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# WEAK s-PROCESS IRRADIATIONS*†

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## ABSTRACT

We calculate the overabundances of rare neutron-rich species produced when seed nuclei between silicon and nickel are exposed to small neutron irradiations in order to ascertain whether those species may owe their natural abundances to such a cause. Particular attention is given to $^{54}$Cr and $^{58}$Fe, two relatively prominent neutron-rich species that have been bypassed by calculation of explosive nucleosynthesis. Although it is possible that $^{58}$Fe is due to weak s-processes, it seems unlikely that $^{54}$Cr can be produced along with it because its calculated overabundance is so much less than that of $^{58}$Fe. Uncertainties in key neutron-capture cross-sections do not allow this statement to be made unequivocally, however. If $^{58}$Fe is due to weak s-process irradiations, moreover, it seems that certain lighter species synthesized satisfactorily in explosive oxygen and silicon burning, such as $^{37}$Cl and $^{41}$K, must also be synthesized in the s-process. We regard this as unlikely and therefore doubt that the s-process has played a major role in the synthesis of these nuclei. Accordingly, the origins of $^{54}$Cr and $^{58}$Fe remain somewhat of a mystery. The suggestion of Amiet and Zeh that the r-process nuclei are the heavy seeds for the s-process is ruled out.

## I. INTRODUCTION

The idea of synthesizing certain neutron-rich nuclei by a slow capture of free neutrons (the s-process) has been well developed (Burbidge et al. 1957; Clayton et al. 1961; Seeger, Fowler, and Clayton 1965 [hereinafter referred to as B²FH, CFHZ, and SFC, respectively]; Clayton 1968a, b). Laboratory measurements of neutron-capture cross-sections have demonstrated the basic correctness of the idea (Macklin and Gibbons 1967; Allen, Gibbons, and Macklin 1971 [hereinafter referred to as AGM]). A proper description of the location and strength of the s-process in the nuclear evolution of the Galaxy can therefore be expected ultimately to yield very important astrophysical information. One of the most interesting questions concerns the fraction of the seed nuclei that have been incorporated into stars, irradiated by neutrons, and returned to the interstellar medium without nuclear disruption, and the distribution of neutron fluxes to which those seeds were exposed. The papers cited offered evidence that the s-nuclei heavier than iron were synthesized from iron-group seed, that no single irradiation of iron seed would produce the observed solar system abundances, and that the number of seed exposed to given neutron irradiation is a decreasing function of that irradiation. It has not been possible to extract the seed fraction irradiated by the smallest significant fluxes, because the requirements of the smallest fluxes have not been clear. In this paper we argue that a major line of contemporary thought indicates that one possible requirement of the weak s-process irradiations is the synthesis of $^{58}$Fe and $^{54}$Cr from seed nuclei of iron and chromium. The origin of these two nuclei must now be regarded as one of the major questions for nuclear astrophysics because it provides a

key to the origin of the iron-group abundance peak. For quantitative evaluation of this s-process hypothesis we will also calculate abundances of several other lighter neutron-rich nuclei that might also be synthesized from abundant lighter seed nuclei. We will indicate several neutron-capture cross-sections that must be measured before a complete answer to this problem can be given.

## II. WHY CONSIDER AN s-PROCESS ORIGIN FOR $^{58}$Fe AND $^{54}$Cr?

The first point of this paper will be to motivate the hypothesis that $^{58}$Fe and $^{54}$Cr are due to the s-process. We must not state the case more strongly, because in a problem of this complexity it is not yet possible to disprove all other suggestions of the origins of these two nuclei. We shall instead list below several of the other potential sources of these nuclei along with a brief discussion of why each of those sources seems quantitatively to fail.

### a) Synthesis during Explosive Burning of Oxygen and Silicon

Outstanding success has been achieved in reproducing the abundance distribution of the nuclei by calculating the nucleosynthesis that occurs when nuclear fuels are overheated and quickly expanded. Such nucleosynthesis calculations have come to be called explosive nucleosynthesis, and their quantitative success in the range of atomic weights $20 \leq A \leq 62$ has recently been summarized by Arnett and Clayton (1970), who also give detailed references to the papers that have established the fruitfulness of this procedure. The success is sufficiently compelling that we presently must believe that the elements have largely been synthesized in exploding objects, probably massive stars.

