

Reaction Rate Sensitivity of the γ -Process Path

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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 recently published reaction rates based on global Hauser-Feshbach calculations. The results can directly be compared to previously published, classic γ -process discussions. The nuclei exhibiting the largest sensitivity to uncertainties in nuclear structure and reaction parameters are specified.

1. INTRODUCTION

Many proton-rich isotopes of naturally occurring stable nuclei cannot be produced by neutron captures along the line of stability. The currently most favored production mechanism for those p-isotopes is photodisintegration of intermediate and heavy elements at high temperatures in late evolution stages of massive stars, the so-called γ -process [1]. 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., [2,3,4,5] 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.

2. CALCULATIONS

This work makes use of the standard rate set (based on FRDM) [6] which is also used in many stellar models, e.g. [7]. Similar to Table 2 in [1] for $T_9 = 2.5$, the resulting branching points in the photodisintegration path are shown in the last 3 columns of Table 1, for three temperatures $T_9 = 2.0, 2.5, 3.0$. Following the definition in [1], for each isotopic chain with charge number Z the neutron number N is specified at 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 N . The branching type is indicated by subscripts.

Usually, experimental investigations primarily focus on nuclei close to these branch points. However, they should rather focus on rates which are sensitive to the nuclear

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input, i.e. nuclei for which $\lambda_{\gamma n}$, $\lambda_{\gamma p}$, and $\lambda_{\gamma\alpha}$ are close. To this end, Table 1 also shows the nuclei for which $\lambda_{\gamma p}$ and $\lambda_{\gamma\alpha}$ are within factors $f \leq 3$ or $3 < f \leq 10$, 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. Note that according to the definition of the factors a nucleus is not repetitively given in the factor 10 columns when it has already been included in the factor 3 column at the same temperature.

3. DISCUSSION

A direct comparison with Table 2 of [1] shows remarkable agreement with a few exceptions. This is surprising insofar as the previous rate predictions made use of a number of simplifying assumptions, such as equivalent square well potentials in the particle channels and total neglect of excited states. The exceptions are Ba, W, Au, Hg where the new branching 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 branching point has 4 neutrons less than previously. The branching type was impacted 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. Incidentally, almost all impacted nuclei 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 [7], thus underlining the improvement of the rate predictions.

As pointed out above, experiments targeting the sensitive rates given in Table 1 will have direct impact on γ -process nucleosynthesis. Among them, sensitive rates at branching points (coinciding with the nuclei given in the last 3 columns) will be the most important.

In recent investigations checking theoretical rates against newly measured ones it has become apparent that the largest problem is in determining optical α +nucleus potentials at low energies (see [3,4,5] 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 [4]. A more detailed study of the branching point sensitivity, also exploring a possible modification of γ -process nucleosynthesis and the impact of different α +nucleus potentials, will be published elsewhere in an extended paper.

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Table 1: Branch points and nuclei with large rate uncertainties (see text). The subscripts at each neutron number indicate which rate ($\lambda_{\gamma p}$ or $\lambda_{\gamma\alpha}$) is close to the $\lambda_{\gamma n}$ rate within the given factor, or the branching type, respectively.

