THE HEAVY ELEMENT YIELDS OF NEUTRON CAPTURE NUCLEOSYNTHESIS

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Abstract. An effort has been made to determine the contributions of the S- and R-processes of nucleosynthesis to the abundances of the heavy element isotopes. It has been concluded that the general previous assumption concerning the exclusive assignment of isobars to one or the other of these processes is probably in error. The R-process abundances are characterized by relatively small fluctuations in the abundances of odd and even mass numbers. If this is always true, and such is assumed here, then there are substantial S-process contributions to the abundances of 'R-process' isobars. This is consistent with transient flashing episodes in the S-process neutron production processes. The primary tool for the separation of the abundances due to the two processes therefore had to be achievement of a reasonably smooth and monotonically-decreasing curve of the abundance of the S-process yields times the neutron capture cross-sections versus mass number. Tables of the separate yields are given.

1. Introduction

For a number of years, in the process of preparing elemental abundance tables (see Cameron, 1973, 1981, for recent examples), I have made approximate classifications of the isotopes to one or more production processes. In the course of doing this, I have always assigned isobars of the same mass number separately to the S- and R-processes, provided both could be formed by neutron capture. The general shape of the S- and R-process yield curves which I then obtained, were heavily influenced by the abundances of these isobars thus assigned. A good account of the history of investigations of the S- and R-processes is given by Trimble (1975).

Recently, together with some colleagues, I have been studying R-process mechanisms in a variety of astrophysical scenarios. Recent results obtained by us (Cowan *et al.*, 1981) suggest that the R-process may take place in ordinary stars as well as, or instead of, in supernova explosions. This result has observational consequences. Many evolved stars contain enhancements of heavy element abundances, and it is necessary to ask whether any of these stars could be exhibiting R-process enhancements. I started the work reported in this paper in order to provide observers with better predictions of the yields due to both S- and R-processes. However, the results proved to be more extensively interesting than I had anticipated.

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2. Procedure

The source of the elemental and isotopic abundance data used in the present work was the paper of Cameron (1981). The first task was to refine the criteria to be used for the separation of the S- and R-process yields.

It has been noticed for a long time, and I have frequently commented on the fact, that the odd-even effect in the abundances is greatly reduced in heavy element regions where the R-process is dominant. This is the fluctuation in abundance of adjacent nuclides of odd and even mass number. This may be seen in the gross abundance curve near mass numbers 104, 130, 165, and 195.

A fairly large odd-even effect is characteristic of the S-process. This arises in the fact that the even mass number isotopes of even atomic number have zero spin, whereas the odd mass number isotopes of both odd and even atomic number have spins appreciably greater than zero. Neutron capture in the S-process predominantly involves incident s-waves and p-waves, with smaller contributions from d-waves, so that the spins of the states excited in the compound nucleus tend to differ little from the spin of the target nucleus. The neutron capture cross-sections vary approximately as $(2J + 1)$, where J is the spin of the compound nucleus state populated. It follows that the cross-sections of odd mass number nuclei are systematically higher than those of even-even nuclei, and hence in a steady-flow situation such as in the S-process the abundances of the odd mass numbers are systematically less than those of the even mass numbers, typically by a factor of three or so.

In the R-process the nuclei are displaced appreciably to the neutron-rich side of the valley of beta stability. The argument given above assures that these nuclei will exhibit the odd-even effect along their neutron capture paths. In fact, should photodisintegration play a significant role in establishing the R-process capture path, as in the classical R-process, then an even more powerful odd-even effect on the abundances will come into play, since the photodisintegration energy threshold for even-even nuclei is greater than that for odd nuclei, and the photodisintegration rates are very sensitive to these energy thresholds.

The great diminution in the odd-even effect in the final frozen R-process abundances must therefore represent some process that occurs during the freezing at the end of the R-process, when the neutron flux is terminated. Such an effect occurs due to the small values of the neutron binding energies of nuclei in the region of the R-process capture path, together with the large values of the beta decay energies for those nuclei. This means that, following beta decay which may leave the daughter nucleus in a highly excited state, one, two, or three neutrons may be emitted in the deexcitation of the daughter nucleus. This smooths out the abundances over neighboring mass numbers.

