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The interpretation of solar system abundances at the $N = 50$ neutron shell

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Abstract. New data on CI chondrite abundances demonstrate a high degree of smoothness for the $A = 75-100$ mass range for odd A nuclei, except for a single element peak at Y ascribable to the s-process peak for the $N = 50$ neutron shell. Literature estimates of s-process abundances, N_s, permit a smooth N_s curve to be drawn; however the resultant "non-s" abundance curve (nominally r-process) does not show a peak analogous to peaks associated with the $N = 82$ or 126 shells. However, both the nominal N_s and "non-s" abundance curves show similar rapid increases below mass 70. It is more reasonable to ascribe the "non-s" rise as an artifact from relatively small differences in the N_s and total abundances, indicating that a relatively broad r-process peak is indeed present. The solar system even A abundances in this mass region are not smooth but show a saw-tooth structure which is also reflected in neutron capture cross sections, indicating that the saw-tooth is an s-process feature. The r-only even A nuclei define the r-process peak assuming that it is smooth. Assuming the systematics of the r-process even and odd A abundance peaks at the $N = 82$ and 126 shells apply to $N = 50$, the odd A r-process peak for $N = 50$ can be obtained, which in turn permits a new calculation of N_s for odd A. The new N_s is relatively smooth, but, contrary to expectations, the product of N_s and the neutron capture cross section is not a smooth function of A, but contains structure, especially a rise between masses 82–84, which is not compatible with an exponential distribution of neutron exposures.

Key words: planets and satellites: abundances – meteor, meteorites – nucleosynthesis

1. Introduction

We have completed an analytical study of the smoothness of the solar system abundance-mass relation, based on analyses of primitive CI chondrites, for the mass region 60–100 (Burnett et al., 1989). The principal CI meteorites, Orgueil and Ivuna, were analyzed for all elements in this mass range in the same sample by the same technique (proton-induced X-rays). Except for Y and As there is good agreement (within either two standard deviations or 10%) between our CI abundances and literature values.

Following tradition (Suess, 1947), smoothness is assessed based on odd A abundances. Until accurate photospheric abundances were available, the smoothness of the odd A CI chondrite abundance curve was the primary argument that these meteorites could be used as sources of average solar system composition. If the true abundance vs. A relation for the solar system was highly irregular, it would be very surprising if cosmochemical fractionation processes would produce the observed smooth abundance curves (Anders, 1971). Using the odd A representation, our abundances are quite smooth, as illustrated in Fig. 1 for the mass region 75–100. Our analytical study has stimulated us to reconsider the nucleosynthesis implications of the abundance curve in this mass region.

The clear r- and s-process double peak structure in the solar system abundance curve associated with the $N = 82$ and 126 neutron shells (see e.g. recent reviews by Woolum, 1988, or Anders and Grevesse, 1989) is not apparent for the $N = 50$ region covered by our data. Our data confirm (Fig. 1) the necessity for a single element ^{89}Y peak in the total solar system abundance curve, presumably of s-process origin by analogy with the peaks at masses 137 and 207. Our measured Y abundance is about 20% lower than that tabulated by Anders and Grevesse, but a peak is still required. The general trend for s-process abundances is for the product of the abundance and stellar-temperature neutron capture cross section (PSI) to be a slowly-varying function of mass number. The relationship breaks down near neutron shells; nevertheless, the low neutron capture cross sections of closed neutron shell nuclei still are reflected in high abundance peaks, and a plot of odd A neutron capture cross sections (e.g. Bao and Käppeler, 1987) shows a strong negative anomaly for ^{89}Y which can explain the corresponding abundance peak.

There is no obvious r-process peak in the curve we have drawn on Fig. 1, but the choice of Br abundance requires some discussion in this context. The two principal CI meteorites available for study, Orgueil and Ivuna, typically show abundance differences less than 10% for most elements (Burnett et al.). However, Br is an exception, as illustrated explicitly on Fig. 1, with the Ivuna abundance being 59% higher than Orgueil. The overall agreement is fortunate because there is no a-priori basis for selecting one of these meteorites as *the* source of solar system abundances. In favoring the Orgueil Br abundance we follow Anders and Ebihara (1982) who adopted a Br abundance based on the ratios of Br to cosmochemically-similar elements (In and Cd) in other types (C2, C3) of carbonaceous chondrites. Their adopted Br abundance was close to that for Orgueil but much

