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Nuclear Isomers and Their Influence on s-Process Astrophysical Reaction Rates

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ABSTRACT:
Background: Nuclear metastable states that is isomers play a distinct roles in the nucleosynthesis of elements by altering reaction paths within stellar environments.
Purpose: This study reviews the existing catalogue of nuclear isomers to analyse their influence on the astrophysically important s-process reaction rates.
Methods: The work utilizes the database of s-process astrophysical reaction rates available at download.nucastro.org/astro/x/xfactors.txt. The focus is made on the nuclei where the ground state contributions could not fully constrain the nuclear reaction rates (metric X < 1) at temperatures relevant for astrophysical scenarios. These nuclei are further analyzed in terms of their spectroscopic properties using the Atlas of Nuclear Isomers.
Results: A data of over 100 isotopes and more than 200 isomers exhibiting $X < 1$ at stellar temperatures (kT = 30 and 80 keV) is compiled and analyzed. Statistical analysis reveals a bimodal distribution in isomeric half-lives and a weak positive correlation between excitation energy and metric X, while half-life shows negligible correlation.
Conclusion: The analysis suggests that the s-process reaction rates are more sensitive to isomeric excitation energies than to half-life of the state. Such insights are crucial for further research and measurements.

Keywords: Astrophysical reaction rates, s-process, nuclear metastable states

1. Introduction

The nucleus is the centre of an atom which contains most of an atom's mass [1]. It is composed of positively charged protons and neutrally charged neutrons. These particles connected by strong nuclear force govern the underlying nuclear structure and the resulting spectroscopic spectra.

Nuclear astrophysics investigates the processes governing energy generation in stars and the nucleosynthesis of elements across the Universe [2]. A critical component of these processes is the astrophysical reaction rate, which quantifies nuclear interactions within stellar environments. While ground state reaction rates are often well-constrained, the stellar environment introduces complexities due to the population of excited nuclear states.

Of particular importance are nuclear isomers- long-lived metastable states inhibited from prompt decay by structural hindrances such as large spin differences or poor wavefunction overlap [3]. These isomeric states hence become a crucial source of special circumstances to understand the nucleonic wave functions and angular momentum couplings. In high-temperature environment of stars (kT=30-80 keV), these isomers can thermally populate, opening unique reaction channels that differ significantly from ground-state interactions [4]. Consequently, understanding the interplay between isomeric properties and reaction cross-sections is vital for refining models of stellar evolution and heavy element formation [5]. Motivated by the need to understand these deviations, this study analyzes public datasets regarding s-process reaction rates and nuclear isomers to identify the trends in nuclei where metastables states significantly impact astrophysical conditions. However, specific nucleonic properties that most heavily dictate such deviations remain an active area of investigation. This study builds upon that

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foundation by aiming to learn the competition between excitation energy and lifetime of nuclear isomers with regard to the reaction measurements. In the present work, it is hypothesized that the thermal population in stellar environments are more dependent on the energy gaps between the states rather than the temporal stability of the isomer itself.

2. Methodology

2.1. Data collection

With the help of the table based on s-process ground state reaction cross-section measurements available at download.nucastro.org/astro/x/xfactors.txt, data were sourced with isotopes along with metric X [6]. This metric X serves as a robust way to determine if experimental data directly translates into a reliable astrophysical reaction rate. The database provides X metric at two temperatures relevant for astrophysical environments, at kT=30 keV and kT=80 keV as listed in Table 1. The higher value of X simply tells if the ground state-contribution to the total cross-section is high. Although excited states can contribute at the typical s-process temperatures, many nuclei can significantly be constrained by simply ground-state contributions by assuming a thermal equilibrium between the ground-state and excited-spectra. However, some nuclei with X values lower than 1, provide the cases where ground-state measurements alone are insufficient and additional experimental and theoretical investigations are required. In this work, I explore the impact of nuclear metastable states on the isotopes where X value remains to be below 1 and see if there is a direct relationship between them. The data of nuclear metastable states for each isotope as listed in Table 1 have been accessed using the Atlas of Nuclear Isomers [5].

Table 1 of isotopes with either X30 or X80 having values below 1, representing the isotopes where ground state measurements alone are not sufficient. Z is the proton number of the isotope. A is the nucleon number of the isotope. Nucl. represents the mass number of the isotope followed by the element symbol. X30 and X80 are the ground state contribution at kT= 30 keV and =80 keV respectively.

Table 1: Table of isotopes.

Z	Nucl.	X 30	X 80
10	21Ne	1	0.993
11	23Na	1	0.997
13	26Al	1	0.995
15	32P	0.945	0.719
19	40K	0.788	0.636
20	43Ca	1	0.995
20	45Ca	0.999	0.954
21	45Sc	0.809	0.765
21	46Sc	0.917	0.737
21	48Sc	0.988	0.798
22	47Ti	0.997	0.906
23	50V	1	0.939
23	51V	1	0.992
25	55Mn	0.989	0.859
26	55Fe	1	0.999
26	57Fe	0.394	0.248
27	60Co	0.909	0.746
28	59Ni	1	0.986
28	61Ni	0.89	0.624
28	63Ni	0.857	0.437
29	64Cu	0.992	0.79
30	65Zn	0.966	0.863
30	67Zn	0.99	0.924
30	69Zn	1	0.975
31	69Ga	1	0.996
31	70Ga	1	0.997
31	71Ga	1	0.996
32	71Ge	0.982	0.53
32	73Ge	0.688	0.575
32	74Ge	1	0.996
32	75Ge	0.956	0.463
32	76Ge	1	0.996
33	75As	1	0.9
33	76As	0.91	0.64
33	77As	0.999	0.92
34	74Se	1	0.997
34	75Se	0.968	0.696
34	76Se	1	0.994
34	77Se	0.965	0.43
34	78Se	1	0.997
34	79Se	0.984	0.836
34	80Se	1	0.999
34	81Se	0.848	0.356
34	82Se	1	0.999
35	79Br	0.997	0.763

