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NEUTRON CAPTURE REACTIONS AND STELLAR NUCLEOSYNTHESIS

by JOHN H. GIBBONS

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John H. Gibbons

(Presented at Space Science Seminar, George C. Marshall Space Flight Center, Huntsville, Alabama, March 31, 1966)

ABSTRACT

Significant recent advances have been made in our understanding of the creation of the heavier elements. Techniques which enable this process are for the most part those of nuclear structure physics and elemental and isotopic abundances. Researchers have taken advantage of "nuclear clues" in unscrambling the processes by which elements are synthesized.

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NEUTRON CAPTURE REACTIONS AND STELLAR NUCLEOSYNTHESIS

By

John H. Gibbons*

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SCIENTIFIC PAYLOADS OFFICE
RESEARCH PROJECTS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

BIOGRAPHICAL NOTE

Dr. John H. Gibbons is a physicist at Oak Ridge National Laboratory. He is now on an assignment which divides his time between nuclear physics research and a National Defense Study Group. Dr. Gibbons began his research career at Duke Nuclear Structure Laboratories in 1954 as a Research Associate. He joined the Union Carbide Corporation at Oak Ridge National Laboratory in November 1954. On loan to the Oak Ridge Associated Universities in 1962-63, he was Head of the University Participation Program. His research has included nuclear reactions and cross sections; time-of-flight measurements of keV range neutron and total capture cross sections; neutron capture gamma-ray spectra; neutron flux calibration; ballistic missile defense; and non-military civil defense.

A native of Harrisonburg, Virginia, John Gibbons attended public schools there and was graduated from Randolph Macon College, Ashland, Virginia, in 1949 with a B.S. degree in mathematics and chemistry. He received his Ph.D. in physics from Duke University, Durham, North Carolina, in 1954.

Dr. Gibbons is a member of the American Physical Society and the National Speleological Society. His honors include Sigma Pi Sigma, Pi Mu Epsilon, Omicron Delta Kappa, Phi Beta Kappa, and Sigma Xi. He is listed in <u>American Men of Science</u>. He is active in industrial development, cave exploration, and various wilderness and conservation activities.

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NEUTRON CAPTURE REACTIONS AND STELLAR NUCLEOSYNTHESIS

SUMMARY

Significant recent advances have been made in our understanding of the creation of the heavier elements. Techniques which enable this process are for the most part those of nuclear structure physics and elemental and isotopic abundances. Researchers have taken advantage of "nuclear clues" in unscrambling the processes by which elements are synthesized.

This report presents methods for solving the problem of heavy element build-up. Notable advances in the past leading up to present technology are summarized, and modern techniques are discussed and explained. The report concludes with a look at future projects in this field.

INTRODUCTION

The abundance distribution of the elements has fascinated researchers for many decades; it must reflect in some way their mode of formation. Goldschmidt showed in 1937 that earth crust chemical abundances are not correlated with chemical properties. He also showed that structure, such as an abundance peak near iron, was present in the abundance distribution of the elements (Fig. 1). Such curves as those shown in Figure 1 may be caused by radioactive decay and spontaneous fission of transplutonium elements. Additional studies of the earth's crust, meteorites, and the sun by Harrison Brown (1949) and finally by Suess and Urey (1956) revealed additional fine structure - tantalizing clues to their origin. Suess and Urey concluded that element formation was based on nuclear properties and that our world bears clear signs of being the collective ashes of a "cosmic nuclear fire." Perhaps we who have followed on in this work should be called ash sifters.

At the same time that these elemental abundance studies were being pursued, the isotopic abundances were measured with mass spectrographs.

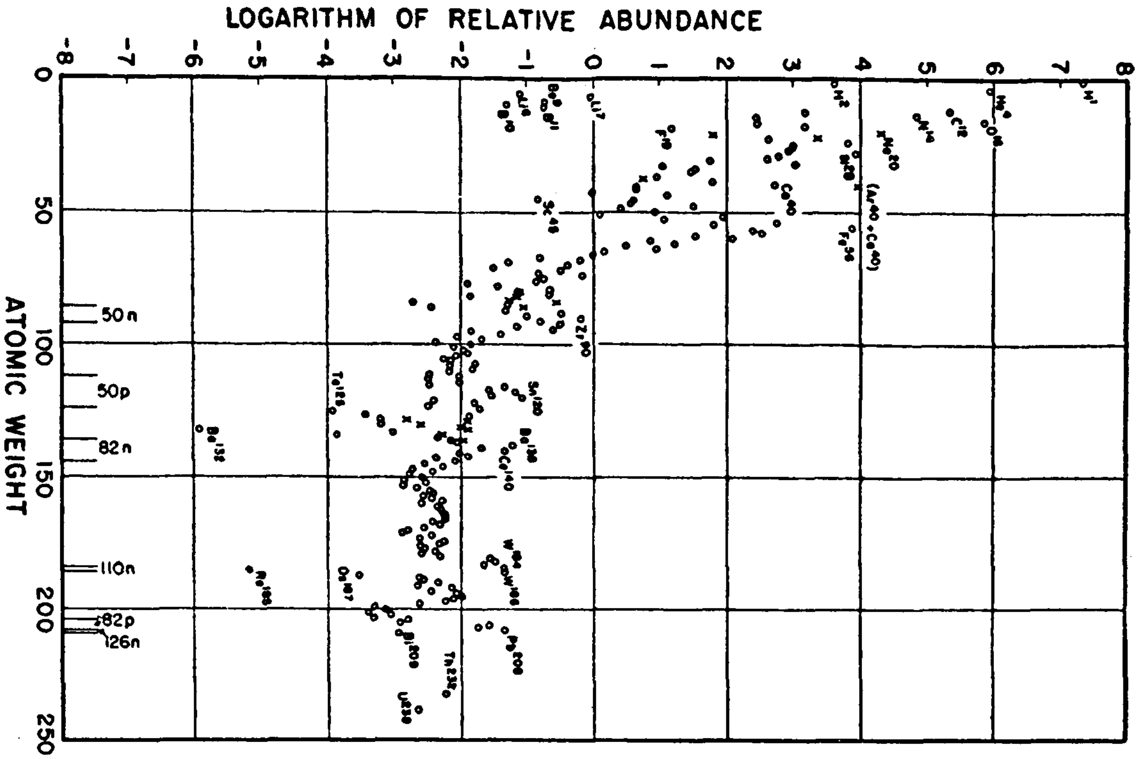


FIGURE 1. ABUNDANCE VERSUS ATOMIC WEIGHT
(FROM GOLDSCHMIDT)

The relative isotopic composition for a given element can be very accurately determined; furthermore, the relative isotopic abundance is unaffected by physical processes such as heat. In contrast relative elemental abundances can be grossly affected by several processes. Thus it should be no surprise that studies involving individual isotopes might be called for when highly accurate correlations are sought.

Parallel to the elemental and isotopic abundance studies were experimental and theoretical advances in nuclear structure physics and astrophysics that resulted in an impressively detailed picture of how stars work. Bethe, Christy, Critchfield, Fowler, Gamow, Herman, Hoyle, Von Weizsacher, Salpeter, and many others unfolded the basic thermonuclear processes involved in energy generation in stars. Although many of the most important reactions for light element productions were identified over two decades ago, we are witnessing today a tremendous surge in new, detailed knowledge of stellar structure and evolution. There were several bases for this rapidly advancing state of learning. Some of the most important are (a) better understanding of nuclear structure physics (low and medium energy nuclear reactions), (b) the availability of high-speed computers and advanced techniques in manipulating magneto-hydrodynamical models, both of which are closely related to the techniques developed to design nuclear weapons, (c) the disciplinary marriage of nuclear physics and astronomy. Our subject for this lecture is the particular problem of heavy element build-up. The weight of the coulomb barrier is such that, when one considers the temperature of most stars, essentially no charged particle reactions occur for elements heavier than iron.

NOTABLE ADVANCES FROM THE PAST

In 1946 the late Don Hughes and co-workers presented a paper on neutron activation cross sections of a large variety of elements for fission neutrons ($\overline{E}_n$ = 1 MeV). Alpher, in collaboration with Gamow, quickly saw that there was an approximate inverse relationship between neutron capture cross sections and relative abundances (Fig. 2). From this there emerged a non-equilibrium

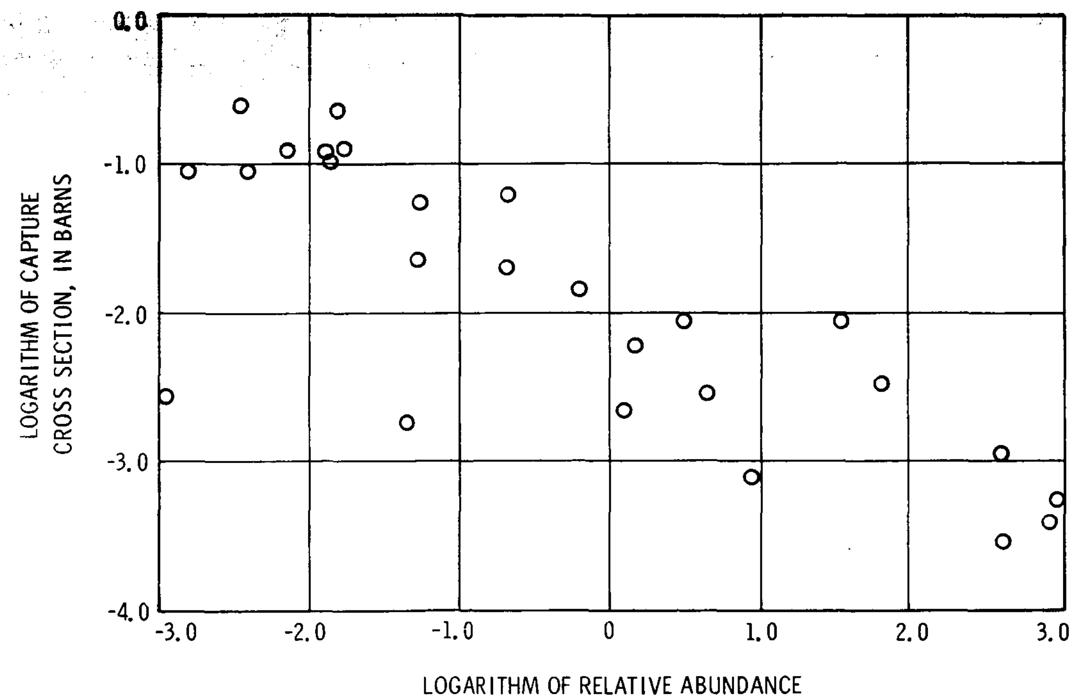


FIGURE 2. THE FIRST CORRELATION REPORTED BETWEEN FAST NEUTRON CAPTURE CROSS SECTION AND COSMIC ABUNDANCE (FROM ALPHER AND GAMOW)

model for element formation involving a neutron gas at high temperature, from which all of the elements were formed in a period of about 15 minutes by means of successive neutron capture. The assumption was made that essentially the entire process of element formation was completed in the pre-galactic phase of the universe. It was established that the average neutron temperature was greater than 10^3 eV since correlations between capture and abundance did not exist for resonance neutrons. Alpher estimated, in fact, that $\overline{E}_n$ probably corresponded to about $10^{9°}$ K. The authors were quick to confess that there were some weak points in their theory. For example they pointed out that isotopes which are "shielded" by other stable isotopes could not be produced by rapid capture, and certain correlations between cross section and abundance at the magic number positions were unaccounted for. In short, the assumption of element formation by a purely "rapid" process of neutron capture was not satisfactory but an intimate connection between neutron capture and element synthesis was clearly established.

