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 be directly compared with 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 effect 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 address 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 solved by improved nuclear input.

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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 the region $151 \leqslant A \leqslant 167$ is also underproduced, even in recent calculations [3]. It is not yet clear whether these deficiencies are due to the astrophysical modeling or the employed nuclear physics. Recent investigations have shown that there are still 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., Refs. [4–8] and references therein). However, many such investigations focused 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 to 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 that 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 modeling, only a range of temperatures has to be assumed, but that can easily be extended. Here I show results for the classical range of $2.0 \leqslant T_9 \leqslant 3.0$ (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 that are present in the stellar plasma. The temperatures required for significant photodisintegration mostly can be achieved only 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 with one another 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 takeover 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 depend only on the ratios of the involved reaction rates.

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Following the definition in Ref. [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 an isotopic chain is followed toward 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:

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

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

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

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

with $n_x n_{\mathcal{B}} \langle \sigma v \rangle^*_{\mathcal{B}(x\gamma)}$ 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 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 review. 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 with 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 α emission. Because of 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 important not only 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 any at all—only few neighboring nuclei exhibiting comparable rates in two or three emission channels owing to the dependence on the separation energy described above. Therefore the location of a branching cannot shift far from the original position. However, when rates are comparable the actual value of the cross sections is also 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 depend 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 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 Ref. [10]) used in many stellar models, which is also the set 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 Ref. [13] was used for the α transitions. Further details of the code and the inputs are described in Ref. [10].

Similar to Table 2 of Ref. [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.

A direct comparison with Table 2 of Ref. [1] shows remarkable agreement, with a few exceptions. At first 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 neglecting excited states. However, the agreement can be explained by the fact that the branch ratios are dependent mainly on the Q value ratios, which are derived from experimental nuclear masses. The aforementioned exceptions are Ba, W, Au, and Hg, where the new branch points are shifted by two 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 two neutrons. Only the branching in Tl has been shifted by a larger amount; the branch point has four 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

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 Ref. [13], set **B** [19], and set **C** [21,22]. Branchings of sets **B** and **C** differing from the standard branchings of [10] (rate set **A**) are marked by an asterisk.

Element	Z	Neutron number N of branch point at given temperature T_9								
		Rate set **A**			Rate set **B**			Rate set **C**		
		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}

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 $125 \leqslant A \leqslant 150$ and $168 \leqslant A \leqslant 200$ where γ process nucleosynthesis consistent with solar p abundances was found by using the new rates [3], thus emphasizing 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 that 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 $f \leqslant 3$ and $f \leqslant 10$, 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 Ref. [10], by using the optical α+nucleus potential of Ref. [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]. Because of the Coulomb barrier, charged particle reactions are more sensitive to the surface potentials. While many proton captures are theoretically described with an accuracy similar to that for 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., Ref. [5]). The photodisintegration rates are expected to show uncertainties similar to those of the capture 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) rates within a factor of 10. An extended table also including (γ, p) uncertainties up to a factor of 10 can be found in Ref. [14].

As pointed out above, experiments targeting the sensitive rates given in Table II will have a direct effect 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 isotopes are shifted from stability to the proton-rich side. Because of 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, even-number targets 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. Access can be achieved by measuring the capture reaction in the relevant energy range, from which the reverse rate can straightforwardly 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, and priority group 2 includes reactions that could become new branchings if their 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 effect 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 Refs. [5–8] 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 to be generally well predicted, with a few exceptions [6,7], as mentioned above.

It is interesting to view the changes brought about by use of different optical potentials. Rate set **A**, discussed so far, has been calculated by using the potential from Ref. [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

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 factors of 3 and 10, respectively.

Z	Neutron number N at given temperature T_9		
	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	$99_{\alpha}, 101_{\alpha}, 104_{\alpha}$	$95_{\alpha}, 97_{\alpha}, 100_{\alpha}, 102_{\alpha}$	$93_{p,\alpha}, 95_{\alpha}, 98_{\alpha}, 100_{\alpha}$
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	$111_{\alpha}, 118_{\alpha}$	$105_{\alpha}, 107_{\alpha}, 109_{\alpha}, 112_{\alpha}, 113_{\alpha}$	$107_{p,\alpha}, 109_{\alpha}, 110_{\alpha}, 113_{\alpha}$

quest for finding improved optical α potentials that also work well at energies close to the Coulomb barrier.

From a number of global potentials [17–21], I choose two publicly available ones for comparison here. The recent potential of Ref. [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. [22] for a possible necessity for modifications). Rate set **B** was calculated with this potential.

