THE EMPIRICAL FOUNDATIONS OF NUCLEOSYNTHESIS

by

W. A. Fowler

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The Empirical Foundations of Nucleosynthesis†

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Abstract

Theories of nucleosynthesis must be based on broad empirical foundations involving experiment in nuclear physics and observation in astronomy and geophysics. Current ideas picture nucleosynthesis taking place in ordinary stars, in supermassive stars and in an early high-temperature stage of the expanding universe.

A survey is presented of new experimental results on certain key reactions in the pp chain, the CNO bi-cycle, helium burning, carbon burning, and neutron production which are important in stellar nucleosynthesis. The role of the reactions \(^{4}\text{He}(\alpha, \gamma)\text{Be}\) and \(^{7}\text{Be}(\alpha, \gamma)^{11}\text{C}\) in bridging the mass gaps at atomic weights 5 and 8 in universal and supermassive star nucleosynthesis is discussed.

A brief review is given of current problems in theories of nucleosynthesis arising (1) from recent observations on helium abundances in stars, (2) from correlations between the chemical composition and the age, location and kinematical motion of stars in the Galaxy. It is concluded that definitive data are now being hard won in the laboratory but that the task of laying solid empirical foundations for theories of nucleosynthesis is only just begun.

It is generally agreed among those working in the field that theories of nucleosynthesis must be based on a solid and extensive empirical foundation. By empirical foundation I mean first of all experiment at the nuclear accelerator and reactor in which measurements are made on the cross-sections of nuclear reactions of astrophysical and geophysical interest. In the second place I mean observation at the telescope and the mass spectrometer by which measurements are made on the abundances of the elements and the nuclear species in nature; in the solar system, in stars, in the interstellar medium both in the Galaxy and in other galaxies. The key to where, when and how the elements were synthesized lies in the correlation between experimental cross-sections and observational abundances. The theories can be simple or complex—preferably simple—but in any case the theories must be able to explain these correlations.

You will hear many beautiful accounts this week of these empirical foundations—from Gibbons, Clayton, Price, Kuroda, Wasserburg, Bernas, and others. Today I first wish to discuss the experiments made recently in our

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laboratory at Caltech on cross-sections of relevance in hydrogen burning, helium burning and carbon burning. Then I wish to mention certain observations in astronomical spectroscopy on the abundance of the heavy elements as a function of stellar age in the Galaxy. Finally I wish to point out the relevance of these experiments and observations to various possible sites of nucleosynthesis. Permit me to list these sites:

1. Nucleosynthesis in ordinary stars ($\sim$1 to 100 $M_\odot$) continuously over the lifetime of the Galaxy.
2. Nucleosynthesis in supermassive stars ($10^3$ to $10^{10} M_\odot$) from time to time in the evolution of the Galaxy but principally during the formative or "collapse" stage.
3. Nucleosynthesis during the early "big bang", high-temperature stage of the expanding universe.

Before beginning with the details let me emphasize once again the importance of experiment and observation. I sometimes think that theoretical ideas have been stressed far too much in the field of nuclear astrophysics and geophysics. I find it rather difficult to put this in the right words, but the politicians have no difficulty in this regard and I have found a quotation from a politician, much in the news of late, which expresses my idea precisely. This quotation is taken entirely out of context, but that doesn't matter—it says what I want to say in down-to-earth language. It reads as follows:

"We got to get all this theory out of things." (GEORGE WALLACE, husband of the Governor of Alabama, Harper's Magazine, April 1967)†

I find myself in disagreement with ex-Governor Wallace (and his wife) on most matters, but in this instance he has phrased my sentiments in very succinct, albeit colloquial, language.

The Proton-Proton Chain

After the production of $^3$He through $^1$H(p,e$^+$ν)$^2$D(p,γ)$^3$He, the pp chain is completed by $^7$He(γ,$^2p$)$^8$He and $^3$He(a,γ)$^7$Be(e$^-$,ν)$^7$Li(p,α)$^4$He or $^3$He(a,γ)$^7$Be(p,γ)$^8$B(e$^+$ν)$^8$Be*(α)$^4$He (Fowler, 1958). These reactions are basic to the synthesis of helium directly from pure hydrogen or catalytically from hydrogen adulterated with helium. However, at the present time the major interest in these processes stems from their intimate connection with neutrino production in the Sun. The detection of solar neutrinos will serve as a decisive check on current concepts of energy generation and helium synthesis in ordinary stars ($M_\odot < M < 100 M_\odot$) (Bahcall, 1964, 1966).

The Brookhaven Neutrino Observatory (Davis, 1964), now under construction in the Homestake Mine, South Dakota, employs a neutrino detection technique, $^{35}$Cl(v,e$^-$)$^{35}$Ar(e$^-$,ν)$^{37}$Cl*(Auger)$^{37}$Cl, which is sensitive only to the neutrinos emitted in the decay of $^7$Be and $^8$B among the reactions of

† I thank Dr. Robert May for bringing this quotation to my attention.
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in hydrogen burning. Then I wish to mention certain observations on the abundance of the heavy elements in the Galaxy. Finally, I wish to point out the observations to various possible sites of these sites:

ne (≈ 1 to 100 M⊙) continuously over five stars (10^3 to 10^10 M⊙) from time to time but principally during the formative "big bang", high-temperature stage of the universe. Let me emphasize once again the importance of this field of nuclear astrophysics and to put this in the right words, but the matter of context, but that doesn't matter—it is a matter of language. It reads as follows:

"Of things." (GEORGE WALLACE, husband of Governor Wallace (and his wife) on Harper's Magazine, April 1967)

Parker and Kavanagh (1963) on S(E) for ³He(a,γ)⁷Be are exhibited in figure 1. Those of Winkler and Dwarakanath (1966, 1967) and of Bacher and Tombrello (1967) for ³He(τ,2p)⁴He are shown in figure 2. Also shown for comparison are recent results obtained by Neng-Ming, Novatskii, Osetinskii, Nai-Kung and Chepurchenko (1966) and early results obtained by Good, Kunz and Moak (1954).

