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DISCOVERY OF *s*-PROCESS Nd IN ALLENDE RESIDUE

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ABSTRACT

New interpretation is given to the isotopic anomalies detected by Lugmair *et al.* in an acid-resistant residue of the Allende meteorite. If the ^{142}Nd excess is due to ^{146}Sm decay, as the discoverers proposed, I argue that the decay has occurred in interstellar grains, so that the conclusion that ^{146}Sm (1.03×10^8 yr) was alive in the solar system is premature. I show by renormalizing their data that the discovery is likely to be *s*-process Nd, confirming the survival of red-giant stardust in carbonaceous interstellar dust.

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

I. INTRODUCTION

Lugmair *et al.* (1983) have discovered isotopically anomalous Nd in an acid-insoluble residue of the Allende meteorite. As they normalize the data, to normal ^{144}Nd and normal ^{148}Nd, the two largest anomalies are at ^{142}Nd and ^{143}Nd. They interpret these as being the result of the decay of live ^{146}Sm (1.03×10^8 yr) at the time of solar formation and, respectively, of the decay of still live ^{147}Sm (1.06×10^{11} yr). They make two important conclusions for astrophysics: (1) that ^{146}Sm was alive in concentration $^{146}\text{Sm}/^{144}\text{Sm} = 4 \times 10^{-3}$ when the solar system formed; (2) that the *p*-process production ratio is $P(146)/P(144) \approx 0.4$. I call both conclusions into question and set forth an even more exciting conclusion, *viz.* the isotopically anomalous Nd is *s*-process Nd, saved in the interstellar carbonaceous dust from red giants.

II. DECAY IN ALLENDE OR INTERSTELLAR DUST

The observed excesses in ^{142}Nd and ^{143}Nd (Lugmair *et al.* 1983) require that $^{146}\text{Sm}/^{147}\text{Sm}$ have the value 7.6×10^{-4} at the beginning of the solar system *if* the excesses are due to *in situ* decay during the 4.56×10^9 yr existence of solar system objects. This ratio in turn requires that the *p*-process isotopes had then the ratio $^{146}\text{Sm}/^{144}\text{Sm} = 4 \times 10^{-3}$. This interpretation is very important to astrophysics, if correct, because it strengthens the argument either for the injection of fresh radioactive nuclei into the forming solar system or for a large *p*-process production ratio, $P(146)/P(144)$.

The survival of ^{146}Sm over galactic nucleosynthesis can be inferred without theoretical models of galactic history simply by considering ^{244}Pu, which has almost the same half-life (0.83×10^8 yr). Galactic decay has reduced the ratio $^{244}\text{Pu}/^{238}\text{U}$ to the value 0.005 (Hudson *et al.* 1982) from a production ratio $P(244)/P(238) = 0.9$ (Schramm 1982). The ratio $^{244}\text{Pu}/^{238}\text{U} = 0.005$ at solar origin would have had the even smaller value 0.003 if ^{238}U were stable. Thus, to good accuracy, one can expect $^{146}\text{Sm}/^{144}\text{Sm} = 3 \times 10^{-3}$ $P(146)/P(144)$ by direct analogy to ^{244}Pu. Because the value required by their interpretation of their data is 4×10^{-3}, it follows that the *p*-process production ratio $P(146)/P(144) \approx 1$ would be needed. [Lugmair *et al.* 1983 estimated $P(146)/P(144) \approx 0.4$ by a less convincing argument.]

It is my opinion, for nucleosynthetic arguments much too complicated to detail, that the correct *p*-process model is the (γ, n)-process described by Woosley and Howard (1978), which predicts $P(146)/P(144) \approx 2 \times 10^{-2}$. The major problems with the (p, γ)-process (Audouze and Truran 1975) are that it produces the tin isotopes in less convincing ratios than does the (γ, n)-process (Clayton 1978*b*) and that it does not seem able to occur during normal stellar evolution. So, although $P(146)/P(144) \sim 1$ seems possible from a (p, γ)-process (Audouze and Truran 1975), we regard the evidence to favor the much smaller production ratio from the (γ, n)-process. In that case, not enough ^{146}Sm can survive from galactic nucleosynthesis to account for the inferred ^{146}Sm. Suppose one nonetheless demands that live $^{146}\text{Sm} = 4 \times 10^{-3}$ ^{144}Sm actually existed in Allende. One is then forced to conclude that a late *p*-process event (supernova?) injected about one-fifth of the *p* nuclei into the forming solar system. Because that event would be required to not also have *r*-process production (since only 10^{-4} of iodine can have been injected), I am skeptical of it.

