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Heavy-element abundances from a neutron burst that produces Xe-H

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Abstract—We examine quantitatively the suggestion that the heavy anomalous isotopes of Xe-HL found in meteoritic diamonds were produced by a short intense neutron burst and then implanted into the diamonds. Using a large nuclear reaction network we establish one (out of many) neutron irradiation histories that successfully reproduces the heavy isotopes of Xe-HL, and then evaluate what that same history would produce in every heavy element. This has become more relevant following recent measurement of anomalous Ba and Sr in those same diamond samples. Therefore we offer these calculations as a guide to the anomalies to be expected in all elements if this scenario is correct. We also discuss several other aspects of the problem, especially the established contradictions for Ba, the observed Kr pattern, the near normalcy of ¹²⁹Xe, and some related astrophysical ideas. In particular we argue from *p*-process theory that the observed deficit of ⁷⁸Kr in correlation with ¹²⁴⁻¹²⁶Xe excess implicates Type II supernovae as the diamond sources. However, our more complete astrophysical conclusions will be published elsewhere. This present work is offered as computational expectation for this class of models and as a guide to considerations that may accelerate the digestion of new experimental results in the diamonds.

INTRODUCTION

THE ISOTOPICALLY HEAVY XENON COMPONENT WITHIN METEORITES that is today known as Xe-HL has been now studied for three decades (Reynolds and Turner, 1964). A useful and brief modern history of it is given by Anders (1988). Although more and more has been learned about it, the circumstances of its implantation into its carriers, themselves now known to be abundant diamonds of very small size (*e.g.*, Lewis *et al.*, 1987), are unknown. It is difficult to use their ubiquitous presence in meteorites as a diagnostic of meteorite history (Huss, 1990) without more complete understanding of the provenance and expected interstellar abundance of the carriers. One active approach to this question is the chemical problem of the origin of diamonds (*e.g.*, Nuth, 1987; Badziag *et al.*, 1990; Bernatowicz *et al.*, 1990; Nuth and Allen, 1991). The present work pursues the analysis of the isotopic structures themselves, augmented by the relative abundances of anomalous atoms of separate elements. In particular, the recent (Lewis *et al.*, 1991) measurement of abnormal Ba in a collection of diamonds and the hope that the laser-extraction technique may soon produce other isotopically analyzable elements prompt us to prepare a lookup table of expectations for one very specific class of model of the nucleosynthetic origin. Our hope is that the predictive aspects of our table of results will facilitate either confirmation or disavowal of that class of models.

The point of view that we take here is that Xe-HL carriers are grains formed either within expanding supernova interiors or in the vicinity of supernovae and that have had the *p*-process isotopes and the neutron-rich isotopes implanted within them before mixing of the supernova ejecta with the interstellar medium (Clayton, 1975; 1976). In principle this implantation could be accomplished by either thermal condensation or high speed bombardment, with modern thinking favoring the latter (Lewis and Anders, 1981) owing both to the implausibly high efficiency that would be required for thermal condensation of noble gas at diamond-condensing temperatures and owing to the large chemical fractionation during thermal condensation that would be expected, for example, to have enriched ¹²⁹I and Ba relative to Xe isotopes.

The supernovae create the *p* isotopes in their inner mantles (Woosley and Howard, 1978), whereas the unshielded neutron-rich isotopes of Xe-H must be created elsewhere because they require neutron capture rather than neutron photoejection. The location depends upon what physical process is actually responsible for the free neutrons. Suggestions for the origin of Xe-H in the meteorites include: *in situ* fission of an extinct superheavy nucleus (*e.g.*, Anders, 1988); actinide fission of sort-lived nuclei in the SUNOCON grains (Clayton, 1975; Arnould *et al.*, 1975); normal *r*-process production and SUNOCON implantation (Clayton, 1975), which fails by making too much ¹³¹Xe; abnormal *r*-process production (Black, 1975; Clayton, 1975), which lacks a plausible reason for having the carriers carry the abnormal *r*-process products rather than the more abundant normal *r*-process products; a weak short burst of neutrons that moves nuclei to more neutron-rich unshielded isotopes (*e.g.*, Heymann and Dziczkaniec, 1979; Clayton, 1981) but that is in other respects quite unlike an *r*-process.

We use this last idea in this work. The neutron burst probably occurs either in explosive carbon burning (Howard *et al.*, 1972; Heymann and Dziczkaniec, 1979) or in the outer He-rich mantle when the supernova shock wave traverses it (Clayton, 1981; 1989). There are a lot of possibilities. We here adopt the He-shell burst, however, both because it seems more physically plausible for the nuclear component and because the He-burning shell actually provides a carbon-rich site (Clayton, 1981), which is, perhaps erroneously, regarded as a prerequisite for condensation of diamonds. We suppose that the great separation between He shell and the true *r*-process site, now regarded as likely to be in a central small *r*-process bubble (Woosley and Hoffman, 1991), offers a chance to understand why the He-shell Xe was sampled by the diamonds whereas the inner bubble was not (see below). Therefore, what we will present is detailed nuclear calculations within one plausible history for some outer mantle material in a supernova, a history having both a weak *s*-process irradiation prior to the shock wave and a rapid neutron burst at shock passage. We tabulate what that Xe-H producing burst would predict for other chemical elements. This procedure is identical to the one used by Clayton (1981; 1989). What we

here add to that discussion is a complete and thoroughly maintained nuclear network for all heavy elements and predictions for their anomalous abundances. This may facilitate validation or falsification of such models. The He-shell model also makes more definitive predictions for other reasons. Because of the modest shock temperature in the He shell the neutron addition process can be calculated without the extra uncertainties associated with gamma erosion at the higher temperatures of the C and O shells (Heymann and Dziczkaniec, 1979). For this reason the He shell sets a more easily falsifiable target.

Separation of H and L Nuclei

Much has been made of the difficulty of separating the *p*-process light isotopes (Xe-L) from the unshielded heavy isotopes (Xe-H). It is tempting to conclude that they are mixed in the carriers. But the data do not require that. So rare is Xe and so small are the diamonds (25 Å) that most diamonds contain not a single atom of Xe. It is only a collection of a large number of diamonds that carries the Xe-HL pattern. It is not known if the Xe-HL carrying diamonds are from the same population as those that do not. It is not known that the Xe-H and Xe-L carrying diamonds are from the same population. Very few diamonds will contain more than one atom of Xe unless those are but a minute fraction of all diamonds. It is perfectly plausible that part of the carriers contain Xe-H and another part Xe-L, with most having no Xe at all. Their relative constancy then reflects the large number of diamonds required for a measurable sample. Viewed in this way, the astrophysical separation of the production sites for Xe-H and Xe-L is not a problem. The problem is instead why they should both be carried in diamonds that are indistinguishable in size, release temperature or oxidizability. Their indistinguishability is a key for the chemical memory theory that underlies this (and most modern) interpretations of the anomalies. Namely, how does it come about that both supernova-source zones have similar diamonds available to them for Xe implantation? The diamonds would seem to have condensed only in carbon-rich portions of the supernova interior (*i.e.*, SUNOCONS), leading Clayton (1981; 1989) to identify the He-burning shell as the only carbon-rich zone and to therefore associate Xe-H with that zone of condensation.