The behaviour of S(E) for the ³He(τ,2p)⁴He reaction can be understood in terms of two distinct intermediate processes as shown in figure 3. At high interaction energies the transfer of a proton and a neutron from one ³He to the other results in the intermediate formation of ⁵Li and the ejection of the remaining proton (Bacher and Tombrello, 1965). These latter protons can be recognized by their small spread (±0.8 MeV) about a relatively high energy.
The $^5\text{Li}$, of course, subsequently breaks up into a proton and alpha-particle characterized by a wide spread in energy. At low interaction energies Clayton (1966) has suggested that proton transfer is inhibited by Coulomb repulsions and only a neutron is transferred forming $^4\text{He}$ directly with the result that two protons are ejected in the first stage of the reaction. For reasons which are not entirely clear (May and Clayton, 1967) the cross-section factor for this mechanism drops off fairly rapidly with increasing energy and the overall factor goes through a minimum as neutron transfer is replaced by neutron plus proton transfer as indicated in figure 3. In early analyses of this reaction (Fowler, 1954, 1958, 1959) the results of Good, Kunz and Moak (1954) were employed. These results are also shown in figure 2 and are seen to give a considerably lower value for $S(E)$ than do the modern measurements. This discrepancy is not completely understood, but probably arises from considerable uncertainty in the amount of $^3\text{He}$ in the target used by Good, Kunz and Moak. The new results revise the earlier estimates for $S(E)$ upward by a factor of $\sim 5$.

Bahcall (1962) has computed the reaction rate for $^7\text{Be}(e^-,\nu)^7\text{Li}$ under astrophysical circumstances from the well-determined terrestrial half-life of $^7\text{Be}$. One of our graduates, Parker (1966), has remeasured at Brookhaven the
se, subsequently breaks up into a proton and a wide spread in energy. At low interaction suggested that proton transfer is inhibited by a neutron is transferred forming He directly are ejected in the first stage of the reaction. rely clear (May and Clayton, 1967) the cross-

$${}^3\text{He}(^3\text{He}, 2p)^4\text{He}$$

$$S(E) = \sigma E \exp \left( + 4.860 E^{-1/2} \right)$$

et al JNP 3, 1064 (1966)

WARAKANATH (CALTECH)

M BRELLO (CALTECH)

mass energy (MeV)

1.5 20 25 30

FIG. 3. High and low energy modes for the reaction $^3\text{He}(r,2p)^4\text{He}$. measurements and calculations on the expected neutrino fluxes from $^7\text{Be}$ and $^8\text{B}$ in the Sun and the Earth. As an illustration the expected fluxes as a function of $S_{13} = S(E \approx 0)$ for $^3\text{He}(r,2p)^4\text{He}$ are shown in figure 5. For

$${}^7\text{Be}^-(e^-{},1)^7\text{Li}$$

well-determined terrestrial half-life of , has remeasured at Brookhaven the

$$(0.150)$$

$$(0.100)$$

$$(0.050)$$

FIG. 4. The cross-section factor $S(E)$ for $^7\text{Be}(p,\gamma)^8\text{B}$ (Parker, 1966).
$S_{33} = 5 \times 10^3 \text{ keV-barns}$ it develops that Davis can expect $4.3$ counts per day when corrections are made to infinite time of bombardment and detection. The expected number of counts depends critically on the opacity of solar material and decreases rapidly if $Z$, the mass fraction of heavy elements, is decreased. We await his actual results with great interest and no little trepidation. Our basic ideas about thermonuclear reactions in stars face a crucial test.

**The CNO Bi-cycle**

The experimental results of Hebbard and Vogl (1960), Vogl (1963) and Seagrave (1952) on the energy dependence of the cross-sections for $^{12}\text{C}(p,\gamma)$

![Graph showing various quantities as a function of $S_{33}$ keV-barns]

$^{13}\text{N}$ and $^{13}\text{C}(p,\gamma)^{14}\text{N}$ have been extensively analyzed in terms of $R$-matrix theory and the results reported in Fowler, Caughlan and Zimmerman (1967). The results produce considerable confidence in the extrapolation of the measurements above 100 keV on these and other CNO bi-cycle reactions to the low energies ($\sim 25 \text{ keV}$) relevant under astrophysical circumstances.

In extrapolating measured cross-sections to lower energies where the Coulomb barrier reduces the reaction rates to values too low to detect the
ps that Davis can expect 4 \pm 3 counts per finite time of bombardment and detection. It depends critically on the opacity of solar \(r\), the mass fraction of heavy elements, and with great interest and no little trepidation - that some nuclear reactions in stars face a crucial test.

Hebbard and Vogl (1960), Vogl (1963) and independence of the cross-sections for \(^{12}\text{C}(p,\gamma)\) ... various elements, \(\phi_{X}(^7\text{Be})\) = neutrinos from \(^7\text{Be}\) decay in the Sun ... (1967) in our laboratory puts this bugaboo to rest! The threshold for \(^{14}\text{N}(p,\gamma)^{15}\text{O}\) occurs at 7.293 MeV. As indicated in figure 6, excited states bracketing this threshold have been known for some time at 6.792(\(\frac{1}{2}\)+), 6.860(\(\frac{1}{2}\)) and 7.552(\(\frac{1}{2}\)+) MeV. These states have analogues in \(^{15}\text{N}\) at 7.300(\(\frac{1}{2}\)+), 7.155(\(\frac{3}{2}\)+) and 8.312(\(\frac{1}{2}\)+) MeV. Note the cross-over in the energy values for the first set of two excited states due presumably to level-shift effects. Hebbard and Povh (1959) found some indication of a state in \(^{15}\text{O}\) at 7.17 \pm 0.05 MeV corresponding to the well-established state in \(^{15}\text{N}\) at 7.563(\(\frac{3}{2}\)+) MeV. Warburton, Olness and Alburger (1965) found no evidence for a state within the Hebbard-Povh error range, but showed that a state did exist near the \(^{14}\text{N}(p,\gamma)^{15}\text{O}\) threshold and assigned an energy 7.284 \pm 0.007 MeV. Within approximately two probable errors this permitted a state energy at \(\sim 7.3\)
MeV with a possible large resonance effect in $^{14}\text{N}(p,\gamma)^{15}\text{O}$. Consternation struck instantly in our laboratory and Hensley undertook an accurate determination of the state energy using $^{16}\text{O}(\tau,\alpha)^{15}\text{O}^*$ as illustrated in figure 7. Differential measurements relative to the well-established 7.552 and 6.860 MeV states using a high resolution magnetic spectrometer as shown in figure 7 enabled Hensley to tie down the state energy at $7.271 \pm 0.002$ MeV, bound by $21.6 \pm 1.1$ keV well below the continuum in $^{14}\text{N}(p,\gamma)^{15}\text{O}$. By angular distribution measurements on $^{16}\text{O}(\tau,\alpha)^{15}\text{O}^*$ Hensley established that

![Energy spectrum of the alpha-particles from $^{16}\text{O}(\tau,\alpha)^{15}\text{O}^*$ at 12.0 MeV laboratory bombarding energy and 50° laboratory angle with the incident beam (Hensley, 1967).](image)

the state spin is $7/2$ and presumably has even (+) parity if the compelling analogy with the 7.563($^2_2^+$) in $^{15}\text{N}$ is accepted. In any case the state can be formed at best by $d$-wave protons in $^{14}\text{N} + \text{p}$ and this implies negligible effect on the thermal cross-section for $^{14}\text{N}(p,\gamma)^{15}\text{O}$ which thus stands as extrapolated from the measurements of Hebbard and Bailey (1963) with $S(O) = 2.75$ keV-barns and $S(O) = 0$.

