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ORIGIN OF HEAVY XENON IN METEORITIC DIAMONDS

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ABSTRACT

The neutrino burst from the collapsed core in Type II supernovae liberates free neutrons by ($\nu, \nu'n$) reactions which drive isotopic abundances several mass steps heavier. The neutron fluence in the He shell, abetted by another burst 10 s later from (α, n) reactions, is about right for rendering ^{136}Xe the most abundant Xe isotope. I calculate explicitly the Xe isotopic composition and find a good match to Xe-H, the unshielded neutron-rich Xe component abundant in carbonaceous meteorites. I specifically implicate the He shell because it is the only C-rich shell in massive stars that can be expected to condense solid carbon thermally, a requirement for locating the Xe-H in meteoritic diamonds, which are so common as to require an abundant Galactic source of unoxidized carbon. I discuss several associated isotopic and chemical problems in the acid-resistant meteoritic residues where this anomaly is purest. My discussion is within the context of the cosmic chemical memory theory of isotopic anomalies.

Subject headings: abundances — meteors and meteorites — nucleosynthesis

I. INTRODUCTION

It is not uncommon for the first measurement in a new scientific field to remain its most significant. This situation seems to me to apply to carbonaceous chondrite fission xenon (CCFXe), discovered by Reynolds (1960; see also Krummenacher *et al.* 1962; Reynolds and Turner 1964) almost three decades ago and still unexplained despite the fact that it constitutes up to 5% of bulk xenon in some meteorites. Its old name (CCFXe) reflects the large overabundance factors for ^{136}Xe and ^{134}Xe , and moderate overabundance factors for the other two unshielded isotopes, ^{132}Xe and ^{131}Xe , isotopes expected to be produced as end members of isobaric decay chains of fission fragments. Its study took a quantum leap when Lewis, Srinivasan, and Anders (1975) showed that it and normal Xe were both concentrated in carbonaceous residues that were not dissolved along with the bulk of the meteorite Allende in acids, and furthermore that subsequent oxidizing acids removed most normal xenon, leaving ^{136}Xe enriched by a factor of roughly 1.5–2.0 with respect to shielded isotopes—a huge isotopic anomaly.

The isotopic composition of the “anomalous part” of the measured xenon has defied unambiguous definition, however, because it depends upon the way this component is defined and upon model-dependent assumptions about the xenon with which it is inextricably mixed. Compositions defined by three-isotope correlation lines generated by temperature-dependent degassing do not agree with those defined by the difference between the accurate measurements and a second component whose composition is assumed known by several competing and differing arguments. Pepin and Phinney (1979) have reviewed all of this in a very clear way, tabulating the CCFXe isotopic compositions inferred by a number of groups and arguments, and demonstrating the perplexing lack of convergence.

One unsolved problem relates to the simultaneous enrichment of the most proton-rich isotopes, ^{124}Xe and ^{126}Xe , a correlation (Manuel, Hennecke, and Sabu 1972) manifestly arguing against fission (for the entire anomaly) and leading to new names, Xe-X, X, CCFX, and/or Xe-HL. Other data have

now almost ruled out fission (e.g., Anders 1988). This writer (Clayton 1976) argued that both r -process and p -process xenon produced in supernovae were trapped in thermal condensates (SUNOCONS) during the expansion of supernova interiors; I presented a table showing the strong dependence of the r -process isotopic composition on the admixed p -process yield of ^{130}Xe , which Lewis, Srinivasan, and Anders (1975) had for simplicity taken to vanish. I showed that with a proton-capture p -process the $^{130}\text{Xe}_p$ yield was probably great enough to shift the inferred composition $^{134}\text{Xe}/^{136}\text{Xe} = 0.67$, $^{132}\text{Xe}/^{136}\text{Xe} = 0.092$, $^{131}\text{Xe}/^{136}\text{Xe} = 0.16$ of the Lewis, Srinivasan, and Anders (1975) correlations for the r -component to $^{134}\text{Xe}/^{136}\text{Xe} \approx 0.67$, $^{132}\text{Xe}/^{136}\text{Xe} \approx 0.2 \pm 0.1$, $^{131}\text{Xe}/^{136}\text{Xe} \approx 0.2 \pm 0.1$ with the same data. Heymann and Dziczkaniec (1979) argued that a (γ, n) p -process would also yield nonnegligible $^{130}\text{Xe}_p$.

None of these problems have been resolved. But widespread agreement exists for ^{136}Xe being the most abundant isotope of the anomalous unshielded component and for the other isotopic ratios of the ubiquitous anomaly being in the ranges

$$\begin{aligned} ^{134}\text{Xe}/^{136}\text{Xe} &= 0.70 \pm 0.05, \\ ^{132}\text{Xe}/^{136}\text{Xe} &= 0.25 \pm 0.15, \\ ^{131}\text{Xe}/^{136}\text{Xe} &= 0.20 \pm 0.10. \end{aligned} \quad (1)$$

A minimal requirement is a source of unshielded isotopes having these ratios, with at least a factor of 10 less ^{130}Xe .

But there are more exciting experimental data. Lewis *et al.* (1987) shocked the world again by characterizing the host phase of Xe-HL as diamonds, coupling the mystery of formation of diamonds to the existing mystery of the isotopic composition of its xenon. Decades of work have singled out graphite as the stable form of condensed solid carbon in thermal equilibrium at low pressures, and even that requires having more carbon than oxygen in order to escape an apparently dead-end CO trap for carbon (Larimer 1975).

