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ISOTOPIC ANOMALIES AND PROTON IRRADIATION IN THE EARLY SOLAR SYSTEM

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ABSTRACT

We calculate certain nuclear cross sections relevant to the idea that energetic-particle irradiation of grains forming in the early solar system may be responsible for several recently discovered anomalies in isotopic abundances. We specialize to low-energy spectra, which we take for definiteness to be of the form $d\phi/dE = kE^{-\gamma}$, with a low-energy cutoff in the few-MeV range and $\gamma = 2.5–4.5$ corresponding to a steep spectrum concentrated toward low energy. The cross sections $\sigma(E)$ are calculated from a statistical compound-nuclear model of the Hauser-Feshbach type. They are then averaged over several typical power-law spectra to obtain $\langle\sigma\rangle$. The reactions are identified as those potentially capable of producing known anomalies for an irradiation $\phi_p T_p > 2 \times 10^{20}$ cm^{-2}, which can result in the primordial concentration ^{26}Al/^{27}Al $= 0.6 \times 10^{-4}$, or as those which should produce as-yet-undetected anomalies.

A proton fluence greater than 2×10^{20} cm^{-2} must not have irradiated surviving solids; otherwise, big excesses of ^{36}Ar, ^{80}Kr, and ^{126}Xe would exist in those grains. Therefore, ^{26}Al producing fluences are limited to gas phases, coproducing ^{129}I and detectable differences in ^{50}V, ^{92}Nb, ^{138}La, and ^{180}Ta between irradiated and unirradiated matter. A proton fluence 1.8×10^{16} cm^{-2} will produce enough ^{22}Na in grains to account for Ne-E, but it is difficult to get proper isotope ratios for Ne-E. Anomalies at ^{36}Ar and ^{80}Kr should reveal themselves in such irradiated grains, however. Considering astrophysical problems that plague the irradiation model, it seems that the attribution of isotopic anomalies to early solar irradiation is unconvincing, especially since presolar grains are needed for anomalies (^{16}O, ^{202}Hg) that cannot be produced by the irradiation.

Subject headings: meteors and meteorites — nuclear reactions — nucleosynthesis — solar system: general

I. INTRODUCTION

In a very influential, but perhaps premature, paper, Fowler, Greenstein, and Hoyle (1962) attempted to explain a variety of special abundances in solar-system objects as being due to irradiation of forming planetesimals by energetic protons from the young Sun. The model fell into disrepute primarily for two reasons: (1) experimental isotopic chemistry at that time indicated only a homogeneous isotopic composition in solar-system samples, and (2) the model was perhaps overly ambitious in its attempt to utilize moderated neutron fluxes in the planetesimals, in the hope of thereby producing deuterium and of fixing the lithium isotope ratio, for example. Experimental advances in the past few years have now discovered many cases of anomalous isotopic composition. Heymann and Dziczkaniec (1976) and Kuroda (1975) have, in particular, readvanced detailed schemes of energetic proton irradiation plus fractionation for explanations of anomalies in Mg, Ne, O, Ar, and Xe. Our major purpose will be to evaluate nuclear cross sections relevant to these and other anomalies in the hope of setting constraints on this process.

Whether the necessarily large proton irradiation has in fact occurred or not has become a question of enlarged significance due to an alternative model advanced by Clayton (1975*a*, *b*). In this model, grains precipitating in the expanding gases of a supernova interior (or more likely, of many supernovae) have formed with anomalous isotopic composition and have later been carried into the solar nebula in grains that were never vaporized prior to the accumulation processes leading to larger solid objects. Such surviving pieces of exploding-star dust would have great impact on our knowledge about nucleosynthesis and about the origin of the solar system. This general model was enlarged by Clayton and Hoyle (1976) to include grains of anomalous isotopic composition precipitated in nova explosions. Because these two very different pictures attempt to account for many of the same isotopic anomalies, and because the issues are major ones, we attempt to analyze the nuclear reactions that seem to offer the best evidence. The main contribution of our paper will consist of identifying these potential anomalies and providing estimates of the relevant cross sections for irradiations in the early solar system. We will do this within the context of power-law particle spectra from the early Sun.

II. THE AVERAGE CROSS SECTIONS

Suppose that during the irradiation the proton flux can be written spectrally as $d\phi(E)/dE$ per unit energy. Then we define the effective flux ϕ_p and the effective cross section $\langle\sigma\rangle$ by

$$\phi_p = \int_0^\infty (d\phi/dE)dE\,, \tag{1}$$

$$\langle\sigma\rangle = \phi_p{}^{-1}\int_0^\infty (d\phi/dE)\sigma(E)dE\,. \tag{2}$$

For simplicity we will regard this flux ϕ_p as occurring constantly over a time T_p, so that the total fluence is $T_p\phi_p$. We could consider two possibilities, both idealizations, of the primitive proton spectrum.

Following Heymann and Dziczkaniec (1976) we let

$$\frac{d\phi}{dE} = kE^{-\gamma} \quad (E_0 < E < E_m)$$
$$= 0 \qquad \text{(otherwise)}\,. \tag{3}$$

In this case the average cross section $\langle\sigma\rangle$ in equation (2) is independent of k, but depends on both the spectral index γ and the energy cutoffs E_0 and E_m. The spectrum (3) is defined for a "laboratory energy," which we routinely convert to center-of-mass energy for the calculation of $\langle\sigma\rangle$ by equation (2). Heymann and Dziczkaniec (1976) utilized this power-law spectrum because it is efficient in specifically producing ^{22}Na and ^{26}Al anomalies with the lowest energy protons, without leading to the many variations in other isotopes of Ne and Mg that might be expected in newly forming grains if the irradiation had been harder. Schramm (1971), for example, has discussed production of ^{26}Al due to a harder spectrum, but he was interested in meteoritic heating at a time when the ^{26}Mg anomaly was still undetected. We find the soft power-law spectrum to be a good idea, and accordingly wish to seek its other consequences. One of the contributions of this paper will be the calculation of $\langle\sigma\rangle$ for several reactions that might also be expected to lead to observable anomalies. We will also suppress considerations of E_m by taking cases where it is sufficiently greater than E_0 and where γ is sufficiently large that the actual value of E_m will be unimportant. We will therefore let $E_m \to \infty$ in computing the values of $\langle\sigma\rangle$.

Protons could, on the other hand, be injected into the nebula at a characteristic energy E_m and be degraded to thermal energies by Coulomb collisions leading to ionization or scattering. The energy loss dE/dx per unit path length is a decreasing function of energy: $dE/dx \approx \kappa E^{-1}$. Therefore, lower energy protons see smaller numbers of targets per unit loss of energy, with the result that the average spectrum is peaked at $E = E_m$. In this case we would approximate $\langle\sigma\rangle$ adequately by $\langle\sigma\rangle \approx \sigma(E \approx E_m)$. However, we find the power-law case to be more appealing physically, considering that nature so often provides power-law spectra. Therefore, the tables of results to follow are constructed with the power-law case. We will assume that the combined effects of particle acceleration and collisional energy losses conspire to maintain this power-law spectrum.

Most of the reactions of interest, especially in heavy nuclei, do not have measured cross sections. An outstanding example is ^{180}Hf$(p, n)^{180}$Ta, which could result in abundance anomalies of the rare nucleus ^{180}Ta. We have therefore calculated the (p, n) cross section for that reaction as well as many others of interest using a Hauser-Feshbach code developed by Woosley *et al.* (1975, 1977). Those papers describe the basic physical and computational techniques. The formalism is especially useful for averages over a range of energies, as we have here. Because we restrict our attention here to proton energies that are less than about 20 MeV, the dominant nuclear reaction mechanism should involve the formation of a compound nucleus. Thus calculations based upon a statistical model should provide realistic estimates of the required cross sections. From studied cases in somewhat lighter nuclei ($A < 100$) this Hauser-Feshbach code is known to reproduce (p, γ), (p, n), and (p, α) cross sections to within roughly a factor of 2 of their measured values. We expect it to be comparably good for (p, n) cross sections on heavy nuclei based upon cases where we could compare to experimental data. Since (p, γ) and (p, α) cross sections for nuclei $A > 100$ are not especially well studied, we cannot guarantee the accuracy of the code in these cases and suggest that the results be treated as only order-of-magnitude estimates. Happily such reactions do not appear to be of great importance in the scenario we are discussing.

Some modifications of the formalism of Woosley *et al.* (1975) were required in order to properly estimate cross sections at energies sufficiently high that the (endoergic) two-particle emission thresholds were surpassed. The original code of Woosley *et al.* (1975) was developed to treat reactions at lower energies than considered here and therefore did not properly include the possibility of compound nuclear decay into two particle channels. For example, when the $(p, 2n)$ threshold is exceeded, the (p, n) cross section is expected to begin a slow decline due to the competition from this new open channel. This behavior is reflected in the experimental data of Thomas and Bartolini (1967) for the ^{181}Ta$(p, n)^{181}$W reaction shown in Figure 1. From the (p, n) threshold to about 1.4 MeV above the $(p, 2n)$ threshold (7.66 MeV + 1.4 MeV = 9.06 MeV) the calculated curve is in satisfactory agreement with the measured values. At higher energies, however, the calculated curve, which is in effect the sum over x of all (p, nx) cross sections, increasingly overestimates the actual (p, n) measurements. In fact, for proton energies greater than about

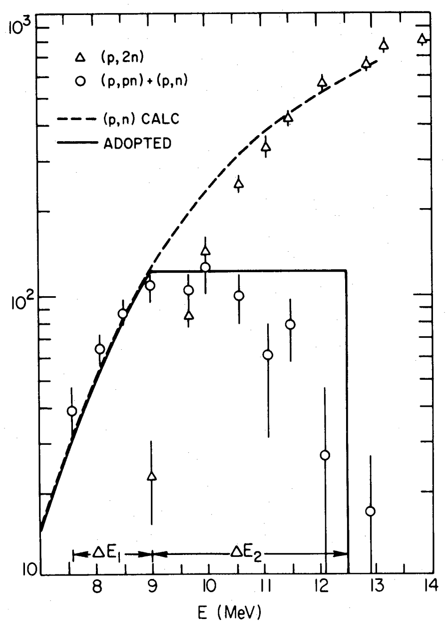

FIG. 1.—Data from Thomas and Bartolini (1976) on ^{181}Ta + p are shown as coded points. The dashed curve is the Hauser-Feshbach calculation for the reaction (p, n) followed by any subsequent de-excitation or particle emission, and it fits the data well. At ΔE_1 above the (p, nn) threshold, that reaction becomes more common than (p, n) without emission of a subsequent neutron. The solid curve shows the prescription we have adopted for (p, n) cross sections above the (p, nn) thresholds.

10 MeV the calculated curve is an excellent representation of the $(p, 2n)$ cross section which is the dominant (p, nx) cross section at those energies.

We adopt the following prescription for the (p, n) cross section. We assume that the (p, n) cross section is correctly calculated by the Hauser-Feshbach code from the (p, n) threshold to an energy ΔE_1 in excess of the $(p, 2n)$ threshold. Based upon the measurements shown in Figure 1, we take ΔE_1 to be 1.4 MeV above the $(p, 2n)$ threshold. We assume that the (p, n) cross section then remains constant for an additional energy ΔE_2, and falls to zero thereafter. We take ΔE_2 to be 3.5 MeV. This prescription is also shown in Figure 1 for the ^{181}Ta$(p, n)^{181}$W reaction. The approximation is admittedly inappropriate at high energies, but that inadequacy has negligible effect on the value of $\langle\sigma\rangle$ in equation (2). In the average over the rapidly falling power-law spectrum, $\langle\sigma\rangle$ is dominated by the lower energies. Little change in the results would be seen if $\Delta E_2 \to \infty$. We defend this characterization of the (p, n) cross sections above the $(p, 2n)$ thresholds only as being reasonable for this particular problem of the power-law spectrum. For clarity, then, we warn the reader that our calculated cross sections are not to be used for hard spectra, especially above 20 MeV where the compound-nucleus reaction mechanism becomes questionable. The spectral parameters of equation (3) will be chosen so that most nuclear reactions occur below 15 MeV per nucleon. The averages for the (p, n) cross sections are listed in Table 1.

