LA-UR-79-2900

TITLE: NEUTRON CROSS SECTIONS OF IMPORTANCE TO ASTROPHYSICS

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SUBMITTED TO: International Conference on Nuclear Cross Sections for Technology, October 22 - 26, 1979

MASTER

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NEUTRON CROSS SECTIONS OF IMPORTANCE TO ASTROPHYSICS

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Neutron reactions of importance to the various stellar burning cycles are discussed. The role of isomeric states in the branched s-process is considered for particular cases. Neutron cross section needs for the ^{187}Re-^{187}Os, ^{87}Rb-^{87}Sr clocks for nuclear cosmochronology are discussed. Other reactions of interest to astrophysical processes are presented.

[Neutron Cross Sections, Stellar Processes, Nuclear Clocks]

Introduction

Neutron physics has played a major role in the understanding of many phenomena associated with astrophysics. Usually it is common to think of the relevance of neutrons to the formation and abundance of the heavy elements via neutron capture. However, there are other aspects which are important in astrophysical processes. In this paper, we will consider a variety of neutron reactions which affect our understanding in very different ways. We will not summarize the wealth of neutron data that already has been obtained which is relevant to nuclear astrophysics. Rather, we will concentrate on areas where no data or discrepancies exist (or where the data are of insufficient accuracy) so as to affect the ability of the astrophysicist to use the information. In addition, other neutron data that can be used indirectly to calculate important effects will be discussed.

The reader is referred to the article of Burbidge et al.[1] for the classic discussion of nucleosynthesis in stars. Also the review articles of Barnes,[2] Allen, Gibbons, and Macklin,[3] and Clayton and Woosley[4] contain very comprehensive information regarding nuclear cross sections of interest to astrophysics.

Neutron Reactions During Various Stellar Burning Phases

Recently, there has been significant development in the detailed calculations of the evolution of stars through their various hydrostatic and explosive burning cycles.[5,6] Figure 1 shows a schematic diagram of the various stages as they progress toward iron core collapse. The stellar burning cycles are referred to by the main nuclear fuel such a hydrogen-burning, helium-burning, carbon-burning, etc. For carbon burning and future cycles, there can be both hydrostatic and explosive burning differing in temperature as well as time scale. The neutron reactions of importance in each of these cycles is discussed in the following paragraphs.

Hydrogen Burning

This phase involves the formation of ^{4}He via p-p chains and the C-N-O cycle where the presence of carbon, nitrogen, and oxygen results in ^{4}He production through a series of proton reactions. There are no neutron reactions of significant importance to this cycle.

Helium Burning and the s-Process

After the hydrogen is exhausted in the stellar core, contraction occurs which increases the temperature to allow hydrogen burning in a shell concentric with the predominantly helium core. Due to the increased outward heat flux, the star expands greatly so that the stellar surface cools and the star

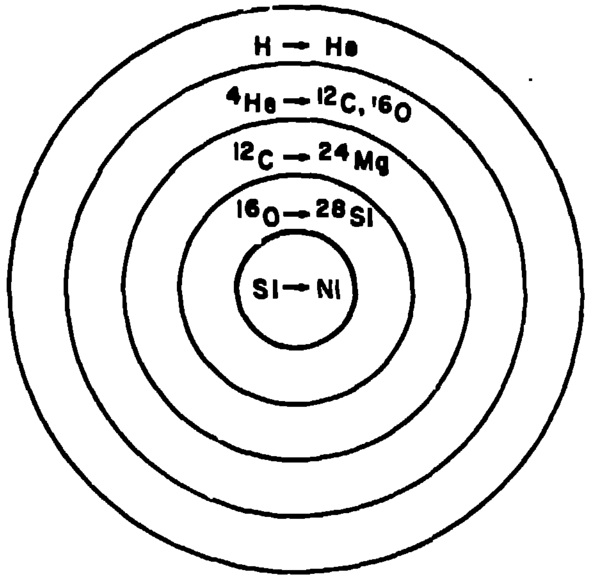

Fig. 1. Schematic diagram of the various stellar burning cycles progressing from hydrogen burning to silicon burning.

