Cross Sections for Nucleosynthesis in Stars and Bombs*†

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Three different processes in which nuclei are synthesized by the multiple capture of neutrons with energies in the keV range are reviewed and compared, namely the *s*-process and *r*-process in stars and the synthesis of very heavy nuclei in thermonuclear explosions. In the *s*-process, neutrons are captured by nuclei in the valley of β-stability. Knowledge of neutron capture cross sections of *s*-process nuclei can clarify such features of the *s*-process as elemental abundances, time scales, and temperatures. For producing the heaviest possible nuclei by neutron capture in thermonuclear explosions there are advantages in using the heaviest obtainable target nuclei, but for these there is the disadvantage of serious competition from neutron-induced fission. A channel theory of capture to fission ratios shows encouraging agreement with experiment. More data on capture to fission ratios would be valuable, particularly for odd–odd target nuclei. From capture to fission ratios, the number of open channels for fission can be deduced.

INTRODUCTION

In this paper we consider some different processes in which nuclei are synthesized by the multiple capture of neutrons, and discuss the kinds of cross-section data which would be most useful for understanding the several types of synthesis. Some cross sections are useful for establishing stellar clocks, thermometers, and calendars, whereas others help in producing nuclei which are heavier than any yet studied.

Let us first consider nucleosynthesis in the stars. Elemental abundances,[1–3] as deduced from terrestrial, meteoritic, and solar data, have shown no correlation between the chemical properties of an element and its abundance. Instead a correlation between abundance and nuclear properties, such as neutron shell structure, has become increasingly evident, and in the words of Suess and Urey[3] "the matter surrounding us bears signs of representing the ash of a cosmic nuclear fire in which it was created."

In the late 1940's Alpher, Gamow, and others[4] developed the hypothesis that all nuclei were created by rapid neutron capture at the time of a great explosion in which the universe was formed. In this undertaking they were encouraged by early $\sigma(n,\gamma)$ data of Hughes[5] for roughly 1-MeV neutrons, which revealed that the products of $\sigma(n,\gamma)$ times isotopic abundance were roughly constant. There were a number of difficulties with Gamow's hypothesis, such as the very short lifetime ($\sim 10^{-21}$ sec) of any nucleus of mass 5, and in detail it appeared that many of the existing nuclides could not have been made by a simple process of rapid capture.

It is now generally believed that no single synthetic process can account for the observed abundances of the nuclides, but that a large variety of nuclear reactions has been involved, and furthermore that these reactions have taken place and are continuing to occur in the stars. In their landmark of 1957, Burbidge, Burbidge, Fowler, and Hoyle[6] reviewed a number of synthetic nuclear processes and for nuclei of $A \gtrsim 60$ they assigned the dominant role of synthesis to multiple neutron capture starting from Fe^{56} or nearby nuclei. In a series of papers, Cameron[7] also emphasizes the role of neutron capture for nucleosynthesis, but many details of his analysis differ from those[6] of B^{2}FH. For comparisons and a recent review, the reader is referred to the paper of Bashkin.[8]

At the outset we note some presumptive evidence for the occurrence of neutron capture in present day stars. For one thing spectral lines of the unstable element technetium have been observed from some stars.[9] Moreover, the decay of light from supernovae with a half-life of about 60 days has been interpreted[6] as indicating the production in supernovae of Cf^{254} which decays by spontaneous fission with a half-life of about 60 days. Both Tc and Cf^{254} would be most naturally accounted for as products of neutron capture in the proper environment, though this is by no means the only explanation available for Tc.[7]

In interpreting the elemental and isotopic abundance data for $A \gtrsim 60$, Burbidge *et al.*[6] found it necessary to assume that two quite different types of neutron capture were involved; namely capture on a slow

* Work performed under the auspices of the U.S. Atomic Energy Commission.

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[1] V. M. Goldschmidt, Skrifter Norske Videnskaps-Akad. Oslo. I. Mat.-Naturv. Kl. No. 4 (1937).

[2] H. Brown, Rev. Mod. Phys. **21**, 625 (1949).

[3] H. E. Suess and H. C. Urey, Rev. Mod. Phys. **28**, 53 (1956).

[4] R. A. Alpher, H. A. Bethe, and G. Gamow, Phys. Rev. **73**, 803 (1948); R. A. Alpher, *ibid.* **74**, 1577 (1948); see also the review: R. A. Alpher and R. C. Herman, Rev. Mod. Phys. **22**, 153 (1950).

[5] D. J. Hughes, R. C. Garth, and J. S. Levin, Phys. Rev. **91**, 1423 (1953) and earlier papers referred to therein.

[6] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).

[7] A. G. W. Cameron, Astrophys. J. **130**, 429 (1959) and other articles referred to therein.

[8] S. Bashkin, "The Origin of the Chemical Elements," in *Stellar Structure*, L. H. Aller and D. B. McLaughlin, Eds. (University of Chicago Press, Chicago, Ill., 1965), Chap. 1.

[9] P. W. Merrill, Science **115**, 484 (1952).

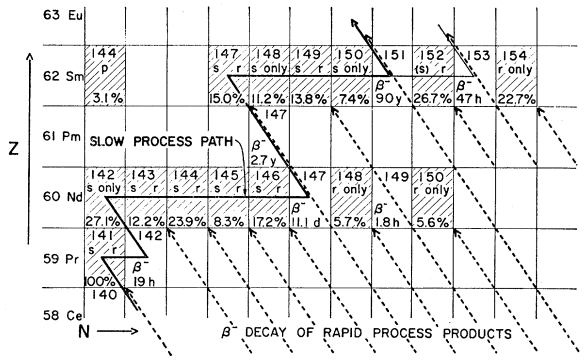

FIG. 1. Products of slow and rapid capture. For slow capture, β^- decay generally precedes the next capture and certain nuclei (Nd 148, Nd 150, and Sm 154 in the figure) are bypassed. The primary products of rapid capture are highly neutron rich and β^- to the first stable mass nuclides. Thus nuclei such as Nd 142, Sm 148, and Sm 150 cannot be formed by decay of r-process products. For nuclides with long lifetimes, such as Sm 151 ($\tau=$ 90 yr) some branching in the s-process path may occur. Neutrons on the proton rich side of the s-process path are attributed[6] to the p-process (proton capture) and are seldom abundant.