These are the unsolved problems that I now address. There are but two fundamentally distinct classes of theory that address the existence of isotopic anomalies in meteoritic

samples. The first is a solar nebula that is inhomogeneously mixed, usually because some specific nucleosynthesis debris near the solar cloud was only inhomogeneously admixed into it. It is envisioned as resulting in spatial variations of composition in the solar nebula, or in some cases temporal variations. The second class maintains a solar nebula that is homogeneous in bulk in the sense that each volume element contains the same abundances, but the grains in the gas contain different isotopic patterns in different chemical structures. These theories are called chemical memory theories because the prior Galactic history has prepared the differing chemical carriers having differing isotopic constitutions. This standpoint takes the memory to exist everywhere throughout the interstellar medium. Heating of the solar nebula to a temperature that vaporizes all dust still leaves the spatial inhomogeneities of the first class of theories but eliminates the isotopic anomalies in the second. There exist many other physical differences between the two theories. I will in this work adhere to the cosmic chemical memory theory (Clayton 1978, 1982) by envisioning diamond dust carrying heavy xenon scattered homogeneously throughout the interstellar medium. To find a common condensation site for those diamonds that will also condense the correct isotopic composition is the objective.

II. HELIUM SHELL IN TYPE II SUPERNOVAE

The solution that I advocate now is the same as the one I advanced previously (Clayton 1981), with the added feature of a burst of neutrino-induced neutron captures. Clayton (1981) singled out the convective shell above the He-burning zone as the only portion of a massive star having $C > O$ at the time of its explosion, and he argued it to be therefore the likely site of origin of Xe-HL, provided that a sufficient burst of free neutrons could be liberated by shock heating there to transform ambient xenon to Xe-H. That requirement of abundant unoxidized carbon remains persuasive today unless one can demonstrate that carbon solids can condense in a bath of hot oxygen. He envisioned ^{13}C , ^{18}O , and ^{22}Ne neutron sources. A new source of the free-neutron burst has now become apparent after the neutrino detection of SN 1987A. Both Woosley and Haxton (1988) and Epstein, Colgate, and Haxton (1988) calculated that the flux of high-temperature tau and mu neutrinos was great enough to produce (ν, n) reactions via neutral currents on about 10^{-4} of abundant stable nuclei. Epstein *et al.* even argued that a new r -process source had thereby been found for the He shell. Although that seems to me to be overoptimistic, considering that they must choose Population II abundances to reduce the neutron poisons, the fluence of neutrons does seem about right in Population I stars to make Xe-H. The carbon is roughly 5% of the mass in a zone about $2 M_{\odot}$ wide (see, for example, Fig. 4 of Woosley 1988), with the remainder being overwhelmingly ^4He . (Note that in that figure the 2% of ^{22}Ne is erroneously labeled ^{20}Ne .) The oxygen abundance so deadly to thermal condensation of carbon is by contrast less than 1%, because the early stages of He burning always produce primarily ^{12}C rather than the ^{16}O that eventually dominates in massive stars at the time of He exhaustion (e.g., Figs. 5-21 to 5-28 of Clayton 1968). The He shell expands at 1000 km s^{-1} and after 20 days has temperature $T \simeq 12,000 \text{ K}$ (Arnett 1988, Fig. 9). When the temperature has fallen to $T < 1500 \text{ K}$ owing to adiabatic decompression (requiring about a year), the diamonds apparently condense metastably and cool sufficiently rapidly to avoid the transition to ground-state graphite (Saslaw and Gaustad 1969). Roy (1987) has also

recently discussed the growth of diamonds at low pressure, contradicting old prejudices in that regard. Angus and Hayman (1988) have comprehensively discussed the experimental evidence for low-pressure metastable growth. As far as the model being presented here is concerned, it is satisfactory if the carbon condenses as graphite and its transmuted to diamonds during grain-grain collisions by shock metamorphism (Tielens *et al.* 1987); however, it then seems to me hard to explain why graphite does not occur in carbonaceous meteorites along with diamonds. I will therefore assume that carbon can condense to diamonds in a cooling gas lacking both oxygen and hydrogen, although the latter has been found helpful in the laboratory processes (Angus and Hayman 1988).

a) Presupernova s -Process

A small but significant amount of ^{22}Ne burns in the He shell in the time left to it by the core evolution. It generates a weak s -process capable of moving heavy nuclei several mass units upward, slowly, moving toward the beta stability line. Prantzos, Arnold, and Casse (1988) found $n_c/\text{Fe} \simeq 0.6$ in this weak s -process, causing an integrated fluence $\phi = 2 \times 10^{25}$ neutrons cm^{-2} , or $\tau_s = 0.02$ in units of 10^{27} cm^{-2} in the usual (Clayton 1968) s -process parlance. Harris (1988) found $\tau_s = 0.06$ in a similar calculation for a $20 M_{\odot}$ star. I take these as indicative of the weak s -processing in the He zone prior to explosion. I have calculated the associated alteration of initially solar abundances there by constructing a small s -process network adequate for the Te-I-Xe region. This network included the abundances of all stable isotopes of Sn, Sb, Te, I, and Xe, with cross sections taken from Bao and Käppeler (1987). I held the abundance of ^{118}Sn constant as a boundary condition to simulate replenishment from lower masses, a totally adequate condition for Te, I, Xe with such small values of τ_s . I integrated the differential equations numerically and checked several solutions for accuracy against the analytic solutions (Clayton 1968). For the weak s -process all beta decays (except ^{129}I) were allowed to occur, whereas in the subsequent neutrino-induced burst none were allowed (see below). The main purpose of this exercise was to establish the Te, I, Xe abundances at the time of the neutrino burst. My results are shown in Figure 1 for a range $0 < \tau_s < 0.03$. Large and rapid rearrangements occur in this mass region because Te, I, Xe constitute the $n = 82$ r -process abundance peak in the solar abundances, and the abundant r -process isotopes are largely consumed during a weak s -process. The major beneficiary is clearly ^{132}Xe , which climbs to abundances roughly threefold greater than solar. ^{130}Xe makes an important early increase before beginning its decline along with most others of high initial abundance. The Xe during this phase resembles s -process xenon; but it does so only roughly because the $^{132}\text{Xe}/^{130}\text{Xe}$ ratio is too large and, importantly, ^{136}Xe is not destroyed because its cross section (2.9 mbarn) is too small to allow erosion by weak fluxes. During this epoch $^{136}\text{Xe} = ^{136}\text{Xe}_{\odot} \exp(-2.9\tau_s)$. ^{134}Xe and even Te isotopes are also hard to erode, as shown in Figure 1.