The *p*-nuclei arise from the O and Ne shells (Woosley and Howard, 1978), which are devoid of carbon after the shock passage. So the idea of condensation of Xe immediately faces a problem. But it now seems that no Xe truly “condensed” in the diamonds, but was instead implanted by high speed collisions. If that be so, the initial zonal separation of the isotopic patterns may be irrelevant, as could then also be Clayton’s (1981) argument that the neutron burst should have occurred in the He shell because of that being where the carbon-rich matter exists. Rather, we would now argue that the supernova was shown by its X and gamma-ray emission to have been extensively mixed in velocity space by post-explosion instabilities. The early appearance of X and gamma rays from supernova 1987A demonstrated that velocity differentials of order 10³ km/sec exist not only between samples of differing zones but even of the same zones (*e.g.*, Leising and Share, 1990). In consequence, the diamonds condensing in the C-rich pockets will, in a statistical sense, be swept past the entire spectrum of gaseous Xe ejecta from the envelope of the supernova. What we now speculate is that most all Xe in the supernova ejecta (exceptions

being the true *r*-process Xe trapped in the high-entropy bubble near the neutron star and isotopically normal Xe in the outer He shell and hydrogen envelope (of the Type II)) is either irradiated during the shock with a brief neutron burst (Xe-H) or lies in the *p*-process zone (Xe-L) where net-neutron sources do not exist (are overwhelmed by gammas). Then three types of Xe gas (normal, *p*, and neutron-irradiated) are sampled at high relative speeds by the diamonds. The *s*-process Xe, which is certainly present in the envelope prior to the shock, suffers the quick irradiation by gammas and neutrons during the shock and disappears. Heymann and Dziczkaniec (1979) discussed the nuclear trends of this within the C and O shells, which they focussed their attention upon, using more preliminary nuclear data and without addressing how that matter may have gotten into the carbonaceous carriers. Not sampled by the diamonds, then, was the *s*-process Xe deficient throughout the interior and the “true” *r*-process Xe, which apparently issues forth in a last-gasp wind to leave the forming neutron star—the high entropy bubble (Woosley and Hoffmann, 1991). The huge ¹²⁹I and ¹³¹Xe abundances of the latter would, if sampled, demolish the Xe-H pattern, which is almost devoid of excesses in these two nuclei. It remains to be seen whether hydrodynamic arguments naturally separate that high-entropy *r*-process bubble from the diamonds and the remainder of the supernova xenon. But that does not seem implausible.

Circumstellar Carbon rather than SUNOCONS

It also remains possible that pre-existing circumstellar carbon dust was chemically transformed to diamonds by the postsupernova environment (Nuth and Allen, 1991), and was irradiated by the Xe-HL wind (Clayton, 1981). In this case the supernova may have either been of Type I (an exploding white dwarf) with the carbon dust having been prepared by a C-star binary companion (Clayton, 1981; Jorgensen, 1988), in which case it could lack completely the true *r*-process component which is not produced in white dwarf explosions, but be very rich in the *p*-process ejecta, which is very rich in those explosions (Howard *et al.*, 1991), and in neutron irradiated ejecta in the mantle of incompletely burned matter—or, alternatively, it may have been a Type II (core collapse to a neutron star) in which the circumstellar diamonds (or graphite) were first prepared in the WC-phase wind prior to the core collapse (Clayton, 1981). In either we may find the desired combination of Xe-H and Xe-L without contamination by Xe-*r* and Xe-*s*, but it may be easier in the Type I models where no true *r*-process is even expected. In our later discussion of Kr data, however, we demonstrate reasons for favoring Type II. One must keep an open mind attuned to such questions at the present time, expecting only to solve them eventually.

The foregoing astrophysical unknowns provide justification for considering herein the production only of Xe-H. Because the Xe-L and Xe-H must have been admixed after their nuclear productions, we simplify matters by calculating only the heavy component. We will not address the *p*-isotopes from the Ne shell photodisintegration (Woosley and Howard, 1978; Howard *et al.*, 1991) except for some specific observations about ⁷⁸Kr. We reiterate only that those nuclei must also have been sampled by differential velocity with the diamonds, in the sense discussed above. Our table of results will contain only Xe-H and the analogous H component of other heavy elements. We present

that table as a predictive diagnostic of this type of Xe-HL theory for forthcoming meteoritic investigations. They may establish that a short neutron burst is indeed implicated, and it is to put that proposal to the test that we submit these calculations.

THE COMPUTATION

The neutron irradiation histories within the supernova mantles will differ from place to place. From all such possibilities we choose a single representative irradiation that reproduces Xe-H reasonably well—in particular the 136/132 and 134/132 isotopic ratios accompanied by only very small ^{129}Xe and ^{131}Xe yields. We then calculate all elements for that one history. The history that we select consists of a weak *s*-process exposure $\tau = 0\text{--}0.02$ neutrons/mb during a 10^6 year history prior to explosion followed by a rapid irradiation $\tau = 0.075$ n/mb over the shock duration (10 sec), for reasons explained for example by Clayton (1989). The latter is fast enough that virtually no beta decays occur during it. Material in the mantle is left in a roughly binary state—it has either been heated to a threshold temperature adequate for neutron release by the shock or it has not. In the latter case the isotopes may be normal; but in the shocked case there is a tendency for the shock to release all the available neutrons stored in the form of neutron-source nuclei (*e.g.*, ^{13}C , ^{17}O , ^{22}Ne). The fast but weak fluence in the hot-shocked mantle may be of the same order throughout it. The hotter parts of the shocked envelopes just release those neutrons faster.

Another justification for presenting but a single history is that we have found by several trials that irradiation histories that give the Xe-H satisfactorily produce almost the same yields for other elements as well—at least in the binary admixture of irradiated and unirradiated matter. That is, the nuclear systematics of successful Xe-H production delimit severely the possibilities for other elements. It is for these reasons that we tabulate below our computation of one such successful history as having some generality. Any single history that produces Xe-H by such a weak-burst scenario will give almost these same answers for other elements. A more subtle question is harder to answer: if Xe-H is a superposition of several widely differing irradiation histories, rather than the binary mixture that we construct, will the yields for other elements be well characterized by our calculations? We believe substantially so—enough so that we here document one complete calculation as a template for theories of this general class. The quantitative improvement that justifies our table's publication is the up-to-date treatment of the neutron cross sections, which are much better known than in early works of this type, and our giving of results across the heavy elements.

The calculation is performed with a neutron capture code that has been constructed to address such fluences. It is time dependent, temperature dependent through the beta decay rates and through excited-state effects in neutron-capture rates, and contains the latest in published and calculated values for the neutron capture cross sections. This is the same code that we have used to study the *s*-process in AGB stars, for example (Howard *et al.*, 1986). It integrates the rates of neutron capture and beta decay over the duration of the irradiation. Neutron captures are allowed on all neutron-rich nuclei having known beta decay half-lives. The network includes sufficiently neutron-rich isotopes for valid burst calculations. We have updated the neutron capture cross sections listed by Howard *et al.* (1986) with those

from Bao and Kaeppler (1987) and from a recent determination of the cross sections for Sr, Kr and Xe isotopes by Beer (1991) and for several neutron-rich isotopes from Cowan *et al.* (1991). The beta rates and the neutron capture rates are temperature sensitive through excited-state effects, although our calculation is carried out at $kT = 30$ keV. Because of the relatively good present state of neutron cross sections, the results in Table 1 have high reliability, although each nucleus is a separate case insofar as accuracy is concerned. Stable-nucleus cross sections are known to 10–20% accuracy, but unstable ones probably to only 50% accuracy. We show that the latter uncertainty is the greater in the calculated H patterns. Considering this good situation, we find it to be realistic to present Table 1 for He-shell neutron bursts.

