s-PROCESS Sr ISOTOPIC COMPOSITIONS IN PRESOLAR SiC FROM THE MURCHISON METEORITE

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ABSTRACT

We have used thermal ionization mass spectrometry to measure the isotopic compositions of Sr in size-sorted samples (the KJ series) of interstellar SiC separated from the Murchison meteorite. The Sr compositions are radically anomalous in comparison to those in normal solar system materials. As for other heavy elements in presolar SiC, the anomalies can be understood to represent enrichment of s-process (slow neutron capture) nucleosynthetic products, plausibly occurring in asymptotic giant branch stars. The inferred s-process $^{88}Sr/^{86}Sr$ ratios are variable and correlate with grain size: this ratio decreases (suggesting lower effective neutron exposure) with increasing grain size. The sense of this trend is the same as that previously observed in Ba, but opposite to that previously observed in Kr, in the same samples. The Sr and Ba trends indicate covariation of the factors governing neutron exposure and grain growth kinetics in a manner not yet understood. The contrasting trend for Kr suggests that the mechanisms for the introduction of volatile (Kr) and refractory (Sr and Ba) elements into SiC produce a biased sampling of the population of different nucleosynthetic products. The relative abundances of s-process ^{86}Sr, ^{87}Sr, and ^{88}Sr in Murchison SiC are very close to those for early solar system Sr, but in view of the different s-process superpositions and other contributions to all three of these isotopes, the close agreement must be regarded as coincidental.

Subject headings: meteors, meteoroids — nuclear reactions, nucleosynthesis, abundances — solar system: formation — stars: AGB and post-AGB

1. INTRODUCTION

Some primitive meteorites have been found to contain small quantities of several mineral phases that have been plausibly identified as relatively pristine interstellar dust, largely unmodified by processing in the solar nebula and meteorite parent bodies (see, e.g., Anders & Zinner 1993; Ott 1993; Bernatowicz & Cowsik 1997; Zinner 1998, 2003). Typically, the isotopic compositions of major, minor, and trace elements in these phases are radically different from solar normal composition; indeed, this is the primary criterion by which they are recognized as presolar. The character, survival, and isotopic compositions of such presolar grains provide important constraints for studies of stellar evolution and nucleosynthesis, processing in the interstellar medium (ISM), and the formation of the solar system (Bernatowicz & Zinner 1997).

One of these presolar phases is SiC, commonly found in trace quantities (a few parts per million) in primitive meteorites (e.g., Huss 1997; Zinner 2003). In broad terms, isotopic compositions observed in SiC, and their inter- and intrasample variations, can be understood to arise from the mixture of two components, a so-called G-component (for AGB [asymptotic giant branch]) and a so-called N-component (for "normal") (Lewis, Amari, & Anders 1990, 1994; Gallino et al. 1990). The isotopic characteristics of the G-component are close to those predicted theoretically for the products of He shell burning in AGB stars (for elements heavier than Fe, this is primarily s-process [slow neutron capture] nucleosynthesis; see Gallino, Busso, & Lugaro 1997). The N-component is more nearly (but not necessarily identically) solar normal in

composition; it might represent the AGB stellar envelope, but it might also be or incorporate true solar normal material as a meteoritic or terrestrial contaminant. It is believed that the SiC condenses in the expanding atmospheres of AGB stars subsequent to the admixture of He shell burning products (e.g., Bernatowicz & Cowsik 1997; Gallino et al. 1997).

In this paper we report the results of Sr isotopic analyses performed on aliquots of the KJ series of SiC bulk samples (aggregates) isolated from the Murchison meteorite (Amari, Lewis, & Anders 1994). Previous studies of these samples include analyses of noble gases (Lewis et al. 1990, 1994), Ba, Sm, and Nd (Zinner, Amari, & Lewis 1991; Prombo et al. 1993), and C, N, Mg, Si, Ca, Ti, Cr, and Fe (Amari, Zinner, & Lewis 2000).