The non-resonant reaction rate for this reaction is the slowest among the CN isotopes in the CNO bi-cycle and means, for example, that the bi-cycle contributes little to energy generation ($\lesssim 5\%$) in the Sun. Thus the neutrinos from $^{13}\text{N}(e^+\nu)^{12}\text{C}$ and $^{15}\text{O}(e^+\nu)^{14}\text{N}$ are not expected to contribute significantly to the Homestake observations, but there is many a slip between
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consternation effect in $^{14}\text{N}(p,\gamma)^{15}\text{O}$. Consternation
and Hensley undertook an accurate
$^{16}\text{O}(\alpha,\alpha)^{15}\text{O}^{*}$ as illustrated in figure 7.

To the well-established 7.552 and 6.860
on magnetic spectrometer as shown in
the state energy at 7.271 ± 0.002 MeV.

By

on $^{16}\text{O}(\alpha,\alpha)^{15}\text{O}^{*}$ Hensley established that

S(O) =

Davis will be a hero whether or not the rest of us are prophets or croppers.

In regard to nucleosynthesis, all of the new results confirm the expectation
that the CNO bi-cycle converts $^{12}\text{C}$ and $^{16}\text{O}$ predominantly into $^{14}\text{N}$ under
equilibrium conditions. There has been some indication that this conclusion
was in contradiction to spectroscopic observations on stellar abundances.

However, Caughlan (1965) has shown that when a limited supply of protons
is available ($\leq 1$ per $^{12}\text{C}$ nucleus) the equilibrium concentration, $\text{N}/\text{C} \sim 1$
to 100, is not reached even though the $^{13}\text{C}/^{12}\text{C}$ ratio may attain its equili-

brium value of $\sim 1/4$. In any case astronomical theorists must learn to live
with the non-resonant, relatively slow rate of the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction and
all the consequences which follow in regard to abundance rearrangements in
the operation of the CNO bi-cycle and in regard to the expectation that the
bi-cycle is so slow that it does not compete significantly with the $\text{pp}$
chain in neutrino or energy production in stars of approximately one solar mass or
less.

Helium Burning

Our most recent experimental determinations of reaction rate parameters
in $^{3}\text{He} \rightarrow ^{12}\text{C}$ and $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ have been reviewed in detail in Fowler,
Caughlan and Zimmerman (1967). In this paper I wish only to discuss the
experimental and theoretical situation concerning $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$. The un-
known in the calculation of the rate of this reaction has for some years
been the reduced alpha-particle width, $\theta_{\text{He}}^{2}$, of the $1^{-}$ excited state at 7.12 MeV
which is bound by 46 keV. Estimates ranging from $0.1 \leq \theta_{\text{He}}^{2} \leq 1$ have been
made by various authors, Burbidge, Burbidge, Fowler and Hoyle (1957),
Salpeter (1957), Reeves (1965), Fowler and Hoyle (1964), for a variety of
reasons, all with little confidence; uncertainty of a factor of 10 either way
being quoted in some cases.

Since the state of interest is bound relative to $^{12}\text{C} + \alpha$, the reduced alpha-
width cannot be measured directly near resonance as is done in the case of
unbound states. The important effect of the state is on the low energy cross-
section of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ above threshold and this is much too small to measure.

However, the reduced width does enter into the rate of transfer reactions in
which an alpha-particle is picked up by $^{12}\text{C}$ to form the excited state $^{16}\text{O}^{*}$.

The case used in our laboratory is illustrated in figure 8 where we depict the
simulation of $^{12}\text{C}(\alpha)^{16}\text{O}^{*}(\gamma)^{16}\text{O}$ by $^{6}\text{Li}(^{12}\text{C},d)^{16}\text{O}^{*}(\gamma)^{16}\text{O}$. This latter
reaction has been studied by Loebenstein, Mingay, Winkler and Zaidins (1967)
whose results for the alpha-particle pick up by $^{12}\text{C}$ into a number of excited
states of $^{16}\text{O}$ from 6.06 to 10.36 MeV are illustrated in figure 9. The reduced
alpha-particle widths of some of the states which are unbound relative to
$^{12}\text{C} + \alpha$ have been measured by direct methods, particularly that for the $1^{-}$
state at 9.84 MeV ($\theta_{\text{He}}^{2} = 0.85$). Of course the reduced alpha width of the
ground state of $^6\text{Li}$, i.e., the fraction of the time $^6\text{Li}$ can be depicted as $\alpha + d$ enters into the calculation of the absolute transfer rate, but cancels out in the ratio of the transfer into the 7.12 MeV and 9.84 MeV states. There is a serious complication in the unknown contribution of compound nucleus formation, $^6\text{Li} + ^{12}\text{C} \rightarrow ^{18}\text{F} \rightarrow ^{16}\text{O}^* + d$, to the overall reaction rates. Loebenstein et al. made a reasonable allowance for this contribution and from data similar to that exhibited in figure 9 concluded that $\theta^2_{\alpha}(^{16}\text{O}^*, 7.12 \text{ MeV})$ falls in the range 0.06 to 0.14. Eventually the measurements must be carried out at higher energy than now available in our laboratory in order to reduce the compound
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of the time $^6$Li can be depicted as $\alpha + d$ solute transfer rate, but cancels out in the $eV$ and $9.84\ MeV$ states. There is a serious

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nucleus contribution. We hope to have the necessary facilities in the not too distant future.

