9-1-1978

On Strontium Isotopic Anomalies and odd-A p-Process Abundances

Donald D. Clayton
Clemson University, claydonald@gmail.com

Recommended Citation

Please use publisher's recommended citation.

1978ApJ...224L..93C

THE ASTROPHYSICAL JOURNAL, 224:L93–L95, 1978 September 1

ON STRONTIUM ISOTOPIC ANOMALIES AND ODD-A p-PROCESS ABUNDANCES

DONALD D. CLAYTON
Rice University

Received 1978 May 8; accepted 1978 June 20

ABSTRACT

I analyze the recent discovery of strontium isotopic anomalies in an inclusion of the Allende meteorite by decomposing Sr into s, r, and p-process abundances. The anomalous sample is most plausibly an excess of s isotopes in their average solar ratio, in which case it suggests gas/dust fractionation in the protosolar accumulation rather than injection by a supernova companion. The initial ^{87}Sr/^{86}Sr ratio seems likely to be less than basaltic achondrites by one part in 10^4. Several relevant nucleosynthesis arguments are introduced. A discussion of the ^{112}Sn, ^{114}Sn, ^{115}Sn trio shows that odd-A p abundances are very small, ^{115}Sn being unexpectedly found to be primarily an r-process product. This conclusion favors a photodisintegration p-process over a radiative-capture picture, and will assume importance in locating the p-process in stellar explosions.

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

I here discuss several aspects of the nucleosynthesis of the isotopes of strontium in an attempt to shed light on the problem of isotopic anomalies. Papanastassiou *et al.* (1978) have reported isotopic anomalies in strontium in inclusion EK1-4-1 of the Allende meteorite, an inclusion revealing isotopic anomalies in every heavy element that has been studied with high precision. One controversial question raised by these findings is the astrophysical nature of the anomalous isotopic pool. Whereas most have preferred an injection of fresh unhomogenized nucleosynthesis products from a neighboring supernova (Cameron and Truran 1977), I have preferred fractionation between gas and varying types of dust (Clayton 1978*b*). Models of the first type should produce specialized anomalies in r-, s-, and p-process nuclei, whereas models of the second type more naturally result in enhancements or deficiencies in the *average* r-, s-, or p-process abundances of the element in question. In this *Letter* I discuss the decomposition of the Sr isotopes into these nucleosynthetic classes. I will conclude that inclusion EK1 has most likely an excess of s-process Sr and that the initial ^{87}Sr/^{86}Sr isotopic ratio is probably slightly more primitive than basaltic achondrites.

This study revealed that ^{115}Sn is mostly due to the r-process, because 5% of ^{115}Cd decays proceed through ^{115m}In to ^{115}Sn. This surprising discovery provides a new diagnostic of the p-process itself. It shows that odd-A yields are very small.

The first line of Table 1 lists the anomaly ϵ in parts per thousand found in the pyroxene of EK1-4-1 by Papanastassiou *et al.* (1978). The ^{86}Sr/^{88}Sr anomalies are zero by definition, because their data were normalized to a standard value for that ratio, whereas $\epsilon(^{87}\mathrm{Sr}) = 0$ because the measured ^{87}Sr/^{86}Sr ratio, when corrected for ^{87}Rb decay in the pyroxene, is equal to the best initial value for basaltic achondrites, $I_{\mathrm{BABI}} = 0.69898$, which will be adopted as a standard reference value. The data as displayed show a deficiency of 0.38% in p-process ^{84}Sr, with the other isotopes normal to high accuracy. Anomalous Ba (McCulloch and Wasserburg 1978) and Sm (Lugmair, Marti, and Scheinin 1978) do not show evidence of p-process depletion, so I prefer to examine the assumption that the s-process isotopes of Sr have been enhanced in EK1-4-1, an alternative suggested by Papanastassiou *et al.* The mechanism envisioned by me recognizes that the fraction of Sr condensed during red-giant injection into the interstellar medium should differ from the fraction condensed during supernova injection. Gas/dust fluctuations during accumulation in the protosolar cloud of the parent of EK1 could then lead to systematic fractionation of s isotopes from the others. Although this scenario is not required by data, I will utilize it as motivation for the decomposition of Sr, just as was previously done for Ba and Nd (Clayton 1978*a*) and for Xe and Kr (Clayton and Ward 1978).