2. SAMPLES AND EXPERIMENTAL PROCEDURES

The KJ series comprises a suite of grain-size–separated, SiC-enriched (>90% in most fractions) samples prepared from the Murchison meteorite at the University of Chicago (Amari et al. 1994). In the present study we analyzed fractions KJB, KJC, KJD, and KJE, with mass-weighted mean particle sizes of 0.49, 0.67, 0.81, and 1.14 μm, respectively. These were aliquots (but not the same sample loads) of the materials analyzed in our prior study of Ba (Prombo et al. 1993).

The SiC grains (approximately 1 μg per sample) were loaded directly (i.e., without being dissolved), with phosphoric acid, onto V-shaped Ta filaments, inserted into a VG 354E thermal ionization mass spectrometer, and heated until Sr⁺ ions were generated. Ion-beam intensities of each isotope were measured in succession (i.e., single-collector analysis) by a Daly detector operated in pulse-counting mode. Data acquisition was organized into "sets," each comprising baseline and interference (at mass 85) measurements along with four cycles in which each Sr isotope was measured for 5 s. Data were acquired at various beam intensities between about 20 and

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200 kcounts s^{-1} of ^{88}Sr, averaging around 80 kcounts s^{-1}. As discussed in more detail below, we made a correction to the mass 87 signal based on the measured signal at mass 85 and an assumed normal ^{87}Rb/^{85}Rb ratio.

The isotopic composition of Sr is of interest in many geochemical and cosmochemical contexts, and in this laboratory there is a substantial foundation of sample and calibration analyses of Sr: specifically, using the small-sample, single-collector, pulse-counting approach (e.g., Podosek & Brannon 1991; Brannon et al. 1991), here used for SiC. Such results indicate that with internal corrections based on ^{88}Sr/^{86}Sr (see below), external precision (reproducibility) for ^{87}Sr/^{86}Sr and ^{84}Sr/^{86}Sr in pulse-counting analysis is essentially governed by Poisson statistics for the number of atoms detected, at least down to error limits much smaller than those important in the present context.

In thermal ionization mass spectrometry there is generally a significant instrumental discrimination, which is a mass-dependent bias of the measured ion intensity ratios relative to true isotopic ratios. The sign and magnitude of the discrimination vary during the course of analysis, but overall the scale and functional form of the bias are set by the factor $(m_i/m_j)^{1/2}$, where m_i and m_j are the masses of the isotopes being compared. The customary practice for thermal ionization analysis of multi-isotope elements is to assume that at least one isotope ratio in the sample has a fixed, known value (for Sr the universal convention is ^{88}Sr/^{86}Sr = 1/0.1194); comparison of the measured ion intensity ratio with the "true" ratio yields the discrimination and thereby a correction for other isotope ratios. This procedure is evidently quite sound for essentially all terrestrial and even most meteoritic Sr analyses, but it cannot be adopted here, since we cannot assume a priori knowledge of any isotope ratio in the SiC samples, nor even that any given ratio is constant throughout the analysis of a given sample. We therefore make no discrimination corrections, and instead must assign an error to reflect the plausible range of instrumental discrimination.

