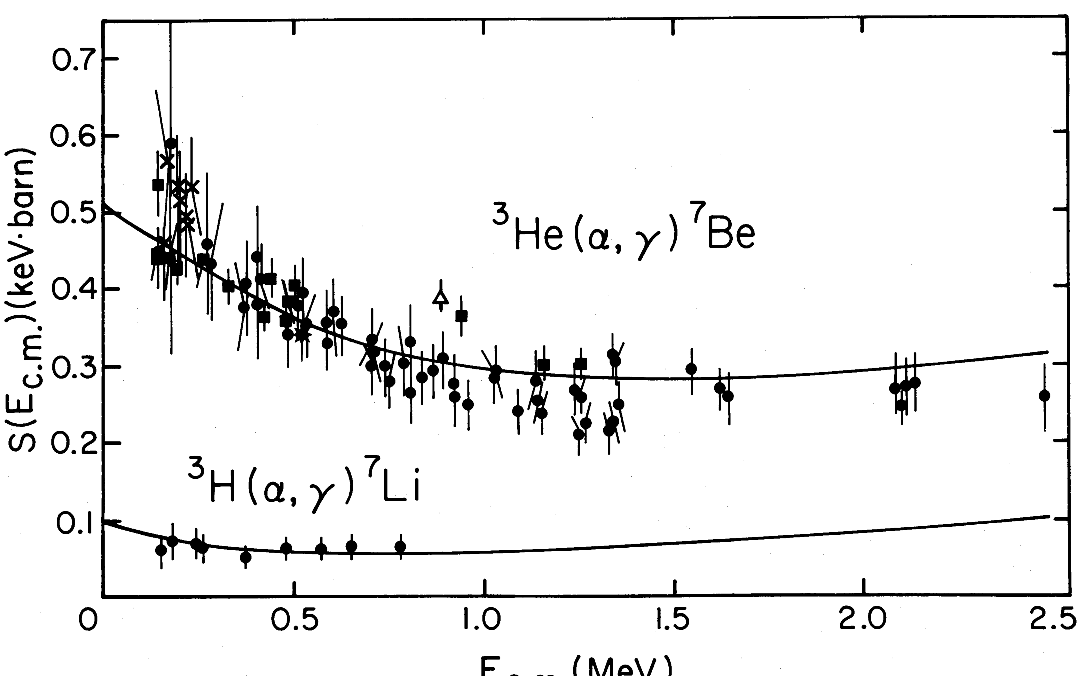


FIG. 1.—Astrophysical *S*-factors for the reactions $^3$He($\alpha$, $\gamma$)$^7$Be and $^3$H($\alpha$, $\gamma$)$^7$Li as functions of the incident energy. Solid curves are the predictions of Kajino and Arima (1984*a*) and Kajino (1985*a*, *b*) using the Hasegawa–Nagata interaction. Experimental data are from Parker and Kananagh (1963) (*closed circles*), Nagatani, Dwarakanath, and Ashery (1969) (*crosses*), Osborne *et al.* (1982) (*closed squares*), Robertson *et al.* (1983) (*open triangles*), and Alexander *et al.* (1984) (*asterisk*) for the $^3$He($\alpha$, $\gamma$)$^7$Be reaction and from Griffiths *et al.* (1961) for the $^3$H($\alpha$, $\gamma$)$^7$Li reaction.

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well the energy dependence of the existing data and have the same energy variation (within 2–3% over the energy range from 0.2 to 2.5 MeV which is due to the different truncation of the model space for intercluster relative motion; Kajino and Arima 1984*b*) as the RGM results of Walliser, Kanada, and Tang (1984). However, the two calculations differ in normalization by $\sim 15\%$, the present results being smaller. This difference (Kajino and Arima 1984*b*; Kajino 1986) arises mainly from the different two-body interactions assumed in the two calculations. Since the choice of two-body interaction is ambiguous at some level, it seems best, for obtaining an astrophysical reaction rate, to normalize the calculated excitation function to experiment.

We then proceed by normalizing the $S(E)$ calculated here to each of the experimental results by a least-squares procedure and take the weighted average value of $S(0)$ thus obtained as the best normalization of the calculated energy dependence. In Table 1 and Figure 2, we give $S(0)$ calculated for the two reactions and those obtained by extrapolating the experimental results. In forming the weighted average, we have omitted the result of Kräwinkel *et al.* (1982), which appears to be anomalously low, and that of Volk *et al.* (1983), which cannot be normalized to our theoretical result in a simple way. The quoted error is larger than the $\pm 0.017$ obtained from a simple weighted average for two reasons. First, the scatter of points about the mean is larger than expected based on the quoted errors. We have followed the common practice of increasing the uncertainties on the measured points so as to make the value of $\chi^2$ per degree of freedom equal to 1.0. In addition, an allowance of 2% for the uncertainty in the theoretical excitation function has been included (Robertson *et al.* 1983).

In order to provide the reaction rates as a function of temperature, useful for astrophysical calculations, we first express the $S$-factors in the form

$$S(E) = S(0) \sum_{n=0} a_n \left(-\frac{d}{d\alpha}\right)^n \exp(-\alpha E)\,, \tag{5}$$

with $a_0 = 1$, $a_1 = 0$, and $S(0)$ the weighted value from Table 1. Taking terms up to the fourth-order derivative for ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ and ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$, we then find the fits depicted in Figures 3 and 4. The results of the fits, in units of keV barns, are

$$S(E) = S(0)e^{-0.548E}(1 - 0.4285E^2 + 0.5340E^3 - 0.1150E^4) \tag{6}$$

for the ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ reaction and

$$S(E) = S(0)e^{-2.056E}(1 + 2.2875E^2 - 1.1798E^3 + 2.5279E^4) \tag{7}$$

for the ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$ reaction. Here $E$ is in MeV. These fits reproduce the calculated values of $S$ within $\pm 3\%$ for $E \leq 1.5$ MeV. The experimental data as well as values of $S(E)$ taken from Harris *et al.* (1983), Caughlan *et al.* (1985), and Fowler, Caughlan, and Zimmerman (1975, hereafter FCZII) are shown for comparison.