By choice I list in the second row of Table 1 the measured anomalies with ^{84}Sr normal and the others in excess by $\epsilon = 3.8‰$. This representation of the data can still be altered by mass fractionation, as I will do below after seeing how much fractionation is needed to bring it into line with the assumed picture. The numbers in the second row share the experimental uncertainty in $\epsilon(^{84}\mathrm{Sr})$, which is 0.3 parts per mil, but they do so in a correlated sense; i.e., if $\epsilon(^{84}\mathrm{Sr}) = -4.1$, then *each* $\epsilon(^{86}\mathrm{Sr}) = \epsilon(^{87}\mathrm{Sr}) = \epsilon(^{88}\mathrm{Sr}) = 4.1$ in the second row. Since my conclusions will not depend greatly on the exact value within this range, I idealize the situation by dispensing with experimental errors in the subsequent discussion.

In rows (3)–(6) I list my best estimates of the s, p, r, and total abundances per 10^6 Si atoms of each isotope. These entries are a major result of this work, and I briefly describe the considerations that have led to them. $N_p(^{86}\mathrm{Sr}) = 0.1$ is taken from comparison of p systematics in other elements, wherein the next-to-lightest even-A isotope is typically two-thirds of the

TABLE 1

STRONTIUM DECOMPOSITION

	^{84}Sr	^{86}Sr	^{87}Sr	^{88}Sr
ϵ_{EK1}(Pyx)..........	-3.8 ± 0.3	0.0	0.0	0.0
ϵ(p norm.).........	0.0	3.8	3.8	3.8
N_s................	0	2.55	$1.74+(0.04)_c$	20.1
N_p................	0.15	0.10	0.01	0.1
N_r................	0	0	$(0.06)_c$	2
N.................	0.15	2.65	1.85	22.2
σ_s(exp ρ)..........	...	76	109	6.1
σ(meas.)...........	...	74 ± 7	109 ± 9	6.9 ± 2.5
N_s/N.............	0	0.962	0.962	0.905
ϵ' (-0.108/amu)...	0	3.58	3.48	3.37
ϵ_s($88\equiv3.37$)........	0	3.58	3.58	3.37
N_p/N.............	1.0	0.038	0.0054	0.0045
ϵ_p.................	3.8	0.00	-0.07	0.00

lighest isotope. $N_p(^{87}\mathrm{Sr}) = 0.01$ is assumed because theoretical arguments suggest that p-process yields at odd-A isotopes are quite small. Confirming data are, however, scarce and complicated. Both ^{138}La and ^{180}Ta (odd-odd nuclei) are vanishingly small, but they are not good guides because they are shielded from proton-rich progenitors. Only ^{115}Sn exists as a traditional p nucleus among odd-A isotopes, and I argue here that it is predominantly due to other effects, resulting from both s- and r-processes when ^{115}Cd decays to ^{115m}In, which decays 5% to ^{115}Sn. This large r-process contribution to ^{115}Sn appears to have been previously overlooked. A simple estimate of s plus r production via ^{115}Cd is $0.05N(^{115}\mathrm{In}) = 0.009$, or about 75% of $N(^{115}\mathrm{Sn})$. Furthermore, Ward, Newman, and Clayton (1976) argue that ^{113}In is due to another s-process branch resulting in another 25% of the ^{115}Sn abundance. This leaves a remainder of order $^{115}\mathrm{Sn}_p \leq 0.001$, which is only 3% of $^{112}\mathrm{Sn}_p$, so I take it that $^{87}\mathrm{Sr}_p$ is less than 10% of $^{84}\mathrm{Sr}_p$, or about 0.01. Published calculations of p yields for Sn seem to also confirm a low p yield for ^{115}Sn, although the following judgment must be made. Woosley and Howard (1978) calculate negligible ^{115}Sn production in the photodisintegration p-process, and although Audouze and Truran (1975) find ^{115}Sn can be made in the (p, γ)-process their failure to account for ^{112}Sn suggests to me that their model is not as realistic as that of Woosley and Howard. Although these conclusions are obviously subject to challenge from more precise definitions of the p-process, a fair working judgment is that Sn isotopes confirm a very small odd-A p abundance, as taken here also for ^{87}Sr. I have also taken $N_p(^{88}\mathrm{Sr}) = N_p(^{86}\mathrm{Sr})$, although this choice introduces no uncertainty into the subsequent analysis, owing to the much larger natural abundance of ^{88}Sr.

The cosmoradiogenic contributions to $N(^{87}\mathrm{Sr})$ from ^{87}Rb decay between nucleosynthesis and the formation of the solar system (Clayton 1964) represent another challenging complication. I estimate this to be $N_c(^{87}\mathrm{Sr}) = 0.10$, of which 0.04 is due to s-process nucleosynthesis based on my conclusion that 40% of ^{87}Rb was synthesized in the s-process and 60% in the r-process. This conclusion follows from the argument that neutron capture by ^{85}Kr, which results in a branch through ^{86}Kr and ^{87}Rb, has accounted for about two-thirds of the ^{86}Kr abundance (Ward *et al.*; Clayton and Ward 1978), in which case it also produces 40% of the ^{87}Rb abundance if we take $\sigma(^{86}\mathrm{Kr}) = 4.4$ mb (Holmes *et al.* 1976) and $\sigma(^{87}\mathrm{Rb}) = 24$ mb (Allen, Gibbons, and Macklin 1971). These cosmoradiogenic contributions are divided correspondingly between s and r in Table 1 for formal consistency, although it can be questioned whether interstellar ^{87}Rb "remembers" its mode of origin. This special problem was discussed by Clayton (1977).

