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Neutron Capture and Stellar Synthesis of Heavy Elements

Correlations between capture and abundance reveal details of the origin of solar system elements.

J. H. Gibbons and R. L. Macklin

Nuclear astrophysics had glorious beginnings in the 1930's, when many perplexing problems, particularly relating to energy sources, were solved. However, the truly explosive development of this field has occurred since World War II. Some of the principal ingredients in this advance were our better understanding of nuclear structure, the advent of high-speed digital computers, advances in ground-based astronomical observations (for example, radio astronomy), and—of great importance—the emergence of astronomers skilled in theoretical nuclear physics and relativity. In fact our knowledge has expanded to such an extent that we address ourselves in this article, without apology, to a very specific subject: synthesis of the heavier elements (atomic number $Z > 26$) by neutron capture reactions in stars. Heavy elements—in fact, any elements other than hydrogen and helium—are relatively rare in the universe, but the study of their abundance and nuclear properties is leading to important new insights into the mechanisms by which the materials that we are composed of came into existence.

It has been known for several decades that internal temperatures of most stars are such that thermonuclear reactions, involving charged particles interacting with other charged particles, become much less frequent as the charge of a particle increases. Thus, while protons or alpha particles may readily undergo a nuclear reaction with a carbon nucleus, they will rarely undergo such a reaction with a magnesium nucleus because of the stronger electric (Coulomb) repulsion between the particle and the magnesium nucleus. The only way to build the heavier elements is to find ways of achieving much higher temperature or to bypass the Coulomb barrier problem by using neutron-capture reactions.

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Earlier Nuclear Clues

The first data available on neutron-capture cross sections of the heavier elements were presented by Hughes and his co-workers (*1*) in 1946. These were activation cross sections for a large variety of elements exposed to fission-produced neutrons ($E_n \approx 1$ million electron volts). Alpher (*2*), in collaboration with Gamow, immediately observed that there is an approximately inverse relationship between neutron-capture cross sections and the relative elemental abundances found in the solar system (Fig. 1). From this there emerged a nonequilibrium model for element formation, involving a neutron gas, at high temperature, from which all of the elements were formed in an interval of about 15 minutes by successive neutron captures. The assumption was made that essentially the entire process of element formation was completed in the primordial "big bang" at the beginning of the pregalactic phase of the universe. It was established that the average neutron temperature was probably greater than 10^3 electron volts, since correlations between capture cross sections and abundance do not exist for "thermal" neutrons (energy of ~0.025 electron volt) or neutrons in the 1- to 1000-electron-volt range. Alpher estimated that the average neutron energy probably corresponded to about 10^9 degrees Kelvin (or about 100,000 electron volts). He admitted that there were some weak points in this theory. For example, he pointed out that some isotopes are "shielded" by other stable isotopes with equal weight but lower Z, and thus could not have been produced in such a rapid chain capture process. Also, the lack of a stable nucleus at mass 5 and mass 8 meant that simple neutron-capture chains could not have been solely responsible for element building. In short, the assumption of element formation by a purely "rapid" process of neutron capture was not entirely satisfactory, but an intimate connection between neutron capture and element synthesis was clearly established.

While these studies were in progress, our knowledge of solar-system elemental and isotopic abundances steadily increased. In 1937 Goldschmidt (*3*) showed that elemental abundances in our solar system are not correleted with chemical properties. His work was followed by further studies, by Brown (*4*) in 1949 and by Suess and Urey (*5*) in 1956, based on measurements in the earth's crust and also on data from meteorites and the atmosphere of the sun, which revealed subtle relationships between elemental abundances and atomic weight. It became increasingly clear that the elements were formed on the basis of their *nuclear* properties, and that our world bears clear signs of being the collective ashes of what Suess and Urey labeled a "cosmic nuclear fire," in which the matter of our sun

and solar system was created. Much rewarding effort has been spent recently in a more and more sophisticated sifting of these ashes, as various nuclear clues have become available to us.

Two observations in the 1950's helped set the stage for the next advance in our knowledge of the role of neutron capture in stellar nucleosynthesis. In 1952 Merrill discovered atomic emission lines of technetium in the atmosphere of type-S stars (red giants) (*6*). Since technetium has a half-life of less than a million years, this observation proved conclusively that significant neutron capture does occur in these stars and that nucleosynthesis by neutron capture is a dynamic, continuing stellar process. In 1956 a correspondence between the spontaneous fission half-life (56 days) of californium-254 and the characteristic (approximately exponential) decay time (50 to 60 nights) of light from type-I supernova explosions was noted (*7*). This indicated that rapid, multiple neutron capture may occur in stellar explosions such as supernovae. We know that some such process *must* have occurred in the case of our solar-system material, since we have a finite abundance of thorium and uranium. These elements could only have been produced in some rapid process, since rather short-lived elements (for example, astatine, whose longest-lived isotope has a half-life of 1 minute) lie between them and their stable progenitors.

Development of Neutron Buildup Theory

In 1957, Burbidge, Burbidge, Fowler, and Hoyle (*8*) and also Cameron (*9*) integrated all of the new ideas and information on element formation into a coherent picture. With regard to heavy-element synthesis, they incorporated 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 and in violent stellar explosions (supernovae).

2) Charged-particle reactions were assigned major responsibilities for production of elements no heavier than iron; for production of elements heavier than iron, neutron capture was considered the predominant mechanism.

3) Two quite different and independent neutron processes were assumed necessary to synthesize the abundant isotopes of elements heavier than iron, which lies at a strong peak in the abundance distribution. According to this hypothesis, the first of these, the rapid process, or r-process, occurs on a rapid time scale (up to 100 neutron captures in 1 to 100 seconds) and builds up neutron-rich isotopes which subsequently undergo beta decay until they achieve stability. The site of r-process isotope production was thought to be supernovae. The second process, the slow- or s-process, also involves neutron capture but proceeds on a slow time scale (10^3 to 10^6 years per capture) and, therefore, involves a succession of stable and nearly stable nuclei. The site of s-process isotope production was thought to be red giant stars, whose effective temperature is 2 to 3×10^8 degrees Kelvin ($E = 20{,}000$ to 30,000 electron volts). The capture path for the s-process follows the "valley of β-stability" through the succession of stable isotopes (Fig. 2). The r-process path, on the other hand, lies far to the neutron-rich side of the stable elements. While most nuclides are formed by both of these processes, certain ones are formed solely by one process. There are some heavy stable isotopes whose next-higher isotope (containing one more neutron) has a relatively short half-life ($\ll 10^3$ years). According to the s-process hypothesis, in these cases the next-heavier isotope cannot be produced since beta decay to the next element would occur before the second neutron was absorbed. Likewise, some stable nuclides exist that are "shielded" against r-process production because a stable nucleus with the same atomic weight but lower Z terminates the chain of beta decays after completion of the r-process for that particular atomic weight.

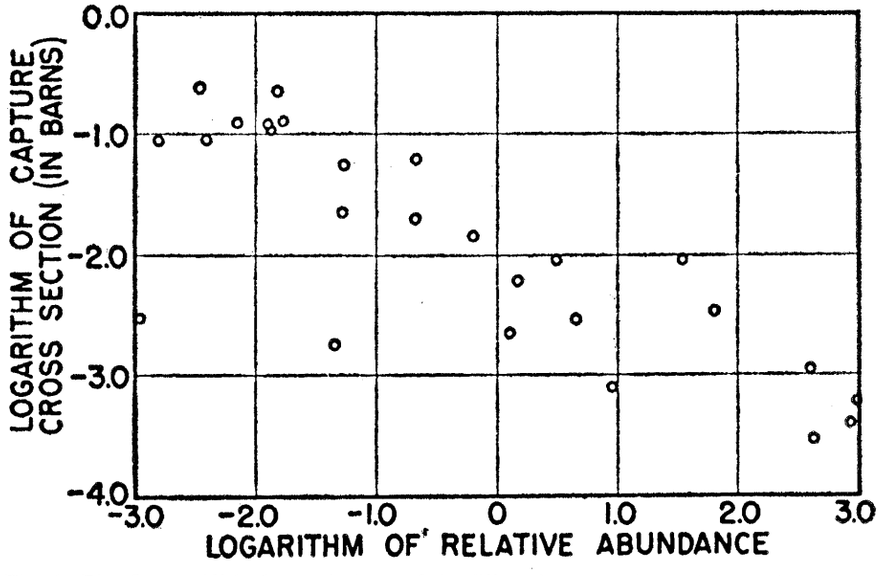


Fig. 1. The first published correlations of 1-million-electron-volt neutron-capture cross sections with relative abundance of nuclear species (*2*).