A characteristic result of this explosive burning is that virtually no $^{58}$Fe and $^{54}$Cr are synthesized. This result was first explained by Bodansky, Clayton, and Fowler (1968), who showed that if $^{28}$Si burns fast enough that no substantial neutron enrichment can occur during the burning, the iron peak will grow about a center at $^{56}$Ni in which $^{58}$Fe and $^{54}$Cr have negligible abundances because the excess neutrons are more tightly bound in other common nuclei (e.g., $^{58}$Ni, $^{54}$Fe). Clayton and Woosley (1969) showed that the situation was no better in partially burned silicon that has become neutron-rich; viz., if one demands that $^{58}$Ni be produced in the quasi-equilibrium in its ratio to $^{56}$Fe, the excess neutrons go overwhelmingly into overabundances of $^{54}$Fe and $^{52}$Cr. Those same authors showed that the natural way to synthesize $^{58}$Ni is in an e-process centered on $^{56}$Ni—a distribution containing no $^{54}$Cr or $^{58}$Fe. All of these results have been confirmed and augmented by Arnett, Truran, and Woosley (1971), by Woosley, Arnett, and Clayton (1972), and by Michaud and Fowler (1972). For the purpose of this paper we note that these ideas seem to imply that the three lightest isotopes of chromium and iron result directly from explosive nucleosynthesis but that the most neutron-rich isotopes are not so produced.

### b) Synthesis in a Neutron-rich e-Process

The alternative and older theory of the synthesis of the iron-peak abundances which does produce $^{54}$Cr and $^{58}$Fe consists of an e-process in neutron-rich matter. In this case the abundance peak centers on $^{56}$Fe. The latest discussion of this idea (Fowler and Hoyle 1964) finds $\langle Z \rangle / \langle N \rangle \simeq 0.87$ at $T = 3.8 \times 10^9$ ° K and $\rho = 3.1 \times 10^6$ g cm$^{-3}$ gives the best fit to the iron isotope ratios. This calculation does not, however, yield the required $^{58}$Ni abundance, which is a serious shortcoming inasmuch as there is no candidate other than the e-process for the source of $^{58}$Ni. In an attempt to meet this problem, Fowler and Hoyle (1964) speculated that a second equilibrium source, namely, one rich in $^{50}$Cr, $^{54}$Fe, and $^{58}$Ni, was necessary to admix to one that reproduces the three heaviest isotopes of chromium and iron. No very detailed model of the ejection and freezing of such e-process sources has been constructed, but e-processes dominated by

$^{54}$Fe and $^{58}$Ni are possible near $\langle Z \rangle / \langle N \rangle = 0.925$, so the possibility that the iron peak was synthesized in this way still exists. At present, however, option $(a)$ for iron-peak synthesis seems more plausible since it is a logical extension of the explosive carbon and oxygen shells which so beautifully reproduce the abundances in the range $20 \leq A \leq 42$, and because it falls more naturally into place in a scheme of explosive ejection from stars. For the present paper, then, we assume that the neutron-rich $e$-process has not been the prime natural source of the iron-group nuclei, in which case it would not seem to be a likely source for $^{58}$Fe and $^{54}$Cr.

Other two-component $e$-process solutions are possible, but we will not discuss them in this paper.

### c) Synthesis from Seed Nuclei in Explosive Carbon Burning

There exists the possibility that $^{54}$Cr and $^{58}$Fe could result from reactions on seed nuclei present during explosive carbon burning. The seed nucleus must be about two orders of magnitude more abundant than these daughters, however, because if we assume that $^{24}$Mg is entirely due to explosive carbon burning in which about 5 percent of the $^{12}$C is converted to $^{24}$Mg it follows that only one percent of matter has been processed through an explosive carbon-burning zone (Howard *et al.* 1972). This high seed-to-daughter requirement leaves only $^{52}$Cr, $^{54}$Fe, and $^{56}$Fe as possible seeds for these two nuclei, but a preliminary investigation reveals that they probably cannot be converted with sufficiently high efficiency into $^{54}$Cr and $^{58}$Fe. The neutron burst during the explosion is sufficient to drive the $^{56}$Fe seed through $^{58}$Fe to very heavy isotopes of iron, so no $^{58}$Fe survives. The exothermic $^{57}$Fe$(n, \alpha)^{54}$Cr reaction with $Q = 2.40$ MeV cannot divert a significant fraction of this flow into $^{54}$Cr because neutron energies in excess of 3 MeV are probably needed in order for this reaction to compete with the $(n, \gamma)$ reaction, and at $T_9 = 2$ a negligible fraction of neutrons have such high energy. Synthesis of $^{54}$Cr from $^{54}$Fe seed, either by two $(n, p)$ reactions or by excited-state $\beta$-decay of $^{54}$Fe, seems to be too slow to compete with other counterproductive reactions. Some of the seed $^{52}$Cr will be left as $^{54}$Cr following two $(n, \gamma)$ reactions, but the conversion is not efficient enough to be significant. A full discussion of the fate of seed nuclei during explosive carbon burning is being prepared by Howard *et al.* (1972). For the purposes of this paper we adopt the conclusion that significant yields of $^{54}$Cr and $^{58}$Fe do not result from this source.