In the r-process yield of ^{88}Sr, considerable uncertainty exists. My decompositions suggest that the following r-abundances in this mass range are reasonable: $N_r(^{82}\mathrm{Se}) = 6.2$, $N_r(^{84}\mathrm{Kr}) = 4.6$ (Clayton and Ward 1978), $N_r(^{85}\mathrm{Rb}) = 2.6$, $N_r(^{86}\mathrm{Kr}) = 3$, $N_r(^{87}\mathrm{Rb}) = 1.0$, and $N_r(^{91}\mathrm{Zr}) = 0.85$. Others are much less reliable, and, taken together, they show a rapidly falling r yield between $A = 82$ and $A = 90$, as illustrated by Cameron (1973). Allowing for an appreciable odd-even effect in this mass range, I take $N_r(^{88}\mathrm{Sr}) = 2$, although the actual number can be seen to be possibly as low as 1. This uncertainty pinpoints another problem for future clarification by nucleosynthesis theory.

Rows (7) and (8) of Table 1 compare the neutron-capture cross sections $\sigma_s(\exp\rho)$ needed for an exponential distribution of neutron exposures $\rho(\tau) = \exp(-0.25\,\tau)$ to account for the s-process abundances with the measured cross sections (Allen *et al.*). The excellent agreement confirms that s-process theory is working well and that the N_s values in row (3) are reliable.

Row (9) lists N_s/N, which is the shape of an enhancement anomaly resulting from the addition of s-process nuclei in their average solar-system ratios. Because this ratio is $\epsilon_s(^{88}\mathrm{Sr})/\epsilon_s(^{86}\mathrm{Sr}) = 0.905/0.962 = 0.94$ instead of unity as given for the observed ratio of anomalies in row (2), I arbitrarily mass fractionate $\epsilon(p$ normal) by subtracting $\Delta\epsilon = 0.108$/amu, leading to the modified values ϵ' in row (10). These numbers, resulting from a modest assumption of mass fractionation, lead to a representation of the data that is as valid as that in row (1). In row (11), the value of $\epsilon_s = 3.37(N_s/N)$ is displayed to compare with the experimental value in row (10). The good agreement confirms that the Sr in EK1-4-1 may be numerically interpreted as an excess in the average *s*-process abundances, as Papanastassiou *et al.* (1978) had surmised.

As displayed, $\epsilon_s(^{87}\mathrm{Sr})$ exceeds $\epsilon'(^{87}\mathrm{Sr})$ by $\Delta\epsilon = 0.1$ parts per thousand. If the anomaly is actually an excess of average *s* abundances, as I have postulated, the remainder of EK1 must have had an initial $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratio smaller than $I_{\mathrm{BABI}} = 0.69898$ by about $\Delta I = \Delta\epsilon \times I_{\mathrm{BABI}} = 0.0007$. Such an initial ratio for these primitive pyroxenes is quite plausible, being similar to Rb-poor chondrules from Allende (Gray, Papanastassiou, and Wasserburg 1973). If this is the case, the relative primitiveness is unlikely to be a time difference, but is instead a deficiency in the cosmoradiogenic component of $^{87}\mathrm{Sr}$, as described also for Allende chondrules by Clayton (1977). Because parent $^{87}\mathrm{Rb}$ is more volatile than is Sr, a higher fraction of interstellar $^{87}\mathrm{Sr}_c$ will reside in the gas phase than of $^{87}\mathrm{Sr}_s$, which may have condensed nicely in minerals growing in escaping red-giant envelopes.

The final two rows reflect the situation for interpreting the data as a deficiency in *p* nuclei. When row (12), listing N_p/N, is multiplied by 4.0 parts per mil, has its zero-point corrected for $^{88}\mathrm{Sr}$ by subtracting 0.02, and is then mass fractionated by $\Delta\epsilon = 0.13/2$ amu, the entry ϵ_p results. If the data of row (1) are a deficiency in this component, the parent of EK1 must again have been more primitive than basaltic achondrites by $\Delta\epsilon(^{87}\mathrm{Sr}) = 0.07$. This conclusion depends explicitly on the argument of a very small $N_p(^{87}\mathrm{Sr})$; in fact, if $N_p(^{87}\mathrm{Sr}) = 0.04$. instead of 0.01, the *p*-process subtraction can fit the data with $I = I_{\mathrm{BABI}}$. The importance of the theoretical arguments for very low odd-*A* *p* abundances is clear.

