New s-process nucleosynthesis predictions for low-mass AGB stars and implications for meteoritic data

Balázs Szányi

s, i & r Element Nucleosynthesis (sirEN) Conference
Giulianova, Italy, June 8-13, 2025

University of Szeged
Institute of Physics

KONKOLY

A&A, 697, A48 (2025)
https://doi.org/10.1051/0004-6361/202453089

Astronomy & Astrophysics

Impact of *T*- and ρ-dependent decay rates and new (n,γ) cross-sections on the *s* process in low-mass asymptotic giant branch stars

B. Szányi[1,2,3,⋆], A. Yagüe López[4], A. I. Karakas[5,6], and M. Lugaro[2,3,5,7]

[1] Department of Experimental Physics, Institute of Physics, University of Szeged, H-6720 Szeged, Dóm tér 9, Hungary
[2] Konkoly Observatory, HUN-REN CSFK/RCAES, Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary
[3] CSFK, MTA Centre of Excellence, Konkoly Thege Miklós út 15-17., H-1121, Budapest, Hungary
[4] Computer, Computational and Statistical Sciences (CCS) Division, Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5] School of Physics and Astronomy, Monash University, VIC 3800, Australia
[6] ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Clayton, VIC 3800, Australia
[7] ELTE Eötvös Loránd University, Institute of Physics and Astronomy, Pázmány Péter sétány 1/A, Budapest 1117, Hungary

Received 20 November 2024 / Accepted 1 March 2025

Nucleosynthesis calculations with the Monash code for 7 stellar models of low-mass AGB stars with 3 different sets of nuclear inputs

↓

Comparison the predictions of the sets relative to each other in terms of final isotopic surface abundances

↓

Comparison to isotopic ratios measured in presolar stardust SiC grains from AGB stars

Set 0

- Constant/terrestrial β-decay rates from JINA reaclib[1]
- Neutron-capture rates: *ka02* fits from JINA reaclib[1]

$$\lambda = \exp\left[a_0 + \sum_{i=1}^{5} a_i T_9^{\frac{2i-5}{3}} + a_6 \ln T_9\right]$$

(1) https://reaclib.jinaweb.org

Set 1

- **Temperature- and density-dependent β-decay rates from NETGEN**
- Neutron-capture rates: *ka02* fits from JINA reaclib

Set 2

- Temperature- and density-dependent β-decay rates from NETGEN
- **92 new neutron-capture rates based on MACS from ASTRAL and SEF from KaDoNiS**

Set 0

- Constant/terrestrial β-decay rates from JINA reaclib[1]
- Neutron-capture rates: *ka02* fits from JINA reaclib[1]

(1) https://reaclib.jinaweb.org

Set 1

- **Temperature- and density-dependent β-decay rates from NETGEN[2]**
- Neutron-capture rates: *ka02* fits from JINA reaclib

(2) http://www.astro.ulb.ac.be/Netgen/

Set 2

- Temperature- and density-dependent β-decay rates from NETGEN
- **92 new neutron-capture rates based on MACS from ASTRAL[3] and SEF from KaDoNiS[4]**

(3) https://www.kadonis.org

(4) https://exp-astro.de/astral/

Set 0

- Constant/terrestrial β-decay rates from JINA reaclib[1]
- Neutron-capture rates: *ka02* fits from JINA reaclib[1]

(1) https://reaclib.jinaweb.org

Set 1

- **Temperature- and density-dependent β-decay rates from NETGEN[2]**
- Neutron-capture rates: *ka02* fits from JINA reaclib

(2) http://www.astro.ulb.ac.be/Netgen/

Set 2

- Temperature- and density-dependent β-decay rates from NETGEN
- **92 new neutron-capture rates based on MACS from ASTRAL[3] and SEF from KaDoNiS[4]**

(3) https://www.kadonis.org

(4) https://exp-astro.de/astral/

A&A, 697, A48 (2025)
https://doi.org/10.1051/0004-6361/202453089

Astronomy & Astrophysics

Impact of T- and ρ-dependent decay rates and new (n,γ) cross-sections on the *s* process in low-mass asymptotic giant branch stars

