ORIGIN OF THE ELEMENTS

1957 - Annus mirabilis

Burbidge, Burbidge, Fowler & Hoyle 1957 Reviews of Modern Physics

Cameron 1957 PASP and unpublished Purdue lecture notes as a Chalk River Report

ORIGINS OF THE ELEMENTS

B2FH

Hydrogen assumed to be the building block
  proton is stable
  H is most abundant elements

Stars are the dominant sites of nucleosynthesis

`element synthesis in a primordial explosive stage of the universe'?
`no evidence for this'

Emphasis of paper on theoretical discussion of nucleosynthesis with few calls for confirmation from stellar abundances (little data then available!)

`progressive conversion of light nuclei into heavier ones as temperature rises' in a star as gravity compresses a star as a fuel runs out

neutron capture synthesis essential beyond the Fe-group
  -- a slow (s) process
  -- a rapid (r) process

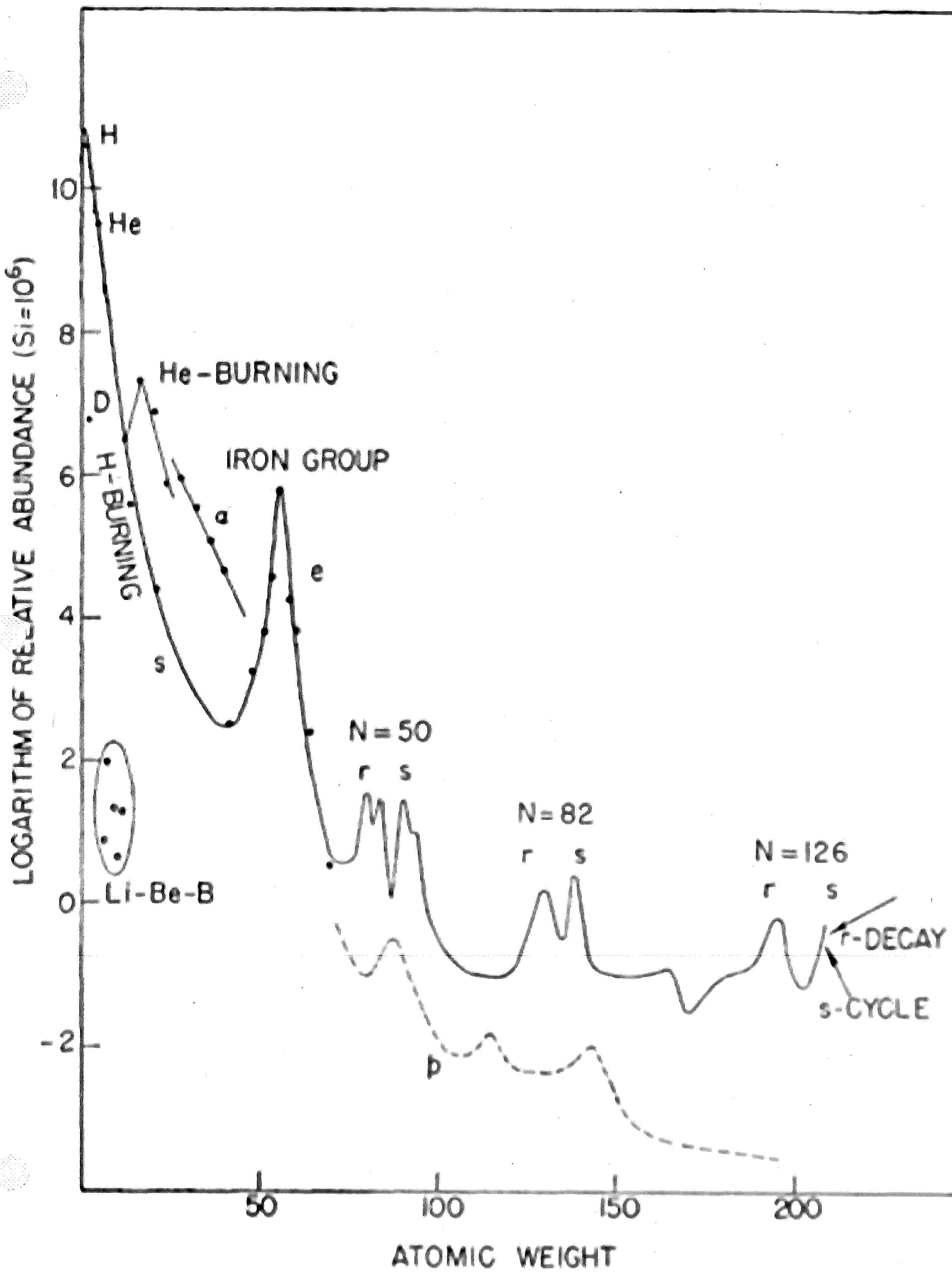
ORIGINS OF THE ELEMENTS

B2FH's suite of processes

H burning
He burning
alpha process
e process
r process
s process
p process
x process

H- burning via pp chain and CNO cycles

He-burning via Triple alpha-process --> C-12 and O-16



LOGARITHM OF RELATIVE ABUNDANCE (Si=10⁶)
ATOMIC WEIGHT
10
8
6
4
2
0
-2
50
100
150
200
H
He
D
He-BURNING
H-BURNING
IRON GROUP
a
e
s
Li-Be-B
N=50
r
s
N=82
r
s
N=126
r
s
r-DECAY
s-CYCLE
p

Feature	Cause
Exponential decrease from hydrogen to $A \sim 100$	Increasing rarity of synthesis for increasing A, reflecting that stellar evolution to advanced stages necessary to build high A is not common.
Fairly abrupt change to small slope for $A > 100$	Constant $\sigma(n,\gamma)$ in s process. Cycling in r process.
Rarity of D, Li, Be, B as compared with their neighbors H, He, C, N, O	Inefficient production, also consumed in stellar interiors even at relatively low temperatures.
High abundances of alpha-particle nuclei such as O^{16}, $Ne^{20} \cdots Ca^{40}$, Ti^{48} relative to their neighbors	He burning and α process more productive than H burning and s process in this region.
Strongly-marked peak in abundance curve centered on Fe^{56}	e process; stellar evolution to advanced stage where maximum energy is released (Fe^{56} lies near minimum of packing-fraction curve).
Double peaks $A = 80, 130, 196$	Neutron capture in r process (magic $N = 50, 82, 126$ for progenitors).
$A = 90, 138, 208$	Neutron capture in s process (magic $N = 50, 82, 126$ for stable nuclei).
Rarity of proton-rich heavy nuclei	Not produced in main line of r or s process; produced in rare p process.

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B2FH's suite of processes

alpha process

He-burning --> C-12 O-16 and Ne-20 and followed by photodisintegration of Ne-20 --> alphas

and

(alpha, gamma) reactions --> Ne-20, Mg-24, Si-28, S-32, Ar-36, and Ca-40 (alpha elements)

Recognition that `reactions between heavier nuclei' might compete with the alpha-process but competition omitted for lack of information on the cross-sections

Today, alpha-process is known to be ineffective relative to reactions providing C burning, O-burning etc BUT Ne burning - photodisintegration is a key process.