An additional problem we faced was the estimation of the $(p, 2\text{-particle})$ cross sections themselves. The cross section code as constructed by Woosley *et al.* does not calculate these. A number of such reactions are of interest, however, so in order to have an order-of-magnitude estimate of their potential roles in low-energy power-law spectra we simply adopted order-of-magnitude estimates, listed in Table 3, for the value of σ at energies sufficiently high to exceed the sum of the threshold plus an effective Coulomb barrier of the

TABLE 1

$\langle\sigma\rangle$ FOR (p, n) REACTIONS*

REACTION	E_0(MeV)	$\langle\sigma\rangle$(mb) $\gamma = 2.5$	$\gamma = 3.5$	$\gamma = 4.5$
^{22}Ne$(p, n)^{22}$Na....	3	1.8 (2)	1.2 (2)	8.3 (1)
	6	3.1 (2)	3.3 (2)	3.3 (2)
	9	2.9 (2)	3.3 (2)	3.5 (2)
^{26}Mg$(p, n)^{26}$Al†...	3	9.3 (1)	5.1 (1)	2.6 (1)
	6	2.3 (2)	2.4 (2)	2.2 (2)
	9	2.3 (2)	2.6 (2)	2.7 (2)
^{40}Ar$(p, n)^{40}$K.....	3	3.1 (2)	2.6 (2)	2.1 (2)
	6	4.6 (2)	5.3 (2)	5.4 (2)
	9	3.5 (2)	4.6 (2)	5.2 (2)
^{50}Ti$(p, n)^{50}$V......	3	3.1 (2)	2.3 (2)	1.7 (2)
	6	5.4 (2)	5.9 (2)	5.7 (2)
	9	4.9 (2)	6.1 (2)	6.1 (2)
^{80}Se$(p, n)^{80}$Br.....	3	1.9 (2)	1.2 (2)	7.6 (1)
	6	4.2 (2)	4.5 (2)	4.4 (2)
	9	4.2 (2)	5.5 (2)	6.2 (2)
^{92}Zr$(p, n)^{92}$Nb....	3	1.4 (2)	7.9 (1)	4.3 (1)
	6	3.3 (2)	3.5 (2)	3.2 (2)
	9	3.7 (2)	4.8 (2)	5.2 (2)
^{126}Te$(p, n)^{126}$I......	3	7.8 (1)	3.8 (1)	2.0 (1)
	6	2.1 (2)	2.1 (2)	2.0 (2)
	9	3.2 (2)	3.7 (2)	4.7 (2)
^{128}Te$(p, n)^{128}$I......	3	6.7 (1)	3.6 (1)	1.7 (1)
	6	1.8 (2)	1.9 (2)	1.7 (2)
	9	2.1 (2)	2.9 (2)	3.3 (2)
^{130}Te$(p, n)^{130}$I......	3	5.2 (1)	3.0 (1)	1.6 (1)
	6	1.4 (2)	1.6 (2)	1.5 (2)
	9	1.3 (2)	1.9 (2)	2.2 (2)
^{138}Ba$(p, n)^{138}$La....	3	6.4 (1)	3.1 (1)	1.5 (1)
	6	1.8 (2)	1.7 (2)	1.5 (2)
	9	2.4 (2)	3.0 (2)	3.4 (2)
^{180}Hf$(p, n)^{180}$Ta....	3	1.5 (1)	7.4	3.3
	6	4.1 (1)	4.1 (1)	3.7 (1)
	9	5.6 (1)	7.7 (1)	9.2 (1)
^{196}Pt$(p, n)^{196}$Au....	3	1.2 (1)	5.7	2.4
	6	3.4 (1)	3.2 (1)	2.7 (1)
	9	5.2 (1)	7.0 (1)	8.0 (1)
^{205}Tl$(p, n)^{205}$Pb....	3	4.0	2.1	9.7 (−1)
	6	1.1 (1)	1.2 (1)	1.1 (1)
	9	1.4 (1)	2.0 (1)	2.4 (1)

* Cross sections calculated from Hauser-Feshbach formulation of Woosley *et al.* 1975, 1977.

† See Note added in proof.

ejected particles. We take the effective Coulomb barrier to be half of $Z_1Z_2e^2/R$ for each outgoing particle. Below the effective threshold the cross section was taken to be zero. The effective threshold $E_{th} = |Q| + \sum E_{Coul}/2$ is also tabulated so that our calculation of $\langle\sigma\rangle$ can be reproduced. For the interaction radii we took: for p or n, $R(\text{fm}) = 1.25\,A^{1/3} + 0.1$; for α, $R(\text{fm}) = 1.09\,A^{1/3} + 2.3$.

These values of $\langle\sigma\rangle$ in Table 3 are to be regarded more as guesses than as calculations and are not on the same footing as values given in Tables 1 and 2. The only calculation performed is of $\langle\sigma\rangle$. This amounts only to determining the fraction of incident protons having sufficient energy to effectively cause the reaction to occur and multiplying by our estimate of $\bar{\sigma}$ above threshold. Our defense of this simplified treatment is that it is simple, is of the correct order of magnitude (at least for the larger $\langle\sigma\rangle$), and allows an estimate to be made of the effects of several interesting reactions. Any experimental determination of these average cross sections would of course be most appreciated.

The format of Tables 1, 2, and 3 warrants additional explanation. The $\langle\sigma\rangle$ are tabulated for three different values of $\gamma = 2.5$, 3.5, and 4.5 and three values of the low-energy cutoff E_0. For the value $E_0 = 3$ MeV, one sees that $\langle\sigma\rangle$ for heavy (p, n) reactions tends to decrease with increasing γ because the cross section itself is, owing to the Coulomb barrier, predominantly an increasing function of energy above the (p, n) threshold. With $E_0 = 9$ MeV, the average $\langle\sigma\rangle$ for heavy (p, n) reactions now increases with the softness γ, because $\sigma(E)$ at high E is a decreasing function of E. Cross section ratios depend upon E_0 primarily through thresholds, and from the definition in equations (1) and (2) one sees that $\langle\sigma\rangle$ must be smallest for small E_0 because the low-energy part of ϕ_p is ineffective at causing reactions. We regard Tables 1, 2, and 3 as a major research result of this paper, even though an exact power-law spectrum down to a sharp cutoff E_0 is clearly an idealization.

The reactions listed are those of outstanding interest in a low-energy power-law spectrum because of anomalies that (1) are known to exist, (2) have been searched for experimentally, or (3) ought to exist at an interesting level on this model. These choices are strictly our own, and we do not claim that Tables 1, 2, and 3 exhaust the list of interesting cross sections.

One of the areas wherein one might find isotopic anomalies on this model is in the light elements Li, Be, B. The irradiated matter will certainly contain newly created light nuclei. Limits to the irradiation would be set by assuming that it is the major source of the light nuclei, as Fowler, Greenstein, and Hoyle (1962) proposed, or by searching for isotopic differences between samples of matter having different irradiations. Bodansky, Jacobs, and Oberg (1975) have published cross sections important for the production of these nuclei, and we have averaged their results over the same power-law spectra and list them in Table 5, which will be found with the Li Be B discussion.

TABLE 2

$\langle\sigma\rangle$ FOR (p, α) REACTIONS*

Reaction	E_0(MeV)	$\langle\sigma\rangle$(mb) $\gamma = 2.5$	$\gamma = 3.5$	$\gamma = 4.5$
$^{16}O(p, \alpha)^{13}N$......	3	3.1 (1)	1.3 (1)	4.8
	6	8.7 (1)	7.1 (1)	5.4 (1)
	9	1.2 (2)	1.3 (2)	1.3 (2)
$^{17}O(p, \alpha)^{14}N$......	3	2.7 (2)	2.5 (2)	2.3 (2)
	6	2.8 (2)	2.9 (2)	2.8 (2)
	9	2.6 (2)	2.9 (2)	2.9 (2)
$^{18}O(p, \alpha)^{15}N$......	3	2.2 (2)	2.3 (2)	2.5 (2)
	6	1.5 (2)	1.7 (2)	1.8 (2)
	9	8.1 (1)	9.3 (1)	1.0 (2)
$^{19}F(p, \alpha)^{16}O$......	3	3.1 (2)	3.0 (2)	2.9 (2)
	6	2.6 (2)	2.8 (2)	2.8 (2)
	9	1.9 (2)	2.2 (2)	2.3 (2)
$^{20}Ne(p, \alpha)^{17}F$......	3	4.4 (1)	1.7 (1)	6.8
	6	1.2 (2)	9.8 (1)	7.7 (1)
	9	1.7 (2)	1.7 (2)	1.6 (2)
$^{23}Na(p, \alpha)^{20}Ne$....	3	1.9 (2)	1.8 (2)	1.7 (2)
	6	1.7 (2)	1.8 (2)	1.8 (2)
	9	1.5 (2)	1.7 (2)	1.7 (2)
$^{24}Mg(p, \alpha)^{21}Na$....	3	1.0 (1)	2.9	7.6 (−1)
	6	2.9 (1)	1.6 (1)	8.6
	9	5.3 (1)	4.4 (1)	3.6 (1)
$^{25}Mg(p, \alpha)^{22}Na$....	3	2.7 (1)	1.1 (1)	4.3
	6	7.6 (1)	6.2 (1)	4.7 (1)
	9	1.1 (2)	1.2 (2)	1.1 (2)
$^{26}Mg(p, \alpha)^{23}Na$....	3	5.1 (1)	3.0 (1)	1.7 (1)
	6	1.2 (2)	1.2 (2)	1.1 (2)
	9	1.1 (2)	1.2 (2)	1.3 (2)
$^{39}K(p, \alpha)^{36}Ar$.....	3	4.4 (1)	3.3 (1)	2.2 (1)
	6	9.5 (1)	1.0 (2)	9.8 (1)
	9	9.6 (1)	1.1 (2)	1.2 (2)
$^{41}K(p, \alpha)^{38}Ar$.....	3	3.7 (1)	3.6 (1)	3.5 (1)
	6	3.5 (1)	4.1 (1)	4.4 (1)
	9	2.1 (1)	2.2 (1)	2.3 (1)
$^{40}Ca(p, \alpha)^{37}K$.....	3	1.5	5.6 (−1)	1.7 (−1)
	6	4.3	3.2	2.0
	9	8.0	8.7	8.1
$^{43}Ca(p, \alpha)^{40}K$.....	3	2.0 (1)	1.0 (1)	5.3
	6	5.2 (1)	5.0 (1)	4.6 (1)
	9	6.0 (1)	6.8 (1)	7.3 (1)
$^{53}Cr(p, \alpha)^{50}V$......	3	2.0	7.5 (−1)	2.7 (−1)
	6	5.7	4.2	3.1
	9	9.6	1.0 (1)	1.0 (1)
$^{54}Fe(p, \alpha)^{51}Mn$....	3	8.1 (−1)	3.2 (−1)	1.0 (−1)
	6	2.2	1.8	1.2
	9	4.2	5.0	5.0
$^{56}Fe(p, \alpha)^{53}Mn$....	3	2.3	9.2 (−1)	3.4 (−1)
	6	6.6	5.2	3.8
	9	1.1 (1)	1.2 (1)	1.2 (1)
$^{132}Xe(p, \alpha)^{129}I$.....	3	3.8 (−3)	1.2 (−3)	3.5 (−4)
	6	1.1 (−2)	7.0 (−3)	4.0 (−3)
	9	2.0 (−2)	1.9 (−2)	1.6 (−2)
$^{205}Tl(p, \alpha)^{202}Hg$....	3	1.3 (−3)	4.0 (−4)	1.0 (−4)
	6	3.8 (−3)	2.3 (−3)	1.2 (−3)
	9	6.9 (−3)	6.3 (−3)	4.8 (−3)

* Calculated from Hauser-Feshbach formulation of Woosley *et al.* 1975, 1977.