There is, however, an independent astrophysical model (Clayton 1975, 1977) for such effects in extinct radioactivities. Clayton (1977) already discussed this in some detail for the case of possible ^{142}Nd excesses. If *p*-process $^{146}\mathrm{Sm}/^{144}\mathrm{Sm} \approx 2 \times 10^{-2}$ condenses in SUNOCON (supernova condensate) stardust before the supernova interior can mix, then anomalies $^{142}\mathrm{Nd}^*/^{144}\mathrm{Sm}$ of that value can reside in some type of interstellar dust, although that value must be decreased for dust destruction by astration and by sputtering (Clayton 1983). A concentration of Nd anomalies into the carbonaceous material is provided by a variant of the scheme proposed by Lugmair *et al.* (1983) within Allende itself. The recoil of ^{142,143}Nd following alpha decay in refractory submicron interstellar grains moves those Nd isotopes, and only those, out of the refractory cores and into the carbonaceous mantles. Then, later in the solar system, those carbonaceous mantles reorganize into the acid-insoluble residue within Allende, where the excess ^{142,143}Nd now survives.

To summarize this section, *if* ^{142}Nd excesses are in fact due to ^{146}Sm decay, that decay occurred in interstellar dust, whose carbonaceous coatings have reorganized into the acid residue extracted from Allende. The ^{146}Sm was probably *not alive* in the solar system, in contrast to the claim by Lugmair *et al.* (1983).

III. *s*-PROCESS NEODYMIUM

When *s*-process Xe was first isolated (Srinivasan and Anders 1978), it was in an acid-insoluble residue of the Murchison meteorite. For this reason, and because ^{142}Nd is an *s*-only isotope, and because of the V-shape of the ^{144,145,146}Nd anomaly pattern, I here advance the possibility that the observed anomaly is of *s*-process Nd.

Table 1 lists the two Allende residues, CE-1 and CF-1, in which Lugmair *et al.* (1983) found deviations δ (in parts per thousand) from normality that are significantly clear for an analysis. The large excesses at ^{142}Nd and ^{143}Nd are the anomalies they addressed. They express these deviations in a normalization for which ^{144}Nd and ^{148}Nd are defined as normal. It is valid, however, to renormalize them according to

$$\delta' = \delta + a - m(A - 142), \qquad (1)$$

where constant a renormalizes the pattern and the m term represents mass-dependent fractionation. Such renormalized δ' are listed in rows (2) and (4) of Table 1, each for a mass fractionation of 2/3 parts per million per atomic mass unit. These independent δ' measurements are dramatically similar to an *s*-process excess, as indicated by the rectangles in Figure 1. I submit this as the first occasion in which an *s*-process pattern in a refractory element has been isolated. The astrophysical scenario is the condensation of dust from a red-giant atmosphere, perhaps even a carbon star, where *s*-process excesses are expected in the presence of abundant carbon.

The large error rectangles for the *s*-process excess reflect uncertainty about the correct neutron capture cross sections for the Nd isotopes. Row (5) of Table 1 shows the "best value" cross sections from Clayton (1978*a*), who performed that analysis to show that the Nd excesses in FUN (fractionation unknown nuclear) inclusion EK1-4 is an (almost) average *r*-process excess. The values of N_s/N in row (6) are also taken from that paper. See Figure 13 of Clayton (1979) for a graphical display of that comparison. The final row of Table 1 lists, for comparison with δ' in Figure 1, the deviation $\delta_s \equiv 6N_s/N$. The error rectangles on δ_s result from assuming $\sigma N_s = 8.4$ throughout Nd and from assuming that the cross sections are uncertain to ±40%. The excellent agreement, for two independent samples having independent counting errors, strongly suggests that *s*-process Nd has been isolated. The weakness in this analysis lies in the uncertainty in the neutron cross

TABLE 1

Nd ISOTOPIC VARIATION δ (parts per million)

A	142	143	144	145	146	148	150
δ(CE-1)[a]	3.9 ± .8	335	≡ 0	−0.7 ± 0.4	1.3 ± 0.4	≡ 0	0.5 ± 1.0
δ'(CE-1)[b] ...	8.5	341	3.3	1.9	3.2	0.60	−0.23
δ(CF-1)[a]	4.0 ± .5	271	≡ 0	−1.9 ± 0.6	1.2 ± 0.5	≡ 0	0.1 ± 0.7
δ'(CF-1)[c] ...	9.2	276	3.9	1.3	3.7	1.2	−0.03
σ_n (mb)[d]	40	175	67	485	105	...	...
N_s/N[d]	1.0	0.51	0.67	0.27	0.60	0–0.16[e]	0
δ_s[f]	$6.0^{+4}_{-1.7}$	$3.0^{+2}_{-0.9}$	$4.0^{+2.7}_{-1.2}$	$1.6^{+1.0}_{-0.5}$	$3.6^{+2.4}_{-1.0}$	0.5 ± 0.5[e]	0

[a] Deviations in parts per thousand measured by Lugmair *et al.* 1983. Those authors normalized their data to $\delta(144) = \delta(148) = 0$.