Two observations helped set the stage for the next advance. In 1952 Merrill discovered the presence of technicium in the atmosphere of s-type stars (red giants), proving conclusively that significant neutron capture does occur in these main line stars and that nucleosynthesis by neutron capture is a dynamic, continuing stellar process. In 1956 the Burbidges, Christy, Fowler, and Hoyle at the California Institute of Technology noted a correspondence between the spontaneous fission half life of ^{254}Cf and the characteristic exponential decay time of light from supernova explosions (Fig. 3). This indicated that

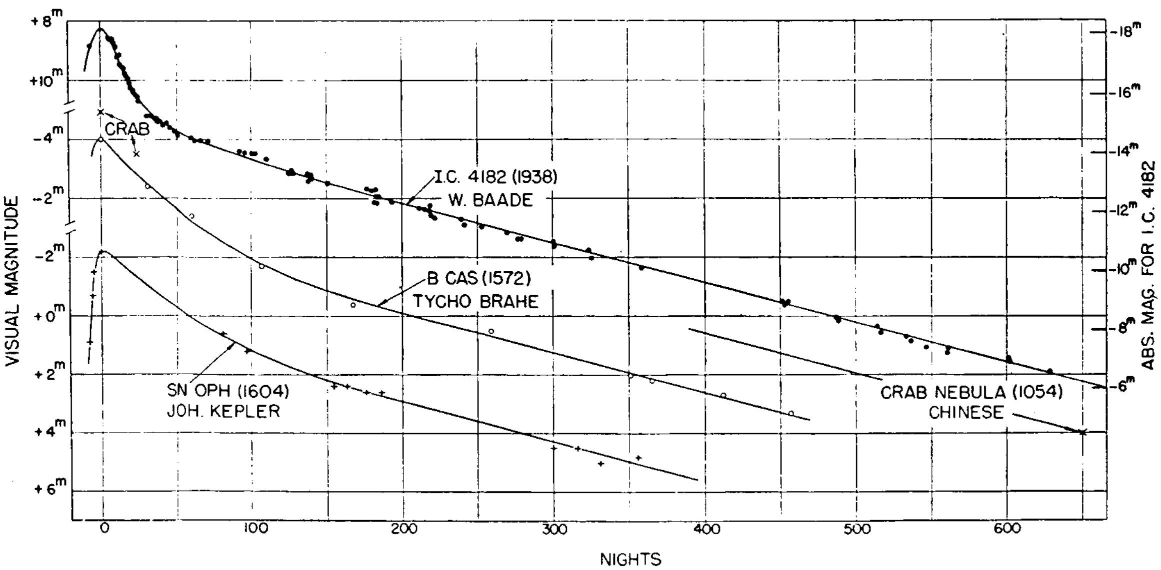


FIGURE 3. CHARACTERISTIC DECAY CURVES OF LIGHT FROM TYPE I SUPERNOVAE (FROM BURBIDGE, BURBIDGE, FOWLER, AND HOYLE)

rapid multiple neutron capture may occur in stellar explosions. One of the most impressive explosions was the star that became the crab nebula (Fig. 4). It thus became evident that elements are synthesized in stars during various phases of stellar evolution.

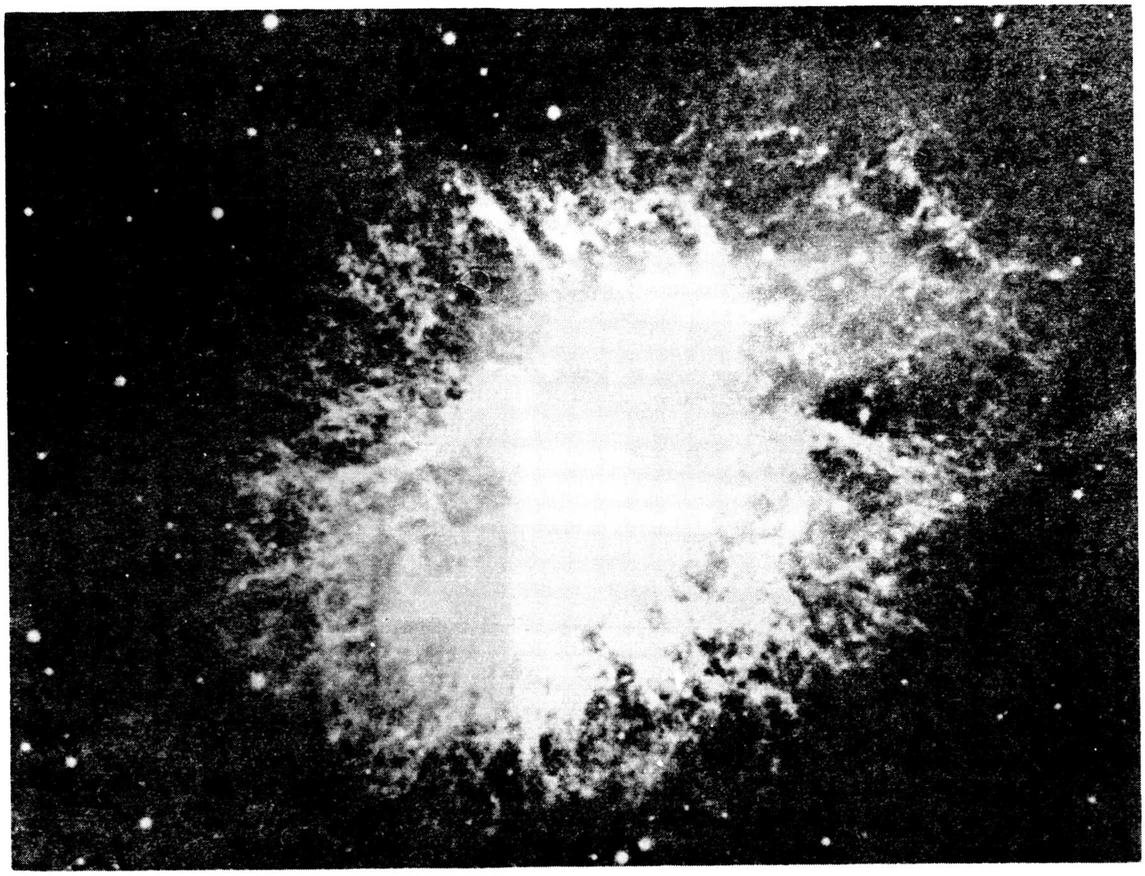


FIGURE 4. THE CRAB NEBULA, RESULTING FROM THE EXPLOSION OF A STAR IN 1054 AD

In 1957 an opus magnum was published by the Burbidges, Fowler, and Hoyle, commonly referred to as B^2FH [1], which attempted to synthesize all the new ideas on element formation in a single work. They incorporated Alpher and Gamow's basic idea of neutron capture but made at least three important modifications:

(1) The location of element synthesis was placed in stellar interiors.

(2) Charged particle reactions were assigned the major responsibility for element production up to iron, above which neutron capture became the predominant mechanism.

(3) Two quite different and independent neutron processes were assumed necessary to synthesize the abundant isotopes of heavy elements (Fig. 5).