And C-burning etc is fed by `reactions between heavier nuclei', i.e., C-12 + C-12 initiates carbon-burning.

In B2FH's Appendix, the neutron-rich isotopes of `alpha`-nuclei such as Si-29 and Si-30 where Si-28 is the alpha nucleus, are attributed to the neutron capture s-process (that is Si-28 --> Si-29 via a (n,gamma) reaction. And I interpret this to be the same s-process as that which makes Tc in red giants.

This is not today's interpretation. The n-rich isotopes are made primarily in hydrostatic oxygen burning (see our discussion of massive stars) when oxygen burning is accompanied by release of free protons, neutrons and alphas and lots of nuclear reactions between these free particles and the principal products of oxygen burning and the elements accompanying the oxygen. These reactions include (n,gamma) reactions.

Although a series of burning episodes have replaced parts of the alpha-process, the name `alpha' elements has been retained for O (sometimes), Ne, Mg, Si, Ca and even Ti, all elements with their most abundant isotope being a multiple of four.

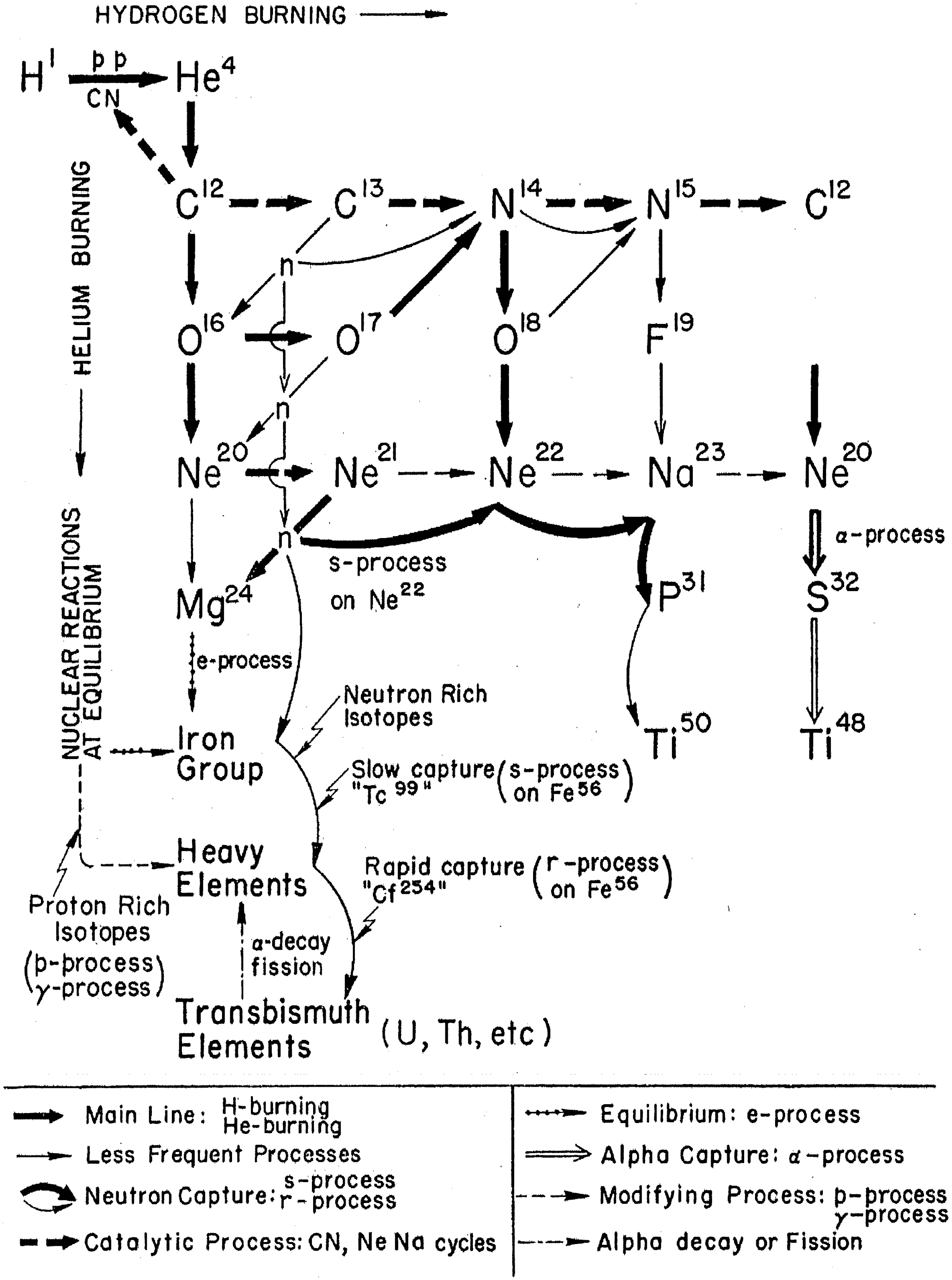

FIG. I,2. A schematic diagram of the nuclear processes by which the synthesis of the elements in stars takes place. Elements synthesized by interactions with protons (hydrogen burning) are listed horizontally. Elements synthesized by interactions with alpha particles (helium burning) and by still more complicated processes are listed vertically. The details of the production of all of the known stable isotopes of carbon, nitrogen, oxygen, fluorine, neon, and sodium are shown completely. Neutron capture processes by which the highly charged heavy elements are synthesized are indicated by curved arrows. The production of radioactive Tc^{99} is indicated as an example for which there is astrophysical evidence of neutron captures at a slow rate over long periods of time in red giant stars. Similarly Cf^{254}, produced in supernovae, is an example of neutron synthesis at a rapid rate. The iron group is produced by a variety of nuclear reactions at equilibrium in the last stable stage of a star's evolution.

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B2FH's suite of processes

The e process

After alpha-process, the core of a (massive) star is made of Fe (the most stable nuclei are near Fe-56)

Core is in statistical equilibrium at high temperature (say 4 billion K)

Can compute abundances from Saha-like equations for a given T, neutron and proton density: timescale for weak interactions which convert n<->p> is too long?

Fitted Fe-group abundances - but Fe solar abundance of by 10!