With these polynomial forms it is easy to obtain the reaction rates $N_A\langle\sigma v\rangle$ as a function of temperature. The energy average is over a Boltzmann distribution and $N_A$ is Avogadro's number. In the approximation of FCZII, we find for the ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ reaction

$$\begin{aligned} N_A\langle\sigma v\rangle = {} & 1.039 \times 10^7 \times S(0)T_{9A}^{5/6}/T_9^{3/2} \exp(-12.81T_{9A}^{-1/3}) \\ & \times (-0.05804T_{9A}^{4/3} - 0.03171T_{9A}^{5/3} + 0.02176T_{9A}^2 \\ & + 0.02805T_{9A}^{7/3} + 0.008633T_{9A}^{8/3} - 0.002144T_{9A}^3 \\ & - 0.002500T_{9A}^{10/3} - 0.0008150T_{9A}^{11/3} - 0.0001052T_{9A}^4)\,, \end{aligned} \tag{8}$$

where $T_{9A} = T_9/(1 + 0.0472T_9)$ and $T_9 = T/(10^9\ \mathrm{K})$.

For the ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$ reaction one obtains

$$\begin{aligned} N_A\langle\sigma v\rangle = {} & 8.246 \times 10^6 \times S(0)T_{9A}^{5/6}/T_9^{3/2} \exp(-8.072T_{9A}^{-1/3}) \\ & \times (0.1230T_{9A}^{4/3} + 0.1066T_{9A}^{5/3} + 0.01125T_{9A}^2 \\ & - 0.02459T_{9A}^{7/3} - 0.007647T_{9A}^{8/3} + 0.01664T_{9A}^3 \\ & + 0.02181T_{9A}^{10/3} + 0.01129T_{9A}^{11/3} + 0.002313T_{9A}^4)\,, \end{aligned} \tag{9}$$

where $T_{9A} = T_9/(1 + 0.1775T_9)$.

For $T_9 < 1$, these expressions are within $\pm 5\%$ of the exact value of $N_A\langle\sigma v\rangle$, obtained by integrating over $E$ numerically and are adequate for calculations of big bang production of ${}^7\mathrm{Li}$ and ${}^7\mathrm{Be}$.

In Figure 5 we compare the reaction rates above with those of Harris *et al.* (1983) and FCZII, as tabulated in Caughlan *et al.* (1985). For $T_9 < 1$, the present rate for ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$ is almost the same as Caughlan's. On the other hand, the reaction rate for ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$ has a stronger temperature dependence and is 50% larger for small temperatures. In the following sections, we shall study the consequence of these changes in the reaction rates for the solar neutrino problem and for the ${}^7\mathrm{Li}$ abundance in the big bang model.

TABLE 1

REACTION RATES FOR ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$ AND ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$

| Reaction | Reference | $S(0)$ (keV barn) |
|---|---|---|
| ${}^3\mathrm{H}(\alpha, \gamma)^7\mathrm{Li}$: | | |
| Experiment ......... | Griffiths *et al.* 1961[a] | $0.100 \pm 0.025$ |
| Theory ............. | Kajino and Arima 1984 | 0.1003[b] |
| | | 0.0981[c] |
| ${}^3\mathrm{He}(\alpha, \gamma)^7\mathrm{Be}$: | | |
| Experiment ......... | Parker and Kavanagh 1963[a] | $0.514 \pm 0.054$ |
| | Nagatini *et al.* 1969[a] | $0.588 \pm 0.071$ |
| | Kräwinkel *et al.* 1982[a] | $0.322 \pm 0.033$ |
| | Osborne *et al.* 1982[a] | $0.521 \pm 0.030$ |
| | Osborne *et al.* 1982[d] | $0.573 \pm 0.050$[e] |
| | Robertson *et al.* 1983[d] | $0.660 \pm 0.036$ |
| | Volk *et al.* 1983[d] | $0.560 \pm 0.03$[f] |
| | Alexander *et al.* 1984[a] | $0.478 \pm 0.041$ |
| Average (excluding Kräwinkel *et al.*; Volk *et al.*) .... | | $0.560 \pm 0.03$ |
| Theory ............. | Kajino and Arima 1984 | 0.511[b] |
| | | 0.500[c] |
| | Walliser *et al.* 1984 | 0.598 |

[a] Prompt capture $\gamma$-ray measurement.

[b] Reduced mass of the ${}^3\mathrm{H} + \alpha$ or ${}^3\mathrm{He} + \alpha$ system is assumed to be $\mu = 12/7(M_n + M_p)/2$.

[c] The same as note (b), with $\mu = M(\alpha)M(\tau)/[M(\alpha) + M(\tau)]$, where $\tau$ denotes ${}^3\mathrm{He}$ or ${}^3\mathrm{H}$.

[d] Activation measurement.

[e] Average of values obtained using the $S$-factors from Table 1 of Osborne *et al.* 1982; the values of their Table 1 do not agree with those quoted in the text of their paper, and have been used upon the advice of C. A. Barnes (1985, private communication).

[f] Not the value normalized to the present theory, but taken directly from Volk *et al.* 1983.