One may conclude from the persistence of the diminished odd-even effect in the final R-process abundances that the supply of neutrons in the R-process is drastically reduced before or during the period of neutron emission following beta decay; even the neutrons emitted must be soaked up by sinks elsewhere, for otherwise any appreciable residual neutron capture once the nuclei have reached the vicinity of the valley of beta stability would reestablish the odd-even effect.

From this discussion it may be concluded that if the R-process abundances demonstrate a small odd-even effect in the range of mass numbers where their abundances are dominant, then it must be expected that the odd-even effect will be small everywhere for this process.

However, the traditional classification of neutron-capture-formable even mass number isobars as S-process or R-process only is inconsistent with the above conclusion. The abundances of some of the 'R-process' isobars greatly exceed the abundances of the preceding odd mass number nuclides which will have been formed by both S- and R-processes. This led me to question the validity of the traditional classification of these isobars.

This questioning undoubtedly should have been done long ago. Discussions of the S-process in recent years have begun to find somewhat complicated astrophysical scenarios in which the neutron production and capture may take place. For example, Truran and Iben (1977) have discussed a cycled S-process involving the burning of ^{22}Ne in helium shell flashes, which is very successful in reproducing the general trend of solar system S-process abundances. When the neutron production occurs in pulses in that way, one must expect that the mean time between neutron captures during the peak neutron flux period will frequently become less than the beta decay lifetimes along what is considered to be the traditional S-process capture path. Under these circumstances the S-process capture path will often pass through nuclei which have traditionally been thought to be R-process products. If the neutron flux decreases very rapidly following such an episode, then a residual amount of yield may remain in the R-process positions.

Once this conclusion had been reached, it followed that I could no longer use the even mass number isobars as a guide to the separation of the S- and R-process product yields. Instead, the separation of these two yield curves was based on the following two principles:

(1) The R-process curve should have a small odd-even abundance fluctuation everywhere.

(2) The S-process abundances should be consistent with a smooth and monotonically-decreasing curve in which the product of the S-process abundance N and its neutron capture cross-section σ is plotted against mass number.

This smooth monotonically-decreasing behavior of the product $N\sigma$ has been recognized for a long time as a characteristic feature of the S-process which provides experimental support for the general validity of the interpretation of this mechanism of nucleosynthesis. The test has always been only an approximate one owing to the uncertainties in both abundances and cross-sections. Figure 13 in Trimble (1975) shows the state of the art as of 1973.

It is not *a priori* obvious that the above two principles should be mutually consistent. In fact, I have been able to subdivide the nuclidic abundances given in Cameron (1981) into S- and R-process contributions in which each of the above two principles is reasonably satisfied.

In using the $N\sigma$ criterion I have used for the most part 30 keV neutron capture cross-section data from the table of Holmes *et al.* (1976), supplemented for nuclei near mass number 70 with data from Woosley *et al.* (1978). For each mass number a nucleus was chosen on the traditional S-process capture path along the valley of beta stability. Since contributions due to the S-process are here, by postulation, also coming from other nuclei at each mass number, the process adopted was necessarily crude and approximate, but to do better would require a detailed dynamical analysis of the S-process. Also for this same reason I did not attempt to use experimental neutron capture cross-sections in place of any of the Holmes *et al.* (1976) values, since the uncertainties did not seem to warrant this refinement.

In the course of adjusting the $N\sigma$ curve, it became obvious that two of the elemental abundances used in Cameron (1981) were badly in need of modification:

(1) The abundance of tungsten was decreased by a factor of two. In Cameron (1981) the abundance of W is based on a single measurement in C1 carbonaceous meteorites, which is twice as great as the values measured in other carbonaceous meteorites (see Mason, 1979). Tungsten is a strongly siderophile element. Other siderophile elements in the same part of the periodic table do not show enhanced abundances in C1 meteorites relative to other carbonaceous meteorites. Therefore, from a cosmochemical point of view, the downward adjustment in the tungsten abundance is reasonable.