becomes a "red giant." The helium in the core will eventually ignite (usually referred to as the helium flash) and the star enters a stage of hydrostatic helium burning. At some point the star will consume its helium in the core and form a helium burning shell. The picture that prevails at this point is one of an inert core, a concentric helium-burning shell surrounded by a concentric hydrogen-burning shell. The calculation of Schwarzchild and Harm[7] indicated that this system exhibited thermal instabilities which lead to helium-shell flashing. Sanders,[8] Ulrich,[9] and Iben[10] have discussed how such a phenomenon may provide an ideal site for the s-process of nucleosynthesis. Sanders and Ulrich argue that mixing of protons from the hydrogen shell into the helium shell during the thermal instability will provide a source of neutrons via the reactions:

$$^{12}C(p,\gamma)^{13}N(\beta^+,\nu)^{13}C;$$

$$^{13}C(\alpha,n)^{16}O;$$

and

$$^{16}O(p,\gamma)^{17}F(\beta^+,\nu)^{17}O;$$

$$^{17}O(\alpha,n)^{20}Ne,$$

where the carbon and oxygen are by-products of the quiescent helium-burning. Iben argues that the $^{22}Ne(\alpha,n)^{25}Mg$ reaction serves as the major source of neutrons where the ^{22}Ne is formed via the following reactions:

$$^{14}N(\alpha,\gamma)^{18}F(\beta^+,\nu)^{18}O(\alpha,\gamma)^{22}Ne.$$

The ^{14}N is a remnant in the helium shell of the hydrogen burning shell. A measurement of the $^{26}Mg(\gamma,n)$ reaction by Berman et al.[11] exhibited a prominent resonance in the ^{26}Mg compound system which was just 54.3-keV above the (γ,n) threshold. In the $^{22}Ne(\alpha,n)$ reaction, the resonance would occur for an α-particle kinetic energy (center-of-mass) of 540 keV. This resonance could affect the neutron production rate dramatically if its alpha width (Γ_α) is significant. The most probable J^π of this resonance was determined to be 1^- by Berman et al. This would require absorption of an $\ell = 1$ alpha particle by $^{22}Ne(0^+)$. This is a difficult experiment because one needs good alpha-energy resolution to observe the resonance and the nature of the noble gas target increases the difficulty. The $^{22}Ne(\alpha,n)$ has been studied between 1.6 and 4.0 MeV by Ashery,[12] but there are no data near this resonance. One solution might be to study the inverse reaction, $^{25}Mg(n,\alpha)^{22}Ne$. Weigmann et al.[13] observed a resonance at E_n(lab) = 62.88-keV in the $^{25}Mg(n,\gamma)$ reaction which corresponds very closely in energy (corrected for kinematics) to the resonance observed by Berman et al. If the J^π is 1^-, this corresponds to $\ell = 1$ neutron capture and would require $\ell = 1$ alpha particle emission as mentioned. Although the $^{25}Mg(n,\alpha)$ reaction is a difficult experiment, if one observed resonant α-emission, the implications for s-process neutron production would be very important.

There are also neutron reactions on the light elements that affect the excess number of neutrons available for the s-process capture on iron (and higher A) seed nuclei. These include any neutron reaction on the primary nuclei producing the neutrons, such as ^{14}N, ^{18}O, ^{21}Ne, ^{22}Ne and the by-products of the (α,n) reactions, such as $^{24,25,26}Mg$. Particularly valuable would be the unmeasured neutron capture cross sections for $^{20,21,22}Ne$.

Although the models of Sanders, Ulrich, and Iben provide for different mechanisms and different neutron sources, the common feature is that the s-process takes place during repeated neutron bursts during these helium-shell flashes which last on the order of 10 years followed by a long quiescent period (∿ 2500 years). This is in marked contrast with the original ideas of Burbidge et al.[1] which indicated that the s-process took place slowly on a time scale of thousands of years. Figure 2 shows the abundance (N) times capture cross section (σ) distribution for the s-process. It was recognized as early as 1961 by Clayton et al.[14] that the seed iron nuclei had to be exposed to several neutron fluxes of different strengths to account for Fig. 2. Seeger, Fowler, and Clayton[15] demonstrated that a good fit to the $N\sigma$ distribution resulted from an exponential exposure distribution. This is consistent with the helium-shell flashing hypothesis producing an intermittent s-process. The effects on the s-process result from the deviation from the hypothesis of Burbidge et al.[1] that the β-decay lifetimes are much shorter than the mean neutron capture time. In a pulsed s-process, this is no longer true. Ward, Newman, and Clayton[16] and Ward and Newman[17] discussed the effects of a pulsed neutron flux on the s-process. If all β-decays were much faster than the mean neutron capture time, one could not distinguish between the different astrophysical scenarios. But the existence of branch points in the s-process may provide the information necessary to determine whether or not the pulsed s-process is important to the formation of the heavy elements. It is clear from Fig. 2 that the $N\sigma$ values on both sides of the magic numbers near A = 90, 140 are needed to determine the steepness of the precipice near these magic nuclei and to the absolute level of the $N\sigma$ values on the plateau regions away from the magic numbers. Neutron capture cross sections for nuclei shielded from the r-process are very important in this respect (e.g., $^{134,136}Ba$). This is particularly true if branching to isomeric states is involved.