### III. PRODUCTION OF $^{54}$Cr AND $^{58}$Fe IN THE $s$-PROCESS

#### a) Introduction

The basic equations for the $s$-process (see, for example, Clayton 1968$b$; B$^2$FH; CFHZ) are

$$\frac{dN(A, \tau)}{d\tau} = \sigma(A - 1)N(A - 1, \tau) - \sigma(A)N(A, \tau) , \qquad (1)$$

where $N =$ the abundance of the $s$-nucleus of atomic mass number $A$, $\tau = \int N_n v_T dt$ (where the integration is from 0 to $t$) is the time-integrated neutron flux or net exposure ($N_n =$ neutron density, $v_T =$ thermal velocity, $t =$ time), and $\sigma(A)$ is an appropriately averaged neutron-capture cross-section. CFHZ developed approximate methods to treat the solution of equation (1) for synthesis of the heavier $s$-process nuclides by neutron capture by iron-peak seed nuclei. Specifically they showed that owing to the relative sharpness of the iron abundance peak and to the statistical nature of the neutron-capture process all seed nuclei could be considered to be the predominant $^{56}$Fe for moderate to large net fluxes. SFC used these methods to derive an exposure distribution valid for moderate to large exposures at $kT = 30$ keV:

$$\rho(\tau) = 10^4 e^{-\tau/0.17} , \qquad (2)$$

where $\rho(\tau)d\tau$ is the number of iron-peak seed nuclei per $10^6$ silicon nuclei which have been exposed to fluxes in the range $\tau$ to $\tau + d\tau$. Equation (2) is not valid for small values of $\tau$; indeed, we must first identify those nuclei owing their abundances to weak irradiations before the correct form of $\rho(\tau)$ for small $\tau$ can be extracted.

CFHZ also discussed the exact solution to the set of differential equations (1). These exact solutions will be the appropriate ones to use for small values of $\tau$. When one allows for multiple seed, the solution is

$$N_k(\tau) = \sum_m S_m \sum_{i=m}^{k} C_{ki}{}^m \exp\left(-\sigma_i \tau\right), \qquad (3)$$

where $S_m$ is the initial abundance of the $m$th seed nucleus, and where

$$C^m{}_{ki} = \frac{\sigma_i}{\sigma_k} \prod_{j=m\neq i}^{k} \frac{\sigma_j}{\sigma_j - \sigma_i}. \qquad (4)$$

For small $\tau$ the abundances produced are largely due to a single seed nucleus $m$. As pointed out by CFHZ, solutions (3) can be computationally laborious and result in considerable loss of significance if the neutron-capture chain is long. However, these solutions work well if one needs to consider only a few nuclei; i.e., if one considers only relatively small exposures ($\tau \lesssim 0.3$ neutrons per mb $= 0.3 \times 10^{27}$ $n$ cm$^{-2}$). The exposure $\tau$ will numerically be expressed in neutrons per millibarn throughout this paper— for example, in equation (2).

One feature of the low-exposures regime is that the stochastic nature of the neutron-capture process will not have operated sufficiently long to wipe out the information about the initial distribution of seed nuclei. The fact that one must take into account the exact distribution of seed nuclei means that with enough experimental knowledge of neutron cross-sections it should eventually be possible to identify those nuclei produced in the weak $s$-process.

As an example of the use of this method, one can show that simple extrapolation of equation (2) to $\tau = 0.0$ will not produce a satisfactory exposure distribution at low exposures. According to it the number of $^{56}$Fe nuclei exposed to neutrons is

$$\int_0^\infty \rho(\tau)d\tau = 1700 \text{ per } 10^6 \text{ Si atoms },$$

or only 0.2 percent of the $8.15 \times 10^5$ $^{56}$Fe nuclei per $10^6$ Si atoms in solar abundances (Cameron 1968). This number is even less than the natural abundance of $^{58}$Fe (2900), so it could not be the source of $^{58}$Fe even if all of the $^{56}$Fe were converted to $^{58}$Fe. The abundance of $^{58}$Fe produced, assuming that $^{56}$Fe is the only seed, is given by equations (2) and (3) as

$$N_{58} = \int_0^\infty \rho(\tau) \sum_{i=56}^{58} C^{56}{}_{58,i} \exp\left(-\sigma_i \tau\right) = 10^4 \sum_{i=56}^{58} \frac{C^{56}{}_{58,i}}{\sigma_i + 1/0.17} = 560, \qquad (5)$$

using the AGM cross-sections $\sigma(56, 57, 58) = 13.5, 30, 4.5$ mb, respectively. The value 560 is only 19 percent of the $^{58}$Fe abundance. An additional 1 percent results from $^{57}$Fe seed. Thus the exposure distribution (2) fails by a factor of 5 to produce sufficient $^{58}$Fe.

The same exposure distribution fails by about a factor of 100 to produce $^{54}$Cr from $^{52}$Cr seed, and therein lies the basic problem; $viz.$, $^{54}$Cr is much harder to synthesize than is $^{58}$Fe by weak $s$-process irradiations. One should emphasize here that production of $^{58}$Fe and of $^{54}$Cr at low exposures utilizes only seed nuclei that are lighter isotopes of the same elements—$^{56}$Fe, $^{57}$Fe, and $^{52}$Cr, $^{53}$Cr, respectively. Thus our arguments are not weakened by the fact that elemental abundances of solar-system material may be

somewhat uncertain (due to unknown fractionation). Isotopic abundance ratios have been measured to be constant throughout the solar-system material to a high degree of accuracy.