| Z | \pm factor 3 | | | \pm factor 10 | | | branch point | | |
|-----|----------------------------|----------------------------|-----------------------------|------------------------|----------------------------|--------------------------------|-----------------|-----------------|-----------------|
| | 2.0 | 2.5 | 3.0 | 2.0 | 2.5 | 3.0 | 2.0 | 2.5 | 3.0 |
| 34 | | | | 42_α | | | 40_α | 40_α | $40_{p,\alpha}$ |
| 35 | 46_p | 46_p | | | | 46_p | 46_p | 44_p | 44_p |
| 36 | $44_{p,\alpha}$ | 44_p | | 41_p | 41_p | 44_p | $44_{p,\alpha}$ | 42_p | 42_p |
| 37 | | 48_p | $45_p, 48_p$ | | 45_p | | 48_p | 48_p | 46_p |
| 38 | 43_p | $43_p, 46_p$ | 46_p | 46_p | | 43_p | 46_p | 46_p | 44_p |
| 39 | 49_p | 49_p | 49_p | | | | 50_p | 50_p | 50_p |
| 40 | 47_p | 50_p | 50_p | | 47_p | 47_p | 50_p | 50_p | 48_p |
| 41 | | 46_p | | | | | 50_p | 50_p | 50_p |
| 42 | 52_α | | | | 52_α | 49_p | 52_α | 50_p | 50_p |
| 43 | | 54_p | | 54_p | | $51_p, 54_p$ | 54_p | 52_p | 52_p |
| 44 | $51_p, 54_\alpha$ | 51_p | $52_{p,\alpha}$ | | 52_α | 51_p | 54_α | 52_α | $52_{p,\alpha}$ |
| 45 | | | | 55_p | | $53_p, 56_p$ | 56_p | 56_p | 56_p |
| 46 | | 53_α | | $53_\alpha, 56_\alpha$ | 56_α | $53_{p,\alpha}, 54_{p,\alpha}$ | 56_α | 54_α | $54_{p,\alpha}$ |
| 47 | $57_p, 60_p$ | | | | $57_p, 60_p$ | $58_p, 60_p$ | 58_p | 58_p | 58_p |
| 48 | | $55_{p,\alpha}, 58_\alpha$ | 55_p | | | $54_\alpha, 58_\alpha$ | 58_α | 58_α | 56_p |
| 49 | | $59_p, 62_p$ | $59_p, 62_p$ | 59_p | | | 62_p | 62_p | 60_p |
| 50 | $59_{p,\alpha}, 62_\alpha$ | | | | 59_p | $59_p, 60_p$ | 62_α | $60_{p,\alpha}$ | 60_p |
| 51 | 62_α | 68_p | $63_p, 68_p$ | 65_p | 63_p | | 68_p | 68_p | 66_p |
| 52 | $65_\alpha, 70_\alpha$ | | 68_α | | 68_α | 63_α | 68_α | 68_α | 66_α |
| 53 | 67_p | 67_p | | 72_p | | $67_p, 70_p$ | 70_p | 70_p | 70_p |
| 54 | 67_α | 70_α | $68_{p,\alpha}$ | 72_α | | $65_\alpha, 70_{p,\alpha}$ | 70_α | 68_α | $68_{p,\alpha}$ |
| 55 | 71_p | 74_p | 74_p | 76_p | 71_p | 69_p | 74_p | 74_p | 72_p |
| 56 | 69_α | | $72_{p,\alpha}$ | | $72_\alpha, 74_\alpha$ | 67_p | 74_α | 72_α | $70_{p,\alpha}$ |
| 57 | $73_p, 78_p$ | $73_p, 78_p$ | 78_p | | | $73_p, 76_p$ | 78_p | 76_p | 76_p |
| 58 | 78_α | 74_α | $74_{p,\alpha}$ | 76_α | 76_α | $71_p, 72_{p,\alpha}$ | 76_α | 74_α | $72_{p,\alpha}$ |
| 59 | 77_p | | $75_p, 80_p$ | $82_p, 84_\alpha$ | $75_p, 77_p, 80_p, 82_p$ | $77_p, 82_p$ | 80_p | 80_p | 80_p |
| 60 | 80_α | $78_{p,\alpha}$ | $73_p, 76_{p,\alpha}, 78_p$ | $75_\alpha, 84_\alpha$ | $73_{p,\alpha}, 75_\alpha$ | | 78_α | $78_{p,\alpha}$ | 74_p |
| 61 | 81_p | | 79_p | 84_α | $77_p, 79_p, 77_p, 81_p$ | | 84_α | 82_p | 82_p |
| 62 | $79_\alpha, 82_\alpha$ | 77_α | | 86_α | $79_p, 81_p$ | $77_{p,\alpha}, 79_p, 80_p$ | 84_α | 80_p | 80_p |
| 63 | 88_α | | | 86_α | 84_α | 84_α | 88_α | 84_α | 82_p |
| 64 | $85_\alpha, 88_\alpha$ | $79_p, 81_p, 86_\alpha$ | $79_p, 81_p, 85_\alpha$ | 79_p | | 77_α | 88_α | 84_α | 82_p |
| 65 | 87_α | 88_α | $86_{p,\alpha}$ | 90_α | 86_α | $83_p, 88_{p,\alpha}$ | 88_α | 86_α | $84_{p,\alpha}$ |