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Z	Nucl.	X 30	X 80
35	80Br	0.582	0.226
35	81Br	1	0.961
35	82Br	0.904	0.777
36	78Kr	1	0.978
36	79Kr	0.882	0.265
36	80Kr	1	0.997
36	81Kr	0.85	0.637
36	83Kr	0.632	0.564
36	85Kr	1	0.996
37	85Rb	0.998	0.956
37	86Rb	1	0.996
37	87Rb	1	0.993
38	85Sr	1	0.966
38	87Sr	1	0.999
39	90Y	0.999	0.918
39	91Y	1	0.992
40	93Zr	1	0.992
40	95Zr	1	0.999
41	93Nb	0.952	0.915
41	94Nb	0.791	0.493
41	95Nb	1	0.99
41	96Nb	0.862	0.625
42	95Mo	1	0.981
42	97Mo	1	0.999
42	99Mo	0.876	0.421
42	100Mo	1	0.993
43	96Tc	0.611	0.392
43	97Tc	0.994	0.922
43	98Tc	0.668	0.421
43	99Tc	0.993	0.876
44	97Ru	1	0.97
44	98Ru	1	0.998
44	99Ru	0.984	0.885
44	100Ru	1	0.992
44	101Ru	0.996	0.911
44	102Ru	1	0.984
44	103Ru	0.363	0.275
44	104Ru	1	0.933
44	105Ru	0.546	0.31
44	106Ru	0.999	0.814
45	103Rh	0.385	0.18
45	104Rh	0.697	0.224
45	105Rh	0.991	0.833
46	102Pd	1	0.995
46	103Pd	0.993	0.869
46	104Pd	1	0.993
46	105Pd	1	0.955
46	106Pd	1	0.988
46	107Pd	0.994	0.813
46	108Pd	1	0.971
46	109Pd	0.991	0.757
46	110Pd	1	0.94
47	107Ag	0.753	0.262

Contd....

Z	Nucl.	X 30	X 80
47	108Ag	0.784	0.245
47	109Ag	0.944	0.727
47	110Ag	0.332	0.188
47	111Ag	0.542	0.214
48	106Cd	1	0.997
48	107Cd	0.999	0.906
48	108Cd	1	0.997
48	109Cd	0.968	0.824
48	110Cd	1	0.998
48	111Cd	0.999	0.794
48	112Cd	1	0.996
48	113Cd	0.999	0.695
48	114Cd	1	0.993
48	115Cd	0.977	0.476
48	116Cd	1	0.988
49	113In	1	0.999
49	114In	0.99	0.589
49	115In	1	0.997
50	115Sn	1	0.991
50	117Sn	0.991	0.686
50	119Sn	0.39	0.151
50	121Sn	0.266	0.242
50	123Sn	0.875	0.795
50	125Sn	0.881	0.803
51	121Sb	0.724	0.528
51	122Sb	0.762	0.268
51	123Sb	0.998	0.938
51	125Sb	1	0.994
51	126Sb	0.638	0.494
51	127Sb	1	0.999
52	120Te	1	0.993
52	122Te	1	0.994
52	123Te	0.986	0.557
52	124Te	1	0.996
52	125Te	0.546	0.204
52	126Te	1	0.998
52	127Te	0.797	0.403
52	128Te	1	0.999
53	127I	0.847	0.584
53	129I	0.823	0.717
53	130I	0.647	0.328
53	131I	0.998	0.945
54	124Xe	1	0.915
54	126Xe	1	0.94
54	128Xe	1	0.97
54	129Xe	0.608	0.271
54	130Xe	1	0.99
54	131Xe	0.965	0.564
54	132Xe	1	0.998
54	133Xe	0.998	0.801
55	133Cs	0.966	0.818
55	134Cs	0.51	0.305

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Z	Nucl.	X 30	X 80
55	135Cs	1	0.972
55	136Cs	0.832	0.61
55	137Cs	1	0.999
56	130Ba	1	0.907
56	132Ba	1	0.98
56	134Ba	1	0.996
56	135Ba	0.999	0.818
56	137Ba	1	0.994
57	138La	0.949	0.768
57	139La	0.999	0.955
57	140La	0.485	0.238
58	132Ce	1	0.882
58	133Ce	0.294	0.133
58	134Ce	1	0.954
58	135Ce	0.874	0.489
58	136Ce	1	0.992
58	137Ce	0.997	0.747
58	139Ce	1	0.991
58	142Ce	1	0.997
58	143Ce	0.358	0.207
59	141Pr	0.991	0.829
59	142Pr	0.203	0.122
59	143Pr	0.933	0.8
60	144Nd	1	0.998
60	145Nd	0.943	0.793
60	146Nd	1	0.977
60	147Nd	0.807	0.487
60	148Nd	1	0.884
60	150Nd	0.926	0.423
61	147Pm	0.963	0.66
61	148Pm	0.854	0.2
61	149Pm	0.988	0.786
62	147Sm	0.992	0.89
62	148Sm	1	0.992
62	149Sm	0.803	0.682
62	150Sm	1	0.913
62	151Sm	0.585	0.244
62	152Sm	0.89	0.363
62	153Sm	0.243	0.086
62	154Sm	0.67	0.219
63	151Eu	0.582	0.379
63	152Eu	0.706	0.165
63	153Eu	0.884	0.441
63	154Eu	0.752	0.223
63	155Eu	0.893	0.473
63	156Eu	0.17	0.033
64	152Gd	1	0.908
64	153Gd	0.58	0.162
64	154Gd	0.88	0.352
64	155Gd	0.662	0.18
64	156Gd	0.703	0.239
64	157Gd	0.685	0.256

Contd....