## III. SOLAR NEUTRINO PROBLEM

In the experiment of Davis, Harmer and Hoffman (1968), neutrinos from the Sun are detected through inverse $\beta$-decay

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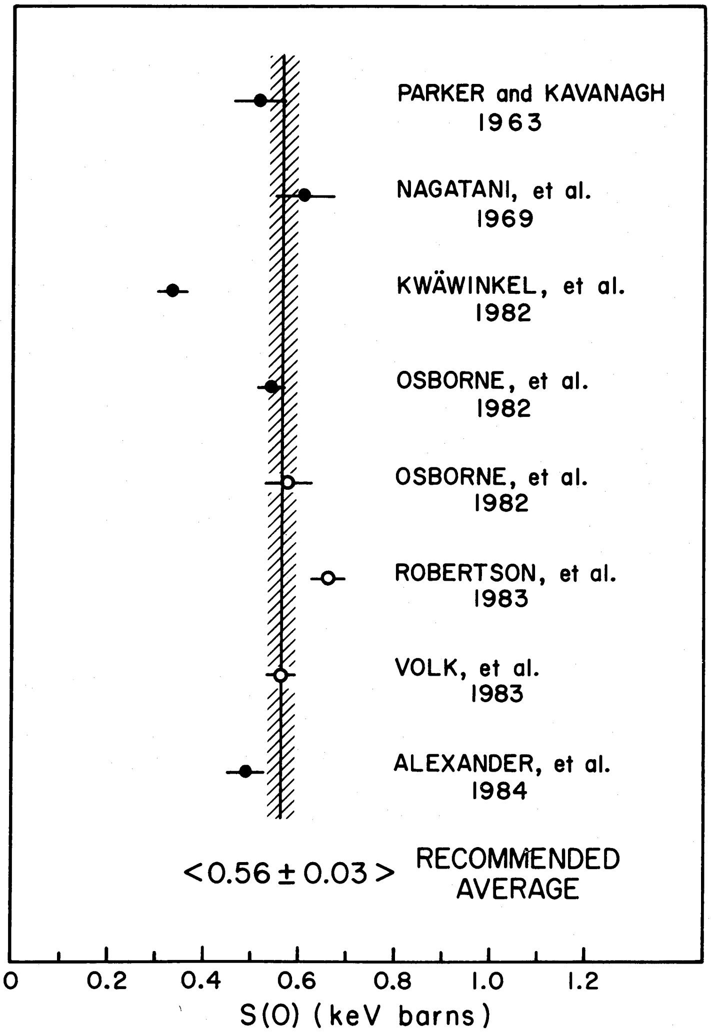


FIG. 2.—Values of $S(0)$ for the $^3He(\alpha, \gamma)^7Be$ reaction obtained by normalizing the experimental $S$-factors to theoretical calculations as described in the text. Closed circles are results from direct observations of the gamma rays, and open circles from observation of the decay of the product $^7Be$. Results of Kräwinkel *et al.* and Volk *et al.* were not used in obtaining the weighted average.

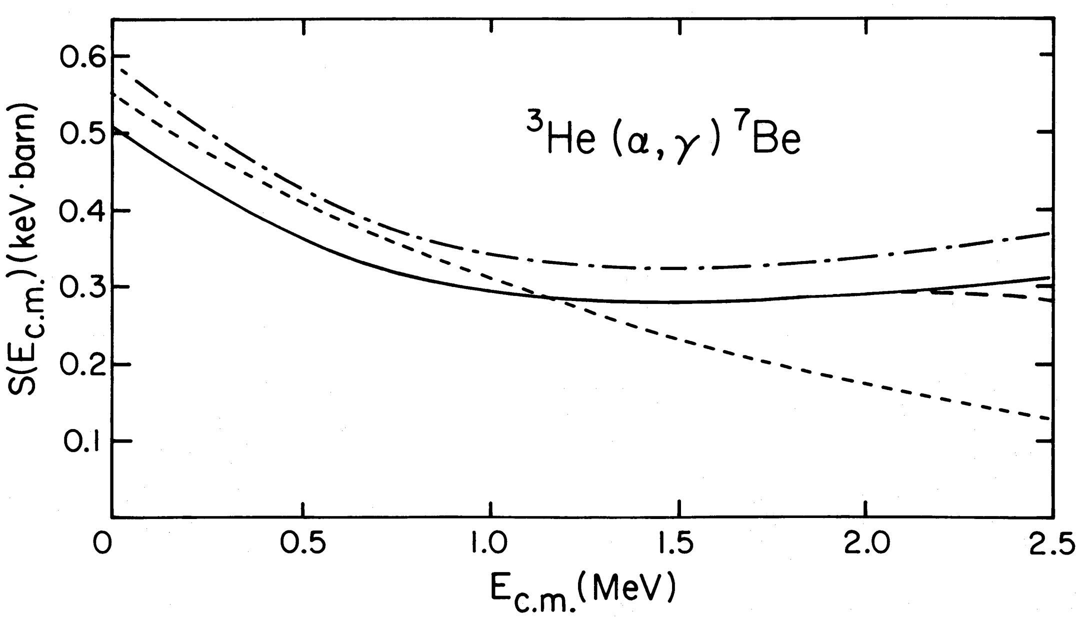


FIG. 3.—Astrophysical $S$-factors for the reaction $^3He(\alpha, \gamma)^7Be$. The theoretical prediction of Kajino and Arima (same as in Fig. 1) is shown as solid curve; long-dash curve is a polynomial fit to it; dot–dash curve is the calculation of Walliser, Kanada, and Tang (1984) (for a different two-body interaction than that of Kajino and Arima); short-dash curve is from Harris *et al.* (1983).

