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AN INTERPRETATION OF SPECIAL AND GENERAL ISOTOPIC ANOMALIES IN *r*-PROCESS NUCLEI

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ABSTRACT

My analysis of new discoveries by McCulloch and Wasserburg of Ba and Nd isotopic anomalies in inclusions of the Allende meteorite argues that (1) these anomalies contain special extinct radioactivities resulting from radioactive decay within grains formed in and ejected from the supernova interior, (2) the inclusions studied are fused assemblies of interstellar grains that were never totally vaporized, and (3) theoretical separation into *r* and *s* abundances suggests that fluctuations between *r* and *s* components has occurred during the accumulation processes. These points lend support to a new chemical picture of the early solar system that I have developed, although many interpretations remain possible. Measurements of the neutron-capture cross sections of Nd isotopes are urgently needed to experimentally validate these conclusions.

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

I. INTRODUCTION

In an important paper McCulloch and Wasserburg (1978) have detected nonlinear isotopic anomalies in the elements Ba and Nd within Ca-Al–rich inclusions of the Allende meteorite. These anomalies are found in very special mineral inclusions having isotopic anomalies in many elements, as described in the references in their paper. The existence of these nonsimple anomalies must have important implications for both the origin of the solar system and the origin of these inclusions as a chemical process within the solar system. In this work I argue that (1) these anomalies contain *extinct radioactivities* resulting from decay within interstellar grains of *r*-process products that have condensed in the expansion of supernova interiors (Clayton 1975*a*, *b*); (2) they indicate that Ca-Al–rich inclusions are not condensates from a hot gaseous solar nebula, but are instead admixtures of precondensed matter fused by heating (Clayton 1977*a*, *b*, *c*); (3) partial separation of *r*-process and *s*-process products has occurred during accumulation processes.

Clayton (1975*a*, *b*) discovered that chemical fractionation between radioactive parents and their daughter elements should result in large isotopic anomalies within supernova condensates (SUNOCONs). The parent need live roughly a year in order to allow sufficient time for refractory condensates to form within the expanding supernova interior where they were synthesized. Clayton (1977*a*) further argued that such presolar condensates with variable SUNOCON admixtures provided the single best explanation of isotopic anomalies, although his arguments were by no means decisive in the face of controversial uncertainties and rapidly evolving knowledge. This beautiful new set of experiments on heavy elements by McCulloch and Wasserburg will now be shown to corroborate my interpretation, although it will also be interpreted by some as supporting the supernova trigger for formation of the solar system.

A major problem in providing the following decompositions into *r* and *s* isotopes is the lack of experimentally determined neutron-capture cross sections for the isotopes of Nd. Measurement of these will be shown to provide valuable clues to the accumulation of the solar system. Lacking measurements, I will choose theoretical calculations by Holmes *et al.* (1976) as a guide.

II. Nd ANOMALIES

Consider first the measured anomalies in the isotopes of Nd, the element having the more straightforward interpretation. Table 2 of McCulloch and Wasserburg (1978) lists the large isotopic anomalies that they found in three samples of EK1-4-1. For purposes of discussion I will adopt the average anomalies in these samples as being the most reasonable single sample to discuss, and that average anomaly $\bar{\epsilon}(A)$ is the first row listed in my Table 1. Before performing this average, I corrected ^{143}Nd for the 2.94% of ^{147}Sm that decays over the 4.56×10^9 yr assumed age of the sample. The Nd/Sm ratios given by McCulloch and Wasserburg are 2.85 in EK1 SC and 3.5 in EK1 MEL, in contrast to the average chondritic value 3.45 (Cameron 1973). These elemental abundance ratios correspond to isotopic ratios $^{147}\text{Sm}/^{143}\text{Nd} = 0.432$ in EK1 SC and 0.351 in EK1 MEL, so that decay over 4.56×10^9 yr augments ^{143}Nd by a fraction $\Delta^{143}\text{Nd}/^{143}\text{Nd} = 0.0127$ in EK1 SC and 0.0103 in EK1 MEL. The MEL excess is almost exactly equal to that of average chondritic matter, and was therefore not corrected before averaging; however, the decay in SC is still greater by an amount $0.0127 - 0.0103 = 0.0024$. In Table 1, I therefore reduced the value of $\epsilon(143)$ in