TABLE 3

ESTIMATED (p, 2 particle) CROSS SECTIONS*

REACTION	$-Q$(MeV) $\frac{1}{2}E_c$(MeV) $E_{\rm th}$(MeV)	$\bar{\sigma}$(mb) $E_p > E_{\rm th}$	E_0(MeV)	$\langle\sigma\rangle$(mb) $\gamma = 2.5$	$\gamma = 3.5$	$\gamma = 4.5$
^{40}Ca(p, $2p$)^{39}K..........	8.3		3	9.3 (0)	1.9 (0)	3.9 (−1)
	6.3	100	6	2.6 (1)	1.1 (1)	4.4 (0)
	14.6		9	4.8 (1)	3.0 (1)	1.8 (1)
^{40}Ca(p, pn)^{39}Ca..........	15.6		3	6.4 (−1)	1.0 (−1)	1.6 (−2)
	3.2	10	6	1.8 (0)	5.8 (−1)	1.8 (−1)
	18.8		9	3.3 (0)	1.6 (0)	7.6 (−1)
^{42}Ca(p, pn)^{41}Ca..........	11.5		3	9.3 (−1)	1.9 (−1)	3.9 (−2)
	3.1	10	6	2.6 (0)	1.1 (0)	4.4 (−1)
	14.6		9	4.8 (0)	3.0 (0)	1.8 (0)
^{44}Ca(p, $n\alpha$)^{40}K..........	11.1		3	8.4 (−1)	1.6 (−1)	3.0 (−2)
	4.6	10	6	2.4 (0)	9.0 (−1)	3.5 (−1)
	15.7		9	4.3 (0)	2.5 (0)	1.4 (0)
^{130}Te(p, $2n$)^{129}I..........	7.7		3	7.3 (1)	2.8 (1)	1.1 (1)
	0	300	6	2.1 (2)	1.6 (2)	1.3 (2)
	7.7		9	3.0 (2)	3.0 (2)	3.0 (2)
^{197}Au(p, $2n$)^{196}Hg.......	8.2		3	6.6 (1)	2.4 (1)	8.9 (0)
	0	300	6	1.9 (2)	1.4 (2)	1.0 (2)
	8.2		9	3.0 (2)	3.0 (2)	3.0 (2)
^{16}O(p, $2p$)^{15}N..........	12.1		3	8.7 (0)	1.7 (0)	3.3 (−1)
	3.2	100	6	2.5 (1)	9.6 (0)	3.8 (0)
	15.3		9	4.5 (1)	2.7 (1)	1.6 (1)
^{16}O(p, pn)^{15}O..........	15.7		3	7.1 (0)	1.2 (0)	2.1 (−1)
	1.8	100	6	2.0 (1)	6.9 (0)	2.4 (0)
	17.5		9	3.7 (1)	1.9 (1)	9.8 (0)

* The cross section $\bar{\sigma}$ above the effective threshold $E_{\rm th} = |Q| + \sum (E_c/2)$ is a guess based on other measurements.

III. SPECIFIC ANOMALIES

a) ^{26}Al

We choose to look at the likelihood of other anomalies by assuming a low-energy flux sufficient to make the ^{26}Mg anomalies from ^{26}Mg(p, n)^{26}Al and chemical fractionation. We therefore regard this anomaly as a flux monitor, since ϕ_p determines $(^{26}{\rm Al}/^{26}{\rm Mg})_e$ according to

$$(^{26}{\rm Al}/^{26}{\rm Mg})_e = \langle\sigma_{p,n}(^{26}{\rm Mg})\rangle\phi_p\tau(^{26}{\rm Al})\,, \qquad (4)$$

which is the equilibrium concentration applicable if the flux acts for an irradiation time $T_p \gg \tau(^{26}{\rm Al})$. Gray and Compston (1974) and Lee and Papanastassiou (1974) first discovered this anomaly and the suggestion that it correlated with the (Al/Mg) chemical abundance ratio. The question is what value to take for the ratio (^{26}Al/^{26}Mg) at the time grains were forming. Heymann and Dziczkaniec (1976) took the value 2×10^{-3}, in part to accommodate a negative anomaly of that magnitude reported by Lee and Papanastassiou (1974). Later, Lee, Papanastassiou, and Wasserburg (1976) graphed an ensemble of detected anomalies and found a good correlation to exist between the fractional excess $\delta(^{26}{\rm Mg})$ of ^{26}Mg and the aluminum concentration:

$$\delta(^{26}{\rm Mg}) = {\rm constant} \times ({\rm Al/Mg})\,, \qquad (5)$$

where (Al/Mg) was the chemical abundance ratio in the mineral sample. They interpreted this as evidence for an enrichment of ^{26}Mg due to an isotopic aluminum ratio (^{26}Al/^{27}Al) $= 0.6 \times 10^{-4}$ in the primordial solar gas; for then in the forming minerals the equation

$$\left(\frac{^{26}{\rm Mg}}{^{24}{\rm Mg}}\right) = \left(\frac{^{26}{\rm Mg}}{^{24}{\rm Mg}}\right)_\odot + \left(\frac{^{26}{\rm Al}}{^{24}{\rm Mg}}\right)$$

$$= \left(\frac{^{26}{\rm Mg}}{^{24}{\rm Mg}}\right)_\odot + \left(\frac{^{26}{\rm Al}}{^{27}{\rm Al}}\right)_\odot \left(\frac{^{27}{\rm Al}}{^{24}{\rm Mg}}\right) \qquad (6)$$

leads naturally to equation (5). If the ^{26}Al is freely decaying, the condensation epoch would have to be much shorter than $\tau(^{26}{\rm Al})$ to give a good correlation line, but on the picture of continuous irradiation examined in this paper the value of $(^{26}{\rm Al}/^{26}{\rm Mg})_e$ could be maintained for the entire duration T_p of the irradiation. In that case the value

$$\left(\frac{^{26}{\rm Al}}{^{26}{\rm Mg}}\right) = \left(\frac{^{26}{\rm Al}}{^{27}{\rm Al}}\right)\left(\frac{^{27}{\rm Al}}{^{26}{\rm Mg}}\right)_\odot = 0.43 \times 10^{-4} \qquad (7)$$

would be the simplest appropriate value to use. This value should be regarded as a lower limit to the required value, because one could assume that the anomaly-bearing minerals are admixtures of one class of small grains bearing the anomaly with another class of small grains having standard composition. If only a fraction f_{Al} of aluminum-rich grains bear the anomaly (correlating with Al/Mg in those grains), then the ratio ($^{26}Al/^{26}Mg$) in those grains must be a factor f_{Al}^{-1} greater than the minimum value of equation (7). There would be two obvious ways to introduce such a special fraction: (1) they could be the grains forming during the irradiation time T_p, whereas aluminum-rich grains forming either before or after T_p or in regions shielded from the irradiation would contain no anomaly, so that the observed mineral could have accumulated from a mixture of the two; (2) the anomalous grains could be presolar, as first suggested for ^{26}Mg anomalies by Clayton (1975*b*), and developed further by Clayton and Hoyle (1976), so that the observed mineral again accumulated from a mixture of the two. If explosive carbon burning produces $^{26}Al/^{27}Al = 2 \times 10^{-3}$ (Arnett 1969), and if these precipitated in Al-rich minerals during the expansion of the supernova interior as Clayton (1975*b*) suggested, one sees that 3% of the Al-rich minerals in the accumulation phase of the solar nebula would have to have been presolar in order to achieve the average mix $\Delta^{26}Mg/^{27}Al = 0.6 \times 10^{-4}$ in these Al-rich accumulations. This fraction is intriguingly near the presolar ^{16}O fraction (Clayton, Grossman, and Mayeda 1973). We will not attempt to judge the relative merits of those pictures here; rather we introduce these considerations to justify our consideration of equation (7) as an appropriate value for ($^{26}Al/^{26}Mg$). If that is taken to be a steady-state concentration as in equation (4), the steady proton flux, if one takes $\langle\sigma\rangle$ from Table 1 with intermediate choices $\gamma = 3.5$ and $E_0 = 6$ MeV, would have had the value $\phi_p = 0.53 \times 10^7$ cm^{-2} s^{-1}, corresponding to a fluence $\phi_p\ \tau(^{26}Al) = 1.79 \times 10^{20}$ cm^{-2} during one ^{26}Al mean lifetime. For constructing a later Table 4, however, we find it convenient to assume for definiteness of comparisons that the flux lasted exactly 10^6 yr and that the value (4) is to obtain at the end of that period. Then the needed fluence is 2.8×10^{20} cm^{-2}. This is a minimum fluence. If the duration of the irradiation exceeds $\tau(^{26}Al)$, this integrated flux requirement must be increased to 1.79×10^{20} cm^{-2} times the ratio $T_p/\tau(^{26}Al)$. The irradiation time T_p is unknown, but longer irradiation times clearly increase yields of stable daughters without affecting steady ^{26}Al. In listing yields of stable products in Table 4, therefore, we must recall that these are minimum yields, and that they may be much greater if $T_p/\tau(^{26}Al) \gg 1$.

The idea of such fluxes is not new, having been suggested by Fowler, Greenstein, and Hoyle (1972) for nucleosynthesis in the early solar system. It would also make ^{26}Al an important heat source. Schramm (1971) calculated that a *high-energy* proton irradiation $\phi_p T_p > 4 \times 10^{18}$ would render ^{26}Al significant in this regard, and the measurement ($^{26}Al/^{26}Mg) \geq 0.4 \times 10^{-4}$ itself requires that ^{26}Al be significant if that value actually existed *in situ* in solid bodies. On Clayton's (1975*b*; Clayton and Hoyle 1976) model, the ^{26}Al decayed long before the solar-system objects accumulated and no significant heat source is required. Our purpose, of course, is to find other nuclear evidence for or against such large fluxes.

