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

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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 $10^6$. Several relevant nucleosynthesis arguments are introduced. A discussion of the $^{111}$Sn, $^{113}$Sn, $^{115}$Sn trio shows that odd-A $p$ abundances are very small, $^{113}$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). 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 $^{111}$Sn is mostly due to the $r$-process, because $5\%$ of $^{114}$Cd decays proceed through $^{114m}$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 $\kappa$ 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 $\kappa (^{87}$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, $I_{BAM}$ = 0.69898, which will be adopted as a standard reference value. The data as displayed show a deficiency of 0.38% in $p$-process $^{86}$Sr, with the other isotopes normal to high accuracy. Anomalous Ba (McCulloch and Wasserburg 1978) and Sm (Lugmair, Marti, and Scheinib 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 1978a) and for Xe and Kr (Clayton and Ward 1978).

By choice I list in the second row of Table 1 the measured anomalies with $^{86}$Sr normal and the others in excess by $\kappa = 3.8\%$. 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 $\kappa (^{86}$Sr), which is 0.3 parts per mil, but they do so in a correlated sense; i.e., if $\kappa (^{86}$Sr) = -4.1, then each $\kappa (^{86}$Sr) = $\kappa (^{87}$Sr) = $\kappa (^{88}$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. $N_p(^{86}$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

<table>
<thead>
<tr>
<th></th>
<th>86Sr</th>
<th>87Sr</th>
<th>88Sr</th>
<th>89Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>e_p (pyx)</td>
<td>-3.8 ± 0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>e_p (norm.)</td>
<td>0.0</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
</tr>
<tr>
<td>N_e</td>
<td>2.55</td>
<td>1.74±(0.04)</td>
<td>20.1</td>
<td></td>
</tr>
<tr>
<td>N_e</td>
<td>0.10</td>
<td>0.01</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>N_e</td>
<td>0</td>
<td>(0.06)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>N_e</td>
<td>2.65</td>
<td>1.85</td>
<td>22.2</td>
<td></td>
</tr>
<tr>
<td>σ(exp)</td>
<td>76</td>
<td>109</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>σ(meas.)</td>
<td>74±7</td>
<td>109±9</td>
<td>6.9 ± 2.5</td>
<td></td>
</tr>
<tr>
<td>N_e/N</td>
<td>0</td>
<td>0.962</td>
<td>0.905</td>
<td></td>
</tr>
<tr>
<td>e_p (-0.108/amu)</td>
<td>3.58</td>
<td>3.48</td>
<td>3.37</td>
<td></td>
</tr>
<tr>
<td>e_p (88 = 3.37)</td>
<td>3.58</td>
<td>3.58</td>
<td>3.37</td>
<td></td>
</tr>
<tr>
<td>N_e/N</td>
<td>1.0</td>
<td>0.038</td>
<td>0.0054</td>
<td>0.0045</td>
</tr>
<tr>
<td>e_p</td>
<td>3.8</td>
<td>0.00</td>
<td>-0.07</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Theoretical arguments suggest that the 87Rb decay is due to a s-process nucelesynthesis base on my conclusion that 40% of 87Rb was synthesized in the s-process and 60% in the r-process. This conclusion follows from the argument that neutron capture by 85Kr, which results in a branch through 86Kr and 87Rb, has accounted for about 60% of the 86Kr abundance (Ward et al.; Clayton and Ward 1978), in which case it also produces 40% of the 87Rb abundance if we take σ(86Kr) = 4.4 mb (Holmes et al. 1976) and σ(85Rb) = 24 mb (Allen, Gibbons, and Macklin 1971). These cosmogenic contributions are divided correspondingly between s and r in Table 1 for formal consistency, although it can be questioned whether interstellar 87Rb "remembers" its mode of origin. This special problem was discussed by Clayton (1977).

In the r-process of 87Sr, considerable uncertainty exists. My decompositions suggest that the following r-abundances in this mass range are reasonable: N_e(86Sr) = 6.2, N_e(84Kr) = 4.6 (Clayton and Ward 1978), N_e(85Rb) = 2.6, N_e(84Kr) = 3, N_e(87Rb) = 1.0, and N_e(86Zr) = 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 r-process contribution to this mass range, I take N_e(86Sr) = 2, although the actual number can be seen to be possibly as low as 1. This uncertainty pinpoints another problem for further clarification by nucleosynthesis theory.

Rows (7) and (8) of Table 1 compare the neutron-capture cross sections σ_p (exp) needed for an exponential distribution of neutron exposures ρ(r) = exp (-0.25 r) 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_e values in row (3) are reliable.

Row (9) lists N_e/N_e, which should be of a small number resulting from the addition of s-process nuclei in their average solar-system ratios. Because this ratio is e_p(87Sr)/e_p(86Sr) = 0.905/0.962 = 0.94 instead of unity as given for the observed ratio of anom-
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The 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 $^{87}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$, though smaller than for $^{87}Sr/^{86}Sr$, are certainly not zero, so that $\Delta e = \pm 0.1$ can result from the data alone. (2) If $N_s/2N_r$ is comparable to $N_p/2N_r$, the $\Delta I$ is less primitive than $I_{\text{BARI}}$ rather than more primitive. (3) If $N_r/2N_r$ is as small as 1, the mass-fractionation correction is negligible, so that agreement obtains with $I = I_{\text{BARI}}$. (4) Because cosmogenic $^{87}Sr$ is "old" $^{87}Sr$, perhaps it should not be arbitrarily divided into $s$ and $r$ in the same ratio as for $^{87}Rb$ itself. Clearly no conclusion can be drawn from $^{87}Rb$ 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 $\rho(r)$ that represents the average of galactic history. Sr is in a complicated and falling portion of the $\alpha N_c$ 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 $^{105}Sn$. The corresponding smallness of its $p$ abundance may become a decisive feature in favoring photoisotopic fractionation, 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.

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REFERENCES

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