It is quite difficult to make direct experimental tests of the r-process theory since this process involves a transient thermodynamic equilibrium between (n,γ) and (γ,n) reactions and beta decay in an environment of radiation and a high-density, high-temperature neutron gas. Such a process is difficult to compute because of our limited ability to predict the behavior of nuclear matter having such large excesses of neutrons. On the other hand there are very explicit tests that one can make of the s-process theory, since this process involves relatively slow neutron capture by nuclides that are stable or that have a long half-life. In fact there should be a relatively simple, approximately inverse, relationship between Maxwellian-averaged capture cross sections and isotopic or elemental abundance for s-process nuclides: for small changes in atomic weight the capture cross section should be inversely proportional to abundance. Cross sections σ referred to in this article are given as Maxwellian averages,

$$\left\langle \frac{\sigma \cdot v}{v_T} \right\rangle,$$

where v_T is the average velocity at temperature T.

Early Capture Results

Experimental results on capture cross sections at neutron energies near 25,000 electron volts were relatively scarce until the late 1950's, when, partly because of the new need for results to test the s-process theory and partly because of similar needs on the part of designers of fast reactors, several new techniques were developed. Earlier techniques for measuring capture cross sections in the many-thousand-electron-volt (kev) range were mostly restricted to measurement of those nuclei that, upon capture, became radioactive and had a half-life of convenient length. Also, the neutron-energy range over which data could be obtained was severely limited by the scarcity of available monoenergetic neutron sources. A favorite source was ^{124}Sb-Be, which produces neutrons of 24 kev from the antimony's 1.7-Mev gamma rays through the reaction ^{9}Be(γ,n) (*10*). A second monoenergetic source was the ^{7}Li(p,n)^{7}Be reaction involving only neutrons emerging at specific angles greater than 90 degrees to the incident-proton direction. In this case protons of energy $E_p \cong 1.9$ million electron volts from a Van de Graaff accelerator were used, and a thin lithium target (*11*). The paucity of data obtained by these activation methods attests to their inadequacy.

Another general technique by which capture can be detected is observation of the nuclear gamma rays that are emitted in the 10^{-12} second or so following neutron capture. This technique requires much more elegant apparatus than the methods described above, but it is not restricted to nuclides that activate. This was very important, since most nuclides of astrophysical interest do not become radioactive upon capturing a neutron. Large liquid scintillators (volumes about 1000 liters) were developed in the late 1950's, and this led to a virtual explosion of new capture-cross-section measurements in the many-thousand-electron-volt range.

We (*12*) built the scintillator (Fig. 3) in such a way as to literally surround the capturing sample, so that a gamma pulse would be produced by virtually every neutron captured. A very severe requirement for the gamma-ray detector for work with neutrons in this energy range is that it be almost completely insensitive to neutrons. This is so because, for many elements, more than

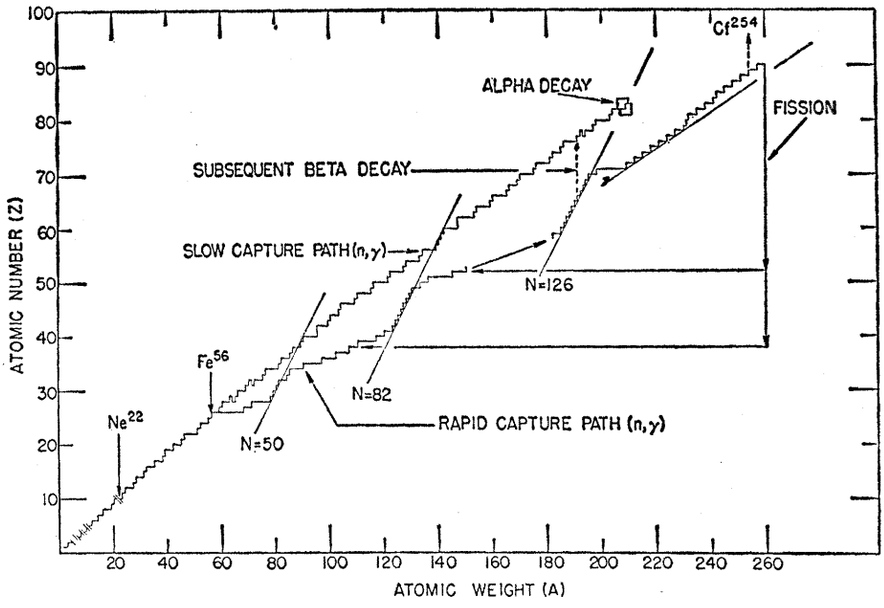


Fig. 2. The paths of the neutron-capture chains produced in the slow (s) and rapid (r) processes as proposed by Burbidge, Burbidge, Fowler, and Hoyle (*8*). The s-process path follows the stable isotopes; the r-process involves rapid, multiple neutron capture, later followed by beta decay.

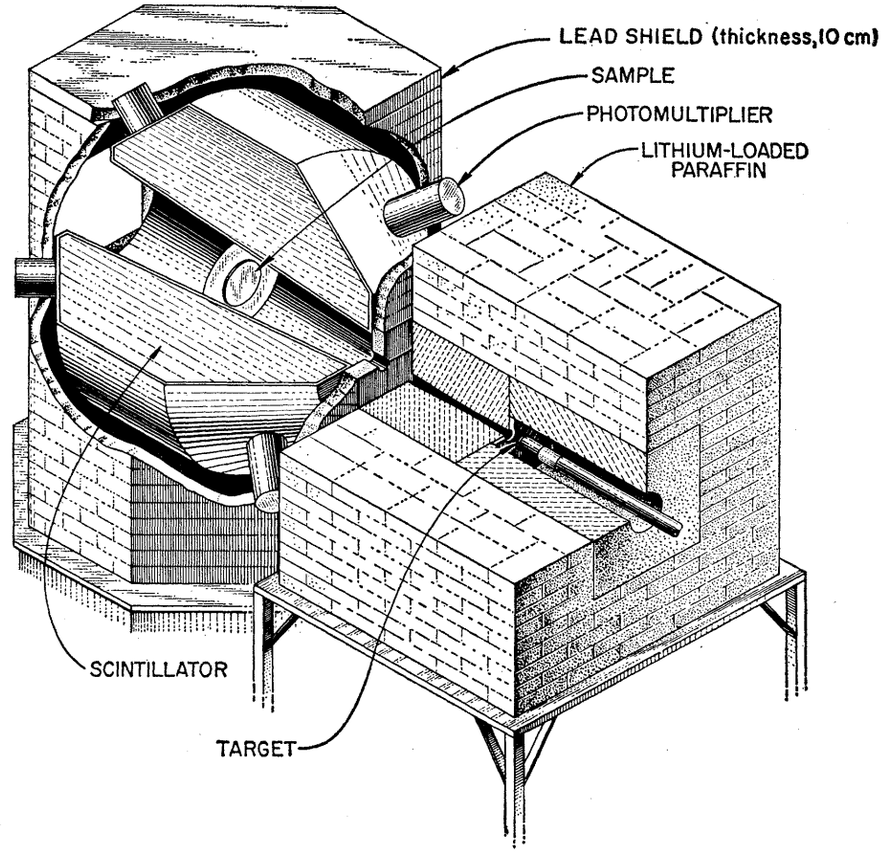


Fig. 3. Cutaway view of a large liquid scintillation detector used for neutron-capture cross section measurements. Neutrons are produced in the target by way of the ^{7}Li(p,n)^{7}Be reaction. After collimation they pass through a hole in the scintillator. Those captured in the sample produce gamma rays which are detected by the scintillator. Energies of the captured neutrons are measured by measuring the time of flight from the target to the sample.

99 percent of all such neutrons that interact undergo an elastic scattering into the detector. Successful application of the technique required the development of another tool—namely, fast pulsing of the neutron source (*13*). Although neutrons in this energy range cannot be easily produced in a monoenergetic beam, they can be produced in a broad band of energies (for example, 10,000 to 60,000 electron volts) by means of the $^{7}Li(p,n)^{7}Be$ reaction. Thus, if the proton beam were pulsed, the time of liberation of the neutron from the ^{7}Li target nucleus would be well known and a fast-response gamma detector at a measured distance could signal the neutron-capture event, giving the energy of the captured neutron from the time-of-flight:

$$E_n \simeq \frac{m}{2}\left(\frac{d}{t_c - t_L}\right)^2,$$

where m is the mass of the neutron, d is the distance from target to capturing sample, t_c is the time of capture, and t_L is the time of liberation of the neutron from the target.