Z	Nucl.	X 30	X 80
64	158Gd	0.652	0.211
64	159Gd	0.675	0.25
64	160Gd	0.629	0.196
65	157Tb	0.817	0.413
65	158Tb	0.743	0.321
65	159Tb	0.785	0.398
65	160Tb	0.747	0.302
65	161Tb	0.793	0.402
66	156Dy	0.922	0.401
66	158Dy	0.82	0.29
66	159Dy	0.79	0.338
66	160Dy	0.696	0.234
66	161Dy	0.53	0.232
66	162Dy	0.636	0.212
66	163Dy	0.896	0.534
66	164Dy	0.596	0.189
67	163Ho	0.959	0.676
67	165Ho	0.95	0.67
67	166Ho	0.042	0.023
68	162Er	0.784	0.291
68	164Er	0.745	0.268
68	166Er	0.636	0.214
68	167Er	0.93	0.598
68	168Er	0.653	0.211
68	169Er	0.611	0.172
68	170Er	0.651	0.205
69	169Tm	0.304	0.159
69	170Tm	0.618	0.237
69	171Tm	0.263	0.144
69	172Tm	0.841	0.486
70	168Yb	0.713	0.251
70	170Yb	0.667	0.23
70	171Yb	0.551	0.129
70	172Yb	0.624	0.207
70	173Yb	0.916	0.578
70	174Yb	0.633	0.198
70	175Yb	0.968	0.715
70	176Yb	0.673	0.214
71	175Lu	0.975	0.728
71	176Lu	0.995	0.83
71	177Lu	0.975	0.695
72	174Hf	0.73	0.26
72	176Hf	0.719	0.244
72	177Hf	0.973	0.724
72	178Hf	0.74	0.257
72	179Hf	0.986	0.763
72	180Hf	0.75	0.258
72	181Hf	0.605	0.215
72	182Hf	0.78	0.268
73	179Ta	0.677	0.434
73	180Ta	0.437	0.109
73	181Ta	0.478	0.378

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Z	Nucl.	X 30	X 80
73	182Ta	0.492	0.285
73	183Ta	0.909	0.547
74	180W	0.805	0.301
74	182W	0.793	0.284
74	183W	0.599	0.206
74	184W	0.841	0.32
74	185W	0.751	0.315
74	186W	0.905	0.38
74	187W	0.897	0.513
75	185Re	0.981	0.744
75	186Re	0.689	0.168
75	187Re	0.987	0.723
75	188Re	0.795	0.263
75	189Re	0.964	0.62
76	184Os	0.884	0.362
76	186Os	0.917	0.41
76	187Os	0.278	0.104
76	188Os	0.957	0.474
76	189Os	0.384	0.153
76	190Os	0.985	0.58
76	191Os	0.967	0.75
76	192Os	0.993	0.658
76	193Os	0.844	0.486
76	194Os	0.995	0.691
77	191Ir	0.949	0.473
77	192Ir	0.331	0.183
77	193Ir	0.747	0.299
77	194Ir	0.789	0.222
78	190Pt	1	0.845
78	192Pt	1	0.869
78	193Pt	0.156	0.08
78	194Pt	1	0.89
78	195Pt	0.888	0.288
78	196Pt	1	0.925
78	197Pt	0.536	0.193
78	198Pt	1	0.964
79	195Au	0.962	0.75
79	196Au	0.631	0.298
79	197Au	0.983	0.841
79	198Au	0.944	0.665
79	199Au	0.988	0.897
80	196Hg	1	0.963
80	198Hg	1	0.961
80	199Hg	0.978	0.59
80	200Hg	1	0.941
80	201Hg	0.449	0.282
80	202Hg	1	0.979
80	203Hg	0.832	0.733
80	204Hg	1	0.982
81	203Tl	1	0.949
81	204Tl	0.998	0.932
81	205Tl	0.998	0.899

Contd....

Z	Nucl.	X 30	X 80
82	205Pb	0.824	0.836
82	207Pb	1	0.998
83	210Bi	0.981	0.625

2.2. *Isomer Identification*

For isotopes identified with X<1 (listed in Table 1), spectroscopic data of isomers were retrieved from the Atlas of Nuclear Isomers. Note that the Atlas has a lower limit on isomeric half-life at 10 nanoseconds [5]. This half-life limit is crucial to separate the meta stable states hindered by significant structural barriers such as large spin differences or K-mixing with the collective states of nucleus. For isotopes having multiple isomers, each isomer is treated as an independent data point to fully capture the spectroscopic range of the nucleus. It is bacause of the fact that different isomers within the same isotope can exhibit vastly different spin, parity, and decay properties.

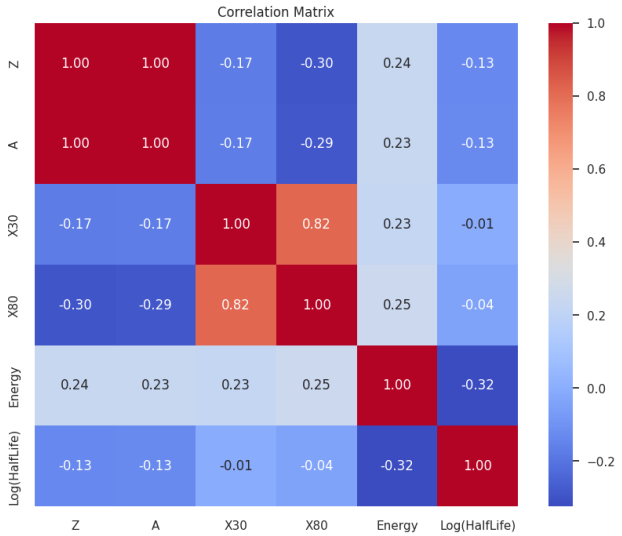


Figure 1: Pearson correlation analysis.