In what follows, we utilize cross section averages from Tables 1, 2, and 3 in evaluating the likely magnitudes of several interesting anomalies. The expected anomalies are listed in two separate columns in Table 4, corresponding in the first case to the ^{26}Al production in a pure gas phase by irradiation of the gas and in the second case to irradiation of condensed grains. These two cases are the simplest limits of a more general problem in which irradiation of a condensing gas and grain mixture could be envisioned. As will be increasingly apparent, this separation will seem necessary if ^{26}Al is to be produced by the irradiation, because irradiation of grains with fluences sufficiently large to produce ^{26}Al will leave very large ($\sim 10^5$) overabundances of selected noble-gas isotopes in those grains, especially ^{36}Ar, ^{80}Kr, and ^{126}Xe. Since large overabundances of these have not been found in meteoritic samples, it seems that any ^{26}Al production by energetic particles in the solar system must occur in a pure gas phase, and that this gaseous ^{26}Al then condenses with stable aluminum as envisioned by Heymann and Dziczkaniec (1976). In considering the irradiation of grains, on the other hand, we will give up hope of producing ^{26}Al there, and concentrate in the second column of Table 4 on interesting anomalies that might be found with much smaller irradiations. For the gas-irradiation column of Table 4 we arbitrarily take a 10^6 yr irradiation, so that $^{26}Al = (1 - e^{-1})^{26}Al_e$, and note as a footnote that if the irradiation greatly exceeds 10^6 yr, the stable yield commensurate with $(^{26}Al/^{26}Mg)_e = 0.43 \times 10^{-4}$ must be increased by the factor $0.63\ T_p/\tau(^{26}Al)$. If, on the other hand, the gas irradiation is much less than 10^6 yr, the stable products need be multiplied by $(1 - e^{-1}) = 0.63$. These factors should be borne in mind in surveying Table 4, where these anomalies are compared with an observed ratio in the final column. In the entries in Table 4, we have used only the spectrum characterized by the low-energy cutoff $E_0 = 6$ MeV and by an index $\gamma = 3.5$. The reader can see from the tables of $\langle\sigma\rangle$ the extent to which the cross section ratio depends upon the power-law spectrum chosen. Comments and clarification of these entries follow in brief subsections.

Thus far considerations have centered upon the irradiation of ^{26}Mg in a gaseous phase followed by chemical concentration of the product ^{26}Al in the solid phase. Obviously such a chemical differentiation must occur if the reaction sequence $^{26}Mg(p, n)^{26}Al$ followed by $^{26}Al(e^+\nu)^{26}Mg$ is to result in a net enhancement of ^{26}Mg. Another possibility to be considered, however, is that the aluminum-correlated ^{26}Mg excesses seen by Lee, Papanastassiou, and Wasserburg (1976) result from the energetic irradiation of ^{27}Al itself in the solid phase. For proton energies in excess of 15 MeV, ^{26}Al can be produced by the reaction $^{27}Al(p, pn)^{26}Al$ with a cross section of roughly 100 mb (Furukawa *et al.* 1971). The high threshold of this reaction implies that either a very

TABLE 4

ISOTOPE PRODUCTION FROM ENERGETIC PARTICLES (E_0 = 6 MeV, γ = 3.5)

Ratio	Reaction	High Flux in Gas*	Low Flux in Solid†	Inferred from Observation	Observation
$^{26}Al/^{26}Mg$..........	$^{26}Mg(p, n)^{26}Al$	4.3 (−5)	...	4.3 (−5)	$^{26}Al/^{27}Al = 6(-5)$ Lee *et al.* 1976
$^{22}Na/^{22}Ne$..........	$^{22}Ne(p, n)^{22}Na$	3.2 (−10)‡	...	3 (−11)	$^{22}Na_E \approx 10^{-9}$ cm^3 g^{-1} Black 1972
$^{22}Na/^{25}Mg$..........	$^{25}Mg(p, \alpha)^{22}Na$	...	1.1 (−9)	1.1 (−9)	$^{22}Ne_E \approx 10^{-8}$ cm^3 g^{-1}
$^{22}Na/^{21}Na$..........	$^{25}Mg(p, \alpha)^{22}Na$ } $^{24}Mg(p, \alpha)^{21}Na$ }	...	0.5	≥40	Eberhardt 1975
$^{20}Ne/^{22}Na$..........	$^{23}Na(p, \alpha)^{20}Ne$ } $^{25}Mg(p, \alpha)^{22}Na$ }	...	1.6	≤1.5	Eberhardt 1975
$^{126}Xe/^{126}Te$.........	$^{126}Te(p, n)^{126}I$	...	1.7 (−9)	1.3 (−7)	Kuroda 1975
$^{22}Ne/^{126}Xe$.........	$^{25}Mg(p, \alpha)^{22}Na$ } $^{126}Te(p, n)^{126}I$ }	...	6 (4)	2 (2)	
$^{129}I/^{130}Te$..........	$^{130}Te(p, 2n)^{129}I$	4.5 (−5)§	...	5 (−5)	$^{129}Xe^*/^{127}I = 10^{-4}$ Podosek 1970
$^{80}Kr/^{80}Se$..........	$^{80}Se(p, n)^{80}Br$	...	8 (−9)	1.2 (−9)	$\Delta^{80}Kr$ Manuel *et al.* 1972
$^{50}V/^{51}V$............	$^{50}Ti(p, n)^{50}V$	9.7 (−5)§	...	$\Delta_{51}{}^{50} \leq 2.4(-5)$	Balsiger *et al.* 1976
$^{92}Nb/^{93}Nb$.........	$^{92}Zr(p, n)^{92}Nb$	3.4 (−4)§	...	2.4 (−2)	If $t_{1/2}$ = 1.7(8) yr (Apt *et al.* 1974)
$^{138}La/^{139}La$.........	$^{138}Ba(p, n)^{138}La$	3.7 (−4)§	...	9.2 (−4)	⊙, Cameron 1973
$^{196}Hg/^{202}Hg$........	$^{197}Au(p, 2n)^{196}Hg$	6.7 (−5)§	...	< 5 (−4)	Jovanovic and Reed 1976
$\Delta^{40}K/^{40}K$..........	$^{43}Ca(p, \alpha)^{40}K$	2.6 (−4)§	...	< 1 (−2)	Begemann and Stegmann 1976
$^{36}Ar/^{38}Ar$..........	$^{39}K(p, \alpha)^{36}Ar$ } $^{41}K(p, \alpha)^{38}Ar$ }	...	33	5.3	⊙, Cameron 1973
$^{36}Ar/^{39}K$...........	$^{39}K(p, \alpha)^{36}Ar$	...	1.8 (−9)	6 (−9)	Manuel *et al.* 1972
$^{17}\delta$................	$^{17}O(p, \alpha)^{14}N$	−6.7 (−5)§		−5 (−2)	Clayton *et al.* 1973
$\Delta^{15}N/^{15}N$..........	$^{16}O(p, 2p)^{15}N$ $^{16}O(p, pn)^{65}O$	7.4 (−3)§		−4.4 to +4.6%	Kung and Clayton 1976
$\Delta^{13}C/^{13}C$..........	$^{16}O(p, \alpha)^{13}N$	3.6 (−5)§	1.2 (−6)	≤6%	Clayton 1963
$^{6}Li/^{4}He$............	$^{4}He(\alpha, x)^{6}Li$	5.9 (−8)§		1.7 (−9)	Cameron 1973
$\Delta^{6}Li/^{13}C$..........	$^{13}C(p, x)^{6}Li$	1.8 (−6)§		5 (−7)	2‰, Gradsztajn *et al.* 1968
$\Delta^{11}B/^{14}N$..........	$^{14}N(p, x)^{11}B$	3.1 (−5)§		7.8 (−4)	⊙, Cameron 1973

* Normalized to ^{26}Al production. Total fluence = 2.8×10^{20} cm^{-2} if uniformly over 10^6 yr, so that $^{26}Al/^{27}Al = (1 - e^{-1})(^{26}Al/^{27}Al)_e$. See Note added in proof.

† Normalized to ^{22}Na production. Total fluence = 1.8×10^{16} cm^{-2}.

‡ Times Max (0.63×10^6 yr/T_p, 1).

§ Times Max (0.63 $T_p/10^6$ yr, 1).

hard irradiation spectrum or a much larger proton flux will be required than for ^{26}Al production via $^{26}Mg(p, n)^{26}Al$. With $\gamma = 3.5$ and $E_0 = 6$ MeV a total fluence $\phi_p \Delta t \approx 6 \times 10^{21}$ cm^{-2}, or about 20 times the flux discussed above, is required to produce the observed ^{26}Mg excesses from ^{27}Al. An interesting consequence of such an irradiation might be the occasional production of ^{26}Mg *deficiencies* relative to ^{24}Mg. This could occur in aluminum-rich minerals as a result of the reaction $^{27}Al(p, \alpha)^{24}Mg$ for spectra sufficiently soft that this reaction occurs 7 times more frequently than $^{27}Al(p, pn)^{26}Al$. Thus the observation by Lee and Papanastassiou (1974) of a sample seeming to have a negative value of $\delta(^{26}Mg)$ might receive a natural explanation. However, as we shall shortly show, such intense fluxes of high-energy protons would lead to large overproductions of ^{21}Ne and other rare gas isotopes. Unless these products can somehow diffuse out of the sample, such heavy irradiations appear to have not occurred.

b) ^{22}Na

The ^{22}Na in the gas will, due to its short 2.6 yr half-life, easily maintain equilibrium between production by $^{22}Ne(p, n)^{22}Na$ and free decay. Heymann and Dziczkaniec (1976) advanced this origin of excess ^{22}Ne in meteorites by noting that the ratio of the equilibrium concentration of ^{22}Na to that of ^{26}Al is roughly equal to the ratio of anomalous excesses discovered in the meteorites. Table 4 shows an equilibrium concentration $(^{22}Na/^{22}Ne)_e = 3.2 \times 10^{-10}$, which is a full order of magnitude greater than the value 3×10^{-11} which could be inferred from the average 10^{-9} cm^{-3} STP per gram of a pure ^{22}Ne source of Ne-E in carbonaceous meteorites (Black 1972) and from a concentration 0.55×10^{-2} $g(^{23}Na)$ g^{-1} in carbonaceous meteorites, which together give $(^{22}Ne/^{23}Na)_e \approx 2 \times 10^{-10}$. Thus the calculated irradiation provides more ^{22}Na than is observed as Ne-E, so that the irradiation can indeed make enough ^{22}Na to be the source of Ne-E, as Heymann and Dziczkaniec (1976) proposed. The amount of ^{22}Na is even greater if the ^{26}Al-producing irradiation occurs in a time less than 10^6 yr. The entry must be multiplied by 0.63×10^6 yr/T_p.

The problem with this explanation of Ne-E is that the carbonaceous meteorites would have to have retained 1–10% of the ^{22}Na concentration during condensation. Since the grains are heated by radiation and collisions, it is difficult to understand how the ^{22}Ne will be trapped in the grain a mere few years after the ^{22}Na atom first attached itself to the grain surface. It would seem if this be so that the grains must grow very quickly, say within a decade, in order to bury a sufficient fraction of the ^{22}Na atoms beneath the grain surface. Perhaps some of the ^{22}Ne could be blasted into the grain by the recoil energy from the positron emission; however, the recoil is only some tens of eV on the average.

One must also consider whether the trapped Ne-E can be due to specific production within the forming grains, where the most likely candidate is ^{25}Mg(p, α)^{22}Na. This reaction is less important than ^{22}Ne(p, n)^{22}Na in the gas, but in grains $^{25}\text{Mg} \gg {}^{22}\text{Ne}$ so that ^{25}Mg will be significant. In this case all of the ^{22}Na produced in a grain will decay to ^{22}Ne within the grain, so it is the integrated production of ^{22}Na, rather than its equilibrium concentration, that is relevant. In a preprint crossing our desks during the writing of this paper, Audouze *et al.* (1976) have in fact made a specific argument for this origin of Ne-E. We include in Table 2 this reaction and also the ^{24}Mg(p, α)^{21}Na cross sections from Woosley *et al.* (1975) averaged over the same exploratory power-law spectra. The latter reaction is important since the work of Eberhardt (1975) has yielded a ^{22}Ne-rich trapped specimen with $^{22}\text{Ne}/^{21}\text{Ne} > 40$. One sees from Table 4 that the power law $\gamma = 3.5$ and $E_0 =$ 6 MeV produces $^{21}\text{Ne}/^{22}\text{Ne} = 2$, an excessive ratio for $(^{21}\text{Ne}/^{22}\text{Ne})_{\text{E}}$. Unless E_0 is low and the spectrum very steep, no chance of a ^{22}Ne-rich result is possible. None of the cross-section ratios in Table 2 will do it. Audouze *et al.* (1976) expressed much the same conclusion, suggesting that a proton pulse between 5 MeV and 10 MeV is needed. Our work complements theirs in this regard. Clearly such a spectrum is a special one. Moreover, the proton energy cannot be too low or the $^{20}\text{Ne}/^{22}\text{Ne}$ will exceed the limit ≤ 1.6 discovered by Eberhardt (1975). The ^{23}Na(p, α)^{20}Ne has a large cross section even at 2 MeV, and Table 2 reports our calculated averages for the power spectra. The mean power law used in Table 4 ($E_0 = 6, \gamma = 3.5$) results in $^{20}\text{Ne}/^{22}\text{Ne} = 1.6$ if we take the chondritic value to be $^{23}\text{Na}/^{25}\text{Mg} = 0.56$, but the value could be excessively large if $E_0 = 3$, as Table 2 shows.