For a single set we assume a discrimination uncertainty (1 σ) of 2.90 permil amu^{-1} (‰ amu^{-1}), which is $1/2[(87/86)^{1/2}-1]$. Nominal single-set errors are then calculated by superposing this discrimination error and Poisson statistics for the number of atoms counted. For a single set, the Poisson term is the dominant error for ^{84}Sr/^{86}Sr, the discrimination term is dominant for ^{88}Sr/^{86}Sr, and the two terms are comparable for ^{87}Sr/^{86}Sr. For sample means, calculated from the 8–11 sets obtained for each sample, we also take nominal errors from the superposition of Poisson statistics for all atoms counted and the *same* discrimination error, 2.90 ‰ amu^{-1} (1 σ). We adopt this error assignment because uncertainty in discrimination is not a random error and is not subject to convergence of the mean in the statistical sense. Experience with calibrations and other kinds of samples suggests that this is a generous error assignment for discrimination averaged over the analysis of a sample run to exhaustion (as the SiC samples were) and likely to be an overestimate. Nevertheless, discrimination is more a function of sample load chemistry than of instrumental characteristics, and since it is impossible to analyze control samples of interstellar SiC, we cannot quantitatively defend a lower error assignment. Because the measured ^{84}Sr/^{86}Sr, ^{87}Sr/^{86}Sr, and ^{88}Sr/^{86}Sr ratios share sources of error (discrimination and the common reference isotope ^{86}Sr), the assigned errors for these ratios are partially correlated. The correlations are stronger in the sample means than in the individual sets (see Fig. 1) because the Poisson term is relatively
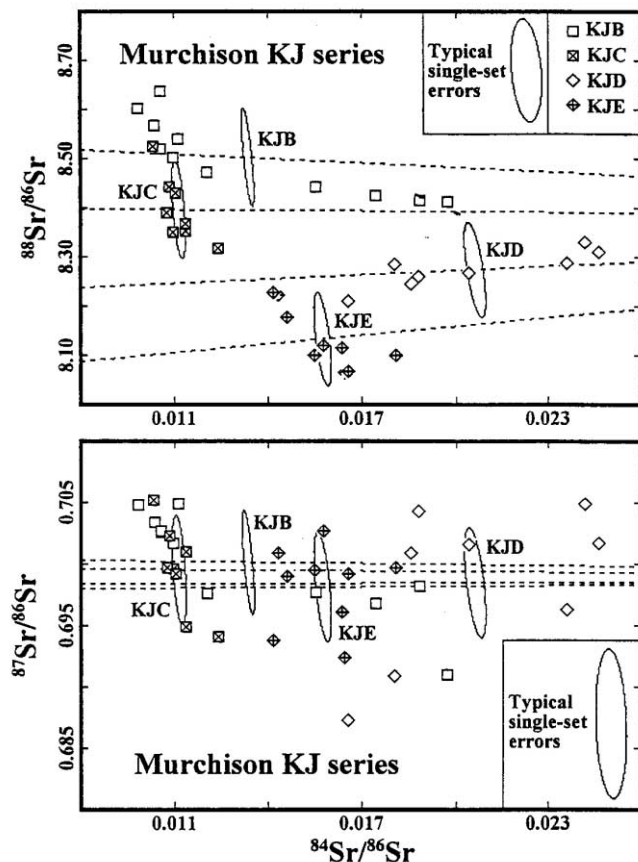

FIG. 1.—Three-isotope diagram displays of the individual set data for Murchison KJ series Sr, with the ratio of *p*-only ^{84}Sr to ^{86}Sr on the abscissa and ordinates of ^{88}Sr/^{86}Sr (*top*) and ^{87}Sr/^{86}Sr (*bottom*). Data are uncorrected for instrumental discrimination. Errors are calculated assuming a superposition of Poisson statistics and a discrimination uncertainty of 2.90 ‰ amu^{-1} (see text). The large ellipse illustrates the representative single-set error (for 100 kcounts s^{-1} of ^{88}Sr); the smaller ellipses show the errors for the sample means. Ellipses are drawn at the 2 σ level. The lines connect sample mean compositions with normal Sr, off the scale to the right (at ^{84}Sr/^{86}Sr = 0.05658); they illustrate the determination of the G-component (*s*-process) composition by extrapolation to the ordinate intercept (^{84}Sr/^{86}Sr = 0).

smaller, and the discrimination term is the dominant source of error.

3. RESULTS

Mean Sr isotopic compositions for all four samples, uncorrected for discrimination, are presented in Table 1. We do not list there individual set compositions, but a tabulation is available on request to the authors. Individual set results, along with sample means, are illustrated in Figure 1; error assignments are as described above.