(2) The abundance of mercury was increased by a factor of two. The measured abundances of this element in carbonaceous meteorites are so unreliable, that in the latest abundance table (Cameron, 1981), I gave up trying to base an abundance on this data and simply did a crude interpolation of the abundance of this element between its neighbors. The present procedure is a more sensitive tool for making this interpolation.

Before attempting to separate the isotopic abundances into S- and R-process contributions, I subtracted from the apparent S-process contributions the P-process abundances. These are known in detail only for the even mass number P-process isobars. The P-process contributions to intervening even mass numbers were estimated by simple logarithmic interpolation. The P-process contributions to odd mass numbers are not known but are expected to be very small. These adjustments were sufficiently small that they had no practical effect on the procedures described here.

3. Results

Figure 1 shows the resulting curves for the S-process and the R-process yields from mass number 70 upwards. There is no difficulty in seeing which is the

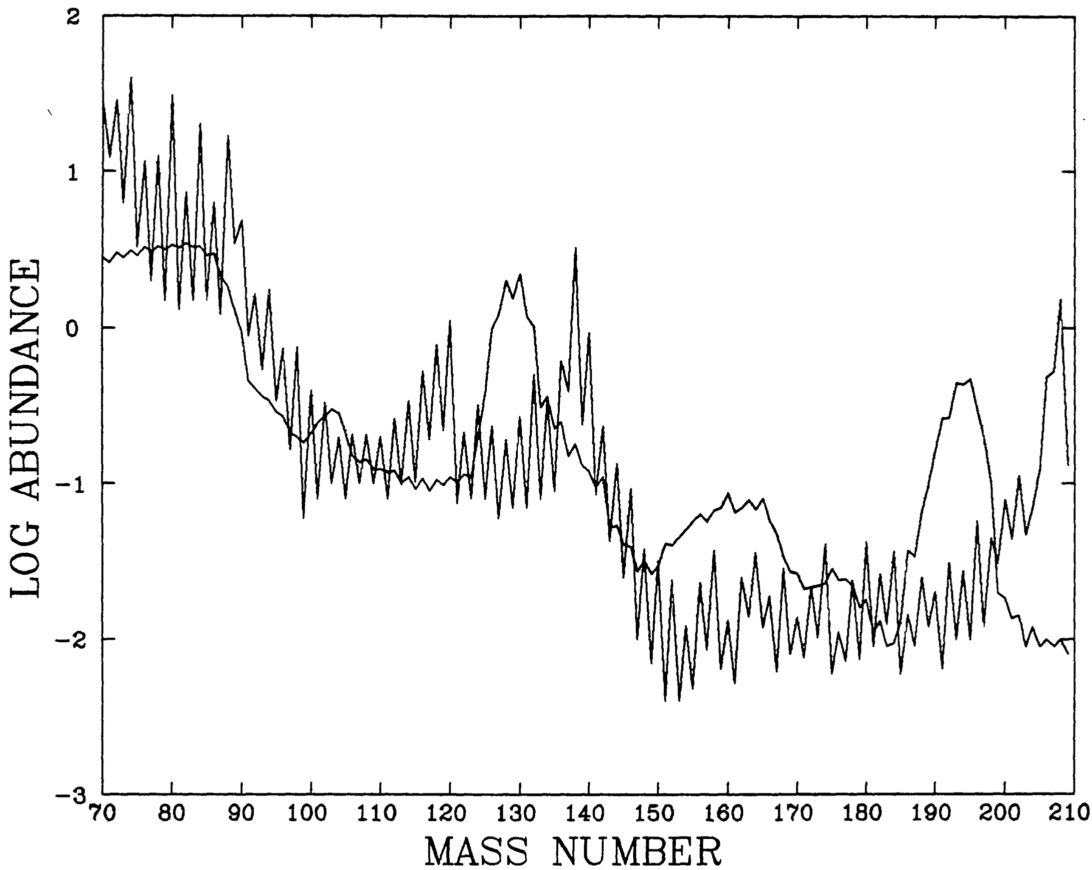

Fig. 1. The S- and R-process abundances plotted as a function of mass number. The curve exhibiting little odd-even fluctuations is due to the R-process, that exhibiting pronounced odd-even fluctuations is due to the S-process. The abundances are normalized to silicon = 10^6.