The limits to the integrated flux from the trapped concentrations are rather more severe, however. The ^{22}Ne-rich gas (as opposed to pure ^{22}Ne) totals about 10^{-8} cm^3 STP per gram in carbonaceous chondrites (Black 1972), which is several percent of the total trapped neon. Taking that estimate one has $^{22}\text{Ne}/^{25}\text{Mg} \approx 10^{-9}$ for the E-type neon. But the ^{26}Al-producing irradiations result in $^{22}\text{Na}/^{25}\text{Mg} > 10^{-5}$ within any carbonaceous-chondrite–like grains that may coexist with the gas. This is four orders of magnitude more trapped Ne-E than exists, even assuming that the correct isotopic ratio could be achieved. Even in the condensation picture for ^{22}Na, the ^{25}Mg (p, α)^{22}Na reaction must be a more prolific source of trapped ^{22}Na than the ^{22}Ne(p, n)^{22}Na reaction can be, because that scenario is constrained by the short ^{22}Na half-life to form grains while the radiation is occurring. Anomalies due to Mg in the solid grains seem unavoidable. This argument, which will be reinforced from ^{80}Kr and ^{126}Xe, seems to rule out radiation as a simultaneous source of ^{26}Al and of Ne-E derived from ^{22}Na in the gas. To avoid the dominance of Mg(p, α) reactions in the grains requires that the ^{26}Al be produced in the gas and that the irradiation terminate before grain formation begins, in which case ^{22}Na in the gas is useless. In an alternate column of Table 4, therefore, we consider irradiating grains of carbonaceous-chondrite composition with the much smaller fluence 1.8×10^{16} protons cm^{-2}, which can produce ^{22}Na so that its total daughter $^{22}\text{Ne}/^{25}\text{Mg} = 1.1 \times 10^{-9}$ as estimated above. This low-flux irradiation of solids does not, of course, make enough ^{26}Al for that anomaly.

These considerations have forced us to consider the two separate scenarios in Table 4: (1) a large irradiation of a pure gas producing $^{26}\text{Al}/^{26}\text{Mg} = 4.3 \times 10^{-5}$, (2) a smaller irradiation producing $^{22}\text{Ne}/^{25}\text{Mg} = 1.1 \times 10^{-9}$ within solids. The latter fluence is chosen to produce that ratio uniformly through the solids, which must therefore be small. The Ne-E concentrations actually observed by Black (1972) may be a mixture of grains having higher ^{22}Ne concentrations with grains having little or no irradiation. In such a case, both the ratio $^{22}\text{Na}/^{25}\text{Mg}$ and the corresponding fluence must be raised appropriately.

c) ^{126}Xe

This anomaly will also occur in already formed small grains and in the grains condensing during the irradiation. The leading low-energy reaction is ^{126}Te(p, n)^{126}I(β^- 44%)^{126}Xe. Kuroda (1975) has estimated the cosmic-ray–produced ^{126}Xe in the Murray meteorite as $^{126}\text{Xe}_c = 4.6 \times 10^{-11}$ cm^3 STP per gram, which is roughly equivalent in the meteorite to $^{126}\text{Xe}_c/^{126}\text{Te} = 1.6 \times 10^{-7}$. The production in any small grains during the high irradiation making ^{26}Al in the gas would be about two orders of magnitude greater than the observed concentrations of ^{126}Xe, confirming, as did ^{22}Na, that such severe irradiations of growing grains did not occur, or that the noble gases so produced were either outgassed almost completely or confined to a very small fraction of meteoritic matter. In Table 4, we give instead the ^{126}Xe production due to the low irradiation of solids that could produce Ne-E *in situ*.

It is of some interest to compare the ^{126}Xe production in the grains with the ^{22}Na production. Taking the seed abundance ratio to be $^{25}\text{Mg}/^{126}\text{Te} = 0.9 \times 10^5$ results in $(^{22}\text{Ne}/^{126}\text{Xe}) = 5 \times 10^4$ for the median power-law spectrum, but with only a mild dependence on E_0 and γ. This result is to be compared to the characteristic observed levels $(^{22}\text{Ne}/^{126}\text{Xe}) \approx 200$, with considerable latitude depending upon the individual sample. The discrepancy is large enough to discount a joint origin of these nuclei by irradiation, unless the neon is to be lost at least 100 times faster from grains than is the xenon.

The reactions $^{128}Te(p, n)^{128}I$ and $^{130}Te(p, n)^{130}I$ also result in trapped xenon. These are not entered in Table 4. These $Te(p, n)$ reactions result in the ratio $(^{128}Xe/^{126}Xe) = 3.4$ at $(E_0, \gamma) = (6, 3.5)$, which would not be without interest if a fraction of primitive grains had received a high irradiation. A significant fraction of trapped ^{126}Xe is apparently cosmic-ray produced (see, for example, Kuroda 1975), in which case several percent of ^{128}Xe and ^{130}Xe will be also (assuming for the argument that low-energy protons are responsible). This observation could play a role in the analysis of the light isotopes of the exotic xenon component X (Manuel *et al.* 1972; Lewis, Srinivasan, and Anders 1976; Clayton 1976). These xenon-producing reactions are of course important only in the solids; therefore, grains forming after the irradiation would not contain this proton-induced $^{126,128,130}Xe$. In principle Xe-P could be influenced by some such effect.

d) ^{129}I

Any consideration of xenon anomalies would want to consider the possibilities for ^{129}I. One straightforward possibility with low-energy protons would be $^{128}Te(p, \gamma)^{129}I$. This cross section is, however, like other (p, γ) cross sections, too small to be of interest. We calculate its value for $E_0 = 6$ MeV and $\gamma = 3.5$ to be $\langle\sigma_{p,y}(^{128}Te)\rangle = 0.2$ mb. The $^{132}Xe(p, \alpha)^{129}I$ cross section ($\langle\sigma\rangle \approx 0.01$ mb) is also too small. Any low-energy particle production of ^{129}I would need to utilize the much larger cross sections involving two nucleons, such as $^{130}Xe(p, 2p)^{129}I$, $^{130}Te(p, pn)$, or $^{130}Te(p, 2n)$. The code does not calculate these explicitly, so we approximated these cross sections in the previously described manner. We expect the $(p, 2n)$ cross section to be the most important of these, having a large estimated cross section once the effective threshold is exceeded and being favored energetically as well. Using the result $\langle\sigma_{2n}(130)\rangle = 160$ mb from Table 3 with $E_0 = 6$ and $\gamma = 3.5$, we find $^{129}I/^{130}Te = 4.5 \times 10^{-5}$ for the 10^6 yr high-flux irradiation of Table 4. That yield must be multiplied by $0.63\, T_p/10^6$ if the irradiation is longer than 10^6 yr but less than the ^{129}I lifetime of 24×10^6 yr. This value equals the mean range observed in meteorites (Podosek 1970); therefore, if one is to take this picture for ^{26}Al production, one must question whether ^{129}I in the meteorities was a by-product of stellar nucleosynthesis. Fowler, Greenstein, and Hoyle (1962) raised the same question. The standard 14-million-year spread in formation times would then be suspect, because factor-of-2 differences in $^{129}I/^{127}I$ could instead reflect differences in irradiation history of the admixtures of irradiated material.

e) ^{80}Kr

An analogous situation exists in krypton, for which (p, n) reactions on selenium produce ratios $(^{80}Kr/^{80}Se)$ and $(^{82}Kr/^{82}Se)$ similar to the Xe/Te ratios. Owing to the relative abundances of parents and products, the effect is a much larger percentage anomaly in ^{80}Kr than in ^{82}Kr. By contrast, high-energy spallation reactions would make the biggest percentage anomaly in rare ^{78}Kr, which cannot be produced from $^{78}Se(p,n)$. This peculiarity at ^{80}Kr should perhaps be searched for in this regard, since low-energy protons would produce this surprise. The high irradiation would produce a whopping $^{80}Kr/^{80}Se \approx 10^{-4}$ in Se-bearing grains, an anomaly that would be very large unless virtually all of the ^{80}Kr were subsequently lost. Manuel *et al.* (1972) have estimated the total amount of excess ^{80}Kr released from the carbonaceous chondrite Allende at 800°–1000° C to be 3.4×10^{-12} cm^3 STP per gram. Taking ^{80}Se to be 1.0×10^{-5} g g^{-1} results in an observed anomaly $\Delta ^{80}Kr/^{80}Se \approx 1 \times 10^{-9}$. They actually argue that this small $\Delta ^{80}Kr$ and an associated $\Delta ^{82}Kr$ are due to thermal neutron capture by ^{79}Br and ^{81}Br, respectively. In any case, it is clear that a very severe limit to the low-energy (p, n) anomaly at ^{80}Kr has been established in the experimental literature. Because Allende is so primitive, one would be forced to acknowledge that the ^{26}Al-producing irradiation occurred at a time and place where the nebula was almost totally gaseous. Even the lower flux producing Ne-E in solids, shown in the alternate column of Table 4, produces a ^{80}Kr anomaly larger than those observed.

f) ^{50}V

This nucleus is one of the rare odd-odd nuclei whose small abundances are of very uncertain origin. For the purposes of this problem one could imagine two kinds of limits: (1) *all* of meteoritic and terrestrial ^{50}V could be due to energetic particles; (2) one could detect *variations* in $^{50}V/^{51}V$ due to differences in irradiation histories. Balsiger *et al.* (1976) summarize detected variations of about $\pm 1\%$ in the meteoritic $^{50}V/^{51}V$ ratio, and could not say whether a real effect was in fact observed, since their experimental uncertainty was of the same magnitude. We therefore take the change $\Delta_{51}{}^{50}$ of the isotopic ratio during the irradiation to be $\leq 10^{-2}$. As listed in Tables 1 and 2, we expect $^{50}Ti(p, n)^{50}V$ and $^{53}Cr(p, \alpha)^{50}V$ to be the major low-energy source of ^{50}V. The cross sections allow many possibilities in small grains of differing compositions, but we concentrate in Table 4 on excesses of ^{50}V due to ^{50}Ti in the gas. Taking the solar ratio $(^{51}V/^{50}Ti)_\odot = 1.76$, one computes $\Delta ^{50}V/^{51}V = 9.7 \times 10^{-5}$ from the high-flux irradiation of unfractionated material. This is larger than the limit of Balsiger *et al.* (1976), $\Delta_{51}{}^{51} \approx 2.4 \times 10^{-5}$, which would be exceeded by comparing irradiated and unirradiated material, suggesting that any ^{26}Al production must have been rather uniform through the nebula. This requirement leads to energetic difficulties.

