Branchings in the γ process path revisited

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The location of the $(\gamma,p)/(\gamma,n)$ and $(\gamma,\alpha)/(\gamma,n)$ line at γ-process temperatures is discussed, using updated reaction rates based on global Hauser-Feshbach calculations. The results can directly be compared to classic γ-process discussions. The nuclei exhibiting the largest sensitivity to uncertainties in nuclear structure and reaction parameters are specified and suggestions for experiments are made. Additionally, the impact of employing two recent global α+nucleus potentials is discussed. It is found that branchings at higher mass depend more sensitively on these potentials. The case of ^{146}Sm/^{144}Sm production is addressed separately. Also in this case, the more recent α+nucleus potentials seem to improve the issues concerning the production of these Sm isotopes in massive stars. In conclusion it is found that it is unlikely that the calculated underproduction of p nuclides in the Mo-Ru region is due to nuclear physics deficiencies but that problems at higher mass number may still be cured by improved nuclear input.

I. INTRODUCTION

A number of proton-rich isotopes of naturally occurring stable nuclei cannot be produced by neutron captures along the line of stability. They are called p isotopes. The currently most favored production mechanism for those 35 p isotopes between Se and Hg is photodisintegration of intermediate and heavy elements at high temperatures in late evolution stages of massive stars, the so-called γ process [1, 2]. However, not all p nuclides can be produced satisfactorily, yet. A well-known deficiency in the model is the underproduction of the Mo-Ru region but also the region $151 \leq A \leq 167$ is underproduced, even in recent calculations [3]. It is not yet clear whether those deficiencies are due to the astrophysical modelling or the employed nuclear physics. Recent investigations have shown that there still are considerable uncertainties in the description of nuclear properties governing the relevant photodisintegration rates. This has triggered a number of experimental efforts to directly or indirectly determine reaction rates and nuclear properties for the γ process (see, e.g., [4, 5, 6, 7, 8] and references therein). However, many such investigations focussed on nuclei in the γ-process path without considering whether the rates involving these nuclei actually exhibit large uncertainties. In this work the sensitivity of the location of the γ-process path on reaction rates is investigated, showing which nuclei should be preferred in experimental studies.

A full γ-process network for a time-dependent calculation comprises several hundreds to thousands of reactions. However, only comparatively few reactions are actually relevant for the determination of the reaction flow. Thus, an investigation of the involved nuclear uncertainties can even be performed without relying on a full network calculation but rather by studying ratios of photodisintegration rates which determine how far the reaction path can extend to the proton-rich side within an isotopic chain. In fact, such a "model-free" approach is not limited to a given scenario, including seed nuclei and density profiles, but has the advantage that principal limiting factors applying to any scenario are derived. Concerning the astrophysical modelling, only a range of temperatures has to be assumed but that can easily be extended. Here, I show results for the "classical" range of $2.0 \leq T_9 \leq 3.0$ (with T_9 being the temperature in 10^9 K).

II. BRANCHINGS IN THE PHOTODISINTEGRATION PATH

A. Definitions

The γ process starts with the photodisintegration of stable seed nuclei which are present in the stellar plasma. The temperatures required for significant photodisintegration can mostly only be achieved in explosive burning, such as explosive O/Ne burning in massive stars. However, a recent study also found some γ processing already happening in late evolution stages of massive stars before the actual explosion [3]. During the photodisintegration period, neutron, proton, and α emission channels compete among each other and with β^+ decays further off stability. In general, the nuclide destruction will commence with a sequence of (γ,n) reactions, moving the abundances to the proton-rich side. At some point in a chain of isotopes, (γ,p) and/or (γ,α) reactions will become faster than the neutron emission and the flow will branch and feed another isotopic chain. At late times, with decreasing temperature, the photodisintegrations become less effective, leading to a shift of the branch points and a take-over of β^+ decay. At the end of the process, photodisintegrations cease quickly and the remaining unstable nuclei will decay back to stability.

Thus, the branchings established by the dominance of proton and/or α emission over neutron emission are crucial in determining the radioactive progenitors of the stable p nuclei. The absolute values of the rates determine the dynamics and time-scales which also depend on the time-dependent temperature profile and thus on the chosen astrophysical scenario. The branchings themselves only depend on the ratios of the involved reaction rates.