Such a technique was developed at Oak Ridge during the late 1950's (Fig. 4). The proton beam was pulsed by careful tailoring of the beam during its transit between the ion source and the acceleration tube of the Van de Graaff accelerator. The tailoring consists of sinusoidally sweeping the beam back and forth across the narrow aperture and focusing (with gridded electrostatic lenses) the beam, to produce a tiny spot at the aperture. With such a system, pulses briefer than 5×10^{-9} second can be formed at repetition rates of $\sim 10^{6}$ per second. This pulsed-beam technique, together with use of the large liquid scintillator gamma-ray detector, made it possible to acquire a great quantity of data for a number of elements. However, measurements were restricted to elements of which reasonably large samples were available—that is, natural elements.

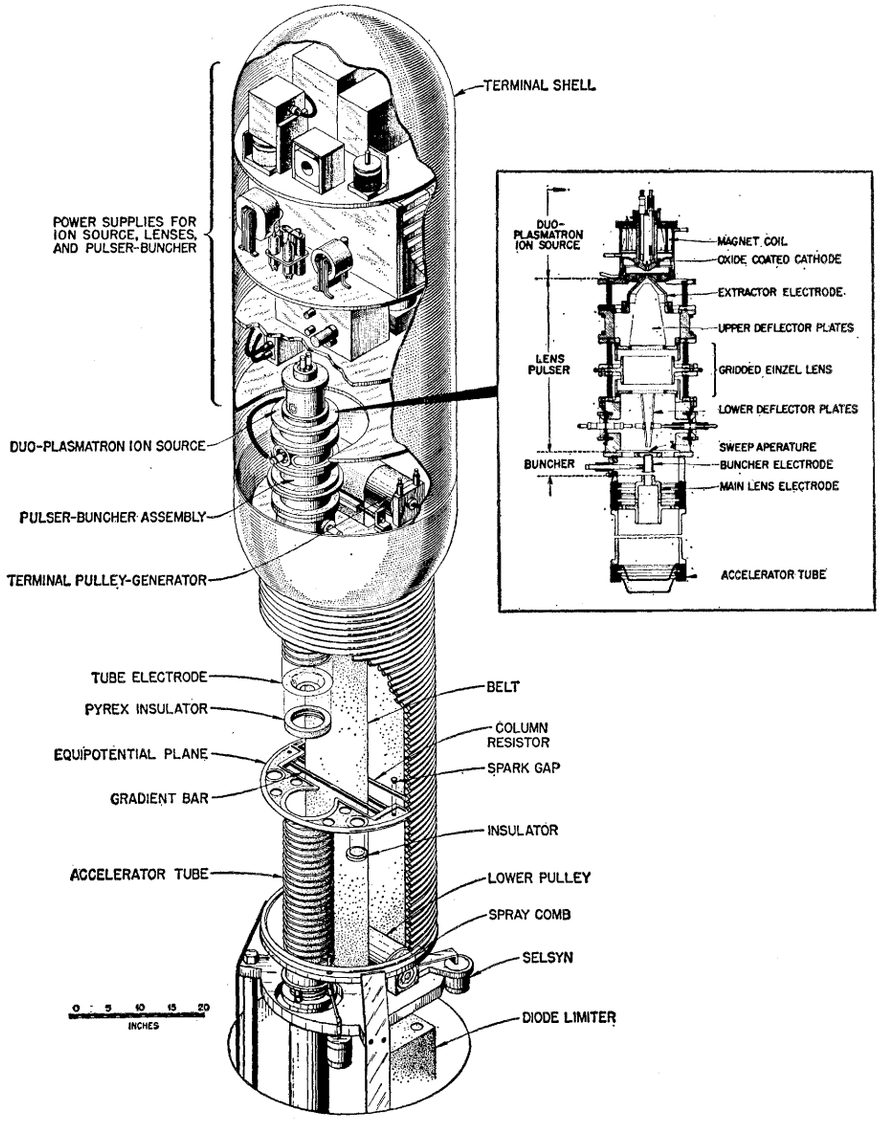


Fig. 4. Cutaway view of the Oak Ridge 3-megavolt Van de Graaff accelerator. Protons from the high-current ion sources are swept sinusoidally in an electric field across an aperture to produce short ($\sim 10^{-8}$-second) bursts of ions. Next the ions are "bunched" by slight deceleration of the leading edge of the pulse and acceleration of the trailing edge. This causes the pulse to be "squeezed" to $\sim 10^{-9}$ second, the time it takes light to travel about 0.3 meter.

S-Process Correlations

Even on the basis of such measurements of natural elements, the s-process correlations between abundance (N) and cross section gave a clear indication (*14*) (Fig. 5) that this hypothesis should be taken seriously and that measurements more critical to the hypothesis should be undertaken. The curve of Fig. 5a, composed mainly of nuclei produced solely by the s-process (s-process nuclei), shows a general clustering of points along an empirical curve, but the curve of Fig. 5b, composed mainly of r-process nuclei, shows no evidence of any such correlation.

Clayton, Fowler, Hull, and Zimmerman (*14*) showed that the observed (solar system) $N_s\sigma$ curve as a function of atomic weight, $N_s\sigma(A)$, could not be the result of exposure of ^{56}Fe "seed" nuclei to a single neutron flux. Thus, according to the s-process hypothesis, the solar system abundances must reflect a superposition of curves corresponding to different neutron fluxes. Each curve, of course, has a normalization proportional to the number of iron nuclei exposed to that flux. Let the $N\sigma$ product, per initial ^{56}Fe nucleus that results from an integrated neutron flux (neutrons per square centimeter) τ, be defined as

$$\Psi(\tau) = N\sigma(\tau)/N_o$$

where N_o is the total initial number of iron seed nuclei. Then, if $\rho(\tau)d\tau$ is the number of iron nuclei exposed to an integrated neutron flux between τ and $\tau + d\tau$, the abundances produced are

$$f(A) \equiv N_s\sigma(A) = \int_0^\infty \rho(\tau)\Psi(\tau)d\tau$$

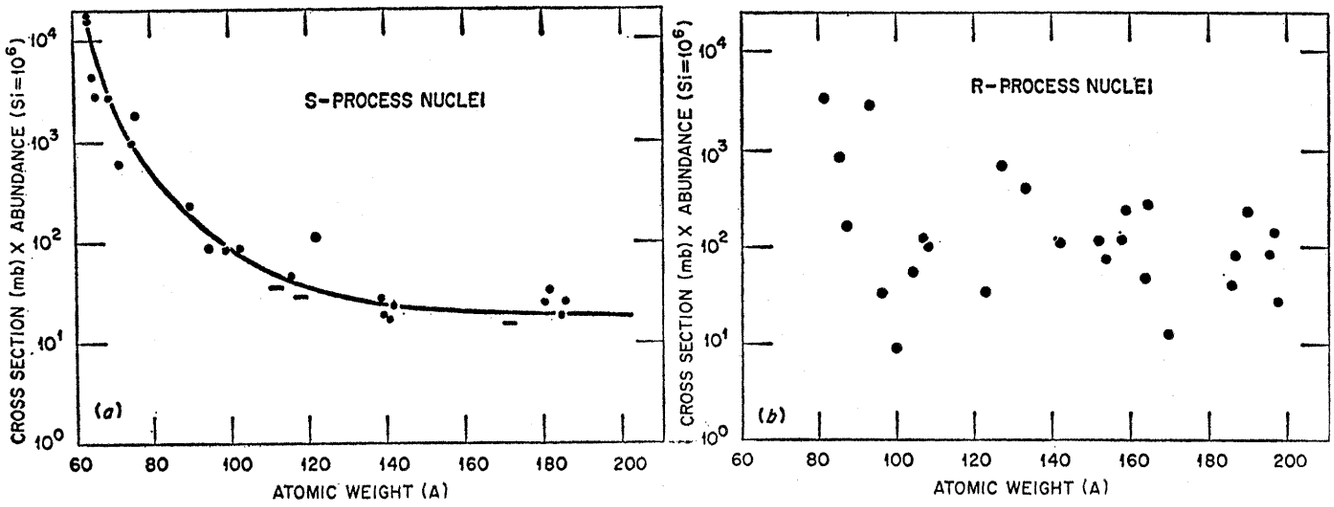


Fig. 5. Correlations of 25,000-electron-volt neutron cross sections times abundance relative to atomic weight for nuclei produced (a) predominantly by the s-process and (b) predominantly by the r-process. The correlation is more clearly seen than in earlier studies (Fig. 1), and the difference in the plots for the two types of nuclei is dramatic.

Since capture cross sections have low minima for certain regions of atomic weight, the calculated shapes of $f(A)$ as a function of atomic weight are characterized by a ledge-precipice structure. This structure is clearly present for any continuously decreasing flux distribution. For example, we see (Fig. 6) that, if a continuously decreasing flux distribution, such as $\rho(\tau) \propto \tau^{-n}$, is assumed (this distribution fit the data surprisingly well), a ledge-precipice structure is predicted at $N = 50$ ($A \sim 90$), $N = 82$ ($A \sim 140$), and $N = 126$ ($A \sim 210$). The characteristic breaks near these neutron magic numbers are a consequence of the systematics of neutron-capture cross sections, and their appearance in observed distributions is a "fingerprint" indicating the presence of neutron capture. Therefore, in order to further test the theory and to map out the s- and r-processes, additional quantitative data on neutron capture and abundance for specific nuclides were obviously needed.