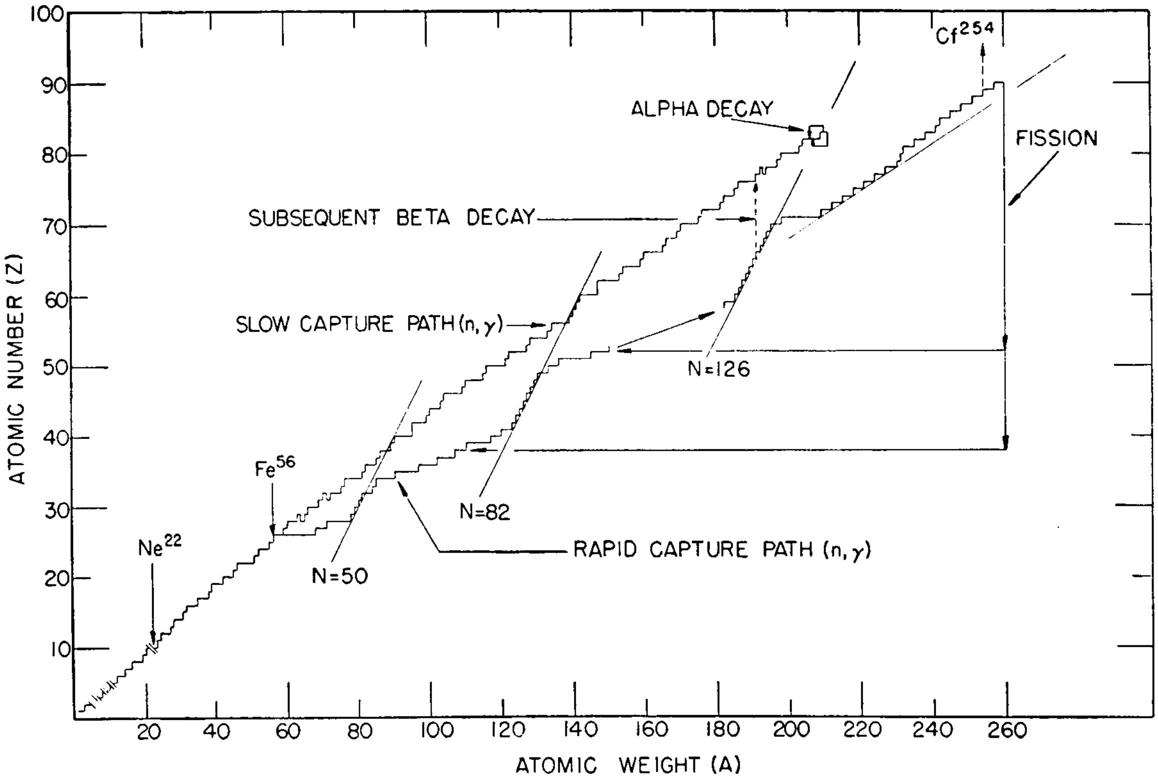


FIGURE 5. SYSTEMATICS OF HEAVY ELEMENT SYNTHESIS BY NEUTRON CAPTURE PROCESSES

Most nuclides were formed by both processes but many were formed solely by one of the others. One, the so-called "r" process, occurred on a rapid time scale (up to 100 neutron captures by a given nucleus in 1 to 100 seconds) and built up (by multiple capture) neutron-rich isotopes which subsequently beta-decayed to stability. The site of this process was thought to be super-novae. The second process, called the "s" process, also involved neutron capture but proceeded on a slow time scale (up to 10^4 years per capture) and therefore involved a succession of stable and nearly stable nuclei along the valley of beta-stability. The s-process formation was attributed to red giant stars, whose effective temperature was (1-2) x $10^{8°}$K(10-20 keV). Other estimates of the effective temperature range up to 8 x $10^{8°}$K (70 keV).

MODERN TECHNIQUES

During the years since 1958 new techniques have been developed to measure capture cross sections in the energy range corresponding to red giant temperatures (10 to 100 keV range). These techniques include activation, spherical shell transmission, lead slowing-down time spectrometer, large liquid scintillators (Fig. 6), and Moxon-Rae detectors, the latter two in

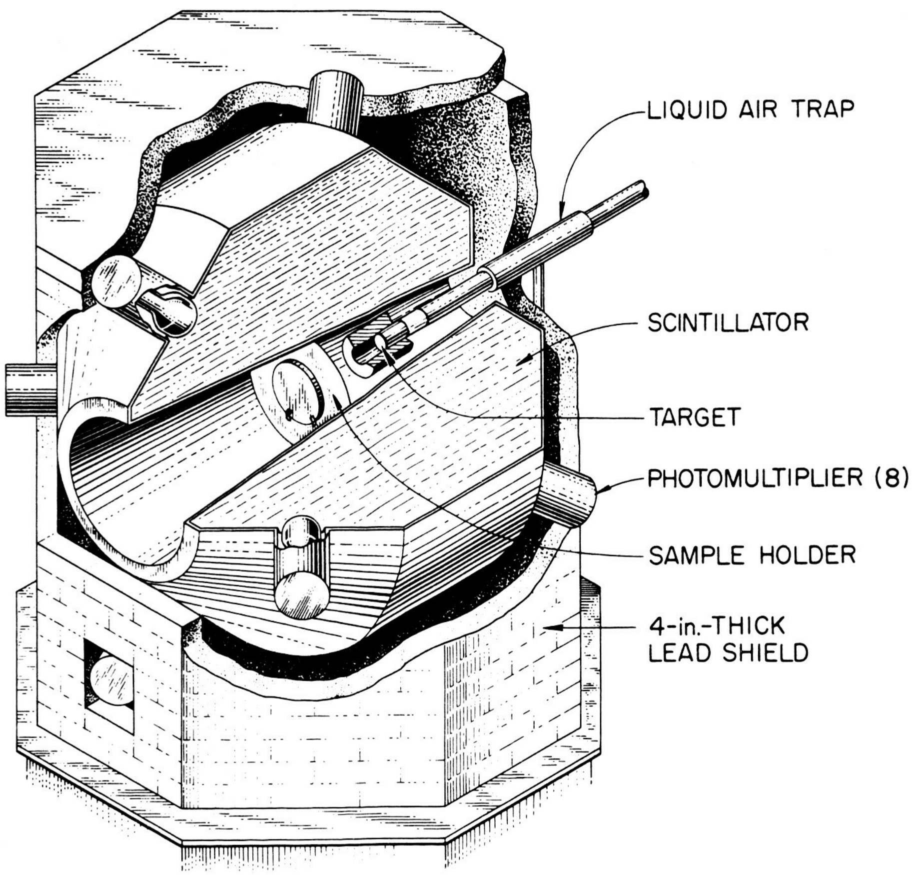


FIGURE 6. A LARGE (1000-LITER) LIQUID SCINTILLATOR USED TO MEASURE RADIATIVE CAPTURE CROSS SECTIONS FOR NEUTRON ENERGIES CORRESPONDING TO STELLAR INTERIORS

conjunction with Van de Graaf pulsed beam time-of-flight techniques. Current investigations of isotopic cross sections are largely restricted to the Van de Graaf time-of-flight techniques. The capture cross section results for heavy elements are typified by the results for $^{127}I(n,\gamma)$ shown in Figure 7. Individual resonance effects are smeared out for energies greater than a kilovolt. If one chooses the cross section at some energy and then plots cross section versus atomic number, the resulting curve (Fig. 8) varies relatively smoothly and shows dramatically the effects of nuclear shell structure. The dips are caused by the increased stability of nuclei with closed shells of protons and neutrons.

Clayton, Fowler, Hull, and Zimmerman, and also Clayton and Fowler, showed in 1961 that if one selects s-process nuclei and plots the product of abundance times capture cross section near 25 keV versus atomic weight, a reasonably smooth curve is obtained (Fig. 9). A corresponding plot for other nuclides shows no such correlation. The detailed shape of this curve contains the basic "history" of the s-process since it is a measure of the integrated flux time (i.e., total number of neutron captures) to which "seed" nuclei such as ^{56}Fe have been subjected. If fast neutron capture is the dominant production mechanism, then the product of capture cross section times abundance (ordinate) should be a smoothly varying function of atomic weight whose exact shape is dependent upon the fast neutron flux exposure history. These authors showed that, rough as it is, the form of the $N\sigma$ versus A curve makes it clear that s-process production of elements in our solar system did not occur through exposure of seed nuclei to a certain average number of neutrons (Fig. 10), but rather to a distribution of average fluxes. Figure 10 shows calculated curves of how the product $N\sigma$ should behave as a function of mass if heavy elements were caused by adding a specific average number of neutrons (7, 20, 34, etc.) to seed nuclei of ^{56}Fe. The breaks clearly evident are caused by the capture cross section minima at neutron magic numbers. In order to test the theory truly and to map out the history of the s- and r-process production, additional quantitative data were needed.

While cross sections are measurable to reasonably good accuracy, the relative natural abundances of elements are sometimes extremely difficult to determine. Despite careful work by geochemists some numbers are still changing by a factor of two or more. Even if the present natural elemental abundances were known, there would be difficulties caused by unknown amounts of physical and chemical fractionation that could have occurred in the past few billion years. A route around these difficulties was proposed by W. A. Fowler in 1961 - to study the correlation of cross section versus abundance for various s-process isotopes of a single element. This avoids chemical fractionation problems and has the further advantage that isotopic abundances are quite