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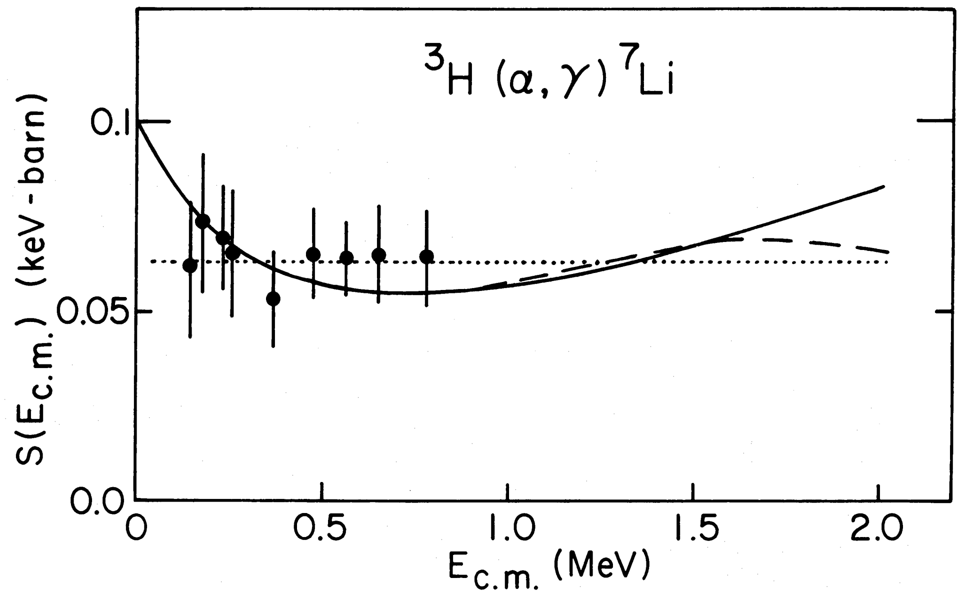


FIG. 4.—Astrophysical $S$-factors for the reaction $^3H(\alpha, \gamma)^7Li$. Solid and long-dash curves have the same meaning as in Fig. 3, and dotted curve is from Fowler, Caughlan, and Zimmerman (1975).

induced in a $^{37}Cl$ detector. Based on reaction rates available at the time, Bahcall *et al.* (1982) predicted a counting rate, and its 3 $\sigma$ uncertainty, of $R = 7.6 \pm 3.3$ SNU (1 solar neutrino unit = 1 capture $s^{-1}$ per $10^{36}$ detector atoms), significantly larger than the observed value (Davis, Cleveland, and Rowley 1984) of $2.1 \pm 0.3$ SNU (1 $\sigma$ uncertainty). Our value of the $S$-factor for the $^3He(\alpha, \gamma)^7Be$ reaction is $\sim$8% larger than the value used by Bahcall *et al.* (1982); since $R \propto S(0)^{0.8}$ (Bahcall and Sears 1972), this tends to increase the predicted value of $R$. However, there have been changes in other reaction rates which affect solar neutrino production; we discuss these changes before presenting a predicted rate. For another recent discussion of the relevant reaction rates, see Filippone (1986).

The largest change is in the value of $S_{17}$ for the $^7Be(p, \gamma)^8B$ reaction, which, in the Sun, leads to the $^8B$ neutrinos predicted to be responsible for most events in Davis's detector. New measurements of the cross section for this reaction and a reanalysis of previous results lead to a recommended value of $S_{17}(0) = 0.0238 \pm 0.0023$ keV barns (Filippone *et al.* 1983*a*, *b*). This value is significantly smaller than that ($0.029 \pm 0.010$ keV barns) used by Bahcall *et al.* (1982) and tends to decrease the predicted rate. There is an additional complication: the estimate of $S_{17}(0)$ given above is based on an extrapolation assuming the excitation function calculated by Tombrello (1965), whereas more recent and complete calculations by Barker (1980) give a somewhat different excitation function and lead to a different value of $S_{17}(0)$, $\sim$10%–15% lower according to Filippone *et al.* (1983*b*) (see also Barker and Spear

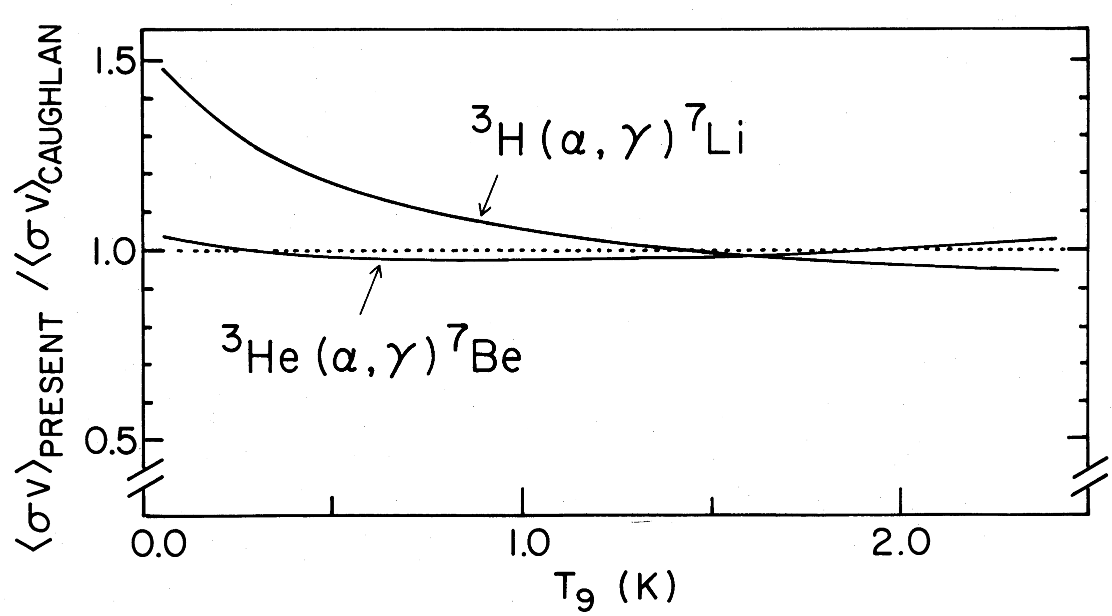


FIG. 5.—Ratio, for the $^3He(\alpha, \gamma)^7Be$ and $^3H(\alpha, \gamma)^7Li$ reactions, of the nuclear reaction rates calculated in this paper to those from Caughlan *et al.* (1985)

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1986). To show the effect of such a change, we also obtain $R$ for $S_{17}(0)$ reduced by 15%. It does not appear to us justified to make the further reductions, based principally on selection of only the most recent data, that are suggested by Barker and Spear. Further theoretical and experimental work addressing this question would be desirable.