At the same time in our laboratory Stephenson (1966) has made theoretical calculations on $\theta_1^2(7.12\ MeV)/\theta_1^2(9.84\ MeV)$ using a model for the excited states of $^{16}$O describable in terms of one-particle, one-hole and three-particles, three-holes in the closed neutron–proton $p$-shells at magic number 8. He finds $0.10 \pm 0.05$ for the above ratio so that $\theta_1^2(^{16}\text{O}^*,\ 7.12\ MeV) = 0.085 \pm 0.040$ in good agreement with the experimental results quoted above. Because of the complications in the experimental determination mentioned above, Fowler, Caughlan and Zimmerman (1967) felt compelled to use Stephenson’s results.

There are numerous consequences of these findings not the least of which concerns the relative production of $^{12}$C and $^{16}$O in helium burning. If $^{12}$C($\alpha,\gamma)^{16}$O is slow compared to $^3$He $\rightarrow$ $^{12}$C, helium burning mainly produces $^{12}$C; if $^{12}$C($\alpha,\gamma)^{16}$O is relatively very fast then helium burning mainly produces $^{16}$O. The problem has been analyzed by Deinzer and Salpeter (1964) and with the new results it can be concluded that $^{12}$C and $^{16}$O are produced in approximately equal amounts at the termination of helium burning during the red giant stage of stars in the wide range of masses from 0.5 $M_\odot$ to 50 $M_\odot$.

Carbon Burning and Subsequent Processes

The experiments performed in our laboratory as discussed above indicate that carbon is produced in substantial quantities in helium burning in stars of “ordinary” mass. Thus the next stage of stellar nuclear evolution involves carbon burning. This occurs through the primary reactions $^{12}$C($^{12}$C,$p)^{23}$N, $^{12}$C($^{12}$C,$\alpha)^{20}$Ne, and $^{12}$C($^{12}$C,$n)^{23}$Mg followed by a variety of secondary reactions. The primary reactions have been studied at Chalk River by Almqvist, Bromley and Kuehner (1960) at center-of-mass energies from 14 MeV down to $\sim 5\ MeV$ and their results for the total reaction cross-section have been analyzed in detail by Reeves (1965). In our laboratory Patterson, Winkler and Zaidins (1967) have repeated the Chalk River measurements below 7.5 MeV and have extended the lower limit to 4 MeV. Particular effort has been made to resolve the various proton and alpha-particle groups observed in the first two reactions mentioned above and to obtain high accuracy in all cross-section determinations. Some of the new results are exhibited in Table 1 and figure 10.

It will be noted that the new results agree fairly well with the Chalk River data at 5.0, 6.25 and 7.5 MeV, but at 4.0 and 4.5 MeV fall below the curve fitted by Reeves to the Chalk River data at higher energies. This leads to considerable uncertainty in the extrapolation to the relevant stellar energy ($\sim 2\ MeV$) and indeed the extrapolation of the Reeves curve may give values too high by one or two orders of magnitude. Further measurements are
underway in our laboratory. It is expected that fluctuations will occur in the cross-section as a function of energy and the two values shown in figure 10 below 5 MeV may indicate minima in the true cross-section.

The rate of carbon burning is of important significance in connection with a possible astronomical test of the universality of the weak nuclear interaction exhibited in beta-decay, electron capture and muon decay and capture. The situation has been discussed by Hayashi and Cameron (1962) and by Hayashi, Hōshi and Sugimoto (1962). These authors suggest that certain
red supergiants in luminous clusters such as \( h \) and \( \chi \) Persei are stars with a mass near \( 15 \, M_\odot \) which are in the carbon-burning stage of stellar evolution with central temperatures in the range \( 0.6 \leq T_9 \leq 0.8 \). They show that energy loss by neutrino emission in electron-positron pair annihilation \( (e^+ + e^- \rightarrow \nu + \bar{\nu}) \) is far greater than ordinary energy loss in this temperature range if the weak interaction is "universal", or more specifically if the coupling constant or interaction strength measured in beta-decay, etc., applies to neutrino emission in pair annihilation. Furthermore they show that

\[
\begin{array}{c|c|c}
\text{MeV} & 7 & 8 \\
\text{Thick Target YIELD} & 10^4 & 10^5 \\
\end{array}
\]

FIG. 11. The thick target neutron yield from \( ^{12}\text{C}(\alpha,n)^{16}\text{O} \) as a function of laboratory alpha-particle energy (Davids, 1967).

in this case the neutrino loss is so great that the carbon burning can sustain the red supergiants for only a very short lifetime (\( \sim 10^4 \) years) which would make the relative number of such stars observable at any one time in a cluster very small indeed. They conclude that the weak interaction is not universal in that the coupling constant for \( e^+ + e^- \rightarrow \nu + \bar{\nu} \) must be less than 0.1 of that for the observable weak interactions. On the other hand it is the current view in theoretical physics that the weak interaction is universal.
The new results previously discussed accentuate the difficulty in requiring carbon burning to occur at still higher temperatures to meet neutrino energy losses, thus indicating still shorter lifetimes. Further measurements are indicated and are underway in our laboratory, but in any case it would seem that either the weak interaction is not universal or that current concepts of the advanced stages of stellar evolution are in error. The details of element building during carbon burning and subsequent processes depend critically upon the considerations just discussed. Thus once again we see the importance and significance of careful measurements in laying firm empirical foundations for nucleosynthesis.

A Stellar Neutron Source

Helium burning in stars containing the debris of hydrogen burning via the CNO bi-cycle produces neutrons through the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction. The lower energy cross-section for this reaction has been measured recently in our laboratory by Davids (1967) whose results are shown in figures 11 and 12.

![Graph showing cross-section factor $S(E)$ for $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction.](image)

**Fig. 12.** The cross-section factor $S(E)$ for $^{13}\text{C}(\alpha,n)^{16}\text{O}$ (Davids, 1967).

The extrapolation to the relevant stellar energies ($E_0 \sim 0.2$ MeV) is considerable but can now be made with some confidence.

The neutrons from $^{13}\text{C}(\alpha,n)^{16}\text{O}$ are captured by "seed" nuclei to form heavier nuclei in the so-called $s$ process. The detailed results depend upon the density and temperature during the capture process and these parameters depend in turn upon the cross-section of the reaction supplying the neutrons,
üssed accentuate the difficulty in requiring higher temperatures to meet neutrino energy rter lifetimes. Further measurements are r laboratory, but in any case it would seem s not universal or that current concepts of solution are in error. The details of element and subsequent processes depend critically used. Thus once again we see the importance ments in laying firm empirical foundations

ining the debris of hydrogen burning via ons through the $^{12}$C($\alpha,n$)$^{16}$O reaction. The reaction has been measured recently in our se results are shown in figures 11 and 12.