A similar calculation was done in the Se-Br-Kr region.

b) Neutrino-induced Neutron Burst

Epstein, Colgate, and Haxton (1988) have evaluated this problem in the He shell. Nuclear transformations spread over the few-second duration of the neutrino burst from the collapsing core are $^4\text{He}(\nu, e^-)^4\text{Li}$ and $^4\text{He}(\bar{\nu}, e^+)^4\text{H}$ followed respec-

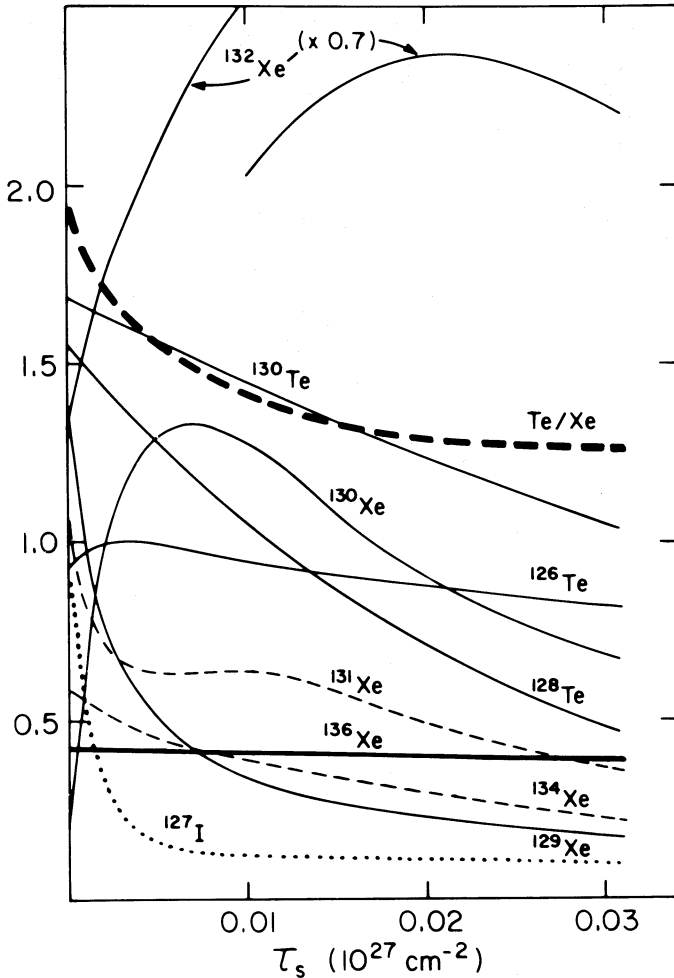


FIG. 1.—Evolution of initially solar abundances ($S_i \equiv 10^6$) under a weak s -process fluence τ_s (units of 10^{27} neutrons cm^{-2}). Early evolution is unusually rapid in this mass region owing to $N = 82$ r -process peak (^{128}Te and ^{130}Te , ^{127}I and ^{129}Xe and ^{131}Xe) in solar abundances. Note that ^{132}Xe quickly becomes the largest abundance, whereas ^{127}I falls to low values. The Te/Xe elemental ratio initially declines.

tively by proton and neutron ejections and, more important, inelastic neutrino scattering ($\nu, \nu'n$) leading to breakup of 4He . They show that the fraction of He destroyed is

$$\phi_\alpha = 4 \times 10^{-4} (T/9 \text{ MeV})^{4.3} (R_\alpha/10^9 \text{ cm})^{-2}. \quad (2)$$

With a full secondary nuclear network they show in their Figure 2 parametric relations among peak free-neutron density $n_{n, \max}$, ϕ_α , and the metallicity Fe/Fe_\odot . I fitted their curves to estimate

$$\log \left(\frac{n_{n, \max}}{10^{18} \text{ cm}^{-3}} \right)^{0.8} \simeq -\log \left(\frac{Fe}{Fe_\odot} \right) + \log \phi_\alpha + 3, \quad (3)$$

giving $n_{n, \max} \simeq 2 \times 10^{16} \text{ cm}^{-3}$ if $Fe/Fe_\odot = \frac{1}{2}$ and the He shell is at $R_\alpha = 4 \times 10^9 \text{ cm}$. Neutron capture times are then several seconds, faster than decays in Xe and Te. Epstein *et al.* assumed the neutrino flux to decay as $e^{-t/(3 \text{ s})}$, in which case the resulting neutron fluence is $\tau_\nu \simeq 0.02$ ($\times 10^{27}$ neutrons cm^{-2}), coincidentally comparable to the weak s -process fluence τ_s . To this must be added the neutrons from ($\nu, \nu'n$) reactions on ^{12}C , for which the cross section is about tenfold greater and which Epstein *et al.* apparently did not include. I also do not attempt

to include them explicitly because the associated network has many complications that I have not solved, preferring instead to survey the effects of the neutron fluence over a range of reasonable fluences. A radial gradient in this fluence exists in the He shell owing to the inverse-square dependence of the neutrino flux. Variations from supernova to supernova will exist as a result of differences in their neutrino emission and in the radii of their He-burning shells.