We also recommend a change in the $S$-factor ($S_{11}$) for the reaction $p + p \rightarrow D + e^+ + \nu$. The value of $S_{11}$ is directly proportional to the square of the axial vector coupling constant, $g_A$, governing Gamow–Teller $\beta$-decay. Bahcall *et al.* (1982) obtained $g_A$ from the value of the neutron half-life; because of the large spread in available measurements of the half-life, the value of $g_A$ obtained was quite uncertain. However, $g_A$ can be obtained in another way. Several measurements of angular correlations among the neutron's decay products form a consistent set (Wilkinson 1982; Bopp *et al.* 1986) and determine accurately the ratio of the axial vector to vector coupling constants, $\lambda = g_A/g_V$. In a summary of most of the available measurements, Wilkinson obtained $\lambda = -1.2590 \pm 0.0086$; combining this with the recent result of Bopp *et al.* (1986), $\lambda = -1.262 \pm 0.005$, yields $\lambda = -1.2612 \pm 0.0043$. Since $g_V$ is well known, one can obtain $g_A$ from $g_A = (g_A/g_V)g_V = \lambda g_V$. The result of Bahcall and May (1969) scaled to this new value of $g_A^2$ is

$$S_{11}(0) = 3.78(0.986 \pm 0.014)(1.0345 \pm 0.0071) \times (1.02 \pm 0.01)^2 \times 10^{-25}\ \text{MeV barns} .$$

Here the first factor is the result from Bahcall and May, and the other terms show changes due to more recent results. The second term takes into account results for the nuclear matrix element of Bargholtz (1979) and Gari (1978); the third factor is the correction for the new value of $g_A^2 = \lambda^2 g_V^2$ and its uncertainty ($g_V$ is from Wilkinson 1982, and $\lambda$ is from above); and the fourth factor is the correction for meson exchange due to Bargholtz (1979) and Gari (1978). Then $S_{11} = (4.01 \pm 0.09) \times 10^{-25}$ MeV barns, compared to Bahcall *et al.*'s (1982) value of $(3.88 \pm 0.12) \times 10^{-25}$ MeV barns. For a more detailed discussion of this subject see Bahcall *et al.* (1982). In Table 2, we summarize the $S$-factors for reaction rates which differ from those used by Bahcall *et al.*, the associated changes in the neutrino detection rates, and the error due to a one standard deviation uncertainty in the reaction rates. Since Bahcall *et al.* (1982)'s event rate is 7.70 SNU after making the small correction for second-order weak interaction effects in the capture rate in $^8$B neutrinos (Bahcall and Spear 1986), the new result corresponds to an event rate of 6.5 SNU and an uncertainty of $\pm 0.76$ SNU associated with the nuclear reaction rates. There are additional uncertainties associated with the detection efficiency of the $^{37}$Cl detector as given by Bahcall and Holstein (1986) (about $\pm 5$% or $\pm 0.3$ SNU) and with the solar physics (about $\pm 0.4$ SNU, one-third of the three standard deviation uncertainty quoted by Bahcall 1982). This yields a total uncertainty of $\pm 0.9$ SNU.

We then have

$$R(\text{predicted}) = 6.5 \pm 0.9\ \text{SNU} ,$$

$$R(\text{measured}) = 2.1 \pm 0.3\ \text{SNU} .$$

The theoretical result is in reasonable agreement with the recent summary of Bahcall *et al.* (1985): $5.8 \pm 2.2$ SNU. (Note the quoted errors here are 3 $\sigma$ errors.) Reducing $S_{17}$ by 15% (i.e. adopting Barker's excitation function) leads to $R = 5.7$ SNU (Filippone *et al.* 1983*b*; Barker 1980) and the solar neutrino problem, though reduced, still remains.

It appears that the remaining uncertainty in the $S$-factors for the nuclear reactions involved [and for the $^3$He($\alpha$, $\gamma$)$^7$Be reaction in particular] is small enough that changes in the nuclear reaction rates are unlikely to be the source of the solar neutrino problem. Its explanation probably lies in the realm of solar physics or particle physics; perhaps the most interesting possibility is that the electron neutrino has mass and decays or oscillates into an undetected state (e.g. $\nu_\mu$), either in the Sun (Mikheyev and Smirnov 1985; Bethe 1986) or on its way to the Earth. A further experiment, using a gallium detector sensitive to the low-energy neutrinos from the $p + p \rightarrow e^+ + {}^2\text{H} + \nu_e$ reaction, appears to have the best chance of resolving this discrepancy (Bahcall *et al.* 1985) and may provide information about possible neutrino mass differences in a mass range of $(m_1^2 - m_2^2) \approx 10^{-10}$–$10^{-12}$ eV$^2$, and $10^{-4}$–$10^{-8}$ eV$^2$ (Haxton 1986) because of the effects of vacuum and matter oscillations, respectively. These ranges are not accessible to terrestrial experiments.

## IV. BIG BANG NUCLEOSYNTHESIS OF $^7$Li

Nuclear reactions occurring when the temperature in the expanding universe is $\sim 10^9$ K synthesize the elements $^2$H, $^{3,4}$He, and $^7$Li in amounts comparable to their observed abundances (Yang *et al.* 1984; Austin 1981; Wagoner 1973). Since the amount of a given isotope which is created depends on the baryon density $\rho_B$, the assumption that a given element is created in the big bang yields an estimate of that density. It has been found that a single value of $\rho_B$ simultaneously reproduces the observed abundances of the four isotopes (Spite and Spite 1982*a*, *b*; Yang *et al.* 1984; Austin 1981), yielding a consistent estimate of $\rho_B$.