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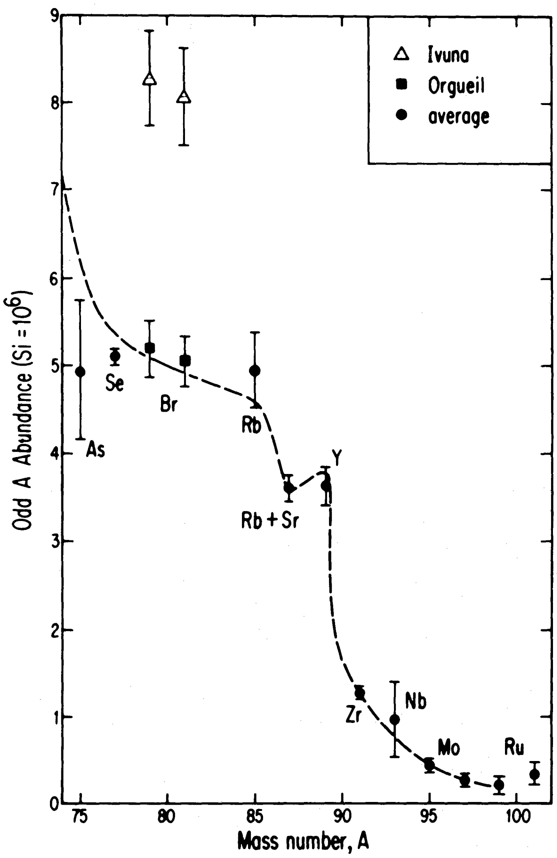

Fig. 1. Measured odd A abundances for CI chondrites for the mass 75–100 region (from Burnett et al., 1989). The curve drawn connects smoothly with the region of the curve from mass 60–75. Except for Br the plotted points are the average of the individual meteorites, Orgueil and Ivuna, which agree well. For Br the individual meteorite results are shown. The small peak at Y is an s-process feature due to the $N=50$ neutron shell, analogous to more prominent features at mass 137 and 207

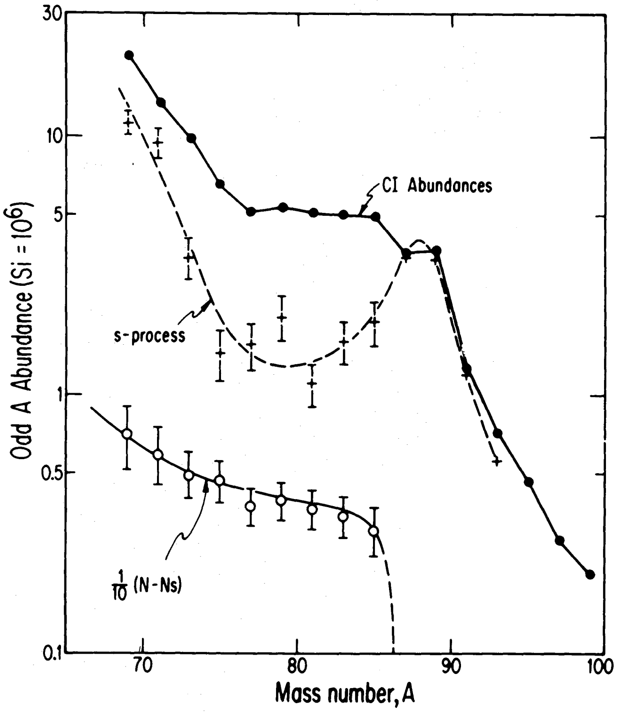

Fig. 2. Decomposition of our measured odd A abundances using literature fractional s-process abundances, N_s (Walter et al., 1986, for mass 69–88; Beer, 1985, for 89–90; Beer and Walter, 1984 for 91–95). Within errors (from cited papers) a smooth N_s curve can be drawn. Using the smooth N_s, a smooth $N-N_s$ curve results, plotted with an offset vertical scale for clarity. Here and in subsequent figures the actual abundances are used rather than the illustrative smooth curve drawn in Fig. 1. Kr abundances have been obtained by interpolation of the CI curve at mass 83

lower than that for Ivuna. For nucleosynthesis considerations it is important to recognize this cosmochemical interpretation because, if the Ivuna Br abundance is used (suppose Orgueil had never fallen), a distinct abundance peak at masses 79 and 81 would be present, which would have a natural interpretation as an r-process feature.

2. s-process contributions

We begin by considering the s-process, as it is the best understood nucleosynthesis mechanism, and model s-process abundances (N_s) are available from many studies. However, the 60–100 mass range has been very difficult to interpret in terms of the s-process (see e.g., Ulrich, 1982; Käppeler et al., 1982, Beer, 1985).

2.1. *Odd A abundance curve*

In evaluating N_s for odd A, the smoothness of the overall odd A abundance curve must be respected; for, if the total abundance curve is smooth but contains contributions from more than one nucleosynthesis process, then it is very likely that at least the major contributing processes also have approximately smooth abundance curves.

In general by smoothness one means that a curve can be drawn through the observed odd A abundances with no discontinuities in slope. However, it is possible that there are 10–20% deviations from smoothness in this mass region. Consequently, in the subsequent discussion the actual CI abundances are used, as opposed to the illustrative smooth curve drawn on Fig. 1, in order to avoid introducing smoothness beyond what is inherent in the data.