g) ^{92}Nb

This nucleus is odd-odd and has a half-life that is very uncertain, but near 1.7×10^8 years. It should therefore be virtually extinct, although Apt *et al.* (1974) have found a low-level activity corresponding to $^{92}Nb/^{93}Nb = 1.2 \times 10^{-10}$ if $t_{1/2} = 1.7 \times 10^8$ yr. This amount could conceivably be left from galactic nucleosynthesis, as Apt *et al.* show, and the ratio 4.7×10^9 years ago would have been $(^{92}Nb/^{93}Nb)_\odot \approx 2.4 \times 10^{-2}$ if the half-life is taken to be exactly 1.7×10^8 yr. One cannot do too much with this number, because small changes in half-life correspond to large changes in requisite primordial ratio. Nonetheless, it is a sufficiently interesting number to be compared with the expectations due to $^{92}Zr(p, n)^{92}Nb$ in the present model. Taking ^{92}Nb as stable during the irradiation T_p leads to the results in Table 4. Early irradiation can perhaps account for the primordial ^{92}Nb, therefore, depending on its exact primordial concentration. We now await a better determination of the half-life, from which one of two conclusions may follow: (1) if it is significantly less than 1.7×10^8 yr, then ^{92}Nb as measured is almost certainly not primordial; (2) if it is longer than 1.7×10^8 yr, then severe limits on the product $T_p\phi_p$ result. This sensitivity reflects only the fact that an uncertainty of 10^7 yr in $t_{1/2}$ is roughly a factor e in the primordial ratio. For the purposes of this paper, the strongest result would be if $t_{1/2} > 1.7 \times 10^8$ yr, so that incompatability with the ^{26}Al-producing flux would result. Of course, this ^{92}Nb activity was found in terrestrial Nb, and one could conceive of a large meteoritic irradiation without an irradiation of matter destined for the Earth.

h) ^{138}La

This nucleus is another rare odd-odd one, whose abundance is of uncertain origin. Its natural isotopic abundance is $^{139}La/^{139}La = 9.2 \times 10^{-4}$. Table 4 shows that almost this much is expected from the ^{26}Al-producing irradiation via the $^{138}Ba(p, n)^{138}La$ reaction. The ^{138}La yield must be increased if $T_p > 10^6$ yr. This abundance therefore constrains the early-irradiation models. We know of no searches for variations in the isotopic ratio, but clearly a much stronger limit to the irradiation could be set if those variations could be shown to be small (as in the case of $^{50}V/^{51}V$). Attempts to measure this meteoritic ratio, and $^{180}Ta/^{181}Ta$ below, could be valuable.

i) ^{180}Ta

This rare odd-odd nucleus also has an abundance of unknown origin, being $(^{180}Ta/^{181}Ta) = 1.2 \times 10^{-4}$. We know of no searches for anomalies in ^{180}Ta, and therefore can at this time use only its total abundance as a limit. Again we find that even the minimal ^{26}Al-producing irradiation is capable of producing a significant part of solar ^{180}Ta through the $^{180}Hf(p, n)^{180}Ta$ reaction in Table 1.

j) ^{196}Hg

This *p*-process nucleus is interesting because of its rarity and because anomalous ratios of $^{196}Hg/^{202}Hg$ have been detected in meteorites (Jovanovic and Reed 1976). However, the detected variations are all in the direction of smaller (196/202) ratios than either terrestrial or average meteoritic ratios, whereas the low-energy protons might be expected to leave excess ^{196}Hg through the reaction $^{196}Pt(p, n)^{196}Au(\beta^- = 6\%)^{196}Hg$. This cross section is listed in Table 1. An order of magnitude more ^{196}Hg is expected from the $^{197}Au(p, 2n)^{196}Hg$ reaction, whose cross section we cannot calculate from the present code. However, if we assume $\bar{\sigma} = 300$ mb above the $(p, 2n)$ threshold, we show in Table 3 that $\langle\sigma(197)\rangle = 140$ mb at $E_0 = 6$ MeV, $\gamma = 3.5$. Using that value results in the ratio shown in Table 4, which is the total expected from the sum of the two reactions. Suppose for comparison that we take the absence of ^{196}Hg excesses in the work of Jovanovic and Reed (1976) to mean that $^{196}Hg/^{202}Hg$ is less than 10%, their experimental sensitivity, so that $^{196}Hg/^{202}Hg < 5 \times 10^{-4}$. One then sees that Hg isotopes are very close to limiting the irradiation. This limit can be strengthened by taking into account fractionation in higher-temperature minerals, which augments parent Pt and Au. Correlations of $\Delta(196/202)$ with Hg/Pt and Hg/Au (or the lack of correlations) would therefore be useful in limiting the relevance of these radiations. Measurements of the $^{197}Au(p, 2n)^{196}Hg$ cross section would also be useful in this regard.

Of course, the radiations cannot solve the very high 202/196 ratios. Enrichment of ^{202}Hg is best brought about by presolar grains, containing either *s*-process or *r*-process enrichments relative to *p*-process, or large *p*-process yields of ^{202}Pb. On simple grounds the former seems quantitatively preferable because large Pb/Hg enrichments, of order 10^3, would be needed to produce 202/196 overabundances in *p*-process ejecta alone.

We examined the possibility of $^{205}Tl(p, \alpha)^{202}Hg$ enriching ^{202}Hg. Because of the large α-channel Coulomb barrier, the cross sections are too small, however. We nonetheless tabulate our calculations of that $\langle\sigma\rangle$ in Table 2 for completeness. Although it is not listed, our calculations of $^{203}Tl(p, \alpha)^{200}Hg$ yields average cross sections roughly half as large as that of $^{205}Tl(p, \alpha)^{202}Hg$. Both of these estimates should be regarded as uncertain by as much as a factor of 10.

k) *Potassium*

Begemann and Stegmann (1976) have looked for isotopic anomalies in potassium, motivated in part by the prediction (Clayton 1975*b*) of a ^{41}K anomaly carried by presolar grains and correlated with the Ca/K abundance ratio. Although they did not find such a correlation in their first attempt, their results also are relevant to the question of a nebular irradiation. The cross sections for $^{40}Ca(p, 2p)^{39}K$, $^{40}Ca(p, pn)^{39}Ca$, $^{42}Ca(p, pn)^{41}Ca$, $^{44}Ca(p, n\alpha)^{40}K$ are estimated in Table 3. The (p, α) reaction $^{43}Ca(p, \alpha)^{40}K$ in Table 2 is of more interest, because it is the main source of ^{40}K. Examination of these cross sections shows that, for the spectra we are considering, the anomalies are largest percentagewise at ^{40}K. The

^{26}Al-producing reactions are seen to result in Ca-correlated excesses of ^{40}K, whose magnitude (see Table 4) for average solar composition is smaller than the published limit to detected variations.

l) *Argon*

The (p, α) reactions on both ^{39}K and ^{41}K, leading to ^{36}Ar and ^{38}Ar, respectively, are given in Table 2. It is of interest that these could produce detectable excesses of ^{36}Ar in small particles in the high ^{26}Al-producing irradiation. Taking the average spectrum $E_0 = 6$ MeV and $\gamma = 3.5$, we see that because of these low-energy reactions $^{36}\mathrm{Ar}/^{38}\mathrm{Ar} = 34$, well in excess of the solar ratio $(^{36}\mathrm{Ar}/^{38}\mathrm{Ar})_{\odot} = 5.3$. The absolute amount is also large, being in excess of $^{36}\mathrm{Ar}/^{39}\mathrm{K} > 10^{-5}$ for the ^{26}Al-producing irradiations. We are not aware of large amounts of excess ^{36}Ar in meteorites, although the 600°–800° C fraction of Allende (Manuel *et al.* 1972) rises to about 6.0, definitely in excess of the normal ratio. We cannot speculate here as to why this excess ^{36}Ar, amounting to about 10^{-9} cm^3 STP per gram, has been released at these specific temperatures. This observed result for a positive ^{36}Ar anomaly corresponds to $\Delta^{36}\mathrm{Ar}/^{39}\mathrm{K} \approx 6 \times 10^{-9}$, indicating once again that either the irradiation was restricted to a gaseous nebula or the anomalous gases were largely lost from the grains existing then. Precisely the same conclusion was inferred from the ^{126}Xe and ^{80}Kr anomalies. Table 4 therefore lists the anomaly in grains from the lower ^{22}Na-producing irradiation.

m) *Oxygen*

The oxygen isotopic anomalies detected by Clayton, Grossman, and Mayeda (1973) play a key role in the entire spectrum of anomalies. Their simplest, and certainly most stimulating, explanation lies in the existence of an extra component of pure ^{16}O. Both Clayton, Grossman, and Mayeda (1973) and Clayton (1975*a*) have advanced arguments that this comes about naturally through unvaporized presolar grains. However, in the spirit of the present paper, we comment on the difficulties in accounting for these anomalies due to early proton irradiation.

With our low-energy spectrum, the reactions we wish to consider are $^{16}\mathrm{O}(p, \alpha)^{13}\mathrm{N}$, $^{17}\mathrm{O}(p, \alpha)^{14}\mathrm{N}$, $^{18}\mathrm{O}(p, \alpha)^{15}\mathrm{N}$, and $^{19}\mathrm{F}(p, \alpha)^{16}\mathrm{O}$. We imagine for definiteness that very small grains bearing these nuclei initially in solar isotopic composition are irradiated by the power-law spectra. Using the quantity displayed by Clayton, Grossman, and Mayeda (1973),

$$^{17}\delta = \frac{^{17}\mathrm{O}/^{16}\mathrm{O}}{(^{17}\mathrm{O}/^{16}\mathrm{O})_{\mathrm{standard}}} - 1\,, \tag{8}$$

one easily sees that for small variations

$$\frac{^{17}\delta}{^{18}\delta} = \frac{\langle\sigma(16)\rangle - (^{19}\mathrm{F}/^{16}\mathrm{O})\langle\sigma(19)\rangle - \langle\sigma(17)\rangle}{\langle\sigma(16)\rangle - (^{19}\mathrm{F}/^{16}\mathrm{O})\langle\sigma(19)\rangle - \langle\sigma(18)\rangle}\,. \tag{9}$$

We have used the ratio $(^{19}\mathrm{F}/^{16}\mathrm{O})$ to represent the ratio of abundances of those two nuclei in the unirradiated grains. The experimental surprise was, of course, that Clayton, Grossman, and Mayeda (1973) found the ratio in equation (9) to be unity.

The very first problem in the present interpretation is the cross sections. Although there exist many measurements of these cross sections in the 2–3 MeV region, the measurements are not to our knowledge adequate at higher energies. The low-energy data indicate that $\sigma(18) \gg \sigma(17)$, and this fact reflects itself in the low-energy thermonuclear evaluations of Fowler, Caughlan, and Zimmerman (1975). However, what appears to us to have happened is a pure accident of nuclear structure—the density of strong reasonances below 2 MeV is much greater for $^{18}\mathrm{O} + p$ than for $^{17}\mathrm{O} + p$. But that situation is not expected to be true above 5 MeV, where the data are no longer adequate. Although the importance of this problem calls for better measurements, in their absence we have chosen to calculate these cross sections with average level-density parameters for the compound nuclei, using the Hauser-Feshbach code previously described. We think that these should be correct to within a factor of 3 when averaged over an energy band. The ratios of $\langle\sigma\rangle$ may be even more accurate.