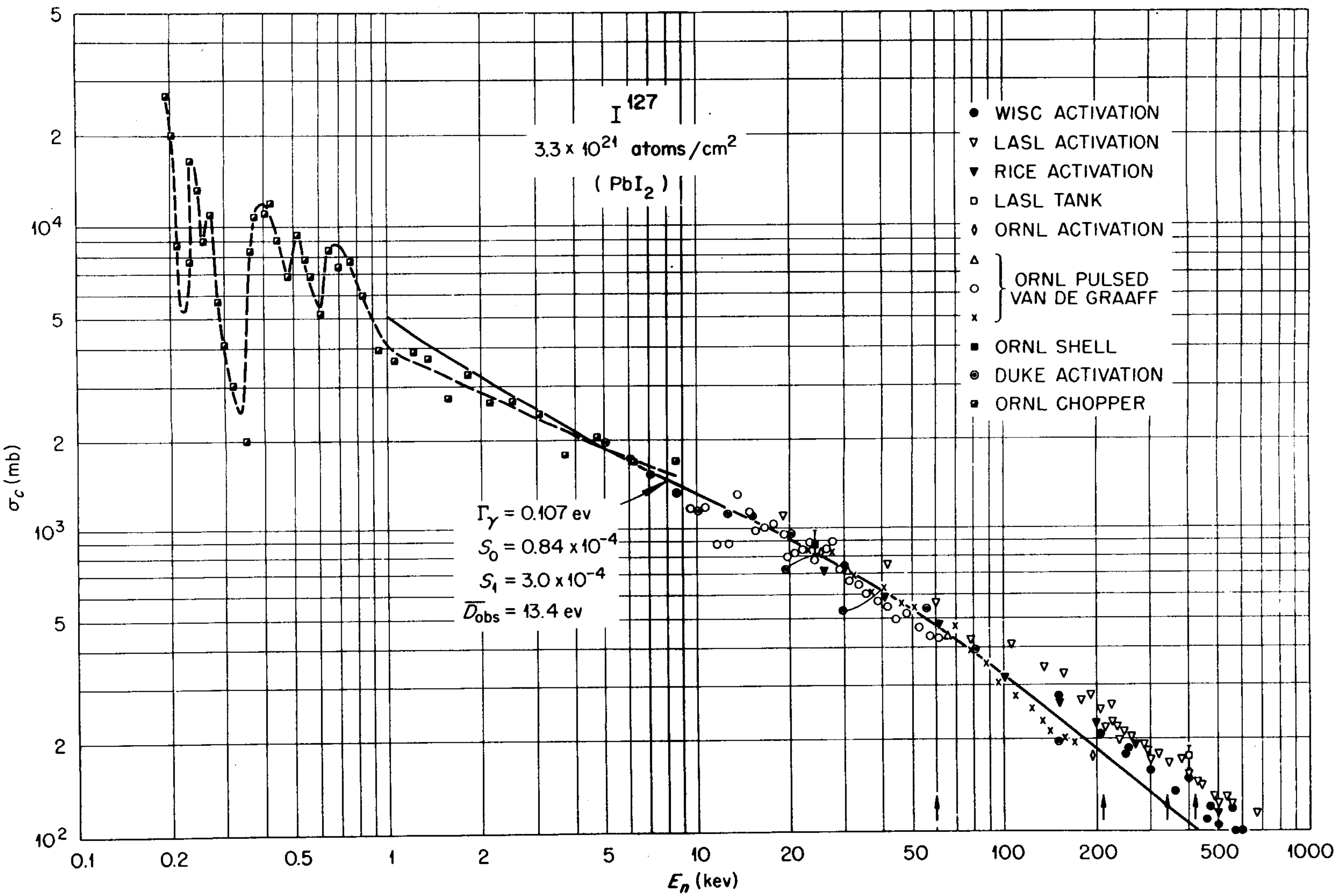
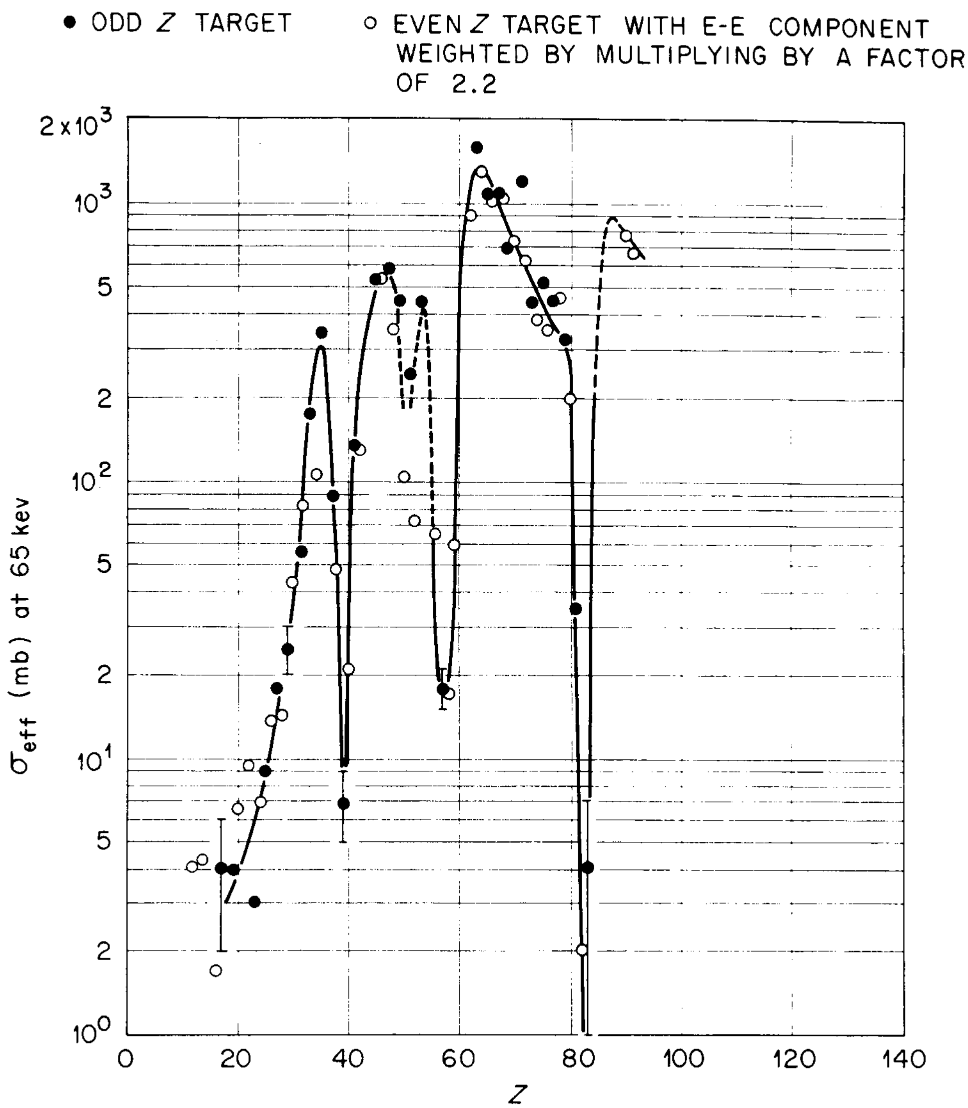


FIGURE 7. CROSS SECTION VERSUS ENERGY OF A TYPICAL HEAVY ELEMENT



Average Capture Cross Sections for 65-kev Neutrons.

FIGURE 8. CROSS SECTION AT 65 keV VERSUS ATOMIC NUMBER

accurately known. It was proposed by Fowler that the isotopes of tin be examined to provide definitive proof of the s-process theory (Fig. 11). The s-process hypothesis predicted that for neutrons near 25 keV the product $N\sigma$ should be equal or slowly varying for neighboring isotopes.