B. Szányi[1,2,3,★], A. Yagüe López[4], A. I. Karakas[5,6], and M. Lugaro[2,3,5,7]

[1] Department of Experimental Physics, Institute of Physics, University of Szeged, H-6720 Szeged, Dóm tér 9, Hungary
[2] Konkoly Observatory, HUN-REN CSFK/RCAES, Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary
[3] CSFK, MTA Centre of Excellence, Konkoly Thege Miklós út 15-17., H-1121, Budapest, Hungary
[4] Computer, Computational and Statistical Sciences (CCS) Division, Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[5] School of Physics and Astronomy, Monash University, VIC 3800, Australia
[6] ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Clayton, VIC 3800, Australia
[7] ELTE Eötvös Loránd University, Institute of Physics and Astronomy, Pázmány Péter sétány 1/A, Budapest 1117, Hungary

Received 20 November 2024 / Accepted 1 March 2025

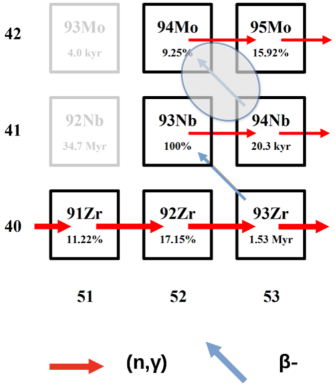
Nucleosynthesis calculations with the Monash code for 7 stellar models of low-mass AGB stars with 3 different sets of nuclear inputs

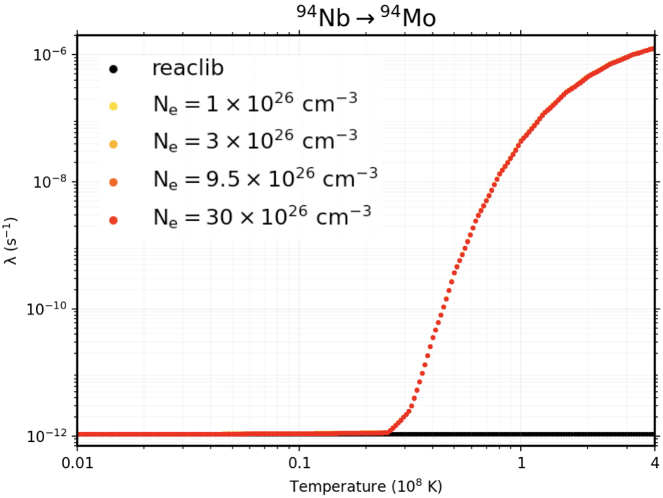
↓

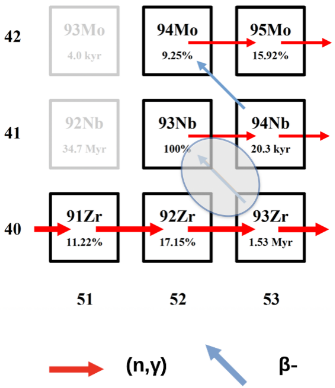
Comparison the predictions of the sets relative to each other in terms of final isotopic surface abundances