Need for Separated Isotopes

It is clear that a quantitative test of the theory of s-process synthesis demands an accurate knowledge both of the neutron-capture cross sections and of the relative abundances of neighboring nuclei in the slow capture path. As the relative elemental abundances can be distorted by indeterminable amounts of physical and chemical fractionation, it is best to study the correlations for various s-process isotopes of a single element. The isotopic (solar-system) abundances are very well known (to within about 0.01 percent for terrestrial material and, in several cases, for meteorites) (*15*), and the only limitation to the accuracy of an $N_s\sigma$ test based on the use of isotopes is the accuracy of the capture-cross-section measurement.

Isotopes of tin were selected for the first such experiment (*14*). Figure 7 shows a portion of the slow-neutron-capture path illustrated in Fig. 2. In Fig. 7 we have plotted atomic number versus mass number, 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 r-process synthesis because they are shielded by isotopes of the same weight but lower Z. The rare isotopes ^{112}Sn, ^{114}Sn, and ^{115}Sn are produced through a separate process (p), through (ρ,γ) or (γ,n) reactions. The heavy isotopes ($A > 122$) should result from r-process synthesis only, because of the short beta-decay half-life of ^{121}Sn. The isotope ^{116}Sn lies directly on the s-process capture path and is shielded from any contribution from

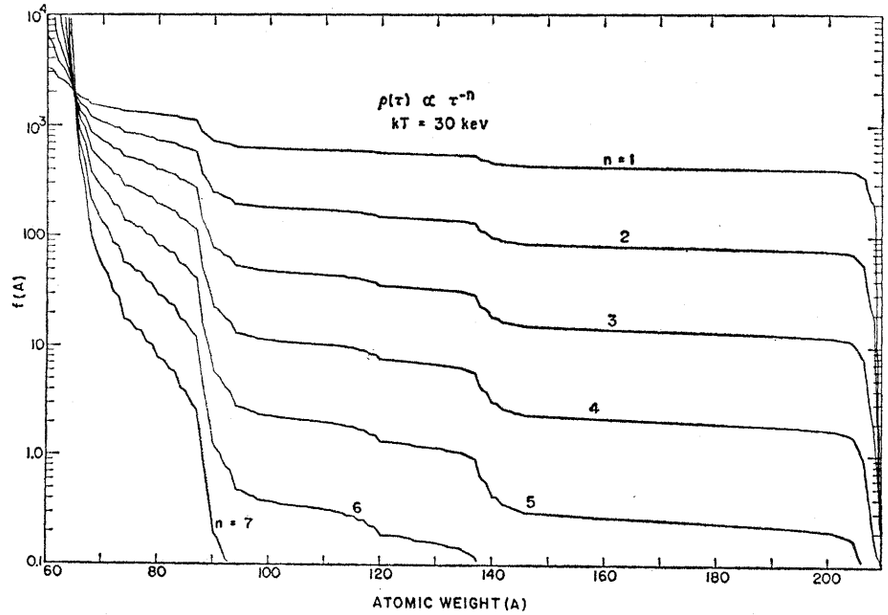


Fig. 6. Distribution of calculated values (see *14*) for cross section times abundance relative to atomic weight for s-process nuclei, an integrated flux-exposure history of the form $\rho(\tau) \propto \tau^{-n}$ being assumed. Characteristic breaks, due to neutron shell effects, persist near $A = 90$, 140, and 210.

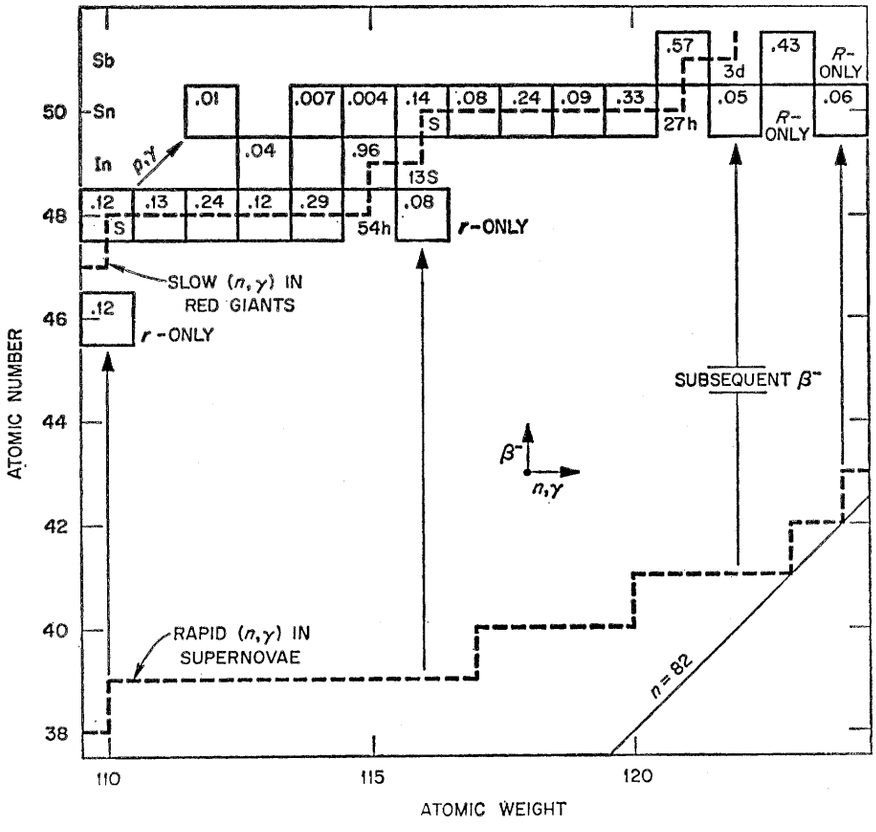


Fig. 7 (left). The s-process path near tin in a plot of atomic number relative to atomic weight. The dotted lines trace the s-process and r-process paths. The numbers in the small squares are the isotopic abundances. Isotope ^{116}Sn is shielded from any r-process contribution by ^{116}Cd, which, in turn, is produced only in the r-process because $\tau_{1/2}(^{115}\text{Cd}) \ll 10^8$ years. Intermediate weight isotopes of tin are produced by both processes; the heaviest isotopes of tin are produced solely by the r-process.

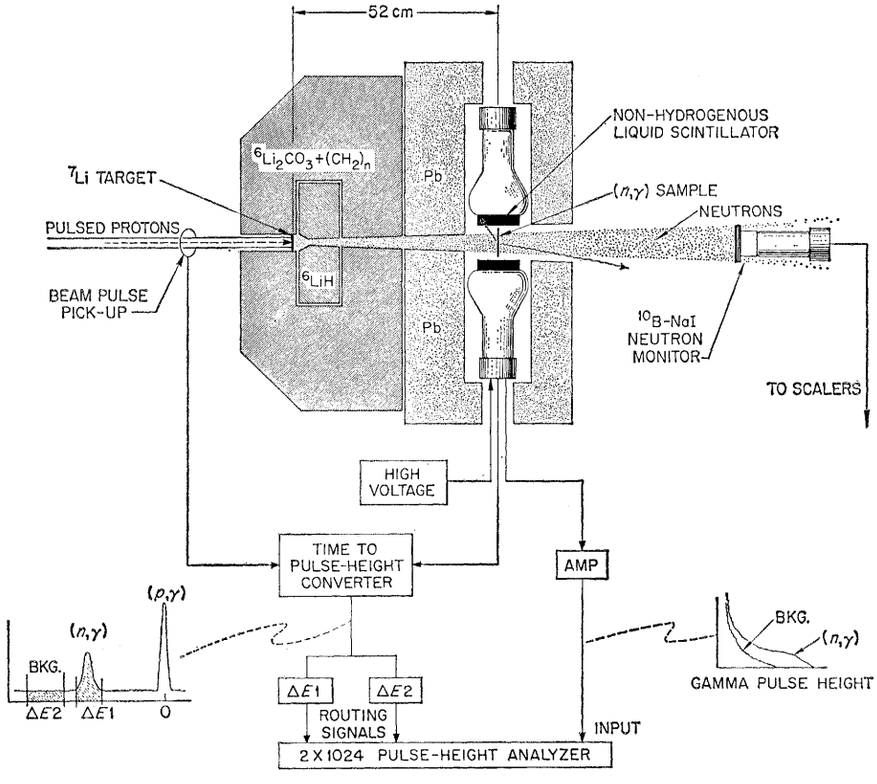


Fig. 8. Experimental arrangement for neutron-capture measurements. Gamma-ray pulses from the detectors are sorted in time [to make possible a continuous measurement of both "on-time" pulses and "off-time," or background (*BKG*) pulses] and in amplitude, in order to obtain absolute values for the cross section. Some (p,γ) and $(p,p'\gamma)$ reactions in the lithium target provide time-zero gamma calibration pulses. Neutron intensity is monitored by a detector placed in the emerging beam. The (n,γ) sample absorbs or scatters less than 10 percent of the beam.

the r-process by ^{116}Cd, which is stable against beta decay. The contribution of r-process synthesis to the abundances of ^{118}Sn and ^{120}Sn is apparently rather small, whereas for ^{117}Sn and ^{119}Sn it could have been significant. The r-process contributions can be fairly well interpolated from the ^{122}Sn and ^{124}Sn abundances, which are attributable to r-process synthesis only, as well as from the abundance of neighboring elements. The s-process hypothesis predicted that, for neutrons of $\sim$ 25,000-electron-volt energy, the product of cross section and isotopic abundance should be the same (or should vary slowly) for neighboring isotopes, since $f(A) = N_s\sigma$ should not change, beyond a few percent, for a small change in A.