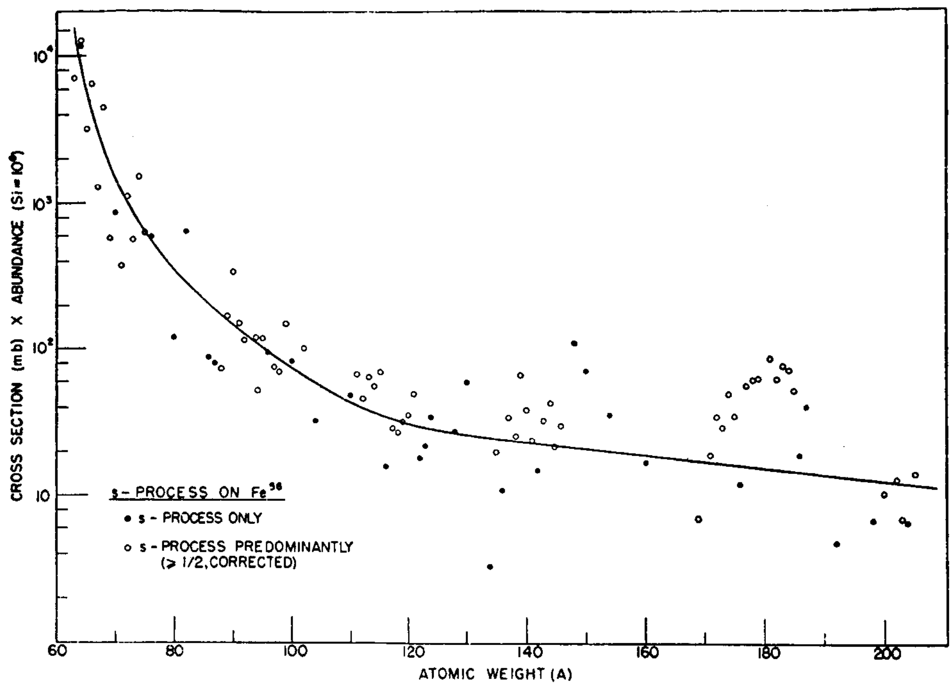


FIGURE 9. RESULTS OF CORRELATION STUDIES UNDER THE S-PROCESS HYPOTHESIS

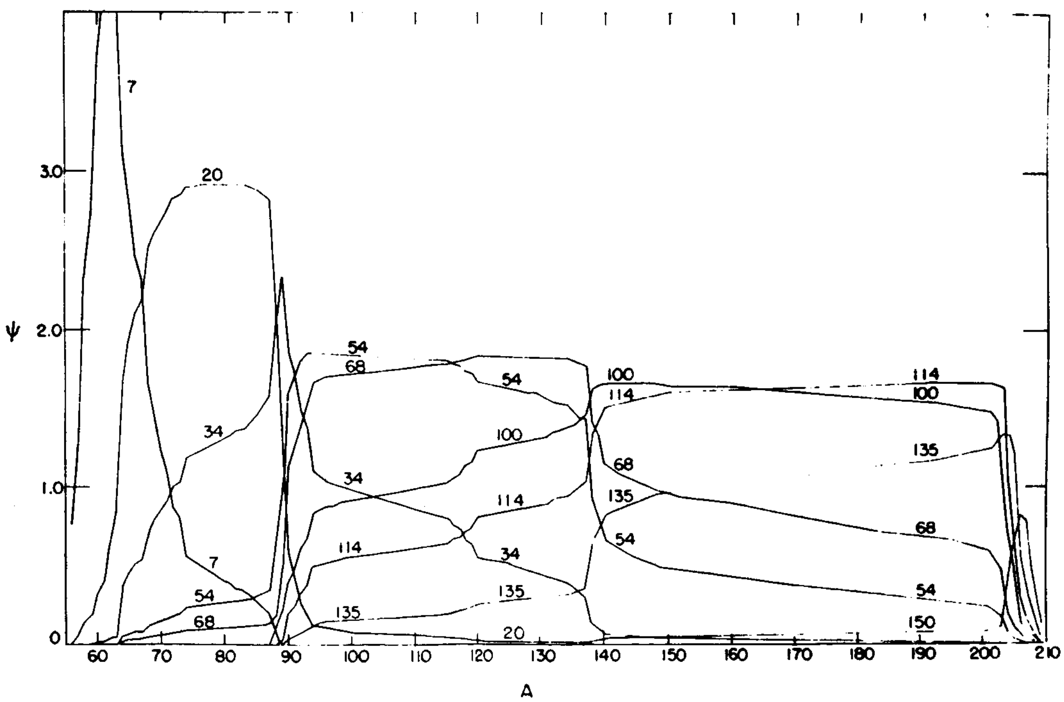


FIGURE 10. CALCULATED CURVES OF Nσ BEHAVIOR AS A FUNCTION OF MASS

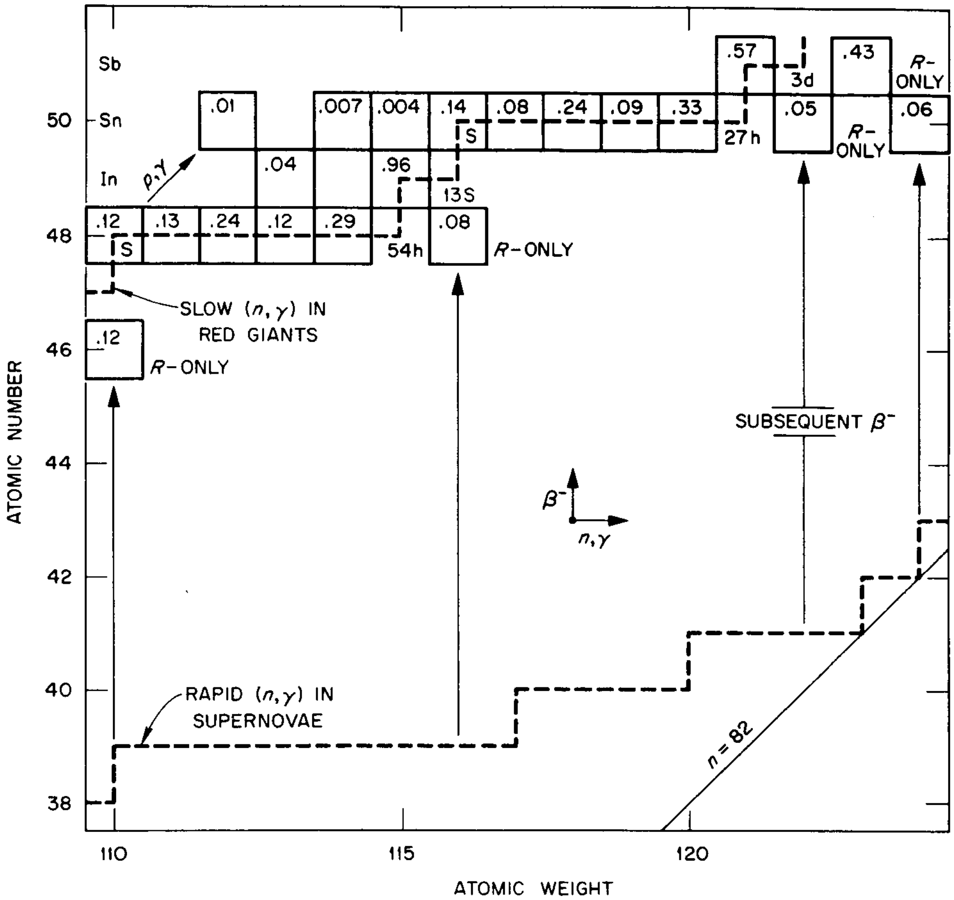


FIGURE 11. THE S-PROCESS PATH NEAR TIN

One difficulty which presented itself was that all existing techniques for measuring capture cross sections called for a large amount (~ 1 mole) of separated isotope. Separations of this magnitude are expensive and require a lot of time. Fortunately a gamma-ray detector was developed in 1961 by M. C. Moxon of Harwell that enabled the measurement of cross sections using samples fully ten times smaller than would have been possible with earlier techniques (Figs. 12 and 13). In Figure 13, one half of the detector and most of the neutron and gamma-ray shielding were removed to take the photograph. To do this the overall time resolution (about 2 nanoseconds) had to be sufficient to measure with an accuracy of a few percent the velocity of a neutron traveling at five million miles per hour over a flight path of only three inches. This required not only the development of the Maxon-Rae type detector, but also a technique (klystron bunching) to "squeeze" the width of the accelerator proton

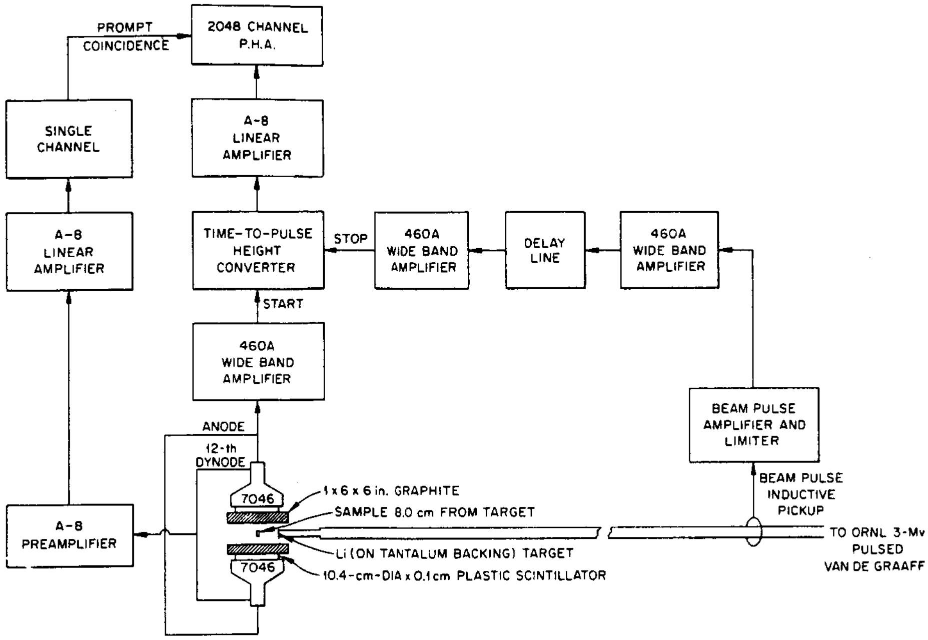


FIGURE 12. BLOCK DIAGRAM OF APPARATUS FOR THE MOXON-RAE CAPTURE DETECTOR

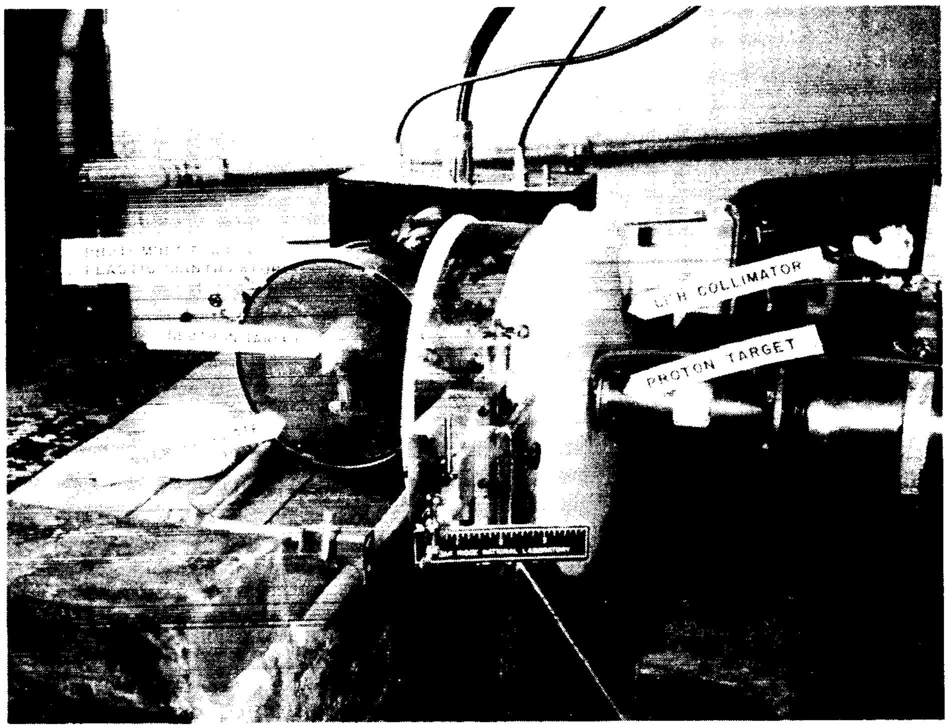


FIGURE 13. PHOTOGRAPH SHOWING MOXON-RAE DETECTOR AND NEUTRON FLIGHT PATH USED FOR CAPTURE MEASUREMENTS ON SEPARATED ISOTOPES

pulse down from about 10^{-8} to 10^{-9} seconds (Fig. 14). In the schematic in Figure 14, the Van de Graaff terminal was used to produce proton pulses of $\sim$ 5 ma peak current and $\lesssim 10^{-9}$ seconds width at a repetition rate of $\sim$ 1 m Hz. These protons produced neutron pulses via the ^{7}Li(p,n)^7 Be reaction.

THE S-PROCESS HYPOTHESIS

We have plotted atomic number versus mass number in Figure 11 so that the r-process beta-decay is vertical. The dashed line traces the s-process path in this region. For the case of tin, we see that the isotopes with $A < 116$ have not resulted from s-process synthesis. The heavy isotopes, $A \geq 122$, should result from r-process synthesis only, because of the short beta decay half life of ^{121}Sn. Lying directly on the s-process capture path, ^{116}Sn is shielded from any contribution from the r-process by beta stable ^{116}Cd. The contribution of r-process synthesis to the abundances of ^{118}Sn and ^{120}Sn is apparently rather small, while for ^{117}Sn and ^{119}Sn it could have been significant.