An example where the branched s-process is important is shown in Fig. 3. It is clear that for the constant exposure model of Burbidge et al., much of the ^{85}Kr would β-decay since the 10.8 yr half-life is shorter than their mean capture lifetime. However, in a pulsed s-process, ^{85}Kr can capture a neutron to form ^{86}Kr and subsequently ^{87}Kr. Since ^{87}Kr will decay to ^{87}Rb, the s-process production of ^{87}Rb clouds the picture of the use of the 5 x 10^{10} yr β-decay of ^{87}Rb to ^{87}Sr as an r-process chronometer. The r-process chronometer will be discussed in the section on Nuclear Cosmochronology. In addition to this problem, neutron capture on ^{84}Kr can result in the formation of the 4.5-hr first excited state of ^{85}Kr whose main mode of decay is β^- decay to ^{85}Rb. This will affect the neutron current through ^{85}Kr into ^{85}Rb, ^{86}Sr, and ^{87}Sr even if the neutron flux during

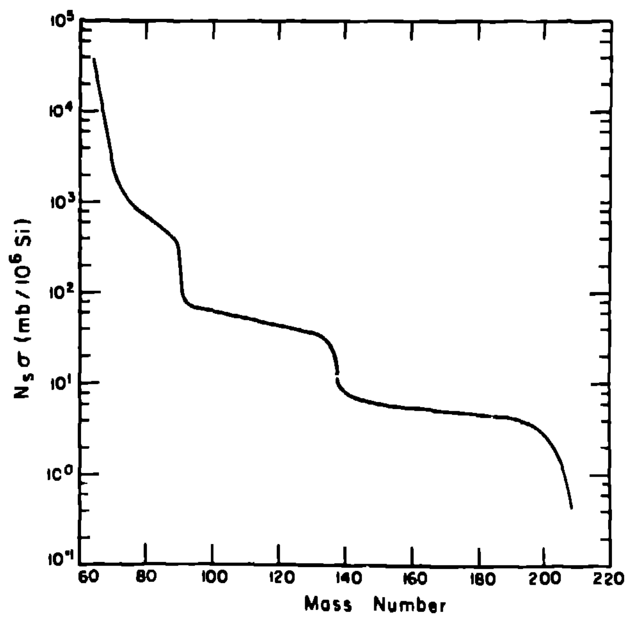

Fig. 2. The s-process abundance (N_s) times neutron capture cross section (σ) plotted as a function of mass number. The precipices near A=90 and 140 are due to the closing of the neutron shell at N=50 and 82.

Table I. Neutron capture cross sections of importance to the s-process (kT = 30 keV) for branched and unbranched solutions.

Ref. 16[a]	Ref. 17[b]	Rev. 19[c]	Ref. 20[a]
		^{58}Fe	^{58}Fe
		^{66,67}Zn	^{64,66,67,70}Zn
		^{70,72,73}Ge	^{70,72,73}Ge
		$^{76-78}$Se	$^{74-78}$Se
^{80,82}Kr	^{80,82,84,86}Kr	$^{82-84}$Kr	$^{78,80,82-84,86}$Kr
		—	^{84}Sr
		—	^{92}Mo
		$^{99-101}$Ru	$^{98-101}$Ru
		$^{104-106}$Pd	$^{102,104-106}$Pd
^{113}Cd		$^{111-113}$Cd	$^{106,108,110-113}$Cd
^{114,115}Sn		—	^{112,114,115}Sn
		—	^{120}Te
		$^{128-132}$Xe	$^{124-136}$Xe
$^{134-136}$Ba		$^{134-137}$Ba	^{130,132,135,137}Ba
			^{136,138}Ce
			^{138}La
		$^{142-145}$Nd	$^{142,143-145}$Nd
			^{152,154}Eu
^{152}Gd	^{152,154}Gd		^{152}Gd
^{160}Dy		^{160}Dy	^{156,158,160}Dy
^{164}Er			^{162,164}Er
^{170}Yb		^{170}Yb	^{168,170}Yb
		$^{177-179}$Hf	$^{174,177-179}$Hf
			^{180}W
			^{184}Os
^{192}Pt		$^{192-195}$Pt	$^{190,192-195}$Pt
^{198}Hg		$^{198-201}$Hg	$^{196,198-201}$Hg

[a]branched s-process.
[b]branched s-process, pulsed-neutron source.
[c]unbranched s-process.

Carbon Burning

The fusion of $^{12}C + ^{12}C$ results when the core remnant from helium burning contracts to produce temperatures near 10^9 K. There are many neutron reactions in this cycle which affect the abundance of nuclei between oxygen and sulfur. Many of the important reactions such as $^{12,13}C(n,\gamma)$ and $^{16}O(n,\gamma)$ have been measured. However, many have not been measured and the accuracy of others could be improved. These are listed in Table III.