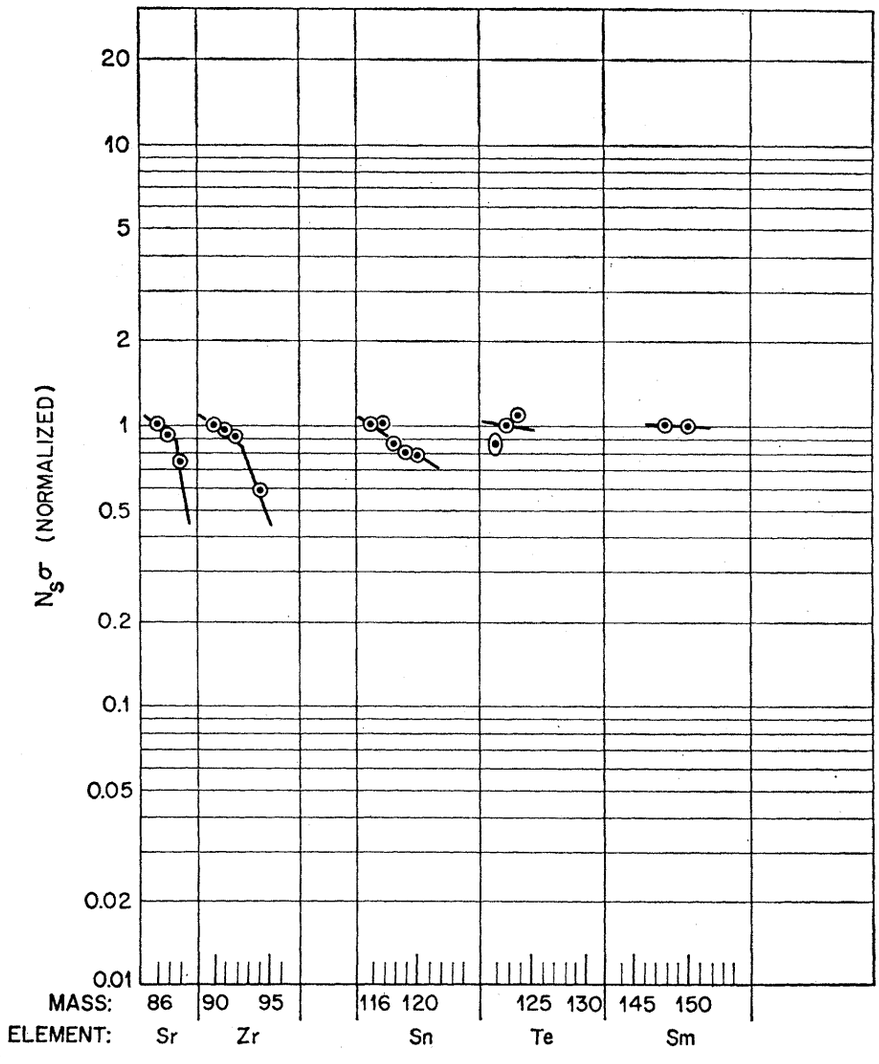
One difficulty was the fact that all existing techniques for measuring the capture cross sections called for a large amount ($\sim$ 1 mole) of separated isotope. Separations of this magnitude are quite expensive and require a lot of time. We concluded that it would be far less expensive to develop advanced detection and beam-pulsing techniques which would permit measurement with about 0.1 mole of each isotope. With such techniques a short neutron flight path could be used and therefore much higher neutron intensities could be obtained. In the case of the ^{7}Li(p,n) source, with samples as small as this, the overall time resolution had to be sufficient for measuring with an accuracy of a few percent the velocity of a neutron traveling at 8 million kilometers per hour over a flight path of as little as 7 centimeters. In other words, in order to use 0.1-mole samples, an overall time resolution of about 2×10^{-9} second was called for. To achieve this resolution required not only the development of a fast-response capture-gamma-ray detector with special characteristics but also a technique (known as klystron bunching) for "squeezing" the width of the accelerated-proton pulse from about 10^{-8} down to 10^{-9} second (*13*) (Fig. 4).

Fig. 9 (right). Summary of studies of cross section times isotopic abundance. The circles represent our experimental results. Results for all isotopes of a given element are plotted relative to each other, with one isotopic $N_s\sigma = 1.0$ for each element (*20, 21*). No deviation from the predicted behavior beyond the limits of experimental uncertainty is observed.

The buncher is a varying-voltage electrostatic lens located immediately beyond the aperture where the pulse is formed. The voltage is precisely phased to decelerate the leading edge of the proton pulse and to accelerate the trailing edge of the pulse just enough to cause the pulse to coalesce by the time it reaches the lithium target. The first detector we used (*16*) consists of a converter plate of graphite and bismuth, which converts gamma rays into electrons; these are, in turn, detected by a thin sheet of plastic scintillator. The efficiency of this detector is proportional to the gamma-ray energy, and thus the overall detector efficiency is dependent only upon the neutron binding energy. This was a distinct advantage over the large liquid scintillator, whose efficiency is strongly dependent upon capture-gamma-ray multiplicity. Later we developed a detector more than five times as efficient, but determination of its efficiency is less simple, and it requires much more sophisticated electronics (*17*). However, the increased efficiency has enabled us to use longer flight paths and therefore achieve much better neutron-energy resolution. A sketch of the experiment is shown in Fig. 8.

Tests of the s-Process Theory

Thus in our first efforts with separated isotopes we used the isotopes of tin (Fig. 7), the Oak Ridge National Laboratory 3-megavolt Van de Graaff accelerator, a 7-centimeter flight path, and a few grams of separated isotopes. The measured capture cross sections vary by an order of magnitude, but the product of cross section and isotopic abundance slowly and smoothly decreases with increasing weight. Figure



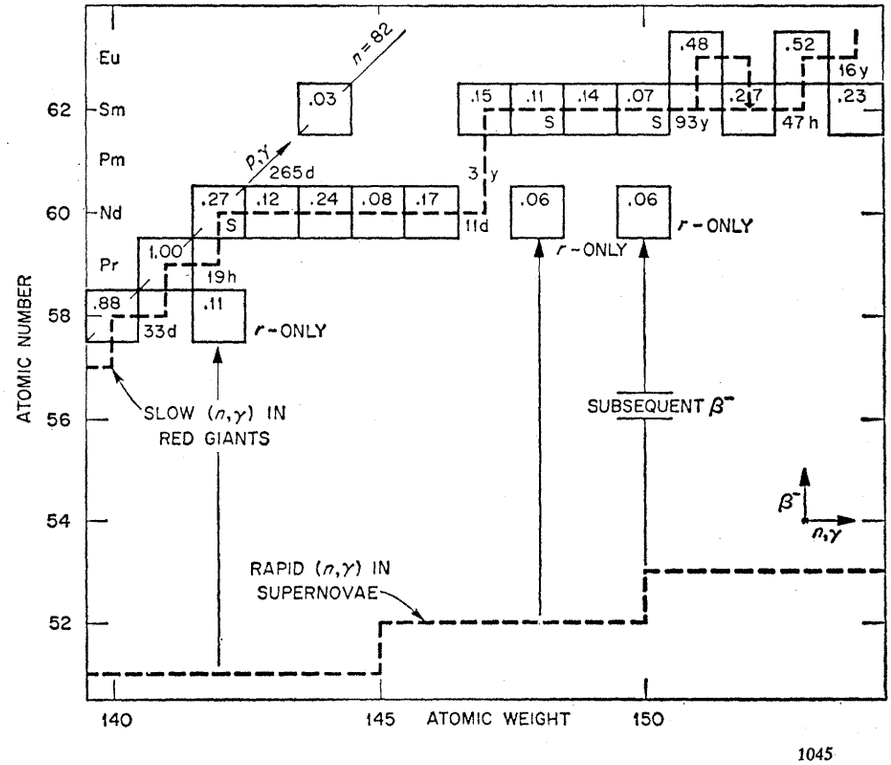


Fig. 10 (right). The s-process path near samarium. While neodymium, like tin, has one isotope produced by the s-process only, samarium has two (^{148}Sm and ^{150}Sm), and thus provided a critical test of the s-process theory.