TABLE 1

Nd ISOTOPIC DECOMPOSITION

A	^{142}Nd	^{143}Nd	^{144}Nd	^{145}Nd	^{146}Nd	^{148}Nd	^{150}Nd
$\bar{\epsilon}$(A)*	-9.57	-0.17	0	2.47	-12.6	-1.17	-9.57
$\bar{\epsilon}'$(A)	0	13.6	18.0	24.6	13.8	33.6	33.6
N†	0.211	0.0949	0.186	0.0647	0.134	0.0447	0.0438
σ‡	40	175	67.3	485	105	...	...
N_s	0.211	0.0482	0.125	0.0173	0.080	$\equiv 0$	$\equiv 0$
N_r	$\equiv 0$	0.0467	0.061	0.0474	0.054	0.0447	0.0438
N_r/N	0	0.492	0.328	0.733	0.403	1	$\equiv 1$
ϵ_r(A)	0	16.5	11.0	24.6	13.5	33.6	33.6

* In parts per 10^4 from McCulloch and Wasserburg 1978 data on EK1-4-1.

† Per 10^6 Si from Cameron 1973*a*.

‡ In mb from Holmes *et al.* 1976 except for my corrected estimate of $\sigma(^{142}\mathrm{Nd})$ and for choosing $\sigma(^{143}\mathrm{Nd}) = 4.4\sigma(^{142}\mathrm{Nd})$ as calculated.

the SC samples by 24×10^{-4}, after which the three samples are virtually indistinguishable. Those entries were normalized to a standard $^{142}\mathrm{Nd}/^{150}\mathrm{Nd}$ abundance ratio, but neither that choice nor their other choice of $^{142}\mathrm{Nd}/^{144}\mathrm{Nd}$ for normalization is really appropriate for detecting the *r*-process component, because both choices mix *r* and *s* isotopic production. A superior choice is a fractionation that results in equal positive anomalies for the two *r*-only isotopes, ^{148}Nd and ^{150}Nd. To make $\bar{\epsilon}(148) = -1.17$ also equal $\bar{\epsilon}(150) = -9.57$ clearly requires fractionation, increasing heavy isotopes by $4.2 = d\epsilon/dA$ per unit mass. This procedure, retaining *s*-only ^{142}Nd as the index isotope, results in the second line $\bar{\epsilon}'$ of Table 1. These values $\bar{\epsilon}'$ will be shown to be almost exactly equal to a small enhancement of the general *r*-process yield plus a special anomaly at ^{144}Nd. These features were seen roughly by McCulloch and Wasserburg, but to see the quantitative agreement requires a brief digression into the nucleosynthesis of the isotopes of Nd.

The third row of Table 1 lists the solar abundances according to Cameron (1973*a*) of Nd isotopes on the scale Si $= 10^6$. The decomposition into *s* and *r* abundances may be performed as in Seeger, Fowler, and Clayton (1965), but with improved numerical information. The fourth row lists neutron-capture cross sections appropriate for *s*-process nucleosynthesis. They are taken from the theoretical compilation of Holmes *et al.* (1976), except for $\sigma(^{142}\mathrm{Nd})$, to which I assign a value 40 mb in place of the calculated value 75.8 mb. The cross section for this neutron-magic nucleus must not be so large as 75.8 mb. Evidence for this can be found in neighboring Ce. For ^{140}Ce, the neighbor even-even $N = 82$ nucleus, both calculated and measured values agree on the 10–20 mb range, and even nonmagic ^{142}Ce has a calculated $\sigma(^{142}\mathrm{Ce}) = 33$ mb, considerably smaller than for magic ^{142}Nd. Were $\sigma(^{142}\mathrm{Nd})$ indeed as large as 75.8 mb, it would also not be possible to understand the high abundance of ^{142}Nd, which is more abundant than ^{144}Nd despite an *r*-process contribution to the latter. For these reasons I feel well justified in deducing $\sigma(^{142}\mathrm{Nd}) = 40$ mb by demanding that $\sigma(^{142}\mathrm{Nd})N(^{142}\mathrm{Nd}) = \sigma(^{144}\mathrm{Nd})N_s(^{144}\mathrm{Nd})$ with the added requirement that $N_r(^{144}\mathrm{Nd}) = 0.061$, which can be inferred from continuity requirements of the *r*-process abundance curve (Cameron 1973*a*). A similar deduction is achieved by comparing ^{142}Nd with ^{141}Pr, whose abundance is about half *s* and half *r* and whose measured $\sigma(^{141}\mathrm{Pr}) = 110$ mb. This reasoning should not be regarded as circular, because it uses only proven theory to adjust the calculated magnitude of a neutron-magic cross section. I then use $\sigma(^{143}\mathrm{Nd}) = 175$ mb to retain the calculated ratio of that cross section to that of ^{142}Nd. The analogous situation in neutron-magic Zr, where measurements show that $\sigma(^{91}\mathrm{Zr})/\sigma(^{90}\mathrm{Zr}) \approx 4.6$ confirms the reasonableness of keeping the computed ratio of 4.4 for Nd from Holmes *et al.* (1976). The remaining cross sections are their actual computed values. The need of these alterations, albeit for good reasons, of computed values emphasizes the importance of having actual measurements.