Following the definition in [1], a branch point is located at the nucleus for which the condition $\lambda_{\gamma p} + \lambda_{\gamma\alpha} > \lambda_{\gamma n}$ is fulfilled for the first time when following an isotopic chain towards decreasing neutron number N. The quantities λ denote the number of photodisintegrations per unit of time. For a reaction $\gamma + \mathcal{A} \longrightarrow x + \mathcal{B}$, they are obtained by folding the stellar photodisintegration cross section $\sigma^*_{\mathcal{A}(\gamma x)}$ of nucleus $\mathcal{A}$ with the energy distribution of the photons in the stellar photon gas with temperature T:

$$\lambda_{\gamma x} = \frac{1}{\pi^2 c^2 \hbar^3} \int_0^\infty \frac{\sigma^*_{\mathcal{A}(\gamma x)}\left(E_\gamma\right) E_\gamma^2}{e^{E_\gamma/kT}-1}\,dE_\gamma \quad . \qquad (1)$$

The photodisintegration rate of nucleus $\mathcal{A}$ is related to the capture rate of nucleus $\mathcal{B}$ by

$$\lambda_{\gamma x} \;\propto\; e^{-\frac{S_x}{kT}} \left\langle \sigma v\right\rangle^*_{\mathcal{B}(x\gamma)} \qquad (2)$$

$$\propto\; e^{-\frac{S_x}{kT}} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma^*_{\mathcal{B}(x\gamma)}\left(E\right) E e^{-\frac{E}{kT}}\,dE \quad ,(3)$$

with $n_x n_{\mathcal{B}} \left\langle \sigma v\right\rangle^*_{\mathcal{B}(x\gamma)}$ being the stellar capture rate, i.e. captures on the thermally excited nucleus $\mathcal{B}$, and n_x, $n_{\mathcal{B}}$ being the number density of the projectiles x and the nuclei $\mathcal{B}$, respectively (see Refs. [9, 10] for details). The separation energy of the emitted particle x in the photodisintegrated nucleus $\mathcal{A}$ is denoted by S_x. It is equal to the reaction Q value of the capture reaction on nucleus $\mathcal{B}$.

The relation between the different particle emission channels is a complex one but some general rules can be stated. Since this has already been discussed extensively in Ref. [1], I limit myself to a brief reminder. Equation 2 shows an exponential dependence of the photodisintegration rate on the separation energy or capture Q value. For neutrons, the capture rate varies slowly compared to the Q values within an isotopic chain. Therefore, the effectivity of neutron emission is governed by the neutron separation energies and will decrease for increasingly proton-rich nuclei. Similar considerations apply for proton and α emission except that for emission of charged particles an additional exponential dependence on the Coulomb barrier enters the cross section. Therefore, for comparable separation energies, neutron emission will occur fastest and proton emission will dominate over α emission. Due to the evolution of the separation energies, there will be a nucleus within each isotopic chain, for which charged particle emission occurs faster than neutron emission. This is the branch point according to the definition given above. Moreover, it is expected that (γ,p) branchings will occur more often in the lower mass

range considered here, whereas (γ,α) branchings will be found more frequently in the higher mass range, due to the distribution of separation energies.

For our considerations, it is not only important where the branchings are located at a given temperature but also how sensitive they are to a variation in the photodisintegration rates. For instance, when a (γ,p) reaction is faster than both neutron and α emission rates by a factor of, say, 100, a variation of either rate by a factor of 10 will not have much effect and the branching can be called robust. On the other hand, when the rates are of the same magnitude, a small variation in any rate might either remove the branching or change its nature (from (γ,p) to (γ,α) or vice versa). Granted that theoretical rates are not incorrect by arbitrarily large factors, the experimental study of such sensitive branchings should be given priority.

It has to be noted that there will be – if at all – only few, neighboring nuclei exhibiting comparable rates in two or three emission channels due to the dependence on the separation energy described above. Therefore, the location of a branching cannot shift far away from the original position. However, when rates are comparable also the actual value of the cross sections is important. Cross sections of nuclei relevant for the γ-process can be calculated with the statistical Hauser-Feshbach model because the level densities at the effective excitation energies are sufficiently high to average over resonances [11]. Thus, sensitive branchings will also dependent on the nuclear properties entering the statistical model. Among those, the optical potentials for charged particle transmission will be the most important ones, especially when dealing with projectile energies close to the Coulomb barrier as it is the case for the γ process.

B. Updated branchings

Let us start studying the branchings with modern rates by applying a rate set (the set called FRDM of [10]) used in many stellar models, also the one of Ref. [3]. Here, it will be called rate set **A**. The rates were calculated using the NON-SMOKER Hauser-Feshbach code and making use of a microscopic optical potential for neutrons and protons [12]. The global potential of [13] was used for the α transitions. Further details of the code and the inputs are described in [10].