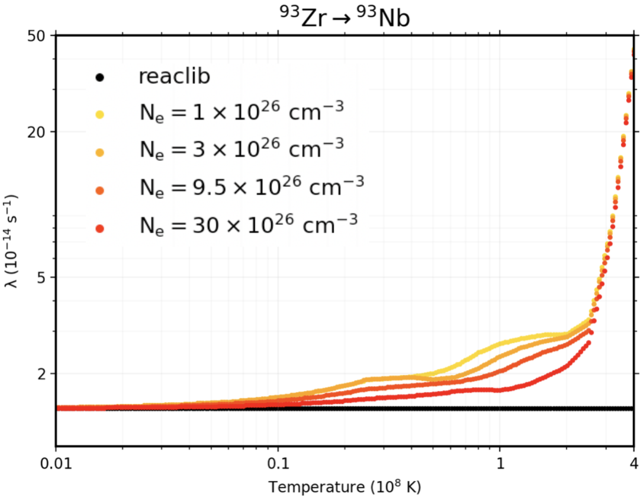
↓

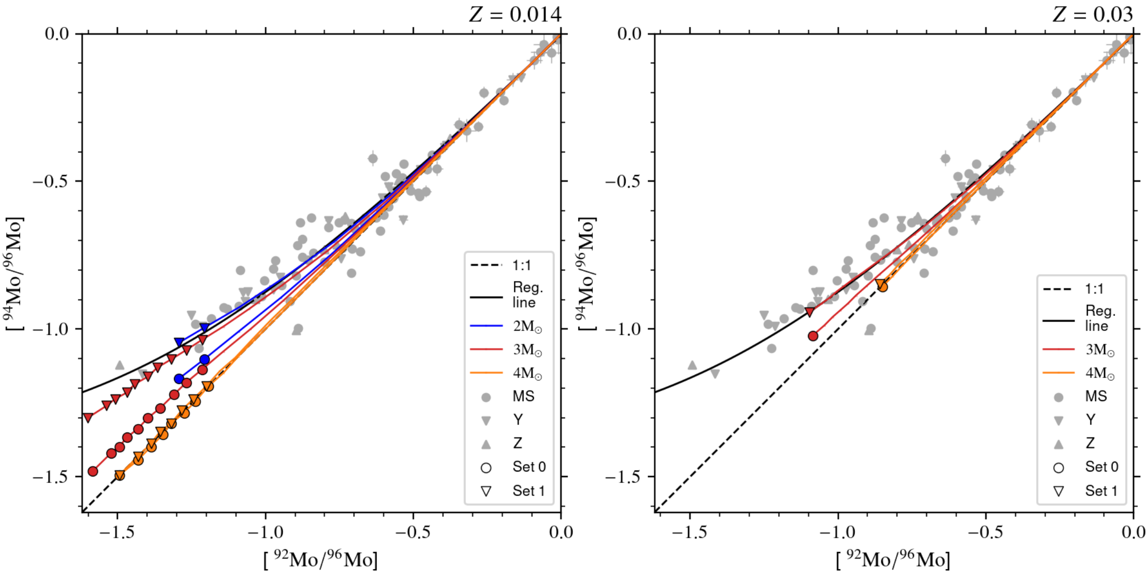
Comparison to isotopic ratios measured in presolar stardust SiC grains from AGB stars

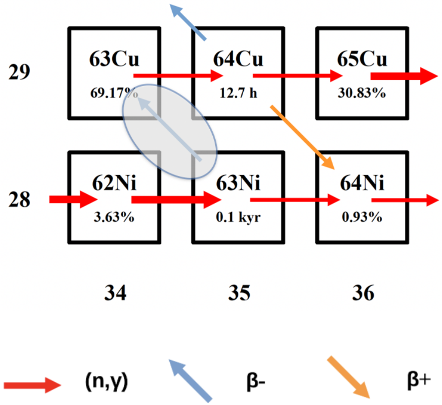

42
41
40
93Mo
4.0 kyr
94Mo
9.25%
95Mo
15.92%
92Nb
34.7 Myr
93Nb
100%
94Nb
20.3 kyr
91Zr
11.22%
92Zr
17.15%
93Zr
1.53 Myr
51
52
53
(n,γ)
β-

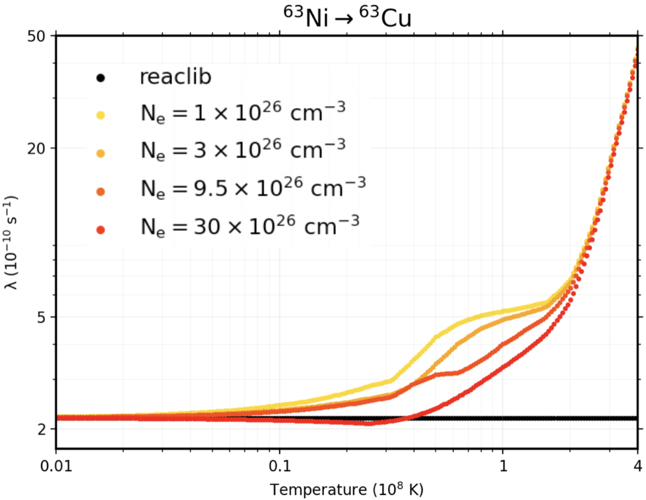

^{94}Nb → ^{94}Mo
reaclib
$N_e = 1 \times 10^{26}$ cm^{-3}
$N_e = 3 \times 10^{26}$ cm^{-3}
$N_e = 9.5 \times 10^{26}$ cm^{-3}
$N_e = 30 \times 10^{26}$ cm^{-3}
λ (s^{-1})
10^{-6}
10^{-8}
10^{-10}
10^{-12}
0.01
0.1
1
4
Temperature (10^8 K)

