Sm-Nd ISOTOPIC SYSTEMATICS IN ANGRA DOS REIS

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We are continuing our Sm-Nd studies of meteorites and report here data on the Angra dos Reis achondrite (Table 1). Data obtained on total rock, pyroxene and whitlockite yield a precise ^{147}Sm-^{143}Nd isochron age of T = 4.562± 0.031 AE (λ_{147} = 0.00654 AE^{-1}) and an initial $^{143}Nd/^{144}Nd$ = 0.505883±37. This gives an initial $^{143}Nd/^{144}Nd$ value relative to the CHUR ("chondritic uniform reservoir") evolution of ε_{Nd} = +0.1±0.2 and is thus fully consistent with our previously published chondrite data [1] to a very high order of accuracy. Four measurements were made of the same total rock solution and their $^{143}Nd/^{144}Nd$ ratios show a total range of 0.30 ε-units (see Table 1). Four measurements were also made of the whitlockite solution and their $^{143}Nd/^{144}Nd$ ratios show a total range of 0.34 ε-units. In addition one analysis was made of pyroxene. All Nd isotopes were measured and found to be within 0.5 ε-units of the average terrestrial values except for ^{142}Nd in the whitlockite and this isotope was therefore avoided for the mass-discrimination correction for this phase. The total rock has a $^{147}Sm/^{144}Nd$ ratio only ~ 2.5% higher than the chondritic value and the $^{142}Nd/^{144}Nd$ ratio in the total rock is identical to the average terrestrial value. However, the whitlockite is substantially fractionated from the chondritic Sm/Nd ratio and appears to have a depletion in ^{142}Nd, giving an average ε(142/144) = -1.6±0.5. This could be due to the presence of ^{146}Sm(λ_{146} = 6.73 AE^{-1}) in this meteorite at its time of crystallization. This short-lived isotope has been proposed as a chronometer for p-process nucleosynthesis by Audouze and Schramm [2]. The abundance of ^{146}Sm at the time of crystallization (T+Δ) relative to ^{144}Sm is related to the isotopic shift ε(142/144) and the chemical fractionation $f_{Sm/Nd} = [(Sm/Nd)_{meas}/(Sm/Nd)_{CHUR} - 1]$ through the following equation

$$\varepsilon(142/144) = Q_{142}\, f_{Sm/Nd}\, (^{146}Sm/^{144}Sm)_{T+\Delta}$$

where $Q_{142} = 10^4\ (^{144}Sm/^{142}Nd)^{o}_{CHUR}$ = 354 using the values given in [1]. Thus, the whitlockite data ($f_{Sm/Nd}$ = -0.3367) may imply that $(^{146}Sm/^{144}Sm)_{T+\Delta}$ = 0.0134±0.0042 at the time of crystallization of the ADOR meteorite.

A detailed Sm-Nd study of ADOR has previously been reported by Lugmair and Marti [3]. The age we obtained is in excellent agreement with their result of T = 4.55±0.04 AE. However, they obtained an initial $^{143}Nd/^{144}Nd$ = 0.506031±50 (renormalized to our $^{148}Nd/^{144}Nd$ value) which is 2.9 ε-units higher than the value we measure. Further, while our Juvinas and chondrite data are in excellent agreement with our ADOR data, Lugmair and Marti [3] suggested that I^{Nd}_{ADOR} may be about 1 ε-unit higher than I^{Nd}_{JUV}.
We also measured the La Jolla Nd standard (Table 1) and our measured $^{143}Nd/^{144}Nd$ value is 1.4 ε-units lower than the value reported by Lugmair et al.[4]. Since 1977 Lugmair has however applied a bias correction of +1.4 ε-units to his $^{143}Nd/^{144}Nd$ data (see Lugmair and Carlson [5]). Thus, the $^{143}Nd/^{144}Nd$ value actually measured at present with Lugmair's mass spectrometer appear to be in excellent agreement with our data on the La Jolla Nd standard. This bias correction is, however, only half of the discrepancy we observe with the ADOR data of Lugmair and Marti [4]. This is presumably due to the fact that their ADOR data were obtained on their mass-spectrometer prior to its substantial improvements in 1977 (see Lugmair and Carlson [5]). We also appear to find small variations in $^{142}Nd/^{144}Nd$ in ADOR as did Lugmair and Marti. However, they obtained ε(142/144) = -0.3±0.2 for whitlockite and ε(142/144) = +0.4±0.2 for pyroxene. These results are slightly different from our values (see Table 1) even though our Sm/Nd ratios for these phases are in excellent agreement with their measurements. In particular it is surprising that their

pyroxenes gave a positive value because their Sm/Nd ratios are only slightly higher than the chondritic value. Scheinin et al. [6] reported $\varepsilon(142/144) \approx +1$ for pyroxenes from one Allende inclusion and $\varepsilon(142/144) \approx 0$ for the bulk inclusion. It is clear that all these data are at the margin of resolution and cannot be considered as a clear demonstration of in situ decay of ^{146}Sm. A more clearcut demonstration of effects in ^{142}Nd due to decay of ^{146}Sm must await analysis of phases that are more substantially fractionated from the chondritic Sm/Nd ratio ($|f_{Sm/Nd}| \gtrsim 0.5$) or a substantial improvement in the measurement of ^{142}Nd/^{144}Nd ratios.