Similar to Table 2 in [1] for $T_9 = 2.5$, the branch points in the photodisintegration path appearing in the new calculation are shown in the second, third, and fourth column of Table I, for three temperatures $T_9 = 2.0$, 2.5, 3.0. In this table the neutron number N of the branch point is specified for each element. The branching type is indicated by subscripts. It can immediately be seen that branchings involving proton emission are more important in the lower half of the mass range whereas α branch points comprise most of the branchings in the upper mass range.

TABLE I: Branch point nuclei obtained with three different rate sets **A**, **B**, **C**; all rate sets were calculated with NON-SMOKER [10] using different optical potentials for α transmission: set **A** employs the potential of [13], set **B** the one of [19], and set **C** the one of [21, 22]. Branchings of sets **B** and **C** differing from the standard branchings of [10] (rate set **A**) are marked by an asterisk.

| | | Neutron number N of branch point at given temperature T_9 | | | | | | | | |
| | | Rate set **A** | | | Rate set **B** | | | Rate set **C** | | |
Element	Z	2.0	2.5	3.0	2.0	2.5	3.0	2.0	2.5	3.0
Se	34	40_α	40_α	$40_{p,\alpha}$	40_α	$^*40_{p,\alpha}$	$40_{p,\alpha}$	$^*40_{p,\alpha}$	$^*40_{p,\alpha}$	$^*40_p$
Br	35	46_p	44_p	44_p	$^*44_p$	44_p	44_p	$^*44_p$	44_p	44_p
Kr	36	$44_{p,\alpha}$	42_p	42_p	$^*42_p$	42_p	42_p	$^*42_p$	42_p	42_p
Rb	37	48_p	48_p	46_p	48_p	48_p	46_p	48_p	48_p	46_p
Sr	38	46_p	46_p	44_p	46_p	46_p	44_p	46_p	46_p	44_p
Y	39	50_p	50_p	50_p	50_p	50_p	50_p	50_p	50_p	50_p
Zr	40	50_p	50_p	48_p	50_p	50_p	48_p	50_p	50_p	48_p
Nb	41	50_p	50_p	50_p	50_p	50_p	50_p	50_p	50_p	50_p
Mo	42	52_α	50_p	50_p	52_α	50_p	50_p	$^*50_p$	50_p	50_p
Tc	43	54_p	52_p	52_p	54_p	$^*54_p$	52_p	54_p	$^*54_p$	52_p
Ru	44	54_α	52_α	$52_{p,\alpha}$	$^*52_\alpha$	52_α	$^*50_p$	$^*52_\alpha$	$^*52_{p,\alpha}$	$^*50_p$
Rh	45	56_p	56_p	56_p	56_p	56_p	56_p	56_p	56_p	56_p
Pd	46	56_α	54_α	$54_{p,\alpha}$	56_α	$^*54_{p,\alpha}$	$^*54_p$	$^*54_{p,\alpha}$	$^*54_p$	$^*54_p$
Ag	47	58_p	58_p	58_p	$^*60_p$	58_p	58_p	$^*60_p$	58_p	58_p
Cd	48	58_α	58_α	56_p	58_α	$^*56_p$	56_p	58_α	$^*56_p$	56_p
In	49	62_p	62_p	60_p	62_p	62_p	60_p	62_p	62_p	60_p
Sn	50	62_α	$60_{p,\alpha}$	60_p	$^*60_{p,\alpha}$	$^*60_p$	60_p	$^*60_{p,\alpha}$	$^*60_p$	60_p
Sb	51	68_p	68_p	66_p	68_p	$^*66_p$	66_p	68_p	$^*66_p$	66_p
Te	52	68_α	68_α	66_α	68_α	$^*66_\alpha$	66_α	68_α	$^*66_\alpha$	$^*66_{p,\alpha}$
I	53	70_p	70_p	70_p	70_p	70_p	70_p	70_p	70_p	70_p
Xe	54	70_α	68_α	$68_{p,\alpha}$	70_α	68_α	$68_{p,\alpha}$	68_α	$^*68_{p,\alpha}$	$^*68_p$
Cs	55	74_p	74_p	72_p	74_p	$^*72_p$	72_p	74_p	$^*72_p$	72_p
Ba	56	74_α	72_α	$70_{p,\alpha}$	$^*72_\alpha$	$^*70_{p,\alpha}$	$^*70_p$	$^*72_\alpha$	$^*70_p$	$^*70_p$
La	57	78_p	76_p	76_p	78_p	76_p	76_p	78_p	76_p	76_p
Ce	58	76_α	74_α	$72_{p,\alpha}$	76_α	74_α	$^*72_p$	74_α	$^*72_p$	$^*72_p$
Pr	59	80_p	80_p	80_p	80_p	80_p	$^*78_p$	80_p	80_p	$^*78_p$
Nd	60	78_α	$78_{p,\alpha}$	74_p	$^*80_\alpha$	$^*76_\alpha$	74_p	$^*78_{p,\alpha}$	$^*76_{p,\alpha}$	74_p
Pm	61	84_α	82_p	82_p	84_α	82_p	82_p	$^*82_p$	82_p	82_p