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<th>Section Factor S(E)</th>
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<td>$E_{\alpha}$ (MeV)</td>
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or $S(E)$ for $^{12}$C($\alpha,n$)$^{16}$O (Davids, 1967).

st stellar energies ($E_\alpha \sim 0.2$ MeV) is con- with some confidence. O are captured by “seed” nuclei to form process. The detailed results depend upon g the capture process and these parameters tion of the reaction supplying the neutrons,

in this case $^{13}$C($\alpha,n$)$^{16}$O. An important part of the necessary information is now available for a detailed treatment of the s-process from initial emission to final capture of the neutrons.

**Observations on the History and the Setting of Galactic Nucleosynthesis**

Nuclear experimentation can elucidate the fine details of the processes of nucleosynthesis—hydrogen burning, helium burning, carbon burning and neutron production, as just discussed and, as we shall learn from other speakers, silicon burning (via the $\alpha$-process), the $e$-process, the $s$-process, the $r$-process and the $L$- (or $\chi$-) process. However, only astronomical observations can elucidate the role these processes have played in galactic nucleosynthesis and the detailed history and setting of that role. The observations to which I refer have been discussed and analyzed in a series of papers by Greenstein (1966), Pagel (1966, 1967) and Dixon (1965, 1966). From the great wealth of information presented by these authors let us concentrate upon the iron to hydrogen ratio in stars of varying age, location and motion in the Galaxy relative to the same ratio in the Sun, namely $f = (\text{Fe/H})/(\text{Fe/H})_\odot$ in a notation used by some authors and $[\text{Fe/H}] = \log (\text{Fe/H})/(\text{Fe/H})_\odot$ as used by others.

One fact of prime importance emerges clearly and unequivocally from these analyses—the stars of the Galaxy do not exhibit a universal, cosmic abundance. The quantity $f$ ranges from values just above $10^{-3}$ in the oldest stars of the Galaxy to values as high as 2 in the youngest stars. There can be no question that nucleosynthesis during stellar evolution has enriched the interstellar medium from which stars are formed over the lifetime of the Galaxy. However, the simple picture of an enrichment, uniform in space and time, can clearly be excluded. There has been a variety of stages and a dramatic historical activity in galactic nucleosynthesis.

Pagel (1966) has studied the correlation of $[\text{Fe/H}]$ with (1) age as judged from position in the Hertzsprung–Russell diagram and (2) various kinematical characteristics such as (2a) motion at right angles to the galactic plane, (2b) galactic rotation velocity relative to circular orbit, (2c) symmetry of velocity distribution and (2d) orbital eccentricity. He finds a general correlation with age and all the kinematical characteristics if fairly wide ranges in $[\text{Fe/H}]$ are considered. There is a general increase in $[\text{Fe/H}]$ in going from the oldest to the youngest stars in the Galaxy and a similar increase in going from halo (Population II) stars to disk (Population I) stars.

The range in the iron to hydrogen ratio involved in these correlations is perhaps most clearly indicated by figures 13 and 14 which are taken with some modification from Dixon (1966). Figure 13 exhibits the frequency distribution function ($N = \text{relative number of stars}$) for metal abundances, specifically $f$, in stars formed in an initial burst of star formation during the collapse
phase of the Galaxy. The idea of a rapid collapse in a period of a few hundred million years during which the halo stars were formed and which terminated in the formation of the galactic disk has been advanced by Eggen, Lynden-Bell and Sandage (1962). Without specific commitment to this particular model and time scale of galactic formation it is clear that during the first billion years of galactic history at the most, considerable nucleosynthesis took place leading to an eventual spread in $f$ from $\sim 10^{-3}$ to $\sim 0.8$ around the value 0.5 in the oldest stars now still on the main sequence in the Galaxy. This nucleosynthesis presumably took place in the more massive, more

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**Fig. 13.** The frequency distribution function for metal abundances in stars formed during the collapse phase (late-type stars at present in a narrow cylinder drawn at right angles to the galactic plane near the Sun). Dixon (1966), except for dashed curve as explained in the text.

**Fig. 14.** The frequency distribution function for metal abundances in the interstellar medium at the present epoch. The curve was derived for the region between 9.5 kpc and 10.5 kpc from the galactic center and may apply to a larger region (Dixon, 1966).
rapid collapse in a period of a few hundred 
rapidly evolving stars formed at roughly the same time as the presently 
rapidly evolving stars formed at roughly the same time as the presently 
existing survivors from the first stage of stellar formation. Dixon's curve 
existing survivors from the first stage of stellar formation. Dixon's curve 
applies to late-type stars at present in a narrow cylinder drawn at right angles 
applies to late-type stars at present in a narrow cylinder drawn at right angles 
to the galactic plane near the Sun. It is my own conviction that if a more 
to the galactic plane near the Sun. It is my own conviction that if a more 
complete sample had been considered a relatively greater number of stars 
complete sample had been considered a relatively greater number of stars 
with \( f \) in the range \( \sim 10^{-3} \) to \( 10^{-1} \) would have been included in the frequency 
with \( f \) in the range \( \sim 10^{-3} \) to \( 10^{-1} \) would have been included in the frequency 
distribution function. This is shown by the dashed curve in figure 13 where 
distribution function. This is shown by the dashed curve in figure 13 where 
an attempt is made to indicate on a very schematic basis both the fact that 
an attempt is made to indicate on a very schematic basis both the fact that 
no stars with \( f = 0 \) have been observed while a fair number with \( 10^{-3} \leq f \leq 10^{-1} \) have been studied.