3. Results and Analysis

Data preprocessing involves several steps. Isomeric excitation energies are not used with uncertainties and non-numeric values are omitted. Isomeric half-lives originally available in units ranging from nanoseconds to years are converted to a standard SI unit of seconds.

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Table 2: Table of Isomers for the isotopes listed in Table 1 with X metrics below 1.

Z	Nucl.	X 30	X 80
19	40K	1643.638(11)	0.336(13)μs
21	45Sc	12.40(5)	0.326(4)s
21	46Sc	52.011(1)	9.4(8)μs
21	46Sc	142.528(7)	18.75(4)s
28	63Ni	87.15(11)	1.67(3)μs
29	64Cu	1594.23(3)	20.4(6)ns
30	65Zn	53.928(10)	1.59(5)μs
30	67Zn	93.312(5)	9.142(24)μs
30	67Zn	604.48(5)	333(14)ns
31	70Ga	166.98(3)	42(21)ns
32	71Ge	18.20(5)	13.7(9)μs
32	71Ge	751.70(6)	105(3)ns
32	73Ge	13.2845(15)	2.91(3)μs
32	73Ge	66.726(9)	0.499(11)s
33	75As	303.9243(8)	17.62(23)ms
33	77As	475.48(4)	114.0(25)μs
34	77Se	161.9223(10)	17.36(5)s
34	79Se	95.77(3)	3.885(9)min
34	81Se	102.966(10)	57.28(2)min
35	79Br	207.61(9)	4.85(4)s
35	80Br	85.843(4)	4.4205(8)h
35	81Br	536.20(9)	34.6(28)μs
35	82Br	45.9492(10)	6.13(5)min
36	79Kr	129.77(5)	50(3)s
36	79Kr	147.06(6)	78.7(10)ns
36	81Kr	190.64(4)	13.10(3)s
36	83Kr	9.4057(6)	156.8(5)ns
36	83Kr	41.5575(7)	1.83(2)h
36	85Kr	304.871(20)	4.480(8)h
36	85Kr	1991.8(2)	1.82(6)μs
37	85Rb	514.0065(22)	1.015(1)μs
37	85Rb	2826.55(14)	12.5(6)ns
37	86Rb	556.05(18)	1.017(3)min
38	85Sr	238.79(5)	67.63(4)min
39	90Y	681.67(10)	3.196(12)h*
39	91Y	555.58(5)	49.71(4)min
41	93Nb	30.760(5)	16.12(12)y
41	93Nb	7435.3+X	1.5(5)μs
41	94Nb	40.892(12)	6.263(4)min
41	94Nb	140.298(12)	30(5)ns
42	99Mo	97.785 (3)	15.5(2) μs
42	99Mo	684.10 (19)	742(13) ns
43	98Tc	90.76 (16)*	14.7(3) μs*
43	99Tc	142.6836 (11)	6.00660(18) h*
44	99Ru	89.57 (6)	20.5(1) ns
44	101Ru	527.56 (10)	17.5(4) μs
44	103Ru	238.2 (7)	1.69(7) ms
44	105Ru	20.606 (14)	340(15) ns
44	105Ru	163.821 (16)	55(7) ns

Contd....

Z	Nucl.	X 30	X 80
45	103Rh	39.753 (6)	56.114(9) min
45	104Rh	128.9679 (5)	4.34(3) min
45	104Rh	344.594 (3)	47(3) ns
45	105Rh	129.782 (4)	42.9(3) s
46	102Pd	1593.16 (22)	14.5(4) ns
46	103Pd	784.79 (10)	25(2) ns
46	105Pd	489.14 (4)	36.1(4) μs
46	107Pd	115.74 (12)	0.85(10) μs
46	107Pd	214.6 (3)	21.3(5) s
46	109Pd	113.4000 (14)	380(50) ns
46	109Pd	188.9903 (10)	4.694(2) min*
47	107Ag	93.125 (19)	44.3(2) s
47	108Ag	109.466 (7)	438(9) y
47	108Ag	215.382 (4)	45.8(7) ns
47	109Ag	88.0337 (10)	39.7(2) s
47	110Ag	1.112 (16)	660(40) ns
47	110Ag	117.59 (5)	249.794(24) d
47	111Ag	59.82 (4)	64.8(8) s
47	111Ag	376.71 (5)	16(1) ns
48	106Cd	4659.71 (9)	62(6) ns
48	106Cd	7118.9 (7)	11(+6-3) ns
48	107Cd	845.54 (6)	70.1(14) ns
48	107Cd	2678.88 (15)	55(4) ns
48	109Cd	59.60 (7)	11.8(18) μs
48	109Cd	463.10 (11)	10.6(6) μs
48	111Cd	245.390 (16)	84.5(4) ns
48	111Cd	396.214 (21)	48.53(5) min
48	113Cd	263.54 (3)	13.89(16) y
48	113Cd	316.206 (15)	10.8(3) ns
48	115Cd	181.0 (5)	44.56(24) d
49	113In	391.699 (3)	99.47(6) min
49	114In	190.2682(8)	49.51(1)d
49	114In	501.948(3)	42.6(9)ms
49	115In	336.244(17)	4.486(4)h
50	115Sn	612.81(4)	3.26(8)μs
50	115Sn	713.64(12)	159(1)μs
50	117Sn	314.58(4)	13.94(3)d
50	117Sn	2406.4(4)	1.75(7)μs
50	119Sn	23.871(8)	18.03(7)ns
50	119Sn	89.531(13)	293.1(7)d

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Contd....