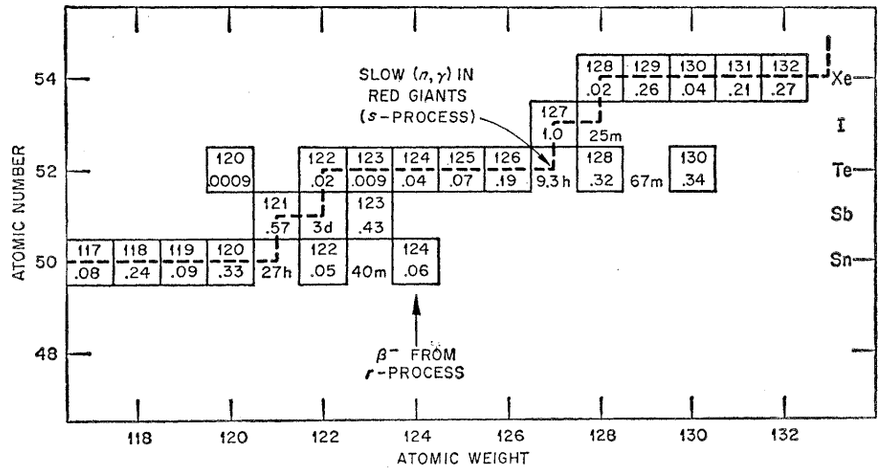


Fig. 11. The s-process path near tellurium. In this case the heaviest isotopes of tin and antimony team up to shield three tellurium isotopes from any r-process contribution and provide another stringent test of the s-process.

9 shows sections of the empirical s-process $N\sigma$ curve referring to selected elements which are especially important in exploring the s-process correlations. For each element, $N\sigma$ has been normalized with respect to a prominent s-process isotope, to eliminate dependence on relative elemental abundances. The results for tin (*18*) show a quite close fit with the slightly sloping curve expected from the s-process theory (*14*). One possible criticism of this result is that there is only *one* isotope produced solely by the s-process and corrections of up to 50 percent must be made for r-process contributions to the abundance of the other isotopes.

A second, more stringent test was provided by the isotopes of samarium (Fig. 10). Here the neutron-capture cross sections are relatively large and easier to measure, and there are two isotopes (^{148}Sm and ^{150}Sm) completely shielded from the r-process by ^{148}Nd and ^{150}Nd. Unlike the case for tin, no "corrections" for r-process contribution are necessary. The measured ratio (*19*) $(N\sigma)_{148}/(N\sigma)_{150}$ was (1.02 ± 0.06), as compared to an "expected" value of 0.98. This was regarded as a remarkably good confirmation of the s-process-synthesis hypothesis.

Recently we have made some measurements with tellurium isotopes, which are unique in that three of them (^{122}Te, ^{123}Te, and ^{124}Te) are completely shielded from r-process contributions (Fig. 11). The minor p-process contributions have been estimated from the abundances of ^{120}Te and the neighboring ^{112}Sn, ^{114}Sn, and ^{115}Sn—isotopes produced by the p-process only. The tellurium cross sections, like cross sections for the heavier tin isotopes, are relatively small, mostly because of the small energy-level density associated with the proximity of the closed shells of 50 protons and 82 neutrons. For example, the resonance spacing is several thousand electron volts for some of the isotopes, and cross section is inversely proportional to spacing. This means that much more experimental sensitivity is needed for measurements with tellurium isotopes than is needed, for example, with samarium isotopes, which have energy-level spacings of a few electron volts. The results obtained to date (see Fig. 9) are not detailed (we used six neutron energy bands, ranging from 30,000 to 125,000 electron volts, to obtain the Maxwellian-averaged cross section for $kT = 30{,}000$ electron volts) but agree with predictions of the s-process theory to within better than two statistical standard deviations. Much credit for these measurements goes to members of the Isotopes Division at Oak Ridge National Laboratory, who enriched the abundances of these rare isotopes sufficiently to permit a measurement to be made.

The cases of strontium and zirconium (Fig. 12) resemble the case of tin in that r-process contributions must be estimated and corrected for, though they are generally very small. For ^{87}Sr, in particular, the contribution is made through the very slowly decaying ^{87}Rb, most of which still exists and thus is available for measurement. Again, the correlations seen in Fig. 9 fit the theory very closely. However, since these nuclides occur near the breaks in the semiempirically predicted curve (*14*),

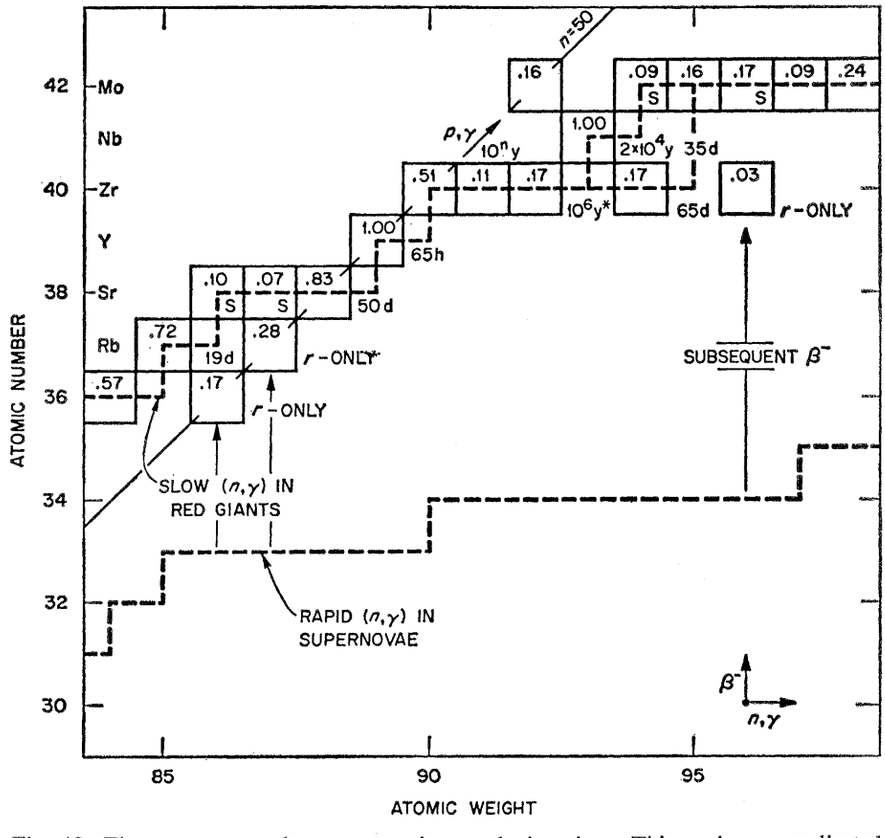


Fig. 12. The s-process path near strontium and zirconium. This region, complicated by the neutron shell $N = 50$, is important because the s-process correlation function, $N_s\sigma$, is rapidly changing with atomic weight.