Our calculated cross-sections are shown in Figure 2. One sees that $\sigma(18)$ exceeds $\sigma(17)$ only below 3 MeV. Above 10 MeV, $\sigma(17)$ has become considerably larger than $\sigma(18)$, in contrast to the low-energy data. We think these calculations are a good guide to the actual situation. They show that roughly equal depletion of ^{17,18}O may occur for a low-energy spectrum in which most of the protons lie between 3 MeV and, say, 7 MeV. It is perhaps interesting that this is roughly the same spectrum needed to get Ne-E from irradiation of Mg, as described in the ^{22}Na section; however, more detailed inspection shows that a very

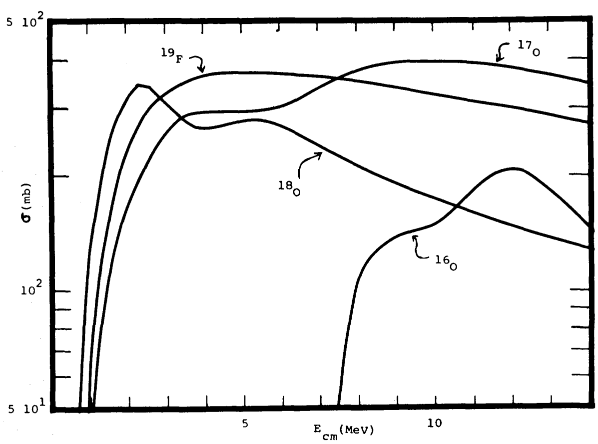

Fig. 2.—Cross sections calculated with the Hauser-Feshbach code for (p, α) reactions on ^{16,17,18}O and on ^{19}F.

carefully circumscribed spectrum would be necessary to get both anomalies right.

With the aid of these cross sections, we can see two ways that equation (9) will naturally yield a ratio equal to one:

1) The proton spectrum can be just the one required. For the power-law spectra, this suggests $3 < E_0(\text{MeV}) < 6$, with the steepest spectra being most satisfactory.

2) The irradiation could, in principle, have been of F-rich minerals, yielding an ^{16}O enrichment if $^{19}\text{F} > {}^{16}\text{O}$. While this might be possible in small amounts, the large quantities of this component in the carbonaceous-chondrite matrix rule it out. Clayton, Grossman, and Mayeda (1973) found that as much as 5% of oxygen was the special component. Since $(^{19}\text{F}/^{16}\text{O})_\odot \approx 10^{-4}$, it is not possible to achieve 5% enrichment of ^{16}O by this ^{19}F reaction. We therefore discard the ^{19}F considerations entirely.

Suppose we take a spectrum that can in principle produce equal depletions of ^{17}O and ^{18}O—say $E_0 = 3$ MeV and $3 < \gamma < 5$, where both cross sections are near $\langle\sigma\rangle = 240$ mb. Taking the product $2.8 \times 10^{20} = \phi_p T_p$ as indicated for the ^{26}Al-producing irradiation, we get $^{17}\delta = {}^{18}\delta = -6.7 \times 10^{-5}$. To achieve 5% depletion would have required a flux $\phi_p T_p = 2 \times 10^{23}$ cm^{-2}. Certainly the evidence we have assembled on other anomalies shows that such a large irradiation of the carbonaceous-chondrite matrix has not occurred. The conclusion that the oxygen anomalies are exotic seems therefore secure. They are very likely an abundant component carried by presolar grains, so that their importance looms large when one considers the set of all isotopic anomalies.

On the other hand, it should not be assumed that the nuclear irradiation has nothing to do with the oxygen isotopic anomalies. Clayton, Onuma, and Mayeda (1976) have developed their laboratory techniques into a sensitive fingerprinting of generic relationships. They detail at least six classes of solar-system objects, based on the oxygen anomalies alone. One type of difference is particularly interesting insofar as our present paper is concerned. The L and LL chondrites appear to have less of the pure ^{16}O component than does terrestrial matter, for one thing; but in addition one notes from Figure 2 of Clayton, Onuma, and Mayeda (1976) that, at a given value of ^{18}O, the chondrites have a value of ^{17}O that is about 0.001 greater than the corresponding value for terrestrial samples. One possibility (out of many that could be constructed) is that the chondrites formed from an ^{17}O reservoir that is 0.1% richer than the terrestrial reservoir. One might wonder if the $^{20}\text{Ne}(p, \alpha)^{17}\text{F}$ reaction could account for this excess if the material of the chondritic meteorites received the irradiation but that of the Earth did not, and indeed it could. We calculate $\langle\sigma_{p,\alpha}(^{20}\text{Ne})\rangle = 98$ mb in the mean conditions of Table 2, so that irradiation of ^{20}Ne gas with the ^{26}Al-producing flux results in $\Delta^{17}\text{O}/^{20}\text{Ne} = 2.7 \times 10^{-5}$. If O and Ne are unfractionated in that gas, an ^{17}O anomaly equal to $\delta^{17}\text{O} = 10^{-2}$ results. This large effect is 10 times the observed difference between L chondrites and Earth. This result, though interesting, seems unable to limit irradiation differences, however, because substantial fractionation of neon from oxygen at the time of the irradiation might be expected.

As a final point we note that the presolar-grain model may also account for the differences in the various classes defined by Clayton, Onuma, and Mayeda (1976). The major effect is the almost 5% component of pure ^{16}O as revealed by the carbonaceous chondrites (Clayton, Grossman, and Mayeda 1973). These presolar grains were precipitated in supernova ejecta where the ^{16}O had just been synthesized. Clayton and Hoyle (1976) showed, on the other hand, that nova dust will be rich in ^{17}O and ^{18}O. They estimated that as much as 10% of interstellar ^{17}O and ^{18}O could reside in nova grains; and although they tentatively expected more ^{18}O than ^{17}O, the percentage anomaly at ^{17}O could be greater than at ^{18}O because of the smaller abundance of ^{17}O. Therefore the nova grains, though less abundant than supernova grains, could be the carriers of the excess ^{17}O. Taking supernova-grain ^{16}O to be 5% of ^{16}O and nova-grain ^{17}O to be 10% of all ^{17}O results in a ratio of oxides in presolar grains

$$\frac{\text{nova-grain oxides}}{\text{supernova-grain oxides}} = \frac{0.10(8040)}{0.05(2.1 \times 10^7)} = 8 \times 10^{-4}\,,$$

where we have inserted Cameron's (1973) values for the oxygen abundances. This is, to order of magnitude, consistent with the estimate of Clayton and Hoyle (1976) that nova dust is about 10^{-3} of interstellar dust.

On this picture then, the L chondrites would contain less supernova dust but more nova dust than does the Earth. It is hard to say whether this is impossible or not, since the nova dust and supernova dust will differ in both size distribution and minerology. If, on the other hand, the nova dust is primarily ^{18}O, as Clayton and Hoyle (1976) initially speculated, the Earth would contain more of both types of dust than do the L chondrites. At this time we do not wish to press further with these arguments, but are content to clarify possible roles of the oxygen anomalies to the basic astrophysical pictures under discussion here.

n) ^{15}N *and* ^{13}C

The same (p, α) reactions on isotopes of oxygen produce isotopes of nitrogen and carbon. Detectable anomalies in those isotopic compositions may occur during a gaseous irradiation and, to a greater degree, during an irradiation of grains. Both nitrogen and carbon are depleted in solid objects, and we survey this problem with the primitive material that is richest in those two elements—the carbonaceous chondrites. In the Cl chondrites we take these abundance ratios to be (Mason 1971):

$$\left(\frac{^{16}O}{^{15}N}\right)_{C1} = 4.3 \times 10^4\,, \qquad \left(\frac{^{18}O}{^{15}N}\right)_{C1} = 88\,,$$

$$\left(\frac{^{16}O}{^{13}C}\right)_{C1} = 970\,.$$

The ^{15}N is produced by low-energy particles primarily by $^{16}O(p, 2p)^{15}N$ and $^{16}O(p, pn)^{15}O$ or, if the spectrum is very soft, by $^{18}O(p, \alpha)^{15}N$. For the power-law parametrizations of $\langle\sigma\rangle$ in Tables 2 and 3 we easily calculated that the relative importance of ^{18}O-derived ^{15}N to ^{16}O-derived ^{15}N ranges from 1.8×10^{-3} for the hardest spectrum tabulated ($E_0 = 9$ MeV, $\gamma = 2.5$) to 1.0 for the softest spectrum tabulated ($E_0 = 3$ MeV, $\gamma = 4.5$). For the median spectrum used in constructing Table 4, the ^{18}O accounts for only 2% of the ^{15}N. The absolute amount is marginally significant. $\Delta^{15}N/^{15}N = 7.4 \times 10^{-3}$ in the ^{26}Al-producing flux within the solar gas, but would be as great as 0.2 within any solids in that irradiation. The smaller ^{22}Na-producing irradiation yields 1.3×10^{-5} within solids there.

Observed variations are even larger. Kung and Clayton (1976) reported variations ranging from $\delta^{15}N = -4.4\%$ in enstatite chondrites to $\delta^{15}N = +4.6\%$ in carbonaceous chondrites. One must therefore entertain the possibility that the enstatite chondritic material was already shielded from the irradiation at a time when a small amount of C1 material was exposed to the large flux.

The situation for ^{13}C, which results from $^{16}O(p, \alpha)^{13}N$, is similar. The ^{26}Al-producing irradiation in grains would yield 2% excess of ^{13}C, whereas Table 4 lists the lower enrichment in the gas. This large anomaly in grains—grains we have argued do not exist—calls to mind the astonishing 6% excess of ^{13}C discovered in the carbonate minerals of C1 Orgueil by Clayton (1963) and studied further by Smith and Kaplan (1970) and by Krouse and Modzeleski (1970). So here too we have a possible suggestion that portions of the C1 matrix received the irradiation under discussion. We do doubt this because of the absence of big anomalies of ^{80}Kr, etc. However, presolar grains remain a viable alternative, according to Clayton and Hoyle's (1976) estimate that 10% of interstellar ^{13}C resides in ^{13}C-rich nova grains. The key to understanding may lie in the discovery of Smith and Kaplan (1970) that the excess ^{13}C resides in the carbonates rather than in the apparently organic material.

o) Li Be B

One of the principal objectives of Fowler, Greenstein, and Hoyle (1962) was the interpretation of the abundances of the light nuclei in terms of nucleosynthesis by nonthermal particles in the early solar system. Many papers followed theirs, and the subject now has an extensive literature. In the spirit of the present work, we rediscover that anomalies in light-element composition would be expected on this model.

One immediate problem even for a hypothetical model is the flux of nonthermal alpha particles. This flux is important for this problem, because $\alpha + {}^4He$ collisions produce isotopes of lithium. To survey this, we took the solar abundances to be unfractionated at the same ion velocity, i.e., at the same energy per nucleon. We took the number flux ratio to be

$$\frac{\phi_\alpha(4E)}{\phi_p(E)} = \left(\frac{He}{H}\right)_\odot = 0.07\,;$$

and if the cutoff energy for protons in the power spectrum was E_0, we took the alpha-particle cutoff to be $4E_0$. This arbitrary choice is made for the sake of definiteness rather than by astrophysical argument.

Cross sections for the relevant reactions for producing Li Be B have been given by Bodansky, Jacobs, and Oberg (1975). Our only computations were to average those cross sections over the power-law spectra that we have utilized in this work. These average cross sections are listed in Table 5. The values of E_0 given there are those characterizing the kinetic energy per nucleon of the spectrum. The outgoing channel x represents all those channels resulting in the final product, after radioactive decay if necessary. For example, $^4He(\alpha, x)^7Li$ is the sum of the two reactions $^4He(\alpha, p)^7Li$ and $^4He(\alpha, n)^7Be$.