R-process curve (very little odd-even effect) and the S-process curve (pronounced odd-even effect).

Figure 2 shows the finally adopted $N\sigma$ curve. This is very much smoother and more successfully monotonically-decreasing than the curve obtained after my initial trial separation of the two classes of abundances. I do not believe that the remaining fluctuations in the curve exceed the uncertainties in the cross-sections, the uncertainties in the elemental abundances, and the uncertainties due to the contributions of more than one nucleus to the S-process yields at each mass number.

Figure 3 shows the elemental abundances separately due to the S- and R-processes. This is the diagram that will be of potential interest to observers interested in separating the effects of the two processes in stellar spectra with enhanced heavy element abundances. The S-process contributions are shown by open symbols and the R-process contributions are shown by filled symbols. It will be apparent from this diagram that it is not as easy as is usually assumed to separate the elements into S and R classes which belong predominantly to one or the other of the two processes. Rather careful abundance determinations of carefully selected elements will be needed for the unambiguous classification of a stellar spectrum as S-process or R-process enhanced.

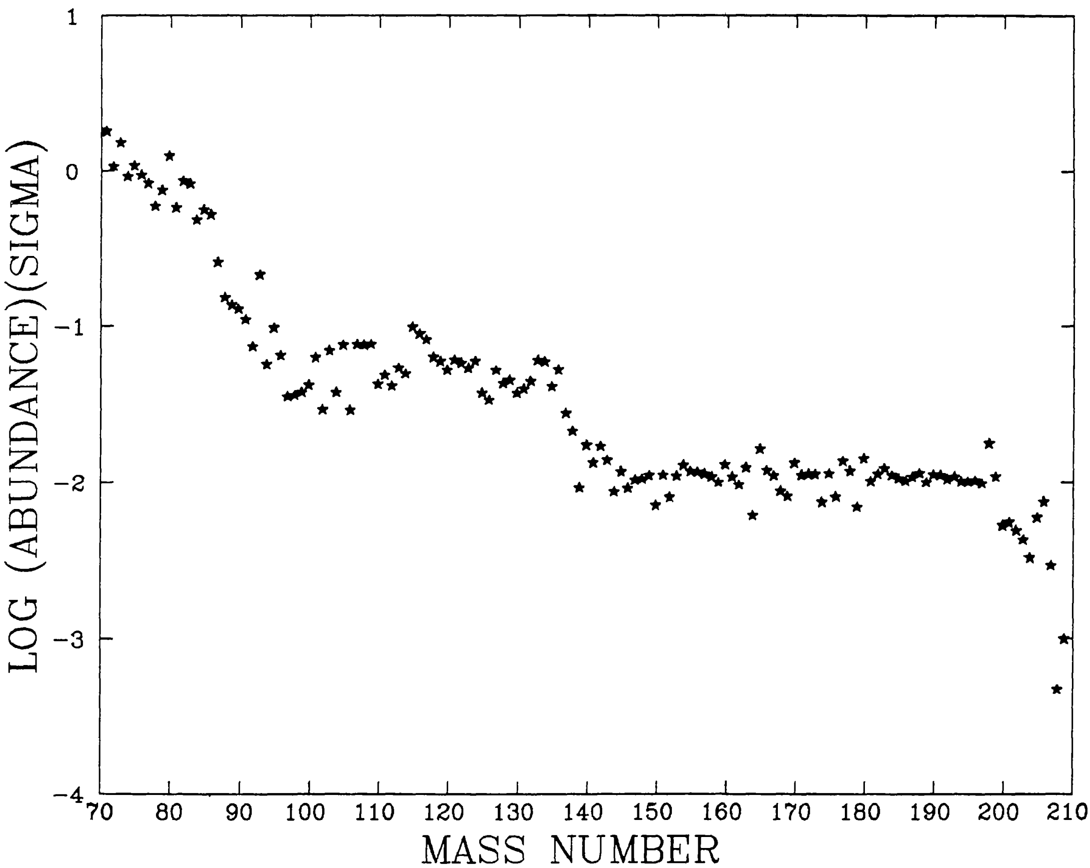

Fig. 2. The plot of $N\sigma$ as a function of mass number.