time scale (s-process) and rapid capture (r-process), where by slow and rapid we mean relative to the lifetimes for β decay. If one considers the addition of several neutrons to a target nucleus it is clear that the results will be affected by the ratio of capture lifetimes (τ_c) to β^- decay lifetimes, τ_β. If the neutron density in the star is so low that $\tau_c \gg \tau_\beta$ then any β unstable capture product will have time to decay back to β stability before the next neutron is captured. If, on the other hand, the neutron density is so high that $\tau_c \ll \tau_\beta$, one will swiftly build up neutron rich nuclides until the neutron binding energies are so low that an equilibrium between (n,γ) and (γ,n) reactions is approached. Changes of Z can then result from β^- decay of these neutron rich nuclides. The nuclide abundances resulting from these two limiting rates of capture are quite different, as a glance at almost any section of the chart of the nuclides for $60 \lesssim A \lesssim 210$ will show. Consider, for example, the region $142 \lesssim A \lesssim 153$ as shown in Fig. 1. It is readily seen that some stable nuclei are bypassed by the slow capture process (Nd 148, Nd 150, and Sm 154 in the figure), while others such as Nd 142, Sm 148, and Sm 150 cannot be reached by β^- decay of the rapid neutron products. By an examination of these "s-only" and "r-only" nuclides one can attempt to disentangle the results of the two capture processes. Some β^- lifetimes in the s process path are so long that alternate routes in the path may occur. The nuclides Ni^{63} (100 yr), Se^{79} (10^5 yr), Kr^{85} (10 yr), Zr^{93} (10^6 yr), Nb^{94} (2×10^4 yr), Tc^{99} (2×10^5 yr), Sm^{151} (90 yr), and Ho^{166} (10^5 yr) are examples. Eventually one may hope that a careful analysis of these alternates will provide more precise information on the time scale of the s-process, which may be of the order of 10^3 yr.[6,10] In stars the decaying nuclei will not always be in their ground states but rather they will have a (temperature-dependent) spectrum of initial states and therefore the lifetimes in stellar interiors may not be the same as the laboratory values which are indicated above. Thus the temperature and time scale will both be involved. At high temperatures this effect may lead to a shortening of β decay lifetimes by many orders of magnitude.[7,10]

THE s-PROCESS

Recent analyses of the s- and r-process chains have been published by Clayton, Fowler, Hull, and Zimmerman[11] and by Seeger, Fowler, and Clayton.[10] For the s-process we need to consider only nuclei with measurable properties and hence the analysis can be made with more assurance than for the r-process where highly neutron rich nuclides are involved. We may analyse the s-process as follows. Consider a homogeneous stellar region in which the neutron density is $n(t)$ and $N_A(t)$ s-process nuclei of mass A are present. Since mass A nuclei are produced through neutron capture by mass A-1 nuclei and depleted through capture by mass A, we have

$$dN_A(t)/dt = \langle\sigma v\rangle_{A-1} n(t) N_{A-1}(t) - \langle\sigma v\rangle_A n(t) N_A(t), \quad (1)$$

where $n\langle\sigma v\rangle_A$ is the capture rate averaged over a Maxwell–Boltzmann neutron energy spectrum corresponding to a temperature in the star. Temperatures of a few tens of kilovolts are typically considered. If we define an average mass A capture cross section $\sigma_A = \langle\sigma v\rangle_A/\bar{v}$, divide Eq. (1) by $n\bar{v}$, and introduce the neutron *exposure*

$$\tau = \int^t n\bar{v}\, dt',$$

then Eq. (1) may be rewritten

$$dN_A/d\tau = \sigma_{A-1}N_{A-1} - \sigma_A N_A. \quad (2)$$

One seeks solutions of the set of equation (2) having for example $56 \lesssim A \lesssim 210$ and an initial condition of $N_A = 0$ for $A \neq 56$. The s-process will evidently be terminated by α decay around mass 210. It can then be seen[11] that for the important nuclei in a capture chain, the two terms on the right-hand side of Eq. (2) are nearly equal, so both production ($\sigma_{A-1}N_{A-1}$) and loss ($\sigma_A N_A$) are large compared to the rate of change of N_A, $dN_A/d\tau$. Thus over a small range of A, one would expect $\sigma_A N_A$ to be nearly constant or more generally, *for s-process nuclei one expects the product of capture cross section and abundance* ($\sigma_A N_A$) *to be a slowly* (*and smoothly*) *varying function of* A. That this is indeed the case can be seen from Fig. 2, where the data are from Ref. 10. This smooth variation of $\sigma_A N_A$ is probably the strongest evidence that neutron capture on a slow

[10] P. A. Seeger, W. A. Fowler, and D. D. Clayton, Astrophys. J. Suppl. No. 97 (1965).

[11] D. D. Clayton, W. A. Fowler, T. E. Hull, and B. A. Zimmerman, Ann. Phys. (N.Y.) **12**, 331 (1961).

time scale has been an important source of the heavier nuclei ($A \gtrsim 60$). If one constructs an analogy to Fig. 2 for the r-process nuclei, no smooth variation with A is found.

Two other general features of the s-process analysis are worth noting. First of all, it is found that the observed abundances cannot be produced by a single exposure, τ, but rather that a range of exposure is required. In Fig. 2 an exposure distribution proportional to $\tau^{-3.18}$ with τ less than 1.35×10^{27} neutrons/cm^2 was used to generate the theoretical curve.[12] It seems quite natural that a considerable range of exposures are involved since the synthesis presumably took place in a variety of stars. For $\tau=0.2$, 0.4, 0.8, or 1.2×10^{27}, the average number of neutrons captured starting from Fe^{56} is, respectively, about 7, 20, 54, or 114.[11]

Secondly, we observe in Fig. 2 that the theoretical curve and perhaps also the experimental data have a ledge and precipice structure. The precipices occur near neutron magic nuclei ($N=50$ and $N=82$) and are a consequence of their small capture cross sections, together with an assumed smooth exposure variation.

For the s-process analysis, it is clear that measured capture cross sections of many of the stable nuclei for neutrons in the energy range 10–100 keV, are of great interest.

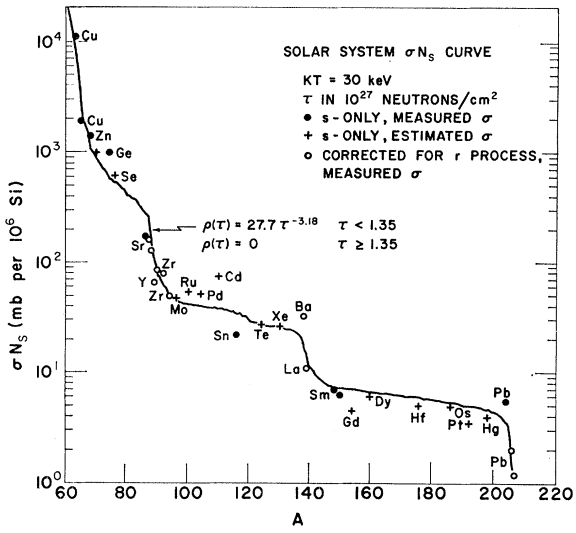

FIG. 2. The product of neutron capture cross section (σ_s) and nuclear abundance (N_s) is plotted for s-process nuclei as a function of atomic weight. Abundance (relative to Si) and cross section data from Ref. 10. The function $\rho(\tau)$ represents the number of Fe 56 seed nuclei subjected to the neutron exposure τ and the solid curve was calculated in Ref. 12 for $\rho(\tau)=27.7\ \tau^{-3.18}$ for $\tau<1.35\times10^{27}$ neutrons/cm^2 and $\rho(\tau)=0$ for larger τ. The general agreement between experimental points and calculations is strong evidence for the reality of the s-process.