With these points in mind the next section will describe the calculation of nucleosynthesis in the weak *s*-process. This examination is necessary, because exposure distributions having a different shape from equation (2) could in principle produce more favorable ratios of $^{54}$Cr to $^{58}$Fe.

### b) The Calculations

In order to evaluate the effects of low exposures in the *s*-process, it is necessary to include the detailed network of neutron-capture reactions among the iron-group seed nuclei. Figure 1 shows the reaction network which was used in the iron-group region. The seed nuclei were chosen to be the products of explosive nucleosynthesis as outlined by Arnett and Clayton (1970). These included all nuclei in figure 1 up to $^{62}$Ni, with the exceptions of $^{54}$Cr and $^{58}$Fe. The abundances of the seed nuclei characteristic of Population I stars were taken to be those of solar-system material as reported by Cameron (1968). Equations (1) were integrated by using a Runge-Kutta method described by Peters (1968). The starting point at $^{51}$V was treated by requiring $N(51, \tau) = $ constant. Owing to the small $(n, \gamma)$ cross-section of $^{52}$Cr this assumption has no effect at the smallest exposures, little effect on the abundance of $^{54}$Cr for $\tau \lesssim 0.3$ neutrons per mb, and no effect on the nuclei beyond the very abundant $^{56}$Fe seed for neutron exposures considered in this paper. As a check on the numerical procedures, the total abundance of all nuclei, allowing for any inflow through $^{51}$V and outflow through $^{65}$Cu, remained constant to better than one part in $10^5$.

The results of a calculation which used the Maxwellian-averaged neutron-capture cross-sections for $kT = 30$ keV reported by AGM are shown in figure 2. The ordinate is the overabundance, defined as the ratio of the calculated abundance to the solar-system abundance,

$$r(A, \tau) = \frac{N(A, \tau)}{N(A, \text{solar system})} .$$ (6)

Thus an overabundance $r > 1$ is required for a nucleus to be produced in the *s*-process. A simple solution to the problem of the abundances of $^{54}$Cr and of $^{58}$Fe would be if
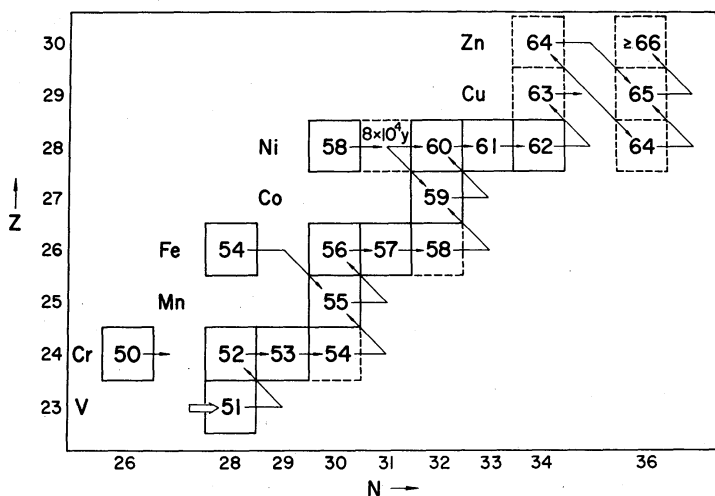


Fig. 1.—The neutron-capture path in the iron group. Stable nuclei are indicated by atomic mass number $A$. Nuclei produced in explosive silicon burning and acting as seed in the *s*-process are enclosed in solid boxes. Candidates for *s*-process synthesis are shown as dashed boxes. Inflow at $^{51}$V is that necessary to maintain the abundance of this nucleus.
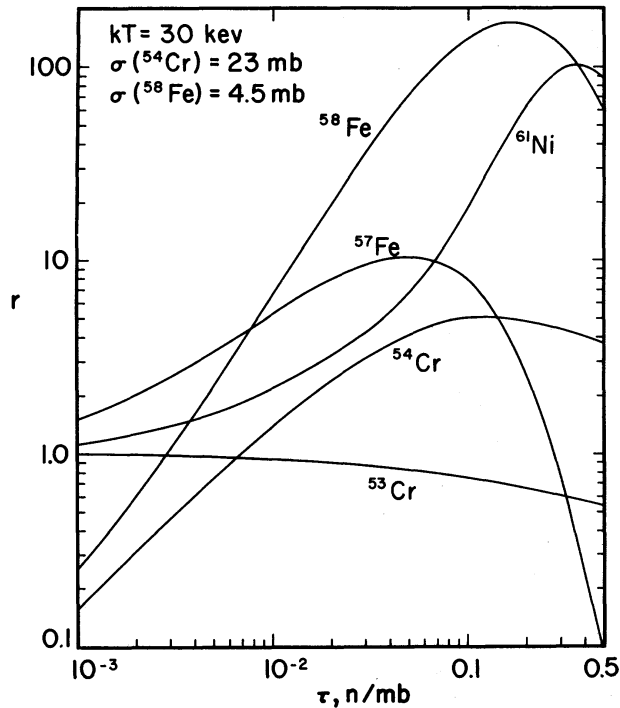
FIG. 2.—The overabundance ratio in the $s$-process, $r = N(\tau)/N$(solar system), plotted as a function of neutron exposure $\tau$. The cross-sections used in these calculations are those reported by AGM for $kT = 30$ keV.