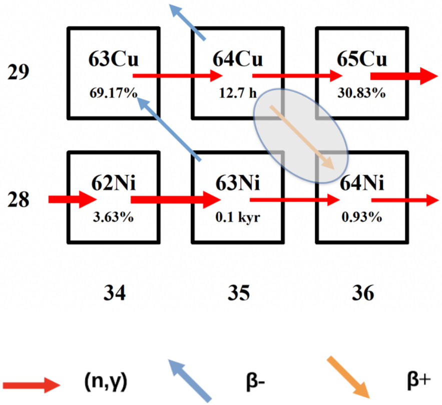

42
41
40
93Mo
4.0 kyr
94Mo
9.25%
95Mo
15.92%
92Nb
34.7 Myr
93Nb
100%
94Nb
20.3 kyr
91Zr
11.22%
92Zr
17.15%
93Zr
1.53 Myr
51
52
53
(n,γ)
β-

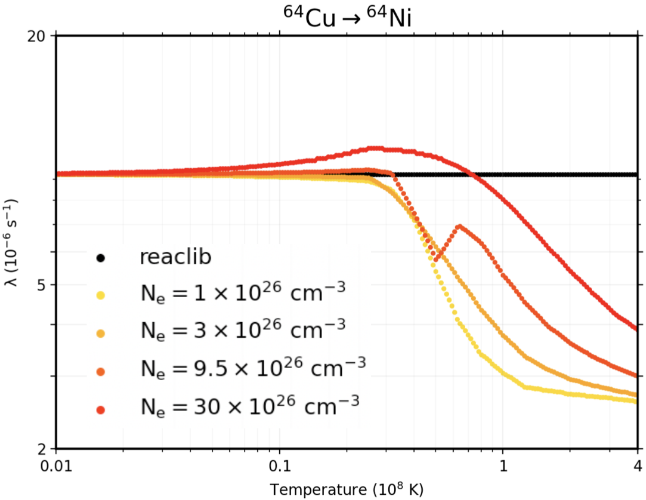

^{93}Zr → ^{93}Nb
reaclib
$N_e = 1 \times 10^{26}$ cm^{-3}
$N_e = 3 \times 10^{26}$ cm^{-3}
$N_e = 9.5 \times 10^{26}$ cm^{-3}
$N_e = 30 \times 10^{26}$ cm^{-3}
λ (10^{-14} s^{-1})
50
20
5
2
0.01
0.1
1
4
Temperature (10^8 K)

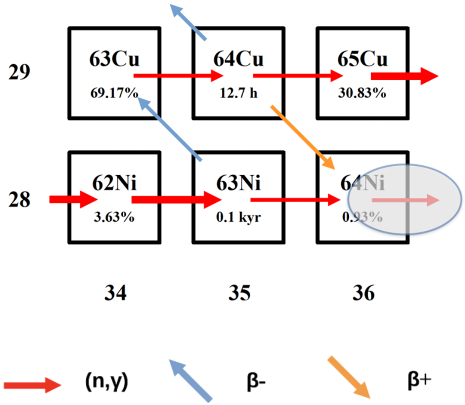

Z = 0.014
Z = 0.03
[^{94}Mo/^{96}Mo]
[^{92}Mo/^{96}Mo]
0.0
−0.5
−1.0
−1.5
1:1
Reg. line
2M⊙
3M⊙
4M⊙
MS
Y
Z
Set 0
Set 1