THE r-PROCESS

The r-process involves neutron capture and β^- decay by neutron rich nuclides far from the valley of β stability. There are several lines of evidence for the r-process. 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[10] for r-process nuclei near $A=80$, 130, and 195 can be correlated with the neutron shells ($N=50$, 82, 126) for neutron rich nuclei. In addition, the mere existence of trans-bismuth nuclides seems most naturally explained as a result of rapid neutron capture. If Cf^{254} is, in fact, responsible for the supernova light curves this would be clear evidence that rapid capture is taking place in supernovae, which are indeed the favored location of the r-process.[6]

For a detailed analysis of the r-process one must predict the neutron binding energies of neutron rich nuclides. Two such predictions from semiempirical mass formulas including shell effects have recently been published by Seeger[13] and Cameron.[14] In the extrapolation from near the valley of β stability to neutron rich nuclides, Seeger used a conventional parabolic form of the symmetry energy while Cameron used an exponential form of the symmetry energy, so chosen as to make infinite neutron matter barely unbound. While Cameron's suggestion that the mass formula should extrapolate to the correct binding energy for neutron matter is certainly a sound one, uncertainty in the theory of neutron matter must render the extrapolation rather uncertain at present. The different treatments of the symmetry energy make Cameron's binding energies fall off less rapidly with $(N-Z)$ than do Seeger's.

Seeger has used his mass formula,[10] together with expressions for the β^- decay lifetimes of the neutron-rich nuclides to study the r-process. The time scale of the r-process is largely determined by the β decay lifetimes and durations for the r-process of the order of seconds to minutes were found by Seeger. As anticipated, the r-process abundance peaks can be attributed to longer β^- decay lifetimes near the neutron shells. Since β^- decay lifetimes are postulated to determine the rate of the r-process, very little can be deduced concerning the actual neutron densities or exposures—except that they must be very large. Seeger considered neutron densities between 10^{18} and 10^{32} neutrons/cm^3 to be acceptable and since he was assuming temperatures of about 100 keV, acceptable exposures ($\int nvdt$) ranged from around 10^{27} to 10^{42} neutrons/cm^2.

When very heavy nuclei ($A\sim270$?) are made in the r-process we may expect spontaneous fission to compete with β decay so that the heavy mass limit of the r-process is determined by spontaneous fission lifetimes of neutron rich nuclides. The heavy nuclei will be in a variety of excited states so that the usual distinctions

[12] P. A. Seeger and W. A. Fowler, Astrophys. J. (to be published in 1966).
[13] P. A. Seeger, Nucl. Phys. **25**, 1 (1961); and Ref. 10.
[14] A. G. W. Cameron and R. M. Elkin, Can. J. Phys. **43**, 1288 (1965); and Goddard Institute for Space Studies Report (1965).

between spontaneous, neutron-induced and photo fission are probably not very useful. In any case, the resulting fission products may then rejoin the r-process path so that there is a possibility of cycling together with a multiplication of nuclei.

If one uses the exponential mass formula of Cameron,[14] instead of Seeger's mass formula it might appear that the r-process abundance peaks could be not duplicated. However with freedom in the choice of neutron density and temperature, it is possible that Cameron's or other mass formulas could be equally successful and recent work by Seeger has confirmed this possibility.[15]

The nuclei participating in the r-process have roughly fifteen to forty[10] more neutrons (for a given A) than any stable nuclides. Therefore it does not appear likely that they can be studied in the laboratory. However, by studying neutron rich nuclides in general, one can gain a better understanding of the physics involved in the r-process. Fission products are the most common neutron rich nuclides in the laboratory and the doubly magic fission product Sn^{132} ($\tau \simeq 2$ min) is only about two mass units away from a calculated r-process path.[10] Of even greater relevance may be the data obtained from multiple neutron capture experiments in thermonuclear explosions. In these experiments one can see how neutron capture cross sections (and binding energies) vary as more and more neutrons are added to a target nucleus.

THERMONUCLEAR EXPLOSIONS

In the first terrestrial thermonuclear explosion, namely the Mike device of 1 November, 1952, heavy nuclei were produced by the exposure of U^{238} to high neutron fluxes. In the resulting debris, nuclides with masses through $A=255$ were found,[16–18] the elements Einsteinium and Fermium[16] were discovered as well as[17] Cf^{254}. In a thermonuclear explosion, neutrons are captured in a time (<1 μsec) short compared to β^- decay lifetimes. Thus starting from a target of U^{238}, it is natural to think of the capture chain proceeding to higher mass uranium isotopes, which later β decay to the nuclides such as Cf^{254} or Es^{255} which are observed in the debris. Thus one would expect that the number of observed nuclei of mass A, $N(A)$, would equal the number of mass A uranium nuclei present at the end of the neutron exposure, and that from the observed mass distribution, $N(A)$, one could deduce the relative capture cross sections of the uranium nuclei having $238 \leq A \leq 255$. Most of the captured neutrons have energies of the order of 10 keV, so that one would also expect the capture cross sections to be predictable by statistical theory. For the Mike device, such an analysis is beset by difficulties. In particular, different portions of the uranium were subjected to quite different exposures. Nevertheless, simple analyses[19–21] seemed to show that the capture cross sections of the uranium isotopes did not noticeably decrease with increasing mass, a conclusion at variance with all semiempirical mass formulas and statistical theories of neutron capture. From mass formulas, we expect the neutron binding energies to decrease with increasing A, and from statistical theory we then expect level spacing to increase and neutron widths to increase. Because of the increased competition from compound elastic scattering, neutron capture cross sections will thus decrease with increasing A. It was partly these Mike results which prompted Cameron to invent his exponential mass formula which would predict larger neutron binding energies and larger $\sigma(n,\gamma)$ for heavy uranium nuclei.

More recently, several low yield nuclear devices have been exploded underground for the purpose of creating heavy nuclides. In the Par[22] and Barbel[23] events of October 1964, small targets of U^{238} were exposed and it is believed for each event that the neutron flux was quite uniform through the target. In the debris which was recovered a day or more after the explosion by drilling back into the explosion site, nuclides through $A=257$ were detected. Once more a simple analysis[21,23] of the mass abundance curve seemed to indicate a remarkable constancy to the uranium capture cross sections. However, odd–even structure in the mass curve pointed the way to a different interpretation of the abundance data.