$r(54, \tau^*) = r(58, \tau^*) \equiv r^*$, some number substantially greater than unity, for some exposure $\tau^*$ when all other nuclides had $r(A, \tau^*) < r^*$. Then one could say that there is a peak in the neutron exposure distribution at $\tau = \tau^*$, implying that a fraction $1/r^*$ of solar-system material had received exposures in the range of that peak. However, this is not the case, because $r(58, \tau)/r(54, \tau) > 3$ in the range of interest. In addition there is the problem that $^{57}$Fe is also produced more readily than $^{54}$Cr, and below $\tau \approx 8 \times 10^{-3}$ more readily than $^{58}$Fe as well. Even if one gives up the hope of synthesizing $^{54}$Cr, the fact that $^{57}$Fe is synthesized so satisfactorily in explosive silicon burning suggests that no more than about 10 percent of the iron seed could have received very weak irradiations in the range $5 \times 10^{-3} < \tau < 10^{-2}$. The discrepancy between $^{58}$Fe and $^{54}$Cr increases at higher exposures where the overabundance of $^{57}$Fe becomes considerably less than those of $^{58}$Fe and $^{61}$Ni, whose high values show that no more than about 1 percent of the iron seed have received weak irradiations in the range $5 \times 10^{-2} < \tau < 5 \times 10^{-1}$.

Figure 3 illustrates the effect of a small modification of the measured cross-sections within the error limits reported by AGM. Because AGM have reported only estimates for the cross-sections of $^{54}$Cr and $^{58}$Fe, we have reduced their estimate of $\sigma(^{54}$Cr$)$ by a factor of about 4 and doubled their estimate of $\sigma(^{58}$Fe$)$ in an attempt to make those overabundances more nearly equal. These changes have little effect at the smaller exposures, but do reduce slightly the height and width of the overabundance of $^{58}$Fe and increase significantly that of $^{54}$Cr. This suggests that laboratory measurements of these isotopic neutron-capture cross-sections will be needed to settle this possibility. However, the difficulty of a solution at exposures larger than $\tau \sim 0.3\ n$ per mb, where $N(58, \tau)$ is decreasing rapidly, is the fact that the $^{56}$Fe peak has been shifted by neutron capture through $^{58}$Fe and produces unacceptable overabundances among the Ni and Cu isotopes, as illustrated by the behavior of $^{61}$Ni. The fact that the $^{57}$Fe seed nuclei are
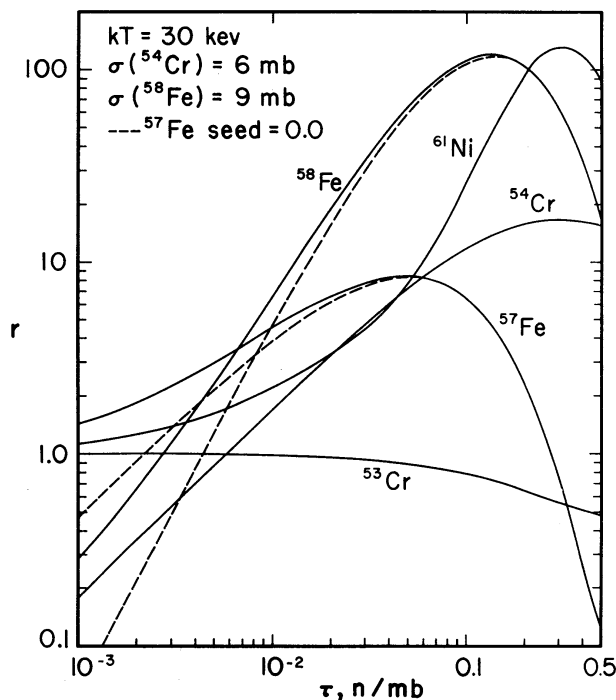
FIG. 3.—The overabundance ratio $r(\tau)$. The values of the cross-sections of $^{54}$Cr and $^{58}$Fe were changed by factors of $\frac{1}{4}$ and 2, respectively, from those used in fig. 2. Dashed curves show the changes produced by removing $^{57}$Fe from the seed nuclei.

playing no major role is illustrated by the dashed curves, which show the change produced when $N(57, 0) = S(57) = 0.0$.