However, there are concerns that this agreement might be fortuitous and that the derived $\rho_B$ is therefore questionable.

TABLE 2

CHANGES IN DETECTION RATE FOR $^{37}$Cl

| Reaction | $S$ (Bahcall *et al.* 1982) | $S$ (new) | $\Delta$ (SNU)[a] | Error (SNU)[b] |
|---|---|---|---|---|
| $p + p \rightarrow D + e^+ + \nu$ | $(3.88 \pm 0.12)10^{-25}$ MeV b | $(4.01 \pm 0.09)10^{-25}$ MeV b | 0.92 | 5% |
| $^3$He + $^3$He $\rightarrow$ $^4$He + $2p$ | $4.7 \pm 0.5$ MeV b | $4.7 \pm 0.5$ MeV b | 1.00 | 7% |
| $^3$He + $^4$He $\rightarrow$ $^7$Be + $\gamma$ | $0.52 \pm 0.05$ keV b | $0.56 \pm 0.03$ keV b | 1.06 | 4% |
| $^7$Be + $p$ $\rightarrow$ $^8$B + $\gamma$ | $0.029 \pm 0.0033$ keV b | $0.0238 \pm 0.0023$ keV b | 0.86 | 7% |
| Total | | | 0.84 | 12% |

[a] $\Delta$ (SNU) is the factor by which the predicted event rate differs from the value of 7.70 SNU predicted by Bahcall *et al.* 1982. It is estimated from the information in Tables XI and XVIII of that source. The total is the product of the individual entries.

[b] Error (SNU) is the uncertainty in the contribution of the given reaction to the total event rate. Total is the sum in quadrature of the individual entries.

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These concerns are based on the fact that stellar processing, or astration, of the primeval material could greatly alter its composition. In the case of $^7$Li, there is such strong evidence of astration for the abundances observed in relatively young stars that the observed $^7$Li abundance has generally been regarded as setting only an upper limit on $\rho_B$ (Austin and King 1977; Austin 1981). However, we may now have a reasonable estimate of the primordial (big bang produced) abundance of $^7$Li from the measurements of Spite and Spite (1982*a*, *b*) and Spite, Maillard, and Spite (1984) on over 20 very old halo stars. Although astration may also have affected the $^7$Li content of these old stars to some extent, the Spites (1982*a*, *b*) and Boesgaard and Steigman (1985) find that known depletion mechanisms are inconsistent with the observations and conclude (tentatively) that the observed abundances reasonably represent the primeval abundance. We take that point of view in this paper.

There was, however, an additional problem with the use of $^7$Li for density determination: the absence of reliable values of the reaction rates involved in the formation of $^7$Li. Calculations using FCZII rates (e.g., those of Yang *et al.* 1984) are known to predict significantly different $^7$Li production than calculations using the rates assumed by Wagoner. In order to assess the effects of the new rates summarized in equations (8) and (9), we have performed calculations of big bang nucleosynthesis with Wagoner's code. The reaction rates of Caughlan *et al.* (1985) as implemented by Scherrer (1984, private communication) were used, except that the new reaction rates were used for the $^3$He($\alpha$, $\gamma$)$^7$Be and $^3$H($\alpha$, $\gamma$)$^7$Li reactions. It was assumed that the neutron half-life is 10.3 minutes, consistent with the value for $g_A/g_V$ obtained in § III, and that there are three light neutrinos ($N_\nu = 3$).

The results for $^7$Li are summarized on Figures 6 and 7. In these figures the abundances are plotted as a function of $\eta$, the ratio of the number of baryons to the number of photons. This number can be converted to the baryon density according to $\rho_B = 8.3 \times 10^{-22}\eta(T/2.9)^3$ g cm$^{-3}$, where $T$ is the temperature of the microwave background radiation. In Figure 6 the predicted abundances are compared with the early results of Wagoner (1973); the predicted abundances differ by more than a factor of 2 at some densities. The present results are much more similar to calculations based on FCZII rates, such as those of Yang *et al.* (1984), typically differing from them by 20% or less. Also shown on Figure 6 is the result of a computation assuming $N_\nu = 4$; as expected, the results do not differ qualitatively from those with $N_\nu = 3$.

Another uncertainty in these predictions involves the rate of the $^7$Li($p$, $\alpha$)$^4$He reaction which acts during the big bang to destroy $^7$Li after its formation. There had been a controversy about the rates for this reaction, with published values of the cross section differing by a factor of 2. Such differences in cross section would lead to differences of a factor of 2.7 in the pro-