The fifth row of Table 1 then lists the *s*-process abundances $N_s(A)$, which are calculated by assuming constant σN_s through Nd isotopes. This last assumption is valid for Nd, although it is not valid for Ba. The *r*-process abundance in the sixth row is the difference $N_r = N - N_s$. It shows normal *r*-process behavior, although perhaps $N_r(^{143}\mathrm{Nd})$ should be larger in light of the high, apparently *r*-process, abundance of ^{142}Ce. This detail cannot be resolved without measured cross sections. The final row shows the anomalies $\epsilon_r(A)$ that would be generated by augmenting normal Nd with this *r*-process abundance pattern normalized to $\epsilon_r(150) = 33.6 \times 10^{-4}$ to agree with the observed $\bar{\epsilon}'(A)$.

What one sees in the comparison of $\bar{\epsilon}'(A)$ with $\epsilon_r(A)$ is that, except for ^{144}Nd and ^{143}Nd, the anomaly pattern $\bar{\epsilon}'(A)$ is almost exactly an enhancement of the *r*-process component. The agreement is probably not accidental, considering that it arose from the most plausible of assumptions concerning the cross sections, which were not chosen to produce such an effect. To make the agreement total one needs a "special ^{144}Nd anomaly" having magnitude $\epsilon^*(^{144}\mathrm{Nd}) = 18.0 - 11.0 = 7.0$ parts per 10^4. Then we may write, in obvious notation.

$$^{A}\mathrm{Nd}_{\mathrm{EK1}} \approx {}^{A}\mathrm{Nd}_{\odot}[1 + \epsilon_r(A) + \epsilon^*\delta_A{}^{144}]\,,$$

which can be read as a function of isotopic mass A, with $\delta_A{}^{144}$ a Kroneker delta. I call the first anomalous term a *general anomaly* and the second a *special anomaly*.

The first question is the special anomaly at ^{144}Nd, which would be much too arbitrary to be believable without a clear cause. I advance the following, which is only another special case of the principles outlined in Clayton (1975*a*, *b*; 1977*a*, *b*, *c*); viz., a significant fraction of r-process yield at $A = 144$ was chemically condensed as ^{144}Ce ($\tau_{1/2} = 285$ d) during the expansion of the supernova in which the r-process occurs. This condensation fractionated Ce from Nd chemically, with the result that Ce-bearing SUNOCONs are specifically enriched in ^{144}Nd. During the presolar accumulation and the chemistry leading to sample EK1-4-1, this Ce-bearing fraction was augmented. This special anomaly was in fact predicted by me in a letter of 1977 July 7, in which I urged Professor K. Marti to examine his Nd data for the effect.