Table 1: Burst Results and Binary Mixture

Table 1 contains the burst results. Column 1 lists solar abundances N_{\odot} on the $\text{Si} = 10^6$ scale (Anders and Grevesse, 1989). Column 2 is the neutron-capture cross sections, evaluated in mb for 30 keV temperature. Should the neutron burst occur at a different temperature, as is likely, our results still have validity, because in that case the cross sections scale almost like T^{-5} for almost all nuclei (see however, Beer *et al.*, 1991), so that the calculated results are instead valid for a fluence $(kT/30 \text{ keV})^5$ times the one given. Column 3 lists the final abundances N^* on the same scale after presupernova weak *s*-process $\tau = 0.002$ n/mb, followed by supernova-shock induced rapid neutron burst $\tau = 0.075$ n/mb, culminated by beta decays to stable isobars. The final column mixes N^* with 5.5 parts N_{\odot} , an arbitrary mix that we call N-H and that characterizes the Xe-H ratios reported by Huss (1990) in the diamond separates. It is this final column that will be of immediate interest to new measurements on other elements. Quantitatively the abundance N-H after that binary mixing is

$$\text{N-H} = (N^* + 5.5N_{\odot})/5.5N_{\odot} = 1 + 0.182N^*/N_{\odot}$$

so that the value $\text{N-H} = 1$ characterizes nuclei that were totally eliminated by the neutron fluence in the irradiated endmember N^* (examples being $^{128,130}\text{Xe}$). The entire N-H complement of those nuclei arises from the solar admixture. The value $\text{N-H} = 1.182$ is then the boundary between nuclei that are depleted or enhanced in their concentrations N^* relative to their initial (solar) concentrations.

There is little physical reason to admix N^* with solar abundances other than the tradition of interpreting isotopically anomalous components as a binary admixture with solar abundances. In a case like this one, where the anomalous dust is stardust, probably SUNOCONS, it makes more sense to calculate the isotopic endmember from the star itself. In this case the N^* column is more meaningful than is the N-H column. The other “endmember” is then the composition of the remaining admixed stellar gas. Nonetheless, we do list N-H with this $5.5N_{\odot}$ dilution in Table 1, both for historical reasons and because it remains possible that solar abundances actually are the other endmember. A solar endmember arises either from laboratory contamination or, in the Xe-HL case, from mean interstellar gas implanted during the presolar history of the diamonds. Neither is unlikely.

We have begun the irradiation table with silicon. The Si-Fe

TABLE 1. Initial, post-burst, and mixed abundances.

	N_{\odot}	$\sigma_{n,\gamma}$	N^*	N-H
28Si	9.220e+05	1.750e+00	7.805e+05	1.154e+00
29Si	4.670e+04	7.900e+00	1.204e+05	1.469e+00
30Si	3.100e+04	6.400e+00	1.945e+05	2.141e+00
31P	1.040e+04	1.740e+00	7.599e+04	2.329e+00
32S	4.890e+05	4.750e+00	3.184e+05	1.118e+00
33S	3.860e+03	8.393e+00	7.004e+03	1.330e+00
34S	2.170e+04	2.918e+00	2.172e+04	1.182e+00
36S	1.030e+02	3.053e-01	3.340e+03	6.895e+00
35Cl	2.860e+03	1.009e+01	5.864e+03	1.373e+00
37Cl	9.130e+02	2.169e+00	2.353e+03	1.469e+00
36Ar	8.500e+04	6.772e+00	4.479e+04	1.096e+00
38Ar	1.600e+04	2.586e+00	4.617e+03	1.525e+00
40Ar	2.600e+01	3.684e+00	1.528e+03	1.169e+01
39K	3.516e+03	1.189e+01	6.268e+03	1.324e+00
40K	5.480e+00	1.879e+01	3.354e+02	1.213e+01
41K	2.537e+02	2.216e+01	7.571e+02	1.543e+00
40Ca	5.920e+04	6.751e+00	3.114e+04	1.096e+00
42Ca	3.950e+02	1.571e+01	1.117e+03	1.514e+00
43Ca	8.250e+01	5.135e+01	6.411e+02	2.413e+00
44Ca	1.275e+03	8.855e+00	1.338e+03	1.191e+00
46Ca	2.400e+00	5.433e+00	2.691e+02	2.139e+01
48Ca	1.140e+02	8.952e-01	1.098e+02	1.175e+00
45Sc	3.420e+01	9.049e+01	5.438e+02	3.891e+00
46Ti	1.920e+02	2.650e+01	3.568e+01	1.034e+00
47Ti	1.750e+02	6.480e+01	7.999e+01	1.083e+00
48Ti	1.771e+03	3.080e+01	2.299e+02	1.024e+00
49Ti	1.320e+02	2.210e+01	6.417e+02	1.884e+00
50Ti	1.300e+02	4.000e+01	1.409e+03	2.970e+00
50V	7.320e-01	4.951e+01	6.682e-03	1.002e+00
51V	2.920e+02	4.221e+01	2.561e+02	1.159e+00
50Cr	5.870e+02	5.257e+01	4.011e+00	1.001e+00
52Cr	1.130e+04	9.849e+00	4.900e+03	1.079e+00
53Cr	1.283e+03	5.827e+01	1.025e+03	1.145e+00
54Cr	3.190e+02	7.309e+00	5.467e+03	4.116e+00
55Mn	9.550e+03	3.977e+01	1.928e+03	1.037e+00
54Fe	5.220e+04	2.923e+01	3.249e+03	1.011e+00
56Fe	8.250e+05	1.316e+01	2.625e+05	1.058e+00
57Fe	1.980e+04	3.514e+01	1.350e+05	2.240e+00
58Fe	2.520e+03	1.305e+01	2.958e+05	2.234e+01
59Co	2.250e+03	3.814e+01	1.445e+05	1.268e+01
58Ni	3.370e+04	3.795e+01	9.183e+02	1.005e+00
60Ni	1.290e+04	3.071e+01	6.217e+04	1.876e+00
61Ni	5.570e+02	8.255e+01	9.611e+03	4.137e+00
62Ni	1.770e+03	3.562e+01	1.283e+04	2.318e+00
64Ni	4.490e+02	1.043e+01	1.080e+04	5.373e+00
63Cu	3.610e+02	9.332e+01	1.416e+04	8.133e+00
65Cu	1.610e+02	5.315e+01	2.381e+03	3.689e+00
64Zn	6.130e+02	5.918e+01	3.161e+01	1.009e+00
66Zn	3.520e+02	3.510e+01	1.164e+03	1.601e+00
67Zn	5.170e+01	1.534e+02	5.700e+02	3.004e+00
68Zn	2.360e+02	1.925e+01	1.123e+03	1.865e+00
70Zn	7.800e+00	1.014e+01	7.113e+02	1.758e+01
69Ga	2.270e+01	1.469e+02	6.636e+02	6.315e+00
71Ga	1.510e+01	1.253e+02	1.608e+02	2.936e+00
70Ge	2.440e+01	9.020e+01	9.493e-02	1.001e+00
72Ge	3.260e+01	5.712e+01	7.744e+01	1.432e+00
73Ge	9.280e+00	2.846e+02	1.256e+01	1.246e+00
74Ge	4.340e+01	5.451e+01	1.921e+01	1.080e+00
76Ge	9.280e+00	1.603e+01	8.990e+01	2.761e+00
75As	6.560e+00	4.559e+02	1.664e+01	1.461e+00

TABLE 1. Continued.

