νpプロセスで重要な天体核反応と超新星ニュートリノへの制限

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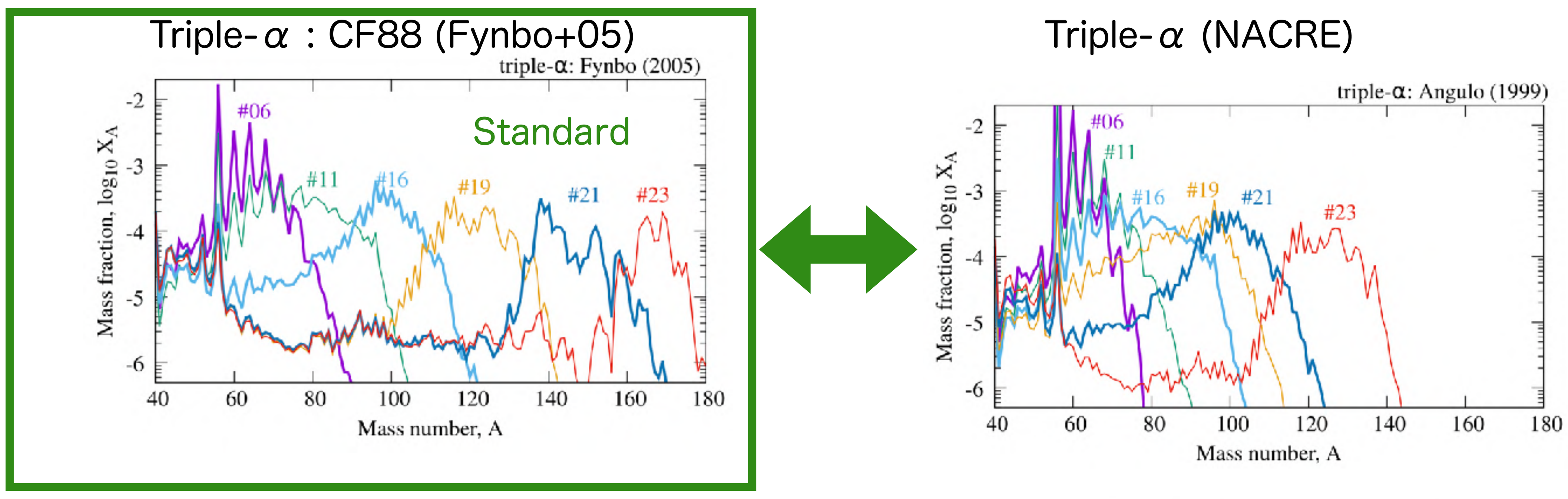
Abstract: The νp process is an explosive nucleosynthesis mechanism that occurs in a proton-rich environment near the central region of a core-collapse supernova. It is responsible for the production of some lighter p-nuclei (proton-rich stable nuclei) in the Universe. A precise understanding of the νp process requires accurate determinations of nuclear reaction rates across a wide range of proton-rich unstable nuclei, as well as insights into the explosion mechanisms of core-collapse supernovae. In this study, we assessed the uncertainties in nuclear reaction rates involved in the νp process and comprehensively analyzed their impact on nucleosynthesis. Our results indicate that variations in several unresolved reaction rates can account for the molybdenum isotope ratios observed in the solar system.

νp-process

The thermodynamic evolution model of neutrino-driven winds (Nishimura et al. 2012) was adopted as the astronomical environment. However, parameter searches were conducted over a wide range of Y_e and entropy values for nucleosynthesis. (Detailed results will be presented in the paper.) Here, we present three representative cases :

- $(Y_e, S/k_B) = (0.64, 47.5)$: #06 "weak νp-process"
- $(Y_e, S/k_B) = (0.665, 70.7)$: #11 "medium νp-process"
- $(Y_e, S/k_B) = (0.690, 105)$: #16 "wtrong νp-process"



Monte Carlo + Reaction Network

- Nuclear reaction networks were incorporated into a Monte Carlo framework ('PizBuin framework') (Rauscher et al. 2016, Nishimura et al. 2017).
- The major astronomical reaction rate library used was REACLIB, supplemented by KaDoNiS for (n,γ) reactions (see Rauscher et al. 2016 for reference).