Carbon burning can also ignite explosively[21] at temperatures near 2×10^9 K. These reactions burn only for a fraction of a second so that an intense bath of free neutrons can become available. This short phase can result in the production of rare isotopes between sulfur and iron. Neutron seed reactions of importance are also listed in Table III. An excellent example of a neutron measurement that directly affected the production of the rare isotope ^{36}S was made by Auchampaugh et al.[22] One chain of reactions involved is

$$^{32}S(n,\gamma)^{33}S(n,\gamma)^{34}S(n,\gamma)^{35}S(n,\gamma)^{36}S.$$

↘ (n,α)

Table II. Unmeasured branching ratios for kT = 30 keV neutron capture important to the branched s-process

Compound Nucleus	Ground State	Isomeric State	
	$t_{1/2}$	E(keV)	$t_{1/2}$
^{85}Kr	10.7 y	305	4.5 hr
^{87}Sr	stable	388	2.8 hr
^{108}Ag	2.4 m	110	127 y
^{110}Ag	24.4 s	118	252 d
^{113}Cd	9×10^{15} y	264	14 [illegible]
^{115}Cd	2.2 d	173	45 d
^{114}In	72 s	190	50 d
^{115}In	5.1×10^{14} y	336	4.5 hr
^{121}Sn	27 hr	6.3	55 y
^{123}Sn	129 d	25	40 m
^{127}Te	9.4 hr	88	109 d
^{129}Te	69 m	106	33.5 d
^{148}Pm	5.4 d	137	41 d
^{152}Eu	13 y	49	9.3 hr
^{166}Ho	27 hr	5	1.2×10^3 y
^{176}Lu[a]	3.6×10^{10} y	127	3.7 hr
^{177}Lu	6.7 d	970	161 d
^{192}Ir	74 d	160	240 y
^{194}Ir	19 hr	< 450	0.47 y
^{210}Bi	5 d	270	3×10^6 y

[a]See H. Beer and F. Kaeppler, ref. 18.

Table III. Neutron cross sections important to the carbon burning cycle.

Reaction	Relevence
$^{12,13}C(n,\gamma)$	3
$^{14}N(n,\gamma)$	1
$^{16}O(n,\gamma)$	3
$^{17}O(n,\gamma)$	1
$^{18}O(n,\alpha)$	1
$^{20,21}Ne(n,\gamma)$	3
$^{23}Na(n,\gamma)$	1
$^{24,25,26}Mg(n,\gamma)$	3
$^{27}Al(n,\gamma)$	2
$^{28,29,30}Si(n,\gamma)$	↓
$^{31}P(n,\gamma)$	↓
$^{32,33,34}S(n,\gamma)$	2,4
$^{33}S(n,\alpha)$	2,4
$^{35,37}Cl(n,\gamma)$	4
$^{36,38,40}Ar(n,\gamma)$	↓
$^{36,38}Ar(n,p)$	↓
$^{36,38}Ar(n,\alpha)$	↓
$^{39}K(n,\gamma)$	↓
$^{40,42,43,44,46,48}Ca(n,\gamma)$	↓
$^{40}Ca(n,p)$	↓
$^{48,49,50}Ti(n,\gamma)$	↓
$^{50}V(n,\gamma)$	↓

1 = hydrostatic burning
2 = explosive burning
3 = hydrostatic and explosive burning
4 = seed reaction for abundance of nuclei below iron.

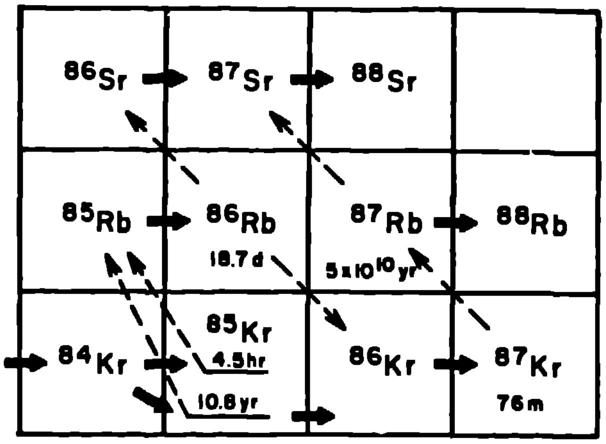

Fig. 3. Diagram of the branched s-process at ^{85}Kr. The 10.8-yr ground state of ^{85}Kr can either β-decay to ^{85}Rb or capture a neutron to form ^{86}Kr. The 4.5-min first excited state can only β-decay to ^{85}Kr.

the s-process path is very high. Therefore, it would be very valuable to have the neutron capture cross sections for ^{84}Kr and ^{86}Kr, but also the branching ratio for 30-keV neutron capture on ^{84}Kr to the g.s. and the first excited state of ^{85}Kr to determine how important the various branches are in the s-process.