More precise details of the contributions of the S- and R-processes to elemental and isotopic abundances are given in Tables I and II. Table I gives the elemental abundances and Table II gives the isotopic abundances. Not given are the P-process contributions, either those known explicitly in the form of even mass number isobars that cannot be formed by neutron capture or the interpolated P-process abundances which were subtracted from the S-process abundances for mass numbers not so shielded from P-process product decay. The P-process abundances can be obtained or inferred if necessary from the data in Cameron (1981).

Table II contains another set of quantities of potential interest. The traditional 'R-process' isobars are here split into both S- and R-process contributions. These separations may be of some statistical value in estimates of the dynamics of the S-process. However, it is necessary to caution that the S-process yields of these isobars represent relatively small differences between larger numbers which themselves have significant probable errors, so that these numbers should be used for this purpose only with suitable restraint.

The details of these abundances may also be of interest to gamma-ray astronomy, where the question arises as to whether supernova remnants are

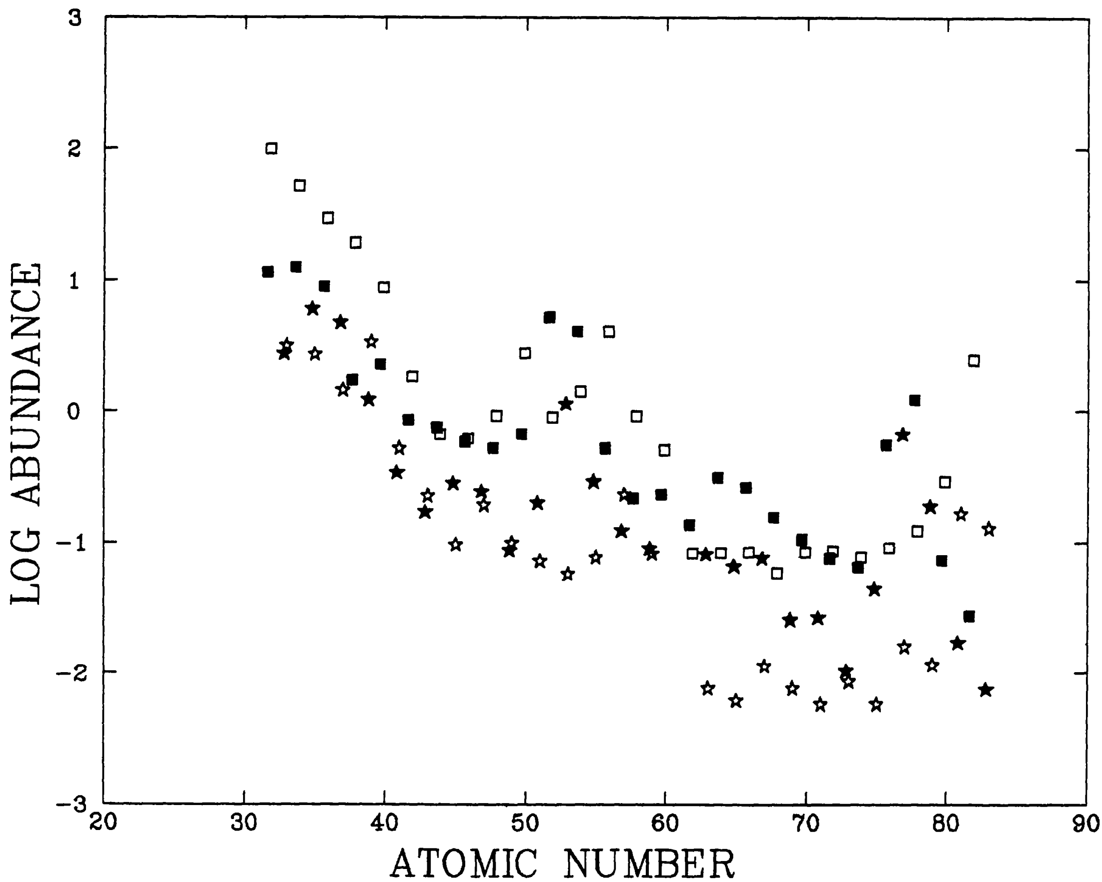

