arXiv:astro-ph/0407324v1 16 Jul 2004

Reaction Rate Sensitivity of the γ–Process Path

T. Rauscher[a] *

[a]Department of Physics and Astronomy, University of Basel,
4056 Basel, Switzerland

The location of the (γ,p)/(γ,n) and (γ,α)/(γ,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 $\lambda_{\gamma\mathrm{p}} + \lambda_{\gamma\alpha} > \lambda_{\gamma\mathrm{n}}$ 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

---

*Supported by the Swiss NSF through a PROFIL professorship (2024-067428.01) and the grant 2000-061031.02.

input, i.e. nuclei for which $\lambda_{\gamma\mathrm{n}}$, $\lambda_{\gamma\mathrm{p}}$, and $\lambda_{\gamma\alpha}$ are close. To this end, Table 1 also shows the nuclei for which $\lambda_{\gamma\mathrm{p}}$ and $\lambda_{\gamma\alpha}$ are within factors $f \leq 3$ or $3 < f \leq 10$, respectively, of the $\lambda_{\gamma\mathrm{n}}$ rate. Subscripts indicate which rate is close to $\lambda_{\gamma\mathrm{n}}$. Two subscripts indicate that $\lambda_{\gamma\mathrm{p}}$ 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 neglection 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 $\gamma\mathrm{p} + \gamma\alpha$ branching was changed into a pure $\gamma\alpha$ one in Ba and Au, and a $\gamma\mathrm{p}$ one has become a combined $\gamma\mathrm{p}+\gamma\alpha$ 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 $\lambda_{\gamma\mathrm{n}}$ and $\lambda_{\gamma\mathrm{p}}$ 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.

REFERENCES

1. S. E. Woosley and W. M. Howard, Ap. J. Suppl. 36 (1978) 285.
2. M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1.
3. E. Somorjai et al., Astron. Astrophys. 333 (1998) 1112.
4. Gy. Gyürky et al., Phys. Rev. C 68 (2003) 055803; see also Zs. Fülöp et al., this volume.
5. P. Descouvemont and T. Rauscher, Nucl. Phys. A, in press (astro-ph/0402668).
6. T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables 75 (2000) 1.
7. T. Rauscher, A. Heger, R. D. Hoffman, and S. E. Woosley, Ap. J. 576 (2002) 323.

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

	± factor 3			± factor 10			branch point		
Z	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_{α}	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_{α}, 56_{α}	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_{α}	55_{p}			54_{α}, 58_{α}	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_{α}				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_{α}, 70_{α}		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_{α}, $70_{p,\alpha}$	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_{α}, 74_{α}	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_{α}	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_{α}, 84_{α}	$73_{p,\alpha}$, 75_{α}		78_{α}	$78_{p,\alpha}$	74_{p}
61	81_{p}		79_{p}	84_{α}	77_{p}, 79_{p}, 81_{p}	77_{p}, 81_{p}	84_{α}	82_{p}	82_{p}
62	79_{α}, 82_{α}	77_{α}		86_{α}	79_{p}, $82_{p,\alpha}$, 84_{α}	$77_{p,\alpha}$, 79_{p}, 80_{p}, 82_{p}	84_{α}	80_{p}	80_{p}
63	88_{α}			86_{α}	84_{α}	84_{α}	88_{α}	84_{α}	82_{p}
64	85_{α}, 88_{α}	79_{p}, 81_{p}, 86_{α}	79_{p}, 81_{p}, 85_{α}	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)

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