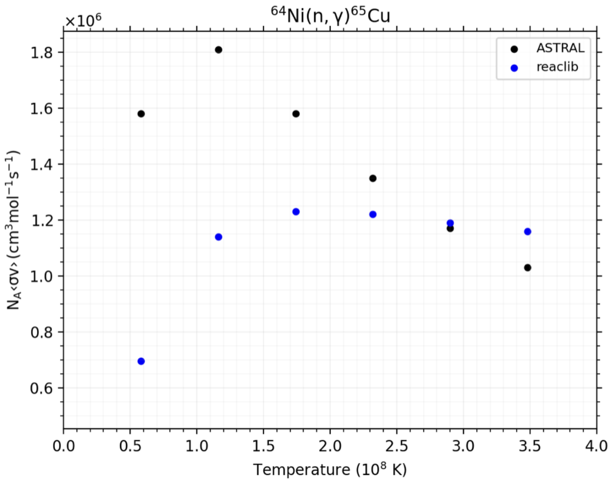

63Cu
69.17%
64Cu
12.7 h
65Cu
30.83%
29
62Ni
3.63%
63Ni
0.1 kyr
64Ni
0.93%
28
34
35
36
(n,γ)
β-
β+

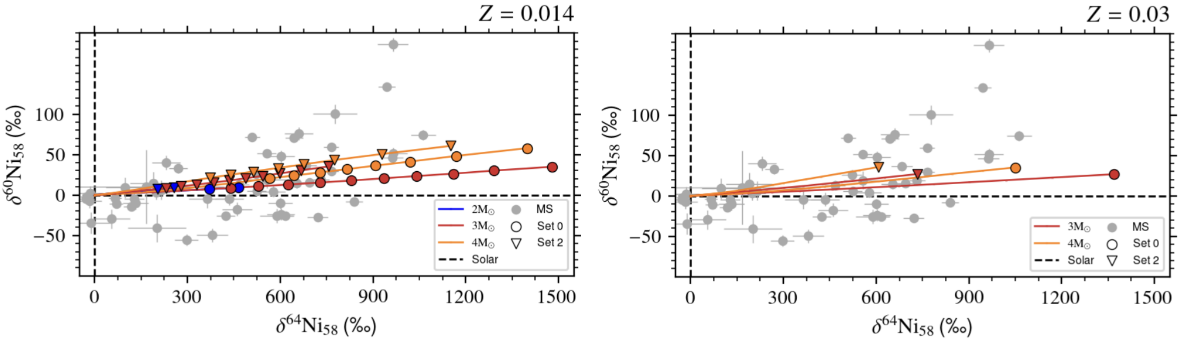

^{63}Ni → ^{63}Cu
reaclib
$N_e = 1 \times 10^{26}$ cm^{-3}
$N_e = 3 \times 10^{26}$ cm^{-3}
$N_e = 9.5 \times 10^{26}$ cm^{-3}
$N_e = 30 \times 10^{26}$ cm^{-3}
λ (10^{-10} s^{-1})
50
20
5
2
0.01
0.1
1
4
Temperature (10^8 K)

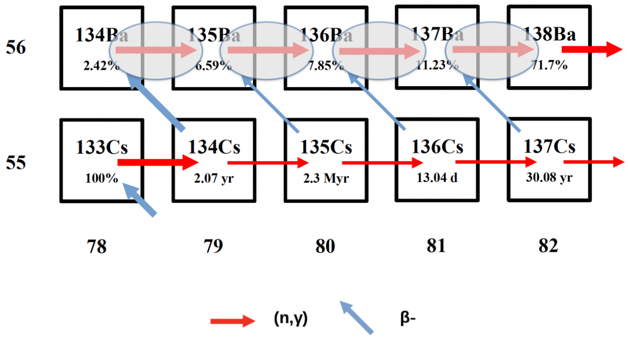

63Cu
69.17%
64Cu
12.7 h
65Cu
30.83%
62Ni
3.63%
63Ni
0.1 kyr
64Ni
0.93%
29
28
34
35
36
(n,γ)
β-
β+


^{64}Cu → ^{64}Ni
λ (10^{-6} s^{-1})
Temperature (10^8 K)
reaclib
$N_e = 1 \times 10^{26}$ cm^{-3}
$N_e = 3 \times 10^{26}$ cm^{-3}
$N_e = 9.5 \times 10^{26}$ cm^{-3}
$N_e = 30 \times 10^{26}$ cm^{-3}
20
5
2
0.01
0.1
1
4