	N_{\odot}	$\sigma_{n,\gamma}$	N^*	N-H
76Se	5.600e+00	1.634e+02	2.989e-04	1.000e+00
77Se	4.700e+00	4.417e+02	3.880e+01	2.501e+00
78Se	1.470e+01	8.966e+01	4.464e+01	1.552e+00
80Se	3.090e+01	4.406e+01	9.481e+00	1.056e+00
82Se	5.700e+00	1.902e+01	2.670e+01	1.852e+00
79Br	5.980e+00	7.427e+02	1.024e+01	1.311e+00
81Br	5.820e+00	2.445e+02	8.610e+00	1.269e+00
80Kr	9.990e-01	2.514e+02	6.818e-08	1.000e+00
82Kr	5.150e+00	7.910e+01	1.136e-01	1.004e+00
83Kr	5.160e+00	2.245e+02	1.306e+01	1.460e+00
84Kr	2.570e+01	3.504e+01	2.041e+01	1.144e+00
86Kr	7.840e+00	3.340e+00	6.437e+01	2.493e+00
85Rb	5.120e+00	2.403e+02	6.785e+00	1.241e+00
87Rb	2.110e+00	2.102e+01	8.057e+00	1.694e+00
86Sr	2.320e+00	6.390e+01	1.009e-01	1.008e+00
87Sr	1.510e+00	9.210e+01	2.066e-01	1.025e+00
88Sr	1.941e+01	6.511e+00	3.093e+01	1.290e+00
89Y	4.640e+00	1.903e+01	7.108e+00	1.279e+00
90Zr	5.870e+00	2.103e+01	7.491e+00	1.232e+00
91Zr	1.280e+00	6.004e+01	3.433e+00	1.488e+00
92Zr	1.960e+00	3.305e+01	5.130e+00	1.476e+00
94Zr	1.980e+00	2.640e+01	3.369e+00	1.309e+00
96Zr	3.200e-01	1.070e+01	3.618e+00	3.056e+00
93Nb	6.908e-01	2.663e+02	1.970e+00	1.513e+00
95Mo	4.060e-01	2.924e+02	2.253e+00	2.009e+00
96Mo	4.250e-01	1.122e+02	6.429e-03	1.003e+00
97Mo	2.440e-01	3.394e+02	1.328e+00	1.990e+00
98Mo	6.150e-01	9.912e+01	5.796e-01	1.171e+00
100Mo	2.460e-01	9.704e+01	1.417e-01	1.105e+00
99Ru	2.360e-01	9.180e+02	6.847e-02	1.053e+00
100Ru	2.340e-01	2.060e+02	1.300e-06	1.000e+00
101Ru	3.160e-01	9.960e+02	1.117e-01	1.064e+00
102Ru	5.880e-01	1.860e+02	1.685e+00	1.521e+00
104Ru	3.480e-01	1.610e+02	9.786e-01	1.511e+00
103Rh	3.440e-01	1.128e+03	1.583e-01	1.084e+00
104Pd	1.550e-01	2.890e+02	2.113e-10	1.000e+00
105Pd	3.100e-01	1.199e+03	9.027e-02	1.053e+00
106Pd	3.800e-01	2.520e+02	3.151e-01	1.151e+00
108Pd	3.680e-01	2.030e+02	4.328e-01	1.214e+00
110Pd	1.630e-01	1.460e+02	2.661e-01	1.297e+00
107Ag	2.520e-01	8.614e+02	5.432e-02	1.039e+00
109Ag	2.340e-01	8.662e+02	6.581e-02	1.051e+00
110Cd	2.010e-01	2.530e+02	2.931e-08	1.000e+00
111Cd	2.060e-01	1.064e+03	3.559e-02	1.031e+00
112Cd	3.880e-01	2.219e+02	1.243e-01	1.058e+00
113Cd	1.970e-01	7.275e+02	2.782e-02	1.026e+00
114Cd	4.630e-01	1.499e+02	3.402e-01	1.134e+00
116Cd	1.210e-01	9.394e+01	2.478e-01	1.372e+00
115In	1.760e-01	7.427e+02	3.623e-02	1.037e+00
115Sn	1.290e-02	2.816e+02	1.581e-06	1.000e+00
116Sn	5.550e-01	9.201e+01	4.166e-03	1.001e+00
117Sn	2.930e-01	4.026e+02	5.665e-02	1.035e+00
118Sn	9.250e-01	6.297e+01	5.739e-01	1.113e+00
119Sn	3.280e-01	3.076e+02	1.048e-01	1.058e+00
120Sn	1.245e+00	3.898e+01	1.672e+00	1.244e+00
122Sn	1.770e-01	2.298e+01	2.488e+00	3.556e+00
124Sn	2.210e-01	2.298e+01	1.455e+00	2.197e+00
121Sb	1.770e-01	7.206e+02	2.647e-01	1.272e+00
123Sb	1.320e-01	4.397e+02	3.815e-01	1.526e+00
122Te	1.240e-01	2.800e+02	3.505e-08	1.000e+00
123Te	4.280e-02	8.193e+02	1.269e-10	1.000e+00

TABLE 1. Continued.