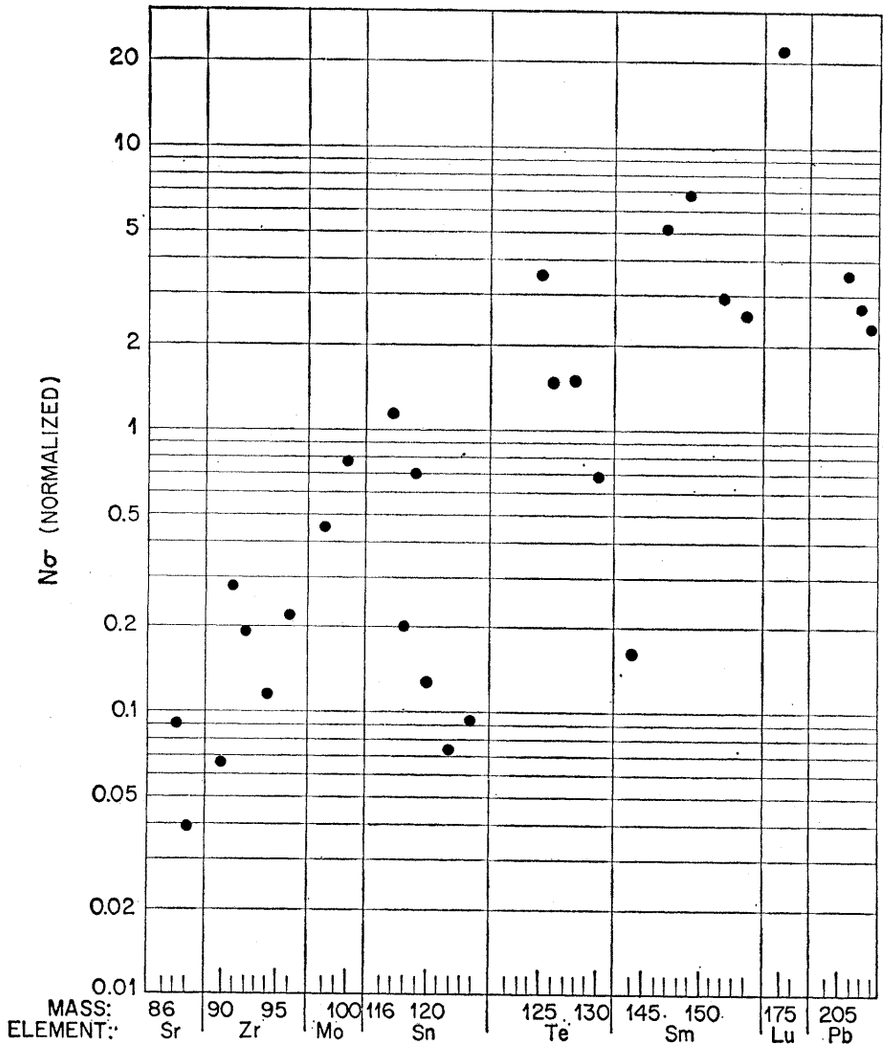
Fig. 13 (right). Normalized $N\sigma$ products for nuclei not produced by the s-process. This plot should be compared with that of Fig. 9. Except for a general upward trend for increasing weight, no correlations are seen, particularly as compared to the close correlations of Fig. 9.

the s-process-theory predictions are less independent in these two cases. Indeed, these cross sections and abundances help the astrophysicist refine the parameters of the s-process history of solar-system material, which differs substantially from, say, the s-process histories of some other stars (for example, the barium stars) in details of neutron flux, energy, and exposure time.

In Fig. 13, which closely follows Fig. 9 in format, we present the $N\sigma$ data for the predominantly r-process-produced and p-process-produced isotopes that have been measured, again normalized with respect to a prominent s-process isotope of each element to eliminate confusion due to uncertainty about elemental abundances. According to the neutron-capture theory, no correlation whatsoever would be expected for these nuclides, other than possibly a general trend, attributable to nuclear systematics—not the tight s-process correlations of Fig. 9. Indeed, the results vary by as much as a factor of 25; the median is a factor of about 4.

While the correlations between isotopic neutron-capture cross sections and solar-system abundances may not be considered absolutely conclusive evidence, they do strongly support the theory of s-process synthesis of heavy elements in stars. The agreement to within a few percent of the several testable and highly specific predictions is in marked contrast to the "order of magnitude" agreement frequently achieved between astrophysical hypothesis and observation.

From these experimental verifications of the s-process hypothesis, workers have gained sufficient confidence to try to fit, in more detail, the observed $N_s\sigma$ distribution with various possible distributions of neutron exposures that



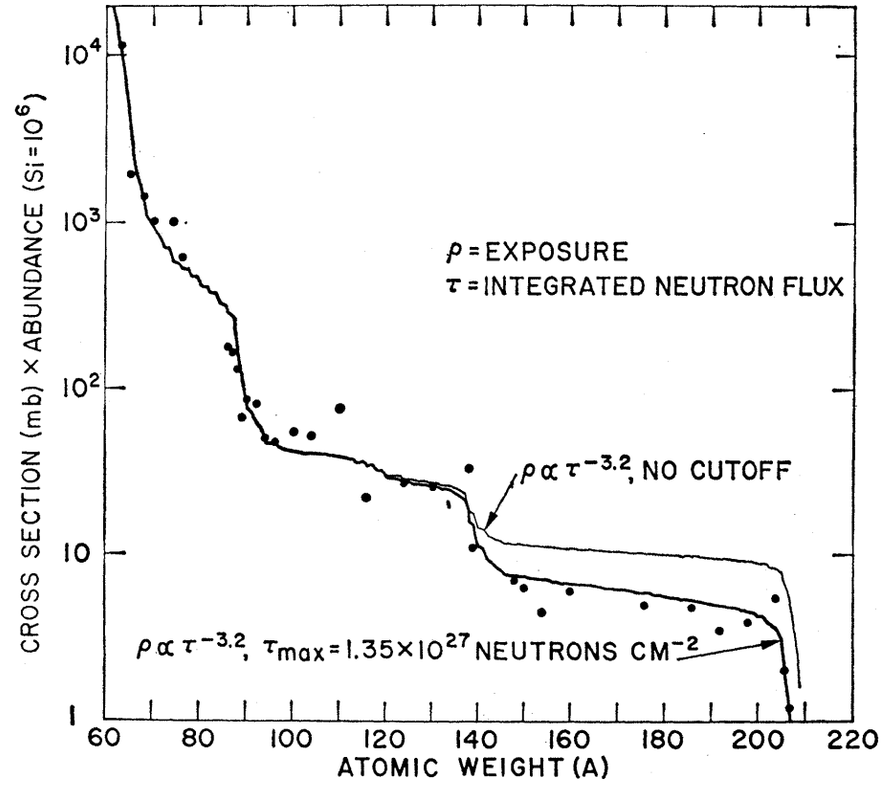


Fig. 14 (right). Summary of studies of cross section times relative abundance. The $N_s\sigma$ products are related to each other through their relative elemental abundance. The characteristic ledge-precipice structure is now evident in the data. The solid curves are computed (*20*, *21*) for the distribution of integrated flux exposures indicated.

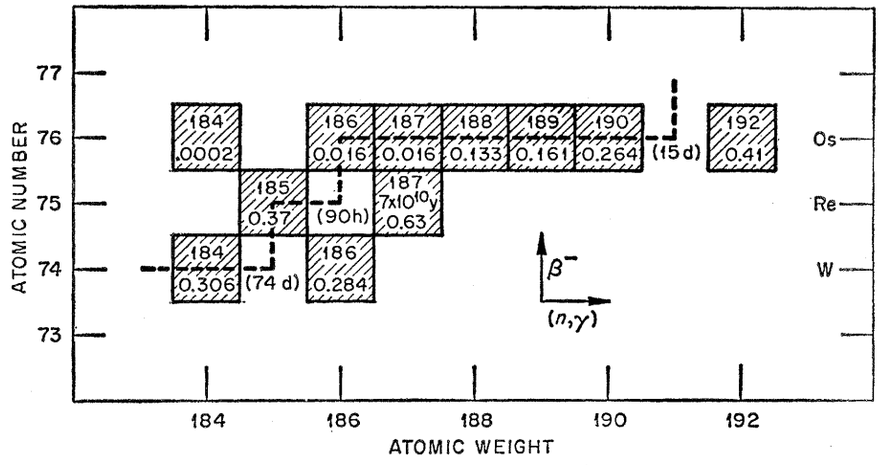


Fig. 15. The s-process path near osmium. Our knowledge of the change of $N_s\sigma$ with atomic weight enables us to compute rather precisely the $N_s\sigma$ product for ^{187}Os, given ^{186}Os. The present abundance of ^{187}Os is due to (i) s-process formation and (ii) beta decay of ^{187}Re. Therefore, once $N_s\sigma$ for ^{187}Os is determined, we can determine the effective time since ^{187}Re (an r-process isotope) was produced.

could have led to the observed solar-system abundances. Seeger, Fowler, and Clayton (*20*) and Seeger and Fowler (*21*) considered exposure distributions of $P(\tau) \propto e^{-\tau/\tau_0}$ and $P(\tau) \propto \tau^{-n}$. The most impressive fit (Fig. 14) results from the latter distribution with τ restricted to an upper-limit cutoff in integrated flux.

This upper limit corresponds to ~ 125 neutrons as the average number *captured* per seed nucleus exposed to the maximum integrated flux. The concept of such a cutoff is equivalent to saying that there is some maximum number of neutrons that can be produced in a certain phase of stellar evolution, and this seems a reasonable assumption. However, recent careful study of abundances and cross sections near the end ($A > 200$) of the s-process chain reveals that there apparently must be an additional component in $P(\tau)$ which peaks strongly for large values of τ, corresponding to > 150 neutrons captured per seed nucleus (*22*).