Sm	62	84_α	80_p	80_p	84_α	80_p	80_p	84_α	80_p	80_p
Eu	63	88_α	84_α	82_p	$^*86_\alpha$	84_α	82_p	$^*84_\alpha$	$^*82_p$	82_p
Gd	64	88_α	84_α	82_p	88_α	$^*86_\alpha$	82_p	$^*86_\alpha$	$^*82_p$	82_p
Tb	65	88_α	86_α	$84_{p,\alpha}$	88_α	$^*86_{p,\alpha}$	$84_{p,\alpha}$	88_α	$^*84_p$	$^*84_p$
Dy	66	90_α	88_α	86_α	90_α	88_α	86_α	90_α	$^*86_\alpha$	$^*84_\alpha$
Ho	67	88_α	88_p	88_p	$^*92_{p,\alpha}$	88_p	88_p	$^*92_p$	88_p	88_p
Er	68	92_α	90_α	88_α	92_α	90_α	88_α	92_α	90_α	88_α
Tm	69	96_α	92_p	92_p	96_α	92_p	92_p	$^*94_p$	92_p	92_p
Yb	70	96_α	94_α	$92_{p,\alpha}$	96_α	94_α	$^*92_\alpha$	96_α	$^*92_\alpha$	$^*90_{p,\alpha}$
Lu	71	96_α	96_p	94_p	$^*98_\alpha$	96_p	94_p	$^*96_p$	96_p	94_p
Hf	72	100_α	96_α	94_α	100_α	96_α	$^*94_{p,\alpha}$	100_α	$^*94_{p,\alpha}$	$^*94_p$
Ta	73	102_α	$98_{p,\alpha}$	98_p	102_α	$98_{p,\alpha}$	98_p	$^*100_\alpha$	$^*98_p$	98_p
W	74	104_α	102_α	98_α	104_α	$^*100_\alpha$	98_α	$^*102_\alpha$	$^*98_\alpha$	$^*96_p$
Re	75	106_α	102_α	$102_{p,\alpha}$	$^*104_\alpha$	102_α	$^*100_{p,\alpha}$	$^*104_\alpha$	$^*102_{p,\alpha}$	$^*100_p$
Os	76	106_α	104_α	102_α	106_α	104_α	$^*100_p$	106_α	$^*102_\alpha$	$^*100_p$
Ir	77	110_α	106_α	104_p	110_α	106_α	$^*102_p$	$^*108_\alpha$	$^*106_{p,\alpha}$	$^*102_p$
Pt	78	109_α	106_α	106_α	109_α	$^*108_\alpha$	$^*104_\alpha$	$^*108_\alpha$	106_α	$^*102_{p,\alpha}$
Au	79	112_α	110_α	110_α	112_α	110_α	110_α	$^*110_\alpha$	110_α	$^*108_p$
Hg	80	110_α	110_α	108_α	$^*112_\alpha$	110_α	$^*106_\alpha$	110_α	110_α	$^*104_\alpha$
Tl	81	112_α	110_p	110_p	$^*112_{p,\alpha}$	110_p	110_p	$^*112_p$	110_p	110_p
Pb	82	114_α	113_α	110_α	114_α	$^*112_\alpha$	$^*112_\alpha$	$^*113_\alpha$	$^*112_\alpha$	110_α

A direct comparison with Table 2 of [1] shows remarkable agreement with a few exceptions. At first sight, this is surprising insofar as the previous rate predictions made use of a number of simplifying assumptions, such as using equivalent square well potentials in the particle channels and neglected excited states. However, the agreement can be explained by the fact that the branch ratios are mainly dependent on the Q value ratios which are derived from experimental nuclear masses. The aforementioned exceptions are Ba, W, Au, Hg where the new branch points are shifted by 2 units to the more neutron-rich side, Pb which is shifted by one unit, and Ce, Gd, Ho, which have become more neutron-deficient by 2 neutrons. Only the branching in Tl has been shifted by a larger amount, the branch point has 4 neutrons less than previously. The branching type was modified even less: a combined $\gamma p + \gamma\alpha$ branching was changed into a pure $\gamma\alpha$ one in Ba and Au, and a γp one has become a combined $\gamma p + \gamma\alpha$ branching in Ta. (Combined branchings are nuclides at which both proton and α emission is faster than neutron emission and within a factor of 3 of each other.) Incidentally, almost all altered branchings are within the mass range $125 \leq A \leq 150$ and $168 \leq A \leq 200$ where γ-process nucleosynthesis consistent with solar p abundances was found using the new rates [3], thus underlining the improvement of the rate predictions.