Z	Nucl.	X 30	X 80
50	119Sn	2127.0(10)	9.6(12)μs
50	121Sn	6.31(6)	43.9(5)y
50	121Sn	1998.3(11)	5.3(5)μs
50	121Sn	2221.98(19)	0.52(5)μs
50	121Sn	2833.9(2)	0.167(25)μs
50	123Sn	24.6(4)	40.06(1)min
50	123Sn	1945.0(10)	7.4(26)μs
50	123Sn	2153.0(12)	6μs
50	123Sn	2713.0(14)	34μs
50	125Sn	27.50(14)	9.70(10)min
50	125Sn	1892.8(3)	6.2(2)μs
50	125Sn	2059.69(17)	0.65(6)μs
50	125Sn	2623.5(5)	161.3(3)
51	121Sb	2721.5+X	179(6)μs
51	122Sb	61.4131(5)	1.86(8)μs
51	122Sb	137.4726(8)	0.53(3)ms
51	122Sb	163.5591(17)	4.191(3)min
51	123Sb	2037.4(3)	37.3(8)ns
51	123Sb	2237.9(4)	214(3)ns
51	123Sb	2613.6(5)	65(1)μs
51	125Sb	1971.25(20)	4.1(2)μs
51	125Sb	2112.1(3)	28.4(6)μs
51	125Sb	2325.0(3)	31(2)ns
51	125Sb	2471.0(4)	277(7)ns
51	126Sb	17.7(3)	19.15(8)min
51	126Sb	40.4(3)	11s
51	126Sb	104.6(3)	553(5)ns
51	126Sb	127.9(3)	78.0(5)ns
51	126Sb	1689.4(13)	60(20)ns
51	126Sb	1810.7(17)	90(16)ns
51	127Sb	1920.19(21)	11.7(1)μs
51	127Sb	2194.4(6)	14(1)ns
51	127Sb	2325.2(7)	269(5)ns
52	123Te	247.45(4)	119.3(1)d
52	123Te	489.78(5)	30.7(4)ns
52	125Te	144.775(8)	57.40(15)d
52	126Te	2974.4(4)	10.7(9)ns
52	127Te	88.23(7)	106.1(7)d
52	128Te	2790.8(3)	236(20)ns*
53	129I	27.793(20)	16.8(2)ns
53	130I	39.9525(13)	8.91(12)min
53	130I	69.5865(7)	133(7)ns
53	130I	82.3960(19)	315(15)ns
53	130I	82.4+X$	66(8)ns
53	130I	85.1099(10)	254(4)ns
53	131I	1918.4(4)	24(1)μs
53	131I	2350.3(5)	42(2)ns
53	131I	4307.4(6)	25(3)ns
54	128Xe	2787.2(3)	78(5)ns
54	129Xe	236.14(3)	8.88(2)d
54	131Xe	163.930(8)	11.939(20)d
54	132Xe	1805.3(3)	14(3)ns

Contd....

Z	Nucl.	X 30	X 80
54	133Xe	233.221(15)	2.212(17)d
54	133Xe	2107()	8.64(13)ms
55	134Cs	11.2442(18)	46.6(6)ns
55	134Cs	138.7441(26)	2.912(2)h
55	134Cs	176.4044(16)	49.7(8)ns
55	134Cs	257.1075(26)	12.3(11)ns
55	135Cs	1632.9(15)	53(2)min
55	136Cs	517.9(1)	17.5(2)s
56	130Ba	2475.12(18)	9.4(4)ms
56	134Ba	1986.35(21)	50(5)ns
56	134Ba	2957.2(5)	2.61(14)μs
56	135Ba	268.218(20)	28.7(2)h
56	135Ba	2388()	1.06(4)ms
56	137Ba	661.659(3)	2.5223(10)min
56	137Ba	2349.1(5)	589(20)ns
57	138La	72.57(3)	116(5)ns
57	138La	738.80(20)	2.0(3)μs
57	139La	1800.4(4)	315(35)ns
58	133Ce	37.2(7)	5.326(11)h
58	134Ce	3208.6(4)	308(5)ns
58	135Ce	445.81(21)	20(1)s
58	136Ce	3095.0(6)	2.0(1)μs
58	137Ce	254.29(5)	34.80(3)h
58	139Ce	754.24(8)	57.58(32)s
58	139Ce	2631.9(3)	70(5)ns
59	142Pr	3.694(3)	14.6(5)min
59	142Pr	911.4(13)	61(6)ns
60	145Nd	67.167(7)	29.4(10)ns
61	147Pm	649.14(6)	27(3)ns
61	148Pm	137.9(3)	41.29(11)d
61	149Pm	240.214(7)	35(3)μs
62	148Sm	6694.32(21)	32(3)ns
62	151Sm	4.821(3)	35(1)ns
62	151Sm	91.532(9)	78(1)ns
62	151Sm	261.13(4)	1.4(1)μs
62	153Sm	98.39 (10)	10.6(3) ms
62	153Sm	182.902 (4)	17(7) ns
63	151Eu	196.245 (10)	58.9(5) μs
63	152Eu	45.5998 (4)	9.3116(13) h
63	152Eu	45.5998 (4)	9.3116(13) h
63	152Eu	65.2969 (4)	0.94(8) μs
63	152Eu	77.2593 (4)	38(4) ns
63	152Eu	78.2331 (4)	165(10) ns
63	152Eu	89.8496 (4)	384(10) ns
63	152Eu	147.86 (10)	95.8(4) min
63	153Eu	1771.0 (4)	475(10) ns
63	154Eu	68.1702 (4)	2.2(1) μs
63	154Eu	82.8200 (6)	20(5) ns
63	154Eu	100.8612 (4)	54(3) ns

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Contd....