Figure 14 stands in marked contrast to figure 13 in several respects. 
Figure 14 stands in marked contrast to figure 13 in several respects. It 
It exhibits the frequency distribution function for metal abundances, against 
exhibits the frequency distribution function for metal abundances, against \( f \), in the interstellar medium at the present epoch. In point of fact it is derived 
\( f \), in the interstellar medium at the present epoch. In point of fact it is derived 
from those stars with maximum age equal to one-quarter that of the Galaxy. 
from those stars with maximum age equal to one-quarter that of the Galaxy. 
The age of the Galaxy is taken to be \( 10^{10} \) years in round numbers. The stars 
The age of the Galaxy is taken to be \( 10^{10} \) years in round numbers. The stars 
involved are young disk stars which have formed from the interstellar medium 
involved are young disk stars which have formed from the interstellar medium 
recently, that is to say, in “the present epoch.” The lower limit, \( f \sim 0.5 \), 
recently, that is to say, in “the present epoch.” The lower limit, \( f \sim 0.5 \), 
is characteristic of practically all disk stars in the solar neighborhood, even 
is characteristic of practically all disk stars in the solar neighborhood, even 
the older ones and can be taken as the mean starting point for nucleo-
the older ones and can be taken as the mean starting point for nucleo-
synthesis in the disk as left over from the initial, perhaps collapse, phase of 
synthesis in the disk as left over from the initial, perhaps collapse, phase of 
star formation and evolution. The distribution over the wide range up to 
star formation and evolution. The distribution over the wide range up to 
\( f \sim 2 \) is of the log normal type which is characteristic of the incomplete 
\( f \sim 2 \) is of the log normal type which is characteristic of the incomplete 
mixing of small quantities of one substance, metals in this case, into large 
mixing of small quantities of one substance, metals in this case, into large 
quantities of another, primordial hydrogen in this case. Dixon comments as 
quantities of another, primordial hydrogen in this case. Dixon comments as 
follows:

“The results indicate that the interstellar medium possessed a high degree 
“The results indicate that the interstellar medium possessed a high degree 
of homogeneity at the end of the contraction phase and that subsequent 
of homogeneity at the end of the contraction phase and that subsequent 
enrichment caused the medium to lose its homogeneity. It seems that mixing 
enrichment caused the medium to lose its homogeneity. It seems that mixing 
processes were much more efficient during the early history of the Galaxy 
processes were much more efficient during the early history of the Galaxy 
than during later periods, a view which is consistent with current ideas on the 
than during later periods, a view which is consistent with current ideas on the 
formation of the Galaxy (cf. Oort, 1958) which picture the interstellar 
formation of the Galaxy (cf. Oort, 1958) which picture the interstellar 
medium in an initial state of disordered motion and in an ordered state of 
medium in an initial state of disordered motion and in an ordered state of 
motion thereafter. Presumably disordered motion is conducive to efficient 
motion thereafter. Presumably disordered motion is conducive to efficient 
mixing, ordered motion to inefficient mixing.”

For our present purposes there are three major conclusions. First, there 
For our present purposes there are three major conclusions. First, there 
is abundant evidence that the main production of the heavy elements has 
is abundant evidence that the main production of the heavy elements has 
occurred in stellar nucleosynthesis in the Galaxy. Second, the primordial 
occurred in stellar nucleosynthesis in the Galaxy. Second, the primordial 
material of the Galaxy may have contained metals in abundances of the 
material of the Galaxy may have contained metals in abundances of the 
order of \( 10^{-3} \) to \( 10^{-2} \) of that in the Sun or certain processes of nucleo-
order of \( 10^{-3} \) to \( 10^{-2} \) of that in the Sun or certain processes of nucleo-
synthesis took place in the Galaxy before the formation of any presently 
synthesis took place in the Galaxy before the formation of any presently 
surviving stars. Third, the metal abundances were brought to the order of 
surviving stars. Third, the metal abundances were brought to the order of 
one-half that in the Sun during the first billion years, at most, of galactic 
one-half that in the Sun during the first billion years, at most, of galactic 
history.
The Special Case of Helium

The observed abundance of helium in galactic objects makes the synthesis of this element a very special case indeed. Hoyle and Tayler (1964) gave a review of the observed helium concentrations in various objects, ranging from about 0.27 by mass in the Sun up to more than 0.40 in some planetary nebulae and they suggested that the helium concentration may never be low, even in the oldest stars. Very convincing computations of pulsation of RR Lyrae stars by Christy (1966) and of evolutionary tracks by Faulkner and Iben (1966) indicate that even very old horizontal-branch stars of the halo Population II may have a He/H ratio not very different from the Sun. Hoyle and Tayler argued that reasonable estimates of the integrated luminosity of the Galaxy over its lifetime indicate an energy generation from $^4\text{He} \rightarrow \text{He}$ consistent with the production of only 0.02 to 0.04 helium by mass.

In apparent contradiction to the above, Sargent and Searle (1966) and Greenstein (père) and Münch (1966) have recently obtained convincing evidence for an abnormally low helium abundance in the atmospheres of old, horizontal branch B stars which therefore differ in this respect from all other stellar objects. A possible conclusion is that these stars contain little or no helium in agreement with the general concept of nucleosynthesis in stars. However, Greenstein (fils), Truran and Cameron (1967) point out that the horizontal branch B stars are the only general class of star in which it can be expected that helium will gravitationally settle out of the photosphere. They conclude that these stars may well have formed with the otherwise apparently “universal” abundance of helium. The issue is unresolved at the present time.

Nucleosynthesis in Big and Little Bangs

The possibility that a small abundance of heavy elements and a substantial fraction of the present helium were incorporated in the primordial material of the Galaxy has led to a rebirth of the concept of universal nucleosynthesis in an early high temperature, high density “big bang” stage of the expanding universe. The alternative possibility that these early contaminations were produced in the Galaxy on an extremely short time scale has led to the suggestion that significant nucleosynthesis took place in rapidly evolving, supermassive stars which terminated their evolutionary history in, by comparison, “little bangs.”

The theory of massive systems, including the Universe, expanding and cooling under the laws of general relativity and thermodynamics from a stage of high temperature and high density, has been understood for some time (cf. Alpher and Herman, 1950; Hayashi, 1950; Alpher, Follin and Herman, 1953). The important ingredients required for a revision of the original calculations of Fermi and Turkevich (1950) on the abundances produced in
W. A. Fowler

The Empirical Foundations of Nucleosynthesis

Helium in galactic objects makes the synthesis case indeed. Hoyle and Tayler (1964) gave a concentrations in various objects, ranging Sun up to more than 0.40 in some planetary the helium concentration may never be low, convincing computations of pulsation of R R of evolutionary tracks by Faulkner and Iben horizontal-branch stars of the halo Population different from the Sun. Hoyle and Tayler of the integrated luminosity of the Galaxy generation from $4^4 H \rightarrow 4^4 He$ consistent 0.04 helium by mass. the above, Sargent and Searle (1966) and (1966) have recently obtained convincing helium abundance in the atmospheres of old, therefore differ in this respect from all other vision is that these stars contain little or no general concept of nucleosynthesis in stars. an and Cameron (1967) point out that the only general class of star in which it can invasionally settle out of the photosphere. may well have formed with the otherwise concentration of helium. The issue is unresolved at the