A first-order characterization of these results is that the observed isotopic compositions are highly anomalous with respect to solar normal composition, in that they are greatly depleted (57%–83%) in ^{84}Sr. This is not unexpected: prior studies on bulk samples (Ott et al. 1988; Lewis et al. 1990, 1994; Ott & Begemann 1990a, 1990b; Zinner et al. 1991; Prombo et al. 1993), as well as on single grains (Nicolussi et al. 1997, 1998a; Savina et al. 2003), have shown that these SiC samples are strongly enriched in *s*-process components (Gallino et al. 1997; Hoppe & Ott 1997). While ^{86}Sr, ^{87}Sr, and ^{88}Sr are made in the *s*-process, ^{84}Sr is not; in the usual (*r*, *s*, *p*) trichotomy for nucleosynthesis of heavy elements, ^{84}Sr is a

TABLE 1
Isotopic Data for Sr

Sample	$^{84}Sr/^{86}Sr$	$^{87}Sr/^{86}Sr$	$^{88}Sr/^{86}Sr$
Normal			
Solar[a]..	0.05658	0.6988	$\equiv 8.375$
Meteoritic (Murchison) SiC-enriched Samples			
R1CPD[b].....................................	0.0502 ± 9	0.700 ± 4	8.39 ± 1
R1CPD[c].....................................	0.0203 ± 9	NR	8.35 ± 7
KJB[d]...	0.0134 ± 2	0.700 ± 4	8.50 ± 10
KJC[d]...	0.0111 ± 2	0.699 ± 4	8.40 ± 10
KJD[d]...	0.0206 ± 3	0.698 ± 4	8.27 ± 10
KJE[d]...	0.0157 ± 3	0.698 ± 4	8.13 ± 10
s-Process Compositions (G-Component Extrapolations)			
R1CPD[b].....................................	$\equiv 0$	0.710^{+50}_{-35}	8.50^{+14}_{-12}
KJB[e]...	$\equiv 0$	0.701 ± 5	8.54 ± 13
KJC[e]...	$\equiv 0$	0.700 ± 5	8.40 ± 12
KJD[e]...	$\equiv 0$	0.698 ± 7	8.22 ± 15
KJE[e]...	$\equiv 0$	0.698 ± 6	8.04 ± 13

[a] $^{84}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$ from Steiger & Jäger 1977. The listed $^{87}Sr/^{86}Sr$ is the early solar system value from Podosek et al. 1991.

[b] Ott & Begemann 1990a. The stated errors evidently do not include discrimination uncertainty.

[c] Richter et al. 1992. NR indicates not reported.

[d] This work. The errors, stated at the 2 σ level, are assumed to arise from Poisson statistics and discrimination uncertainty (see text) and are partially correlated (see Fig. 1).

[e] This work. These values are calculated by resolving tabulated sample mean compositions into an N-component with normal composition and a G (s-process) component with vanishing ^{84}Sr abundance. The errors, stated at the 2 σ level, are partially correlated (see Fig. 2).

p-process (or γ-process) isotope. The degree of enrichment of s-process Sr is comparable to that previously observed in Kr, Xe, Ba, and Nd.

The observed intrasample variations in $^{84}Sr/^{86}Sr$ are too large to be attributed to analytical uncertainty, even for KJC and KJE, in which the variations are small compared to those in KJB and KJD (Fig. 1, *top*). Comparable variations in other elements have been interpreted as resulting from the separation of incompletely mixed components, and we presume this interpretation applies to Sr as well. In keeping with prior nomenclature (Lewis et al. 1990, 1994; Gallino et al. 1990), we designate these as G-components (low $^{84}Sr/^{86}Sr$) and N-components (high $^{84}Sr/^{86}Sr$).

The most relevant data for comparison of the G-N mixing trends are our prior results for Ba (Prombo et al. 1993), which were obtained by essentially the same analytical technique. Out of four KJ fractions analyzed for Ba, two (the parent KJ and KJE) exhibit about the same degree of separation as is evident for Sr in KJB and KJD, while two others (KJC and KJD) exhibit very little separation of G- and N-components. For Ba in KJ and KJE, the G-component is most enriched early in the analysis. Sr in KJD shows a trend in the same sense as Ba in KJ and KJE, but it is worth noting that Sr in KJB trends in the opposite sense; i.e., in KJB Sr it is the N-component that is most enriched early in the analysis. This is possibly a blank effect, but if not, it indicates a previously unobserved complexity in the distribution of components within Murchison SiC.