Table 1: (Continued)

| Z | \pm factor 3 | | | \pm factor 10 | | | branch point | | |
|-----|-------------------------------------|--|-----------------------------------|-------------------------------|---|--|--------------|-----------------|------------------|
| | 2.0 | 2.5 | 3.0 | 2.0 | 2.5 | 3.0 | 2.0 | 2.5 | 3.0 |
| 66 | 83_α | | $85_\alpha, 86_\alpha$ | $87_\alpha, 90_\alpha$ | $87_\alpha, 88_\alpha$ | 88_α | 90_α | 88_α | 86_α |
| 67 | $90_{p,\alpha},$ $92_{p,\alpha}$ | $83_{p,\alpha},$ $87_{p,\alpha}$ | 85_α | | 90_p | $83_p, 87_p$ | 88_α | 88_p | 88_p |
| 68 | 89_α | 83_α | $83_p, 90_\alpha$ | $91_\alpha, 94_\alpha$ | $87_\alpha, 90_\alpha,$ 92_α | $87_\alpha, 88_\alpha$ | 92_α | 90_α | 88_α |
| 69 | $91_\alpha, 96_\alpha$ | $89_p, 94_{p,\alpha}$ | $89_p, 94_p$ | 89_α | | | 96_α | 92_p | 92_p |
| 70 | 91_α | $89_\alpha, 94_\alpha$ | $92_{p,\alpha}$ | $93_\alpha, 98_\alpha$ | | $87_\alpha, 89_\alpha,$ 94_α | 96_α | 94_α | $92_{p,\alpha}$ |
| 71 | $98_\alpha, 100_\alpha$ | $93_p, 96_p$ | $93_p, 96_p$ | 95_α | 91_p | 91_p | 96_α | 96_p | 94_p |
| 72 | 102_α | $93_\alpha, 98_\alpha$ | $91_\alpha, 96_\alpha$ | $95_\alpha, 100_\alpha$ | 96_α | $89_\alpha, 94_\alpha$ | 100_α | 96_α | 94_α |
| 73 | 104_α | $95_p,$ $100_\alpha,$ 102_α | 95_p | $97_\alpha, 99_\alpha$ | | $98_p,$ $100_{p,\alpha},$ $102_{p,\alpha}$ | 102_α | $98_{p,\alpha}$ | 98_p |
| 74 | 99_α | 102_α | $93_{p,\alpha}, 98_\alpha$ | $101_\alpha,$ 104_α | $95_\alpha, 97_\alpha,$ 100_α | $95_{p,\alpha},$ 100_α | 104_α | 102_α | 98_α |
| 75 | $101_\alpha,$ 106_α | $99_{p,\alpha}$ | 99_p | | $97_p, 104_\alpha$ | $97_p,$ $102_{p,\alpha}$ | 106_α | 102_α | $102_{p,\alpha}$ |
| 76 | 103_α | $101_\alpha,$ 106_α | $97_{p,\alpha},$ 102_α | 108_α | $99_\alpha, 104_\alpha$ | $99_\alpha, 104_\alpha$ | 106_α | 104_α | 102_α |
| 77 | 105_α | | $106_{p,\alpha}$ | $103_\alpha,$ 110_α | $106_\alpha,$ 108_α | 101_p | 110_α | 106_α | 104_p |
| 78 | $109_\alpha,$ 112_α | $105_\alpha,$ 108_α | | $107_\alpha,$ 110_α | 103_α | $101_\alpha,$ $103_\alpha,$ 106_α | 109_α | 106_α | 106_α |
| 79 | | $107_{p,\alpha},$ 109_α | 107_p | $111_\alpha,$ 112_α | | $105_{p,\alpha}$ | 112_α | 110_α | 110_α |
| 80 | | $107_\alpha,$ 109_α | $105_\alpha,$ 108_α | | | $109_\alpha,$ 110_α | 110_α | 110_α | 108_α |
| 81 | | | | 112_α | $109_{p,\alpha},$ 112_p | $109_p,$ $110_p,$ 112_p | 112_α | 110_p | 110_p |
| 82 | 111_α | $109_\alpha,$ $112_\alpha,$ 113_α | $107_{p,\alpha},$ 110_α | 118_α | $105_{p,\alpha},$ 107_α | $105_p,$ $109_\alpha,$ 113_α | 114_α | 113_α | 110_α |