Bangs

Knowledge of heavy elements and a substantial incorporated in the primordial material of the concept of universal nucleosynthesis density "big bang" stage of the expanding lity that these early contaminations were extremely short time scale has led to the synthesis took place in rapidly evolving, ted their evolutionary history in, by com

which bridges the gap at atomic weight 5. Our measurements have shown that this reaction has a rate one hundred times that estimated by Fermi and Turkevich in 1950. The reaction $^3 He(α,γ)^7 Be$ is followed by $^7 Be(α,γ)^{11} C$ which bridges the gap at atomic weight 8. Fermi and Turkevich did not include this reaction in their studies and, in fact, it has not yet yielded to observation and Wagoner, Fowler and Hoyle (1967) were compelled to estimate a reaction rate in this case. One of our former students, Dr. Donald Kohler and his collaborators at the Lockheed Missiles and Space Company,
Fig. 16. Flow diagrams indicating all reactions included by Wagoner, Fowler and Hoyle (1967). All inverse reactions were also included except in the case of the nuclear beta-decays. For all nuclei heavier than $^{16}$O, the other initial nucleus is either a proton or $^4$He.

are now attempting to measure the cross-section of this important reaction. The primary difficulty lies in the strong activity (through $^7$Be$(e^-,\nu)^7$Li*(\gamma)$^7$Li) of targets containing sufficient $^7$Be to yield detectable results under alpha-particle bombardment.

**TABLE 2. MAJOR DIFFERENCES WITH FERMI AND TURKEVICH (1950)**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Production of $^4$He</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D(n,\gamma)T(p,\gamma)He^4$</td>
<td>$\times 10$</td>
</tr>
<tr>
<td>$D(p,\gamma)He^3(n,\gamma)He^4$</td>
<td>$\times 10$</td>
</tr>
<tr>
<td>$He^3(He^4, 2p)He^4$</td>
<td>$\times 10^{-2}$</td>
</tr>
</tbody>
</table>

Bridging the Mass Gaps at 5 and 8

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$He^3(\alpha,\gamma)Be^7$</td>
<td>$\times 100$</td>
</tr>
<tr>
<td>$Be^7(\alpha,\gamma)C^{13}(\alpha,p)N^{14}$</td>
<td>not included</td>
</tr>
<tr>
<td>$3He^4 \rightarrow C^{12}$</td>
<td>by F. and T.</td>
</tr>
</tbody>
</table>

Typical results obtained by Wagoner, Fowler and Hoyle are shown in figures 17, 18 and 19. The free parameter of prime importance in the
The calculations is the constant $h$ relating baryon density to the cube of the temperature (usually in units of $10^9\text{K}$). Thus

$$\rho_b \approx hT_0^3 \text{ g cm}^{-3}$$

In the Universe problem $h$ is related to the current mean density of the Universe, $\rho_0$, and the present value of the universal deceleration parameter, $q_0$, as indicated in the various horizontal scales of figure 17. This relation is fixed only if a value for the current universal background temperature is adopted. Dicke, Peebles, Roll and Wilkinson (1965) have interpreted recent radio observations in microwave wavelengths as indicating that this tem

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**Fig. 17.** Element production in a universal fireball or a massive object expanding from $T_9 \gtrsim 20$. The particular universe can be specified by either the parameter $h$, the present baryon density $\rho_0$ and photon temperature $T_0$, or the present deceleration parameter $q_0$ and $T_0$. The symbol $\theta$ represents $T_0/3^\circ\text{K}$, where the $3^\circ\text{K}$ has been adopted from recent measurements at radio frequencies of a presumed universal background radiation. Solar system abundances are given on the right-hand ordinate of the figure. For $A > 4$, Population II abundances are of order $10^{-2}$ of solar system values (Wagoner, Fowler and Hoyle, 1967).
perature is $T_0 \sim 3^\circ \text{K}$. Alpher and Herman (1948, 1949) predicted 5° K as long ago as 1948! In supermassive stars $h$ is related to the mass by

$$h \approx 10^5 \left( \frac{M_\odot}{M} \right)^4$$

so that figures 18 and 19 apply to $M \approx 10^6 M_\odot$.

The major conclusions of Wagoner, Fowler and Hoyle can be summarized as follows:

1. Helium is produced in a universal fireball as well as in supermassive objects which have bounced, provided that both emerged from temperatures $T \leq 20$. The mass fraction of $^4\text{He}$ produced lies between 0.2 and 0.3 for the universal fireball (assuming $T_0 \sim 3^\circ \text{K}$), but can be higher in a supermassive object. The Galactic helium abundance could approach 40% once all Galactic material has been processed in supermassive stars. It is therefore of great importance to determine helium concentrations in different astronomical bodies. A confirmation of $X(^4\text{He}) \approx 0$ for old stars and of $X(^4\text{He}) \approx 0.4$ for young stars and for some planetary nebulae would point towards supermassive objects as the site of origin for the helium. On the other hand, if it could be shown that $X(^4\text{He})$ is always close to 0.27, this would be evidence favorable to a universal fireball.

2. D, $^3\text{He}$, and $^7\text{Li}$ are also produced in a universal fireball. The ratio $^3\text{He}/^4\text{He}$ appears to have been $\sim 3 \times 10^{-4}$ in the Sun at the time of expansion.
and Herman (1948, 1949) predicted 5°K as the bounce temperature above which stars are related to the mass by

$$M \approx 10^6 M_\odot.$$ 

Wagoner, Fowler and Hoyle can be summarized in Table 1:

<table>
<thead>
<tr>
<th>Mass Fraction</th>
<th>Initial Mass Fractions</th>
<th>Also Final Mass Fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>He4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>He3</td>
<td>10^{-4}</td>
<td></td>
</tr>
<tr>
<td>H1</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>O6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ne23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na22</td>
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<tr>
<td>Ne23</td>
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<tr>
<td>O17</td>
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<tr>
<td>Mg2</td>
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<td>Na22</td>
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<td>Ne23</td>
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<td>Mg2</td>
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<td>Na22</td>
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<tr>
<td>Ne23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For supermassive objects ($h \approx 10^3$, $M \approx 10^6 M_\odot$) which bounce at temperatures in the range $0.5 \lesssim T_B \lesssim 2.0$ with initial composition $X(H) = 0.7$, $X(^4\text{He}) = 0.3$, and $X(^3\text{He}) = 10^{-4}$ (Wagoner, Fowler and Hoyle, 1967).