Z	Nucl.	X 30	X 80
63	154Eu	145.3 (3)	46.3(4) min
63	156Eu	87.4897 (3)	12.0(3) ns
64	153Gd	95.1737 (8)	3.5(4) μs
64	153Gd	171.188 (4)	76.0(14) μs
64	154Gd	2137.48 (4)	68 ns
64	155Gd	121.05 (19)	31.97(27) ms
64	156Gd	2137.60 (5)	1.3(1) μs
64	157Gd	63.916 (5)	0.46(4) μs
64	157Gd	426.539 (23)	18.5(23) μs
64	159Gd	67.829 (24)	26.2(8) ns
65	158Tb	110.3 (12)	10.70(17) s
65	158Tb	388.39 (11)	0.40(4) ms
65	160Tb	63.6856 (20)	60(5) ns
66	159Dy	352.77 (14)	122(3) μs
66	161Dy	25.65136 (3)	29.10(11) ns
66	161Dy	485.7 (2)	0.76(17) μs
66	162Dy	2187.9 (10)	8.3(3) μs
67	163Ho	297.88 (7)	1.09(3) s
67	163Ho	1506.4 (4)	41(11) ns
67	163Ho	2109.4 (4)	0.80(15) μs
67	165Ho	361.675 (11)	1.512(4) μs
67	166Ho	5.969 (12)	1132.6(39) y
67	166Ho	190.9021 (20)	185(15) μs
68	162Er	2026.7 (6)	77(4) ns
68	164Er	1985.06 (6)	23.0(12) ns
68	164Er	3377.57 (11)	68(2) ns
68	167Er	207.801 (5)	2.269(6) s
68	168Er	1094.0383 (16)	109.0(7) ns
68	169Er	92.05 (10)	285(20) ns
68	169Er	243.69 (17)	200(10) ns
68	170Er	1268.68 (3)	42.8(17) ns
69	169Tm	316.14633 (11)	659.9(23) ns
69	169Tm	379.26678 (12)	52.2(8) ns
69	170Tm	183.197 (4)	4.12(13) μs
69	171Tm	424.9560 (15)	2.60(2) μs
69	171Tm	1674.5 (3)	1.7(2) μs
69	172Tm	476.2 (2)	132(7) μs
70	168Yb	1998.74 (6)	82(5) ns
70	168Yb	2222.37 (20)	62(8) ns

Contd....

Z	Nucl.	X 30	X 80
70	170Yb	1258.46 (14)	370(15) ns
70	171Yb	95.282 (2)	5.25(24) ms
70	171Yb	122.416 (2)	265(20) ns
70	172Yb	1550.43 (6)	3.6(1) μs
70	173Yb	398.9 (5)	2.9(1) μs
70	174Yb	1518.148 (13)	830(40) μs
70	174Yb	1765.2 (5)	256(11) ns
70	174Yb	3698.8 (6)	55(4) ns
70	174Yb	6146.6 (9)	28.4(14) ns
70	175Yb	514.866 (4)	68.2(3) ms
70	176Yb	1049.8 (6)	11.4(3) s
71	175Lu	353.48 (13)	1.49(7) μs
71	175Lu	626.53 (15)	10.6(5) ns
71	175Lu	1392.2 (6)	984(30) μs
71	176Lu	122.845 (4)	3.68(4) h
71	176Lu	194.358 (4)	35.0(10) ns
71	176Lu	1514.5 (5)	312(69) ns
71	176Lu	1587.5 (11)	40(3) μs
71	177Lu	150.3984 (10)	133.1(44) ns
71	177Lu	569.6721 (15)	155(7) μs
71	177Lu	761.7063 (14)	33(2) ns
71	177Lu	970.1757 (24)	160.4(3) d
71	177Lu	1356.860 (7)	10.8(5) ns
71	177Lu	2771.7 (5)	625(62) ns
71	177Lu	3530.4 (6)	6(2) μs*
72	174Hf	1549.3 (18)	138(4) ns
72	174Hf	1797.5 (18)	2.39(4) μs
72	174Hf	3311.7 (18)	3.7(2) μs
72	176Hf	1333.07 (7)	9.6(3) μs
72	176Hf	1559.31 (9)	9.9(2) μs
72	176Hf	2865.8 (7)	401(6) μs
72	176Hf	4376.6 (16)	34 ns
72	176Hf	4863.5 (16)	45(13) μs
72	177Hf	1315.4502 (8)	1.09(5) s
72	177Hf	1342.4 (10)	55.9(12) μs
72	177Hf	2740.02 (15)	51.4(5) min #
72	178Hf	1147.416 (6)	4.0(2) s
72	178Hf	1553.997 (4)	77.5(7) ns
72	178Hf	2446.09 (8)	31(1) y
72	178Hf	2572.4 (3)	68(2) μs

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Contd....