As one step in quantifying the components present, we make the plausible assumption that the G-component indeed represents the products of s-process nucleosynthesis and is thus constrained to have a vanishing abundance of ^{84}Sr. An additional constraint on the N-component is also required. The data themselves do not provide much of a constraint, particularly in view of likely systematic changes in discrimination during the course of analysis (e.g., Prombo et al. 1993). We therefore adopt the additional assumption that the N-component actually has normal composition. The data are certainly consistent with this assumption and are even suggestive of it in that the relative abundances of ^{86}Sr, ^{87}Sr, and ^{88}Sr are so nearly normal despite the large anomaly at ^{84}Sr. Still, it must be recognized explicitly that we do not infer, but rather must assume, normal composition for the N-component.

With the assumption of a normal N-component and vanishing ^{84}Sr in the G-component, we can calculate the composition of the G (s-process) component by simple component resolution of the mean compositions (Table 1). The results, also included in Table 1, are illustrated in Figure 2. Most of the stated errors arise from the assigned uncertainty in discrimination. We consider that this procedure adequately represents the analytical uncertainties; we have no basis, however, for quantitative evaluation of how much uncertainty is attendant on the assumption of a normal N-component.

It is qualitatively evident in Figure 1 (*top*) that the various samples have different G-component compositions, at least in $^{88}Sr/^{86}Sr$. The distinctions among the samples are actually sharper than would be evident from comparing error limits in Table 1, because the errors in $^{87}Sr/^{86}Sr$ and $^{88}Sr/^{86}Sr$ are so strongly correlated (Fig. 2).

There might also be some intrasample variation in the G-component $^{88}Sr/^{86}Sr$. This would be manifested as a departure of the set data from the G-N tie-lines in Figure 1 (*top*)
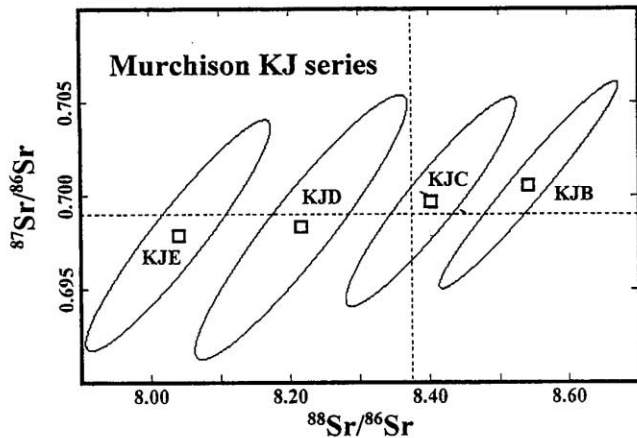
Fig. 2.—Inferred G-component (*s*-process) compositions for Murchison KJ series Sr (cf. Fig. 1). Error ellipses are drawn at the 2 σ level; note that the errors are strongly correlated. The lines indicate normal composition.

(as opposed to variation in the G-N mixing ratio, manifested as variation along the tie-line). The strongest case for such variation is that of KJB (Fig. 1, *top*). The degree of variation about the tie-line for KJB might merely reflect underassessment of the discrimination error, but in view of the intersample variation in $^{88}Sr/^{86}Sr$, some degree of intrasample variation would not be unexpected, even if for no other reason than that the samples are not perfectly separated.

^{87}Sr is a special case in that it is subject to correction for isobaric interference by ^{87}Rb; for the present samples this interference is in some cases nontrivial. In thermal ionization analysis of Sr, it is customary to monitor ^{85}Rb and make a corresponding correction for ^{87}Rb, and we have done so here. Considering the nature of the samples, however, it is not legitimate merely to assume a (normal) $^{87}Rb/^{85}Rb$ ratio: if the observed Rb is a constituent of SiC, rather than blank or normal meteoritic contaminant, it is likely to be isotopically anomalous. Predictions for *s*-process $^{87}Rb/^{85}Rb$ are complicated by the branch at ^{85}Kr, but in general, theoretical expectations are for $^{87}Rb/^{85}Rb$ to be substantially higher than normal (e.g., Käppeler, Beer, & Wisshak 1989).