It is well known[24] that even–even nuclides have average capture cross sections for keV neutrons which are smaller than those of nearby odd-A nuclides. Thus the even-A uranium nuclides should have smaller capture cross sections than the odd-A uranium nuclides. The development of a uranium capture chain is described by equation (2) and as before $\sigma_A N_A$ should be a smooth function of A. Hence for a uranium capture chain we expect even-A nuclides to be relatively more abundant than the odd-A nuclides. Such an odd–even effect is indeed observed for Mike, Par, and Barbel so long as we consider nuclides with $A<250$. But for heavier nuclides, the odd–even effect reverses and odd-A nuclides are relatively more abundant. When this reversal became evident in the Par and Barbel data, Diamond and Fields[25] at once suggested that

[15] P. A. Seeger, private communication and paper presented at Conf. on "Why and how should we study nuclides far from the line of β stability," Lysekil, Sweden, August 1966.
[16] A. Ghiorso *et al.*, Phys. Rev. **99,** 1048 (1955).
[17] P. R. Fields *et al.*, Phys. Rev. **107,** 1087 (1957).
[18] H. Diamond *et al.*, Phys. Rev. **119,** 2000 (1960).
[19] A. G. W. Cameron, Can. J. Phys. **37,** 322 (1959).
[20] D. W. Dorn, Phys. Rev. **126,** 693 (1962).
[21] G. I. Bell, Phys. Rev. **139,** B1207 (1965).
[22] D. W. Dorn and R. W. Hoff, Phys. Rev. Letters **14,** 440 (1965).
[23] Los Alamos Radiochemistry Group, Phys. Rev. Letters **14,** 962 (1965).
[24] H. W. Newson and J. H. Gibbons, "Neutron Cross Sections in the keV Region," in *Fast Neutron Physics,* J. B. Marion and J. F. Fowler, Eds. (Interscience Publishers, Inc., New York, 1963), Chap. V. L.
[25] H. Diamond and P. R. Fields (private communication).

perhaps some captures were taking place in odd-Z nuclei. Since odd–odd nuclei are expected[21] to have even larger capture cross sections than odd-Z, even-N nuclei, the odd–even effect should be reversed for capture in an odd-Z chain.

A detailed analysis[21] has shown that capture in odd-Z chains can explain the observed mass abundance curves. The production of odd-Z nuclides resulting from exposure of U^{238} (and deuterium) to 14-MeV neutrons was estimated. It was concluded that the reaction $U^{238}(n,p)Pa^{238}$, $U^{238}(d,n)Np^{239}$, and $U^{238}(d,2n)Np^{238}$ could lead to an abundance of Pa and Np about equal to 10^{-4} or 10^{-3} times the uranium abundance. Capture cross sections were then calculated using Seeger's[13] mass formula and statistical theory and it was found that the odd-Z capture cross sections averaged over an odd-even neutron pair exceed the even-Z cross sections by more than a factor two. Thus after ten or twelve captures, an odd-Z chain of initial abundance 10^{-3} may predominate over an even-Z chain of initial unit abundance.

In Fig. 3, we see that good agreement can be obtained between this theoretical interpretation and experiment. In the theory the neutron exposure is treated as an adjustable parameter and amounts of exposed U and Np are adjustable within limits.

Thus by considering capture in odd-Z chains we can understand the abundances of the heavy nuclides produced in thermonuclear explosions. Conventional mass formulae and statistical theory suffice for the interpretation. This conclusion lends support to the

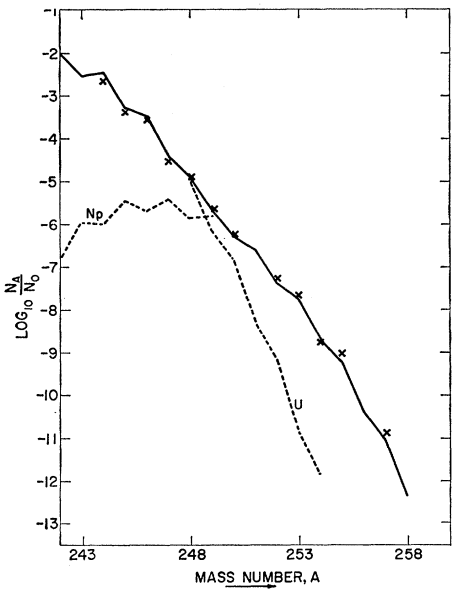

FIG. 3. Mass abundance versus mass number for the Barbel device. For the calculations, described in detail in Ref. 21, it was assumed that the amount of uranium and neptunium exposed to a 20-keV neutron flux were 10^{-1} and 10^{-4} of the initial uranium, respectively. The dashed lines show contributions of the uranium and neptunium fractions separately.

r-process analysis of Seeger.[10] When the exponential mass formula of Cameron is used, together with his parameters for statistical capture theory, it is not possible to obtain as good agreement with experiment as is shown in Fig. 3. However, in view of the uncertainties in calculations of capture cross sections, this cannot be taken as strong evidence against the Cameron mass formula.

From observed abundance data, as in Fig. 3, together with assumptions about the relative contributions of odd- and even-Z chains, it should be possible to deduce relative capture cross sections. A method for making this analysis has been developed by Ingley.[26]

According to our analysis, the capture cross sections for any given Z, decrease as A increases. For example, we computed[21] that $\sigma(n,\gamma)$ for U^{256} is 5% of the U^{238} value (Cameron found 13%). Thus it appears that to make the heaviest possible nuclei, it will be fruitful to use the heaviest possible target nuclei. Further, odd-Z targets would seem attractive. However, as one considers heavier target nuclei it becomes evident that the capture chain will suffer from competition with neutron-induced fission.

One experiment has been performed using heavier target nuclei. In the Tweed event[26,27], Pu^{242} was used as the target material. The resulting mass abundances, however, are disappointing compared to Par and Barbel. Even starting four mass units higher, the Tweed debris did not contain detectable amounts of $A=257$. Whether this poor performance is due to a lower neutron exposure in Tweed, or rather indicates that Pu^{242} is a poorer target material than U^{238} is not entirely clear. In both Par and Tweed, Dy^{164} was included in the target material as a neutron exposure monitor. However, due to chemical fractionation in the bomb debris and background problems, the results are uncertain. If one interprets them as indicating that the Tweed exposure was at least as good as that in Par, then the results indicate that Pu^{242} is a poor target material compared to U^{238}. This may be attributed[26] to fission competition for odd-A plutonium isotopes. If, on the other hand, one assumes that the Tweed exposure was low, then the competition from fission does not appear so serious, and one may be encouraged to use heavier target nuclides. In the next Los Alamos experiment of this kind we plan to use Am^{243} as the target, together with U^{238} as an exposure monitor.[27a]

It is clear that nucleosynthesis in terrestrial thermonuclear explosions occurs in times short compared to the times for stellar processes. For convenience we summarize in Table I the orders of magnitude of duration, neutron flux, and exposure for the three processes

[26] J. Ingley, Bull. Am. Phys. Soc. **11**, 655 (1966) and see also J. W. Truran, C. J. Hanson, A. G. W. Cameron, and A. Gilbert, Can. J. Phys. **44**, 151 (1966).

[27] Los Alamos Progress Report, Sept. 1965, unpublished.

[27a] *Note added in proof*: In this experiment, the cyclamen event of May 1966, the Americium capture chain appears to have been disastrously depleted by fission.

TABLE I. Neutron exposures.