The supernova shock wave arrives about 10 s later, faster than beta decays in Te and Xe, raising the He-burning shell temperature to almost 10^9 K at its base (Weaver and Woosley 1980). This releases more prompt neutrons by destroying a small fraction of abundant ^{22}Ne via $^{22}Ne(\alpha, n)^{25}Mg$ and by similar reactions on unburned ^{18}O , ^{17}O , and ^{13}C in the convective He shell, leading to another mini- r -process. Especially large quantities of ^{18}O may exist (Nomoto and Hashimoto 1988). There exist many subtleties in the calculation of those survivors in a convective He shell. Truran, Cowan, and Cameron (1978) estimated neutron fluences large enough to produce 20 or so captures, but Cowan, Cameron, and Truran (1985) and Harris (1988) showed (the latter's footnote 13) that this estimate is excessive. Still, additional fluences $\Delta\tau \simeq 0.01$ – 0.05 , adequate for moving ^{132}Xe to ^{136}Xe , may exist there. These must be recalculated with greater care.

The foregoing raises many questions for future research; but for this preliminary report I find it most reasonable to envision a supernova burst of neutrons producing fluence in the range $\tau_{SN} \simeq 0.02$ – 0.1 (10^{27} cm^{-2}) over a few seconds of time, too fast for any beta decays. I ran my network with such fluences to evaluate the isotopic composition of xenon that would be embedded in this material that may condense diamonds about a year later. Table 1 reports selected results of interest, and Figure 2 displays the xenon composition as a function of τ_{SN} if τ_s was 0.02. Table 1 shows the τ_{SN} survey for $\tau_s = 0.02$ for the two different sets of specific cross sections. The basic set (labeled σ) was changed to an altered set (labeled σ') for those five cross sections noted in the footnote in order to show that much work remains to be done to pin those down. Note Table 1 also contains the absolute overabundances of ^{136}Xe and ^{86}Kr , so that the absolute abundance of lighter isotopes can be computed from the ratios.

Figure 2 (using the σ' set) shows that if $\tau_s = 0.02$, the supernova burst τ_{SN} makes ^{136}Xe become more abundant than ^{134}Xe if $\tau_{SN} > 0.055$, in which case ^{132}Xe and ^{131}Xe are even less abundant. In fact, this xenon composition is very similar to that of Xe-H discussed in equation (1). Heymann and Dziczkaniec (1979) have shown in a different astrophysical context that Xe-H could result from fluences of this general magnitude. The abundance of ^{130}Xe (not shown) is very small. Thus I find a very plausible candidate for carbon-dominated zones carrying Xe-H.

The results depend only weakly on the prior weak s -process τ_s . Larger τ_s drives down the $^{131}Xe/^{136}Xe$ and $^{132}Xe/^{136}Xe$ ratios produced. The main reason for that is that ^{131}Xe and ^{132}Xe are not produced as themselves but as ^{131}Te and ^{132}Te parents that decay to ^{131}Xe and ^{132}Xe after the nuclear reactions but long before the diamonds condense. And, as Figure 1 shows, increasing τ_s drives down the elemental Te/Xe abundance ratio that controls $(^{131}Xe + ^{132}Xe)/(^{134}Xe + ^{136}Xe)$. It is also for this reason that the ^{130}Te , ^{131}Te , ^{132}Te cross sections are of such importance to the final Xe composition, explaining how the modest changes to σ' could alter the results to the extent shown in Table 1.

TABLE 1
ISOTOPIC YIELDS FROM NEUTRON-BURST FLUENCE $\tau_{\text{SN}} (10^{27} \text{ cm}^{-2})$

RATIO	τ_{SN}													
	0.03		0.04		0.05		0.06		0.07		0.08		0.09	
	σ	σ'	σ	σ'	σ	σ'	σ	σ'	σ	σ'	σ	σ'	σ	σ'
$^{134}\text{Xe}/^{136}\text{Xe}$	3.6	...	2.6	1.9	1.7	1.2	1.1	0.78	0.77	0.52	0.53	0.36	0.38	0.27
$^{132}\text{Xe}/^{136}\text{Xe}$	2.0	...	1.0	0.63	0.64	0.37	0.48	0.28	0.41	0.25	0.38	0.24	0.37	0.22
$^{131}\text{Xe}/^{136}\text{Xe}$	0.57	...	0.46	0.30	0.38	0.25	0.32	0.21	0.28	0.19	0.24	0.17	0.21	0.15
$^{136}\text{Xe}/^{136}\text{Xe}_{\odot}$	1.5	...	2.2	...	3.1	...	4.1	...	5.0	...	6.0	...	6.8	...
$^{84}\text{Kr}/^{86}\text{Kr}$	0.95	...	0.62	...	0.46	...	0.39	...	0.36	...	0.37	...	...	...
$^{83}\text{Kr}/^{86}\text{Kr}$	0.16	...	0.14	...	0.15	...	0.16	...	0.16	...	0.17	...	...	...
$^{82}\text{Kr}/^{86}\text{Kr}$	0.083	...	0.030	...	0.011	...	0.005	...	0.002	...	0.001	...	...	...
$^{86}\text{Kr}/^{86}\text{Kr}_{\odot}$	2.5	...	3.3	...	3.8	...	4.2	...	4.5	...	4.6	...	...	...

NOTE.—The prior weak s -process fluence was $\tau_s = 0.02 (10^{27} \text{ cm}^{-2})$. The cross-section set σ was taken from Bao and Käppeler 1987. The cross-section set $\sigma' = \sigma$ except for the following modest but significant combined changes:

CROSS SECTION	NUCLEUS				
	^{130}Te	^{132}Te	^{132}Xe	^{134}Xe	^{135}Xe
σ (mbarn)	15.5	9	57.5	27.3	32
σ' (mbarn)	12	12	65	31	45