Reaction rate uncertainties

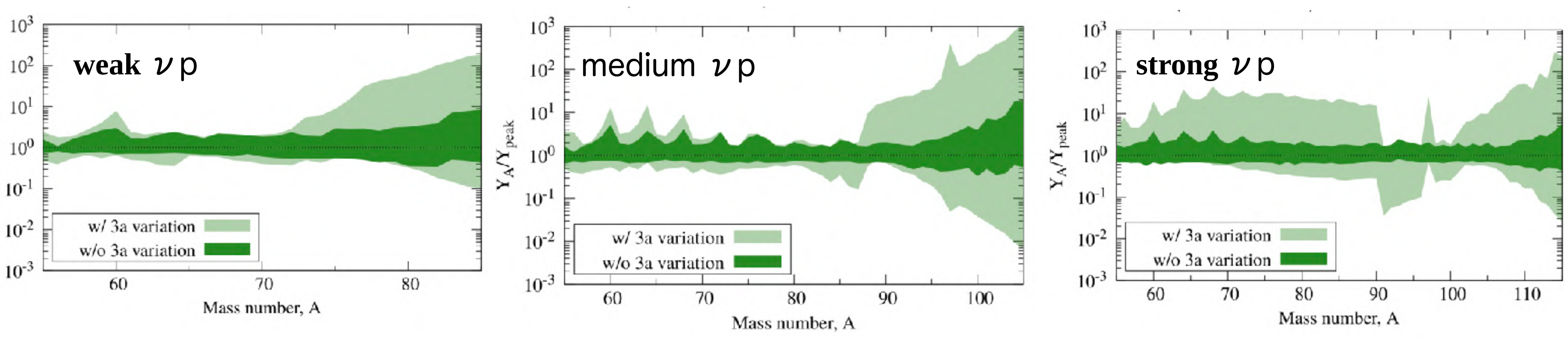
The nuclear reaction network includes (n,γ), (p,γ), (p,n), (α,γ), (α,n), (α,p) and their reverse reactions, incorporating proton-rich unstable nuclei. The effects of weak processes, such as beta decay, are also considered. The uncertainty of each reaction is determined by setting upper and lower limits (as shown in the table on the right) and varying them randomly. Here, we focus on nuclear reaction rates in the trans-iron region, while the uncertainties in the triple-alpha reaction for lighter elements are not taken into account.

Reaction	U^{hi}_{th}	U^{lo}_{th}
(n,γ)	2.0	2.0
(p,γ)	2.0	3.0
(p,n)	2.0	3.0
(α,γ)	2.0	10.0
(α,n)	2.0	10.0
(α,p)	2.0	10.0

U^{hi}_{th} : upper limit
U^{lo}_{th} : lower limit

Uncertainty of products

The figure shows the uncertainty range (90% confidence region, including the peak) for the amount of produced nuclei (total isobar). The darker regions represent results where the triple-α reaction rate is fixed, while the wider, lighter-colored regions consider the triple-α reaction unceraity.



"Key reaction" List

Based on Monte Carlo nucleosynthesis calculations, reaction and decay rates and nucleosynthesis yields are statistically compared. This analysishelps identify key reactions that influence observed elemental abundances in the Universe.

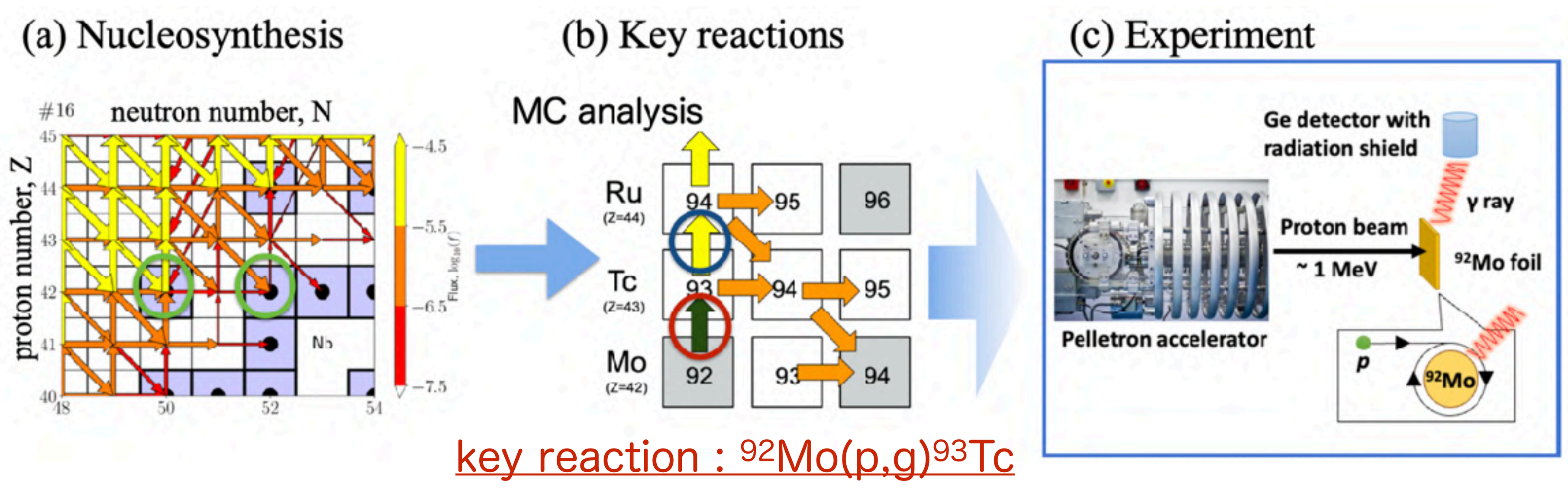
To quantify the correlation between reaction rates and products, we adopt Pearson's correlation coefficient.