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Neutron-capture processes

n-capture essential as thermonuclear fusion as an energy supplier ceases at the Fe-group

Signature of s- and r-process clearly present in the standard (cosmic) abundance table

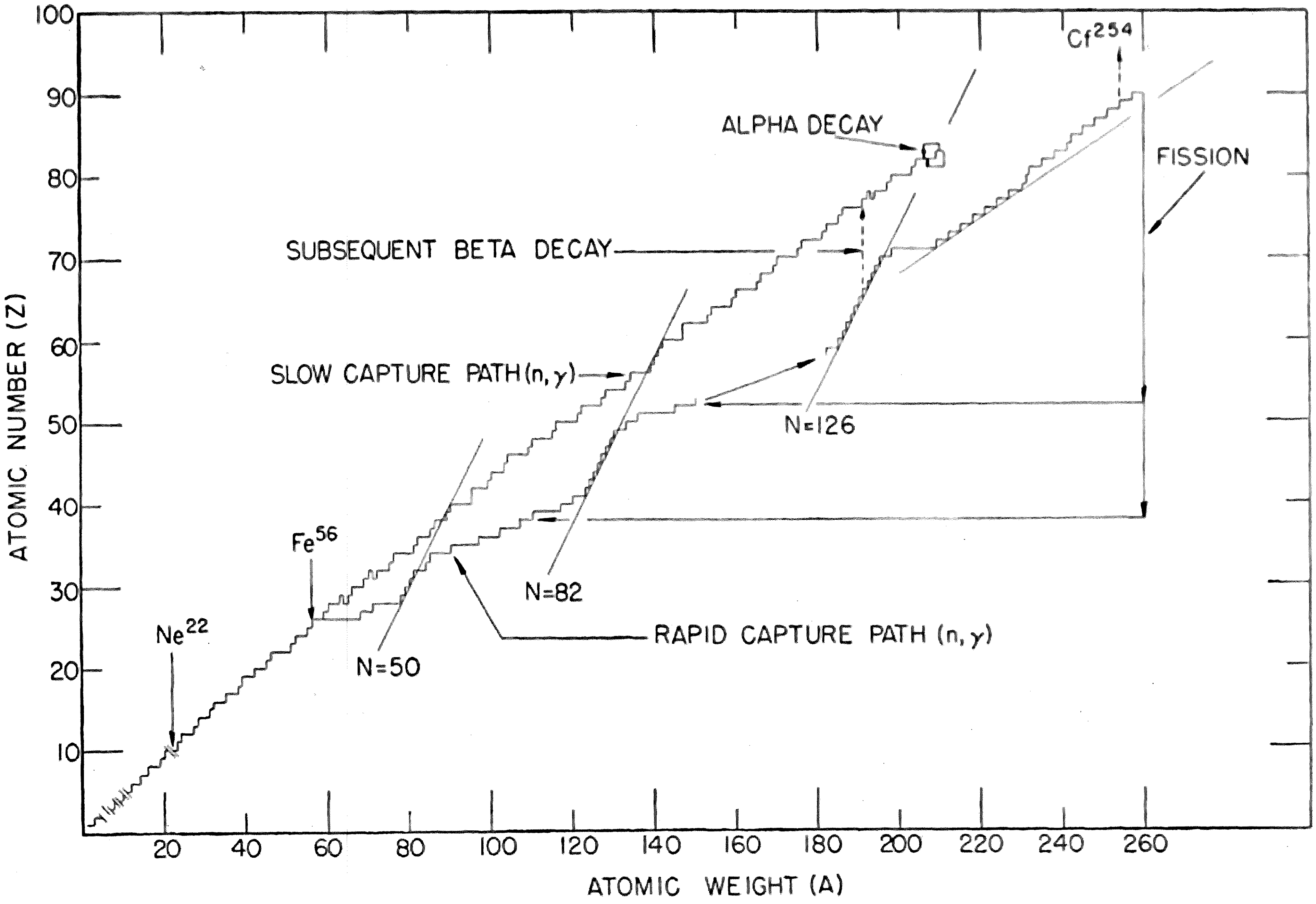
Essence of s- and r-process in the next two figures

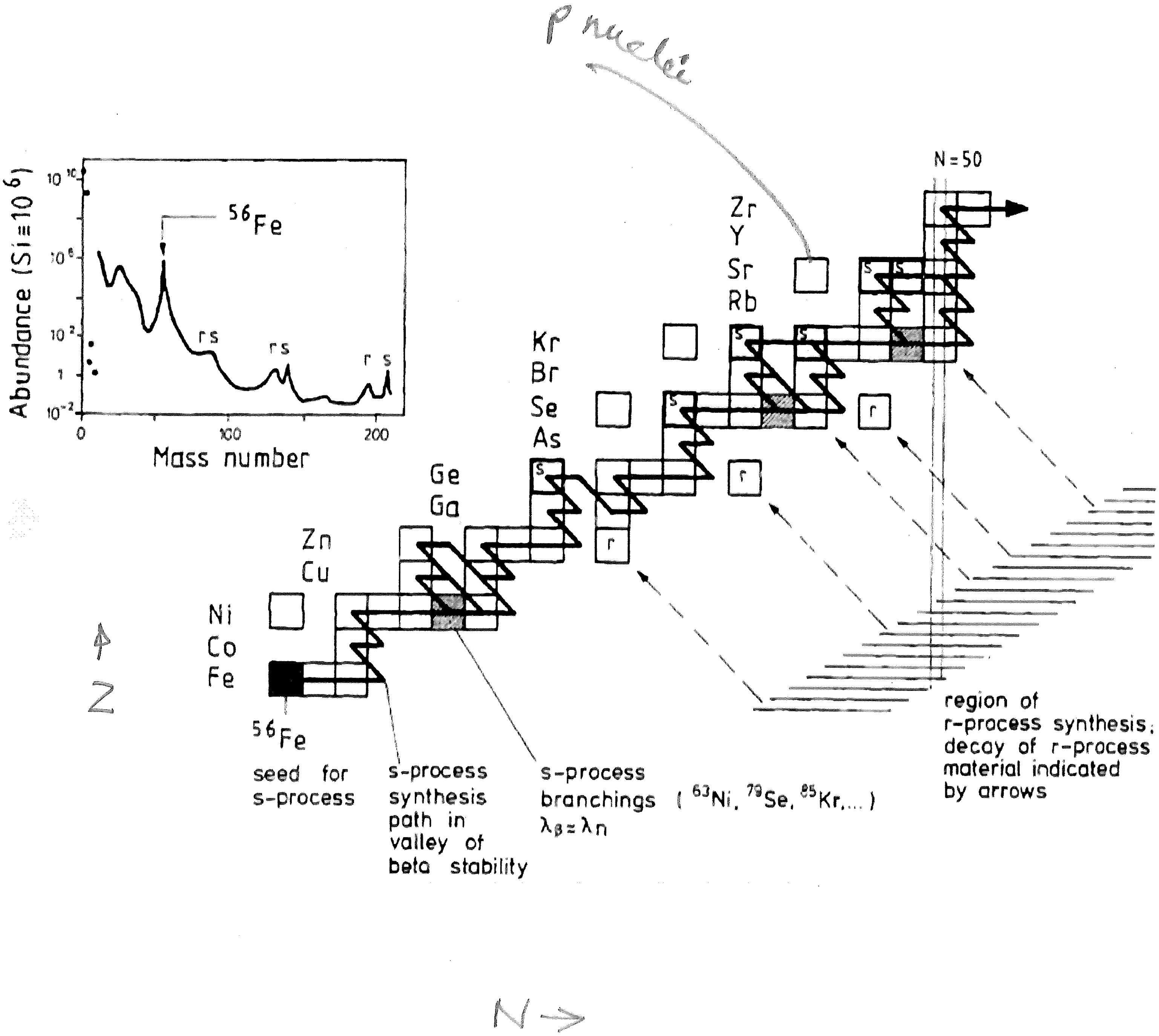
s-PROCESS - expect peak abundance at n magic number where sigma for
                neutron capture is reduced
            expect `smooth' sigma x N vs A relation
            linked with red giants (Tc et al.)

