Chapter 12
Branching Points on the Path of the *Slow* Neutron-Capture Process

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We supplement this book, and in particular the discussion of stellar nucleosynthesis presented in Chap. 3, with a list of the unstable isotopes at which branching points become relevant in the s-process reaction chain in AGB stars. For sake of clarity and a better understanding it is advisable to go through the list with a chart of the nuclides at hand. For each branching point a brief description of its operation and its relevance in the study of the s process in AGB stars is presented. The 21 branching points highlighted by a star symbol next to their atomic mass are those that Käppeler et al. (2011) considered as interesting candidates for future Time-Of-Flight (TOF) measurements of their neutron-capture cross sections. All listed isotopes suffer β^- decay, unless specified otherwise. It should also be noted that usually in s-process conditions nuclear energy metastable levels higher than the ground state are not populated, thus the effect of these states does not need to be included in the study of branching points, except for the special cases reported in the list (see also Ward 1977).

Branching factors for each branching point can be calculated in each case at a given temperature, density, and neutron density conditions referring to Takahashi

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R. Diehl et al. (eds.), *Astrophysics with Radioactive Isotopes*, Astrophysics and Space Science Library 453, https://doi.org/10.1007/978-3-319-91929-4_12

and Yokoi (1987) for the β decay rates, and to Rauscher (2012) for the neutron-capture cross section, unless advised otherwise in the description below.[1]

^{35}S This branching point may lead to production of the rare neutron-rich ^{36}S, whose abundance can be observed in stars via molecular lines, and may be measured in sulphur-rich meteoritic materials (for discussion and models see Mauersberger et al. 2004).

^{36}Cl and ^{41}Ca These are both long-living nuclei produced and destroyed—mostly via (n, p) and (n, α) channels—via neutron captures in AGB stars, and discussed in detail in Sect. 3.6.4 of Chap. 3. While ^{36}Cl behaves as stable nucleus during the *s* process, the half life of ^{41}Ca against electron captures has a strong temperature and density dependence, which could make it act as a branching point and most importantly prevent its survival instellar environments as in the case, e.g., of the other long-living ^{205}Pb.

^{45}Ca This branching point may lead to production of the rare neutron-rich ^{46}Ca, which could be measured in Ca-rich meteoritic material.

^{59}Fe This important branching point leads to the production of the long-living radioactive nucleus ^{60}Fe. See Sect. 3.6.3 of Chap. 3 for a detailed description and AGB model results.

^{63*}Ni The half life of this nucleus decreases from 100 years to $\simeq$12 years at 300 MK. The associated branching point affects the production of the rare neutron-rich ^{64}Ni as well as the ^{65}Cu/^{63}Cu ratio.

^{64}Cu The half life of this nucleus is short, of the order of a few hours, however, this isotope is a branching point on the *s*-process paths as it has comparable β^+ and β^- decay rates. The branching point may affect the production of ^{64}Ni and ^{65}Cu.

^{65}Zn This nucleus suffers β^+ decay and the branching point may affect the production of ^{65}Cu.

^{71}Ge This nucleus suffers β^+ decay and the branching point may affect the production of ^{71}Ga.

^{79*}Se This branching point may lead to production of the long-living radioactive isotope ^{81*}Kr. This production occurs when the temperature increases in the thermal pulse, and the half life of ^{79}Se decreases from the terrestrial half life of 65,000 years to roughly 4 years at 300 MK due to population of the shorter-living isomeric state (Klay and Käppeler 1988, and see Sect. 3.6.5 of Chap. 3 for model results). Operation of this branching point also affects the ^{81}Br/^{79}Br ratio.

^{80}Br The half life of this nucleus is short, of the order of minutes, however, it is a branching point on the *s*-process paths as it can decay both β^+ and β^-, with the β^- roughly ten times faster than the β^+ channel. It can affect the production of ^{81}Kr.

^{81}Kr This nucleus is too long living ($T_{1/2} = 0.23$ Myr, down to 2300 years at temperature 300 MK) to act as a branching point during the *s* process and rather

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[1] Maria Lugaro thanks Roberto Gallino and Franz Kaeppeler for communicating the passion for branching points and for help with this section.

behaves as a stable nucleus. Its production during the s-process is discussed in detail in Sect. 3.5 of Chap. 3. Its radiogenic decay leads to ^{81}Br.