	Flux (nv)	Duration (Δt)	Exposure ($nv\Delta t$)
s-process	$\sim 10^{16}$/cm^2 sec	$\sim 10^3$ yr	10^{26}–10^{27}/cm^2
r-process	$\gtrsim 10^{27}$	1–100 sec	$>10^{27}$
nuclear explosion	$>10^{31}$	$<10^{-6}$ sec	10^{25}

we have discussed. Note that to date the exposures achieved in nuclear explosions are one to two orders of magnitude smaller than those believed to be important in the stellar processes. In all cases the relevant neutrons have energies between about 10 and 200 keV.

Just as stellar neutron capture can take place in times either short or long compared to β decay lifetimes, so heavy nuclei can be synthesized not only rapidly in explosions but also slowly in reactors. When thermal neutrons are being captured, statistical theory is no longer adequate for predicting capture cross sections since, especially for even–even nuclei, the cross sections depend on the random positions of a few resonances.

NEEDED CROSS-SECTION MEASUREMENTS

We have now completed our survey of three kinds of nucleosynthesis that involve multiple neutron capture, namely the s-process and r-process in stars, and extremely rapid capture in nuclear explosions. Let us now consider what sorts of cross-section measurements would be useful for furthering our understanding of these nucleosynthetic process.

CROSS SECTIONS FOR THE s-PROCESS

Inasmuch as the s-process involves neutron capture by stable or long-lived nuclides, there are evidently a large number of (n, γ) cross sections which would be useful for the analysis. Clearly one needs kilovolt capture cross sections for individual nuclides and not just elements. Moreover, because of uncertainties in the relative abundances of elements it is evidently most desirable to have measured cross sections for several isotopes of the same element. Several measurements of this sort have been reported by the Oak Ridge group.[28] In particular results for Sr(86, 87, 88), Zr(91, 92, 94, 96), Sn(116, 117, 118, 119, 120), and Sm(144, 147, 148, 149, 150, 152, and 154) have been published. Most of these nuclei are formed both by the s- and r-processes. However the pair Sm^{148} and Sm^{150} can be formed only by the s-process and these two nuclides are found to have nearly the same values of $\sigma_A N_A$, as expected. For many of the other nuclides the s-process is believed to be the predominant source[10] and the measured cross sections were used in constructing Fig. 2.

Let us now consider in more detail a few regions of s-process abundance curve. We have already noted that if a smooth spectrum of neutron exposures is assumed, then the general structure of the abundance curve (and in particular the precipices of the ledge and precipice structure) is determined by the near neutron magic nuclei with their small capture cross sections. Consider, for example, in Fig. 4 the chart of the nuclides near $N=50$, where one such precipice is expected. The lightest closed shell nuclides is seen to be Kr^{86}. The nuclides Sr^{86}, Sr^{87}, Sr^{88}, Y^{89}, Zr^{90}, and Zr^{91} all lie on the s-process path, which explains why the cross sections of these particular isotopes have been measured. A number of Kr isotopes are involved in the s-process but unfortunately the abundance of the element Kr is very uncertain. If the capture cross section of the s-only isotope, Kr^{82}, were known it should be possible to deduce[10] the Kr abundance from s-process systematics. Indeed, it would be very valuable to know capture cross sections of all the Kr isotopes; for example, Kr^{84} looks peculiarly abundant[10] unless its capture cross section should be unexpectedly small.

In Fig. 4, a branch in the s-process is indicated at Se^{79}. The possibility of β^- decay before capture is apparently required by the large abundance of Br^{79}. At first sight it would appear that the lifetime of Se^{79} (7×10^4 yr) is too long for appreciable decay on the s-process time scale. However, an enhancement of the decay due to population of the excited states in stellar thermal equilibrium seems to provide the required shorter β^- decay lifetimes.[10] The lifetime of Se^{79} is expected to be quite temperature sensitive so that a good knowledge of the s-process path near Se^{79} could be used as a stellar thermometer. Cross sections of the next lower and higher s-only nuclides, namely Se^{76} and Kr^{80}, as well as the cross section of Se^{79} would help to establish the thermometer.

Figure 4, also shows that there is an interesting possibility at mass 87, which arises from the long β^- halflife (4.7×10^{10} yr) of Rb^{87}. If it could be determined how much of the Sr^{87} were due to production by the s-process, and how much were due to decay of Rb^{87}, then one could deduce how long ago the Rb^{87} was

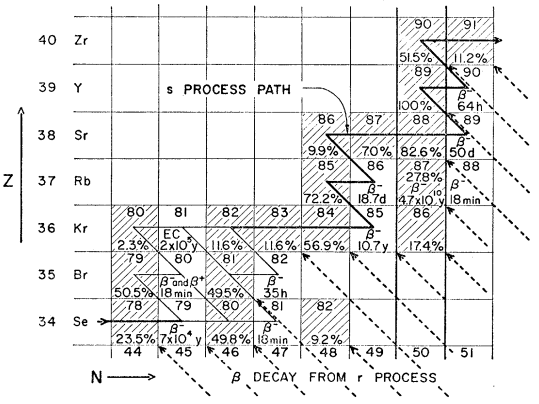

FIG. 4. s-process and r-process nuclides near $N=50$. Note that the $N=50$ shell is first closed in Kr 86. The branch in the s-process at Se 79 is likely because of a much shorter lifetime for Se 79 in stars than in the laboratory. For further discussion, see text.

[28] R. L. Macklin and J. H. Gibbons, Rev. Mod. Phys. **37**, 166 (1965).

formed. There is a difficulty here in that only rather little (~10%) of the Sr^{87} appears to have been formed from the decay of Rb^{87} and it is thus difficult to estimate the precise amount.[29]

Other heavy nuclides can also be used for dating the origin of the elements. Decay of the uranium and thorium nuclides to lead,[24] Lu^{176} to Hf^{176} ($t_{\frac{1}{2}}=2.2\times10^{10}$ yr), and Re^{187} to Os^{187} ($t_{\frac{1}{2}}=4\times10^{10}$ yr) may be used to date the origin and duration of the "cosmic nuclear fire." Let us consider this last possibility in more detail.[29] In Fig. 5 we see a portion of the chart of the nuclides near $A=187$. Both Os^{187} and Os^{186} are included in the *s*-process. Neither can be made from the *r*-process, except that decay of Re^{187} will produce Os^{187}. The Re^{187} will come from the *r*-process and perhaps also from an *s*-process branch. In either case from the Os^{186} and Os^{187} cross sections one could deduce (by assuming $\sigma_A N_A \simeq$constant) how much Os^{187} was made in the *s*-process. The remainder must have come from Re^{187} decay so that one can infer how long ago the Re^{187} was formed. The relative Re and Os abundances are quite well known[29] and Re^{187} is a more attractive clock than Rb^{87}. For this analysis, $\sigma(n,\gamma)$ of the nearest *s*-only nuclide (Pt^{192}) would also be useful.

We have now seen how the measurement of various (n,γ) cross sections in the keV range can be used for improving our understanding of the *s*-process; for determining the exposure distribution, the time scale for neutron capture, and for disentangling *s*- and *r*-process abundances. Moreover, we have seen that the appropriate (n,γ) cross sections can be used to establish elemental abundances, stellar thermometers, and cosmic calendars. While in our discussion we have considered only nuclei having $A\geq56$ in the *s*-process it should not be concluded that capture cross sections of lighter nuclei need not be considered. They will compete with *s*-process nuclei for the available neutrons and hence are of importance.