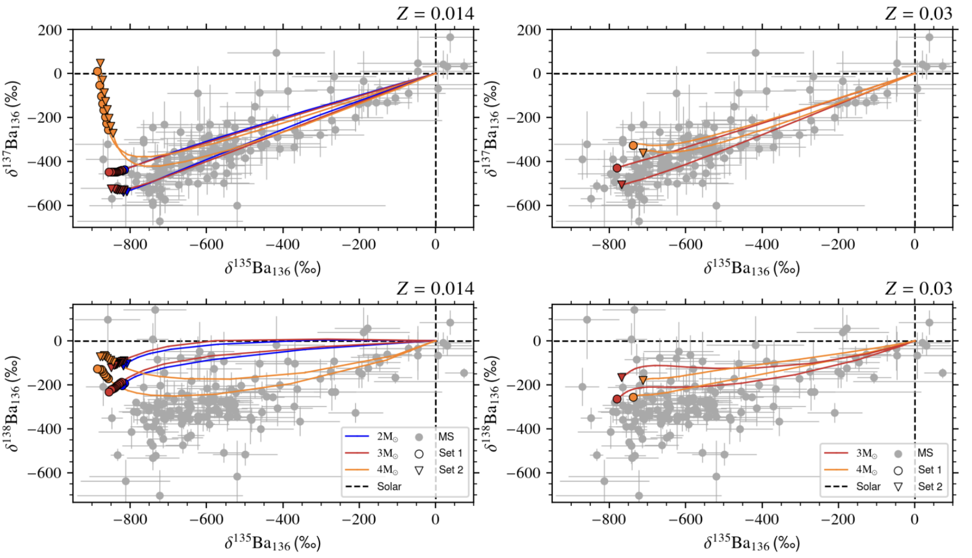

29
28
63Cu
69.17%
64Cu
12.7 h
65Cu
30.83%
62Ni
3.63%
63Ni
0.1 kyr
64Ni
0.93%
34
35
36
(n,γ)
β-
β+


^{64}Ni(n, γ)^{65}Cu
×10^{6}
ASTRAL
reaclib
N$_A$<σv> (cm^{3}mol^{-1}s^{-1})
Temperature (10^8 K)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

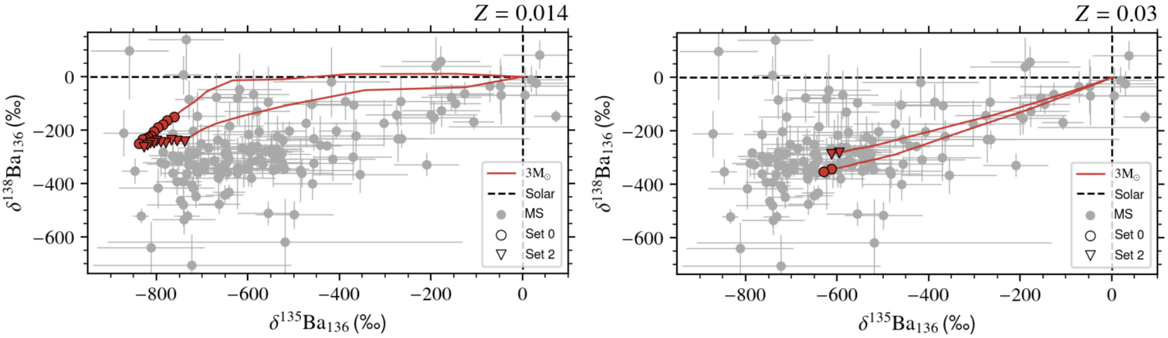

Z = 0.014
δ60Ni58 (‰)
δ64Ni58 (‰)
2M⊙
3M⊙
4M⊙
Solar
MS
Set 0
Set 2
Z = 0.03
δ60Ni58 (‰)
δ64Ni58 (‰)
3M⊙
4M⊙
Solar
MS
Set 0
Set 2