^{85*}**Kr** The relatively long half life of ^{85}Kr (11 years) allows this branching point to activate already at low neutron densities, $> 5 \times 10^8$ n/cm^3. The actual operation of this branching point is complicated by the fact that roughly 40% of ^{84}Kr(n, γ) reactions during the s process result in the production of the isomeric state of ^{85}Kr. Approximately 80% of these nuclei quickly decay into ^{85}Rb, with a half live of 4.5 h, while the remaining 20% relax into the ground state. The production of ^{87}Rb, a very long-living isotope with half live of 48 Gyr and a magic number of neutrons N = 50, has traditionally been attributed to the activation of the branching point at ^{85}Kr (Lambert et al. 1995; Abia et al. 2001). However, van Raai et al. (2012) showed that the activation of the branching point at ^{85}Kr mostly results in the production of ^{86}Kr, a nucleus with a magic number of neutrons N=50 and a very small neutron capture cross section of only $\simeq$3.4 mbarn. ^{86}Kr is thus more likely to accumulate than to capture the further neutron that would allow the production of ^{87}Rb. The importance of the production of ^{86}Kr in meteoritic SiC grains and the s-process is discussed in Sect. 3.5.5 of Chap. 3.

^{86}**Rb** The branching point at ^{86}Rb is activated at relatively high neutron densities, above 10^{10} n/cm^3, being the half life of this nucleus 18.7 days, and it leads directly to the production of ^{87}Rb. The importance of ^{87}Rb in s-process observations and models is discussed in Sect. 3.5.4 of Chap. 3.

^{89,90}**Sr** and ^{91}**Y** The branching point at ^{89}Sr may produce the unstable ^{90}Sr, also a branching point producing ^{91}Sr, which quickly decays into unstable ^{91}Y. This is also a branching point, producing ^{92}Y, which quickly decays into stable ^{92}Zr. The final result of the operation of this chain of branching points is to decrease the production of ^{90}Zr and ^{91}Zr, with respect to that of ^{92}Zr. This point is discussed by Lugaro et al. (2003), in relevance to the Zr isotopis ratios measured in meteoritic silicon carbide (SiC) grains from AGB stars.

^{93}**Zr** This nucleus is too long-living ($T_{1/2} = 1.5$ Myr) to act as a branching point during the s process and rather behaves as a stable nucleus (see Sect. 3.5.2 and Fig. 3.10 of Chap. 3), with an experimentally determined neutron-capture cross section (Macklin 1985b). Its production during the s-process is discussed in detail in Sect. 3.6.5 of Chap. 3. Its radiogenic decay produces most of the solar abundance of ^{93}Nb. (A small fraction of the ^{93}Nb is also contributed by the radiogenic decay of ^{93}Mo ($T_{1/2} = 3500$ years) which is not on the main s-process path but can be produced by neutron-capture on the relatively abundant p-only ^{92}Mo, 15% of solar Mo.)

^{95*}**Zr** This important branching point can lead to production by the s process of ^{96}Zr if $N_n > 5 \times 10^8$ n/cm^3 (Toukan and Kaeppeler 1990; Lugaro et al. 2014; Yan et al. 2017). Zr isotopic ratios have been estimated in MS and S stars via molecular lines and measured in meteoritic SiC grains, providing constraints on the neutron density in the thermal pulses. This point is further discussed in Sects. 3.4.1 and 3.4.4.

^{94,95}**Nb** The half life of ^{94}Nb decreases from terrestrial 20,000 years to $\simeq$0.5 years at 100 MK and $\simeq$9 days at 300 MK. This branching point can produce the unstable ^{95}Nb, which is also a branching point producing the unstable ^{96}Nb, which quickly decays into stable ^{96}Mo. Via the operation of the ^{94}Nb branching point the ^{94}Mo nucleus is skipped during the s-process chain, this nucleus is in fact classified among p-only nuclei.

^{99}**Tc** The half life of ^{99}Tc is 0.21 Myr, and decreases to 0.11 Myr at 100 MK and to 4.5 years at 300 MK. Thus, the neutron-capture path of the branching point is mostly open, producing ^{100}Tc, which quickly decays into ^{100}Ru, thus skipping ^{99}Ru (Fig. 3.10). Then, radiogenic decay of ^{99}Tc produces ^{99}Ru. The production of ^{99}Tc is discussed in detail in Sect. 3.5.5, and mentioned in Sect. 3.5.6 of Chap. 3 in relation to ^{99}Ru in meteoritic SiC grains.