III. DISCUSSION

The calculations presented here are far more accurate than the astrophysical model, which is replete with uncertainties. Foremost among these are (1) the distribution of mass with radius (and hence neutrino fluence) in massive-star He-burning shells; (2) the numbers and energies of the higher energy tau and mu neutrinos (their temperature); (3) the neutrino cross sections themselves; (4) reliable nuclear reaction networks in the He shell for the explicit compositions of those shells; (5) condensation and trapping calculations to test whether a $^{136}\text{Xe}/\text{C}$ ratio comparable to solar is adequate to account for the concentration found in diamonds and whether diamonds truly do condense metastably from hot C vapor; (6) the exact preexplosive composition of He shells (vis-à-vis ^{13}C , ^{17}O and ^{18}O , and ^{21}Ne and ^{22}Ne) and accurate calculations of the neutron burst accompanying the shock wave passage; (7) neutron capture cross sections, especially for ^{134}Xe , ^{135}Xe , and ^{136}Xe and for ^{128}Te , ^{129}Te , ^{130}Te , ^{131}Te , and ^{132}Te ; (8) the extent and time of radial mixing. Within the compounded uncertainties of these issues, I have presented calculations showing that a weak s -process followed by a rapid neutron burst in the range $0.04 \leq \tau_{\text{SN}} \leq 0.1$ in carbon-dominated (chemically) stellar matter found in the He shell provides a suitable origin for Xe-H in diamonds. My instinct is that it is correct, primarily because Xe-H in diamonds is so abundant in meteorites and, correspondingly, because the scenario advanced is so universal to all massive-star carbon production. That is, rare events or meager quantities are not called for. The invocation of rare processes has been common in inhomogeneous injection theories calling for a special neighboring event, but they are not in the spirit of cosmic chemical memory theory, which seeks to define the abundant main-line chemical clues imprinting the bulk interstellar medium. There exist several other very important points that must be stressed even in this preliminary report, however.

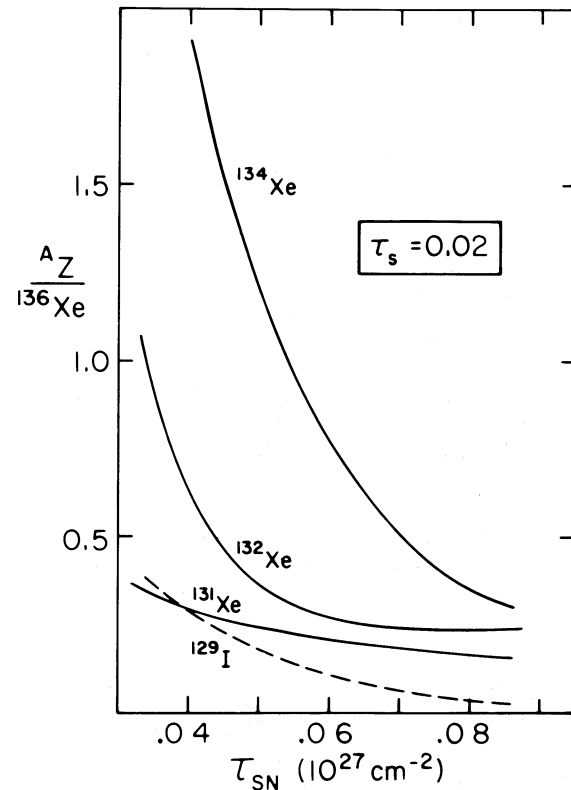


FIG. 2.—Evolution of abundance ratios under a rapid neutron burst of fluence $\tau_{\text{SN}} (10^{27} \text{ cm}^{-2})$. Initial abundances were weak s -process $\tau_s = 0.02$ from Fig. 1. Note that ^{131}Xe and ^{132}Xe are ^{131}Te and ^{132}Te radioactive parents, from Te seed nuclei. The cross-section set shown is σ' . The range $\tau_{\text{SN}} = 0.06$ – 0.07 is very like Xe-H, as described by eq. (1). Note that ^{129}I is rare, about 0.1 ^{136}Xe near $\tau_{\text{SN}} = 0.06$, but ^{130}Xe (not shown) is then very small, about 10^{-3} of ^{136}Xe .

a) Smallness of ^{129}Xe Excess

Lewis and Anders (1981) presented a good argument that they believe dooms supernova condensation of r -process products, causing them to favor instead an alternate implantation scenario (advanced also by Clayton 1981 and improved by Jørgensen 1988). Since ^{129}I is normally an abundant r -process product, the $^{129}\text{I}/\text{Xe}$ ratio in r -process events would be expected to be of order unity, and much greater in diamonds if iodine is, like Br and Te, apparently condensed with 10^4 times greater efficiency than Xe, as indicated by measured concentrations in the carbonaceous residues (Lewis and Anders 1981).

As Figure 2 shows, because this neutron burst is not a true r -process, however, the ^{129}I (primarily its ^{129}Te parent) is only 5%–10% of ^{136}Xe in this process. This is small enough to be in agreement with the small excess of ^{129}Xe in Xe-H provided that ^{129}I and Xe are trapped with equal efficiencies in the diamonds. The latter may be possible, despite prejudices gleaned from bulk meteoritic samples. In the actual vapor condensation of diamonds, the I/Xe ratio may not be enhanced above the ambient ratio. Conceivably the I has condensed in other solids, especially if the carbon must actually be cooled to supersaturation before it nucleates. After all, the X- and γ -ray environment remains quite hostile even as temperature drops. This speculation concerning the Te in the present context can be tested experimentally, because the Te in this process carries a huge isotopic anomaly $^{130}\text{Te}/^{128}\text{Te} \simeq 5$, about 5 times solar. The Te in diamonds (or residues) must be tested for this anomaly. In a study of Te isotopes by neutron activation, Oliver *et al.* (1981) found a 10% enrichment of $^{130}\text{Te}/^{128}\text{Te}$ in the acid residues of Allende, a large anomaly that must be confirmed in light of its significance to this problem. Heymann and Dziczkaniec (1981) also discuss this measurement. If no large Te anomaly comparable to that in Xe-H is confirmed, then Te at least must be regarded as being largely a nebular condensate picked up by the residue in the solar collapse or during its interstellar growth, probably in molecular clouds, or on the Allende parent body (Heymann 1981) rather than coproduced with Xe-H. This model requires, therefore (in order to be correct and *not* produce a large ^{129}Xe excess), that Te *not* show a large ^{130}Te excess. It is conceivable that Xe-H and Te-H containing diamonds, once formed in supernovae, grow larger by nebular C deposition onto those seed diamonds with a much larger associated deposition of normal Te, diluting its isotopic anomaly. E. Anders (1988, private communication) expresses some doubt whether the Te that they measured is actually within the C δ diamonds or within associated phases.