	N _o	σ _{n,γ}	N*	N-H
124Te	2.290e-01	1.540e+02	1.251e-05	1.000e+00
125Te	3.420e-01	4.230e+02	4.259e-01	1.226e+00
126Te	9.090e-01	8.828e+01	5.890e-01	1.118e+00
128Te	1.526e+00	3.897e+01	3.778e-01	1.045e+00
130Te	1.634e+00	1.549e+01	1.512e+00	1.168e+00
127I	9.000e-01	6.244e+02	1.028e-01	1.021e+00
128Xe	1.030e-01	3.470e+02	4.388e-09	1.000e+00
129Xe	1.280e+00	7.570e+02	1.644e-01	1.023e+00
130Xe	2.050e-01	1.750e+02	5.565e-06	1.000e+00
131Xe	1.020e+00	4.530e+02	6.136e-01	1.109e+00
132Xe	1.240e+00	6.460e+01	8.310e-01	1.122e+00
134Xe	4.590e-01	2.020e+01	1.726e+00	1.684e+00
136Xe	3.730e-01	9.100e-01	2.368e+00	2.154e+00
133Cs	3.720e-01	4.994e+02	2.473e-01	1.121e+00
134Ba	1.090e-01	2.208e+02	7.478e-08	1.000e+00
135Ba	2.960e-01	2.950e+02	9.063e-01	1.557e+00
136Ba	3.530e-01	6.893e+01	2.176e-02	1.011e+00
137Ba	5.040e-01	5.694e+01	4.377e-01	1.158e+00
138Ba	3.220e+00	3.896e+00	5.864e+00	1.331e+00
139La	4.460e-01	3.838e+01	1.070e+00	1.436e+00
140Ce	1.005e+00	1.059e+01	9.873e-01	1.179e+00
142Ce	1.260e-01	1.808e+01	3.927e-01	1.567e+00
141Pr	1.670e-01	1.189e+02	1.249e-01	1.136e+00
142Nd	2.250e-01	4.595e+01	8.711e-03	1.007e+00
143Nd	1.000e-01	2.527e+02	1.360e-01	1.247e+00
144Nd	1.970e-01	1.099e+02	1.256e-01	1.116e+00
145Nd	6.870e-02	4.718e+02	5.650e-02	1.150e+00
146Nd	1.420e-01	1.568e+02	1.108e-01	1.142e+00
148Nd	4.770e-02	1.917e+02	7.918e-02	1.302e+00
150Nd	4.670e-02	1.892e+02	5.778e-02	1.225e+00
147Sm	3.870e-02	9.974e+02	3.889e-02	1.183e+00
148Sm	2.920e-02	2.666e+02	2.040e-09	1.000e+00
149Sm	3.560e-02	1.334e+03	7.135e-02	1.364e+00
150Sm	1.910e-02	4.464e+02	2.358e-08	1.000e+00
152Sm	6.890e-02	3.986e+02	5.804e-02	1.153e+00
154Sm	5.860e-02	3.087e+02	1.626e-01	1.504e+00
151Eu	4.650e-02	4.383e+03	2.344e-02	1.091e+00
153Eu	5.808e-02	3.083e+03	4.386e-02	1.157e+00
154Gd	7.190e-03	8.773e+02	1.544e-14	1.000e+00
155Gd	4.880e-02	2.719e+03	6.977e-02	1.260e+00
156Gd	6.760e-02	6.833e+02	1.521e-01	1.409e+00
157Gd	5.160e-02	1.354e+03	8.268e-02	1.291e+00
158Gd	8.200e-02	2.185e+02	7.830e-02	1.174e+00
160Gd	7.210e-02	1.464e+02	5.463e-02	1.138e+00
159Tb	6.030e-02	1.804e+03	4.550e-02	1.137e+00
160Dy	9.220e-03	7.979e+02	2.897e-14	1.000e+00
161Dy	7.450e-02	1.828e+03	3.270e-02	1.080e+00
162Dy	1.010e-01	4.996e+02	5.200e-02	1.094e+00
163Dy	9.820e-02	1.121e+03	1.996e-02	1.037e+00
164Dy	1.110e-01	2.866e+02	5.071e-02	1.083e+00
165Ho	8.890e-02	1.304e+03	2.345e-02	1.048e+00
166Er	8.430e-02	6.458e+02	1.068e-01	1.230e+00
167Er	5.760e-02	1.525e+03	3.235e-02	1.102e+00
168Er	6.720e-02	3.822e+02	4.992e-02	1.135e+00
170Er	3.740e-02	2.415e+02	4.404e-02	1.214e+00
169Tm	3.780e-02	1.469e+03	1.583e-02	1.076e+00
170Yb	7.560e-03	7.936e+02	1.246e-15	1.000e+00
171Yb	3.540e-02	1.448e+03	1.983e-02	1.102e+00
172Yb	5.430e-02	4.502e+02	3.742e-02	1.125e+00
173Yb	4.000e-02	8.579e+02	1.348e-02	1.061e+00
174Yb	7.880e-02	1.899e+02	3.403e-02	1.079e+00
176Yb	3.150e-02	1.162e+02	7.552e-02	1.436e+00

TABLE 1. Continued.

	N _o	σ _{n,γ}	N*	N-H
175Lu	3.570e-02	1.197e+03	1.263e-02	1.064e+00
176Lu	1.035e-03	1.534e+03	1.268e-13	1.000e+00
176Hf	7.930e-03	4.918e+02	4.429e-17	1.000e+00
177Hf	2.870e-02	1.359e+03	2.274e-02	1.144e+00
178Hf	4.200e-02	3.233e+02	7.766e-02	1.336e+00
179Hf	2.100e-02	9.822e+02	1.979e-02	1.171e+00
180Hf	5.410e-02	1.822e+02	9.286e-02	1.312e+00
181Ta	2.070e-02	8.027e+02	2.055e-02	1.181e+00
182W	3.500e-02	2.778e+02	1.128e-01	1.586e+00
183W	1.900e-02	5.253e+02	2.007e-02	1.192e+00
184W	4.080e-02	2.362e+02	1.082e-01	1.482e+00
186W	3.800e-02	1.770e+02	1.467e-01	1.702e+00
185Re	1.930e-02	1.521e+03	3.924e-02	1.370e+00
187Re	3.510e-02	1.567e+03	3.324e-02	1.172e+00
186Os	1.070e-02	4.254e+02	1.739e-15	1.000e+00
187Os	8.070e-03	1.091e+03	9.737e-16	1.000e+00
188Os	8.980e-02	4.009e+02	1.054e-01	1.213e+00
189Os	1.090e-01	1.166e+03	4.020e-02	1.067e+00
190Os	1.780e-01	2.950e+02	2.288e-01	1.234e+00
192Os	2.770e-01	3.103e+02	1.914e-01	1.126e+00
191Ir	2.470e-01	1.322e+03	1.006e-01	1.074e+00
193Ir	4.140e-01	9.097e+02	7.532e-02	1.033e+00
192Pt	1.050e-02	3.872e+02	2.229e-14	1.000e+00
194Pt	4.410e-01	3.123e+02	1.190e-01	1.049e+00
195Pt	4.530e-01	1.059e+03	7.793e-02	1.031e+00
196Pt	3.380e-01	1.766e+02	1.002e-01	1.054e+00
198Pt	9.860e-02	6.286e+01	5.434e-02	1.100e+00
197Au	1.870e-01	5.714e+02	2.672e-02	1.026e+00
198Hg	3.390e-02	1.726e+02	1.395e-06	1.000e+00
199Hg	5.740e-02	3.746e+02	4.946e-02	1.157e+00
200Hg	7.850e-02	1.147e+02	8.666e-02	1.201e+00
201Hg	4.480e-02	2.358e+02	2.581e-02	1.105e+00
202Hg	1.015e-01	7.385e+01	1.051e-01	1.188e+00
204Hg	2.330e-02	4.190e+01	6.253e-01	5.880e+00
203Tl	5.430e-02	1.237e+02	2.250e-01	1.753e+00
205Tl	1.297e-01	5.388e+01	2.131e+00	3.988e+00
204Pb	6.110e-02	8.931e+01	2.020e-04	1.001e+00
206Pb	5.930e-01	1.400e+01	3.679e-01	1.113e+00
207Pb	6.500e-01	8.420e+00	7.567e-01	1.212e+00
208Pb	1.837e+00	3.647e-01	2.353e+00	1.233e+00
209Bi	1.440e-01	3.120e+00	1.701e-01	1.215e+00

region contains several elements that may yet be detected within diamond aggregates and that may be highly diagnostic. Table 1 shows very large enhancements for ³⁶S, ⁴⁰Ar, ^{43,46}Ca, ⁵⁰Ti, ⁵⁴Cr and ⁵⁸Fe. The ³⁶S, ⁴⁰Ar and ⁴⁶Ca are of such low absolute abundance that their excesses may not ever be measurable in diamonds; however, other more abundant isotopes of those elements also show large overabundances. Detection of these would greatly aid diagnosis.