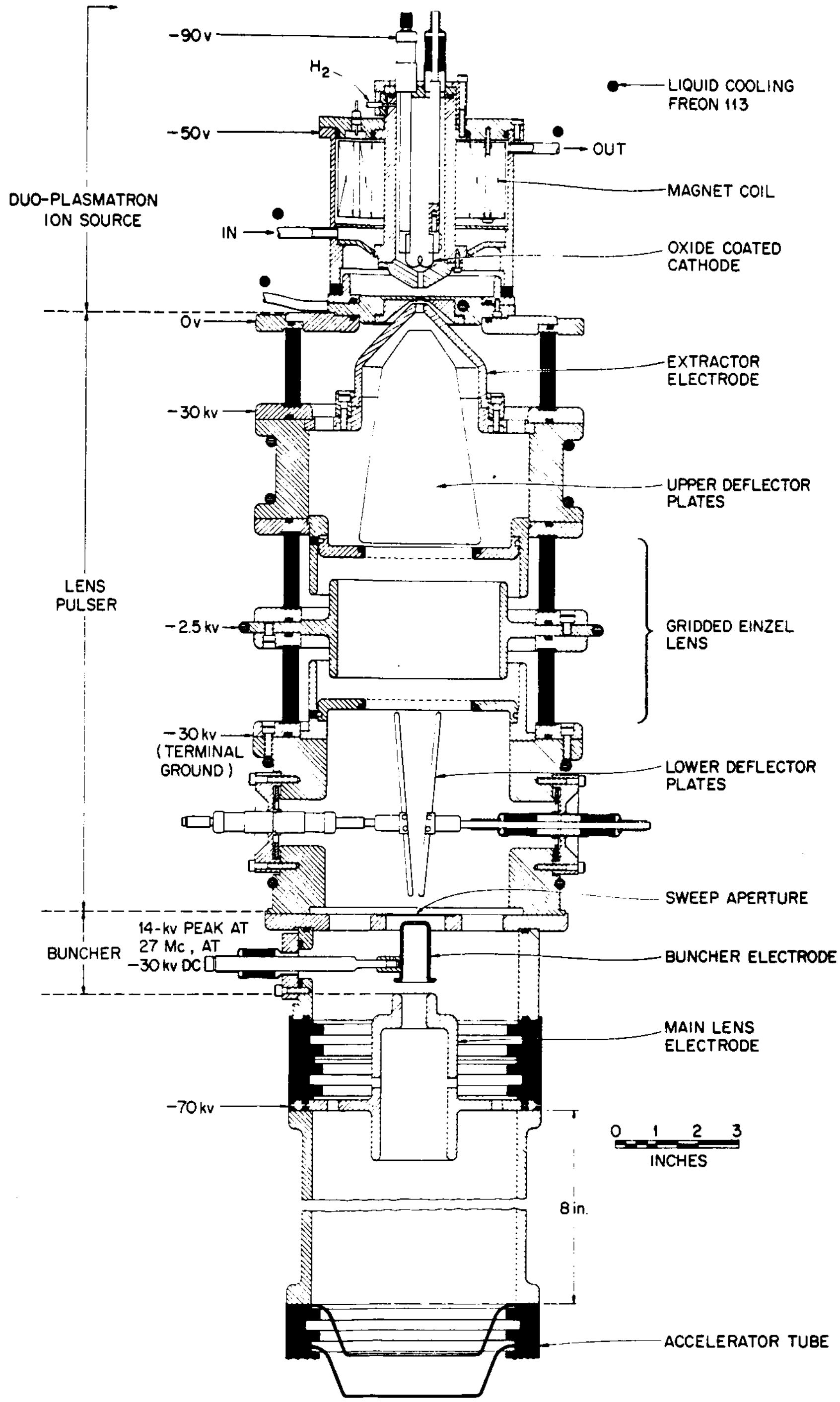
The problem, therefore, was to measure the capture cross sections for these isotopes at any energy corresponding to the conditions in the interiors of red giant stars. Under these conditions the relative velocity v between neutron and target is determined by the Maxwell-Boltzman distribution, and the reaction rates are weighted averages of the product of the velocity, v, the capture cross section, σ, the abundance, N, for each target isotope, and the local free neutron density.

The weighting function is

$$\varphi(v)\, dv = \frac{4}{\sqrt{\pi}} \left(\frac{v}{v_T}\right)^2 \exp - \left(\frac{v}{v_T}\right)^2 \frac{dv}{v_T}$$

where $v_T = (2kT/m)^{1/2}$ and m is the reduced neutron mass. We calculated the average

$$\langle \sigma v \rangle = \int_0^\infty \sigma v \, \varphi(v)\, dv$$



Accelerator Terminal Assembly Nanosecond Pulsing System.

FIGURE 14. SCHEMATIC CROSS-SECTIONAL VIEW OF PULSING AND KLYSTRON BUNCHING ASSEMBLY

from our measurements of the energy dependence of σ. The results are expressed in cross section units (millibarns) as

$$\langle\sigma\rangle = \langle\sigma v\rangle / v_T$$

for convenience.

The resulting correlations for the isotopes of tin are presented in Table I.

TABLE I. TIN ISOTOPES AT kT = 30 keV

A	Class	$\langle\sigma_c\rangle$ mb	N (atom %)	N_r	N_s	$N_s\langle\sigma_c\rangle$**
116	s-o	104 ± 21	14.2	--	14.2	14.8 ± 3
117	sr	418 ± 88	7.6	(4.0)*	3.6	15.0 ± 3
118	sr	65 ± 13	24.0	(4.5)*	19.5	12.7 ± 2.6
119	sr	257 ± 54	8.6	(4.0)*	4.6	11.8 ± 2.5
120	sr	41 ± 8	33.0	(4.5)*	28.5	11.7 ± 2.3
122	r-o	--	4.7	4.7	--	--
124	r-o	--	5.9	5.9	--	--

*W. A. Fowler, private communication.

**Errors do not include uncertainties arising from r-process estimates.

The cross sections quoted here are calculated for kT = 30 keV. When the estimated r-process contributions were taken into account we found the product $N_s\langle\sigma_c\rangle$ to be roughly constant, decreasing by some 30 percent over the range $116 \leq A \leq 120$. The smooth variation of this product is consistent with the formation of these isotopes by s-process synthesis. However, we felt that the uncertainties associated with the estimate of the magnitude of the r-process contributions render this a perhaps less than satisfactory proof of the existence of the slow neutron capture process.

There is another case which we felt should yield more conclusive results. The s-process capture path in the samarium region is illustrated in Figure 15. For samarium, one has the advantage of two isotopes which can be

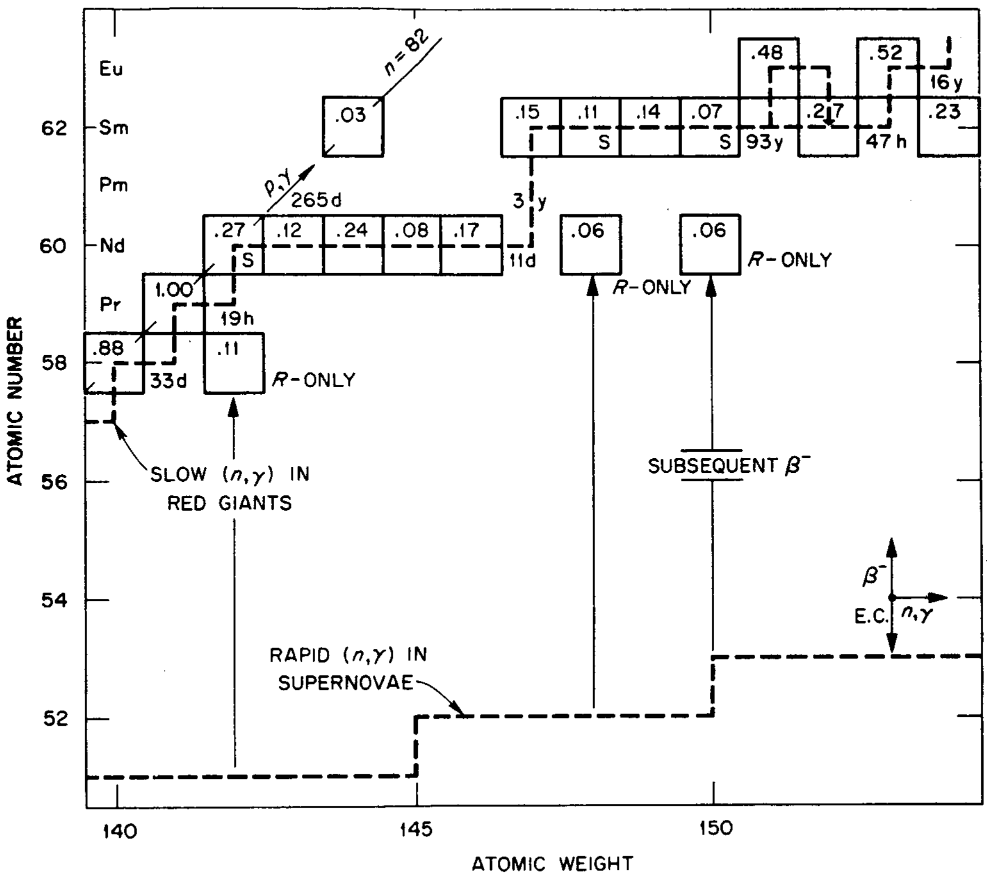


FIGURE 15. THE S-PROCESS PATH NEAR SAMARIUM

produced only by the s-process (^{148}Sm and ^{150}Sm), as they are shielded from r-process contributions by ^{148}Nd and ^{150}Nd. Furthermore, in this region (in contrast to the region near tin) one would expect the product $N_s \langle \sigma_c \rangle$ to vary quite slowly with mass number. Thus, having accurately determined the neutron capture cross sections for these two isotopes, an equality of the products $N_s \langle \sigma_c \rangle$ should constitute conclusive proof of the existence of s-process synthesis. Our results for the samarium isotopes are presented in Table II. The products $N_s \sigma_c$ for ^{148}Sm and ^{150}Sm are equal within the limits of uncertainty of these measurements.

TABLE II. SAMARIUM ISOTOPES AT kT = 30 keV

A	Class	$\langle\sigma_c\rangle$	N (atom %)	N_r	N_s	$N_s \langle\sigma_c\rangle$
144	p(m)	150 ± 70	2.87	--	--	--
147	rs	1170 ± 190	14.9	12.5 ± 0.4*	2.4 ± 0.4*	(2810)*
148	s-o	257 ± 50	11.24	--	11.24	2900 ± 560
149	rs	1620 ± 280	13.85	12.1 ± 0.3*	1.7 ± 0.3*	(2810)*
150	s-o	370 ± 72	7.36	--	7.36	2720 ± 530
152	rs	410 ± 70	26.90	20.0 ± 1.*	6.9 ± 1.*	(2810)*
154	ro	325 ± 60	22.84	22.8	--	--

* Inferred from the ^{148}Sm and ^{150}Sm results.

We were able, therefore, to confirm the s-process hypothesis by the accurate determination of the neutron capture cross sections and their correlation with isotopic abundance. Further cross section data are required, however, to determine the s-process contribution to nuclei which can also be formed by r-processing. This would allow an indirect measurement of the r-process abundances as a function of mass number. For example, in the case of samarium the results for ^{148}Sm and ^{150}Sm enable us to obtain fairly reliable estimates of the r-process for ^{147}Sm, ^{149}Sm, and ^{152}Sm (Table II). In addition to the r-process mapping, the fine details of the s-process function (cross section times abundance) versus atomic weight, which apparently has structure await a better determination.