Fig. 3. The abundances of the various elements produced by the S- and R-processes. Open symbols represent the S-process and filled symbols represent the R-process. Squares represent even atomic numbers and stars represent odd atomic numbers. The filled symbols are displaced slightly to the left to clarify overlapping situations.

TABLE I

The contributions of the S- and R-processes to elemental abundances.

Element		R		Element		R		Element		R	
32	Ge	103.13	12.18	49	In	0.103	0.092	67	Ho	0.0118	0.0802
33	As	3.3	2.9	50	Sn	2.8906	0.717	68	Er	0.0614	0.1643
34	Se	53.71	13.28	51	Sb	0.075	0.212	69	Tm	0.008	0.027
35	Br	2.8	6.4	52	Te	0.9354	5.581	70	Yb	0.0875	0.1116
36	Kr	30.515	9.56	53	I	0.06	1.21	71	Lu	0.006	0.0281
37	Rb	1.5	5.02	54	Xe	1.4843	4.347	72	Hf	0.09	0.0803
38	Sr	20.07	1.83	55	Cs	0.08	0.31	73	Ta	0.009	0.011
39	Y	3.5	1.3	56	Ba	4.2307	0.556	74	W	0.0806	0.0687
40	Zr	9.17	2.42	57	La	0.24	0.13	75	Re	0.006	0.0467
41	Nb	0.54	0.36	58	Ce	0.9586	0.23	76	Os	0.0947	0.5907
42	Mo	1.916	0.913	59	Pr	0.085	0.095	77	Ir	0.0165	0.7035
43	Tc	0.235	0.182	60	Nd	0.5313	0.248	78	Pt	0.1268	1.3035
44	Ru	0.699	0.798	62	Sm	0.0855	0.1444	79	Au	0.012	0.198
45	Rh	0.1	0.3	63	Eu	0.008	0.0859	80	Hg	0.304	0.0776
46	Pd	0.648	0.625	64	Gd	0.087	0.3314	81	Tl	0.1721	0.018
47	Ag	0.2	0.26	65	Tb	0.0064	0.0696	82	Pb	2.5702	0.029
48	Cd	0.955	0.557	66	Dy	0.0881	0.2806	83	Bi	0.132	0.008

TABLE II

The contributions, organized by element, to each mass number from the S- and R-processes