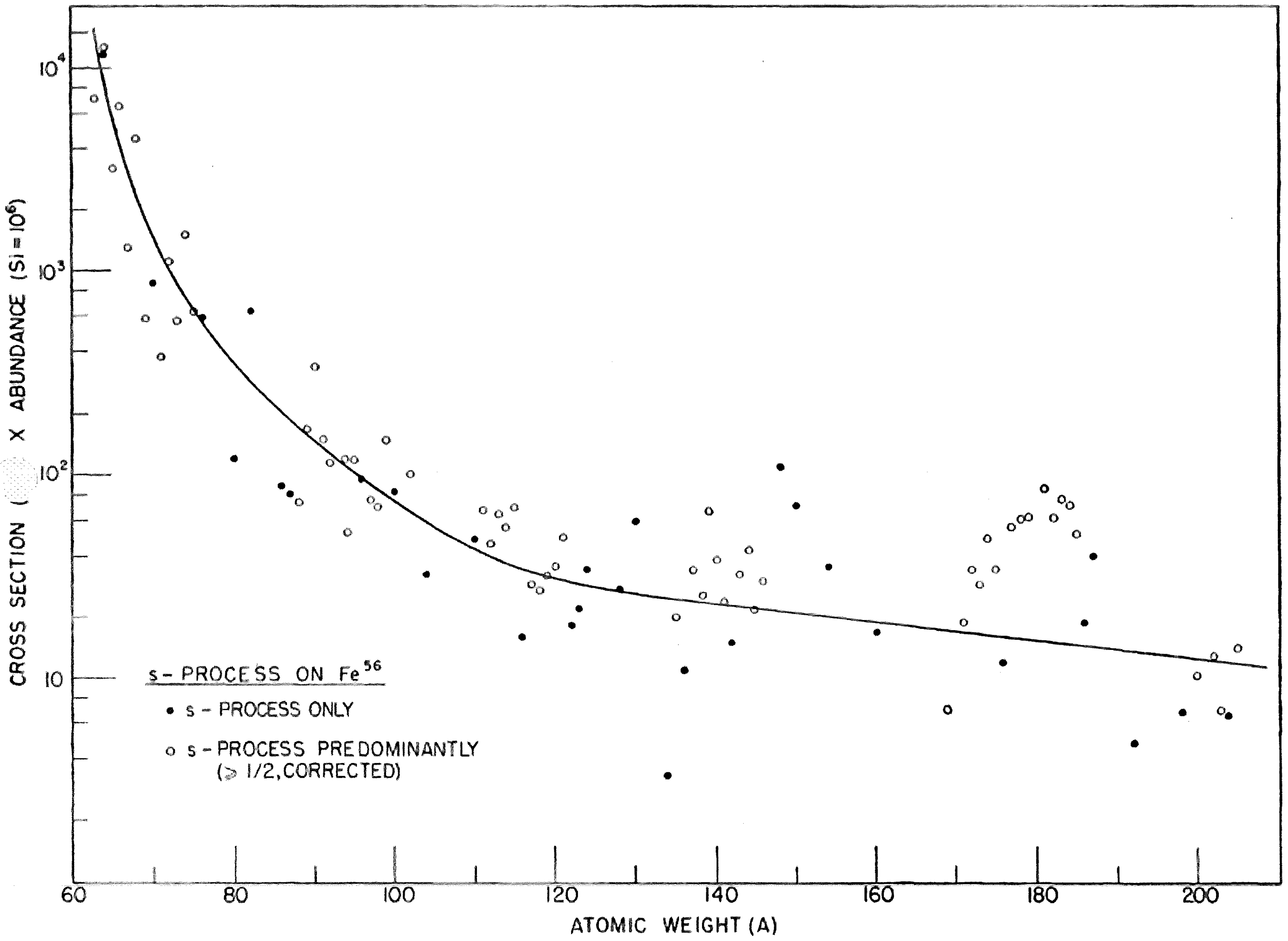
r-PROCESS - far from valley of stability
            quasi-equilbrium flow
            linked with Type I SN (light curve --> Cf-254!)

Discussion of neutron sources

Contrast experimental/theoretical data on nuclei needed for understanding of s and r processes.


100
90
80
70
60
50
40
30
20
10
ATOMIC NUMBER (Z)
20
40
60
80
100
120
140
160
180
200
220
240
260
ATOMIC WEIGHT (A)
Cf^{254}
ALPHA DECAY
FISSION
SUBSEQUENT BETA DECAY
SLOW CAPTURE PATH (n, γ)
N=126
Fe^{56}
N=82
Ne^{22}
RAPID CAPTURE PATH (n, γ)
N=50


Abundance (Si = 10^6)
10^10
10^6
10^2
1
10^-2
0
100
200
Mass number
56Fe
r s
r s
r s
p nuclei
N = 50
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
Ni
Co
Fe
s
r
Z
56Fe
seed for s-process
s-process synthesis path in valley of beta stability
s-process branchings (63Ni, 79Se, 85Kr, ...) λβ ≈ λn
region of r-process synthesis; decay of r-process material indicated by arrows
N →


CROSS SECTION (X ABUNDANCE (Si = 10^6)
10^4
10^3
10^2
10
s - PROCESS ON Fe^{56}
● s - PROCESS ONLY
○ s - PROCESS PREDOMINANTLY ($\geqslant$ 1/2, CORRECTED)
60
80
100
120
140
160
180
200
ATOMIC WEIGHT (A)