Lighter Elements: Argon Example

One such element, argon, has already been measured (Lewis *et al.*, 1977) to have 10% ³⁸Ar richness relative to ³⁶Ar (the only isotopes measurable). These measurements may be barely compatible with the 38/36 ratio in Ar-H mixture shown in Table 1, which is 39% greater than solar (1.525/1.096). The agreement cannot be taken as highly significant for this model, however, unless the implanted Ar can truly be restricted to the He-and-C

shells, because new $^{36,38}\text{Ar}$ are abundantly synthesized in the underlying explosive oxygen burning (Woosley *et al.*, 1973). That new Ar constitutes a third Ar endmember within Type II supernovae. Moreover, the nucleosynthesis of this new Ar dominates the total supernova ejecta (about 10:1), unlike the situation in the heavy elements, so the 38/36 ratio contained in that new nucleosynthesis, which depends on the initial fractional neutron excess (Woosley *et al.*, 1973) comes directly into play. This same caveat applies to the entire Si-Fe region, so “predictions” in Table 1 must be evaluated with that new endmember in mind. Another technical difference in the Si-Fe mass region is the significance of (n,α) and (n,p) reactions. Bao and Kaeppler (1987) tabulate these special reactions in this mass region that we have included in our code. For example, the $^{33}\text{S}(n,\alpha)^{30}\text{Si}$ reaction renders ^{33}S much less overabundant and ^{30}Si much more overabundant than they would have been in the absence of that reaction, and $^{41}\text{Ca}(n,\alpha)^{38}\text{Ar}$ plays a major role in the ^{38}Ar overabundance mentioned above.

The Xe-Ba Region Illustrated

Figure 1 shows the distribution of postburst abundances prior to their final beta decays in the interesting portion of the nuclide chart containing Te, Xe and Ba. It shows illuminating nuclear and chemical details not contained in Table 1. The final abundances after the burst of all radioactive species are shown. One sees there that ^{134}Xe and ^{136}Xe are primarily synthesized in the elemental Xe capture chain, with neither I nor Te contributing significant extra parents. ^{129}Xe , ^{131}Xe and ^{132}Xe , on the other hand, are produced primarily as Te parents. The sum, as discussed below, makes an acceptable caricature of Xe-H. It is this systematic result that has encouraged calculations of Xe-H from both carbon zones (Heymann and Dziczkaniec, 1979) and He zones (Clayton, 1981, 1989). ^{124}Xe and ^{126}Xe (not shown) and ^{128}Xe and ^{130}Xe are annihilated by these histories, so that their final overabundances in Table 1 are equal to 1.00; *i.e.*, they arise entirely from the solar endmember of the mixtures. As a second example in Fig. 1, the final $^{137}\text{Ba} = 0.438$ abundance in Table 1 can be seen to be 39% direct production in the Ba isotopic chain and 61% radioactive progenitors, especially the neutron-magic ^{137}Cs , which plugs the Cs chain and which arrests all progenitors at 30.2 year ^{137}Cs . Whether the implantation into diamonds happens in times shorter or longer than 30 years thus becomes an interesting question for chemical memory. For ^{135}Ba , by contrast, the entire yield is radioactive progenitors, arrested at 2.3 Ma ^{135}Cs after being mostly synthesized as ^{135}Xe but partly as neutron-magic ^{135}I . Certainly the implantation precedes that decay. Although it is too much to publish in entirety, readers wishing a parentage breakdown for other elements may request it privately. We have included Fig. 1 for better communication of the nature of the results that Table 1 is based upon.

DISCUSSION

How well does this simple calculation work for Xe-H? For data we take the gas ratios reported by Huss (1990) within a separate of diamonds themselves. For Xe one can define the experimentally determined *overabundance factors* ^iO relative to ^{130}Xe to be $\text{O}(^i\text{Xe}/^{130}\text{Xe})/(^i\text{Xe}/^{130}\text{Xe})_{\odot}$. The values of $\text{O}(\text{Xe-H})$ from Huss’s data and for the calculated results N-H in Table 1 (excluding the *p*-process isotopes) are:

N =	74	75	76	77	78	79	80	81	82	83	
56 Ba	130 0.00476 1(-18)		132 0.00453 7(-13)		134 0.109 6(-8)	135 0.296 6(-8)	136 0.353 0.0197	137 0.504 0.166	138 3.22 5.816		0.983
55 Cs					133 0.372 2(-8)	9(-9)	1(-5)	7(-6)	0.199	0.044	
54 Xe	128 0.103 2(-12)	129 1.28 2(-12)	130 0.205 3(-6)	131 1.02 2(-6)	132 1.24 0.0427	0.0331	134 0.459 1.620	0.800	136 0.373 2.366		0.062
53 I	127 0.90 9(-9)	4(-9)	6(-6)	2(-6)	1.5(-4)	1(-4)	0.0042	0.0026	0.105	0.0022	
52 Te	126 0.909 0.0046	0.0023	128 1.526 0.254	0.128	130 1.634 1.493	0.564	0.766	0.193	0.0974	0.0012	

FIG. 1. The Ba-Xe-Te region of the chart of nuclides. Stable isotopes have solid square boundaries, and contain both atomic number A and the value of N_{\odot} . Numbers at the bottom of each square show N^* prior to final beta decays. Very small abundances show the power of ten in parentheses. From these details the entries in Table 1 are constructed.

$$\begin{aligned} \text{O}(^{128}\text{Xe}) &= 1.150 \quad (1.00), & \text{O}(^{129}\text{Xe}) &= 1.078 \quad (1.023), \\ \text{O}(^{130}\text{Xe}) &= 1 \quad (1), & \text{O}(^{131}\text{Xe}) &= 1.081 \quad (1.109), \\ \text{O}(^{132}\text{Xe}) &= 1.060 \quad (1.122), & \text{O}(^{134}\text{Xe}) &= 1.686 \quad (1.684), \\ \text{O}(^{136}\text{Xe}) &= 2.262 \quad (2.154), \end{aligned}$$

where the first number is Huss’s result and the number in parentheses is the result listed (Xe-H) in Table 1 in the column labeled N-H. How well those two sets of numbers agree is a matter of debate, which we will not resolve. Instead we point out that two ratios, $^{134}\text{Xe}/^{130}\text{Xe}$ and $^{136}\text{Xe}/^{130}\text{Xe}$, have been fitted with two parameters, the shock fluence $\tau = 0.075$ and the admixture with 5.5 times as much solar abundance. The $\tau = 0.02$ n/mb pre-irradiation has negligible influence and is thus not really a fitting parameter. So the most important part of the fit is made true by construction. The rough agreement of the other five isotopes, whose measured overabundances are much smaller, is a result suggesting that the ballpark may be the right one but the details are not. The conclusion could be stated that it is possible for such calculations to overproduce 134 and 136 by the correct factors without greatly violating other of the non-*p* abundances. This result has long been known, but our calculation is more accurate than previous ones. And in that regard the recent lowering of the ^{134}Xe cross section (Beer, 1991) to 20.2 mb at $kT = 30$ keV has increased the requisite fast fluence to $\tau = 0.075$, whereas Clayton (1989) found that $\tau = 0.065$ would be adequate. This stronger requirement for neutrons will place a heavy burden on the astrophysical models (in preparation).