The Lewis and Anders (1981) argument remains, nonetheless, the most robust one extant in opposition to this model, so all of its aspects require critical reevaluation.

b) Associated Krypton Anomaly

Experimental teams (e.g., Lewis, Srinivasan, and Anders 1975) normally measure isotopically the Kr gas released with Xe-H. Although anomalous, its anomaly is percentagewise about threefold smaller. The largest percentage increase is observed at ^{86}Kr , but it is observed to be several times smaller than the overabundance at ^{136}Xe ; furthermore, the most abundant nucleus in Kr-H may actually be ^{84}Kr (Lewis, Srinivasan, and Anders 1975), even though only ^{86}Kr is enhanced. My calculations in the Kr region show that ^{84}Kr is actually depleted in absolute abundance by the process, leaving ^{86}Kr

roughly fourfold enriched (Table 1). By contrast in Xe, while ^{136}Xe was being increased fivefold in absolute abundance, ^{134}Xe was also roughly tripled. Also of interest in Table 1 is that ^{83}Kr retains an absolute abundance very nearly equal to its solar abundance, whereas ^{82}Kr is severely depleted. These features too bear strong similarity to the Kr-H associated with Xe-H (Lewis, Srinivasan, and Anders 1975). But problems of baseline and magnitude plague an accurate description of Kr-H at this time. Perhaps these interesting absolute differences between Kr and Xe may in nature's mix account for the "apparently smaller" ^{86}Kr excess. I will only note in passing that a much stronger s -process preirradiation during hydrostatic burning (requiring a revised scenario) would elevate the Xe/Kr ratio prior to the supernova burst, so that the burst itself would have produced a larger $^{136}\text{Xe}/^{86}\text{Kr}$ ratio than the ones I calculated for Table 1. Heymann and Dziczkaniec (1980) surveyed krypton isotopes in a number of parameterized expansions of core material.

c) Interzone Mixing

Supernova 1987A has demonstrated that substantial radial mixing occurs (e.g., Leising 1988; Pinto and Woosley 1988), at least within the He-depleted core. There are yield advantages of producing Xe-H deeper than I have suggested, within the oxygen-dominated core: namely, the neutrino flux is higher and the seed Xe is higher, owing to the stronger s -process during prior core He burning. The disadvantage is the chemical implausibility of condensing diamonds in a bath of hot oxygen. But consider the following. The mixing induced by Rayleigh-Taylor instability is penetration of fingers rather than microscopic. Oxygen core with larger Xe-H concentration may be commonly mixed into the carbon-dominated He shell in a way that leaves carbon only slightly more abundant than the admixed oxygen. During the cooling expansion most carbon may form inert CO molecules if the radiation environment is not too hostile, leaving a greatly enhanced Xe/C ratio in the remaining ambient carbon that will shortly thereafter condense as diamonds (speculating that CO is an inert gas insofar as further C condensation is concerned). I estimate that Xe/C can be increased by a factor of 10^2 in this way, potentially improving the Xe-H concentration in the diamonds. This explanation requires that a large mass, at least $0.1 M_{\odot}$, of CO form during the expansion of the supernova interior. This signature has now been seen in the outflow from SN 1987A (Spyromilio *et al.* 1988), but only $5 \times 10^{-5} M_{\odot}$ of CO. Either much more CO is still to form, or the CO trap is not the impediment to carbon condensation that it is commonly expected to be. Continuing analysis of SN 1987A in this regard thereby impacts a major cosmochemical problem.

d) Light Xenon Isotopes

The p -process isotopes ^{124}Xe and ^{126}Xe are also enhanced in the diamonds. This could be interpreted as isotopic mass fraction favoring light isotopes, but I take it to represent p -process nucleosynthesis and condensation within the common carriers called for in my (Clayton 1976, 1981) condensation model. These p -process isotopes can be overproduced by factors of several hundred in the oxygen shell near shock temperatures $2.4 < T_0 < 3.0$ (Arnold 1976; Woosley and Howard 1978; Heymann and Dziczkaniec 1979). The relative amount of such material that must be mixed outward into the He shell is therefore only about 10^{-2} to produce Xe-HL with comparable ^{124}Xe and ^{136}Xe enhancement factors. This small amount of

associated oxygen will not endanger diamond condensation, but its occurrence would strengthen the plausibility of the scenario that even larger fractions of the cooler parts of the oxygen core were also mixed outward, strengthening the above speculation that large portions of Xe-HL may be produced in the oxygen core and admixed into the carbon-dominated He shell before it has expanded to the epoch of CO molecule formation.

e) Noble Gas Concentrations: Helium and Neon

It is perhaps worth mentioning that the typical meteoritic C δ diamond has no Xe atoms of any persuasion in it. The concentration of Xe-HL in C δ is $^{136}\text{Xe}_{\text{HL}} = 15 \times 10^{-8} \text{ ml g}^{-1}$ at standard temperature and pressure (Anders 1988). This translates to $4 \times 10^{12} \text{ atoms g}^{-1}$ of $^{136}\text{Xe}_{\text{HL}}$. The C δ diamonds are typically 25–50 Å (Lewis *et al.* 1987), or $\lesssim 10^{-18} \text{ g of C}$. Thus one needs a collection of 10^6 diamonds to expect a single $^{136}\text{Xe}_{\text{HL}}$ atom! That Xe-HL can be up to 5% of carbonaceous chondrite Xe reemphasizes how truly abundant are the C δ diamonds there. They constitute several percent of the total meteoritic carbon. This has guided me to seek one of nature's main-line processes, not some obscure event from the stellar zoo. It is also evident that $^{136}\text{Xe}/\text{C}$ in the diamond is some 500 times smaller than in solar abundances, showing that high condensation efficiency is not required.