In our interpretations N_s is *assumed* to be a relatively smooth function of A for odd A nuclei. Marti and Suess (1988) argue that the smoothness of the odd A solar system abundance curve in general is primarily an r-process feature. However, in this mass range s-process contributions are not always negligible, and we conclude that both the s- and r-process odd A curves need to be relatively smooth to explain the smoothness of the total solar system abundance curve.

Figure 2 compares our measured CI abundances with literature s-process abundances (N_s) obtained from the % N_s given by Walter et al. (1986), Beer and Walter (1984), and Beer (1985) in the 70–100 mass range. Our As concentrations appear low (Burnett et al., 1988), and the error on our Nb concentration is large; thus for masses 75 and 93 we have used the values compiled by Anders and Grevesse. The N_s values shown on Fig. 2 were calculated using a "two-component" s-process model for the total

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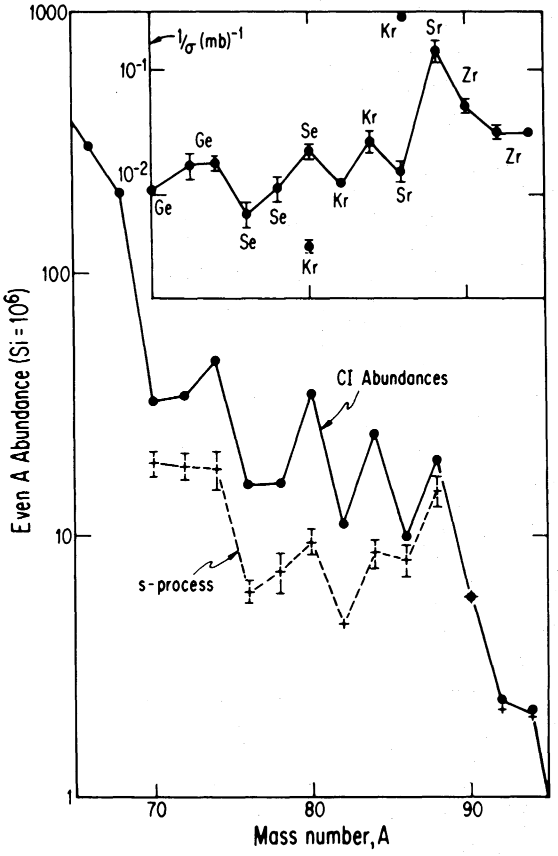

Fig. 3. Our even-A meteorite abundances show a distinct saw-tooth structure, which is qualitatively reflected in the literature N_s (references in caption of Fig. 2). The N_s structure is reflected in the neutron capture cross sections (Bao and Käppler, 1987), as displayed in the insert in a plot of reciprocal cross section

mass range, 56 to 200, which assumes the superposition of two exponential fluence *distributions* ("main" and "weak" s-process) and is adjusted to fit the abundances of s-only nuclei over the total 56–200 mass range. The effects of s-process branchings, e.g. at ^{79}Se and ^{85}Kr, are included in these calculations. The s-only nuclei are all even A, so none are present on an odd A plot such as Fig. 2. The N_s errors were taken from Walter et al. (1986).

Within the errors a smooth s-process abundance curve can be drawn, as shown in Fig. 2.

In the total abundance curve there are strong "non-s" contributions in the mass 75–85 region, as shown by the $(N-N_s)$ curve on Fig. 2. We calculated the $(N-N_s)$ curve from the smooth N_s curve with error bars from the actual N_s values. Smoothness is obviously assumed, but within the errors the non-s abundances could be flat in the mass 75–85 range or show a continual rise below mass 85. The flat portion would be analogous to the r-process peaks at mass 129 or 195.

In general the reason that the two-peak structure for $N=50$ is not apparent in the total abundance curve is the obscuring effect of the rise in abundance below mass 70–75 which has no analog in the mass regions around the $N=82$ and 126 shells.

The rise in N_s below $A=75$ is ascribable both to a decrease in neutron capture cross sections for ^{69,71}Ga and ^{73}Ge and to a rising PSI (using the s-only nuclei ^{70}Ge and ^{76}Se as guides).