CROSS SECTIONS FOR THE *r*-PROCESS

Those nuclides which participate in the *r*-process are so far from β stability that they are not available for laboratory study. Therefore, it is clear that cross section measurements are not as directly useful for the *r*-process as for the *s*-process. Nevertheless, the study of neutron rich nuclides should help to establish the dependence of neutron binding energies, capture cross sections, and β decay lifetimes on neutron excess. Some plans are being made for measuring (n,γ) cross sections of fission products using nuclear explosions as neutron sources for time of flight measurements.

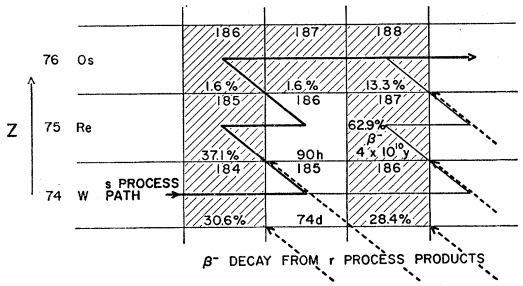

FIG. 5. Nucleosynthesis near $A=187$. Os 186 is formed only in the *s*-process. Os 187 can be formed in the *s*-process (from Os 186+*n*) or by decay of Re 187. From the relative Re/Os abundance and (n,γ) cross sections of Os 186, Os 187 one can examine when the Re 187 was made, as described in text.

[29] D. D. Clayton, Astrophys. J. **139**, 637 (1964).

Neutron-rich nuclides can, as we have seen, be produced by exposing target nuclei to the neutron fluxes available in nuclear explosions, and the program to produce heavy elements has already led to information on the neutron cross sections of very neutron-rich nuclides. While one might think of using lighter nuclides, these always involve additional difficulties, among which we may mention possible backgrounds from fission products and the products of neutron capture in soil, and possible chemical fractionation of the neutron-rich nuclides. In the heavy element experiments,[22,23] amounts of Fm^{257} were detected that were only 10^{-11} of the initial target, so that very small backgrounds could lead to a loss of much data.

Thus more information on the systematics of capture cross sections of the neutron-rich nuclei will be forthcoming from using heavy targets in nuclear explosions than by switching to other lighter targets. Combinations of targets are possible in principle, though in practice the number of radiochemists available to analyse the debris will limit the information which can be gleaned in a given experiment.

If one views the exposure of a target in a nuclear explosion as an experiment to determine capture cross sections of neutron-rich nuclei, then evidently requirements are placed on the target material which are not present in an effort simply to make the heaviest possible nuclei. In particular one would like to have the target isotopically pure and to minimize the transmutation of the target induced by fast neutrons. In addition it would appear from the Tweed experiment (using a Pu^{242} target) that some independent monitor of the neutron exposure is most desirable. Among others, the nuclei Dy^{164} and Sc^{45} are being considered as monitors[26] and it would be desirable to know their capture cross sections. U^{238} and Tm^{169} are possible monitors with known cross sections. Actually, when a stable nuclide is used as an exposure monitor, it is never detected in the debris. Instead some radioactive products of one or more captures will be detected and it may be difficult to infer any absolute exposures. Nevertheless, it is useful to know the capture cross section of the starting nuclide as a point of reference.

CROSS SECTIONS FOR HEAVY ELEMENT NUCLEOSYNTHESIS

In our discussion of the Par and Barbel results we concluded that the capture cross sections of the nuclides concerned decrease in an understandable way as more neutrons are added. Thus as one strives to make

heavier nuclides it becomes increasingly difficult to gain simply by increasing the neutron exposure, and it becomes attractive to consider heavier target nuclides, and especially those of odd-Z. We have already noted some uncertainty in the results obtained with a Pu^{242} target and for this it would be useful to know more about the (n,γ) and (n,f) cross sections of the heavier Pu nuclei.

In general, as one considers heavier target nuclides the loss of material from the target chain, due to neutron-induced fission becomes more and more severe. For any target nuclide with $A \geq 238$, some of the target will be destroyed by fast neutron fission, but this destruction, although it may amount to 99% of the target, is still quite acceptable. More important is the competition between fission and capture in the successive nuclides. In particular, the capture to fission ratio for a nuclide of mass $A(\alpha_A)$ and for about 10-keV neutrons will determine what fraction of the capture chain can survive to mass $A+1$. In going from mass A_0 to A_f, the chain will thus be depleted by something like

$$\prod_{A=A_0}^{A_f} \alpha_A/(1+\alpha_A)$$

which could be very small if there were several small values of α_A, or many moderate values in the chain.

The capture to fission ratios of the important fissionable materials, U^{233}, U^{235}, and Pu^{239} have been measured[30,31] for a wide range of neutron energies. In addition, for thermal, or "pile" neutrons α has been measured for a number of nuclei including[32] Pa^{232}, U^{232}, Pu^{241}, Am^{242m}, Cm^{243}, Cm^{245}, Cf^{249}, Cf^{251}, and Es^{254}. Of these nuclides, the odd-odd target Es^{254} has by far the lowest value of $\alpha(0.02)$, followed by $Cm^{245}(0.07)$ and $U^{233}(0.11)$. Some of the low-energy α values may be atypical because of the dominance of a single resonance. Of particular interest (for odd-Z chains) are the capture to fission ratios of the odd–odd nuclei. Except for Es^{254}, the odd–odd α examples (Pa^{232} and Am^{242m}) appear to be encouragingly high ($\alpha \simeq 1.0$). A general tendency[32] for odd–odd nuclei to have the largest thermal fission cross sections appears to be caused by their small level spacing[21] rather than necessarily any especially large values of Γ_f. For small level spacing one will approach an average (optical model) thermal cross section for compound nucleus formation of about $2\pi^2\lambda^2(E_n)^{\frac{1}{2}}S_0$ with λ the neutron wavelength, E_n the neutron energy and S_0 the s-wave strength function. With $S_0=10^{-4}$, this cross section is 2600 b so that it is not surprising that odd–odd fission cross sections are frequently around 2000 b.

Let us next consider briefly the theory of capture to fission ratios. It is not too difficult to make a reasonable prediction of $\bar{\Gamma}_\gamma$, the average radiative capture width for any heavy nucleus. Indeed Γ_γ varies but little from one heavy nucleus to the next.[30] Of much greater difficulty is the prediction of average fission widths, $\bar{\Gamma}_f$. One must be able to predict the height of the fission barrier. This involves not only a smooth dependence on Z^2/A but also shell effects[33] and probably pairing effects[34] which are not negligible. I am not aware of any method for predicting the "known" fission barriers to better than within a few hundred keV and extrapolation to unknown nuclei is doubtless more uncertain.