Figure 4 shows a different situation for the production of ^{113}In, ^{114}Sn, and ^{115}Sn due to an s-process branch at ^{113}Cd. If the 14-yr 270-keV first excited state of ^{113}Cd is populated significantly by 30-keV neutron capture by ^{112}Cd, then ^{113}In, ^{114}Sn, and ^{115}Sn can be produced in the s-process in amounts which are a large fraction of their solar-system abundance. At this branch point, the neutron-capture cross sections (kT = 30 keV) for ^{113}Cd, ^{114}Sn, ^{115}Sn, and ^{113}In are needed to reduce the sensitivity of the branch calculations. Also, the branching ratio for 30-keV neutron capture to 270-keV state compared to the g.s. for ^{112}Ca + n would provide valuable data to asess its importance.

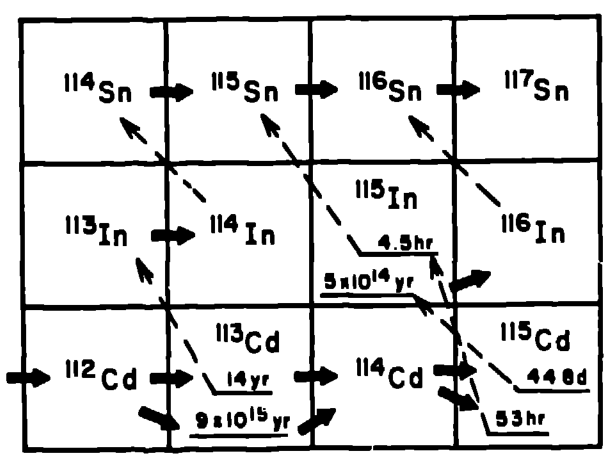

Fig. 4. Diagram of the branched s-process at ^{113}Cd. Population of the 14-yr, 270-keV first excited state of ^{113}Cd can result in the population of ^{113}In, ^{114}Sn and ^{115}Sn.

Figure 5 shows a similar branch point at ^{151}Sm. Since the 90-yr ^{151}Sm can either β-decay or capture a neutron in a pulsed s-process, the amount of ^{152}Gd formed in the s-process will be dependent on this branch. Both ^{152}Gd and ^{154}Gd are shielded from the r-process and therefore provide a constraint on the lower bound of the mean s-process neutron flux so that there is not an overproduction of ^{152}Gd. Neutron capture on ^{151}Eu can result in the population of either the 1 -yr g.s. of ^{152}Eu or the 9-hr first excited state both of which can decay to either ^{152}Gd or ^{152}Sm. However, if the pulsed s-process neutron flux is high enough, then the 1 -yr ^{152}Eu g.s. can capture a neutron and thus bypass ^{152}Gd. The cross sections which would provide valuable information on the absolute level of the σN curve beyond the s-only ^{148}Sm and ^{150}Sm are the kT = 30 keV neutron capture cross sections for ^{152}Gd and ^{154}Gd as well as the branching ratio for 30-keV capture on ^{151}Eu to the g.s. and first excited state of ^{152}Eu.

The region near ^{176}Lu is another important example of s-process branching. Since ^{176}Lu is shielded from the r-process by ^{176}Yb, the 3.6 x 10^{10} yr half-life for β-decay of ^{176}Lu to ^{176}Hf can be used as a purely s-process chronometer. However, neutron capture on ^{175}Lu can lead either to production of the 127-keV first excited state of ^{176}Lu whose β-decay half-life is 3.7 hrs or the 3.6 x 10^{10} yr g.s. Depending on the branching ratio, fast β-decay to ^{176}Hf will compete with neutron capture on ^{176}Lu. Some of the relevant neutron data has been obtained recently by Beer and Kappeler[18] and will be discussed in the section on Nuclear Cosmochronology.

There are other branch points to be studied which can be important under the hypothesis of a pulsed s-process. A summary of neutron capture cross sections relevant to both the branched and unbranched s-process solutions is listed in Table I. Although many nuclei are listed, there are clearly several important cases in common. Table II lists nuclei for which the kT = 30 keV branching ratios to the ground and isomeric states would be valuable to these studies. There are virtually no data for these cases.

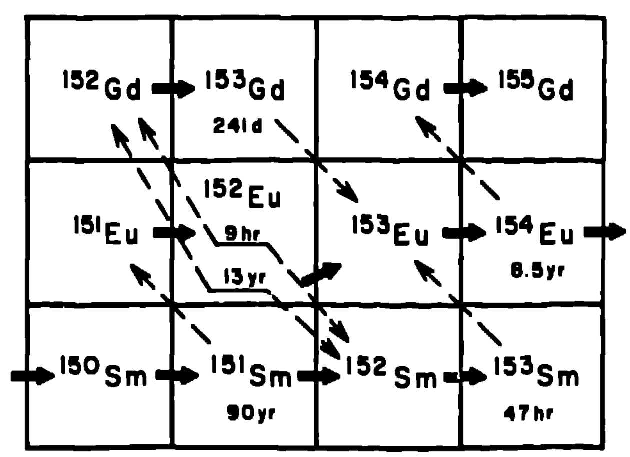

Fig. 5. Diagram of the branched s-process at ^{151}Sm. The branches at ^{151}Sm and ^{152}Eu can affect the amount of ^{152}Gd produced in the s-process. This puts restrictions on the s-process flux so that the low abundance ^{152}Gd is not overproduced.