These accurate determinations of the s-process distribution function can yield further nuclear clues to the history of our solar system abundances. For example ^{149}Sm has an enormous thermal neutron capture cross section (41,500 barns) while that for ^{147}Sm is only ~ 90 barns. Assuming the s-process picture to be valid, samarium must not have been exposed to a significant flux of thermal neutrons during the early history of the solar system or we would note an enhancement of ^{150}Sm abundance with respect to ^{148}Sm (or a depletion of ^{149}Sm with respect to ^{147}Sm). Such an exposure was proposed by Fowler and others to account for some light element isotopic abundances.

We have recently also obtained data on isotopes of strontium, zirconium, and most recently tellurium, which provide further tests of the neutron capture s-process. Lying in the s-process capture path (Fig. 16), ^{86}Sr is shielded

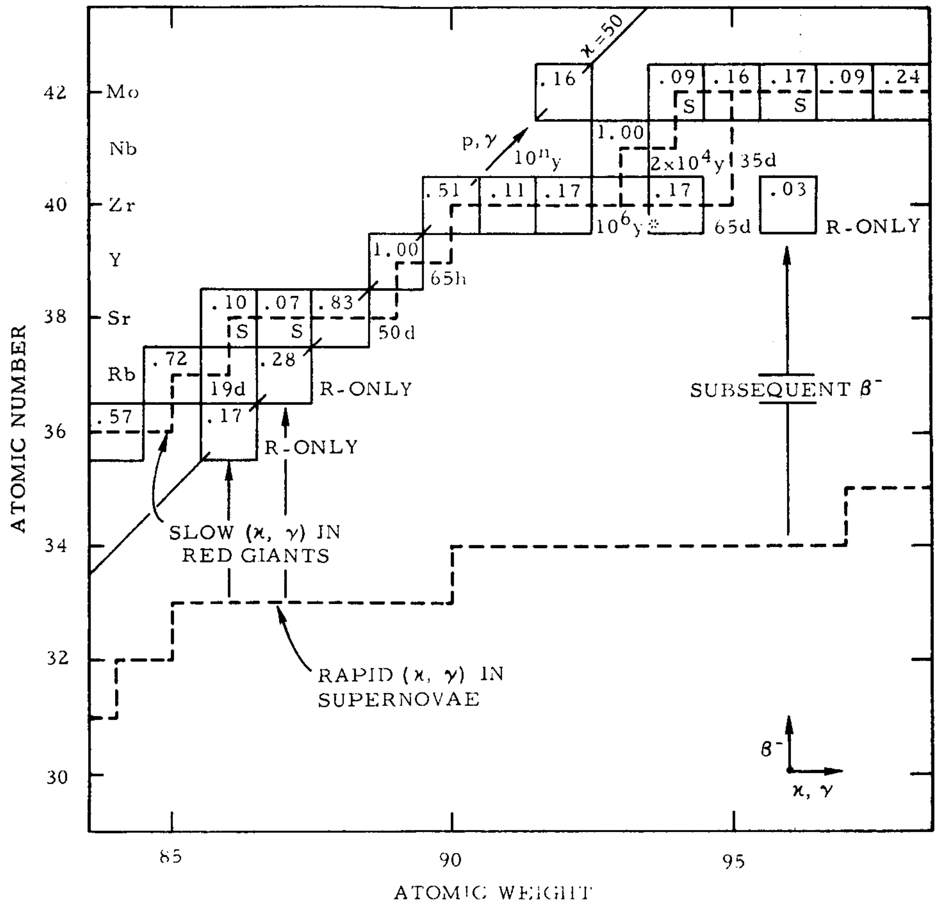


FIGURE 16. THE S-PROCESS PATH NEAR STRONTIUM AND ZIRCONIUM

by ^{88}Kr from any r-process production. Similarly, ^{87}Sr is produced only by the s-process as it is shielded by ^{87}Rb. The small cosmoradiogenic contribution from radioactive ^{87}Rb ($t_{1/2}$ = 4.7 x 10^{10} years) can be quite satisfactorily taken into account. Results of this measurement are summarized in Table III. It is clear that, even with the rather large experimental errors, the $N_S \langle\sigma\rangle$ product is rapidly decreasing in this region. The cross section for ^{88}Sr is quite small because of the closed neutron shell, and the result is subject to large experimental errors, as noted.

TABLE III. STRONTIUM ISOTOPES AT kT = 30 keV

A	Class	$\langle\sigma_c\rangle$, mb	N (atom %)	N_r *	N_s	$N_s \langle\sigma_c\rangle$
86	s-o	75 ± 15	9.86	--	9.9	740 ± 150
87	sr	108 ± 20	7.02	(0.7)	6.3	680 ± 120
88	sr	6.9 ± 1.7	82.56	(7.8)	71.8	500 ± 130

*Seeger, P. A., Fowler, W. A., and Clayton, D. D., Astrophys. J. Supplement No. 97, Vol. XI (1965) pp. 121-166.

^{87}Sr is s-only but has a cosmoradiogenic decay contribution from the r-only ^{87}Rb.

Although the zirconium isotopes are not shielded from the r-process capture production, the contributions from the r-process as inferred from the isotope produced only in this manner (^{96}Zr) should be small (Fig. 16). We felt that this would provide another test of the validity of the s-process. However, as in the case of the strontium isotopes and yttrium, we ran into some difficulties in obtaining these cross sections.

Strontium, yttrium, and zirconium are characterized by a magic or nearly magic number of neutrons and protons (Z = 40 and N = 50). For such nuclei, the level density and consequently the capture cross section is markedly decreased relative to its neighbors (Fig. 8). In contrast, for samarium the levels are very closely spaced and the widths are broadened by the greater s-wave strength function. Therefore, for elements in the vicinity of closed shells the properties of individual resonances will be important to the capture cross section. These effects are accentuated by the use of thick samples, required in order to obtain good counting statistics because of the small cross sections encountered. Thus the closure of nuclear shells, which can produce marked structure in the $N_s\langle\sigma_c\rangle$ versus A curve (Fig. 10), has played havoc in our ability to make accurate cross section measurements. There are satisfactory correction factors for such effects as resonance self-shielding and neutron scattering in the case of nuclei with high level density (in our case, up to about one keV). Likewise one can make reasonably accurate corrections in the case of isolated, resolved resonances. But intermediate cases are much more difficult and at present, nuclei typified by ^{88}Sr, ^{89}Y, and ^{90}Zr pose a severe problem when accuracies of better than ± 20 percent are sought.

The capture cross sections for the zirconium isotopes are presented in Table IV. The associated uncertainties, due to the effects we have discussed,

TABLE IV. ZIRCONIUM ISOTOPES AT kT = 30 keV

A	Class	$\langle \sigma_c \rangle$, mb	N (atom %)	N_r *	N_s	$N_s \langle \sigma_c \rangle$ **
90	s (m)	11 ± 3	51.46	(3.0)	48.5	535 ± 160
91	sr	59 ± 10	11.23	(2.5)	8.7	515 ± 100
92	sr	34 ± 6	17.11	(3.0)	14.1	480 ± 90
94	sr	21 ± 4	17.4	(2.8)	14.6	310 ± 60
96	r-o(?)	41 ± 12	2.8	≤2.8	--	--

* Estimated from systematics.

** Errors do not include uncertainties arising from r-process estimates.

are as high as nearly 30 percent. These isotopes are believed to be produced primarily by s-process synthesis. Assuming this contribution to be constant, except for a small odd-even effect, we were able to obtain the products $N_s \langle \sigma_c \rangle$ for the light zirconium isotopes. The results reveal that $N_s \langle \sigma_c \rangle$ is constant (to about 10 percent) for the lightest three isotopes of zirconium, while it is significantly decreased for ^{94}Zr. This may well indicate some significant branching at ^{93}Zr. The beta decay lifetime for ^{93}Zr is ~ 10^6 years. Assuming a neutron capture lifetime ~ 10^4 years, ^{93}Zr should be a stable nucleus with respect to this process, and the product $N_s \langle \sigma_c \rangle$ for ^{94}Zr should not fall so far below that of the lighter zirconium isotopes. An alternate possibility is that the $N_s \langle \sigma_c \rangle$ product decreases smoothly from about 600 for ^{90}Zr to about 300 for ^{96}Zr. Better data are obviously needed in this case.

A recent summary of results obtained for the s-process σN correlation is shown in Figure 17. The solid curve is calculated and corresponds to an exponential neutron flux distribution, possibly implying that the solar system material has been in the interior of red giant stars on many past occasions.

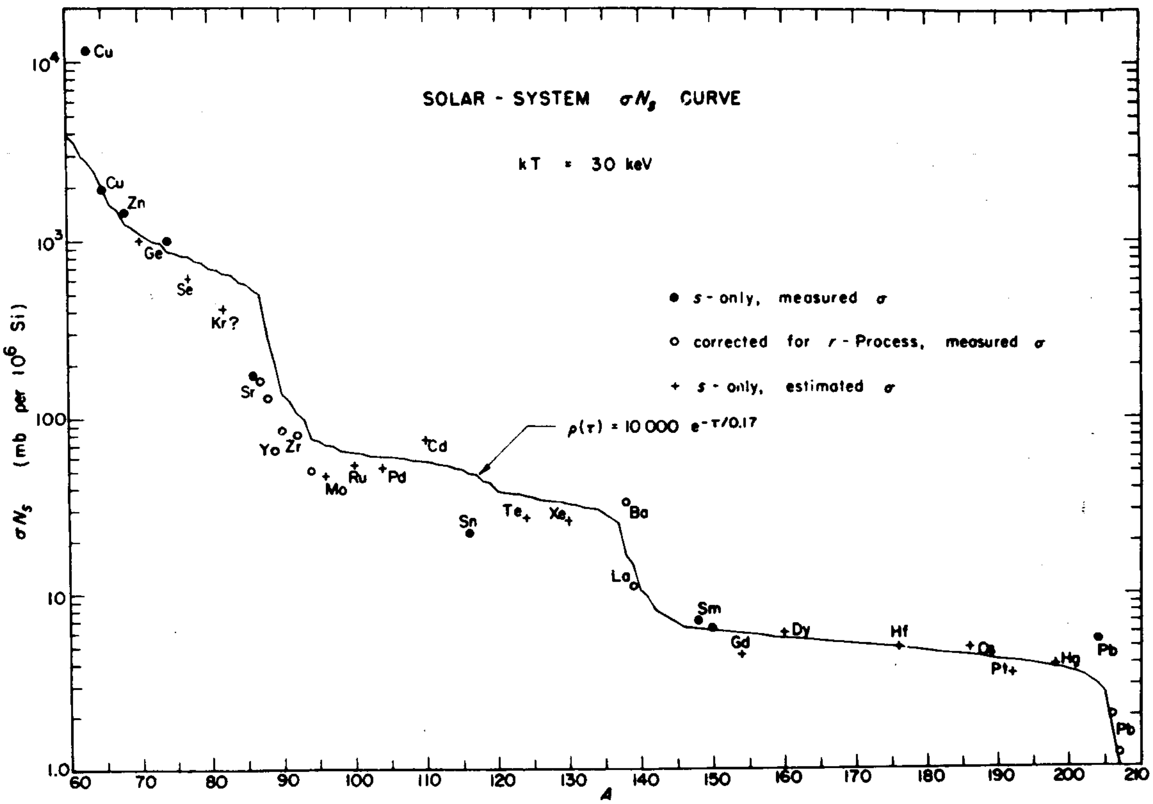


FIGURE 17. A RECENT PLOT OF S-PROCESS CROSS SECTION TIMES SOLAR SYSTEM ABUNDANCE ($N_s\sigma_s$) VERSUS ATOMIC WEIGHT

(FROM SEEGER, CLAYTON, AND FOWLER)