^{107}**Pd** This nucleus is too long-living ($T_{1/2} = 6.5$ Myr, down to $\simeq$700 years at 300 MK) to act as a branching point during the s process and rather behaves as a stable nucleus, with an experimentally determined neutron-capture cross section (Macklin 1985a). Its production during the s-process is discussed in detail in Sect. 3.6.5 of Chap. 3. Its radiogenic decay is responsible for production of ^{107}Ag.

^{128}**I** The decay half life of this nucleus is too short to allow for neutron captures, however, there is a marginal branching point here due to the fact that ^{128}I has both β^+ and β^- decay channels. The β^+ channel has significant temperature and density dependence and represents only a few percent of the decay rate. Nevertheless, this branching point has been investigated in detail because it affects the precise determination of relative abundances of the two s-only isotopes ^{128}Xe and ^{130}Xe, and because the timescale for its activation of the order of 25 min is comparable to that of the convective turn-over timescale of the material inside AGB thermal pulses of hours (Reifarth et al. 2004).

^{133}**Xe** May lead to production of the ^{134}Xe. Of interest in relation to the Xe-S component from SiC grains in primitive meteorites, as discussed in Sect. 3.5.4 of Chap. 3.

^{134*,135*,136,137}**Cs** The chain of branching points at the Cs isotopes is of particular interest because it affects the isotopic composition of the s-process element Ba and in particular the relative abundances of the two s-only nuclei ^{134}Ba and ^{136}Ba, as it is discussed in Sect. 3.5.5 in relation to Ba data from meteoritic SiC grains. The branching point at ^{134}Cs allows production of the long-living isotope ^{135}Cs (see Sect. 3.6.5 of Chap. 3 for model results). The half lives of both ^{134}Cs and ^{135}Cs have a strong theoretical temperature dependence, decreasing by orders of magnitude in stellar conditions. Specifically for the long-living ^{135}Cs, $T_{1/2}$ varies from terrestrial of 2 Myr down to $\simeq$200 years at 300 MK, while its neutron-capture cross section has been experimentally determined (Patronis et al. 2004). The branching point at ^{135}Cs can produce the unstable ^{136}Cs, which is also a branching point producing the unstable ^{137}Cs. With a constant half life of $\simeq$30 years, this is also a branching point producing the unstable ^{138}Cs, which quickly decays into stable ^{138}Ba.

^{141}**Ce** this branching point may lead to production of the neutron-rich ^{142}Ce, thus skipping the *s*-only ^{142}Nd and affecting the Nd isotopic ratios, which are measured in SiC stardust grains (Gallino et al. 1997).

^{142,143}**Pr** The branching point at ^{142}Pr is affected by the temperature dependence of the β^- half life of ^{142}Pr, which increases to $\simeq$4 days at 300 MK from the terrestrial 19 h. The neutron-capture branch may produce the unstable ^{143}Pr, which is also a branching point producing the unstable ^{144}Pr, which quickly decays into ^{144}Nd. The operation of this chain of branching points may affect the isotopic composition of Nd because ^{142}Nd and ^{143}Nd are skipped by the neutron-capture flux and their abundances are decreased.

^{147*}**Nd** This branching point may lead to the production of the neutron-rich "r-only" ^{148}Nd, which is of interest in relation to stellar SiC grain Nd data (Gallino et al. 1997).

^{147*,148*}**Pm** The branching point at ^{147}Pm is affected by the strong temperature dependence of the β^- decay of this nucleus, where the half life decreases from the terrestrial value of 2.6 years down to $\simeq$1 years at 300 MK. The neutron-capture cross section of this nucleus is experimentally determined (Reifarth et al. 2003). When the branching is open, it produces the unstable ^{148}Pm, a branching point that may lead to production of ^{149}Pm, which quickly decays into ^{149}Sm. The operation of this chain of branching points affects the isotopic composition of Sm, by skipping ^{147}Sm and the *s*-only ^{148}Sm. This is of interest in relation to stellar SiC grain Sm data (Gallino et al. 1997).

^{151*}**Sm** The operation of this branching point is affected by the temperature dependence of the β^- decay rate of ^{151}Sm, where the half life of this nucleus decreases from 93 years to $\simeq$3 years at 300 MK. Its operation changes the ^{153}Eu/^{151}Eu ratio, which can be measured in stars (Sect. 3.5.4 of Chap. 3) and in SiC stardust grains (Sect. 3.5.5 of Chap. 3). Note that ^{151}Sm is one of few radioactive nuclei acting as branching points on the *s*-process path for which an experimental determination of the neutron capture cross section is available (Abbondanno et al. 2004; Wisshak et al. 2006), however, some uncertainty is due to the contribution of excited states, which could be significant (Ávila et al. 2013; Rauscher 2012).