Table 1. Estimated s-process abundances for the Ga isotopes[a]

Mass	σ^b (mb)	N_s	N^c (Si$=10^6$)	N^d
69	146 ± 6	$16.3+1.0$	20.5	22.7
71	125 ± 8	19.0 ± 1.5	13.6	15.1

[a] N_s calculated assuming that the abundance-cross section product (2380 ± 120 mb/10^6 Si) for ^{70}Ge applies to Ga isotopes and that ^{70}Ge is an s-only nucleus
[b] From compilation of Bao and Käppler (1987)
[c] CI abundance, Burnett et al. (1989)
[d] CI abundance, Anders and Grevesse (1988)

Nevertheless, the total ^{69,71}Ga, and ^{73}Ge abundances are sufficiently high that a rise in the $(N-N_s)$ is also indicated. However, it seems a strange coincidence that the s and non-s abundances should show qualitatively parallel increases between mass 75 and 69. It may be that the rise in the $N-N_s$ curve is an artifact resulting from relatively small errors in the N_s from the two component model in this mass region. This is plausible given the relatively detailed level of the s, non-s decomposition being discussed here. A higher level for PSI than that adopted for Fig. 2 appears necessary. In fact the global "two-component" s-process fit gives an abundance, cross section product for the nominally s-only isotope, ^{70}Ge, which is 30% too low, relative to the empirical value which is known to 5%. (Walter et al. (1986) assume that about 30% of ^{70}Ge is produced by the *e*-process.) However, if ^{70}Ge is assumed to be s-only, "local" N_s can be estimated for ^{69}Ga, and ^{71}Ga assuming that the empirical PSI for ^{70}Ge applies to masses 69 and 71 (Table 1). This calculation is not exact because PSI is decreasing with mass in this region, and, in fact, the estimated N_s are (low, high) for (^{69}Ga, ^{71}Ga). Nevertheless, Table 1 illustrates that the total abundances of ^{69}Ga and ^{71}Ga can probably be accounted for by the s-process. Thus, the non-s contributions in the 69–71 mass range could be much lower than shown in Fig. 2. Assuming that other N_s values used for Fig. 2 are approximately correct, an apparent r-process peak from mass 75–85 does appear to be present. The above analysis would be unchanged if the Anders and Grevesse abundances or if alternative N_s values, e.g. from Marti and Suess (1987) had been used.

There are obvious concerns about the assumptions made in the above analysis, possibly the most serious being the assumption that ^{70}Ge is produced entirely by the s-process. However, if there are non-s contributions to ^{70}Ge, then there are also likely to be non-s *and non-r* contributions to masses 69, 71, and 73 making the existence of an r-process peak plausible even if the s-only assumption for ^{70}Ge is not strictly true.

2.2. *Even A abundance curve*

Figure 3 shows that in the mass 70–100 range the solar system even A abundance curve is not smooth, showing a sawtooth structure with maxima at masses 74, 80, 84, and 88. Above mass 100 the even A curve is not as jagged, although still much less smooth than the odd A curve.

From the point of view of identifying CI abundances with average solar system composition it is not necessary that the

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even A curve be smooth. Following the arguments given in the Introduction, it is sufficient that the odd A curve be smooth.

The calculated even A s-process abundances, N_s, from the same sources as for Fig. 2, are also shown on Fig. 3. These are not especially smooth, but they show similar structure to what is present in the total abundance curve. This structure is also found in the neutron capture cross sections for s-process even A nuclei as illustrated in the insert to Fig. 3, in which the reciprocals of the cross sections are plotted, permitting a direct comparison. The similarity is striking in that a curve can be drawn, connecting the inverse cross section points, which shows peaks at ^{74}Ge, ^{80}Se, ^{84}Kr, and ^{88}Sr, corresponding to the abundance peaks. By choosing ^{80}Se rather than ^{80}Kr and ^{86}Sr rather than ^{86}Kr, the curve connects points on an s-process path in which ^{79}Se does not beta decay and ^{85}Kr does beta decay, presumably a relatively low temperature, low flux path. (The similarity in ^{76}Se and ^{78}Se cross sections matches similar total abundances at masses 76 and 78, but this is in part of fortuitous, because over half of the total mass 76 abundance is due to the non-s nucleus ^{76}Ge, independent of any nucleosynthesis models).

There is thus a strong suggestion that the sawtooth structure in the mass 74–86 region on Fig. 3 is an s-process feature. Again, this interpretation would not be changed if the Anders and Grevesse total abundances or the Marti and Suess N_s were used.

However, Fig. 3 also shows that, quantitatively, the literature N_s, based on the two-component s-process model, are insufficient to account for the sawtooth. For clarity the inferred $(N-N_s)$ curve is not shown on Fig. 3, but it is obvious that it would still contain the spikes at masses 74, 80, and 84. It is not reasonable for the s- and r-process abundance curves to have the same fine structure. One possibility is that the calculated s-process abundances are low, at least at mass 80 and 84, qualitatively similar to the situation in the 69–75 mass region discussed above in connection with Fig. 2. However, arbitrarily raising the N_s abundances is not acceptable, as the N_s at mass 76 is constrained by the abundance of the s-only nucleus, ^{76}Se.