III. EXPERIMENTAL CONSIDERATIONS

Usually, experimental investigations primarily focus on nuclei close to the branch points as given in Table I. However, they should rather focus on rates which are sensitive to the nuclear input, i.e. nuclei for which $\lambda_{\gamma n}$, $\lambda_{\gamma p}$, and $\lambda_{\gamma\alpha}$ are close. To this end, Table II also shows the nuclei for which $\lambda_{\gamma p}$ and $\lambda_{\gamma\alpha}$ are within factors $f \leq 3$ and $f \leq 10$, respectively, of the $\lambda_{\gamma n}$ rate. Subscripts indicate which rate is close to $\lambda_{\gamma n}$. Two subscripts indicate that $\lambda_{\gamma p}$ or $\lambda_{\gamma\alpha}$ are within the quoted range but that they are also within a factor of 3 of each other. The nuclei shown in Table II were identified in the NON-SMOKER calculations of [10], using the optical α+nucleus potential of [13], similar to the results shown for rate set **A** of Table I.

The factors were chosen according to the assumed uncertainties in the predicted rates. The γ process path is not located very far from stability, therefore a comparison of theory and experiment for stable targets gives a good estimate of the involved uncertainties. For neutron capture, an average uncertainty of 30% was found [11]. Due to the Coulomb barrier, charged particle reactions are more sensitive to the surface potentials. While many proton captures are theoretically described with a similar accuracy as neutron captures, some local deviations of up to factors $2-3$ have been found. By far the largest uncertainty is found in reactions involving low-energy α particles (see, e.g., [5]). The photodisintegration rates are expected to show similar uncertainties as the capture

TABLE II: Nuclei with large rate uncertainties (derived from rate set **A** [10], see text); subscripts at each neutron number indicate which rate ($\lambda_{\gamma p}$ or $\lambda_{\gamma\alpha}$) is close to the $\lambda_{\gamma n}$ rate within a factor of 3 and 10, respectively.