We have examined Rb directly in samples of the KJ series. A Rb$^+$ ion beam is produced in the general range of filament temperature at which Rb ions are typically observed (substantially below Sr ionization temperatures): the observed $^{87}Rb/^{85}Rb$ ratio is normal within errors. Rb composition can also be examined indirectly, during the Sr analysis, by considering the relationship between the ratio of mass 87 (including both ^{87}Sr and ^{87}Rb) to mass 86 ion signals and the ratio of mass 85 to mass 86 signals. This is illustrated in Figure 3 for the first five sets of the Sr analysis of KJD (the other samples, and later sets for KJD, had severalfold lower $^{85}Rb/^{86}Sr$ ratios). The correlation expected for normal $^{87}Rb/^{85}Rb$ (0.3857) is shown by the steeper dotted line. A free fit to the data (*shallower line*) yields a lower slope (0.26). In view of the errors and the likelihood that discrimination varies between sets (possibly also the true $^{87}Sr/^{86}Sr$ ratio), we do not consider that this constitutes compelling evidence for nonnormal Rb. The data do seem to preclude $^{87}Rb/^{85}Rb$ ratios much higher than normal, however. All factors considered, we conclude that interference corrections at ^{87}Sr are best made using the normal $^{87}Rb/^{85}Rb$ ratio. We do not conclude that Rb in SiC is isotopically normal, however, since we are unsure of

the source of the Rb, which might be the SiC but which might also be blank or normal meteoritic contaminant.

With normal Rb correction the $^{87}Sr/^{86}Sr$ data (Fig. 1, *bottom*; Table 1), unlike the $^{88}Sr/^{86}Sr$ data, display no significant intersample trends. For three samples the range of variation in $^{87}Sr/^{86}Sr$ is consistent with the nominal assigned errors; the fourth, KJD, shows a larger degree of scatter, and it is probably not coincidence that this sample also has the largest interference corrections. Sample mean compositions and extrapolated G-component compositions (Table 1; Fig. 2) are consistent with each other and with solar normal $^{87}Sr/^{86}Sr$.

The most comparable prior data for Sr in SiC are those for Murchison R1CPD (Ott & Begemann 1990a; Richter, Ott, & Begemann 1992), which are included in Table 1. The R1CPD data have thus far been reported only in abstract, so that a detailed comparison is not possible, particularly concerning the treatment of discrimination. Nevertheless, it is evident that the principal differences among all the data can be accommodated by varying proportions of G- and N-components, and that in terms of end-member components, the two data sets are consistent within nominal errors. In addition, Nicolussi et al. (1998b) have reported Sr isotopic data for a suite of individual SiC grains from Murchison. The individual-grain data are less precise than, but on the whole quite consistent with, the "bulk" sample analyses reported here, and they show that there is a substantial degree of variation in the proportions of G- and N-components from one grain to another, along with more modest grain-to-grain variations in $^{88}Sr/^{86}Sr$.

4. DISCUSSION

There is a clear trend of variation of G-component composition, specifically the $^{88}Sr/^{86}Sr$ ratio, among the four samples. This is evidently a grain-size effect: the larger grains have lower $^{88}Sr/^{86}Sr$ (Table 1; Fig. 2). G-component compositional variations correlating with grain size in this same suite of samples have previously been noted for Kr (Lewis et al. 1990, 1994) and Ba (Zinner et al. 1991; Prombo et al. 1993). Evidently, fundamental stellar parameters such as mass, metallicity, and stage of evolution control the kinetics of grain
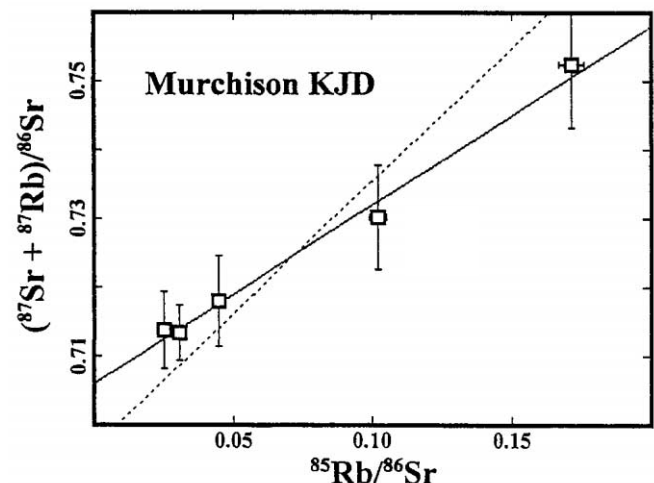