What general remarks should one make about the lack of exact agreement for the other Xe isotopes? We here detail three.

Firstly, the isotopic abundances have been measured with much more accuracy than they can be calculated. For each nucleus that remains in the burst-irradiated endmember, the deviation from 1.00 in the calculated ratio reflects its final abundance. That abundance depends most strongly on its neutron capture cross section, which is known to accuracies varying between about 10% in the best cases to about 50% in the least well known cases. Therefore the deviations from 1.00 in Table 1 are uncertain to comparable degrees according to the well-known basic inverse correlation of *s*-process abundance with cross section. This renders some small discrepancies with measured Xe-H unmeaningful at the present time.

Secondly, the calculated productions depend to some degree on the extent of *s*-process pre-irradiation prior to the burst, whereas we have taken $\tau = 0.02$ for that value. These pre-irradiations change the elemental abundance ratios present during the burst (see Fig. 1 of Clayton, 1989), again leading to 10–50% variations in some cases. For example, one sees from our Fig. 1 that about 12% of $^{135}\text{Ba}^*$ was synthesized as ^{135}I progenitor; but the initial I/Xe ratio, which enters into that result, depends on the *s*-process pre-irradiation. In our comparison calculation made without pre-irradiation, iodine is more abundant so that the ^{135}I progenitor is also, by the large factor of 7.9, causing the final ^{135}Ba -H of Table 1 to be 1.98 instead of 1.56. The final value of ^{137}Ba -H, on the other hand, is reduced slightly by the lack of pre-irradiation, as is even more the value for ^{138}Ba -H, which is reduced from 1.332 (see Table 1) to 1.196 by its absence. For Xe the important $^{134}\text{Xe}^*$ and $^{136}\text{Xe}^*$ overabundances are hardly changed at all, although those for $^{131}\text{Xe}^*$ and $^{132}\text{Xe}^*$ are increased by almost 50%, causing $^{131-132}\text{Xe}$ -H in the admixture with $5.5N_{\odot}$ to lie nearer 1.2 than 1.1. These examples show that the uncertain pre-irradiation does carry interesting consequences, but not ones that alter the basic shape and identity of the large overabundances in N^* .

Thirdly, and most importantly we believe, the calculation assumed solar abundances for the initial stars. This is certain to be wrong in detail, for we are here concerned with several contributing supernova progenitors that were formed, evolved and exploded prior to the formation of the solar system. It is the average of the initial abundances in those stars that would presumably be averaged, 5.5 parts to one (in our Table 1) with the irradiated mass—at least if the “solar” admixture is taken to have arisen from the star’s own atmosphere rather than from contamination in the solar system. In other words, the “normal” endmember is necessarily unidentified in STARDUST cases, whereas the data are nonetheless compared to solar abundances. Consider an example. The rather large disagreement for ^{129}Xe , namely ^{129}Xe -H = 1.078 vs. calculated 1.023, is resolved if the initial 129/130 ratio of the precursor stars is a mere 5% greater than solar. This is not at all implausible for presolar star formation, and even matches the tendency for the *r*-process galactic yield to have risen sooner than its *s*-process yield (*cf.* Mathews *et al.*, 1992). Indeed a good scientific question for future research is the near normalcy of the endmember, which is apparently about 5.5 times more abundant (in our Table 1) than the irradiated endmember. The issue of radiogenic ^{129}Xe may be of relatively less importance, except for its arguing against a condensation process for entrapment (Lewis and Anders, 1981), because although Fig. 1 shows that $^{129}\text{I}^*$ dominates N^* at $A = 129$, it is swamped in ^{129}Xe -H by the much larger admixture of the “normal ^{129}Xe endmember,” which we have taken to be solar simply for definiteness.

Finally, the disagreement at ^{128}Xe , where the measured 1.15 is unquestionably greater than 1.00, may reflect initial nonsolar abundances but may also be reflecting that 10% or so of the solar ^{128}Xe abundance is instead a *p*-process product (Woosley and Howard, 1978) and would therefore have been enriched by the Xe-L portion rather than by the Xe-H portion that we have calculated. In that case the calculated result ^{128}Xe -H = 1.00 is indeed appropriate for the Xe-H portion. These remarks may assure the reader that the disagreements at the level given for $^{128-132}\text{Xe}$ are not unreasonable for this model. It is only those

isotopes much enriched by the neutron burst that carry meaningful information at the present state of knowledge. In the question of initial abundances we also glimpse an even deeper layer of cosmochemical memory, predating not only the solar system but perhaps even the formation of the supernova progenitors of the Xe-H bearing diamonds.

Krypton: Type II Supernova Indicator

Another noble gas, krypton, has been long known (Lewis *et al.*, 1975) to be associated with Xe-HL. See also Anders (1988). This observed Kr-HL is indeed enriched $O(^{86}\text{Kr}) = 1.4$ relative to ^{82}Kr ; but the *p* isotope ^{78}Kr is instead slightly deficient. The enrichment of neutron-magic ^{86}Kr is expected on this model, although the calculated ^{86}Kr -H = 2.49 in Table 1 is larger than the measured value 1.4. The significance of this discrepancy is not presently clear to us because of cross section uncertainties, *etc.* But we remark that the overabundance $N^*/N_{\odot} = 8.2$ of ^{86}Kr in the irradiated endmember itself is about 78% greater than in Clayton’s (1989) calculation, showing that modest improvements sometimes bring significant changes. This overabundance is comparable to that for ^{136}Xe , namely 6.3 for N^*/N_{\odot} .

The discrepancy at ^{78}Kr , on the other hand, has long been recognized to be significant. Our calculation of neutron-rich isotopes sheds no insight into that; however, our *p*-process work (Woosley and Howard, 1978; Howard *et al.*, 1991) shows strong tendency for *p* yields that tend to be much smaller in the Kr region than in the Xe region (relative to solar). It was to solve that old problem that Howard *et al.* (1991) called upon a stronger *s*-process pre-irradiation of material in the CO white dwarf progenitors of Type I owing to their containment of ashes of the He-shell thermal pulses of the parent AGB stars. In the Type I deflagrations that follow, they show that proton captures also come into play causing overproduction of ^{78}Kr but good results for heavier *p* nuclei (see their Fig. 2). The solar *p* abundances are, in the context of the chemical evolution of our galaxy (Clayton, 1988) an admixture of Type I and Type II supernova yields. If Type I supernovae alone do overproduce ^{78}Kr , therefore, then Type II supernovae must underproduce it, as calculations confirm (Woosley and Howard, 1978). This clue, which we will pursue in further work, suggests Type II supernovae as the originators of the Kr-H and Xe-H patterns. The negative sign of that ^{78}Kr anomaly, however, could also be achieved by an initial composition for the presupernova having subsolar 78/82 ratio. This again would point to an alternate interpretation in terms of chemical evolution of the solar neighborhood. In that case the different behaviour from Xe-H would arise from the larger overabundances of *p* yields in the Xe region in Type II supernovae, so that after dilution with an assumed atmospheric *p*-deficient endmember, ^{78}Kr -H would remain negative whereas $^{124,126}\text{Xe}$ -H would become positive. Either of these new interpretations leads to many exciting questions.