An interesting alternative is suggested by the calculations of Hartmann et al. (1985) of abundances produced by n-rich nuclear statistical equilibrium (e-process) nucleosynthesis. In these calculations significant element production as far out as mass 90 was found with abundance peaks at some of the same nuclei as for the peaks of the sawtooth in Fig. 3. It is conceivable that this mechanism contributes significantly to solar system abundances in this region. This has been suggested previously by Walter et al. (1986). Also, the n-rich e process has previously been invoked to explain the relatively frequent occurrence of correlated meteoritic isotopic anomalies in ^{48}Ca, ^{50}Ti and ^{54}Cr (Papanastassiou, 1986). As Fig. 3 shows, the sawtooth peaks correspond to low neutron capture cross sections, and, to the extent that this is a reflection of local excess nuclear stability, then it is reasonable that these nuclei should also have enhanced abundances in an e-process situation, and especially in a n-rich environment, which would facilitate mass addition to Fe-group nuclear seeds.

A second alternative to an s-process origin for the even A structure is beta-delayed neutron emission in the decay of r-process progenitors (e.g. Marti and Suess, 1988; Kratz, 1988). Beta-delayed neutron effects have been proposed to account for the systematic odd-even r-process abundance differences in this mass region, but it is also conceivable that structure in both the odd and even-A abundance curves would also result.

We prefer the s-process interpretation for the even A abundance structure because the abundance patterns from either the Hartmann et al. e-process calculations or from the beta-delayed neutron branching ratios from Kratz do not match those in the CI abundances. It is, however, possible that the lack of agreement might simply reflect the uncertainties in the nuclear and astrophysical parameters required for the r- or e-process calculations.

3. An alternative abundance decomposition for the $N=50$ mass region

The validity of the s- and r-processes has been qualitatively established for over 30 yr, but, primarily through the measurements of neutron capture cross sections from Karlsruhe, it has only recently been possible to demonstrate a good quantitative fit to the abundances of s-only nuclei (N_s) for masses above 90. (see e.g., Fig. 5 in Anders and Grevesse, 1989). Further, several independent measurements of s-process Xe isotopic anomalies in acid-insoluble residues from carbonaceous chondrites show the same s-process abundance pattern; moreover, this abundance pattern is the same as for average solar system s-process Xe abundances (see, e.g., Anders, 1988; Ott et al., 1988). The heavy element ($A>90$) s-process appears to be very well-defined.

However, the improved knowledge of cross sections has only accentuated the problem, first pointed out by Ulrich (1973), that the parameters which describe the s-only abundances above mass 90 do not account for N_s below mass 90. This has led to the two component s-process model (see, e.g., Käppeler et al., 1982; Beer, 1985) used to obtain the N_s values used in Figs. 2 and 3. Most of the s-process production below mass 90 is ascribed to the "weak" s-process component. Moreover, in contrast to Xe, meteoritic Kr isotopic anomalies, apparently of s-process origin, have variable compositions (Ott et al., 1988), which do not match the average solar system N_s for Kr. as deduced by Walter et al. (1986). Consequently, several lines of evidence suggest a greater variety of astrophysical sites synthesizing s-process nuclei below mass 90 than for heavier nuclei.

The discussion of Figs. 2 and 3 above suggests that there are s-process abundance features in this mass range that are not completely described by the two component model. In the following we propose an alternative model, relying heavily on abundance systematics.

Following the discussion of Figs. 2 and 3 and abundance systematics in general, a plausible set of features which we would expect to be present for the $N=50$ neutron shell region would be:

(1) To be consistent with other mass regions smooth *r-process* abundance peaks are present for both even and odd mass nuclei in the $N=50$ region.

(2) The N_s curve for odd A nuclei is smooth, but the N_s curve for even A is not.

(3) PSI is a smooth function of mass number, except for regions where branching occurs (masses 79–81 and 85–87).

(4) ^{70}Ge, ^{76}Se, and ^{82}Kr are s-only nuclei. We assume negligible e- and p-process contributions for these and other nuclei considered. The former is a major model assumption.

(5) ^{70}Zn, ^{76}Ge, and ^{82}Se are r-only nuclei.

(6) ^{69}Ga and ^{71}Ga are primarily produced by the s-process (compare discussion of Fig. 2 and Table 1).

Features (1), (4), and (5) are crucial assumptions to our model. Features (2), (3), and (6) are not explicit assumptions in the subsequent s–r decomposition.