^{153}**Sm** This branching point can produce the neutron-rich ^{154}Sm and affect the ^{153}Eu/^{151}Eu ratio.

^{152}**Eu** This nucleus suffers both β^- and β^+ decays, with rates showing a strong temperature dependence covering several orders of magnitude variation in stellar conditions. The β^+ decay rate also has a strong dependence on density. The operation of this branching point, in combination with that at ^{151}Sm, makes possible the production of the rare *p*-only isotope ^{152}Gd by the *s* process.

^{154*,155*}**Eu** The decay rate of ^{154}Eu has a strong temperature dependence, with its half life decreasing from 8.8 years down to $\simeq$11 days at 300 MK. If activated, it leads to production of the unstable ^{155}Eu, a branching point also with a temperature dependence, and an experimentally determined neutron-capture cross section (Jaag and Käppeler 1995), which may produce ^{156}Eu, which quickly decays into ^{156}Gd. The operation of this chain of branching points affects the isotopic composition of Gd, which is a refractory element present in stellar SiC grains (Yin et al. 2006).

^{153*}**Gd** This nucleus suffers β^+ decay with a temperature dependence, where the terrestrial half life of 239 days increases with increasing the temperature by up to an order of magnitude in AGB stars conditions. The operation of this branching point may affect the ^{153}Eu/^{151}Eu ratio.

^{163}**Dy** and ^{163*,164}**Ho** The nucleus ^{163}Dy is stable in terrestrial conditions, but it can become unstable inside stars: at 300 MK the half life of this isotope becomes $\simeq$18 days. Thus, a branching can open on the s-process path, leading to the production of the unstable ^{163}Ho via β^- decay of ^{163}Dy. In this conditions, the β^+ half life of ^{163}Ho (which also has a strong temperature and density dependence) is $\simeq$12 years, so another branching can open on the s-process neutron capture path. Neutron captures on ^{163}Ho lead to production of the unstable ^{164}Ho, which has fast β^- and β^+ channels, both temperature dependent. The β^- channel can eventually lead to the production of ^{164}Er, a p-only nucleus, which may thus have a s-process component in its cosmic abundance.

^{169}**Er** This branching point may lead to the production of the neutron-rich ^{170}Er.

^{170*,171*}**Tm** The branching point at ^{170}Tm may produce the unstable ^{171}Tm, which is also a branching point (with a temperature dependence) producing the unstable ^{172}Tm, which quickly decays into ^{172}Yb. By skipping ^{171,172}Yb during the s-process flux, these branching points affect the isotopic composition of Yb, which is a refractory element present in meteoritic stellar SiC grains (Yin et al. 2006).

^{176}**Lu** A branching point at ^{176}Lu is activated because of the production of the short-living (half life of $\simeq$4 h) isomeric state of ^{176}Lu via neutron captures on ^{175}Lu. The situation is further complicated because, at around 300 MK, the isomeric and the ground state of ^{176}Lu are connected via the thermal population of nuclear states that can act as mediators between the two. Hence, the half life of the ^{176}Lu system can decrease at such temperatures by orders of magnitude. This branching point is of importance for the production of the very long-living ground state of ^{176}Lu (half life of 380 Gyr) and of the stable ^{176}Hf, which are both s-only isotopes, shielded by ^{176}Yb against r-process production. Hence, the relative solar abundances of these two isotopes need to be matched by s-process in AGB stars. For details and models see Heil et al. (2008) and Mohr et al. (2009).

^{177}**Lu** This branching point may lead to production of the unstable ^{178}Lu, which quickly decays into ^{178}Hf, thus decreasing the abundance of ^{177}Hf.

^{179}**Hf**, ^{179*,180}**Ta** A branching point at ^{179}Hf may be activated on the s-process path because this stable nucleus becomes unstable in stellar conditions (as in the case of ^{163}Dy) with a β^- half life of $\simeq$40 years at 300 MK. This may allow the production of the unstable ^{179}Ta, which is also a branching point with a temperature-dependent β^+ decay rate, which may lead to the production of ^{180}Ta, the least abundant nucleus in the solar system (Käppeler et al. 2004) as a few percent of neutron captures on ^{179}Ta lead to production of the very long-living isomeric state of ^{180}Ta, instead of the ground state, which suffers fast β^+ and β^- decays. As in the case of ^{176}Lu, the ground and the isomeric states of ^{180}Ta can be connected via the thermal population of nuclear states that act as mediators between the two. It is still unclear if the cosmic abundance of ^{180}Ta is to be ascribed to the *s* process or to nucleosynthetic processes in supernovae connected to neutrino fluxes.