The second question concerns whether the remaining general anomaly $\epsilon_r(A)$ is an enhancement of the *average* r-process component or is instead an exotic r-process component. My decomposition in Table 1 looks like the former except for ^{143}Nd, but the question cannot be resolved without measured cross sections. Having chosen $\sigma(^{142}\mathrm{Nd}) = 40$ mb, $\epsilon_r(143) = 13.6 = \bar{\epsilon}'(143)$ only if $\sigma(^{143}\mathrm{Nd}) = 107$ mb. Clearly that is possible, although it would require $N_r(^{143}\mathrm{Nd}) = 0.038$, which looks a bit too small. It is also clear that the good agreement in the four heaviest isotopes is destroyed if their cross sections are not close to these calculated by Holmes *et al.* These cross section measurements therefore assume a role of great importance to astrophysics and to information on the accumulation of the solar system. The unshielded-isotope anomalies in xenon, which were chemically isolated so beautifully by Lewis, Srinivasan, and Anders (1975), are decidedly not an average r-component.

The lack of agreement at ^{143}Nd may conceivably also be confused by a special anomaly there deriving from the separation of ^{147}Sm and Nd in the interstellar medium. Since only about 1% of ^{147}Sm can have decayed in the interstellar medium, one would think that any associated special anomaly must be much smaller than at ^{144}Nd, where all of ^{144}Ce has decayed. This difference can be made up, however, if only a small portion of the rare earths condense in the first year of the supernova expansion, whereas a large fraction of Sm condenses during interstellar residence. Further speculation at the moment does not seem justified.

There is another specific Nd anomaly in the decay of extinct ^{146}Sm, either live in the sample, which is the interpretation given by its discoverers (Scheinin, Lugmair, and Marti 1976), or extinct in SUNOCONs (Clayton 1977*a*). If this has contributed to ^{142}Nd in sample EK1, the $\bar{\epsilon}$ need renormalization; but an r-process component will remain having the correct shape for ϵ_r. The magnitude of a special anomaly at ^{144}Nd is, however, adjusted by any special anomaly at ^{142}Nd. So the system is quite complex.

The close agreement of the general Nd anomaly with ϵ_r would indicate that this sample accumulated with a uniform excess of the solar r-process abundances. This appears to be not an "exotic" r-process, but rather a fluctuation owing to physical separation of normal r and s components. Cameron (1973*b*) argued that such fluctuations could happen in interstellar gas, whereas Clayton (1977*b*) argued that fractionation owing to different chemical sites of residence in the interstellar medium is a more likely process. After all, the physical surroundings of s and r nuclei differ when they are ejected from their different sites of nucleosynthesis. The key to the fractionation seems to be partial condensation of the supernova ejecta before mixing with the interstellar medium, followed by lack of vaporization in the solar nebula. It also does not seem that such a normal ϵ_r would have been injected from a single supernova triggering the formation of the solar system. Cameron and Truran (1977) specifically suggested that such an event, it if occurred, was not a typical r-process event or it would have injected too much ^{129}I. Of course, one could argue that the close agreement to ϵ_r is fortuitous. No agreement can be decisive until the theoretical estimates of Nd neutron-capture cross sections are replaced by accurate measurements. Nonetheless, my quantitative decomposition of Nd sheds new light on the McCulloch and Wasserburg measurements. A philosophical point is the demonstration by these measurements that the decomposition into s and r isotopes is not just a theorist's toy. The special ^{144}Nd anomaly would also demonstrate the occurrence of the supernova-condensation mechanism.

III. Ba ANOMALIES

McCulloch and Wasserburg (1978) suggested normalizing their Ba compositions to a standard ^{134}Ba/^{138}Ba ratio because these two isotopes are dominated by the s-process. Table 2 shows their average anomaly $\bar{\epsilon}_{\mathrm{EK1}}$ for three measurements on sample EK1 and $\bar{\epsilon}_{\mathrm{C1}}$ for five measurements on sample C1. Such averages are by no means an obvious way to treat their more complete data; but I have done so for