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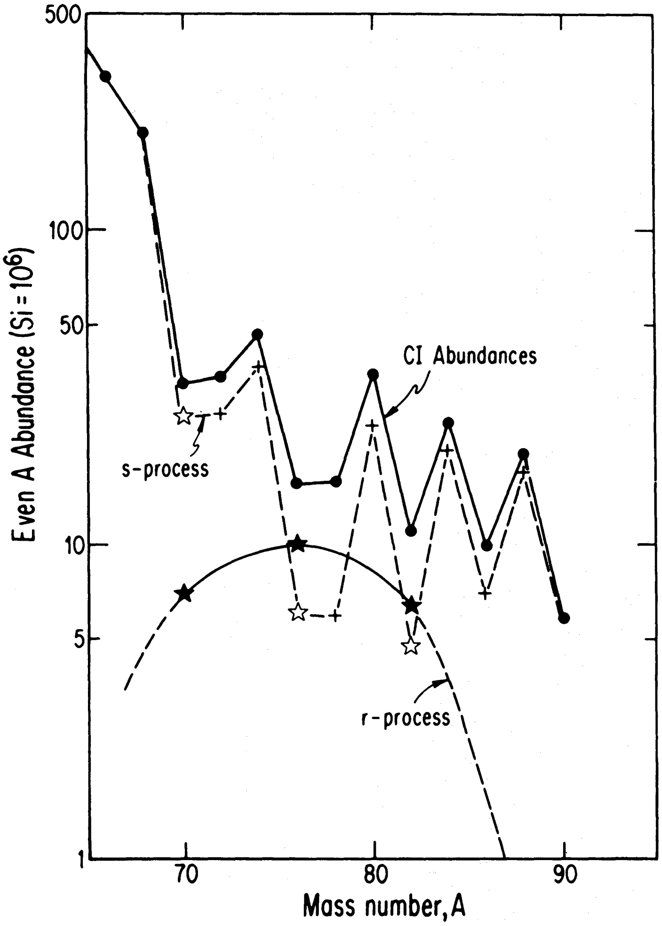

Fig. 4. Our proposed decomposition of the even A abundances. A smooth r-process peak is assumed and drawn based on the abundances of assumed r-only nuclei at masses 70, 76, and 82 (solid stars). The saw-tooth structure in the total abundance curve is thus ascribed to the s-process. Assumed s-only nuclei are shown as open stars

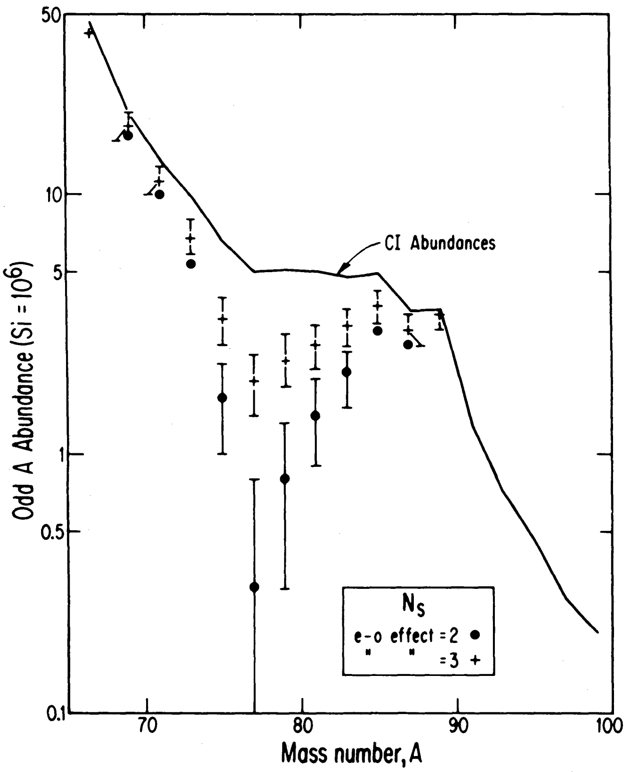

Fig. 5. Our proposed decomposition of the odd A abundance curve. N_s are shown obtained by subtracting a smooth r-process contribution based on reducing the even A r-process peak from Fig. 4 by a factor of 2 (circles) or a factor of 3 (crosses) to account for the even-odd effect in r-process abundances. Most of the abundances of the odd A nuclei from mass 67–73 are ascribed to the s-process. In general one should possibly consider e-process contributions in this mass range

Detailed evaluation shows that the available data are not consistent with all of these features, with (2) and (3) being difficult to satisfy simultaneously. As discussed below, the most plausible solution to us is to allow a relatively large amount of structure in PSI.

Using (1) and (5) as assumptions, a relatively well-defined even A r-process peak can be drawn for the mass 68–84 region, as shown on Fig. 4. The resultant s-process even A abundance curve contains all the saw-tooth structure of the total abundance curve, following the discussion for Fig. 3. Given the smoothness assumption the even A r-process curve is well-defined between masses 70 and 82. Extrapolations beyond this range are clearly uncertain; however, no major conclusions depend on these extrapolations. Extrapolation above mass 82 is somewhat constrained in that N_r for Kr^{86} not exceed the difference between the observed abundance and that for the main s process. With the N_r from Fig. 4 the observed abundances for ^{80}Se and ^{86}Kr are mostly due to the s process.