^{181}**Hf** This branching point leads to production of the long-living radioactive nucleus ^{182}Hf (one of the few radioactive isotopes with an experimentally determined neutron-capture cross section available, Vockenhuber et al. 2007) whose decay into ^{182}W is of extreme importance for early solar system datation. The half life of ^{181}Hf is relatively long (42 days) allowing production of ^{182}Hf in AGB stars when the ^{22}Ne(α,n)^{25}Mg reaction is activated (see also Sect. 3.5 of Chap. 3).

^{182,183}**Ta** The branching point at ^{182}Ta is temperature dependent and may produce the unstable ^{183}Ta, also a branching point, producing ^{184}Ta, which quickly decays into the stable ^{184}W. These branching points may affect the isotopic composition of W, which is a refractory element that is present in stellar SiC grains.

^{185*}**W** This branching point may produce ^{186}W, and affect the isotopic composition of W as well as the ^{186}Os/^{188}Os ratio. Its signature may be seen in data from stellar SiC grains for W and Os (Humayun and Brandon 2007; Ávila et al. 2012). Note that ^{185}W is one of few radioactive nuclei acting as branching points on the *s*-process path for which an experimental determination of the neutron capture cross section is available, even thought only via indirect (γ, n) studies, which have rather large uncertainties of about 30% (Sonnabend et al. 2003; Mohr et al. 2004).

^{186}**Re** This isotope decays in $\simeq$89 h, and has both β^- and β^+ decay channel. The β^- decay channel is faster by one to two orders of magnitude depending on the temperature, which affects the β^+ decay rate. This branching point can affect the production of ^{186}Os, ^{186}W, and the very long-living ^{187}Re, whose slow decay into ^{187}Os is used as a cosmological clock (see discussion in Chap. 2).

^{191}**Os** This branching point has a mild temperature dependence whereby the half life of ^{191}Os decreases with the temperature from the terrestrial 15 days to $\simeq$8 days at 300 MK. If activated, the neutron-capture branch can decrease the *s*-process abundances of ^{191}Ir and ^{192}Pt and lead to production of ^{192}Os, thus affecting the isotopic composition of Os, which is measured in meteoritic materials (Brandon et al. 2005), and ^{193}Ir.

^{192}**Ir** This branching point can produce ^{193}Ir, and affect the *s*-process production of the rare proton-rich ^{192}Pt. A few percent of the decay rate of ^{192}Ir is made by β^+ decays.

^{193}**Pt** This isotope decays β^+ with a half life of $\simeq$50 years, which may affect the production of ^{193}Ir.

^{204*}**Tl** This branching point has a strong temperature dependence with its half life decreasing from the terrestrial value of $\simeq$3.8 years to $\simeq$7 days at 300 MK, leading to production of the *s*-only ^{204}Pb.

^{205}**Pb** This nucleus is long-living in terrestrial conditions ($T_{1/2} = 15$ Myr), but its half life against electron captures has a strong temperature and density dependence, which affects its survival in stellar environments, as in the case of ^{41}Ca. Its production during the *s*-process is discussed in detail in Sect. 3.5 of Chap. 3. Its radiogenic decay is responsible for production of ^{105}Tl.

^{210}**Bi** This temperature-dependent branching point may lead to production of the unstable ^{211}Bi, which α decays into ^{207}Tl, which quickly decays β^{+} into ^{207}Pb.

^{210}**Po** May produce ^{211}Po, which quickly α decays into ^{207}Pb. The α decay of ^{210}Po, and ^{211}Bi above, represent the chain of reactions that terminates the *s* process (Clayton and Rassbach 1967; Ratzel et al. 2004).

To complete the picture we list nuclei that could be classified as potential *s*-process branching points, given that their terrestrial half life is greater than a few days, however, they do not open during the *s* process because their half life decreases with the temperature to below a few days. These are: ^{103}Ru, ^{123}Sn, ^{124}Sb, ^{156}Eu, ^{160*,161}Tb, ^{175}Yb, ^{198}Au, and ^{205}Hg. Finally, we point out the special case of ^{157}Gd, a stable nucleus which becomes unstable at stellar temperatures, but not enough to open a branching point on the *s*-process path in AGB stars.

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