TABLE 2

Ba ISOTOPIC DECOMPOSITION

A	^{134}Ba	^{135}Ba	^{136}Ba	^{137}Ba	^{138}Ba
$\bar{\epsilon}_{\mathrm{EK1}}$*	$\equiv 0$	12.7	-0.7	12.1	$\equiv 0$
$\bar{\epsilon}_{\mathrm{C1}}$*	$\equiv 0$	-2.2	$+0.1$	-0.4	$\equiv 0$
N†	0.116	0.316	0.375	0.543	3.44
σ‡	225	472	75.5	72.6	4.29
N_s	0.116	0.063	0.375	0.370	3.24
N_r	$\equiv 0$	0.253	$\equiv 0$	0.173	$\equiv 0.20$
N_r/N	0	0.801	0	0.319	0.058
ϵ_r	0	$\equiv 12.0$	0	4.78	0.87

* In parts per 10^4 from McCulloch and Wasserburg 1978.

† Per 10^6 Si from Cameron 1973*a*.

‡ In mb from Holmes *et al.* 1976 for 135 and 137, my corrected estimate of $\sigma(^{138}\mathrm{Ba})$, and measured values at 134 and 136.

brevity because the identity of individual measurements on one sample showed the important result that the Ba isotopic compositions of different mineral separates of the same sample are statistically identical. I have for brevity omitted their experimental errors. The statistically significant anomalies are the excesses of ^{135}Ba and ^{137}Ba in EK1 and the deficiency of ^{135}Ba in C1. These two large anomalies seem to lie in the *r*-process component, which contributes substantial fractions of the nucleosynthesis of these two isotopes. The two *p*-process isotopes seem normal and are not included in my Table 2; however, owing to their small abundances, anomalies for them would have to have been as large as those of ^{137}Ba and ^{135}Ba in EK1 to have been significant statistically. I now add the following analysis to McCulloch and Wasserburg's discussion of their dramatic discovery.

They speculate that the EK1 anomaly having $^{137}\mathrm{Ba}^*/^{135}\mathrm{Ba}^* = 1.6$ may be a simple excess in the general *r* abundance component, but I must point out instead that it must be an exotic *r*-process rather than the average *r*-process that sufficed for Nd. My current decomposition of Ba into *s* and *r* components is included in Table 2, where the total abundance N is from Cameron (1973*a*) and the cross sections are again from Holmes *et al.* (1976). I have chosen $\sigma(^{138}\mathrm{Ba}) = 4.29$ mb in order to be consistent with my choice $N_r(^{138}\mathrm{Ba}) = 0.20$. The *s*-process yield is calculated from an exponential distribution of exposures (Clayton and Ward 1974) characterized by $\tau_0 = 0.25\ \mathrm{mb}^{-1}$, instead of simple σN_s constancy as for Nd. The *r*-process yield is decreasing with A in this mass region, though modified by odd-even effects. I calculate $N_r(^{137}\mathrm{Ba})/N_r(^{135}\mathrm{Ba}) = 0.68$ instead of the value 1.6 that they require for this anomaly. The last row shows the shape of the *r* component ϵ_r normalized to $\epsilon_r(^{135}\mathrm{Ba}) = 12$. It bears resemblance neither to $\bar{\epsilon}_{\mathrm{C1}}$ nor to $\bar{\epsilon}_{\mathrm{EK1}}$, although it could just about resemble $-\bar{\epsilon}_{\mathrm{C1}}$ since the (suppressed) experimental errors could barely allow the value $\bar{\epsilon}_{\mathrm{C1}}(^{137}\mathrm{Ba}) = -0.9$. But on the face of things, the shape of ϵ_r lies between those of EK1 and C1. EK1 demands, in addition to a general *r* excess, either a special positive anomaly at ^{137}Ba or a special negative anomaly at ^{135}Ba. Similarly, if C1 is interpreted as a deficiency in the *r* component, it also needs an extra positive anomaly at ^{137}Ba or an extra deficiency at ^{135}Ba, although in this case the statistical certainty is not so great. However, both anomalous samples have been reduced to the same pattern—a fluctuation in the average *r*-process component accompanied by a special deficit of ^{135}Ba or a special excess at ^{137}Ba. This description is obviously far from unique with only two isotopes affected, but it is suggestive of a description in the same spirit as the Nd case.