To perform a similar decomposition for the odd A abundance curve as was done for even A on Fig. 4 we assume that the even and odd A r-process peaks have the same shape, as is true for the $N=82$ and $N=126$ peaks. We allow, however, for an even-odd effect in the r-process abundance levels. The $N=126$ r-process abundance peak is remarkable in showing no obvious even-odd effect, but even A abundances are systematically higher by a factor of about 1.4 for the $N=82$ peak. A significant even-odd effect (at least a factor of 2) must be present in the $N=50$ r-process abundance peak; otherwise the calculated N_r at mass 75 is greater than the total abundance (compare Marti and Suess, 1988). The observed value of PSI for ^{76}Se is distinctly less than that for ^{70}Ge; thus an upper bound on the even-odd effect of approximately a factor of 3 can be set by requiring that PSI for mass 77 be less than that for mass 76. The true even-odd effect is required to be within these limits. Figure 5 shows odd A N_s calculated by reducing the r-process peak from Fig. 4 by an even-odd effect of a factor of 2 or a factor of 3. The resultant N_s are only sensitive to the choice of even-odd factor for the mass 75–81 range. It is possible to draw relatively smooth curves for these N_s. Following the discussion for Fig. 2 the rise in total abundance as A decreases from 75 to 67 is ascribed to the s-process.

Figure 6 shows the PSI trend for the mass 67–90 region obtained with our N_s abundances from Figs. 4 and 5. As we accept the Walter et al. (1986) calculations for the main s process, we have applied a main s correction to the points plotted on Fig. 6. As noted by Walter et al., the main s-process accounts for most of the s-process abundances above mass 86. For clarity only the results for an r-process even-odd factor of 3 are shown. The

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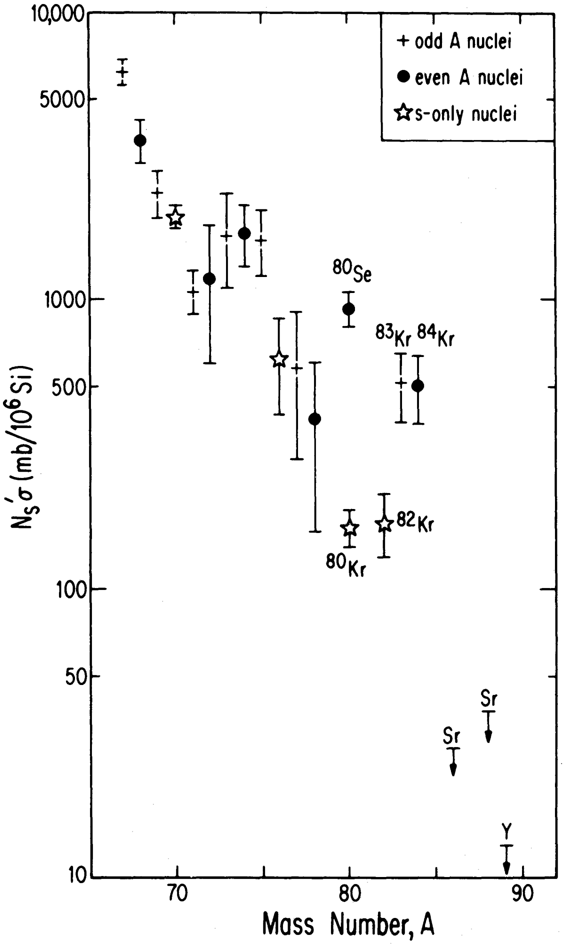

Fig. 6. The N_s from Figs. 4 and 5 have been corrected for contributions from the "main s process", which quantitatively accounts for nuclei at masses greater than 100 (Walter et al., 1986). The resultant N_s' define an s-process abundance, cross section product (PSI′) curve for mass 67–90 which is not smooth, but which contains significant structure, most conspicuously a rise in PSI′ at ^{82,83,84}Kr, possibly also at masses 71–75. This structure is not compatible with the traditional assumption of an exponential distribution of fluences. Above mass 86 the main s-process can account for most of the total N_s abundances

equivalent trend for an even-odd factor of 2 is similar except that it has more scatter in the mass 75 region, whereas the factor of 3 case shown is relatively smooth.

The issue in Fig. 6 is the smoothness of the PSI curve (model assumption 3). However, in the mass ranges affected by the branchings at masses 79 and 85, PSI need not be smooth and not necessarily even monotonically decreasing (Ward et al., 1976), e.g. at mass 80. In our case starting from a set of empirical N_s, it is not possible to plot values for PSI for masses 79, 81, 85, and 87, as there are not unique progenitors for the solar system abundances at these masses. For example at mass 79, the ^{79}Br s-process abundance has contributions from ^{79}Se and ^{79}Br progenitors which cannot, a-priori, be resolved. It is possible to plot PSI values for the even A nuclei involved in the branchings, e.g. for ^{80}Se, as there is no ambiguity in progenitors in these cases.