The $^{33}S(n,\alpha)$ reaction can therefore reduce the amount of ^{36}S formed in an explosive process. The cross section had been estimated originally via optical-model calculations by Truran.[23] The result of his calculation was overproduction of ^{36}S by a factor of 10. The measurements of $^{33}S(n,\alpha_0)$ and $^{33}S(n,\gamma)$ by Auchampaugh et al.[22] reduced this factor to 2.5. Further measurements along this chain and other chains will help to clarify the production of rare nuclei in explosive carbon burning.

Oxygen Burning

Fusion of oxygen can occur in a similar manner to the carbon cycle, but at a temperature near 2.5 x 10^9 K. However, this cycle does not last long. There are several neutron reactions in the "hydrostatic" burning phase that are important in determining the evolution of the stellar composition. Those parasitic neutron capture reactions that affect the excess number of neutrons can influence the future composition. Those of importance are listed in Table IV and include poorly known neutron capture cross sections for ^{27}Al, ^{31}P, and ^{32}S.

Oxygen will burn explosively near 4 x 10^9 K with one of the main burning reactions being the $^{16}O(n,\alpha)$ reaction. Similar to the explosive carbon burning phase, there will be an intense bath of neutrons producing nuclei between ^{28}Si and ^{54}Fe. Neutron reactions important to such synthesis are listed in Tables III and IV.

Silicon Burning

After the depletion of oxygen, a very short-lived stage of silicon burning will produce nuclei up to iron. Explosive silicon burning can also occur under certain conditions in ejected debris. Some of the main neutron burning reactions incude $^{16}O(n,\alpha)$, $^{20}Ne(n,\alpha)$, and $^{24}Mg(n,\alpha)$. Other neutron reactions on nuclei between ^{32}S and ^{56}Fe will affect the production of isotopes below iron and any neutron data would be welcome. This is particularly true where little information exists such as for the isotopes of chlorine, potassium, and argon (see Tables III and IV).

Supernovae - r Process

It is during a supernovae explosion, when the density of neutrons is extremely high, that the r-process is believed to occur. Multiple-neutron capture forms nuclei far from the line of β-stability which eventually β-decay back toward this region. Neutron capture cross sections do not directly affect the r-process abundances because the captures occur much faster (∿ 1 s) than β-decays. Thus, there will be considerable smoothing of the final abundances by the nature of the multiple β-decays, many of which involve neutron emission. However, neutron cross sections are indirectly important for determining the r-process abundances in the following way. There are nuclei which can be formed only in the s-process and those which can be formed only in the r-process. The cases that can be formed in both require a knowledge of the s-process abundance, N_s, to extract the r-process portion, N_r, from the solar abundance, N. Improvements in the $N_s\sigma$ curve in Fig. 2 therefore permit better determinations of N_r. These improvements will result from better neutron data near the precipices in Fig. 2 and cross sections on the plateaus for s-only cases, such as ^{134}Ba and ^{136}Ba, ^{160}Dy, ^{170}Yb, and others listed in Table I.

Table IV. Neutron reactions of importance during oxygen and silicon burning cycles.

Reaction	Relevance
$^{16}O(n,\alpha)$	1,2
$^{20}Ne(n,\alpha)$	2
$^{24}Mg(n,\alpha)$	2
$^{27}Al(n,\gamma)$	3
$^{28,29,30}Si(n,\gamma)$	4
$^{31}P(n,\gamma)$	3
$^{32,33}S(n,\gamma)$	3,4
$^{33}S(n,\alpha)$	4
$^{36}Ar(n,\gamma)$	↓
$^{40}Ca(n,\gamma)$	↓
$^{50}Cr(n,\gamma)$	↓
$^{54}Fe(n,\gamma)$	↓

1 - explosive oxygen burning
2 - explosive silicon burning
3 - hydrostatic oxygen burning
4 - seed reactions for abundance of nuclei below iron

Nuclear Cosmochronology

The relative abundance of radioactive nuclei can be used to determine the time scale for nucleosynthesis. Probably the best known of these is the uranium-thorium dating which was extensively developed by Fowler and Hoyle[24] to determine the duration of r-process nucleosynthesis (Δ) in our galaxy. The best current value based on this chronometer assuming an exponential distribution of supernova events in our galaxy is $\Delta = 7 \pm 2 \times 10^9$ yr.