TABLE III. Suggestions for reactions to be studied experimentally. Shown are sensitive reactions involving stable or long-lived ($T_{1/2} \geqslant 10^6$ 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^n, ^{152}Gd^n, ^{150}Gd^n, ^{154}Dy^n, ^{168}Yb, ^{174}Hf^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^n, ^{146}Sm*, ^{151}Eu, ^{156}Dy, ^{158}Dy, ^{164}Er, ^{170}Yb, ^{180}W, ^{184}Os, ^{186}Os^n, ^{196}Hg

The potential of Refs. [20,21] 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 [22,23]. In Ref. [22] 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 two 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 Ref. [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 products 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 used either 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 acts mainly around $T_9 = 2.5$, producing ^{144}Sm. The nucleus ^{144}Sm is also produced at higher temperatures, 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 temperatures, ^{144}Sm is bypassed because the reaction flow already branches off at larger N in both the Gd and Sm isotopic chains. Thus the production ratio of ^{144}Sm and ^{146}Sm is determined not only 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 Ref. [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 Ref. [19], the situation remains unchanged for the high- and the low-temperature regions. At intermediate temperatures an α branching already appears at ^{150}Gd, feeding into ^{146}Sm.

An even larger change can be found when using the potential of Refs. [20,21]. 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 the branching at $T_9 = 2.0$ is also shifted. It appears as an α emission at ^{150}Gd. Thus ^{146}Sm will be produced only at low temperature but possibly at a higher level than found in the other two calculations.

Although detailed production ratios can be obtained only 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 with the values derived in Ref. [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 Ref. [1] that Mo and Ru would still remain underabundant even if all seed material were 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 for γ process calculations there. It is conceivable that the deficiences found in the p mass range $151 \leqslant A \leqslant 167$ are due to nuclear uncertainties.

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[1] S. E. Woosley and W. M. Howard, Astrophys. J. Suppl. **36**, 285 (1978).
[2] M. Rayet, N. Prantzos, and M. Arnould, Astron. Astrophys. **227**, 271 (1990).
[3] T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, Astrophys. J. **576**, 323 (2002).
[4] M. Arnould and S. Goriely, Phys. Rep. **384**, 1 (2003).
[5] E. Somorjai *et al*., Astron. Astrophys. **333**, 1112 (1998).
[6] Gy. Gyürky, Zs. Fülöp, E. Somorjai, M. Kokkoris, S. Galanopoulos, P. Demetriou, S. Harissopulos, T. Rauscher, and S. Goriely, Phys. Rev. C **68**, 055803 (2003).
[7] Zs. Fülöp, Gyürky, and E. Somorjai, Nucl. Phys. **A758**, 90c (2005).
[8] P. Descouvemont and T. Rauscher, Nucl. Phys. A (in press), arXiv:astro-ph/0402668.
[9] W. A. Fowler, Quart. J. Roy. Astron. Soc. **15**, 82 (1974).
[10] T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables **75**, 1 (2000).
[11] T. Rauscher, F.-K. Thielemann, and K.-L. Kratz, Phys. Rev. C **56**, 1613 (1997).
[12] J.-P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rev. C **16**, 80 (1977).
[13] L. McFadden and G. R. Satchler, Nucl. Phys. **84**, 177 (1966).
[14] T. Rauscher, Nucl. Phys. **A758**, 549c (2005).
[15] H. Utsonomiya, P. Mohr, A. Zilges, and M. Rayet, Nucl. Phys. A (in press), arXiv:nucl-ex/0502011.
[16] P. Mohr, AIP Conf. Proc. **704**, 532 (2004).
[17] T. Rauscher, *Proc. IX Workshop "Nuclear Astrophysics*," edited by W. Hillebrandt and E. Müller (MPA/P10, Garching, 1998), p. 84, arXiv:nucl-th/0007070.
[18] P. Demetriou, C. Grama, and S. Goriely, Nucl. Phys. **A707**, 253 (2002).
[19] M. Avrigeanu, W. von Oertzen, A. J. M. Plomben, and V. Avrigeanu, Nucl. Phys. **A723**, 104 (2003).
[20] C. Fröhlich, diploma thesis, University of Basel, Switzerland, 2001.
[21] T. Rauscher, Nucl. Phys. **A719**, 73c (2003); **A725**, 295 (2003).
[22] M. Avrigeanu, W. von Oertzen, and V. Avrigeanu, Nucl. Phys. **A764**, 246 (2006).
[23] D. Galaviz, Zs. Fülöp, Gy. Gyürky, Z. Maté, P. Mohr, T. Rauscher, E. Somorjai, and A. Zilges, Phys. Rev. C **71**, 065802 (2005).
[24] S. E. Woosley and W. M. Howard, Astrophys. J. Lett. **354**, L21 (1990).
[25] T. Rauscher, F.-K. Thielemann, and H. Oberhummer, Astrophys. J. Lett. **451**, L37 (1995).
[26] A. Prinzhofer, D. A. Papanastassiou, and G. A. Wasserburg, Astrophys. J. Lett. **344**, L81 (1989).