This *Letter* represents not so much a firm conclusion as it does a set of nucleosynthetic ideas needed to evaluate the new discovery of Sr isotopic anomalies. Because I have presented a much more complicated discussion of an anomaly that looks at face value like a simple *p*-process deficiency, let me reiterate uncertainties, especially since I have treated the values in Table 1 as being accurate. (1) The measured errors on $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ and $^{88}\mathrm{Sr}/^{86}\mathrm{Sr}$, though smaller than for $^{84}\mathrm{Sr}/^{88}\mathrm{Sr}$, are certainly not zero, so that $\Delta\epsilon = \pm 0.1$ can result from the data alone. (2) If $N_p(^{87}\mathrm{Sr})$ is comparable to $N_p(^{86}\mathrm{Sr})$, the ΔI is *less primitive* than I_{BABI} rather than more primitive. (3) If $N_r(^{88}\mathrm{Sr})$ is as small as 1, the mass-fractionation correction is negligible, so that agreement obtains with $I = I_{\mathrm{BABI}}$. (4) Because cosmoradiogenic $^{87}\mathrm{Sr}_c$ is "old" $^{87}\mathrm{Sr}$, perhaps it should not be arbitrarily divided into *s* and *r* in the same ratio as for $^{87}\mathrm{Rb}$ itself. Clearly no conclusion can be drawn from Sr anomalies alone, because they alone are not enough data. In fitting them into the canvas of the other heavy-element anomalies, others may find this decomposition helpful, although it can reasonably be modified within the limits stated.

If the anomaly is an average *s* enhancement, it argues somewhat in favor of my model of gas/dust fractionations of *s* from *r* rather than in favor of a supernova injection. Although the supernova shells will have *s*-enhanced elements, it is not likely that *s* processing in that single star will have produced *s*-process Sr with the same isotopic composition as has the exponential $\rho(\tau)$ that represents the average of galactic history. Sr is in a complicated and falling portion of the σN_s curve, wherein many varied results in individual stars are possible (Ward *et al.*). This seems to me in accord with Ba, Nd, and Sm, whose anomalies do not appear to be the exotic ones expected of a special injection event.

Last, I must return to the importance for *p*-process theory of this discovery of a large *r*-process contribution to $^{115}\mathrm{Sn}$. The corresponding smallness of its *p* abundance may become a decisive feature in favoring photodisintegration, which suppresses odd-*A* nuclei owing to their smaller binding energies, over radiative capture as a *p*-process mechanism. It will also become a major factor in locating the astrophysical site of the *p*-process.

This research has been supported in part by the National Science Foundation under grant AST 74-20076 and in part by the National Aeronautics and Space Administration under grant NSG-7361.

REFERENCES

Allen, B. J., Gibbons, J. H., and Macklin, R. L. 1971, *Adv. Nucl. Phys.*, **4**, 205.
Audouze, J., and Truran, J. W. 1975, *Ap. J.*, **202**, 204.
Cameron, A. G. W. 1973, *Space Sci. Rev.*, **15**, 121.
Cameron, A. G. W., and Truran, J. W. 1977, *Icarus*, **30**, 447.
Clayton, D. D. 1964, *Ap. J.*, **139**, 637.
——— 1977, *Earth Planet. Sci. Letters*, **35**, 398.
——— 1978*a*, *Ap. J.*, **224**, in press.
——— 1978*b*, *Moon and Planets*, in press.
Clayton, D. D., and Ward, R. A. 1978, *Ap. J.*, **224**, in press.
Gray, C. M., Papanastassiou, D. A., and Wasserburg, G. J. 1973, *Icarus*, **20**, 213.
Holmes, J., Woosley, S., Fowler, W., and Zimmerman, B. 1976, *Atomic Data Nucl. Data Tables*, **17**, 305.
Lugmair, G. W., Marti, K., and Scheinin, N. B. 1978, *Lunar Planet. Sci.*, **9**, 672.
McCulloch, M., and Wasserburg, G. J. W. 1978, *Ap. J.* (*Letters*), **220**, L15
Papanastassiou, D. A., Huneke, J. C., Esat, T. M., and Wasserburg, G. J. 1978, *Lunar Planet. Sci.*, **9**, 859.
Ward, R. A., Newman, M. J., and Clayton, D. D. 1976, *Ap. J. Suppl.*, **31**, 33.
Woosley, S. E., and Howard, W. M. 1978, *Ap. J. Suppl.*, **36**, 285.

Donald D. Clayton: Department of Space Physics and Astronomy, Rice University, Houston, TX 77001