	Neutron number N at given temperature T_9		
Z	2.0	2.5	3.0
34	42_α		
35	46_p	46_p	
36	$44_{p,\alpha}$	44_p	
37		48_p	$45_p, 48_p$
38	43_p	$43_p, 46_p$	46_p
39	49_p	49_p	49_p
40	47_p	50_p	50_p
41		46_p	
42	52_α	52_α	
43		54_p	
44	$51_p, 54_\alpha$	$51_p, 52_\alpha$	$52_{p,\alpha}$
46	$53_\alpha, 56_\alpha$	$53_\alpha, 56_\alpha$	$53_\alpha, 54_\alpha$
47	$57_p, 60_p$		
48		$55_{p,\alpha}, 58_\alpha$	$55_p, 54_\alpha, 58_\alpha$
49		$59_p, 62_p$	$59_p, 62_p$
50	$59_{p,\alpha}, 62_\alpha$		
51	62_α	68_p	$63_p, 68_p$
52	$65_\alpha, 70_\alpha$	68_α	$63_\alpha, 68_\alpha$
53	67_p	67_p	
54	$67_\alpha, 72_\alpha$	70_α	$68_{p,\alpha}, 70_\alpha$
55	71_p	74_p	74_p
56	69_α	$72_\alpha, 74_\alpha$	$72_{p,\alpha}$
57	$73_p, 78_p$	$73_p, 78_p$	78_p
58	$76_\alpha, 78_\alpha$	$74_\alpha, 76_\alpha$	$72_\alpha, 74_{p,\alpha}$
59	$77_p, 84_\alpha$		$75_p, 80_p$
60	$75_\alpha, 80_\alpha, 84_\alpha$	$73_\alpha, 75_\alpha, 78_{p,\alpha}$	$73_p, 76_{p,\alpha}, 78_p$
61	$81_p, 84_\alpha$		79_p
62	$79_\alpha, 82_\alpha, 86_\alpha$	$77_\alpha, 82_\alpha, 84_\alpha$	77_α
63	$86_\alpha, 88_\alpha$	84_α	84_α
64	$85_\alpha, 88_\alpha$	$79_p, 81_p, 86_\alpha$	$77_\alpha, 79_p, 81_p, 85_\alpha$
65	$87_\alpha, 90_\alpha$	$86_\alpha, 88_\alpha$	$86_{p,\alpha}, 88_\alpha$
66	$83_\alpha, 87_\alpha, 90_\alpha$	$87_\alpha, 88_\alpha$	$85_\alpha, 86_\alpha, 88_\alpha$
67	$90_{p,\alpha}, 92_{p,\alpha}$	$83_{p,\alpha}, 87_{p,\alpha}$	85_α
68	$89_\alpha, 91_\alpha, 94_\alpha$	$83_\alpha, 87_\alpha, 90_\alpha, 92_\alpha$	$83_p, 87_\alpha, 88_\alpha, 90_\alpha$
69	$89_\alpha, 91_\alpha, 96_\alpha$	$89_p, 94_{p,\alpha}$	$89_p, 94_p$
70	$91_\alpha, 93_\alpha, 98_\alpha$	$89_\alpha, 94_\alpha$	$87_\alpha, 89_\alpha, 92_{p,\alpha}, 94_\alpha$
71	$95_\alpha, 98_\alpha, 100_\alpha$	$93_p, 96_p$	$93_p, 96_p$
72	$95_\alpha, 100_\alpha, 102_\alpha$	$93_\alpha, 96_\alpha, 98_\alpha$	$89_\alpha, 91_\alpha, 94_\alpha, 96_\alpha$
73	$97_\alpha, 99_\alpha, 104_\alpha$	$95_p, 100_\alpha, 102_\alpha$	$95_p, 100_\alpha, 102_\alpha$
74	$99_\alpha, 101_\alpha, 104_\alpha$	$95_p, 97_\alpha, 100_\alpha, 102_\alpha$	$93_{p,\alpha}, 95_\alpha, 98_\alpha, 100_\alpha$
75	$101_\alpha, 106_\alpha$	$99_{p,\alpha}, 104_\alpha$	$99_p, 102_\alpha$
76	$103_\alpha, 108_\alpha$	$99_\alpha, 101_\alpha, 104_\alpha, 106_\alpha$	$97_{p,\alpha}, 99_\alpha, 102_\alpha, 104_\alpha$
77	$103_\alpha, 105_\alpha, 110_\alpha$	$106_\alpha, 108_\alpha$	$106_{p,\alpha}$
78	$107_\alpha, 109_\alpha, 110_\alpha, 112_\alpha$	$103_\alpha, 105_\alpha, 108_\alpha$	$101_\alpha, 103_\alpha, 106_\alpha$
79	$111_\alpha, 112_\alpha$	$107_{p,\alpha}, 109_\alpha$	$105_\alpha, 107_p$
80		$107_\alpha, 109_\alpha, 110_\alpha$	$105_\alpha, 108_\alpha, 110_\alpha$
81	112_α	109_α	
82	$111_\alpha, 118_\alpha$	$105_\alpha, 107_\alpha, 109_\alpha, 112_\alpha, 113_\alpha$	$107_{p,\alpha}, 109_\alpha, 110_\alpha, 113_\alpha$

rates, provided the Q value is known accurately. Consequently, (γ,p) rates are considered with a variation by a factor of 3 and (γ,α) ones within a factor of 10. An extended table also including (γ,p) uncertainties up to a factor of 10 can be found in [14].

As pointed out above, experiments targeting the sensitive rates given in Table II will have direct impact on γ-process nucleosynthesis. Among them, sensitive rates at branch points (coinciding with the nuclei given in Table I) will be the most important. Because of the rapid evolution of Q values within an isotopic chain, reactions on nuclei next to branchings are usually not important anymore.

Concerning the reaction type, channels with charged particles are more sensitive than neutron emission. The latter plays a role in determining the time scale when shifting isotopes from stability to the proton-rich side. Due to the Q value, (γ,n) reactions on targets with an even neutron number are slower than the ones on odd-N targets. Since the time scale in a reaction chain is governed by the slowest rates, those have to be checked primarily.