$$r = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

Nuclide	Reaction	r_{cor}(Weak)	r_{cor}(Medium)	r_{cor}(Strong)
^{56}Fe	$^{57}Co + p \leftrightarrow n + ^{57}Ni$	0.67 (Lv3)		
^{56}Fe	$^{56}Ni + \alpha \leftrightarrow p + ^{59}Cu$		0.66 (Lv2)	
^{57}Fe	$^{57}Ni + p \leftrightarrow \gamma + ^{58}Cu$	-0.73 (Lv2)	-0.70 (Lv3)	
^{59}Co	$^{59}Zn + \leftrightarrow^{+} e + ^{59}Cu$	-0.90 (Lv3)		
^{59}Co	$^{59}Cu + p \leftrightarrow \gamma + ^{60}Zn$	-0.73 (Lv2)	-0.81 (Lv3)	
^{59}Co	$^{59}Cu + p \leftrightarrow n + ^{59}Zn$	-0.67 (Lv1)		
^{58}Ni	$^{58}Cu + p \leftrightarrow \gamma + ^{59}Zn$	-0.77 (Lv1)	-0.68 (Lv1)	
^{60}Ni	$^{57}Co + p \leftrightarrow n + ^{57}Ni$	-0.70 (Lv3)		
^{60}Ni	$^{59}Cu + p \leftrightarrow n + ^{59}Zn$		-0.78 (Lv2)	
^{60}Ni	$^{60}Cu + p \leftrightarrow n + ^{60}Zn$	-0.88 (Lv1)	-0.86 (Lv1)	-0.78 (Lv1)
^{61}Ni	$^{60}Cu + p \leftrightarrow \gamma + ^{61}Zn$	0.68 (Lv2)		
^{61}Ni	$^{61}Zn + p \leftrightarrow \gamma + ^{62}Ga$	-0.77 (Lv1)	-0.71 (Lv2)	
^{62}Ni	$^{62}Zn + p \leftrightarrow \gamma + ^{63}Ga$		-0.70 (Lv3)	
^{63}Cu	$^{63}Ga + p \leftrightarrow \gamma + ^{64}Ge$		-0.74 (Lv2)	
^{63}Cu	$^{63}Ga + p \leftrightarrow n + ^{63}Ge$		-0.65 (Lv1)	
^{64}Zn	$^{64}Ga + p \leftrightarrow n + ^{64}Ge$	-0.75 (Lv1)	-0.86 (Lv1)	-0.75 (Lv1)
^{67}Zn	$^{67}As + p \leftrightarrow \gamma + ^{68}Se$	-0.75 (Lv2)	-0.67 (Lv1)	
^{68}Zn	$^{68}As + p \leftrightarrow n + ^{68}Se$	-0.83 (Lv2)	-0.84 (Lv1)	-0.75 (Lv1)
^{69}Ga	$^{69}Se + p \leftrightarrow \gamma + ^{70}Br$	-0.75 (Lv3)		
^{71}Ga	$^{71}Br + p \leftrightarrow \gamma + ^{72}Kr$	-0.71 (Lv3)	-0.67 (Lv3)	
^{70}Ge	$^{70}Se + p \leftrightarrow \gamma + ^{71}Br$	-0.65 (Lv3)	-0.66 (Lv1)	-0.65 (Lv2)
^{72}Ge	$^{72}Br + p \leftrightarrow n + ^{72}Kr$	-0.69 (Lv3)	-0.78 (Lv1)	-0.66 (Lv1)
^{73}Ge	$^{73}Kr + p \leftrightarrow \gamma + ^{74}Rb$		-0.65 (Lv3)	
^{75}As	$^{75}Rb + p \leftrightarrow n + ^{75}Sr$		-0.68 (Lv1)	
^{74}Se	$^{74}Kr + p \leftrightarrow \gamma + ^{75}Rb$		-0.70 (Lv2)	
^{76}Se	$^{76}Rb + p \leftrightarrow n + ^{76}Sr$		-0.74 (Lv1)	
^{77}Se	$^{77}Rb + p \leftrightarrow n + ^{77}Sr$		-0.75 (Lv1)	
^{78}Kr	$^{78}Sr + p \leftrightarrow \gamma + ^{79}Y$		-0.65 (Lv2)	
^{80}Kr	$^{80}Sr + n \leftrightarrow \gamma + ^{81}Sr$			-0.65 (Lv2)
^{80}Kr	$^{80}Y + p \leftrightarrow n + ^{80}Zr$		-0.66 (Lv3)	
^{85}Rb	$^{85}Nb + p \leftrightarrow n + ^{85}Mo$		-0.65 (Lv3)	
^{94}Mo	$^{94}Ru + p \leftrightarrow \gamma + ^{95}Rh$			-0.65 (Lv3)
^{97}Tc	$^{97}Rh + n \leftrightarrow \gamma + ^{98}Rh$			-0.70 (Lv1)