However, there are other chronometers with which the U-Th clock can be compared. The most promising of these is the ^{187}Re-^{187}Os chronometer proposed by Clayton[25] which involves the 4.5 x 10^{10} yr β-decay of ^{187}Re. Figure 6 shows the s- and r-process paths in the vicinity of Re and Os. ^{186}Os and ^{187}Os are shielded from the r-process and the s-process is unbranched in this region so that we can write

$$N^{186}\sigma_{186} = N^{187}\sigma_{187}$$

where N refers to the isotopic abundance and σ is the Maxwellian-averaged cross section for kT ∿ 30-keV (3 x 10^8 K) appropriate for the site of the s-process. The abundance of ^{187}Os that is found in meteorites is then a composite of s-process material and radiogenic material. One can ultimately obtain a ratio of radiogenic ^{187}Os to its parent ^{187}Re that depends on the ratio of the kT = 30 keV Maxwellian-average neutron capture cross sections for ^{186}Os and ^{187}Os. Using this cross section ratio and the half-life for β-decay, one can obtain a value for Δ. However, nature is never that kind. ^{187}Os has an excited state at 9.8 keV which clearly can be populated in a stellar interior. One therefore needs the ratio of the neutron capture cross sections for a stellar environment or alternatively the neutron capture cross section for the first excited state of ^{187}Os. Woosley and Fowler[26] defined a correction factor, f, as

$$f = [\sigma^*(186)/\sigma^{LAB}(186)]/[\sigma^*(187)/\sigma^{lab}(187)],$$

where the asterisk (*) refers to stellar environment cross sections. Their Hauser-Feshbach calculation yielded a value of f = 0.83. The same calculations predict that $\sigma_{n,n'}$ (E_n = 30 keV) to the 9.8-keV state in ^{187}Os should be about 800 mb. A recent measurement by Winters et al.[27] of the $^{187}Os(n,n')$ cross section is substantially smaller (< 250 mb). The use of ^{187}Re-^{187}Os depends critically on both the $^{186}Os/^{187}Os$ cross section ratio and the correction factor, f. Calculating the duration of r-process nucleosynthesis (Δ) using the same model as Fowler and Hoyle for U-Th, Winters, Macklin, and Halperin[28] obtain from their ^{186}Os and ^{187}Os capture data a value of $\Delta = 10.3 \pm 2.5 \times 10^9$ yr for f = 0.83. The above (n,n') measurement would imply that f is closer to 1.0 in which case one would calculate $\Delta \sim 8 \times 10^9$ yr which agrees incredibly well with the U-Th method. It should be noted that earlier measurements of $\sigma_c(186)/\sigma_c(187)$ reported by Browne and Berman[29] were found to have a systematic error in the $\sigma_c(186)$ cross section. Correction of their results leads to a value of $\Delta = 11 \pm 3 \times 10^9$ yr for f = 0.83 and $\Delta = 8.7 \pm 3 \times 10^9$ yr for f = 1.0. It is clear that one may have concordance of the r-process chronometers, ^{187}Re-^{187}Os and U-Th, if further measurements and calculations can improve our knowledge of the correction factor f. In addition, the half-life of ^{187}Re has a large uncertainty at this point and an improved accuracy is critical to use of this chronometer.

Another r-process chronometer that possibly could be used in a similar manner to ^{187}Re-^{187}Os is the ^{87}Rb-^{87}Sr clock, which involves a half-life for β-decay of 4.8×10^{10} yr. In this case, the half-life is well measured and one does not have the problem of excited state cross sections. However, in the case of Re-Os, the radiogenic component of ^{187}Os relative to total ^{187}Os is large and the σN equality is a good approximation. In the case of Rb-Sr, the radiogenic enrichment of ^{87}Sr is only on the order of 10%. Also, as can be seen in Fig. 2, σN is decreasing in this mass region as the N = 50 neutron shell is approached. To use this chronometer, therefore, will require very accurate neutron

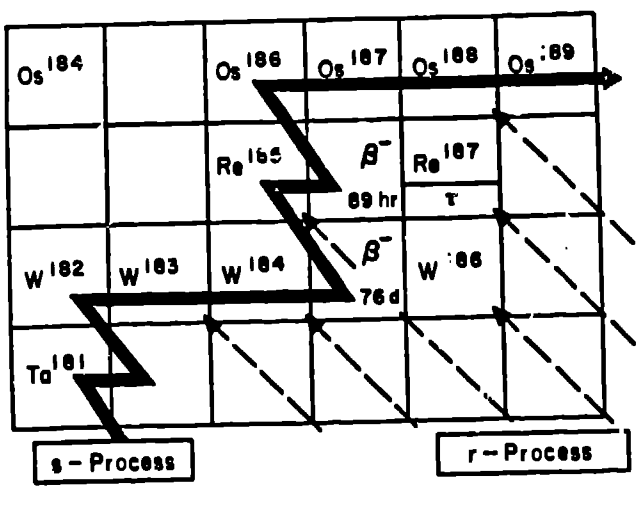

Fig. 6. The s-process path in the vicinity of the Re and Os isotopes. Both ^{186}Os and ^{187}Os are shielded from the r-process and hence are pure s-process nuclei. ^{187}Re is an r-process nucleus hence its β-decay can be used as a chronometer.