TABLE 5

$\langle\sigma\rangle$ FOR Li Be B PRODUCTION

		$\langle\sigma\rangle$(mb)		
REACTION	E_0(MeV)*	$\gamma = 2.5$	$\gamma = 3.5$	$\gamma = 4.5$
$^{13}C(p, x)^6Li$.......	3	3.6	1.2	3.3 (−1)
	6	1.0 (1)	6.5	3.7
	9	1.8 (1)	1.8 (1)	1.5 (1)
$^4He(\alpha, x)^6Li$......	3	1.5	5.3 (−1)	1.6 (−1)
	6	4.1	3.0	1.8
	9	7.6	8.2	7.6
$^{14}N(\alpha, x)^6Li$......	3	1.1 (1)	8.0	5.3
	6	2.5 (1)	3.0 (1)	3.1 (1)
	9	1.7 (1)	2.5 (1)	3.2 (1)
$^{14}N(p, x)^7Li$......	3	1.7	4.5 (−1)	1.0 (−1)
	6	4.8	2.5	1.2
	9	8.8	7.0	4.8
$^4He(\alpha, x)^7Li$......	3	8.9	3.6	1.3
	6	2.5 (1)	2.0 (1)	1.5 (1)
	9	4.6 (1)	4.6 (1)	6.0 (1)
$^{13}C(p, x)^9Be$......	3	1.8	4.8 (−1)	1.1 (−1)
	6	5.0	2.7	1.2
	9	9.3	7.4	5.1
$^{13}C(p, x)^{10}B$......	3	2.1	1.1 (1)	4.8
	6	6.0 (1)	6.0 (1)	5.4 (1)
	9	7.3 (1)	9.4 (1)	1.1 (2)
$^{14}N(\alpha, x)^{10}B$.......	3	2.8 (1)	2.0 (1)	1.2 (1)
	6	7.0 (1)	9.2 (1)	9.9 (1)
	9	2.4 (1)	3.7 (1)	4.7 (1)
$^{14}N(p, x)^{11}B$.......	3	3.8 (1)	2.4 (1)	1.4 (1)
	6	9.5 (1)	1.1 (2)	1.2 (2)
	9	6.3 (1)	7.7 (1)	8.2 (1)

* Low-energy cutoff in MeV per nucleon.

One peculiarity of these reactions is that they involve targets that are more volatile than meteoritic material: He, N, C, in order of decreasing volatility. There is therefore a good chance of fractionating these elements from those more characteristic of solids, making a computation of abundance yield problematical. If the fast-particle irradiation is of a mixture of gas and grains, these light reaction products will be found primarily in the gas, so that the anomalies would reflect additional condensation of the reaction products onto the grain component. If, on the other hand, the gas has been swept clear of the grains before irradiation, the anomalies due to these reactions will be small.

The result of these calculations with unfractionated solar material is included in Table 4. The $\alpha + {}^4$He reaction produces a ratio ^{6}Li/^{4}He that is 40 times the solar ratio. Clearly this overproduction limits some aspect of the model. For the steep power-law spectra, Table 5 shows that the production ratio due to $\alpha + {}^4$He collisions is about ^{7}Li/^{6}Li ≈ 7, considerably smaller than the average meteoritic value of 12. (See also Clayton and Dwek 1976 for a discussion of the same problem around young pulsars.) Quite clearly, then, one could anticipate variations of lithium ratios in material condensing from nebular gas during the irradiation.

Lithium isotopic variations seem to have been detected by Gradsztajn *et al.* (1968). They reported variations of $\pm 10\%$ from the terrestrial ratio for measurements of meteoritic samples, whereas the same technique on terrestrial Li set their systematics at $\pm 2\%$. Because the reactions ^{13}C(p, x)^{6}Li, ^{14}N(α, x)^{6}Li, and ^{14}N(p, x)^{7}Li also produce Li isotopes whereas secondary neutrons destroy Li isotopes, little can be concluded other than a reasonable expectation of obtaining useful limits to this problem from further studies of Li isotopic ratios. In summary, one would say that if the ^{26}Al-production is to be taken seriously for a large fraction of meteoritic and terrestrial matter, the origin of Li Be B by the same scenario must be considered. Certainly one must expect isotopic variations.

V. DISCUSSION

We have imagined throughout that it is possible for planetary matter to have received this irradiation. However, rather severe constraints of an astrophysical type quickly emerge. Suppose we assume that the total gas plus grain mixture from which the planetary system will form, which has been estimated by others as 0.03 $M_{\odot}$, has been irradiated with the minimum irradiation $\phi_p T_p = 2 \times 10^{20}$ cm^{-2} needed to produce the ^{26}Al anomaly. Taking an energy-loss cross section for MeV protons in average solar matter, we find that the associated ionization losses attendant to the power-law spectrum would amount to 2×10^{48} ergs. This very large energy is a significant fraction (one-third) of the total gravitational binding energy of the Sun. It does not seem physically reasonable that a contracting star could convert so much gravitational work into energetic particles. Such a massive nebula would, furthermore, be highly self-shielding.

The latter problem remains even if we assume that only one Earth mass, 6×10^{27} g, is irradiated. If that mass is spread into a ring 1 AU wide at a mean heliocentric distance of 1 AU, it must still be 4 g cm^{-1} thick. MeV protons are stopped in the outer 1% of that thickness. Therefore, only about 0.01 $M_{\rm E}$ could receive the irradiation. The entire Earth mass could receive the irradiation if the disk is slowly "gardened," i.e., mixed in such a way that all fractions of it spend time on the irradiated surface fractions. But then the irradiation must either take 100 times as long to occur or be 100 times as intense. The total irradiation would in this case require 2×10^{44} ergs.

For ^{26}Al to reach its equilibrium concentration requires an irradiation of about 10^6 years, which suggested a flux $\phi_p = 5 \times 10^6$ cm^{-2} s^{-1} to produce (^{26}Al/^{26}Mg)$_e = 0.43 \times 10^{-4}$. If an Earth mass is to be gardened by mixing to achieve the same equilibrium concentration of ^{26}Al, the flux at the outer layers of the disk must be 100 times more intense, $\phi_p = 5 \times 10^8$ cm^{-2} s^{-1}, because each rapidly gardened nucleus would spend only 1% of its time exposed to the flux. However, it is well known that continuous mixing does not produce a uniform irradiation, but rather a distribution of irradiations clustered about the mean. That is, a continuous gardening model will produce a distribution in (^{26}Al/^{26}Mg) ratios, and that distribution should show in the data. Actually, however, the data of Lee, Papanastassiou, and Wasserburg (1976) show a very good straight line, seeming to suggest that there was once a rather well defined (^{26}Al/^{27}Al) ratio rather than a distribution of such ratios. On the other hand, a distribution in ^{26}Al/^{27}Al ratios could have been well mixed into the studied samples, so that they would have registered only the mean irradiation. Such arguments lie outside the scope of this paper, but it does appear to us that the evidence is somewhat against gardening, without which the several million year irradiation that may have occurred has irradiated no more than 10^{-2} $M_{\rm E}$ of planetary material.

We have argued from the absence of noble-gas anomalies that grains were absent when the large irradiation produced ^{26}Al in the gas; and yet this ^{26}Al must be condensing into grains to produce the effect (Heymann and Dziczkaniec 1976). If the grains form only after the irradiation, it is not clear that the condensation can be fast enough to trap the well-defined ratio ^{26}Al/^{27}Al (Lee, Papanastassiou, and Wasserburg 1976) in the meteorite Allende. If other carbonaceous chondrites, having ^{129}Xe*/^{127}I ages different from Allende, also have the ^{26}Al anomaly, one must puzzle that meteorites having different condensation ages can both have short-lived ^{26}Al, which can have been produced only in a pure gas. The existence of ^{26}Al in other meteorites is a speculation at present, but it will be an astonishing coincidence if the best carbonaceous meteorite sample in existence happened to form at the only time when ^{26}Al exists in the gas. We await experimental clarification. However, one reasonable astrophysical speculation would be that the energetic solar protons are stopped in a gas above the dusty disk, and that the ^{26}Al produced in that "atmosphere" is mixed down to the disk where the actual accumulation is occurring.

Of course, the ^{26}Al may never have achieved equilibrium. The ratio $^{26}\text{Al}/^{26}\text{Mg} = 4.3 \times 10^{-5}$, for example, can be achieved by a flux much stronger than $5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ acting for a time much less than $\tau(26)$. In that case ^{26}Al is essentially stable during the period of its buildup. One advantage of this possibility is the larger equilibrium concentrations of ^{22}Na that will exist. Irradiation of more than $10^{-2} M_{\text{E}}$ would again require extensive gardening, leading to a spread in condensed $^{26}\text{Al}/^{27}\text{Al}$ ratios. The power dissipation due to energetic particles producing the uniform ratio $^{26}\text{Al}/^{26}\text{Mg} = 4.3 \times 10^{-5}$ during a shorter T_p is

$$L_p \approx 10^{31} \left(\frac{m}{M_{\text{E}}}\right) \left(\frac{T_p}{10^6 \text{ yr}}\right)^{-1} \text{ ergs s}^{-1} ,$$

where m/M_{E} is the mass of the uniformly gardened and irradiated disk. We know of no argument limiting the fraction of the young Sun's power that can be radiated as MeV-range particles, but we instinctively feel that it must be much less than 1% of $L_{\odot}$. If so, irradiation of one Earth mass over a time $T_p \ll 10^6$ yr may dissipate unreasonable amounts of power. It seems likely that if the meteoritic anomalies are due to such a radiation, it has been only of a small mass of material that was destined for the meteorites.

If that be the case, one would expect isotopic differences between meteoritic and terrestrial ratios such as $^{50}\text{V}/^{51}\text{V}$, $^{138}\text{La}/^{139}\text{La}$, $^{180}\text{Ta}/^{181}\text{Ta}$. That bulk differences seem not to exist further restricts the proposed irradiation to a small fraction of meteoritic matter. That small fraction should be very much richer in ^{22}Ne, ^{126}Xe, ^{80}Kr, and ^{36}Ar than observed, and those Ne-E samples have not disclosed the other rare-gas anomalies. At the present time it seems to us that the picture of presolar-grain carriers accounts for the facts more naturally than do irradiation models.

Our inclination is to not pursue theoretical possibilities any further. Experimental facts will be of more immediate value. We submit the cross section tables and the Table 4 of anticipated anomalies as purely nuclear considerations that will go a long way toward answering the many questions that arise concerning energetic-particle irradiation. Measurements of the more important cross sections in Tables 1–3 will be a great aid to resolving these questions. Clearly the issues involved are of great importance to all of astrophysics.

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Note added in proof.—Wm. A. Fowler has called our attention to the fact that $^{26}\text{Mg}(p, n)^{26}\text{Al}$ reactions leading to the isomeric state of ^{26}Al (E = 230 keV, τ_{β^+} = 6 s) do not result in a net accumulation of ^{26}Al. Our calculated cross section in Table 1 is explicitly a sum $\sum_{n'} \sigma(p, n')$ over all excited states of ^{26}Al that can be reached by the incident energy. In the range 6 MeV < E_p < 10 MeV only a small fraction of reactions lead directly to the ground state, which is instead primarily the product of γ-ray cascades from excited state produced directly by the exiting neutron n'. We have accordingly overestimated the production of ^{26}Al by a factor of about 3, since, as a simple estimate, about two-thirds of the reactions lead ultimately to the isomeric state. The fluence required in Table 4 for ^{26}Al production in the gas should therefore be a factor of approximately 3 larger than indicated.

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