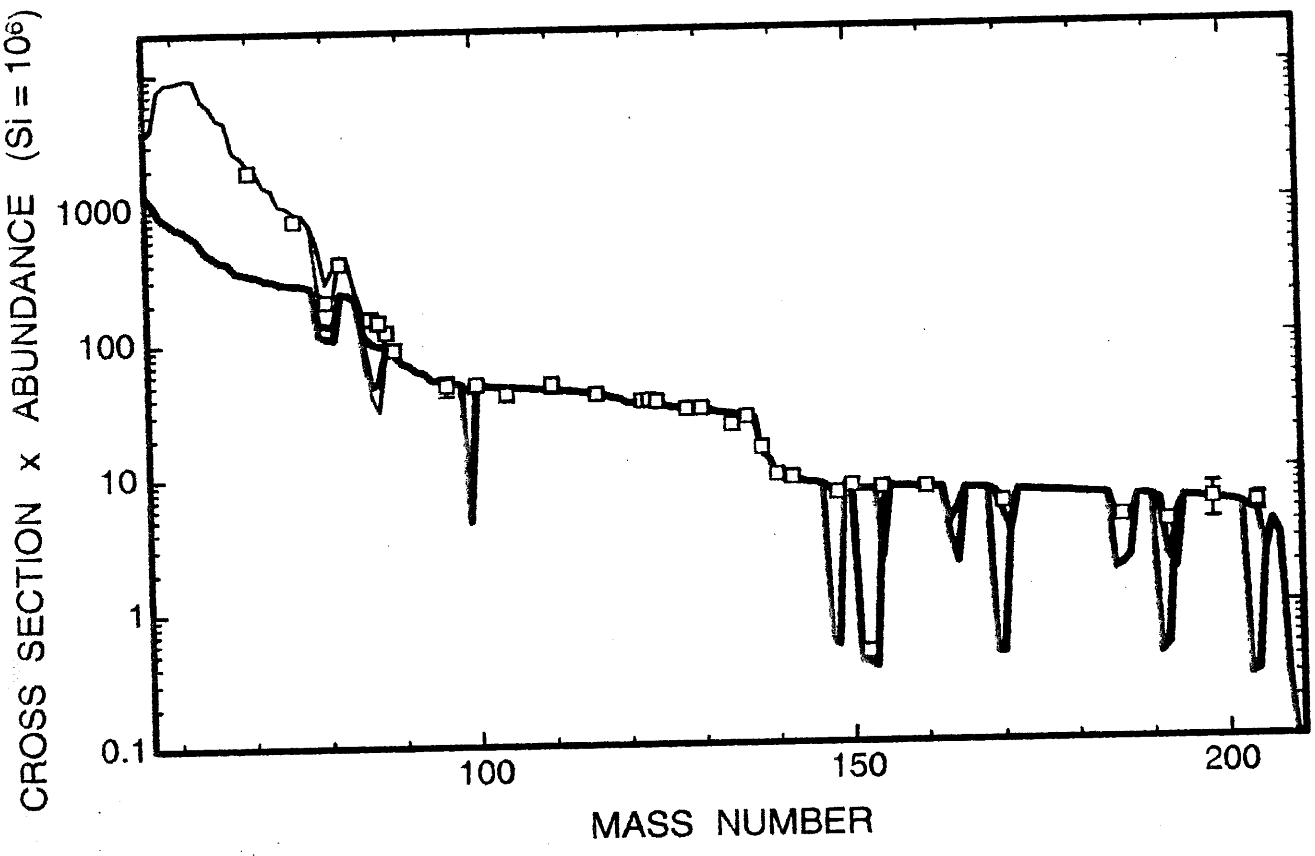


FIG. 2. The characteristic product of cross section times s-process abundance $\langle\sigma\rangle N_s$ plotted as a function of mass number. The thick solid line represents the main component obtained by means of the classical model, and the thin line corresponds to the weak component in massive stars (see text). Symbols denote the empirical products for the s-only nuclei. Some important branchings of the neutron-capture chain are indicated as well.

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r-process ---> SN Ia light curve

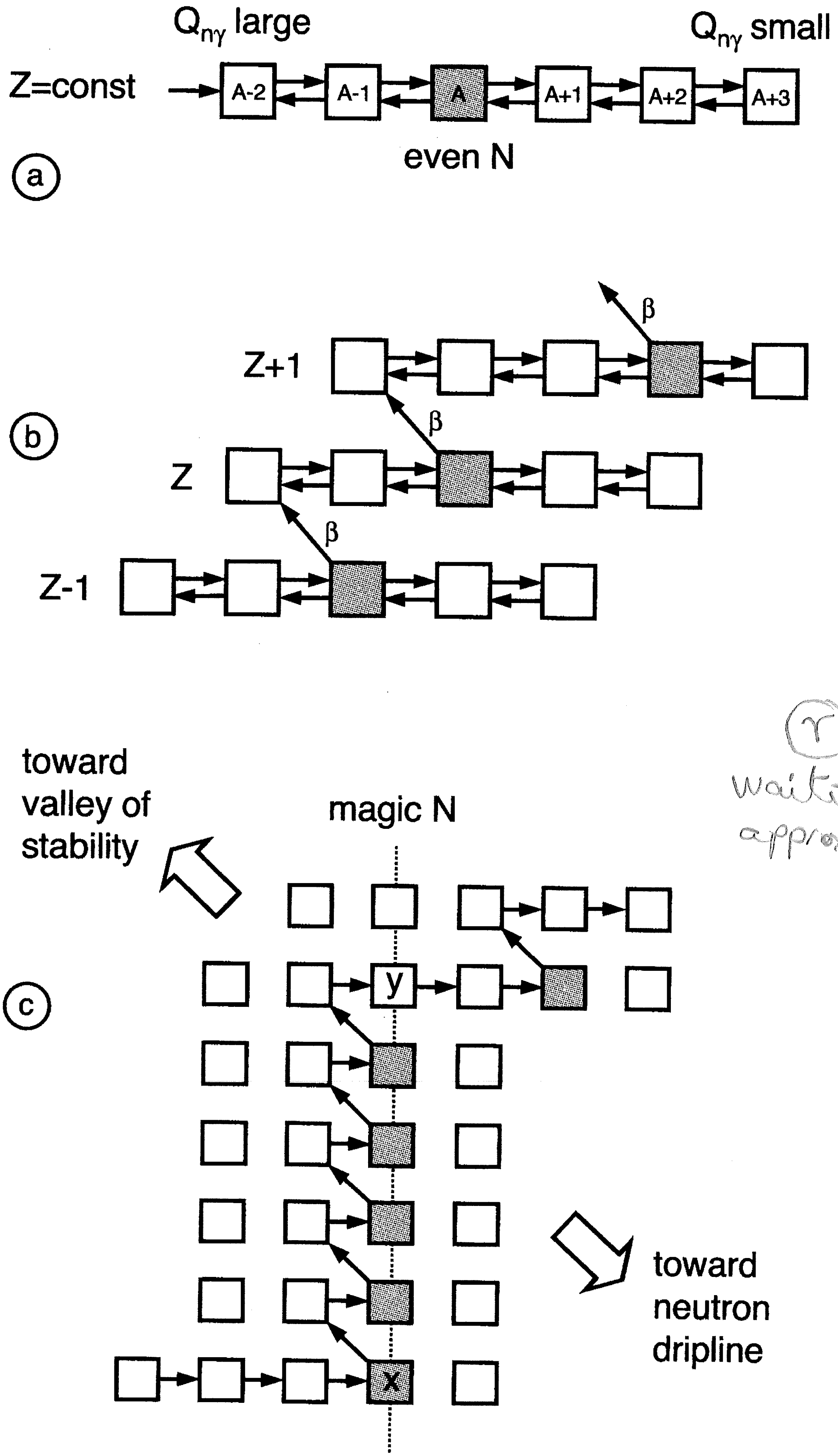
Fig. XII.1 Half-life of SN in IC 4128 = 55 +/- 1 days