Element	A	S	R	Element	A	S	R	Element	A	S	R
Ge 32	70	23.0			117	0.192	0.09		161	0.0052	0.0647
	72	28.35	3.0		118	0.7746	0.105		162	0.025	0.0695
	73	6.28	2.8		119	0.22	0.097		163	0.014	0.0784
	74	39.7	3.1		120	1.11	0.11		164	0.0357	0.068
	76	5.8	3.28		122	0.06	0.115	Ho 67	165	0.0118	0.0802
As 33	75	3.3	2.9		124	0.02	0.2	Er 68	166	0.0187	0.0578
Se 34	76	5.75		Sb 51	121	0.075	0.102		167	0.0062	0.0465
	77	2.0	3.08		123		0.11		168	0.0285	0.0338
	78	12.5	3.3	Te 52	122	0.1524			170	0.008	0.0262
	80	30.8	3.4		123	0.081		Tm 69	169	0.008	0.027
	82	2.66	3.5		124	0.299		Yb 70	170	0.0058	
Br 35	79	1.5	3.15		125	0.08	0.374		171	0.0076	0.021
	81	1.3	3.25		126	0.233	0.987		172	0.0217	0.0216
Kr 36	82	4.635			128	0.07	2.0		173	0.0103	0.022
	83	1.5	3.27		130	0.02	2.22		174	0.0407	0.023
	84	20.18	3.32	I 53	127	0.06	1.21		176	0.0015	0.024
	86	4.2	2.97	Xe 54	128	0.1213		Lu 71	175	0.006	0.0281
Rb 37	85	1.5	2.9		129	0.07	1.54	Hf 72	176	0.0096	
	87		2.12		130	0.25			177	0.0072	0.0243
Sr 38	86	2.07			131	0.07	1.18		178	0.0239	0.022
	87	1.21			132	0.503	1.017		179	0.0074	0.016
	88	16.79	1.83		134	0.23	0.36		180	0.0419	0.018
Y 39	89	3.5	1.3		136	0.24	0.25	Ta 73	181	0.009	0.011
Sr 40	90	4.82	0.94	Cs 55	133	0.08	0.31	W 74	182	0.026	0.0131
	91	0.89	0.46	Ba 56	134	0.1127			183	0.0125	0.0091
	92	1.64	0.41		135	0.09	0.226		184	0.0365	0.0095
	94	1.75	0.34		136	0.375			186	0.0056	0.037
	96	0.07	0.27		137	0.393	0.15	Re 75	185	0.006	0.0129
Nb 41	93	0.54	0.36		138	3.26	0.18		187		0.0338
Mo 42	95	0.339	0.29	La 57	139	0.24	0.13	Os 76	186	0.0088	
	96	0.661		Ce 58	140	0.9356	0.12		187	0.0091	
	97	0.165	0.213		142	0.023	0.11		188	0.0248	0.0667
	98	0.751	0.2	Pr 59	141	0.085	0.095		189	0.012	0.099
	100		0.21	Nd 60	142	0.2083			190	0.02	0.162
Tc 43	99	0.06	0.182		143	0.0431	0.053		192	0.02	0.263
	100	0.175			144	0.134	0.054	Ir 77	191	0.0065	0.2625
Ru 44	100	0.219			145	0.025	0.0406		193	0.01	0.441
	101	0.08	0.244		146	0.0927	0.039	Pt 78	192	0.0108	
	102	0.33	0.271		148	0.0132	0.032		194	0.0271	0.4365
	104	0.07	0.283		150	0.015	0.0294		195	0.01	0.467
Rh 45	103	0.1	0.3	Sm 62	147	0.01	0.0271		196	0.057	0.3
Pd 46	104	0.128			148	0.0245			198	0.022	0.1
	105	0.08	0.209		149	0.007	0.0262	Au 79	197	0.012	0.198
	106	0.205	0.15		150	0.0165		Hg 80	198	0.0224	
	108	0.205	0.142		152	0.024	0.0401		199	0.031	0.0198
	110	0.03	0.124		154	0.0035	0.051		200	0.0787	0.0182
Ag 47	107	0.1	0.136	Eu 63	151	0.004	0.0409		201	0.044	0.0136
	109	0.1	0.124		153	0.004	0.045		202	0.1109	0.0142
Cd 48	110	0.17		Gd 64	154	0.0086			204	0.017	0.0118
	111	0.08	0.118		155	0.0048	0.0571	Tl 81	203	0.0471	0.009
	112	0.26	0.122		156	0.023	0.063		205	0.125	0.009
	113	0.098	0.1		157	0.0086	0.0573	Pb 82	204	0.0512	
	114	0.337	0.11		158	0.037	0.067		206	0.48	0.01
	116	0.01	0.107		160	0.005	0.087		207	0.527	0.009
In 49	115	0.103	0.092	Tb 65	159	0.0064	0.0696		208	1.512	0.01
Sn 50	116	0.514		Dy 66	160	0.0082		Bi 83	209	0.132	0.008

likely to emit gamma-rays from R-process products, and in cosmic ray astrophysics, where the issue of the assignment of the abundances of the heaviest cosmic rays predominantly to a single production process has probably been made more difficult by this work.

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