Z	Nucl.	X 30	X 80
72	179Hf	375.0352 (25)	18.67(4) s
72	179Hf	1105.74 (16)	25.00(27) d
72	179Hf	1404.5+X	14(2) ns
72	179Hf	2549.6 (13)	30(10) ns
72	179Hf	3439.2 (18)	12(6) ns
72	179Hf	3775.2 (21)	15(5) μs
72	180Hf	1141.552 (15)	5.49(3) h
72	180Hf	1374.36 (4)	0.57(2) μs
72	180Hf	2485.5 (5)	0.94(11) μs
72	180Hf	3597.5 (10)	90(10) μs
72	181Hf	595.27 (4)	80(5) μs
72	181Hf	1043.5 (8)	100 μs
72	181Hf	1741.9 (13)	1.5(5) ms
72	182Hf	1172.87 (18)	61.5(15) min
72	182Hf	2571.3 (12)	40(10) μs
73	179Ta	30.7 (1)	1.42(8) μs
73	179Ta	238.56 (9)	65(10) ns
73	179Ta	520.23 (18)	0.28(8) μs
73	179Ta	627.98 (15)	80(7) ns
73	179Ta	1252.60 (23)	322(16) ns
73	179Ta	1317.2 (4)	9.0(2) ms
73	179Ta	1328.0 (4)	1.6(4) μs
73	179Ta	2639.5 (5)	54.1(17) ms
73	179Ta	2792.8 (4)	17(3) ns
73	179Ta	5391.8 (8)	53(+3-7) ns
73	180Ta	76.79 (55)	4.5E+16 y
73	180Ta	107.78 (4)	19.2(7) ns
73	180Ta	177.87 (11)	70.0(14) ns
73	180Ta	357.01 (12)	42(3) ns
73	180Ta	463.62 (13)	31.2(19) ns
73	180Ta	520.04 (9)	37.4(20) ns
73	180Ta	594.43 (16)	16.1(19) ns
73	180Ta	1452.39 (22)	31.2(1) μs
73	180Ta	2588.3 (3)	22(2) ns
73	180Ta	3678.9 (10)	2.0(5) μs
73	180Ta	4169.9+X (18)	17(5) μs
73	181Ta	6.237 (20)	6.05(12) μs
73	181Ta	482.168 (23)	10.8(1) ns
73	181Ta	615.19 (3)	18.5(4) μs
73	181Ta	1403.2+X	140(36) ns
73	181Ta	1483.43 (21)	25(2) μs
73	181Ta	2227.9 (9)	210(20) μs

Contd....

Z	Nucl.	X 30	X 80
73	182Ta	16.273 (4)	283(3) ms
73	182Ta	519.577 (16)	15.84(10) min
73	183Ta	73.164 (14)	109(3) ns
73	183Ta	1332()	832(97) ns
74	180W	3547.9 (12)	20.3(6) ns
74	182W	2230.65 (14)	1.3(1) μs
74	182W	3754.89 (21)	37(2) ns
74	182W	4040.6 (3)	20(1) ns
74	183W	309.492 (4)	5.32(10) s
74	183W	453.0695 (17)	18.9(4) ns
74	183W	1746.11 (7)	12.7(20) ns
74	184W	1284.997 (8)	8.33(18) μs
74	184W	3863.2 (25)	188(38) ns*
74	185W	197.383 (23)	1.67(3) min
74	185W	243.62 (5)	19.3(5) ns
74	185W	243.62 (5)	19.3(5) ns
74	186W	1517.2 (6)	18(1) μs
74	186W	3542.8 (21)	2.0(2) s*
74	186W	3542.8 (21)	2.0(2) s*
74	187W	410.06 (4)	1.38(7) μs
75	185Re	368.3 (5)	33(3) ns
75	185Re	2123.8 (11)	121(13) ns
75	186Re	99.361 (3)	25.5(25) ns
75	186Re	148.2 (5)	2.0E+5 y
75	186Re	314.009 (5)	24.1(11) ns
75	186Re	324.4 (9)	17.3(6) ns
75	187Re	206.2473 (10)	555.3(17) ns
75	187Re	1681.8 (4)	354(62) ns
75	188Re	172.0848 (24)	18.59(4) min
75	188Re	182.7594 (24)	20.3(18) ns
75	188Re	230.9213 (12)	21.2(15) ns
75	189Re	1692.9 (5)	51(17) ns
75	189Re	1770.9 (6)	223(14) μs
76	184Os	2366.81 (19)	23.6(14) ns
76	184Os	4756.71 (24)	48(5) ns
76	187Os	100.45 (4)	112(6) ns
76	187Os	257.10 (7)	231(2) μs
76	188Os	1771.0 (4)	14.0(2) ns
76	188Os	2144.2 (7)	12.3(1) ns

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Contd....

Z	Nucl.	X 30	X 80
76	189Os	30.812 (15)	5.81(6) h
76	190Os	1705.4 (2)	9.86(3) min
76	191Os	74.382 (3)	13.10(5) h
76	191Os	2640	61(4) ns
76	192Os	2015.40 (11)	5.9(1)s
76	193Os	4113.8 (20)	0.19(10) μs
76	193Os	4580.3 (1)	205(7) ns
77	191Ir	171.29 (4)	4.899(23) s
77	191Ir	2101.1 (9)	5.8(6) s
77	192Ir	56.720 (5)	1.45(5) min
77	192Ir	66.830 (20)	15(4) ns
77	192Ir	104.776 (5)	17.4(26) ns
77	192Ir	118.7824 (18)	> 15 ns
77	192Ir	168.14 (12)	241(9) y
77	193Ir	80.239 (6)	10.53(4) d
77	193Ir	2277.4 (7)	124.8(21) μs
77	194Ir	147.072 (2)	31.85(24) ms
77	194Ir	190+X	171(11) d
78	190Pt	2297.45 (17)	48(5) ns
78	192Pt	2172.37 (13)	272(23) ns
78	193Pt	149.78 (4)	4.33(3) d
78	195Pt	259.077 (23)	4.010(5) d
78	197Pt	53.088 (19)	16.58(17) ns
78	197Pt	399.59 (20)	95.41(18) min
78	197Pt	1753.2+X	9.5(5) ns
78	198Pt	3017.0 (17)	36(2) ns
79	195Au	318.58 (4)	30.5(2) s
79	195Au	2460.84+X	12.89(21) μs
79	196Au	84.656 (20)	8.1(2) s
79	196Au	595.66 (4)	9.605(22) h
79	197Au	409.15 (8)	7.73(6) s
79	197Au	2532.5 (1)	150(5) ns
79	198Au	312.2200 (20)	124(4) ns
79	198Au	811.7 (15)	2.272(16) d
79	199Au	548.9405 (21)	0.44(3) ms
80	199Hg	532.48 (10)	42.67(9) min
80	201Hg	1.5648 (10)	81(5) ns
80	201Hg	766.22 (15)	94(2) μs
80	202Hg	2059	10.4(4) ns

Contd....