It has not been widely appreciated that most of meteoritic He and Ne (after subtracting solar wind implantation) also resides in these diamonds. This led Clayton (1981) to advance the argument that meteoritic He and Xe are also "presolar"—i.e., a component within interstellar dust (now known to be C δ) rather than a component picked up from the solar parent cloud. Clayton (1981) reviews also the prior less sweeping interpretations by those who discovered the correlation between Xe-HL and He and Ne. In what follows I continue my presolar interpretation, which today looks secure.

Because He and ^{22}Ne are the major species along with carbon (e.g., Woosley 1988, Fig. 4) in the shell, the associated trapping of He and ^{22}Ne -rich neon during the condensation of the diamonds follows. Chemically it requires He and Ne to be trapped in forming diamonds with efficiencies about 10^{-5} of those for xenon trapping. The C δ neon composition Ne-A2 (Anders 1988) is $^{20}\text{Ne}/^{22}\text{Ne} = 8.4$, in contrast to the usual solar value 13.7, which is taken from the solar wind itself (Geiss *et al.* 1972) in order to know the bulk gaseous ratio. These facts lend strong support to my argument, but the question is raised of where the ^{20}Ne came from, because the ratio in the He shell itself is $^{22}\text{Ne}/^{20}\text{Ne} \approx 8$ (almost pure ^{22}Ne). ^{20}Ne -rich neon is found only interior to the He shell, within the carbon-burned core, bathed in oxygen. It would appear that mixing it outward to achieve $^{20}\text{Ne}/^{22}\text{Ne} \approx 8.4$ would defeat diamond condensation by making $\text{O} > \text{C}$. This could remain a problem; but what is wanted is more attention from other astrophysicists if the whole range of complex issues is to be elucidated.

I make one more suggestion. The bulk of He and Ne in C δ may have been implanted as fast ions in the diamonds during their interstellar residence. Implantation begins with the deceleration of the diamonds from 1000 km s^{-1} to ambient dust, and continues with the suprathreshold interstellar flux of He and Ne generated by interstellar shock wave acceleration. The integrated flux of such suprathreshold ions during the average interstellar lifetimes of diamonds may be large.

There do exist in meteorites carriers of very ^{22}Ne -rich neon,

the so-called Ne-E, and it is tempting to speculate that they may have condensed from this same ^{22}Ne -rich helium shell—even though they are not known to be carriers of Xe-HL. Jungck and Eberhardt (1979) showed two distinct carriers of Ne-E, with distinctly different mass densities and gas release temperatures. The lighter carrier is carbonaceous (now called C α) and has $^{22}\text{Ne}/^{20}\text{Ne} > 10^2$. This Ne-E(L) ratio is so much greater than the value $^{22}\text{Ne}/^{20}\text{Ne} \approx 6-8$ that exists in the He shell that simple trapping of ambient neon is ruled out for this origin of Ne-E(L). Apparently the condensation of explosively synthesized ^{22}Na as progenitor of ^{22}Ne (Clayton 1975a; Clayton and Hoyle 1976) is required. Interestingly, however, ^{22}Na can be synthesized in those C-poor, ^{14}N -rich portions of the He shell lying above the He-burning convection zone if the shock heats it to $T > 6 \times 10^8 \text{ K}$, in which case the zone mixing might yet result in Ne-E(L). In that case, however, we can hope for successful detection of ^{22}Na γ -ray lines from SN 1987A (Clayton 1975b). The heavier Ne-E(H) carrier has the more modest requirement $^{22}\text{Ne}/^{20}\text{Ne} > 5$, and thus could condense ambient neon in the carbon-rich portions of the He shell; however, it has not been firmly established that this carrier is carbonaceous.

The ^{38}Ar is also enhanced by about 10% (Anders 1988). Clayton (1981) has already described how this supports this model by admixing material from the shocked He-exhausted core. The ^{14}N -richness of nitrogen in C δ also points to a presolar component (Anders 1988). I achieve that very easily by mixing of the He-burning convective shell with the radiative portion of the He shell above it, for it is very rich in pure ^{14}N . Such mixing surely occurs. These issues have a great astrophysical future.

f) Isotopically Light Diamonds

The carbonaceous chondrite diamonds are among the few isotopically anomalous carriers in which the carbon is enriched in ^{12}C (Anders 1988). Although they are only 4% enriched in ^{12}C , even that enrichment is in striking contrast to the very large ^{13}C excesses in numerous other isotopically anomalous samples (Anders 1988). The scenario that I have described involves pure ^{12}C created by the 3α processes in the He-burning shell, so it is in the right direction—but exuberantly so. Because $^{13}\text{C}/^{12}\text{C} \approx 0.2$ in that portion of the He shell lying above the convection zone connecting to the He-burning zone itself, a nearby source of ^{13}C exists, suggesting, as in the case of ^{14}N , rather through mixing of the entire He shell after the neutron burst. The problem is that ^{13}C concentration is only about 10^{-4} in the He zone above its convective shell, whereas the ^{12}C concentration is 5% or so within that convective shell. Mass balance does not easily achieve the puzzling observed $^{12}\text{C}/^{13}\text{C}$ ratio in the diamonds—only that they are ^{12}C -rich rather than ^{13}C -rich. An alternative possibility may be some type of further diamond growth after ejection, or perhaps the metamorphic shock transition to diamond of initially condensed graphite during grain collisions (Tielens *et al.* 1987). The first very ^{12}C -rich carbon has just recently been reported by Ash *et al.* (1988), not in diamonds but perhaps within spinel (MgAl_2O_4), a prominent high- T thermal condensate (SUNOCON) anticipated in supernova shells (Clayton 1978). The He shell is the logical venue for its formation as well in order to have unoxidized carbon present. Spinel was originally suggested also as Ne-E(H) carrier, but that identification is in doubt (Anders 1988).

g) Conclusion

So many exciting questions remain for future research into the origins of this common and significant isotopic pattern, Xe-HL, that I must for the moment content myself with the simple calculations and arguments presented here. But if these arguments do point in the correct direction, the diamonds are either SUNOCONs (Clayton 1978) or have SUNOCON cores, in which case they support cosmic chemical memory interpretations over inhomogeneous admixture interpretations. Furthermore, the correct details of diamond formation and survival will become one of the most profound examples of cosmic chemical memory, a new field of astronomy (Clayton 1982), describing intricate details of Type II supernovae.