capture cross section measurements (< 5%) over the energy range 1 to 200 keV to determine the temperature sensitivity of the Maxwellian-averaged cross sections. Even if this is possible, we noted in the earlier discussion of s-process branching that it is possible to produce an s-process component of ^{87}Rb in a pulsed s-process environment. If sizable, this would increase the difficulty of using this chronometer. An accurate determination of the capture cross sections of ^{86}Sr and ^{87}Sr as well as any cross sections that affect the s-process path in this region would be valuable.

The β-decay of ^{176}Lu (3.6×10^{10} yr half-life) can be used as an s-process chronometer because it is shielded from the r-process by ^{176}Yb. As mentioned earlier, the use of this chronometer is affected by s-process branching. ^{175}Lu can capture a neutron to form either the long-lived g.s. of ^{176}Lu or the 3.7-hr first excited state. A knowledge of this branching ratio for kT = 30 keV is required to use this chronometer. Such a measurement by Beer and Kappeler[18] is reported at this conference. If they use the same exponential model for s-process nucleosynthesis, Beer and Kappeler obtain a value for the duration of s-process nucleosynthesis which is consistent with the Re-Os and U-Th r-process ages. Improvements could be made for this chronometer if the kT = 30-keV value of the neutron total capture cross section for ^{175}Lu were improved. The current values are 1460±110 mb from Ref. 30 and 1260±190 from Ref. 31. The reader is referred to the article by Beer and Kappeler for more details.

Solar Physics

It was proposed by Kuroda[29] in 1971 that it may be possible to determine the temperature of the sun shortly after formation from the difference in isotopic compositions of terrestrial and extraterrestrial xenon. His analysis of xenon isotope ratio data for carbonaceous chrondrite meteorites, lunar soil samples, and atmospheric samples indicated that xenon found in lunar soil is likely to represent the isotopic composition of almost pure solar xenon. Atmospheric xenon appeared to have the least solar xenon with meteoritic xenon falling in between. He speculated that the solar xenon was transported to the earth, moon, and meteorites via the solar wind early in the history of the solar system. The excess of ^{128}Xe in lunar soil can be explained[33] by cosmic ray neutron capture on ^{127}I. The excess of ^{131}Xe can be explained by cosmic ray neutron capture on ^{130}Ba (or ^{130}Te) as shown by the neutron capture measurements of Browne and Berman.[34,35] However, the excesses at ^{130}Xe and ^{132}Xe can only be explained by neutron capture on ^{129}Xe and ^{131}Xe. Kuroda concludes that neutron capture occurred on these isotopes in the interior of our sun during the deuterium-burning phase. The ratio of the neutron capture cross sections can be related to the ratio of the excess ^{130}Xe and ^{132}Xe and yield the most probable temperature at which the reactions occurred. From this, he concludes that the $D(d,n)^3He$ reaction is the probable source of the neutrons. However, it is necessary to measure the $^{129,131}Xe(n,\gamma)$ cross sections from 100 eV to 100 keV to provide the information needed to check his hypothesis that the temperature obtained is that of the core of the sun shortly after its birth.

Summary

Nuclear astrophysics poses a wonderful challenge to the neutron physicist, experimentalist and theorist alike. As was seen, there is a need for a large quantity of data across the periodic table. There are neutron measurements needed on abundant nuclei which will be difficult because of the small cross sections involved. There are some where the cross sections are large, but the isotopic abundance is small. There are some measurements which require new and more sensitive techniques, e.g., capture cross sections on the noble gases and isomeric branching ratios for kT = 30 keV.

This paper cannot possibly point out all the areas that neutron physics is of interest to astrophysics. Indeed, the needs will continually change as improvements are made in models of nucleosynthesis. Perhaps the best statement that can be made is that any high-quality neutron measurement will be of interest to the astrophysicist. Some directly because of their bearing on a specific problem. Others will be only indirectly of interest to check calculations or semi-empirical estimates for cross sections that cannot be measured in the laboratory. In the same manner, improvements in nuclear modeling techniques, such as better calculations of level densities and gamma-ray strength functions, will allow the astrophysicist to obtain more accurate data to check various theories.

Acknowledgment

The author would like to thank Stan Woosley and Mike Newman for interesting and helpful discussions.

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