Z	Nucl.	X 30	X 80
80	203Hg	932.1 (7)	21.9(10) μs
80	203Hg	8281.0 (5)	146(30) ns
80	204Hg	4388.71 (13)	21.4(20) ns
80	204Hg	7226.08 (17)	>485 ns
81	203Tl	3265.6 (4)	6.9(5) μs
81	204Tl	145.89 (5)	18.7(14) ns
81	204Tl	1103.9 (3)	61.7(12) μs
81	204Tl	2319.07 (20)	2.6(2) μs
81	204Tl	4391.62 (24)	420(30) ns
81	204Tl	6239.4 (3)	90(3) ns
81	205Tl	3290.60 (17)	2.6(2) μs
81	205Tl	4835.6 (15)	235(10) ns
82	205Pb	2.329 (7)	24.2(4) μs
82	205Pb	1013.85 (3)	5.55(2) ms
82	205Pb	3195.8 (6)	217(5) ns
82	205Pb	5161.9 (7)	63(3) ns
82	207Pb	1633.356 (4)	0.805(8) s
83	210Bi	271.31 (11)	3.04E+6(6) y
83	210Bi	433.48 (12)	57.5(10) ns
83	210Bi	439.24 (4)	38(1) ns

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Due to the wider range of isomeric half-lives, a logarithmic transformation to the base 10 is applied to identify the otherwise obscure trends [7].

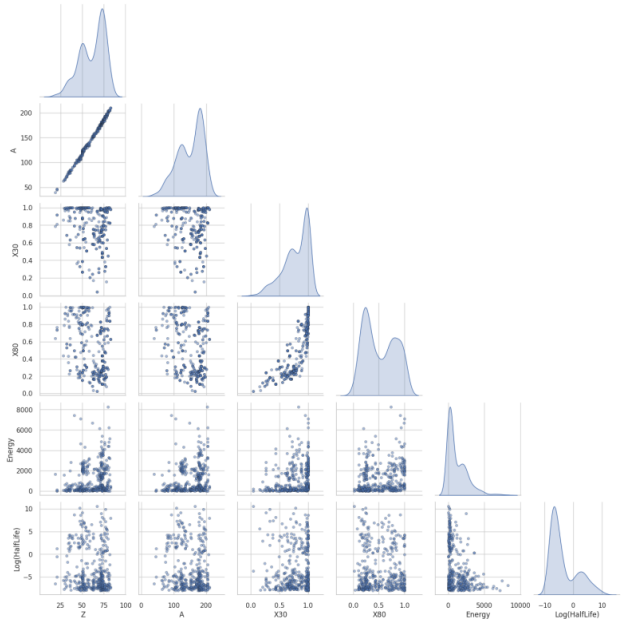


Figure 2: Pairwise distribution analysis.

I have performed a Pearson correlation analysis [8] among the proton number Z, mass number A, X30, X80, Energy of the isomer and logarithmic value of isomeric half-life. The correlation heatmap is shown in Fig. 1 to quantify the strength of linear relationships between all the pairs. This correlation measures the linear relationship between two variables. It measures how much one variable changes in a straight line as the other changes. It is calculated by diving the covariance of two variables by the product of their standard deviations. As expected Z and A show nearly perfect correlation.

A near-zero correlation between X30, X80 values and isomer half-life suggests that the probability of s-process neutron capture is independent of the temporal stability of the resulting state. It may imply that the resonance mechanism and hindrance mechanism behind the isomeric states are decoupled to each other. However, a weak positive correlation of about 0.23-0.25 is observed between isomeric energy and X30, X80. This suggests a increase in the probability of capture at higher isomeric excitations; however, it is not a strict rule. In the high-temperature environments of stellar interirors (KT=30-80 keV), a Boltzmann distribution allows these higher excitation energy states to become thermally populated. Because neutron-capture cross-sections are highly sensitive to the spin and parity of the target state, these higher excitation energies open distinct reaction channels that deviate significantly from the ground state predictions. Also, a slightly higher correlation for X80 rather than X30 informs about the temperature dependence of the s-process reaction rates.

We further perform a pairwise distribution analysis which is used to observe the global cluster behavior and distribution of properties across the data as depicted in Fig. 2. The diagonal plots show that the majority of isomeric states in the dataset are concentrated in specific energy ranges and follow a bimodal distribution in half-lives, representing two distinct classes of isomers, short-lived and long-lived. The extreme correlation between X30 and X80 indicates that most nuclei respond linearly to temperature change. However, one must study about the outliers in detail, which could be interesting for future research work in this domain. These outliers may also correspond to the waiting point nuclei in s-process path which may stall or redirect nucleosynthesis flux, altering final elemental abundances in ways, not captured by the models relying solely on the ground-state interactions.

4. Conclusion

This study investigates the relationship between nuclear isomers and s-process reaction rates. The analysis demonstrates that reliability of ground-state measurements, represented by X-metric, is more closely linked to isomeric excitation energies than to isomeric half-lives. This highlights that thermal population dynamica and the resulting spin/parity channel openings dictate reaction probabilities far more than the temporal stavility of the isomers.

The identification of hidden clusters, particularly the bimodel distribution of half-lives, provides a pathway for future research to investigate specific outliers where long-lived isomers might drastically alter the stellar nucleosynthesis predictions. These outliers may help in refining the stekkar nucleosynthesis models.

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Ultimately, understanding these specific isomer deviations is essential for accurately mapping the formation of heavy elements across the Universe.

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Declaration: It is an original data and has neither been sent elsewhere nor published anywhere.

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