Nevertheless, even if the fission barrier is known, there remains the problem of estimating average fission widths $\bar{\Gamma}_f{}^J$ for the relevant spin states. There is new hope for estimating fission widths based largely on the work of Lynn[35] in applying the channel theory of fission[36] to interpret the fission cross sections of U^{233}, U^{235}, and Pu^{239}. According to the channel theory of Bohr and Wheeler,[37]

$$\bar{\Gamma}_f{}^{J\pi} = (D^{J\pi}/2\pi)N^{J\pi}, \tag{3}$$

where $D^J{}_\pi$ is the average spacing of spin J and parity π levels and $N^{J\pi}$ is the effective number of open channels at the fission barrier. If we let E be the nuclear excitation energy, E_i be the excitation energy in channel i at the barrier, and $\hbar\omega_i$ be the characteristic energy of the barrier curvature, then[36]

$$N^{J\pi} = \sum_i \{1 + \exp 2\pi[(E_i - E)/\hbar\omega_i]\}^{-1}, \tag{4}$$

where the sum is over all channels of spin J and parity π. The relevant energies are sketched in Fig. 6.

Thus according to channel theory, if one has a complete description of the nuclear states for deformations near the fission barrier (i.e., the transition states) one could predict $\bar{\Gamma}_f$ from Eq. (3). The capture to fission ratio could then be deduced. For even–even compound nuclei, which are in particular formed from U^{233}, U^{235}, or Pu^{239} plus a neutron, all the transition states in the lowest 2 MeV or so [34] are collective in nature. Some predictions[36] can be made concerning the spectrum of the lowest collective vibrational and rotational excitations and Lynn has considered[35] whether the resonance parameters deduced therefrom are consistent with the "resonances" that are observed when low-energy neutrons interact with U^{233}, U^{235}, Pu^{239}, and Pu^{241}. He concludes that the expected and observed resonance parameters are consistent if and

[30] J. R. Stehn *et al.*, *Neutron Cross Sections*, $Z=88$ *to* 98, Brookhaven Report BNL 325 2nd ed., Suppl. No. 2, Vol. III, U.S. Dept. Comm. Springfield, Va. (1965).
[31] G. deSaussure *et al.*, Nucl. Sci. Eng. **23**, 45 (1965).
[32] E. K. Hyde, *Nuclear Properties of the Heavy Elements* (Prentice-Hall, Inc., Englewood Cliffs, N.J., 1964), Vol. III, Table 1.6.
[33] W. J. Swiatecki, Phys. Rev. **100**, 937 (1955).
[34] H. C. Britt, W. R. Gibbs, J. J. Griffin, and R. H. Stokes, Phys. Rev. **139**, B354 (1965).
[35] J. E. Lynn, "Quasi-Resonances and the Channel Theory of Neutron Induced Fission," paper at Antwerp Conf., Study of Nuclear Structure with Neutrons, July 1965.
[36] J. A. Wheeler, "Channel Analysis of Fission," in *Fast Neutron Physics*, J. B. Marion and J. L. Fowler, Eds. (Interscience Publishers, Inc., New York, 1963), Chap. V. S.
[37] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).

only if due allowance is made for interference between resonances, or in other words for multilevel fission effects. A similar analysis has recently been reported by Moore[38] for Pu^{241}.

We may now consider whether the resonance parameters which are consistent with channel theory can be used to predict capture to fission ratios. A first question is whether or not the single-level formalism may be used for estimating α. If one considers the R matrix cross sections for two interfering levels[39] it can be shown that the effect of interference of random sign is to *increase* α. The increase is of the order of magnitude[40]

$$\Delta\alpha/\alpha \simeq \Gamma_f(\Gamma_f+\Gamma_\gamma)/D^2 \qquad (5)$$

so that for $\bar{\Gamma}_f/D \simeq 1/\pi$, as one would deduce from Eq. (3) for two open channels, the change in α caused by two-level interference is only of the order of 10%. One may hope that the additional effects of interference between more than two levels do not more substantially change α, but this is a question which can only be answered by explicit multilevel calculations.

At any rate in our study[40] we considered only single-level effects, in which case $\bar{\alpha}$, averaged over many resonances, may be written

$$\bar{\alpha} = \frac{\sum_{lJ\pi}(2l+1)\,(g_J/D^{J\pi})\,\langle\Gamma_n\Gamma_\gamma/\Gamma\rangle}{\sum_{lJ\pi}(2l+1)\,(g_J/D^{J\pi})\,\langle\Gamma_n\Gamma_f/\Gamma\rangle}. \qquad (6)$$

We have applied this equation to U^{233}, U^{235}, and Pu^{239}. Neutron widths were assumed to have a Porter–Thomas distribution (χ^2 with one degree of freedom), capture widths were taken constant, fission widths for N open channels were taken to be χ^2 distributed with N degrees of freedom, and D_J was assumed to vary as $(2J+1)^{-1}$. For strength function we used $S_0=1.1\times10^{-4}$ and in order to fit σ_f[30] between 10 and 100 keV we required $S_1\simeq 2\times10^{-4}$ with R, the nuclear radius 8×10^{-13} cm. Our preliminary results may be summarized as follows.

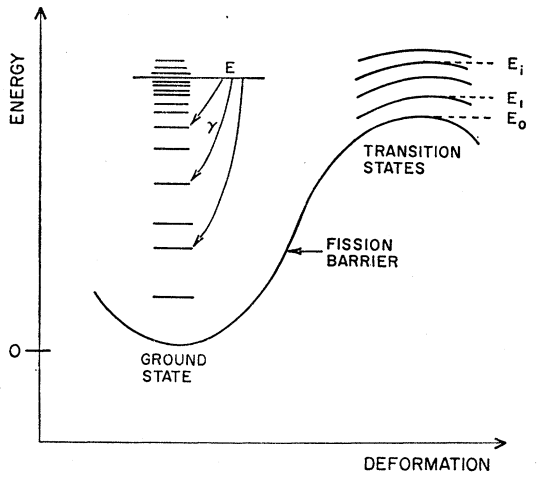

FIG. 6. Energy diagram for compound nucleus at excitation energy E. The excited compound nucleus can decay by γ emission or by fission through the various channels with barrier energies E_i. De-excitation may also occur by neutron emission which is not shown in this diagram.

For Pu^{239}, we assumed that the observed resonances could be divided into two classes[41–43]: narrow resonances having $J=1^+$ and wide resonances with $J=0^+$. We assumed that the $J=0^+$ states have one or two fully open fission channels and that $J=1^+$ states have one partially open channel. For the p-wave states, $J=1^-$ and $J=2^-$, we assumed two fully open channels. With these assumptions, we computed values of $\bar{\alpha}$ which are in quite good agreement with observations, as summarized, for example, by Schmidt.[43] The pronounced drop in $\bar{\alpha}$ between low neutron energies and the 100-keV region is largely due to opening of the $J=1^+$ channel, for which we took $\hbar\omega=0.40$ MeV, together with the onset of p-wave fission. The Wigner effect[44,45] of increasing Γ_n also plays a role in this decrease.