Fig. 3.—Relation between measured (uncorrected for ^{87}Rb interference) $^{87}Sr/^{86}Sr$ and $^{85}Rb/^{86}Sr$ for the first five sets of Murchison KJD. The steeper solid line is not a fit but rather the correlation expected if all samples have the same true $^{87}Sr/^{86}Sr$ (ordinate intercept of 0.697) and the interference is for normal Rb (slope = $^{87}Rb/^{85}Rb$ = 0.3857). The shallower line is a free fit to the data, with a slope of 0.26. The illustrated errors are 2 σ Poisson errors only.

formation, as well as *s*-process composition, but the manner in which this control is effected is not understood. It is also nontrivial to note that this size-composition relationship has survived processing in the ISM (e.g., Jones et al. 1997).

The grain-size trends for Sr and Ba are qualitatively similar and have the same sense: in both elements, the largest effects are for low cross section (neutron-magic) isotopes (^{88}Sr and ^{138}Ba), whose production is particularly sensitive to neutron exposure, and in both cases the sense of the trend (lower ^{88}Sr/^{86}Sr and lower ^{138}Ba/^{136}Ba in larger grains) is for lower exposure in the larger grains. An additional effect is possible for Sr because of the well-known *s*-process branch at ^{85}Kr (half-life of 10.8 yr), which makes the production of ^{86}Sr dependent on neutron density as well as exposure. If ^{85}Kr decays, the *s*-process flow is through ^{85}Rb, ^{86}Sr, ^{87}Sr, and ^{88}Sr; if ^{85}Kr captures a neutron, the flow is through ^{86}Kr, ^{87}Rb, and ^{88}Sr, bypassing ^{86}Sr (and ^{87}Sr) and thereby increasing ^{88}Sr/^{86}Sr. Qualitatively, to the extent that this branching is important for Sr, the sense of the trend is for lower neutron densities (as well as lower neutron exposures) recorded in the larger grains.

The sense of the trend for Kr is the opposite of that seen in Sr and Ba: ^{86}Kr/^{82}Kr increases (and ^{80}Kr/^{82}Kr decreases) with increasing grain size (Lewis et al. 1990, 1994), suggesting greater neutron exposures and/or greater neutron densities for the larger grains. The contrast between Kr and Sr is less easy to excuse than that between Kr and Ba, since Kr and Sr are much closer in mass and should be coproduced, and because both elements are sensitive to branching at ^{85}Kr. Resolution of the discrepancy likely lies in chemical rather than nuclear effects. Relative to Ba and Sr, the noble gases Kr and Xe are greatly depleted in Murchison SiC (Ott & Begemann 1990b; Zinner et al. 1991; Amari et al. 1995). Whatever mechanism is responsible for the presence of Kr in SiC could thus be highly selective, incorporating Kr produced in a more restricted phase of stellar evolution than the source of Sr. In addition, Nichols et al. (1992) have observed that most of the Ne-E(H) (nearly pure ^{22}Ne, also believed to be part of the G-component) in these samples is carried in only a small fraction of the individual grains, so it may be that noble gases in SiC (Ne, Kr, Xe) represent an entirely different population of nucleosynthetic processes than do chemically reactive elements such as Sr and Ba.