The major problem is that the abundances of the Fe isotopes fall off more rapidly with $A$ than do those of the Cr isotopes. In order for $r(^{54}$Cr) to increase more rapidly than $r(^{58}$Fe), the cross-sections of $^{52}$Cr and $^{53}$Cr would have to be larger than those of $^{56}$Fe and $^{57}$Fe. This is not the case. This problem is aggravated by the relatively low cross-section of $^{52}$Cr (3.8 ± 1.0 mb) owing to its closed neutron shell (magic $N = 28$).

Macklin and Gibbons (1965) reported the variation of Maxwellian-averaged neutron-capture cross-sections with energy. The cross-section of $^{56}$Fe increases much less rapidly with decreasing temperature than do the cross-sections of most nuclei, which vary roughly as $(kT)^{-1/2}$. To investigate the possibility that the s-process overabundances of $^{58}$Fe and $^{57}$Fe would be reduced relative to that of $^{54}$Cr if the s-process were to occur at temperatures lower than 30 keV, we used the 30-keV cross-sections of figure 3 and the temperature dependences reported by Macklin and Gibbons [along with reasonable $(kT)^{-1/2}$ extrapolations where necessary] to estimate the cross-sections at $kT = 5$ keV. This is a reasonable temperature for the low neutron exposures which one would expect to result from $(\alpha, n)$ reactions on the relatively scarce neutron-source nuclei $^{13}$C and $^{17}$O which remain with the relatively abundant $^{14}$N neutron poison at the end of the CNO bi-cycle of hydrogen burning. One might expect that a relatively large fraction of material remixed into the interstellar medium would have received low exposures due to these small neutron sources active during the early phases of helium burning.

The results of this calculation are shown in figure 4 for two methods of extrapolating the cross-sections. The temperature dependences of the critical cross-sections of $^{56}$Fe and $^{57}$Fe are reported by Macklin and Gibbons, but only elemental measures are available for Cr. The solid lines in figure 4 show the results if all isotopes of Cr are assumed to have this elemental temperature dependence. In this case there is a slight decrease in
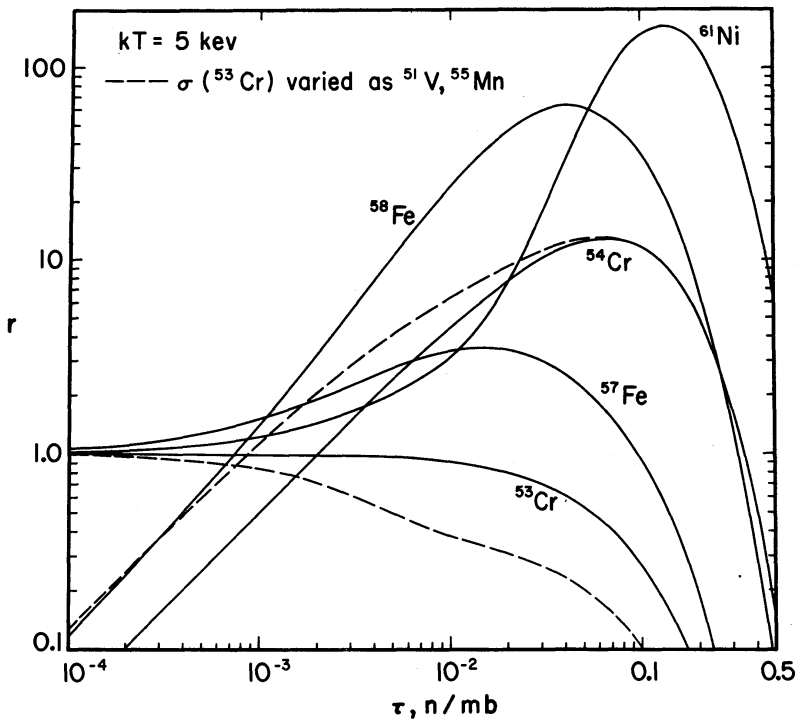
Fig. 4.—The overabundance ratio $r(\tau)$. Cross-sections appropriate to $kT = 5$ keV were used for these calculations. Solid lines show the results of varying the cross-section of $^{53}$Cr according to the measured temperature variation of the elemental cross-section of Cr. Dashed lines show the changes which result when this cross-section is assumed to vary with temperature as do those of other odd-$A$ nuclei in this region.