Traditional approaches to the s-process, dating back to at least Seeger et al. (1965), result in the expectation that away from closed neutron shells PSI should be approximately constant. This is clearly not true for the mass 70–85 region, independent of any models, as shown by the factor of 5 decrease in PSI for s-only nuclei on Fig. 6.

However, taking our decompositions at face value, there is additional structure, most prominantly a rise in PSI between masses 82 and 84 and, possibly, between masses 71 and 75. If the errors are interpreted as 1 standard deviation, only a flattening of the trend at mass 71 may be required. A rise in PSI at these mass regions appears to be incompatible with s-process abundances arising from an exponential fluence distribution. Alternative distributions of neutron exposures would be required to explain the N_s derived from this model.

Summarizing, we have presented an alternative model for r- and s-process abundances in the $N=50$ range. By demanding smoothness in N_r and N_s for odd A our model produces structure in the N_s, cross section product (PSI). The model discussed here is not necessarily better (or worse) than the previously-developed two component model. Both are models. In addition, as discussed above, contributions from a neutron-rich *e*-process cannot be ruled out. The two-component s-process model is plausible in that it adopts a formalism that successfully describes the s-process abundances for masses above 90 and that it has an astrophysical justification in terms of pulsed He-shell burning (e.g. Ulrich, 1982). Our model, on the other hand, preserves to the maximum extent the well-established s- and r-process abundance peaks of the $N=82$ and 126 regions, at the $N=50$ shell. Differentiation between these or other models ultimately can probably only be accomplished by adequate understanding of the range of consequences of He burning stages in evolved stars. However, in principle our model could be invalidated if the required PSI structure, especially the rise at masses 82–84, could be shown to be theoretically impossible. In general it may be that focusing on "fine structure" features in the solar system abundances, as we have done here, e.g. in Fig. 3, can provide additional constraints on the most probable out of a very wide range of theoretical astrophysical possibilities. Ironically, if unique nucleosynthetic interpretations can be found, it could be the deviations from smoothness in the solar system abundance curve that are the most important.

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References

Anders, E.: 1971, *Geochim. Cosmochim. Acta* **35**, 516
Anders, E., Ebihara, M.: 1982, *Geochim. Cosmochim. Acta* **46**, 2363
Anders, E.: 1988, in *Meteorites and the Early Solar System*, eds. J. Kerridge, M.S. Matthews, Univ. Arizona Press, Tuscon
Anders, E., Grevesse, N.: 1988, *Geochim. Cosmochim. Acta* **53**, 197, 1989
Bao, Z.Y., Käppeler, F.: 1987, *Atomic Data and Nuclear Data Tables* **36**, 411
Beer, H.: 1985, in *Nucleosynthesis and its implications on nuclear and particle physics*, eds. J. Audouze, N. Mathieu, Reidel, Dordrecht, p. 263

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1990A&A...228..253B

Beer, H., Walter, G.: 1984, *Astron. Astrophys.* **133**, 317

Burnett, D.S., Woolum, D.S., Benjamin, T.M., Rogers, P.S.Z., Duffy, C.J., Maggiore, C.: 1989, *Geochim. Cosmochim. Acta* **53**, 471

Hartmann, D., Woosley, S.E., El Eid, M.F.: 1985, *Astrophys. J.* **297**, 837

Käppeler, F., Beer, H., Wisshak, K., Clayton, D.D., Macklin, R.L., Ward, R.A.: 1982, *Astrophys. J.* **257**, 821

Kratz, K.-L.: 1988, *Rev. Modern Astronomy* **1**, 184

Marti, K., Suess, H.: 1988, *Astrophys. Space Sci.* **149**, 507

Ott, U., Begemann, F., Yang, J., Epstein, S.: 1988, *Nature* **332**, 700

Papanastassiou, D.A.: 1986, *Astrophys. J. Letters* **308**, L27

Seeger, P.A., Fowler, W.A., Clayton, D.D.: 1965, *Astrophys. J. Suppl.* **11**, 121

Suess, H.: 1947, *Z. Naturforsch.* **2a**, 311, 604

Ulrich, R.K.: 1973, in *Explosive Nucleosynthesis*, eds. D.N. Schramm, W.D. Arnett, Univ. Texas Press, Austin, p. 139

Ulrich, R.K.: 1982, in *Essays in Nuclear Astrophysics*, eds. C.A. Barnes, D.D. Clayton, D.N. Schramm, Cambridge Univ. Press, Cambridge, p. 301

Ward, R.A., Newman, M.J., Clayton, D.D.: 1976, *Astrophys. J. Suppl.* **31**, 33

Walter, G., Beer, H., Käppeler, F., Reffo, G., Fabbri, F.: 1986, *Astron. Astrophys.* **167**, 186

Woolum, D.S.: 1988, in *Meteorites and the early solar system*, eds. J. Kerridge, M.S. Matthews, Univ. Arizona Press, Tuscon, Chap. 14.1

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