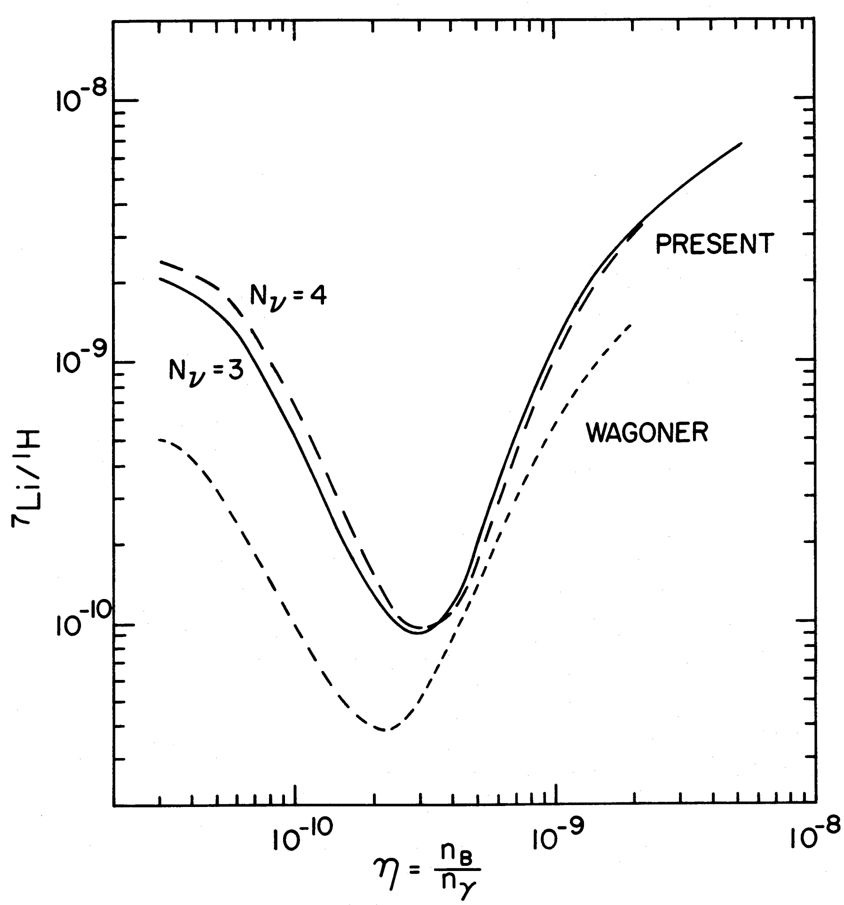


FIG. 6.—Primordial abundance of $^7$Li produced in a standard big bang expansion (see text for details). Solid (dashed) curve is the result of the present calculations for $N_\nu = 3$($N_\nu = 4$). Dotted curve is from Wagoner (1973).

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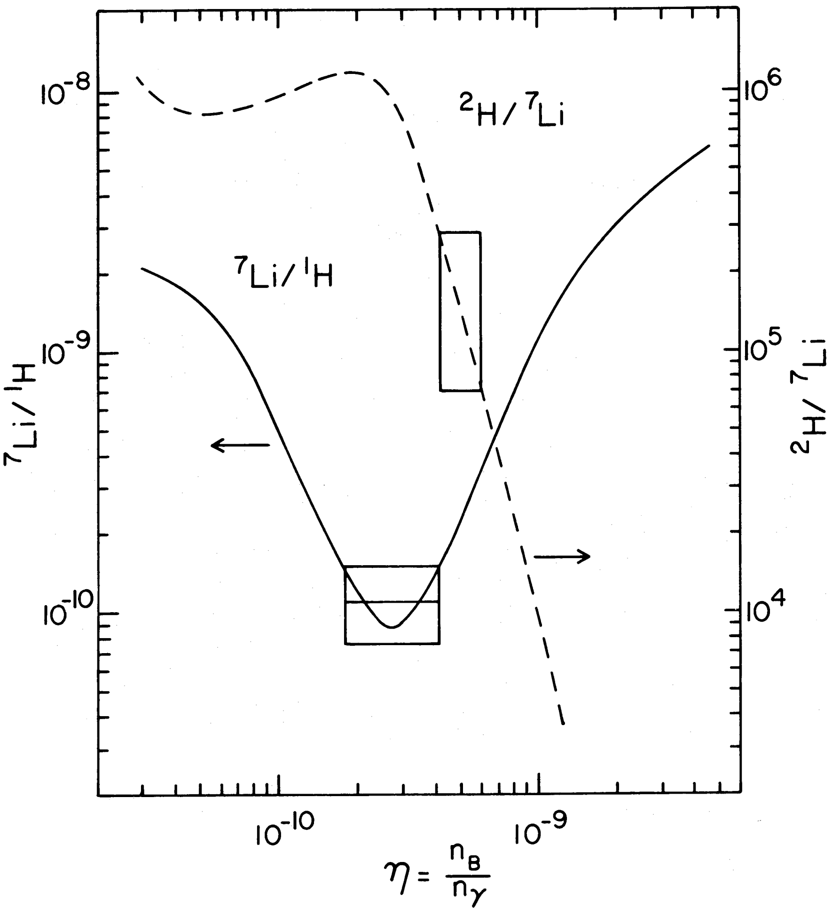


FIG. 7.—Solid line shows big bang production of $^7$Li from the present calculation ($N_\nu = 3$) and the associated rectangle the Li abundance measured by Spite and Spite (1982*a*, *b*). Dashed line is the ratio by number of the $^2$H and $^7$Li produced in the big bang, and the associated rectangle is the experimental ratio (see text for details) with its one-standard-deviation uncertainty.

duction of $^7$Li at low density where the $^3$H$(\alpha, \gamma)^7$Li reaction is dominant (Yang *et al.* 1984). However, this controversy had been resolved earlier (see King *et al.* 1977; see also Rolfs and Kavanagh 1986). The rate given in FCZII is close to the true value. As a further check we have independently derived a value of the reaction rate from the *S*-factor for the reaction obtained by Barker (1972) (FCZII did not use this *S*) and have used it in a big bang calculation; the predicted abundances of $^7$Li at low density change by less than 5%. We conclude that the reaction rates for $^7$Li$(p, \alpha)^4$He, $^3$H$(\alpha, \gamma)^7$Li, and $^3$He$(\alpha, \gamma)^7$Be are known to within about $\pm 15\%$, $\pm 25\%$ and $\pm 6\%$, respectively. Based on the sensitivity studies of Yang *et al.* (1984), which include the above three reactions and a number of others, we assign an overall uncertainty of $\pm 20\%$ to $^7$Li production at high density (near $\eta = 10^{-9}$) and $\pm 35\%$ at low density (near $\eta = 10^{-10}$). The dominant uncertainty is from the $^1$H$(n, \gamma)^2$H and $^7$Be$(n, p)$ reactions at high density and the $^7$Li$(p, \alpha)$ and $^3$H$(\alpha, \gamma)^7$Li reactions at low density. For a given baryon density the abundance of $^7$Li is now predicted more accurately than it is measured.