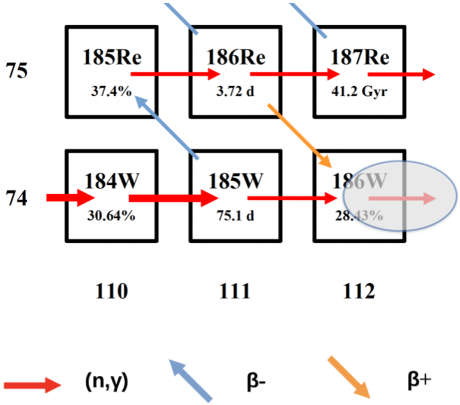


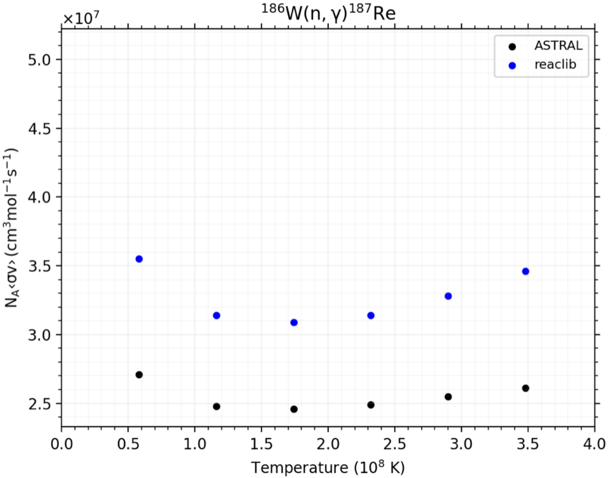
	$(\mathrm{MACS})_{\mathrm{Set\ 2}}/(\mathrm{MACS})_{\mathrm{Set\ 1}}$				
Energy (keV)	10	15	20	25	30
$^{134}\mathrm{Ba}(n,\gamma)$	1.12	1.10	1.08	1.06	1.05
$^{135}\mathrm{Ba}(n,\gamma)$	1.07	1.07	1.08	1.07	1.07
$^{136}\mathrm{Ba}(n,\gamma)$	1.12	1.11	1.10	1.10	1.10
$^{137}\mathrm{Ba}(n,\gamma)$	1.44	1.30	1.24	1.21	1.18

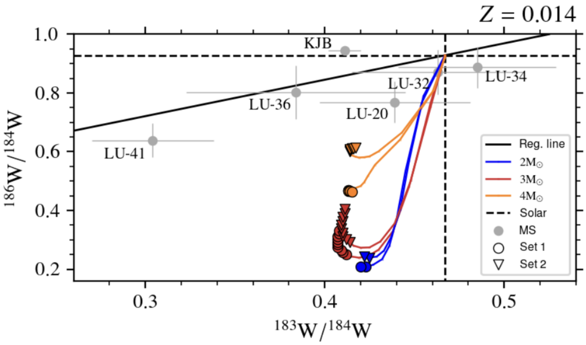


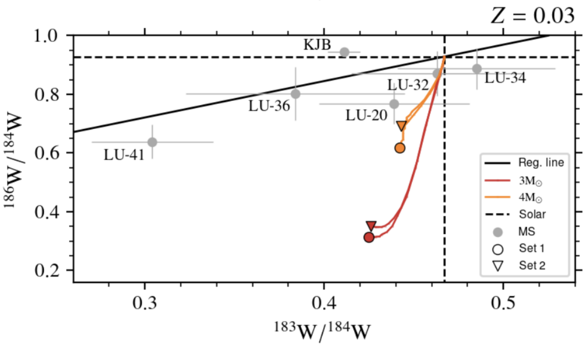
Z = 0.014
Z = 0.03
Z = 0.014
Z = 0.03
δ137Ba136 (‰)
δ138Ba136 (‰)
δ135Ba136 (‰)
2M⊙
3M⊙
4M⊙
Solar
MS
Set 1
Set 2