Recently, there has been increased interest in directly studying photodisintegration reactions in experiments with Bremsstrahlung or Laser inverse-Compton scattering photons, also motivated by the astrophysical importance of such reactions [15]. However, most of the relevant γ transitions cannot be accessed in this manner [16]. Therefore such measurements can be used to test reaction models selectively but not to directly access the required reaction for the p process. This can be achieved by measuring the capture reaction in the relevant energy range, from which the reverse rate can straighforwardly be derived by applying detailed balance [10] when the Q value is known to good accuracy. This even applies in the case of reactions with negative Q value for capture because the stellar photodisintegration rate differs by several orders of magnitude from the ground state photodisintegration rate measured in the laboratory [16]. In consequence, the nuclei given in the tables are then the *final* nuclei of the respective capture reactions.

Many of the sensitive branchings occur at nuclei with half-lives of less than a month. Future radioactive ion beam facilities such as GSI (Germany) and RIKEN (Japan) upgrades or the planned RIA (USA) will be able to access most of them although it remains an open question whether reaction studies can be performed. Conventional nuclear experiments are limited to stable or long-lived targets. An overview of the most important reactions on stable or long-lived targets is presented in Table III. There may be data available for several of the given reactions but not necessarily in the p process energy range. Extrapolations into the energy range are discouraged, especially for the lighter targets, because of possible resonance contributions, neglected in statistical model calculations. In Table III, priority group 1 includes reactions in sensitive branchings, priority group 2 are reactions which could become new branchings if their

TABLE III: Suggestions for reactions to be studied experimentally. Shown are sensitive reactions involving stable or long-lived ($T_{1/2} \geq 10^6$ a) targets. Unstable targets are marked by an asterisk, naturally occuring unstable nuclides with superscript 'n'. Note that α capture on the unstable targets shown here always has a negative Q value.

Target nuclei	
Priority 1:	
(p,γ)	^{80}Se, ^{79}Br, ^{84}Kr, ^{89}Y, ^{93}Nb, ^{97}Tc*, ^{110}Cd, ^{118}Sn, ^{128}Xe, ^{134}Ba, ^{138}Ce
(α,γ)	^{76}Se, ^{92}Mo, ^{94}Mo, ^{96}Ru, ^{98}Ru, ^{102}Pd, ^{108}Cd, ^{116}Sn, ^{124}Xe, ^{130}Ba, ^{141}Pr, ^{148}Sm$^{\text{n}}$, ^{152}Gd$^{\text{n}}$, ^{150}Gd$^{\text{n}}$, ^{154}Dy$^{\text{n}}$, ^{168}Yb, ^{174}Hf$^{\text{n}}$
Priority 2:	
(p,γ)	^{96}Mo, ^{106}Pd, ^{150}Gd*, ^{156}Dy, ^{158}Dy, ^{162}Er
(α,γ)	^{72}Ge, ^{90}Zr, ^{118}Sn, ^{120}Te, ^{122}Te, ^{126}Xe, ^{132}Ba, ^{139}La, ^{136}Ce, ^{140}Ce, ^{142}Nd, ^{144}Nd$^{\text{n}}$, ^{146}Sm*, ^{151}Eu, ^{156}Dy, ^{158}Dy, ^{164}Er, ^{170}Yb, ^{180}W, ^{184}Os, ^{186}Os$^{\text{n}}$, ^{196}Hg

rate is found to be increased.

Finally, it should be noted that in this "model-free" approach equal weight is given to each Z chain. In an astrophysical network calculation, the impact of certain isotopic chains may be enhanced or suppressed according to the chosen seed abundance as more or less seed nuclei are available for photodisintegration for a given element. However, the main features will still be determined by the underlying nuclear physics.

IV. DIFFERENT α+NUCLEUS POTENTIALS

In recent investigations it has become apparent that the most important problem for the calculation of reaction rates is the determination of the optical α+nucleus potentials at low energies (see [5, 6, 7, 8] and references therein). Thus, the $\lambda_{\gamma\alpha}$ rates bear the largest inherent uncertainty whereas $\lambda_{\gamma n}$ and $\lambda_{\gamma p}$ have been found generally well predicted, with a few exceptions [6, 7], as mentioned above.

It is interesting to view the changes brought upon by using different optical potentials. Rate set **A**, discussed so far, has been calculated using the potential by [13] which was fitted to α scattering data across a large mass range at intermediate energies. Although the potential works well also for many reaction data even at the comparatively low projectile energies of astrophysical interest, large deviations have been found for a number of cases. This motivated the quest for finding improved optical α potentials which also work well at energies close to the Coulomb barrier.

From a number of global potentials [17, 18, 19, 21, 22], I choose two publicly available ones for comparison here. The recent potential of [19] has been fitted to a large data compilation at low and intermediate energies and describes well both scattering and reaction data across a large mass range (see, however, Ref. [20] for a possible

necessity for modifications). Rate set **B** was calculated with this potential.