The Ba cross sections are in better shape than those of Nd. Calculated and measured values are in reasonable agreement for the even-A isotopes, and I have used those values except for the modest reduction in $\sigma(^{138}\mathrm{Ba})$ that was needed to fit general *s*-process theory, as noted above. The cross sections at $A = 135$ and 137 are calculated only, so the validation of my conclusions must again await better measurements. Almost certainly the key result will remain, however: that $\epsilon_r(135)$ is considerably larger than $\epsilon_r(137)$.

In the expansion of the *r*-process supernova, both *r*-process isotopes should condense, if at all, as isotopes of cesium, $^{135}\mathrm{Cs}(\tau_{1/2} = 2 \times 10^6\ \mathrm{yr})$ and $^{137}\mathrm{Cs}(\tau_{1/2} = 30.1\ \mathrm{yr})$. Only $^{138}\mathrm{Ba}_r$ will condense directly as Ba. Although Ba probably condenses more readily than Cs in an *r*-process expansion, this fractionation does not alter the 135/137 ratio. That fractionation must result from a process sensitive to the great difference in half-lives. Such processes might be (1) condensation after 30 yr, (2) sputtering or evaporation after 30 yr, or (3) injection of ^{135}Cs still live from the supernova trigger that some (Cameron and Truran 1977) postulate to have initiated the solar system, which is a special form of process (1). There are so many possibilities that, with anomalies only at two Ba isotopes, it does not seem possible to single out the correct one. That will require correlations with other anomalies in heavy elements, such as the Nd case.

IV. OTHER SUNOCON EXTINCT RADIOACTIVITIES

In Table 3 I list what seem to be the outstanding possibilities in the heavy elements for finding extinct *r*-process radioactivities in SUNOCONs condensing within about a year. I provide this list to stimulate further searches for this important process for producing special anomalies. Only when this process of special anomalies is either established or discounted can one with confidence identify a general anomaly in the *r*-process components, such as I have demonstrated for Nd. I list the radioactive *r*-process progenitor, its half-life, and the stable nucleus to which it contributes. Theory maintains (cf. Seeger, Fowler, and Clayton 1965) that the *r* nuclei are produced very neutron-rich, so that all such nucleosynthesis must, at these isobars, decay through these long-lived parents.

TABLE 3

EXTINCT *r*-PROCESS RADIOACTIVITIES IN SUNOCONs

r-Product	$\tau_{1/2}$	Daughter
^{60}Fe............	10^5 yr	^{60}Ni
^{63}Ni............	100 yr	^{63}Cu
^{79}Se............	6.5×10^4 yr	^{79}Br
^{85}Kr............	10.76 yr	^{85}Rb
^{90}Sr............	28.5 yr	^{90}Zr
^{99}Tc............	2.1×10^5 yr	^{99}Ru
^{106}Ru...........	368 d	^{106}Pd
^{107}Pd...........	6.5×10^6 yr	^{107}Ag
^{125}Sb...........	2.77 yr	^{125}Te
^{126}Sn...........	10^5 yr	^{126}Te
^{129}I............	1.6×10^7 yr	^{129}Xe
^{135}Cs...........	2×10^6 yr	^{135}Ba
^{137}Cs...........	30.1 yr	^{137}Ba
^{144}Ce...........	285 d	^{144}Nd
^{147}Pm..........	2.62 yr	^{147}Sm
^{151}Sm..........	93 yr	^{151}Eu
^{155}Eu...........	4.96 yr	^{155}Gd
^{171}Tm..........	1.92 yr	^{171}Yb
^{182}Hf...........	9×10^6 yr	^{182}W
^{194}Os...........	6.0 yr	^{194}Pt

In my discovery paper (Clayton 1975*a*, *b*) on this general process, I already emphasized the most important cases in the intermediate-mass elements. All cases in Table 3 are of great interest. Several of the daughter elements (Ru, Pd, Te, Nd, Sm, Gd, Yb, W, and Pt) have at least four *r*-process isotopes, so that, as in the Nd case shown above, a convincing demonstration of a special anomaly at a specific *r* isotope is possible. Other remarks according to radioactive parent are:

^{129}I.—This was the first case of this phenomenon ever speculated upon (Clayton 1975*a*). It is still greatly in doubt (Trivedi 1977; Clayton 1977*d*) and has profound implications for meteoritic chronology.