3. Universal synthesis of the heavy elements in the big bang is impossible if the background microwave observations are interpreted to indicate a present-day universal temperature of 3°K and if the red-shift observations are interpreted to set an upper limit on the present-day universal density of $10^{-28}$ g cm$^{-3}$. It is necessary to take $T_0 \approx 3^\circ K$ or $\rho_0 \approx 10^{-28}$ g cm$^{-3}$ if the big bang is to produce heavy elements. Calculations for $T_0 \approx 3^\circ K$, the cold universe, are now underway.

4. The abundances of $^2\text{D}$, $^3\text{He}$, $^4\text{He}$, and $^7\text{Li}$ calculated for $h \approx 7 \times 10^{-6}$ may be taken to support the view that a universal fireball existed in the early stages of the expansion of the universe. The evidence on this point is not unequivocal, however. If the present radiation temperature $\approx 3^\circ K$, this value of $h$ corresponds to a present deceleration parameter $q \approx 5 \times 10^{-3}$ and present universal density $\rho_0 \approx 2 \times 10^{-31}$ g cm$^{-3}$. The search for $^2\text{D}$, $^3\text{He}$, $^4\text{He}$ and $^7\text{Li}$ in the interstellar medium should be given high priority.

5. If the universe contains degenerate electron neutrinos or antineutrinos, then the big bang produced no helium as well as no other heavy elements. Only formation of certain meteorites. This is explicable in terms either of spallation, synthesis in ordinary stars, or production in a fireball. In addition, if D/H was equal to the terrestrial value, $1.5 \times 10^{-4}$, in the primitive Sun then $^3\text{He}/^4\text{He}$ should equal $1.5 \times 10^{-3}$ now. The ambiguity regarding spallation and fireball production also applies to $^7\text{Li}$. 

5. If the universe contains degenerate electron neutrinos or antineutrinos, then the big bang produced no helium as well as no other heavy elements. Only
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hydrogen emerged from the early high temperature, high density stage of the expanding universe. This may be in accord with recent observations which indicate a very low helium content in the surface layers of old B stars. It has been suggested, however, that gravitational settling may have reduced the surface helium abundance below that in the primordial material of these stars.

6. Metals of the iron group are produced in supermassive objects which bounce at very high temperatures, \( T_{9,\text{m}} \approx 20 \). As the first of these metals are synthesized they are built by neutrons to still heavier elements (60 \( \leqslant A \leqslant 100 \)) by a new kind of \( r \)-process. However, this process only affects a mass fraction of \( \sim 10^{-5} \), for by the time the main bulk of the metals are synthesized the neutrons have disappeared.

7. Elements heavier than \( ^{24}\text{Mg} \) are also synthesized at lower bounce temperatures, \( T_{9,\text{m}} \approx 2 \), in supermassive objects initially composed of H and \( ^{4}\text{He} \). In this case, however, there are no neutrons to produce an \( r \)-process.

8. A supermassive object composed initially of essentially pure \( ^{4}\text{He} \) can also synthesize \( ^{12}\text{C} \), but little else that is of interest. This indicates the fact that \( ^{3}\text{He} \rightarrow ^{12}\text{C} \) can bridge the mass gaps at \( A = 5 \) and 8.

9. Significant quantities of \( ^{7}\text{Li}, ^{12}\text{C}, ^{13}\text{C}, ^{14}\text{N}, ^{15}\text{N}, ^{16}\text{O}, ^{21}\text{Ne}, ^{22}\text{Ne} \), and metals are produced in supermassive objects having the range of parameters \( 1 \leqslant h \leqslant 10^3 \) and \( 0.5 \leqslant T_{9,\text{m}} \leqslant 2.0 \), provided a concentration \( \geqslant 10^{-5} \) of \( ^{3}\text{He} \) is initially present in the material along with H and \( ^{4}\text{He} \). This is an example of the effectiveness of the reactions \( ^{3}\text{He}( ^{4}\text{He},\gamma) ^{7}\text{Be}( ^{4}\text{He},\gamma) ^{11}\text{C} \) in bridging masses 5 and 8 if sufficient \( ^{3}\text{He} \) is present, and the density and temperature are high enough.

10. None of the cases we have investigated in this paper produce abundances for \( A \geq 12 \) at all similar to the abundances found in the solar system and in Population I stars. This points strongly to those abundances being due to synthesis in ordinary stars.

11. The heavy element abundances produced in supermassive stars correspond quantitatively to the small abundances of the order of 1% of solar values found in the oldest Population II stars. The relative abundances among elements and isotopes are quite different than those found in the solar system. For example, in some cases \( ^{13}\text{C} \) is produced in greater abundance than \( ^{12}\text{C} \) and N and C are produced in comparable abundances which are considerably greater than that for O. Additional spectroscopic observations on Population II stars are needed to settle this point.

Concluding Remarks

In this talk I have discussed some of the experiments in nuclear physics and the observations in astrophysics which constitute in part the empirical foundations for the theory of nucleosynthesis in ordinary stars, supermassive stars and the early high temperature stage of the expanding Universe. I have not discussed the relevant mass spectroscopic and chemical observations on
The Empirical Foundations of Nucleosynthesis

W. A. Fowler

by high temperature, high density stage of the be in accord with recent observations which pertain in the surface layers of old B stars. It has vitational settling may have reduced the surface the primordial matter of these stars.

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Li, \( ^{12}\text{C}, ^{13}\text{C}, ^{14}\text{N}, ^{15}\text{N}, ^{16}\text{O}, ^{21}\text{Ne}, ^{22}\text{Ne}, ^{24}\text{Mg} \), are not found in the solar system. For example, the reactions \( ^{3}\text{He}(^{4}\text{He}, \gamma) ^{8}\text{Be}(^{4}\text{He}, \gamma) ^{11}\text{C} \) are considered in this paper produce abundances found in the solar system. 3\( ^{2}\text{He} \) is present, and the density and nes investigated in this paper produce abundances found in the solar system, points strongly to those abundances being s.

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ome of the experiments in nuclear physics es which constitute in part the empirical leosynthesis in ordinary stars, supermassive se stage of the expanding Universe. I have pectroscopic and chemical observations on

meteooritic and terrestrial material but this conference will hear a full exposition of this important field by many others including Professors G. J. Wasserburg and D. S. Burnett, my colleagues at the California Institute of Technology. I can only conclude as I began. There are plenty of theories and speculations concerning nucleosynthesis. What is needed now are more numbers, more hard data. I hope I have convinced you that we in experimental nuclear physics are trying to do our part.

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