Theoretical predictions of *s*-process compositions, based on experimental data for neutron capture cross sections and plausible astrophysical scenarios for the AGB phase of low-mass stars (1.3–$4 \, M_\odot$), can match the inferred (Table 1) SiC *s*-process compositions quite well (e.g., Gallino et al. 1997). In addition, the SiC compositions are very similar to solar Sr composition (Table 1): the SiC ^{87}Sr/^{86}Sr ratio is indistinguishable from the solar ratio within narrow experimental limits, and the ^{88}Sr/^{86}Sr ratios vary only modestly over a range that includes solar normal. It might thus be inferred that the SiC *s*-process Sr is nearly the same as the *s*-process contribution to solar Sr. Such an inference would be incorrect, however; the situation for solar Sr is more complicated, and the close similarity of SiC and the solar relative abundances of ^{86}Sr, ^{87}Sr, and ^{88}Sr must be viewed as coincidental.

^{86}Sr and ^{87}Sr are produced on the same *s*-process branch (at ^{85}Kr) and would be expected to be produced in a ratio less

variable than the ratio of either one of them to neutron-magic ^{88}Sr. Some of the ^{87}Sr in the early solar system was not produced directly on this branch, however, but rather by the decay of ^{87}Rb (half-life of 49 Gyr, produced by the *r*-process and also on the other *s*-process branch at ^{85}Kr) over the lifetime of the Galaxy prior to formation of the solar system. For a present solar Rb/Sr of $\sim$0.30 (Humayun & Group 1991), ^{87}Rb/^{86}Sr was $\approx$0.92 at the time of formation of the solar system, presumably representative of the ISM from which the Sun formed. For a Galactic age of $\sim$10 Gyr at that time, the mean age of the Rb would have been $\sim$5 Gyr, assuming linear growth of Rb in the ISM. Some 7% of all the ^{87}Rb produced to that time would thus already have decayed to ^{87}Sr, accounting for some 10% of the solar inventory of ^{87}Sr. This contribution might have been lower if the mean age of ^{87}Rb were lower than that assumed, or higher if the ISM value of Rb/Sr were higher (e.g., Hauge 1972). In addition, approximately 6% of solar ^{86}Sr, but a substantially smaller fraction of ^{87}Sr, was contributed by the *p*-process rather than the *s*-process (Käppeler et al. 1990). Combining these effects, the direct *s*-process production ratio ^{87}Sr/^{86}Sr in solar Sr is inferred to be 0.67. This is outside the analytical limit for ^{87}Sr/^{86}Sr in the SiC (we assume, albeit without the support of elemental concentration measurements, that Rb/Sr in the SiC itself is sufficiently low to preclude significant growth of radiogenic ^{87}Sr in situ), but with reasonable allowance for uncertainties in estimating direct *s*-process composition in solar Sr, the solar and SiC *s*-process ^{87}Sr/^{86}Sr ratios might well be essentially indistinguishable.

More latitude is needed to account for ^{88}Sr/^{86}Sr, which is more variable in *s*-process production because of the small cross section of neutron-magic ^{88}Sr, as well as the branch at ^{85}Kr. Gallino et al. (1997), for example, infer a best fit to the so-called main component *s*-process (primarily responsible for the solar *s*-process nuclides between Sr and Pb) in terms of an AGB nucleosynthetic scenario that would also produce an ^{88}Sr/^{86}Sr ratio nearly twice the solar value. That the actual solar value is so much lower evidently reflects superposition of the so-called weak component (lower neutron exposure and thus lower ^{88}Sr/^{86}Sr) invoked to account for solar *s*-process nuclides with $A < 90$ (e.g., Clayton & Ward 1974). Moreover, besides the *p*-process contribution to ^{86}Sr, there is an *r*-process contribution to ^{88}Sr.

The foregoing considerations illustrate the wealth of quantitative detail available through laboratory study of presolar circumstellar grains, a discipline that grew from the pursuit of isotopic anomalies in meteorites (Reynolds & Turner 1964; Lewis, Srinivasan, & Anders 1975). The resulting constraints have posed a wealth of challenges to astrophysical theory, many of which have been met with gratifying success, but many of which await future work.

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