The distribution is characterized by a series of plateaus separated by sharp breaks that are associated with neutron magic numbers. Because of the highly quantitative tests using isotopes of Sn, Sm, Sr, Zr, and Te we have good reason to have a high degree of confidence in the vasic validity of the s-process hypothesis. Seeger, Fowler, and Clayton have calculated families of curves corresponding to exposure distributions, $\rho(\tau)$, of the forms $\rho(\tau) \sim e^{-\tau/\tau_0}$ and $\rho(\tau) \sim \tau^{-n}$ where τ is a parameter which represents the time-integrated neutron flux to which the seed nuclei (e. g., ^{56}Fe) have been exposed. The results can be reasonably well fit with either distribution and more precise data will be required to clarify this point. One result is patently clear however: the material of our solar system has been exposed to a wide range of neutron fluxes. Such a situation would imply that the material of which we are composed has made many round trips through the hearts of stars -- through their evolution and explosion, scatter to the interstellar medium only to be gathered up again in new stars. A century ago Walt Whitman wrote in Leaves of Grass, "I believe every leaf of grass is the journeywork of the stars." He was more correct than he knew.

DEDUCTION OF THE R-PROCESS ABUNDANCES

We have seen that the s-process is capable of careful testing by means of a combination of abundance and neutron capture cross section measurements. Once the s-process path is well-determined we can deduce the r-process abundances by subtraction of s-process from total abundances. This abundance distribution in turn gives clues to the source of the r-process.

The r-process involves neutron capture and beta-decay by neutron-rich nuclides far from the valley of beta stability. There are several lines of evidence for the r-process. First of all, the existence of abundant nuclides well to the neutron-rich side of the s-process path certainly suggests a synthesis by rather rapid capture. Moreover, abundance peaks for r-process nuclei near A = 80, 130, and 195 (Fig. 18) can be correlated with the neutron shells (N = 50, 82, 126) for neutron rich nuclei. In Figure 18, the solid and dotted curves show the trend of the data. These are clues to the mechanism of heavy element formation. In addition the simple fact that trans-bismuth nuclides exist (Th and U) means that some of the solar system material has been exposed to an intense flux of neutrons in order to get past the several very short-lived trans-bismuth elements. These clues, combined with the observation of the exponential decay of light from type I supernovas, gave rise to the hypothesis that at least one source of the r-process is the type I supernova. This hypothesis soon ran into some difficulties. The energy emitted under the exponential part of the light curve ($\sim 10^{48}$ ergs) requires at least 10^{-4} solar masses of ^{254}Cf to be produced in the explosion even if we assume a very efficient mechanism to convert fission fragment and beta and gamma decay energy into light. Fowler and Hoyle pointed out in 1960 that, using 10^{-4} solar masses and assuming one type I supernova each 300 years, we should expect a hundred-fold greater amount of thorium and uranium than we observe in the solar system. In 1964, Hoyle, Fowler, and the Burbidges showed that the ^{254}Cf hypothesis could still be valid if type I supernovas have a long evolution time ($\sim 10^{10}$ years), but they also considered an alternative scheme for the characteristic light production involving relativistic oscillations in gravitating masses. They stated that they

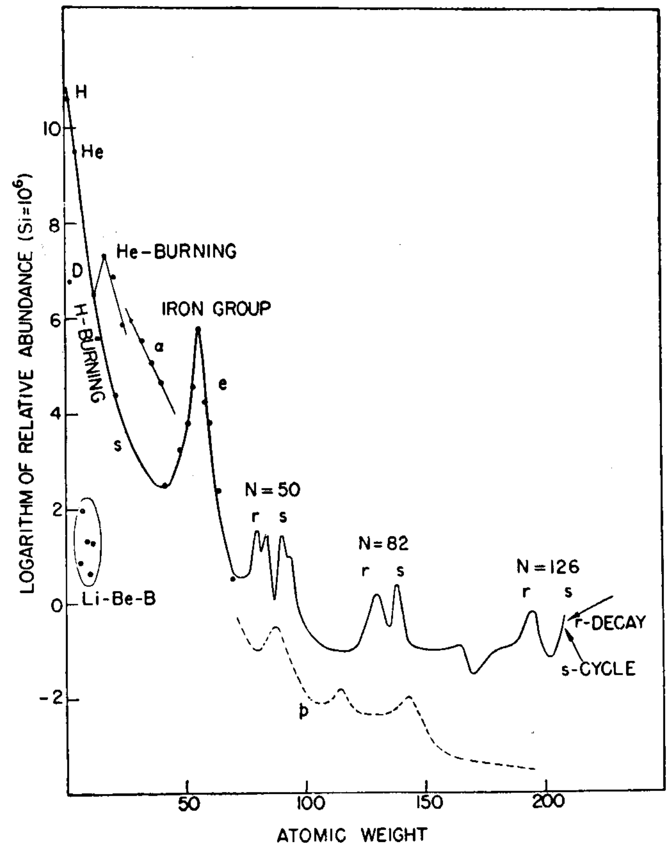


FIGURE 18. A SOMEWHAT IDEALIZED PLOT OF THE ABUNDANCE DISTRIBUTION OF THE ELEMENTS (FROM BURBIDGE, BURBIDGE, FOWLER, AND HOYLE)

were unable to resolve this point theoretically: "... We urge that observational astronomers turn their attention to the question of which of the two alternatives we have suggested for the light curves of type I supernovae is the correct one. Is the source of energy radioactivity or gravitation?"

Seeger, Fowler, and Clayton reported theoretical calculations in 1965 that the two r-process peaks (A = 80 and A = 130) can be produced in an environment of temperature $T \sim 2.4 \times 10^{9\circ}$ K and neutron density $n_n = 5 \times 10^{26}$ cm^{-3} over a time of about 4 seconds. If one assumes that the neutrons come from the breakdown of $^{56}Fe \rightarrow 13\ ^4He + 4n$ then an exploding mass of $\sim 10^5$ M is implied, which is about five orders of magnitude greater than that involved in a type I supernova. However, they also showed that trans-bismuth element production requires a considerably different environment, namely $T \sim 1 \times 10^{9\circ}$ K,

$n_n \sim 3 \times 10^{25}\ cm^{-3}$. Thus it could be that the first two r-process peaks are caused by synthesis in massive objects and the trans-bismuth synthesis by type I supernovae. They conclude, "... It becomes increasingly important to have some independent evidence for locating the r-process site, whether massive objects, conventional supernovae, or both."

FUTURE PROJECTS

The most obvious experiment to make a direct check on these speculations is to look for radioactivity emanating from supernova remnants. The crab nebula in Tarus is an almost immediate choice since it is in our galaxy (about 3500 light years distant), has been identified as a type I supernova, and is old enough (910 years) to have a reasonably simple spectrum of gamma rays from trans-bismuth radioactive decay products. Clayton and Craddock at Rice University, recently calculated the line gamma-ray flux in the solar system expected from the crab and estimate individual intensities of up to 10^{-4} gammas per square centimeter per second if the ^{254}Cf light-curve hypothesis is correct and about 10^{-6} gammas per square centimeter per second even if the light curve is caused by some other process. There may, of course, be other type I supernovae that are more intense but whose "birth" was not recorded by man. In any event, an experiment with a sensitivity of $< 10^{-4}\ \gamma \cdot cm^{-2} \cdot sec^{-1}$ can resolve the ^{254}Cf hypothesis and if the sensitivity is $\lesssim 10^{-6} \gamma \cdot cm^{-2} \cdot sec^{-1}$ one could hope to test the hypothesis of a more minor role in r-process production.

There already have been some attempts to observe these gamma rays. Hames and his colleagues at Rice University have flown a shielded (NaI-T1) crystal to > 100 thousand feet and have observed the high energy portion of the X-ray continuum that is emitted by the crab (about $3 \times 10^{-4} \gamma \cdot cm^{-2} \cdot sec^{-1}$ at 70 keV), but they have not obtained to date any evidence for line gammas. The two basic limitations are exposure time ($\lesssim$ 6 hours) and detector energy resolution. We feel that a very worthy experiment to consider would be a satellite-mounted (long counting times), highly collimated (lower backgrounds), Ge(Li) gamma-ray spectrometer (vastly improved energy resolution). Such an experiment would require collective skills of Marshall and Oak Ridge National Laboratory and almost should certainly include active collaboration of colleagues from Rice University and the California Institute of Technology.

This experiment should be feasible to design now and to "fly" within a few years. There are no great extensions required in present nuclear electronics or germanium detector fabrication other than hardening for the harsh environment of launch and orbit. The goal is a worthy one, for we would be seeking to:

(1) Examine a prime suspect source for the r-process and therefore the site where gravitational energy is converted into the fission energy which we on earth are now becoming so dependent upon,

(2) Test the ^{254}Cf light-curve hypothesis (radioactivity or gravitation?),

(3) Open a new field of astronomical observation: line gamma-ray astronomy with its disadvantage of low intensity but with its tremendous advantage of the indelible fingerprint of discrete electromagnetic radiation.

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