the overabundance of $^{57}$Fe, but $r(^{58}\text{Fe}) \geq 4r(^{54}\text{Cr})$ for the exposure range in which $^{54}$Cr is produced in greater overabundance than $^{57}$Fe and $^{61}$Ni. However, the cross-sections of the odd-$A$ nuclei such as $^{57}$Fe, $^{55}$Mn, and $^{51}$V increase considerably more rapidly than $(kT)^{-1/2}$. The dashed lines of figure 4 show the changes produced if one assumes that the temperature dependence of the cross-section of $^{53}$Cr is similar to those of $^{51}$V and $^{55}$Mn. The higher cross-section of $^{53}$Cr results in a more rapid initial increase of $^{54}$Cr, making its overabundance comparable to that of $^{58}$Fe at the lower exposures. This result suggests the possibility that the low-exposure component of $s$-processed material could result from exposures of a sizable fraction of the initial seed nuclei at energies closer to 5 than to 30 keV. The dashed curves in figure 4 suggest that about 15 percent of the seed would have to be exposed to fluxes near $\tau = 6 \times 10^{-3}$ for this possibility to work, and even so the $^{58}$Fe/$^{54}$Cr ratio is still too large by a factor of 2. We regard this as marginally possible, considering that some of the key cross-section measurements have not been made. Another vexing problem lies with the lighter nuclei, because the same irradiation seems likely to produce too much $^{37}$Cl from $^{36}$Ar seed nuclei. This comes about because for small $\tau$ the ratio $^{37}\text{Cl}/^{36}\text{Ar} \approx \sigma(36)\tau$, whereas the solar ratio is $(^{37}\text{Cl}/^{36}\text{Ar})_\odot = 0.5 \times 10^{-2}$. Thus the $^{37}$Cl overabundance factor for small $\tau$ is $r(37) \approx 200 \, \sigma(36)\tau$. For the choices $\tau = 6 \times 10^{-3}$ and $\sigma(36) \approx 8$ mb, which seems reasonable at $kT = 5$ keV, we get $r(37) \approx 10$, which is somewhat greater than $r(58)$ in figures 2, 3, and 4 at that value of $\tau$. The difficulty with this is that we do not presently regard $^{37}$Cl as an $s$-process nucleus because it is made easily and convincingly in explosive oxygen burning (Truran and Arnett 1970; Woosley, Arnett, and Clayton 1972; Michaud and Fowler 1972). This criticism also depends strongly on the value of an unmeasured

cross-section, $\sigma(36)$, so we feel that this possibility, though unlikely, must await more laboratory data for final evaluation.

All of the above remarks for $^{37}$Cl production from $^{36}$Ar can be repeated almost exactly for $^{41}$K production from $^{40}$Ca, because $^{41}$K is also believed to be produced in explosive oxygen and silicon burning.

## IV. PRODUCTION OF LIGHTER NUCLEI BY WEAK s-PROCESSES

What overabundances would result from capture of one or two neutrons by the relatively abundant nuclides produced in explosive carbon, oxygen, or silicon burning? Some of these seed nuclei and their daughters (produced by neutron capture) are shown in table 1, which also lists their neutron-capture cross-sections at $kT = 30$ keV

### TABLE 1

#### OVERABUNDANCE FACTORS

| NUCLEUS | $\sigma$ (mb) (or $\tau_{1/2}$) | SEED/ DAUGHTER | OVERABUNDANCE FOR $\tau=$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.007 | 0.01 | 0.02 | 0.04 | 0.07 | 0.10 | 0.15 | 0.25 |
| $^{32}$S | 3 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{33}$S | 10.7 | 125 | 2.5 | 3.5 | 6.5 | 11.4 | 16.4 | 19.3 | 21.2 | 19.6 |
| $^{34}$S | 3.7 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{35}$S | 10(87 d) | .... | ... | ... | ... | ... | ... | ... | * | ... |
| $^{36}$S† | 3 | 310 | ... | ... | 2.1 | 7.4 | 19.2 | 33.3 | 57.5 | 96 |
| $^{36}$Ar | 5.5 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{37}$Ar | (34 d) | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{37}$Cl‡ | 3 | 200 | 7.5 | 10.5 | 20 | 37 | 57 | 72 | 88 | 97 |
| $^{38}$Ar | 5 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{39}$Ar | 11(269 yr) | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{40}$Ar† | 4.5 | 900 | 1.2 | 2.3 | 8.7 | 30 | 76 | 127 | 205 | 300 |
| $^{39}$K | 16 | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{40}$K‡ | 24 | 420 | 0.7 | 1.5 | 5.0 | 15 | 30 | 40 | 47 | 39 |
| $^{39}$K | 16 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{40}$K§ | 24 | 70 | 6.8 | 9.2 | 15 | 20 | 20 | 16 | 8.9 | 2.2 |
| $^{40}$Ca | 7 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{41}$Ca($^{41}$K) | 22(8×10⁴ yr) | 320‖ | 14.2 | 19 | 34 | 51 | 59 | 58 | 47 | 25 |
| $^{42}$Ca | 14 | 152 | 0.5 | 1.0 | 3.5 | 10.6 | 21 | 29 | 34 | 27 |
| $^{43}$Ca | 30 | 666 | ... | 0.2 | 1.3 | 7.5 | 24 | 42 | 62 | 61 |
| $^{44}$Ca | 10 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{45}$Ca | 23(163 d) | ... | ... | ... | ... | ... | # | ... | ... | ... |
| $^{46}$Ca† | 8.6 | 626 | 3.2 | 6.3 | 22 | 67 | 137 | 189 | 225 | 185 |
| $^{45}$Sc‡ | 44 | 46 | 2.7 | 3.5 | 5.5 | 6.8 | 6.1 | 4.8 | 3.0 | 1.1 |
| $^{48}$Ti | 12 | Seed | ... | ... | ... | ... | ... | ... | ... | ... |
| $^{49}$Ti | 20 | 13.4 | 1.0 | 1.4 | 2.3 | 3.4 | 3.7 | 3.3 | 2.3 | 0.9 |
| $^{50}$Ti | 2 | 13.8 | 0.2 | 0.3 | 0.9 | 2.3 | 4.5 | 6.5 | 8.7 | 10 |
| $^{54}$Cr | ** | 35 | 1.2 | 1.7 | 3.3 | 6.0 | 9.4 | 12 | 15 | 16 |
| $^{58}$Fe | ** | 278 | 3.8 | 6.6 | 19 | 50 | 88 | 113 | 120 | 82 |