- Table VIII.2 for principal radioactive decays
- Fig. VIII.2 for light curve powered by these decays
- NOTE major role of Cf-254 with halflife given as 61 or 56.2 days (60.5 days) [NOW: Ni56--> Co56--> Fe56]

- Nucleocosmochronology
  minimum age of the isotopes of uranium determined to be 6.6 Gyr with uncertainty of 0.6 Gyr and definitely older than age of solar system

Site(s) of r-process still quite uncertain

Nuclear physics of r-process is a theoretical challenge with virtually no experimental checks



(r)
waiting point approx.

capture, the resultant I^{130} decays in 12.6 hr to Xe^{130} which is thus produced in the *s* chain instead of Te^{130}. The isotopes Te^{125}, Te^{126}, and Te^{128} can be produced in either the *s* or the *r* process, although Te^{128} is produced in the slow capture of neutrons only in a weak side link of the chain resulting from the fact that I^{128} decays 5% of the time by positron emission or electron capture. Thus we believe that it is synthesized predominantly by the *r* process. The rarest and lightest isotope Te^{120} cannot be built by either process and it is for this isotope that the *p* process is demanded. Te^{120} is about 1% as abundant, and Te^{122}, Te^{123}, and Te^{124} are about 10% as abundant, as Te^{128} and Te^{130}. This suggests that we assign Te^{126}, which has an abundance comparable to Te^{128} and Te^{130}, to the *r* process. Te^{125} is an intermediate case, but it follows the trend of the *r* process and to this we assign its production. Assignments between the *s*, *r*, and *p* processes have been made in this way. In Figs. II,1; II,2; and II,3, the separation of the isotopes in the region $120 < A < 150$ is shown. In Fig. II,1 the abundances are plotted logarithmically after the manner of Suess and Urey (Su56). Nuclear species produced in the same process are connected by shaded curves and the general trend of the production becomes clear. In order to show more clearly the great increase in abundance in the peaks, linear plots of the abundances of the odd and even isotopes, respectively, are shown in Figs. II,2 and II,3. The magic-number peaks stand out clearly in both odd-*A* and even-*A* nuclei.

C. Abundances and Synthesis Assignments Given in the Appendix

The Appendix contains all of the information we have been able to collect which is relevant to the synthesis problem. All of the stable isotopes in order of increasing *A* are given in this table. We also include the beta-unstable isotopes which lie on the main neutron-capture chain in the *s* process, together with a few others which are given for special reasons. The table was originally drawn up to represent the building of elements by the *s* process. For this reason the left-hand columns follow the main chain of nuclei synthesized by neutron capture in the *s* process. The right-hand columns give information concerning the isotopes which are either completely by-passed by the *s* process or which lie in the subsidiary loops of the chain. These loops can be formed in two ways. Either they form at nuclei which beta decay with a half-life such that in the *s* process a proportion of the nuclei will capture a further neutron before beta decay, while the remainder beta decay directly (the next step in the chain following the nucleus $X_Z{}^A$ being either $X_Z{}^{A+1}$ or $X_{Z+1}{}^A$). Alternatively a loop will be formed if a nucleus can decay either by emitting an electron or by emitting a positron or capturing a *K* electron (the next step in the chain following the nucleus $X_Z{}^A$ being either $X_{Z+1}{}^A$ or $X_{Z-1}{}^A$). A few isomeric states are also given [an example is ${}_{48}Cd_{66}{}^{(m)}(\beta^-)$] in cases in which they also lead to the development of loops. In all cases the side of the loop which is in the main chain will be determined by the faster of the reactions (either neutron-capture or beta-decay) which can take place. To distinguish between nuclei which lie in the weak branch of a loop, and those which are completely by-passed

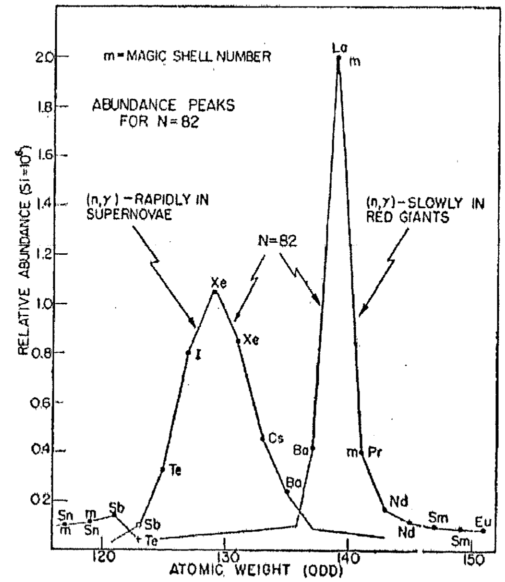


FIG. II,2. The odd *A* abundance peaks near $A = 129$ and 139 shown on a linear scale. See Fig. II,1 for comments.

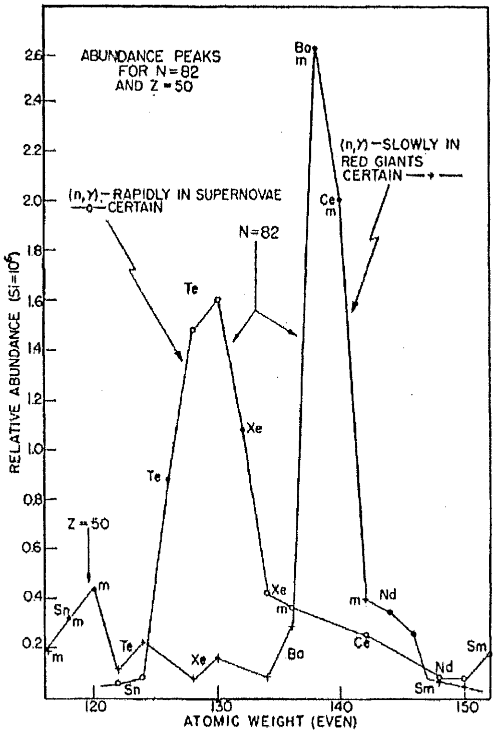


FIG. II,3. The even-*A* abundance peaks near $A = 130$ and 138 shown on a linear scale. See Fig. II,1 for comments.

Table VIII,2. Principal radioactive decays of Table VIII,1.