The potential of [21, 22] was employed for rate set **C**. It is fitted to low-energy reaction data around mass $A \simeq 145$. Although it does not describe scattering data, reaction data at lower masses ($A > 90$) are reproduced well [20, 23]. In Ref. [20] it is argued that optical potentials may depend on the nuclear temperature and thus the idea is supported that this potential may be well suited to describe reactions even though it is not suited for scattering data.

Columns six to eleven of Table I show the branchings obtained with the two potentials (all other inputs remained unchanged). Branchings differing from the ones obtained with the standard rate set **A** either by neutron number or by branch type are marked by an asterisk. As expected, the branchings in the lower mass range remain mostly unchanged whereas considerable changes are found for the heaviest nuclides. With a few exceptions, the branchings are shifted to lower neutron number within an isotopic chain by about 2 units, i.e. further off stability. This helps the faster processing of material to lower charge number and may indeed help to cure the underproduction in the region between Eu and Yb found in [3].

V. PHOTODISINTEGRATION OF ^{148}GD

The (γ,n)-(γ,α) branching at ^{148}Gd has received frequent attention [1, 5, 24, 25]. It determines the production ratio of ^{144}Sm and ^{146}Sm (as decay product of ^{146}Gd$(\beta^+)^{146}$Eu$(\beta^+)^{146}$Sm). The abundance ratio of ^{144}Sm and ^{142}Nd can be measured in circumstellar grains embedded in meteorites [26]. Since ^{142}Nd is a decay product of the long-lived ^{146}Sm ($T_{1/2} = 1.03 \times 10^8$ a), the ratio can be either used as a chronometer if the initial production ratio is known or to determine the initial production ratio if the time scale is known.

As can be seen in Table I, this branching mainly acts at around $T_9 = 2.5$, producing ^{144}Sm. The nucleus ^{144}Sm is also produced at higher temperature although neutron emission dominates. It can still be reached via two (γ,p) branchings at ^{146}Gd and ^{145}Eu. In both cases, ^{146}Sm production is suppressed. At lower temperature, ^{144}Sm is bypassed because the reaction flow branches off already at larger N in both the Gd and Sm isotopic chains. Thus, the production ratio of ^{144}Sm and ^{146}Sm is not only determined by the ratio $\lambda_{\gamma n}/\lambda_{\gamma \alpha}$ but also by the temperature history. Therefore, a change in this rate ratio does not linearly enter the final production ratio, as was also found in [5].

Moreover, it has to be considered that with an improved α+nucleus potential not only the α emission of ^{148}Gd will change but also others in its vicinity. This effect can be seen in Table I in the results obtained with the other two global optical potentials (rate sets **B** and **C**). With the potential of [19], the situation remains unchanged for the high and the low temperature region. At intermediate temperature, an α branching appears already at ^{150}Gd, feeding into ^{146}Sm.

An even larger change can be found when using the potential of [21, 22]. Again, the situation remains similar to the standard case at $T_9 = 3.0$. At $T_9 = 2.5$ the main branching in the chain still is the proton branching at ^{146}Gd, bypassing ^{146}Sm. This time also the branching at $T_9 = 2.0$ is shifted. It appears as an α emission at ^{150}Gd. Thus, ^{146}Sm will only be produced at low temperature but possibly at a higher level than found in the other two calculations.

Although detailed production ratios can only be obtained in time-dependent simulations, my estimate is that the production of ^{146}Sm will be enhanced with the recent global potentials. This appears to be a trend into the desired direction as the predicted ^{146}Sm/^{144}Sm production ratios [1, 2, 25] were too low compared to the values derived in [26].

VI. SUMMARY

The nuclear uncertainties in the γ process were explored and a number of sensitive reaction rates were identified. Some of the rates can be studied experimentally. However, it became clear that nuclear uncertainties cannot be the cause for the underproduction of p nuclides in the Mo-Ru region as the branchings seem to be robust. This appears to be consistent with other considerations, e.g., it was pointed out already in [1] that Mo and Ru would still remain underabundant even if all seed material would be ideally photodisintegrated. Thus, a different production mechanism has to be found, perhaps involving higher temperatures and/or a different seed composition. On the other hand, the less robust α branchings dominate in the higher mass range and further (experimental) work has to be done to provide a sound footing of γ-process calculations there. It is conceivable that the deficiences found in the p mass range $151 \leq A \leq 167$ are due to nuclear uncertainties.

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