^{125}Sb, and ^{126}Sn.—Daughter Te has four *r* isotopes of special interest because they lie in the *r*-process peak (Seeger, Fowler, and Clayton 1965).

^{85}Kr.—This arrest for a 10.76 yr half-life as a noble gas can greatly reduce the SUNOCON fraction of ^{85}Rb, as Clayton (1977*b*) has already discussed. Gray, Papanastassiou, and Wasserburg (1973) present evidence against such a *bulk* fractionation in Allende inclusions.

^{147}Pm.—Daughter ^{147}Sm is of cosmoradiogenic interest.

^{151}Sm and ^{155}Eu.—Both decays involve Eu, which is known to be strongly fractionated from other rare earths (Boynton 1975) so that their fractionation in SUNOCONs is also likely.

^{182}Hf and ^{194}Os.—These elements and their daughters, which each have four *r* isotopes, are exceedingly refractory heavy metals that are very likely to condense after nucleosynthesis. The *Fremdlinge* discovered in Allende inclusions (El Goresy *et al.* 1977) may be related to such heavy-metal SUNOCONs, which in the Fe-depleted regions may condense as pure droplets unalloyed with Fe and Ni.

Following the discoveries of McCulloch and Wasserburg, it appears even more likely that others from this list will also contain special extinct radioactivities. These plus associated general *r*-process anomalies, as in Nd, confirm that the solar nebula was never a hot gas (no solids). This in turn suggests that the Ca-Al–rich inclusions are not high-temperature solar system condensates, but are instead fused collections of the refractory component of interstellar dust, as I have argued previously on other grounds (Clayton 1977*b*). If this new general picture continues to gain scientific support, we may have not only new evidence on the physical processes associated with the origin of the solar system, but a new and previously unexpected evidence of explosive nucleosynthesis and of chemical fractionation in the interstellar dust. Clayton (1977*c*) has already used these principles to advance a new explanation of the great depletion of Ca, Al, and Ti in interstellar gas (Spitzer and Jenkins 1975). I am presently almost finished with a review paper systematizing my heretofore scattered development of this new chemical picture of the early solar system.

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Note added in proof.—I am grateful to R. L. Macklin for pointing out that the Nd neutron capture cross sections have been measured. The appropriate thermal averages at 30 keV are given in a 1977 unpublished Australian Atomic Energy Commission Report by A. R. de L. Musgrove, B. J. Allen, J. W. Boldeman, and R. L. Macklin as:

$A_{\rm Nd}$	142	143	144	145	146	148
σ_A(mb)	77 ± 15	175 ± 75	84 ± 20	...	123 ± 20	113 ± 20.

These mean values, taken to be exact, would cause severe problems in understanding the average solar abundances, suggesting that ^{142}Nd, ^{143}Nd, ^{144}Nd, and ^{146}Nd are almost entirely due to the *s*-process. Such a conclusion would be difficult to reconcile with a smooth *r*-process abundance curve, having large *r*-abundances at ^{142}Ce, ^{146}Nd, and ^{148}Nd. Apparently, one of the following is true: (1) σ_{142} is much less than 77 mb; (2) characterizing the solar σN_s curve by a continuous monotonic distribution of neutron irradiations is incorrect; or (3) the *r*-process yield has jagged structure having a sudden minimum (almost zero) for $143 \leq A < 146$. My accumulated experience suggests to me that (1) is correct and the values I adopted in Table 1 are best, although I am reluctant to doubt experimental data obtained by a leading research collaboration. In the spirit of seeking a resolution I note that if σ_{142} is taken at the minimum of its experimental range $(77 - 15 = 62)$ and the others at the maximum of their ranges, the decomposition becomes almost identical to the one that I have given in Table 1. The special anomaly at ^{144}Nd remains unless σ_{144} is arbitrarily increased to a value much in excess of either the measured or calculated value. An ideal experiment to resolve these problems would be an accurate measure of the ratio $\sigma_{142}/\sigma_{144}$, which may be obtainable with higher precision than their absolute values.

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