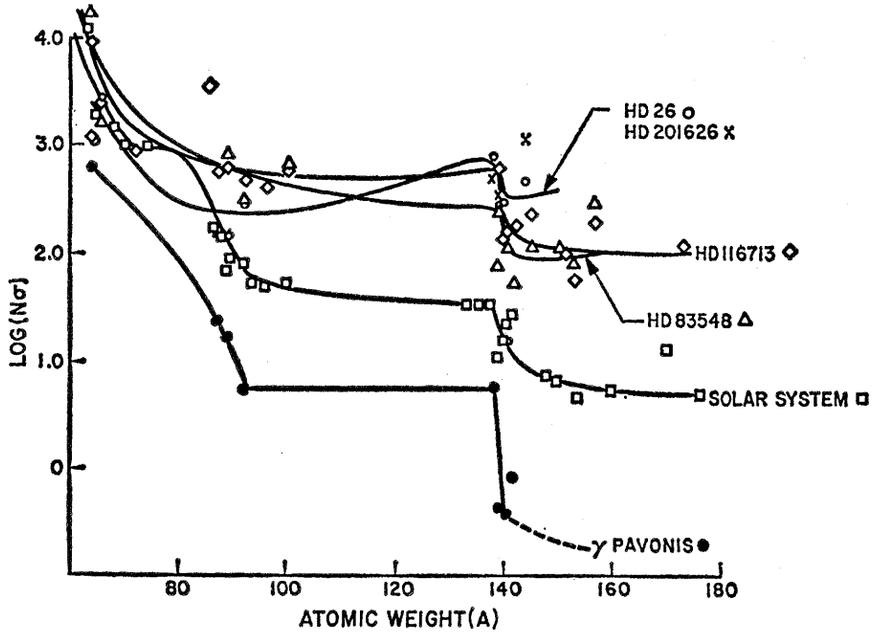


Fig. 16. Plot of $N\sigma$ products relative to atomic weight for several stars (see *24*). Elemental abundances do differ considerably, but the characteristic ledge-precipice structure, with breaks corresponding to shell effects on neutron capture, are clearly evident; γ Pavonis, which is most deficient in the heaviest elements, shows the largest discontinuity, near $A = 140$, as predicted by the s-process theory.

Our knowledge of the s-process has thus considerably increased over the past decade, but many mysteries remain, to focus our attention on the nuclear clues that still abound.

Further Implications

Several possible extensions of the s-process studies may be made in future, depending upon the success of the current studies. One is the determination of the abundance distribution of r-process nuclides. There are a few nuclides produced by the r-process only, but most are mixed with s-process nuclides. As the distribution of the s-process nuclides becomes better determined we can unscramble the mixture and obtain r-process-nuclide abundances, which are very important in deducing the r-process mechanisms (*14*). For example, Seeger, Fowler, and Clayton (*20*) have already found that the abundance distribution of r-process nuclides calls for two different production environments.

Another application dependent upon the details of the s-process is independent determination of the time that has elapsed since r-process synthesis of our solar-system material occurred (*23*). Osmium has two isotopes produced solely by the s-process (Fig. 15), but the abundance of the heavier one has been increased through radioactive decay of ^{187}Re. If the capture cross sections of ^{186}Os and ^{187}Os were accurately known, then, using s-process systematics, we could determine accurately that portion of ^{187}Os which is due to s-process synthesis. The difference must be due to the beta decay of rhenium. Therefore, given the relative abundances of rhenium and osmium, the time since synthesis of ^{187}Re can be calculated. This measurement awaits production of isotopes of osmium, which are unfortunately highly toxic and therefore difficult to prepare.

The s-process theory can also be an aid in the determination of solar-system abundances, particularly of gaseous, volatile, or strongly segregated elements whose abundances are quite uncertain. The method of obtaining the relative abundance of two elements is straightforward if the capture cross section of at least one isotope produced solely by the s-process is known for each element. Elements which have one or more such isotopes and which should therefore be examined from this point of view include krypton, xenon, osmi-

um, mercury, and lead, but such an examination should by no means be restricted to these elements, since many other elemental abundances are also poorly known.

Finally, it is known (*24*) that elemental abundance distributions in other parts of the Galaxy are significantly different from abundances in our solar system. These abundance distributions have been measured by observing atomic absorption lines from stars. The different $N\sigma$ distributions for these stars reveal some otherwise cloudy details about nucleosynthesis of materials outside our solar system. For example, it is already clear from the data thus far obtained (Fig. 16) that the ledge-precipice structure inherent in s-process nucleosynthesis is probably present in all cases to differing degrees. Those stars that show the largest discontinuity, near $A = 140$, are the most deficient in the heaviest elements, as predicted. Thus, while the materials of the solar system may be considered a typical sample of the Galaxy, the observed variations in other regions of the Galaxy can be understood in terms of continuing synthesis by neutron capture in individual stars.

As for ourselves, it is increasingly evident that we arise from a complicated past, intimately connected with the stars. Walt Whitman said it a century ago: "I believe every leaf of grass is the journey work of the stars."

Summary

The neutron buildup processes of heavy-element synthesis in stars have left us a number of tantalizing nuclear clues to the early history of solar-system material. Considerable illumination of our past history has been achieved through studying the correlations between abundance and neutron-capture cross section. Measurement of these cross sections required the development of new techniques for measuring time of flight of pulsed neutron beams. A clear conclusion is that many of our heavy elements were produced inside stars, which can be thought of as giant fast reactors. Extensions of these capture studies have given a clearer picture of additional, violent processes which produced some heavy elements, particularly thorium and uranium. In addition, the correlations have been used for obtaining an independent measure of the time that has elapsed since the solar-system material was synthesized. Finally, data on capture cross section relative to abundance will enable us to determine rather accurately the solar-system abundances of gaseous, volatile, and highly segregated elements.

References and Notes

1. D. J. Hughes, R. C. Garth, J. S. Levin, *Phys. Rev.* **91**, 1423 (1953); see also D. J. Hughes, *ibid.* **70**, 106A (1946).
2. R. A. Alpher, *ibid.* **74**, 1577 (1948); a preliminary account of this work was given by R. A. Alpher, H. Bethe, G. Gamow, *ibid.* **73**, 803 (1948).
3. V. M. Goldschmidt, *Skrifter Norske Videnskaps-Akad. Oslo. I: Mat. Naturv. Kl.* **1937**, No. 4 (1937).
4. H. Brown, *Rev. Mod. Phys.* **21**, 625 (1949).
5. H. E. Suess and H. C. Urey, *ibid.* **28**, 53 (1956).
6. P. W. Merrill, *Science* **115**, 484 (1952).
7. G. R. Burbidge, F. Hoyle, E. M. Burbidge, R. F. Christy, W. A. Fowler, *Phys. Rev.* **103**, 1145 (1956).
8. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957).
9. A. G. W. Cameron, *At. Energy Can. Ltd. AECL-454* (1957).
10. See, for example, R. L. Macklin, N. H. Lazar, W. S. Lyon, *Phys. Rev.* **107**, 504 (1957); H. W. Schmitt and C. W. Cook, *Nucl. Phys.* **20**, 202 (1960).
11. E. G. Bilpuch, L. W. Weston, H. W. Newson, *Ann. Phys. N.Y.* **10**, 455 (1960).
12. J. H. Gibbons, R. L. Macklin, P. D. Miller, J. H. Neiler, *Phys. Rev.* **122**, 182 (1961).
13. C. D. Moak, W. M. Good, R. F. King, J. W. Johnson, H. E. Banta, J. Judish, W. H. duPreez, *Rev. Sci. Instr.* **35**, 672 (1964).
14. D. D. Clayton, W. A. Fowler, T. E. Hull, B. A. Zimmerman, *Ann. Phys. N.Y.* **12**, 331 (1961).
15. V. R. Murthy and R. A. Schmitt, *J. Geophys. Res.* **68**, 911 (1963).
16. R. L. Macklin, J. H. Gibbons, T. Inada, *Nucl. Phys.* **43**, 353 (1963).
17. R. L. Macklin and J. H. Gibbons, *Phys. Rev.*, in press.
18. R. L. Macklin, T. Inada, J. H. Gibbons, *Nature* **194**, 1272 (1962).
19. R. L. Macklin, J. H Gibbons, T. Inada, *ibid.* **197**, 369 (1963).
20. P. A. Seeger, W. A. Fowler, D. D. Clayton, *Astrophys. J. Suppl.* **97**, 121 (1965).
21. P. A. Seeger and W. A. Fowler, *Astrophys. J.* **144**, 822 (1966).
22. D. D. Clayton, private communication, 1966.
23. ———, *Astrophys. J.* **139**, 637 (1964).
24. I. J. Danziger, *ibid.* **143**, 527 (1966).

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