* Maximum $^{35}$Cl from $^{35}$S decay is $r \leq 3$. This limit also applies if $^{35}$S decays before neutron capture.

† Assumes preceding nucleus captures neutron before decay; i.e., the irradiation is not slow. The overabundance is zero if the preceding nucleus decays before neutron capture.

‡ Assumes preceding radioactive nucleus decays before capturing neutron; i.e., the irradiation is slow. The $^{37}$Cl and $^{45}$Sc overabundances are approximately independent of this assumption, however.

§ Total $^{40}$K overabundance is sum of this and the one due to $^{38}$Ar seed.

‖ The cross-section of $^{41}$Ca is taken equal to that of $^{41}$K. The overabundances of $^{41}$K, $^{42}$Ca, and $^{43}$Ca are then independent of whether $^{41}$Ca decays or captures neutrons during the irradiation.

# Maximum $^{45}$Sc from the decay of $^{45}$Ca after exposure is $r \leq 10.5$.

** Results of the numerical calculation for figure 3.

TABLE 2

TARGETS FOR IMPORTANT $(n, \gamma)$ CROSS-SECTIONS

| Element | Isotopes |
|---|---|
| Sulfur........... | 32, 33, 34, 35*, 36 |
| Chlorine......... | 37 |
| Argon........... | 36, 37*, 38, 39*, 40 |
| Potassium....... | 39, 40, 41 |
| Calcium......... | 40, 41*, 42, 43, 44, 45*, 46 |
| Chromium....... | 52, 53, 54 |
| Iron............ | 56, 57, 58 |
| Cobalt.......... | 59 |
| Nickel.......... | 58, 59*, 60, 61, 62 |

* Radioactive nucleus.

abundance could not have exceeded 1 percent of the solar value without producing an overabundance of $^{58}$Fe and other nuclei listed in table 1. This scheme would require the physically implausible situation that virtually all of r-process and s-process nucleosynthesis occurred at a stage of galactic evolution before 1 percent of the nuclei in the S–Fe range had been synthesized. There is no evidence for such a stage of galactic evolution; in fact, there is convincing evidence against it. Many metal-poor stars—for example, HD 122563—are more deficient in heavy s-nuclei (e.g., Ba) than they are in iron (Pagel 1965), showing that the s-nuclei grew more slowly than the iron group. The existence of s-process overabundances in many barium stars and CH stars (Danziger 1966) shows that the s-process is active in recent times and is not confined to some ancient epoch. These observations rule out the Amiet and Zeh suggestion that the heavy s-nuclei are due to weak exposures.

### V. SUMMARY

We have examined weak s-process irradiations in an attempt to ascertain which rare neutron-rich nuclei are synthesized in that way. The most stringent limit to weak irradiations comes if we regard $^{37}$Cl and $^{41}$K as being primarily due to explosive nucleosynthesis. For example, if we require that three-fourths of the $^{37}$Cl is the result of explosive nucleosynthesis, we conclude that no nucleus in the S–Fe region is likely to be an s-product. The crucial limitation of $^{37}$Cl and $^{41}$K points up the need for laboratory measurements of the neutron-capture cross-sections of $^{36}$Ar, $^{37}$Ar, $^{37}$Cl, $^{40}$Ca, $^{41}$Ca, and $^{41}$K on which this limitation depends. If the cross-sections for $^{36}$Ar and $^{40}$Ca are considerably less than 5 mb at $kT = 30$ keV and/or if $^{37}$Cl and $^{41}$K are regarded as being largely s-products, then $^{58}$Fe and $^{40}$K are also good candidates for s-products, and $^{36}$S, $^{40}$Ar, and $^{46}$Ca will be also if the timescale is much less than 1 year for the weak s-process. The chance that $^{54}$Cr is s-process is small, and $^{50}$Ti is not s-process. Since the nuclear properties of $^{50}$Ti, $^{54}$Cr, and $^{58}$Fe suggest that they might be coproduced under some other circumstances, we hesitate at present to assign any of them to s-process production. Thus the findings of this paper are essentially negative, suggesting that some major aspects of nucleosynthesis are still being overlooked. To finalize any of these conclusions will require more measurements of the several neutron-capture cross-sections upon which they depend. These target nuclei are listed in table 2.

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