"Key reaction" for ^{92}Mo/^{94}Mo

For the production of ^{92}Mo and ^{94}Mo, ^{92}Mo(p,g)^{93}Tc is most important reaction.



key reaction : ^{92}Mo(p,g)^{93}Tc

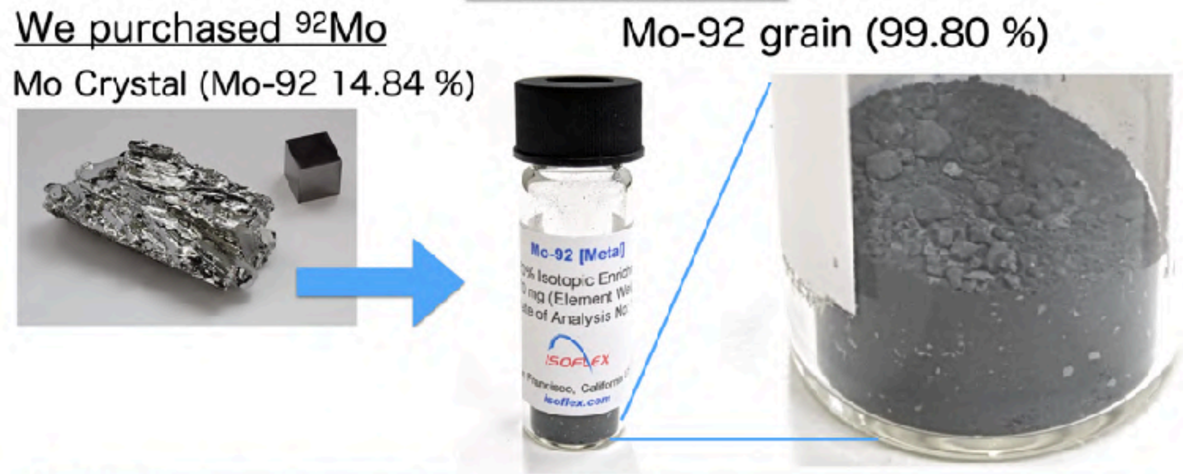
(next priority: ^{93}Tc(p,g)^{94}Ru)

FY2024: status

We purchased ^{92}Mo

Mo Crystal (Mo-92 14.84 %)

Mo-92 grain (99.80 %)



FY2025:

1. make targets (thin foils < 2 mg/cm²) of ^{92}Mo.
2. experiment at e.g., Pelletron accelerator (Sci. Tokyo)

References:

- Nishimura+2012, ApJ 758 9
- Rauscher + 2011, ApJ 738 143
- Rauscher + 2016, MNRAS 463 4153
- Nishimura+2017, MNRAS 469 1752
- Rauscher, 2012, ApJS 201 26
- Nishimura+2019, MNRAS 478 4101