Shown on Figure 7 is a comparison of the present predictions (same as the solid curve on Fig. 6) with the $^7$Li abundance measured by Spite and Spite (1982*a*, *b*) and Spite, Maillard, and Spite (1984) for some very old stars in the galactic halo: $^7\mathrm{Li}/^1\mathrm{H} = (1.12 \pm 0.38) \times 10^{-10}$. For the central value of this measurement, only a very small range of densities near $\eta = 3 \times 10^{-10}$ is allowed; the one standard deviation upper limit corresponds to $1.7 \times 10^{-10} \leq \eta \leq 4 \times 10^{-10}$.

It is also possible to place an upper bound on $\eta$, which may be less dependent on models of astration (Yang *et al.* 1984; Mathews and Viola 1979). The predicted value of the ratio $^2$H/$^7$Li is shown in Figure 7, where it is compared to an experimental ratio based on the value of Spite and Spite (1982*a*, *b*) for $^7$Li/$^1$H and a value of $^2\mathrm{H}/^1\mathrm{H} = (2 \pm 1) \times 10^{-5}$ from Yang *et al.* (1984) and Austin (1981). The abundance of $^2$H should be affected more by astration than that of $^7$Li because $^2$H is more fragile and because it has had more time to suffer astration, the $^2$H measurements reflecting abundance values at a later time than the $^7$Li measurements. The present value of the ratio is then smaller than the primeval value and the value of $\eta$ obtained from it is an upper limit on the actual value of $\eta$. One obtains $\eta \leq 6 \times 10^{-10}$.

These values are consistent with the results of the extensive analysis by Yang *et al.* which yields $\eta = (4\text{–}7) \times 10^{-10}$ and are slightly smaller than the value obtained by Austin (1981): $\eta = 6.5 \times 10^{-10}$.

The nature of the effects of astration remains uncertain. It is usually assumed (see Yang *et al.* 1984, for example) that the effect of astration is to destroy both $^2$H and $^7$Li. However, if one accepts the new results for the $^7$Li abundance in old halo stars as representing the primeval $^7$Li abundance (see the discussion in Boesgaard and Steigman 1985), then the present

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abundance of $^7$Li is over 7 times the primeval abundance (Boesgaard and Steigman 1985). Since cosmic rays cannot produce this amount of $^7$Li (Austin 1981), only stellar production remains as a possibility. Thus, at least some stars must make $^7$Li rather than destroying it. Indeed some stars are observed with $^7$Li/H up to $10^{-7}$, compared to the value of $10^{-10}$ observed in the old halo stars and the value of $10^{-9}$ observed in young Population I stars (Trimble 1975). Possible production sites involve shell burning in red giants and nova events (Trimble 1975). This would reduce the upper limit on $\eta$ based on the ratio of $^2$H to $^7$Li. On the other hand, there could not have been significant production of $^7$Li contributing to its abundance in the stars observed by Spite and Spite or the inferred (smaller) primeval abundance would be too small to be consistent with the big bang.

## V. SUMMARY

New theoretical expressions for the radiative capture reactions $^3$He($\alpha$, $\gamma$)$^7$Be and $^3$H($\alpha$, $\gamma$)$^7$Li have been used to extrapolate available experimental information to $E = 0$. The values of the astrophysical $S$-factors so obtained are $0.56 \pm 0.03$ and $0.100 \pm 0.025$ keV barns, respectively; see Table 1 for details. Expressions for the reaction rates have been obtained in a form convenient for astrophysical computations and are presented in equations (8) and (9). These new rates have been applied to study the production of solar neutrinos and the nucleosynthesis of $^7$Li in the big bang expansion.

During our consideration of solar neutrino production, we surveyed other reactions important for this process and present a set of recommended reaction rates in Table 2. These rates yield a detection rate for a $^{37}$Cl detector (Davis, Harmer, and Hoffman 1968; Davis, Cleveland, and Rowley 1984) of $R = 6.5 \pm 2.3$ SNU compared to the experimental value of $2.1 \pm 0.3$ SNU. It appears that future changes in the nuclear reaction rates are not likely to remove this discrepancy and that the solution of the solar neutrino problem must be sought elsewhere.

For big bang nucleosynthesis, we found that use of the new rates did not greatly change the results of Yang *et al.* (1984), but put the predicted big bang nucleosynthesis of $^7$Li on a sounder footing; predicted production is now known to within an uncertainty of $\pm 35\%$ at low density ($\eta \approx 10^{-10}$) and $\pm 20\%$ at high density ($\eta \approx 10^{-9}$). Combining these results with the measurement of the primeval $^7$Li abundance of Spite and Spite (1982*a*, *b*) and Spite, Maillard, and Spite (1984) yields both upper and lower bounds on the universal baryon density: $1.7 \times 10^{-10} \leq \eta \leq 4 \times 10^{-10}$. Comparison of the predicted and experimental ratios for $^7$Li/$^2$H yields an upper bound on the baryon density: $\eta \leq 6 \times 10^{-10}$.

These values appear to be consistent with earlier estimates (Yang *et al.* 1984; Austin 1981) of $\eta$ and together with them imply a value of $\eta \approx 4 \times 10^{-10}$. At this value of $\eta$ the fractional abundance by mass, $Y_p$, of $^4$He produced in the big bang is calculated to be $Y_p = 0.2413(0.2535)$ if there are three (four) light neutrino species. Here the $-1\%$ correction determined by Dicus *et al.* (1982) has been taken into account. These values appear consistent with the observed abundances of $^4$He (see Yang *et al.* 1984 for a review), at least for $N_\nu = 3$.

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