[b] Calculated from δ(CE-1) by eq. (1) with $a = 4.6$, $m = 2/3$.

[c] Calculated from δ(CF-1) by eq. (1) with $a = 5.2$, $m = 2/3$.

[d] "Most plausible σ" from Clayton 1978*a*. Corresponding "best values" of N_s/N from Table 1 of Clayton 1978*a*.

[e] $N_s(148) = 0$ in classical *s*-process. Upper limit from high-flux pulsed *s*-process Cosner, Iben, and Truran 1980.

[f] $\delta_s \equiv 6\,N_s/N$ for comparison to δ' in Fig. 1. Error bars result from calculating $N_s = \sigma N/\sigma$ with $\sigma N = 8.4$ mb and with σ range of $(1 \pm 0.4)\sigma$ of row (5).

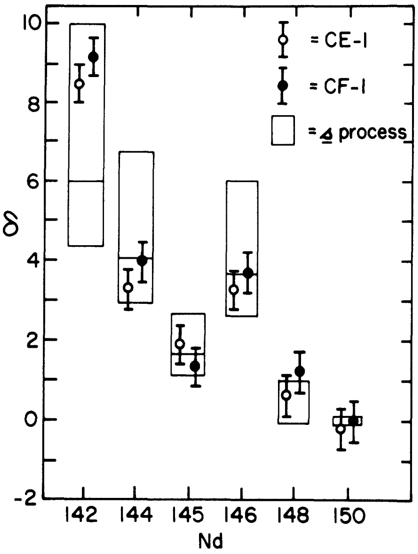

FIG. 1.—Isotopic deviations δ from normal Nd in parts per thousand are shown for two samples (open circles are sample CE-1; closed circles are sample CF-1) of an acid-insoluble residue from the Allende meteorite (Lugmair *et al.* 1983). Error bars reflect their counting statistics. Solid rectangles at each atomic weight show the range of expectations for an *s*-process enrichment, with the central bar reflecting a "most plausible form" for *s*-process. See Table 1 for numeric details and text for clarification. The isotope ^{143}Nd has been omitted because of its large excess from ^{147}Sm decay.

sections, because the "best values" in Table 1 do not agree either with those given in the *Note added in proof* by Clayton (1978*a*) or those recommended by Käppeler *et al.* (1982). The justification of the "best value cross sections" does not lie in the present attempt, which obviously postdates Clayton (1978*a*), but rather that the best values *do allow* a sensible decomposition of Nd into *s* and *r* components for average solar matter. For all of these reasons, we badly need an authoritative study of Nd experimental cross sections.

Finally, I note that the elements Sr and Sm were also isotopically analyzed by Lugmair *et al.* (1983), as was Ba by Lewis *et al.* (1983), in the same residues. I have not commented upon them because the deviations from normality are so small as to be not statistically significant. Only the Nd data seem good enough to play with in the manner I have described.

While suggesting the excitement of isolating *s*-process Nd from carbonaceous interstellar dust, I must also remark that attributing a smaller portion of the ^{142}Nd excess to ^{146}Sm decay in interstellar dust is a complementary possibility. All have profound implications for astrophysics.

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REFERENCES

Audouze, J., and Truran, J. W. 1975, *Ap. J.*, **202**, 204.
Clayton, D. D. 1975, *Ap. J.*, **199**, 765.
______. 1977, *Icarus*, **32**, 255.
______. 1978*a*, *Ap. J.*, **224**, 1007.
______. 1978*b*, *Ap. J.* (*Letters*), **224**, L93.
______. 1979, *Space Sci. Rev.*, **24**, 147.
______. 1983, in *Chondrules and Their Origins* (NASA special publication), in press.
Cosner, K., Iben, I., and Truran, J. W. 1980, *Ap. J.* (*Letters*), **238**, L91.
Hudson, B., Hohenberg, C. M., Kennedy, B. M., and Podosek, F. A. 1982, *Lunar Planet. Sci.*, **13**, 346.
Käppeler, F., Beer, H., Wisshak, K., Clayton, D. D., Macklin, R. L., and Ward, R. A. 1982, *Ap. J.*, **257**, 821.
Lewis, R. S., Anders, E., Shimamura, T., and Lugmair, G. W. 1983, *Lunar Planet. Sci.*, **14**, 436.
Lugmair, G. W., Shimamura, T., Lewis, R. S., and Anders, E. 1983, *Lunar Planet. Sci.*, **14**, 448.
Schramm, D. N. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press), p. 325.
Srinivasan, B., and Anders, E. 1978, *Science*, **201**, 51.
Woosley, S. E., and Howard, W. M. 1978, *Ap. J. Suppl.*, **36**, 285.

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