For U^{233} we used the suggested parameters of Lynn,[35] including three open 2^+ fission channels and two open 3^+ channels. The resulting low energy $\bar{\alpha}$ is in reasonable agreement with experiment.[30] To obtain the observed decrease in α by 100 keV one requires the opening of further s-wave channels or p-wave fission through at least three open channels.

For U^{235}, the results are less satisfactory. Using Lynn's parameters[35] corresponding to $N(J=3^-)=1.25$ and $N(J=4^-)=0.25$, the calculated $\bar{\alpha}$ values are larger than observed for $E_n \gtrsim 100$ eV, by nearly a factor two. A similar discrepancy was found by Schmidt[43] using experimentally derived single level parameters and $N=4$. The problem seems simply to be that $\bar{\alpha}$ is higher for the low energy U^{235} resonances ($E_n \lesssim 100$ eV) than for the larger statistical sample above 100 eV[31]. We presume that this is a statistical fluctuation, though a curious and almost periodic structure of $\alpha(E)$ may be noted for α of U^{235}.[43] If one were to assume $N(J=3^-)=2.0$ and $N(J=4^-)=1.0$, much better agreement would be found with the experimental $\bar{\alpha}$. The states formed with p-wave neutrons (2^+, 3^+, 4^+, 5^+) must then, on the average, have about two open channels in order to give a small enough $\bar{\alpha}$ near 100 keV.

From our examination of the capture to fission ratios of U^{233}, U^{235}, and Pu^{239} we may conclude that the

[38] M. S. Moore and O. D. Simpson, *Fission Cross Sections*, paper at A.N.S. topical meeting "Reactor Physics in the Resonance and Thermal Regions," San Diego (1966).
[39] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).
[40] G. Bell (to be published).
[41] G. Cowan (private communication).
[42] G. D. Sauter and C. D. Bowman, Phys. Rev. Letters **15**, 761 (1965).
[43] J. J. Schmidt, *Resonance Properties of the Main Fertile and Fissile Nuclei*, paper at A.N.S. topical meeting "Reactor Physics in the Resonance and Thermal Regions", San Diego (1966).
[44] E. P. Wigner, "On the Variation of η in the 100–1000 eV Region," unpublished Brookhaven report, BNL-25 (1949).
[45] S. Oleksa, Nucl. Energy I **5**, 16 (1957).

channel theory of fission gives encouraging agreement with experiment. For Pu^{239}, the agreement seems particularly nice, while for U^{235} it seems that the low-energy resonances may form an atypical sample. In any attempt to predict $\bar{\alpha}$ for an unknown even–even compound nucleus, there would remain the major uncertainty of predicting the fission barrier for the lowest 0^+ transition state, as well as some uncertainty in the spacing of the other vibrational states relative to the 0^+.

For neutron-induced fission of even–even or odd–odd nuclei, the compound nuclei have odd-A. Therefore, in addition to the collective states near the barrier which we had to consider for even–even compound nuclei, there is a spectrum of one quasiparticle states (together with their rotational bands) which may afford fission channels of the appropriate quantum numbers ($J\pi$) for low energy fission. These quasiparticle states may, on the average, be separated by about 200 keV but little can be said at present about their precise locations. Therefore it would appear that while qualitative estimates may be made of $\bar{\Gamma}_f$ and $\bar{\alpha}$ for odd-A compound nuclei, quantitative results can only be found at present from experiment. For fission of odd–odd compound nuclei, one would similarly expect two quasiparticle states to be important for low energy fission.

We have already noted that for production of heavy nuclei, odd-Z targets are attractive and we are therefore concerned by the possible neutron induced fission of the odd–odd members of the chain, that is by fission of odd-A compound nuclei. If, for simplicity, we ignore the complications caused by availabliity of several spin states we may write

$$\bar{\alpha}=f[(\Gamma_\gamma/\bar{\Gamma}_f), N]\simeq f[(2\pi\Gamma_\gamma/ND), N], \qquad (7)$$

where we have used Eq. (3) for $\bar{\Gamma}_f$. If there were no fluctuations of $\bar{\Gamma}_f$, $\bar{\alpha}$ would simply equal the first argument of f; with fluctuations and constant D, α is an even more sensitive function of $\Gamma_\gamma/\bar{\Gamma}_f$. Thus if one believes channel theory and has some knowledge of D, then from $\bar{\alpha}$ one can deduce N, the number of open fission channels. In practice, if one had energy resolved measurements of some cross section for a nuclide of interest, D would be deduced thereform. Otherwise D could probably be calculated to within a factor two from level density systematics.

In general when considering fission of odd-A compound nuclei as compared to even–even compound nuclei, we expect that for a fixed energy above the lowest fission barrier state there will be more open channels for the odd-A nucleus. On the other hand, we anticipate[21] that for the odd–odd targets plus a neutron, the average level spacing, D, will be particularly small. Thus it would appear that $\bar{\alpha}$ for odd–odd targets may not be much different from $\bar{\alpha}$ for the even-Z odd-A targets.

It would be most helpful to have more and better measurements of the capture to fission ratios of odd–odd target nuclei. Energy-dependent measurements would be ideal but in the absence of these, Cd shielded results would be desirable to reduce the dominance of one or a few low-energy resonances. As noted before, from $\bar{\alpha}$ measurements, one could find the effective number of fission channels competing with γ emission for de-excitation of the compound nucleus. In general, measured capture to fission ratios will be useful for determining parameters in the channel theory of fission.

CONCLUSION

We have considered three physical situations in which nuclei are synthesized by the multiple capture of neutrons. We first examined stellar nucleosynthesis on a time scale slow compared to β decay lifetimes (s-process). Since nuclei in this capture chain are in the valley of β stability they are generally accessible for laboratory study. Measurements of their (n, γ) cross sections for 10–100-keV neutrons are of great interest. Some capture cross sections, such as that of Kr^{82}, would be useful for establishing uncertain elemental abundances from the s-process systematics. Other capture cross sections for nuclides near possible branching points, such as Se^{79}, could be used to analyse the time and temperature scales in the s-process. Cross sections of such nuclides as Os^{186} and Os^{187} are needed to establish how long ago the nucleosynthesis took place.

We next examined stellar neutron capture on a rapid time scale compared to β decay lifetimes, the r-process. In this capture process neutron rich nuclei are involved, and for an understanding of the r-process, the dependence of neutron binding energy and $\sigma(n, \gamma)$ on neutron excess needs to be known. Measurements of $\sigma(n, \gamma)$ for fission products, and study of the capture chains produced in thermonuclear explosions should help to clarify the r-process.

Finally we have seen that in attempting to produce the heaviest possible nuclei by multiple neutron capture in thermonuclear explosions, one is led to consider the heaviest possible target nuclei. For such heavy nuclei competition between fission and capture may be decisive and more data on capture to fission ratios of heavy nuclei is needed, especially for odd–odd target nuclei and for epithermal neutrons. From capture to fission ratios one can draw some conclusions regarding the number of open channels for fission.

Once again we see that in the appropriate barns there are many mansions.

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