Another puzzle is that ^{83}Kr and ^{84}Kr are both observed to be overabundant with respect to ^{82}Kr by factors near 1.2, whereas our Table 1 computation gives 1.46 for ^{83}Kr but only 1.14 for ^{84}Kr . A figure similar to Fig. 1 but for the Kr region would show one important factor to be that about 95% of ^{83}Kr in the calculated N^* is actually synthesized as ^{83}Se , whose cross section must be counted as very uncertain. Almost half of ^{84}Kr is, moreover, produced as ^{84}Se with analogous problem. It is conceivable that better known cross sections in Se could resolve the lion’s

share of this discrepancy. The size of *s*-process pre-irradiation plays only a minor role here. Omitting it reduces N^* for ^{86}Kr by 43%, which is the most significant effect. It reduces ^{84}Kr very little, with no significant decrease of $^{84}\text{Kr-H}$ because of its huge abundance in the unirradiated endmember. ^{84}Kr is in fact actually depleted by the irradiation, as Clayton (1989) also showed. The calculated $^{83}\text{Kr-H}$ is increased only from 1.46 to 1.52 by omitting the *s*-process pre-irradiation. Thus the pre-irradiation question, though interesting, does not alter the fact that the calculated Kr-H value for ^{83}Kr is much bigger than that for ^{84}Kr . Omitting the *s*-process pre-irradiation also decreases ^{82}Kr , the common reference isotope, by a rather hefty factor of 5 (by virtue of eliminating its early *s*-process enrichment from ^{81}Br). But ^{82}Kr is actually being depleted by the neutron flux, as Table 1 shows; therefore, the “normal endmember” so dominates $^{82}\text{Kr-H}$ that the final column would be negligibly altered.

Thus, in summary, the initial fit to Kr-H data is not very good, except for the hefty $^{86}\text{Kr-H}$ and the strong $^{83}\text{Kr-H}$. We believe that more elements need examining, because the disparity between Kr and Xe patterns is an old one (*e.g.*, Lewis *et al.*, 1975) that will not be easily resolved without more such information. Unquestionably Kr is a pivotal element for nucleosynthesis and chemical evolution treatment. We note that trends of Kr systematics during carbon burning have been discussed by Heymann and Dziczkaniec (1980).

Barium and Strontium

In a technological step forward that has inspired this paper, Lewis *et al.* (1991) have measured anomalous Ba and Sr in an aggregate of diamonds from Allende. The Ba data are the most interesting. They find deviations relative to ^{138}Ba , corrected to solar $^{134}\text{Ba}/^{138}\text{Ba}$ ratio, given by $\delta(^{135}\text{Ba}) = 1.22 \times 10^{-3}$ and $\delta(^{137}\text{Ba}) = 0.6 \times 10^{-3}$, with about 25% accuracy. Two immediate conflicts appear. Firstly, those anomalies in unshielded isotopes were already noted by Lewis *et al.* (1991) to be about three orders of magnitude smaller than the Xe anomalies. Secondly, Table 1 shows that ^{138}Ba should also be very overabundant, whereas Lewis *et al.* (1991) normalized to it. It seems unlikely that their isotopic data can be renormalized because of the large difference in 134/138 ratio between Table 1 and solar. It would require an implausible 8% per amu, which would surely have been recognized in their data analysis. If one formally performed such large mass-dependent fractionation of their data the ^{137}Ba excess relative to ^{134}Ba would become three times larger than the corresponding ^{135}Ba excess, in contrast to our prediction that the $^{135}\text{Ba-H}$ should be the larger of the two. Although there seems no possibility of avoiding a ^{138}Ba excess in models of this type, the absence of an *s*-process pre-irradiation would lower that excess (from 1.33 to 1.20), while slightly lowering the ^{137}Ba excess and increasing the ^{135}Ba excess to almost ninefold greater than the calculated ^{137}Ba excess (in N-H).

Perhaps we must seek reasons for ^{134}Ba overproduction in other zones of the supernova to compensate the ^{138}Ba overproduction in N^* , *i.e.*, seek peculiarities in the other endmember to be mixed with N^* . In such a way the 134/138 ratio could appear normal in the diamonds without having to be normal in the N-H component; but then the ^{136}Ba would show deficiency unless all three *s*-process isotopes were enhanced in the other member. Such an approach takes us outside the more limited objectives of this work, however. Speculations without more

data and theory on this point are useful only in reminding that other possibilities exist.

Any difference in precondensation between Ba and Cs would also rear its head. The causative features, the long lifetimes of $^{135,137}\text{Cs}$, were described above in the discussion of Fig. 1. So our present understanding of Ba data stalls in the face of problems of ^{138}Ba renormalization, of *s*-process pre-irradiation and of Ba/Cs and Ba/Xe fractionation owing to gas condensation into dust prior to implantation (see below). On the positive side Ba, like Kr, has features suggestive of this type of process (*viz.* $^{135,137}\text{Ba}$ excesses), but their magnitudes do not agree in detail. Any *p*-process anomalies in $^{130,132}\text{Ba}$, on the other hand, are lost in statistical uncertainties, so that that valuable information does not yet exist. We note that features of the Ba systematics have been previously discussed by Heymann (1983) in the context of carbon burning.

In addition to the suggestive shape of the Ba anomaly, one is struck by its surprisingly small magnitude. This means that the actual number of anomalous Ba atoms is about 10^{-3} of the number of anomalous Xe atoms in the samples. To reconcile this fact to models of this type one seems to be forced to assume that most of the Ba in the experiment is actually solar contamination. Then the smallness of the Ba-H concentration could be ascribed to precondensation of the Ba into refractory particles prior to that time when the gas particles are implanted by high relative speeds with respect to the diamonds—*i.e.*, only 10^{-3} of the Ba remains in the gas when it is implanted (Lewis *et al.*, 1991). This suggestion is in good accord with astrophysical possibilities.

For strontium the situation is even more confusing. Table 1 unequivocally predicts ^{88}Sr excess to be the largest in Sr-H; but Lewis *et al.* (1991) argue that ^{88}Sr is normal relative to ^{84}Sr . Omitting the *s*-process pre-irradiation does reduce ^{88}Sr by 42% in N^* abundances, leaving its concentration almost unchanged, but that still leaves a positive $^{88}\text{Sr-H} = 1.17$ after admixture with the solar endmember. (Recall that N-H = 1.182 represents the dividing value between nuclei that are enriched in absolute concentration in N^* and those that are depleted in N^* .) Their observed excess at ^{87}Sr is probably largely radiogenic—all the more so if our Table 1 prediction of ^{87}Rb -rich Rb-H bears up. The $^{87}\text{Rb}/^{87}\text{Sr}$ ratio in N^* is some 28 times greater than solar in Table 1, leaving a significant enrichment in ^{87}Rb even after dilution with the other endmember. Thus Rb-H becomes a good target for experimental isotopic study. More Sr data could help if even better quality can be achieved. The volatility of Rb relative to Sr will also play a role if precondensation of (preferentially) Sr occurs as speculated for Ba. And the *p* isotope ^{84}Sr will probably, for the same reasons as ^{78}Kr , be negative if the interpretation implicating Type II described above holds up.

Our purpose in discussing the existing data in this brief way is not to suggest a final answer. That is clearly going to take much more data. Rather we hope to have illustrated the ways in which our calculated results can be used to challenge models of this type. We offer our predictions for such models in the hope that more data will be forthcoming and that our calculations can accelerate their application to the problem.

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