A	Element	Longest half-life, days or years	Decay type	Decay energy Q Mev	Initial abund. n_0 (Si $=10^6$)	Total energy n_0Q Mev	Initial en. rate $0.7\ n_0Q/t_{\frac{1}{2}}$ Mev/day
33	P	25*d*	β	0.12	50	5.95	0.165
47	Ca	4.7*d*	β	1.83	100	183	26.9
59	Fe	45*d*	β	1.36	30	40.8	0.628
85	Kr	10.4*y*	β	0.31	3.4	1.05	1.9×10^{-4}
89	Sr	54*d*	β	0.66	3.4	2.24	0.0287
91	Y	58*d*	β	0.70	2.2	1.54	0.0183
95	Zr	65*d*	β	1.73	2.2	3.81	0.0408
131	I	8.05*d*	β	0.50	1.73	0.865	0.0745
140	Ba	12.8*d*	β	~2.4	0.45	~1.08	~0.058
144	Ce	285*d*	β	~1.5	0.45	~0.68	~0.0016
194	Os	~2*y*	β	1.01	0.88	0.889	$\sim8.4\times10^{-4}$
225	Ra	14.8*d*	$\alpha+\beta$	27.9	0.045	1.26	0.059
228	Ra	6.7*y*	$\alpha+\beta$	35.2	0.032	1.13	3.2×10^{-4}
250	Cm	$7.5\times10^3 y$	α, SF(75%)	170	0.139	23.6	5.97×10^{-6}
252	Cf	2.2*y*	α, SF(3%)	12.9	0.097	1.25	0.0011
254	Cf	61 or 56.2*d*	SF	220	0.139	30.6	0.349
257	Fm	~10*d*	α, SF(6%)	18.5	0.091	1.68	~0.116

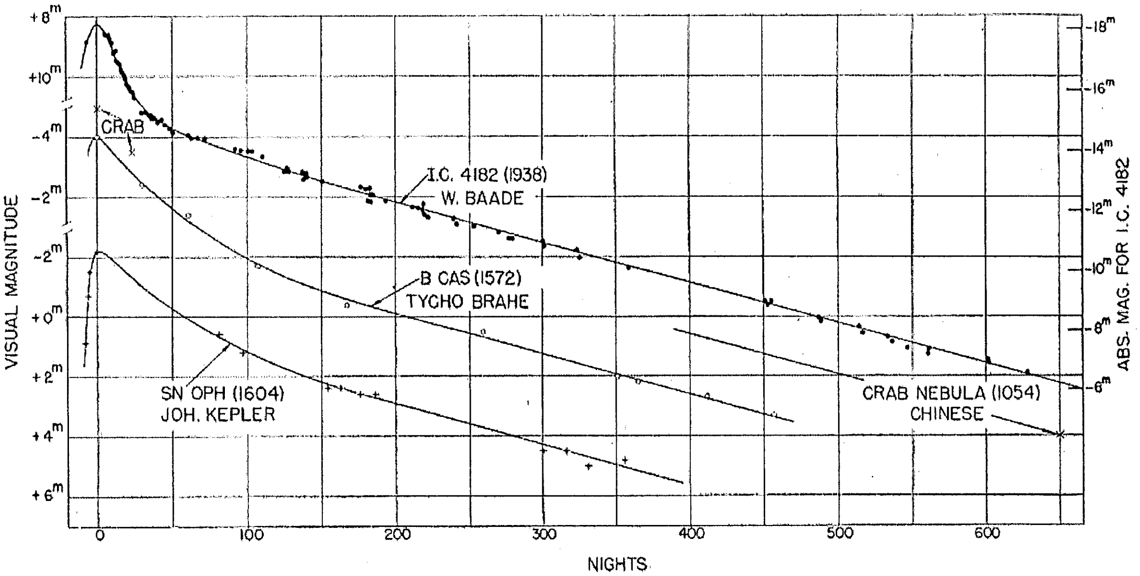


FIG. XII,1. Light curves of supernovae by Baade (Ba43, Ba45, Ba56). Measures for SN IC 4182 are by Baade; those for B Cassiopeiae (1572) and SN Ophiuchi (1604) have been converted by him to the modern magnitude scale from the measures by Tycho Brahe and Kepler. The three points for the supernova of 1054 are uncertain, being taken from the ancient Chinese records (Ma42). The abscissa gives the number of nights after maximum; the left-hand ordinate gives the apparent magnitude (separate scale for each curve); the points for the Crab Nebula belong on the middle scale, i.e., that for B Cassiopeiae. The right-hand ordinate gives the absolute magnitude for SN IC 4182 (Ba57a) derived by using the current distance scale. Compare with Fig. VIII,3.

estimated, with the best current value for the distance scale correction, to be -18.1 (Ba57a). The absolute magnitude of the Crab at its maximum in 1054 has been estimated to be -17.5 to -16.5 (To1355, Ma42, Ba57a). The value of 55 days for the half-life of SN IC 4182 was derived mainly from the points far out in the light curve where apparent magnitudes fainter than $+19$ had to be measured. Any systematic errors in measuring the faint magnitudes in this region would have the effect of changing the estimated value of this half-life and the possibility that such errors are present cannot be ruled out (Ba57a). The uncertainties in the measurements of other supernovae, which are not described here, are such that either all supernovae have true half-lives of 55 days, or they may have a unique half-life slightly different from 55 days, but lying in the range 45–65 days. Alternatively there may be an intrinsic variation between different light curves. These observational uncertainties must be borne in mind when considering the following discussion.

The only comparisons that we shall attempt to make will be between the total radiant energy emitted by a supernova and the form of the light curve, and the total energy emitted and the energy decay curves based on the calculations in Sec. VIII. No direct comparison between the early parts of the supernova light curve and the energy decay curve are possible, since the energy-degradation processes and the energy-transfer processes in the shell of the supernova will distort the relation between the two. Some aspects of this part of the problem have recently been studied by Meyerott and Olds (Me57).

Astrophysical arguments concerning the amounts of the *r*-process elements which are built in supernovae come from three different directions:

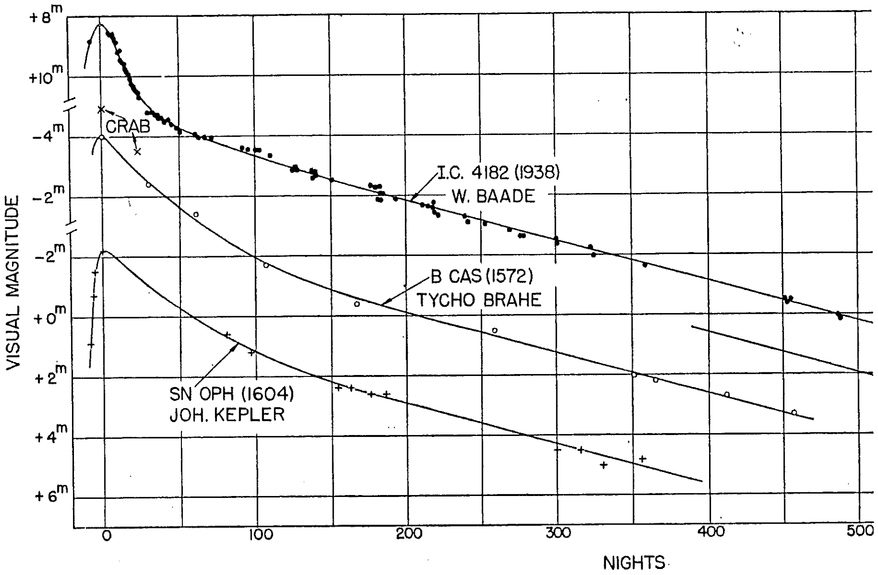
(i) The supernova or the supernovae which synthesized the *r*-process material of the solar system.