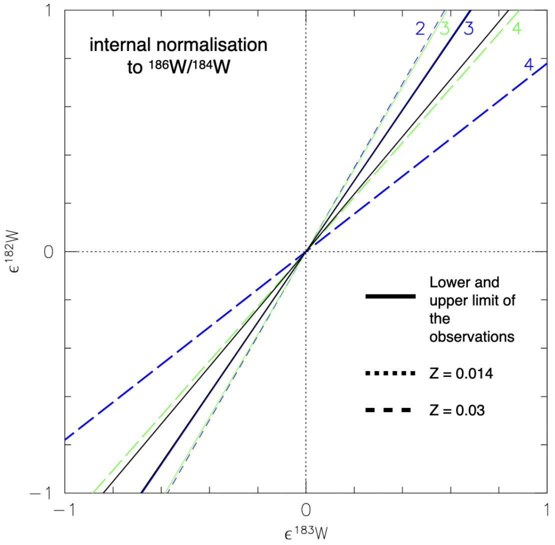

Z = 0.014
Z = 0.03
$\delta^{138}Ba_{136}$ (‰)
$\delta^{135}Ba_{136}$ (‰)
3M$_\odot$
Solar
MS
Set 0
Set 2
0
−200
−400
−600
−800


75
74
185Re
37.4%
186Re
3.72 d
187Re
41.2 Gyr
184W
30.64%
185W
75.1 d
186W
28.43%
110
111
112
(n,γ)
β-
β+


186W(n, γ)187Re
×10^7
ASTRAL
reaclib
N_A<σv> (cm^3 mol^-1 s^-1)
Temperature (10^8 K)
5.0
4.5
4.0
3.5
3.0
2.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Z = 0.014
KJB
LU-34
LU-32
LU-36
LU-20
LU-41
Reg. line
2M⊙
3M⊙
4M⊙
Solar
MS
Set 1
Set 2
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
183W/184W
186W/184W


Z = 0.03
KJB
LU-34
LU-32
LU-36
LU-20
LU-41
Reg. line
3M⊙
4M⊙
Solar
MS
Set 1
Set 2
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
183W/184W
186W/184W


internal normalisation
to 186W/184W
2
3
3
4
4
Lower and
upper limit of
the
observations
Z = 0.014
Z = 0.03
ε 182W
ε 183W
1
0
−1
−1
0
1

References

- Ávila, J. N., et al. 2012, ApJ, 744, 49
- Barzyk, J. G. 2007, Ph.D. Thesis, University of Chicago, USA
- Budde, G., et al. 2016, Proc.Nat. Academy Sci., 113, 2886
- Kruijer, T. S., et al. 2014, Earth Planet. Sci. Lett., 403, 317
- Liu, N., et al. 2014, ApJ, 786, 66
- Liu, N., et al. 2015, ApJ, 803, 12
- Liu, N., et al. 2017a, Meteor. Planet. Sci., 52, 2550
- Liu, N., et al. 2017b, ApJ, 844, L12
- Liu, N., et al. 2019, ApJ, 881, 28
- Liu, N., et al. 2022, Eur. Phys. J. A, 58, 216
- Marhas, K. K., et al. 2007, Meteor. Planet. Sci., 42, 1077
- Savina, M. R., et al. 2003, Geochim. Cosmochim. Acta, 67, 3215
- Stephan, T., et al. 2018, Geochim. Cosmochim. Acta, 221, 109
- Stephan, T., et al. 2019, ApJ, 877, 101
- Trappitsch, R., et al. 2018, Geochim. Cosmochim. Acta, 221, 87

Conclusions

- Taking into account the T and ρ dependence of the decay rates of the ^{93}Zr and ^{94}Nb branching isotopes, the surface evolution of the 2 and 3 $M_\odot$ models follows closely the regression line of the $[^{94}Mo/^{96}Mo]$ versus $[^{92}Mo/^{96}Mo]$ data.
- With the new (n,γ) cross sections of ^{64}Ni and T- and ρ-dependent decay rates of ^{63}Ni and ^{64}Cu, the $\delta^{64}Ni_{58}$ values derived from our models better cover the SiC grain data.
- With the new (n,γ) cross sections of ^{136,137}Ba, the models fit better to the $\delta^{137}Ba_{136}$ SiC grain data, but produce higher $\delta^{138}Ba_{136}$ than the typical values of the grains.
- The Set 2 models produce higher ^{186}W, although they still do not match well the W isotopic composition of large SiC stardust grains well, but they do match well the W composition observed in other types of meteoritic materials.