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REFERENCES

- Anders, E. 1988, in *Meteorites and the Early Solar System*, ed. J. Kerridge (Tucson: University of Arizona Press).
- Angus, J. C., and Haymann, C. C. 1988, *Science*, **241**, 913.
- Arnett, W. D. 1988, *Ap. J.*, **331**, 377.
- Arnould, M. 1976, *Astr. Ap.*, **46**, 117.
- Ash, R. D., Arden, J. W., Grady, M. M., Wright, I. P., and Pillinger, C. T. 1988, *Nature*, **336**, 228.
- Bao, Z. Y., and Käppeler, F. 1987, *Atomic Data Nucl. Data Tables*, **36**, 411.
- Clayton, D. D. 1968, *Principles of Stellar Evolution and Nucleosynthesis* (New York: McGraw-Hill).
- . 1975a, *Nature*, **257**, 36.
- . 1975b, *Ap. J.*, **198**, 151.
- . 1976, *Geochim. Cosmochim. Acta*, **40**, 563.
- . 1978, *Moon and Planets*, **19**, 109.
- . 1981, *Proc. Lunar Planet. Sci. Conf.*, **12B**, 1781.
- . 1982, *Quart. J.R.A.S.*, **23**, 174.
- Clayton, D. D., and Hoyle, F. 1976, *Ap. J.*, **203**, 490.
- Cowan, J. J., Cameron, A. G. W., and Truran, J. W. 1985, *Ap. J.*, **294**, 656.
- Epstein, R. I., Colgate, S. A., and Haxton, W. C. 1988, *Phys. Rev. Letters*, **61**, 2038.
- Geiss, J., Buehler, F., Cerutti, H., Eberhardt, P., and Filleaux, D. 1972, in *Apollo 16 Prelim. Sci. Rept.* (NASA SP-315), § 14, p. 1.
- Harris, M. J. 1988, *Science*, **240**, 60.
- Heymann, D. 1981, *Proc. Lunar Planet. Sci. Conf.*, **12B**, 1803.
- Heymann, D., and Dziczkaniec, M. 1979, *Proc. Lunar Planet. Sci. Conf.*, **10**, 1943.
- . 1980, *Proc. Lunar Planet. Sci. Conf.*, **11**, 1179.
- . 1981, *Geochim. Cosmochim. Acta*, **45**, 1829.
- Jørgensen, U. G. 1988, *Nature*, **332**, 702.
- Jungck, M. H. A., and Eberhardt, P. 1979, *Meteoritics*, **14**, 439.
- Krummenacher, D., Merrihue, C. M., Pepin, R. O., and Reynolds, J. H. 1962, *Geochim. Cosmochim. Acta*, **26**, 231.
- Larimer, J. W. 1975, *Geochim. Cosmochim. Acta*, **39**, 389.
- Leising, M. D. 1988, *Nature*, **332**, 516.
- Lewis, R. S., and Anders, E. 1981, *Ap. J.*, **247**, 1122.
- Lewis, R. S., Srinivasan, B., and Anders, E. 1975, *Science*, **190**, 1251.
- Lewis, R. S., Tang, M., Wacker, J. F., Anders, E., and Steele, E. 1987, *Nature*, **326**, 160.
- Manuel, O. K., Hennecke, E. W., and Sabu, D. D. 1972, *Nature Phys. Sci.*, **240**, 99.
- Nomoto, K., and Hashimoto, M. 1988, *Phys. Rept.*, **163**, 13.
- Oliver, L. I., Ballard, R. V., Richardson, J. F., and Manuel, O. K. 1981, *J. Inorg. Nucl. Chem.*, **43**, 2207.
- Pepin, R. O., and Phinney, D. 1979, *Moon and Planets*, submitted.
- Pinto, P. A., and Woosley, S. E. 1988, *Ap. J.*, **329**, 820.
- Prantzos, N., Arnould, M., and Casse, M. 1988, *Ap. J. (Letters)*, **331**, L15.
- Reynolds, J. H. 1960, *Phys. Rev. Letters*, **4**, 351.
- Reynolds, J. H., and Turner, G. 1964, *J. Geophys. Res.*, **69**, 3263.
- Roy, R. 1987, *Nature*, **325**, 17.
- Saslaw, W. C., and Gaustad, J. E. 1969, *Nature*, **221**, 160.
- Spyromilio, J., Meikle, W. P. S., Learner, R. C. M., and Allen, D. A. 1988, *Nature*, **334**, 327.
- Tielens, A. G. G. M., Seab, C. G., Hollenbach, D. J., and McKee, C. F. 1987, *Ap. J. (Letters)*, **319**, L109.
- Truran, J. W., Cowan, J. J., and Cameron, A. G. W. 1978, *Ap. J. (Letters)*, **222**, L63.
- Weaver, T. A., and Woosley, S. E. 1980, *Ann. NY Acad. Sci.*, **336**, 335.
- Woosley, S. E. 1988, *Ap. J.*, **330**, 218.
- Woosley, S. E., and Haxton, W. C. 1988, *Nature*, **334**, 45.
- Woosley, S. E., and Howard, W. M. 1978, *Ap. J. Suppl.*, **36**, 285.

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