(ii) The Crab Nebula, the only remnant of a supernova which has been studied in any detail.

(iii) The light curves of supernovae which enable us to estimate how much material has been involved in the outburst, either on the assumption that the energy released by one or two of the isotopes dominates, and defines the light curve, or on the assumption that all of the decay activity is important.

Let us suppose that a total mass $mM_\odot$ is ejected in a particular supernova outburst and that a fraction f of this mass is in the form of *r*-process elements. Further, let us suppose that a fraction g of the heavy elements is in the form of Cf^{254}, or alternatively that a fraction g' of the heavy elements is in the form of Fe^{59}. In Sec. VIII it was shown that under specific conditions this was the only other isotope which could be expected to contribute an amount of energy comparable with Cf^{254}. Since it has a half-life of 45 days it cannot be *a priori* excluded from the discussion, particularly if, as has been stated above, some of the supernova light curves may have half-lives which are near to 45 days.

On the basis that Cf^{254} is responsible for the total



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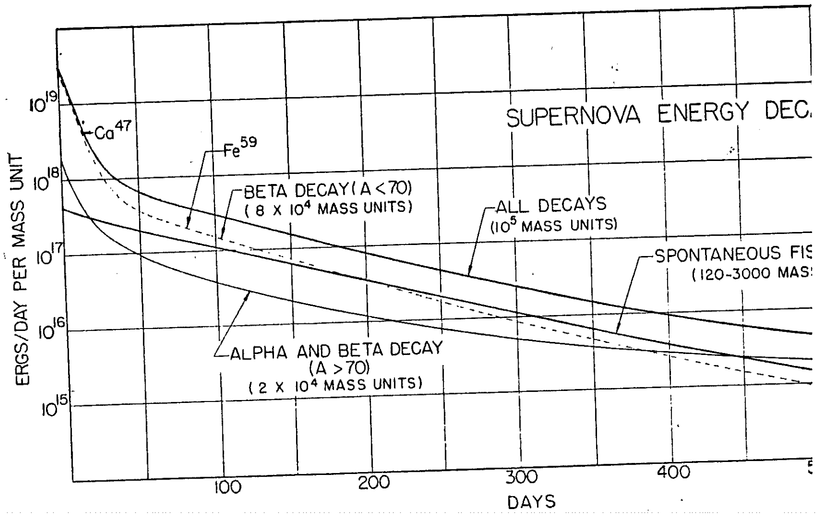

FIG. VIII,2. The radioactive energy release of the products of the r process. Radi less than 3 days has been neglected. Individual curves are shown for the beta decays for the products with $A > 70$, for the products which decay

ORIGINS OF THE ELEMENTS

The p-process or excluded isobars

Proton-rich nuclei that cannot be made by s or r processes
- examples: Kr-78 and Sr-84

p-process said to involve (p,gamma), (gamma,p) and (gamma,n) reactions

site - speculation - H-rich outer layers of Type II SN at T= 2-3 billion K and rho = 100 g/cm-3 with timescale set by SN explosion and not the reaction rates

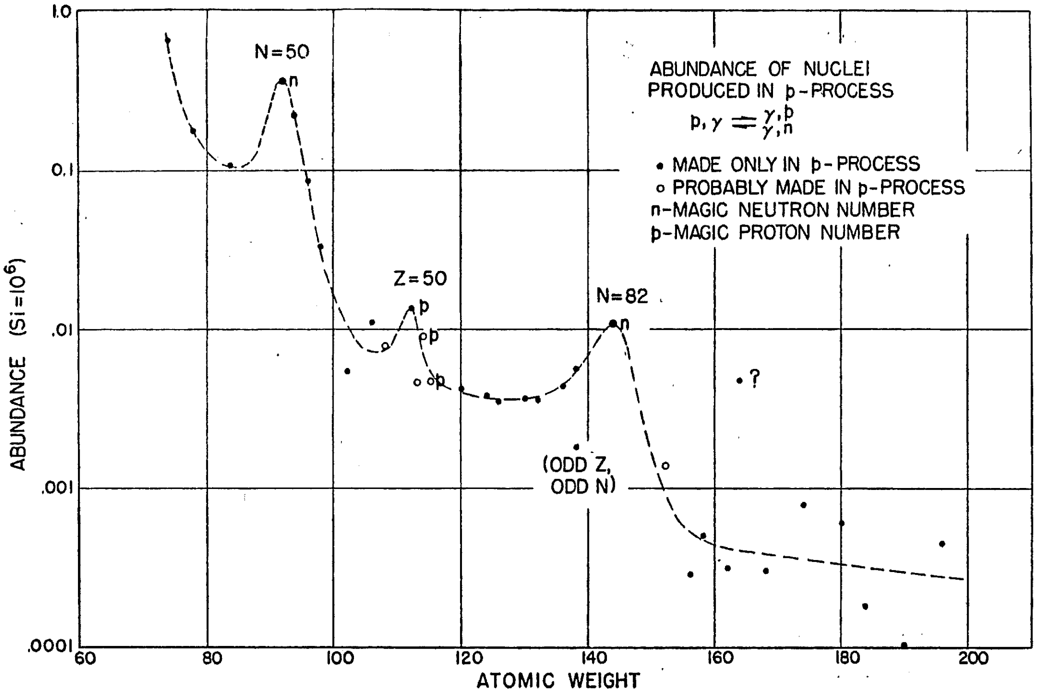

FIG. IX,1. Here we show a plot of the abundances of the isotopes made in the *p* process. The isotopes with magic N or magic Z are marked *n* and *p*, respectively. A curve has been drawn through the points to show the general trends. Note the peaks at $N=50$ and 82 and the lesser peak at $Z=50$.

ORIGINS OF THE ELEMENTS

The x-process: Origins of D, Li, Be and B?

These nuclides are destroyed by protons at `low' temperatures,
i.e., stars destroy them over large parts or all of their interiors

Destruction greatest for D and least for B - why?

B2FH suggested production in stellar atmospheres in magnetic regions (stellar flares) OR in regions such as interstellar gas, H II regions, SN II ejecta by SPALLATION reactions (e.g., p + O-16 --> X where X is bits of an O-16 nucleus such as Li Be and B nuclei.

But this scheme cannot produce D at the observed (!) level so special process needed

Dearth of observational data on Li Be and B abundances in stars and interstellar gas - why?

`possible modes of production' were `little more than qualitative suggestions'