Woosely and Howard [7] have examined nucleosynthesis of p-process isotopes. They suggest that these nuclei are produced by photodisintegration reactions operating on r- and s-process seeds and predict a production ratio of $P(^{146}Sm/^{144}Sm) = 0.024$ for the two p-process isotopes ^{146}Sm and ^{144}Sm. Following Schramm and Wasserburg [8] one obtains for the ^{146}Sm-^{142}Nd cosmo-chronometer that the expected effect in ^{142}Nd/^{144}Nd for a sample is

$$\varepsilon(142/144) = Q_{142}\, f_{Sm/Nd}\, P(^{146}Sm/^{144}Sm)\frac{\exp(-\lambda_{146}\Delta)}{\lambda_{146}T^*}$$

due to galactic nucleosynthesis.

Here Δ is the free decay interval between the last p-process nucleosynthetic event and the formation of objects in the solar system. $T^* = T\langle p\rangle/p(T)$ where T is the entire timespan of nucleosynthesis, $\langle p\rangle$ the mean production rate, and p(T) the final production rate. Thus, for continuous uniform nucleosynthesis $T^* \sim 5$ AE while values of $T^* \sim 1$ AE have been estimated for some r-process chronometers [8] and correspond to nucleochronologies which are significantly spiked close to the separation of the solar system. Thus if P = 0.024, $T^* = 1$ AE and $\Delta = 0.1$ AE we get $\varepsilon(142/144) \approx 0.64\, f_{Sm/Nd}$ which should give $\varepsilon(142/144) = -0.22$ in the ADOR whitlockite while if $T^* \sim 5$ AE then the effects would be a factor of five smaller. However, if ^{146}Sm was injected in a very late spike from a supernovae, then since the observed excesses of ^{144}Sm in Allende inclusions C-1 and EK-1-4-1 are only 15 to 30 ε-units [9,10] the addition of ^{146}Sm would be less than 1 ε-unit if P = 0.024. Thus a late spike could clearly never produce any measurable variation in ^{142}Nd/^{144}Nd for such a low production ratio. If, however, $P \approx 0.5$ as predicted by Audouze and Schramm [2] from the solar abundance pattern of p-process isotopes, one may expect much larger effects [$\varepsilon(142/144) \approx 13\, f_{Sm/Nd}$] of $\varepsilon(142/144) \approx -4.5$ in the ADOR whitlockite due to galactic nucleosynthesis if $T^* = 1$ AE and a factor of five smaller effects for continuous uniform nucleosynthesis. Due to the relatively long half-life of ^{146}Sm (103 m.y.) one should note that about the same effects should be expected in all meteorites of about 4.56 AE age.

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TABLE 1. Sm-Nd analytical results for Angra dos Reis.

Sample	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon(142/144)^{e}$	$f_{Sm/Nd}$	$\varepsilon(143/144)^{f}$	Mass Spec.
Total rock	0.20171	0.511986±52[b]	−0.5±0.8	+0.02547	+2.93±1.02	L1
		0.511990±28[a]	+0.1±0.5		+3.01±0.54	L1
		0.511994±17[a]	0.0±0.3		+3.08±0.34	L3
		0.512001±19[a]	−0.1±0.3		+3.23±0.38	L1
Whitlockite	0.13047	0.509830±20[d]	−1.4±0.8	−0.3367	−39.19±0.39	L3
		0.509833±22[c]	−2.1±0.7		−39.13±0.44	L3
		0.509848±28[c]	−1.1±0.5		−38.85±0.54	L1
		0.509832±27[c]	−1.8±0.9		−39.16±0.53	L1
Pyroxene	0.20685	0.512140±18[b]	−0.2±0.4	+0.05160	+5.94±0.35	L3
La Jolla Nd Standard	-	0.511061±22[a]	+0.2±0.4	-	−15.15±0.43	L1
CIT Sm/Nd Standard	-	0.511127±10[a]	−0.1±0.2	-	−13.85±0.20	L1/L3
CHUR	0.1967	0.511836	≡ 0	≡ 0		

a)Normalized to $^{150}Nd/^{142}Nd = 0.2096$;b)Spiked sample normalized to $^{146}Nd/^{142}Nd = 0.636151$; c)Normalized to $^{150}Nd/^{144}Nd = 0.238581$; d)Spiked sample normalized to $^{148}Nd/^{144}Nd = 0.243079$; e)Deviations in parts in 10^4 from the average terrestrial value of $^{142}Nd/^{144}Nd = 1.138266$; f)Deviations in parts in 10^4 from the CHUR value of $^{143}Nd/^{144}Nd = 0.511836$.