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Effect of Excited States on Thermonuclear Reaction Rates

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Abstract

Values of the ratio of the thermonuclear reaction rate of a reaction, with target nuclei in a thermal distribution of energy states, to the reaction rate with all target nuclei in their ground states are tabulated for neutron, proton and α-particle induced reactions on the naturally occurring nuclei from ^{20}Ne to ^{70}Zn, at temperatures of 1, 2, 3·5 and 5×10^9 K. The ratios are determined from reaction rates based on statistical model cross sections.

1. Thermonuclear Reaction Rates

The main experimental input to the theory of nucleosynthesis in evolving and exploding stars is the large body of reaction cross-section measurements reported in the literature. Cross sections are fed into the nucleosynthesis calculations in the form of thermonuclear reaction rates $\langle\sigma v\rangle$. Here σ is the cross section corresponding to a relative collision velocity v, and the averaging is carried out for a Maxwellian distribution of velocities. The expression for the thermonuclear reaction rate is given by Fowler *et al.* (1967) as

$$\langle\sigma v\rangle = (8/\pi M)^{\frac{1}{2}}(kT)^{-3/2}\int_0^\infty \sigma(E)E\exp(-E/kT)\,\mathrm{d}E, \tag{1}$$

where M is the reduced mass and E the c.m. energy in the incident channel.

If experimental cross sections are substituted into equation (1), then the reaction rate obtained is non-physical at stellar temperatures in that it is arrived at on the assumption that all target nuclei are in their ground states. However, in a star, nuclei are thermally excited into excited states, and the true stellar reaction rate is given by

$$\langle\sigma v\rangle^* = \sum_\mu P^\mu\langle\sigma v\rangle^\mu, \tag{2}$$

where P^μ is the probability that the target nucleus is in its energy state μ, with the ground state given by $\mu = 0$, and $\langle\sigma v\rangle^\mu$ is the corresponding reaction rate. In

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this notation, the reaction rate obtained by direct substitution of experimental cross sections into equation (1) is $\langle\sigma v\rangle^0$. If the probabilities P^μ follow a thermal distribution, the true stellar reaction rate is given by

$$\langle\sigma v\rangle^* = \left(\sum_\mu (2J^\mu+1)\exp(-\varepsilon^\mu/kT)\langle\sigma v\rangle^\mu\right)\Big/\left(\sum_\mu (2J^\mu+1)\exp(-\varepsilon^\mu/kT)\right), \quad (3)$$

where J^μ and ε^μ are the spin and excitation energy of energy state μ.

If a nucleus possesses one or more isomeric excited states, it is possible that the time required to achieve a thermal distribution of excited states is long compared with the lifetime of the nucleus in the stellar environment, in which case a thermal distribution of states would not be attained. This problem has been investigated for equilibration of specific nuclei by means of electromagnetic transitions by Solomon and Sargood (1978) and Ward and Fowler (1980), and for equilibration by means of proton scattering by Anderson *et al.* (1980, 1981). Ward and Fowler (1980) also presented the formalism for the general case, including all equilibration processes.

To obtain $\langle\sigma v\rangle^*$ from experimental cross-section data one needs to be able to evaluate the ratio $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$. Since it is, in general, not possible to measure cross sections for $\mu \neq 0$, the evaluation of this ratio depends on theoretical values for the reaction rates $\langle\sigma v\rangle^\mu$. Woosley *et al.* (1975) used a statistical model formalism to calculate $\langle\sigma v\rangle^0$ and $\langle\sigma v\rangle^*$ for neutron, proton and α-particle induced reactions on all naturally occurring target nuclei from ^{20}Ne to ^{70}Zn, the values of $\langle\sigma v\rangle^*$ being based on the assumption of a thermal distribution of states, and tabulated the results for the temperature range $T_9 = 0\cdot1$–10, where T_9 is the temperature in units of 10^9 K. The ratio $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$ may therefore be obtained, for this range of reactions and temperatures, from their tables. Tables 1–4 of the present paper list the results so obtained for $T_9 = 1, 2, 3\cdot5$ and 5. These temperatures were chosen as being broadly representative of the conditions corresponding to the major post helium burning processes: $T_9 \sim 1$ for hydrostatic carbon burning (Arnett and Truran 1969), $T_9 \sim 2$ for explosive carbon burning (Pardo *et al.* 1974) and hydrostatic oxygen burning (Woosley *et al.* 1972), $T_9 \sim 3\cdot5$ for explosive oxygen burning (Woosley *et al.* 1973) and hydrostatic silicon burning (Arnett 1977), and $T_9 \sim 5$ for the onset of nuclear statistical equilibrium. Woosley *et al.* (1975) rounded all their reaction rates to three figures. The presently tabulated ratios calculated from them have also been rounded to three figures and will therefore be reliable to better than $1\cdot5\%$ in every case.

2. Discussion

From Tables 1–4 it is clear that excited states in target nuclei play a very important role in determining thermonuclear reaction rates under stellar conditions. The most dramatic effects occur very largely for reactions [such as (n, p) and (n, α) reactions on neutron rich isotopes, and (p, n) reactions on α-particle nucleus targets] for which the stellar reaction rates are very small and are at least two, and sometimes as many as eight, orders of magnitude less than those for one or more competing reactions from the same entrance channel. However, ratios of ~ 2 are common, and some of ~ 10 occasionally occur, for strongly competing and even dominant channels. Furthermore, even weakly competing exit channels may be of great importance in synthesis networks leading to rare nuclei.

Table 1. Values of the ratio $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$

$T_9 = 1\ (\equiv 1\times 10^9\ \mathrm{K})$

Target nucleus	Reaction (n, γ)	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(α, γ)	(α, n)	(α, p)
^{20}Ne	1·00	8·31	1·94	1·00	34·0	5·74	1·00	4·05	1·02
^{21}Ne	0·983	7·38	1·11	0·980	1·93	1·47	0·998	1·00	1·82
^{22}Ne	1·00	185	15·3	1·00	7·24	1·82	1·00	1·00	1·66
^{23}Na	0·997	4·81	6·30	0·992	2·40	1·00	0·997	1·96	1·00
^{24}Mg	1·00	50·6	4·48	1·00	135	7·33	1·00	5·06	1·00
^{25}Mg	1·00	3·80	1·69	1·00	3·10	2·47	1·00	1·00	1·00
^{26}Mg	1·00	41·9	27·4	1·00	14·3	2·17	1·00	1·00	1·01
^{27}Al	1·00	3·62	5·05	1·00	2·70	1·00	1·00	1·02	1·00
^{28}Si	1·00	5·81	5·10	1·00	128	8·63	1·00	3·33	1·00
^{29}Si	1·00	6·25	1·35	1·00	2·49	43·1	1·00	1·00	1·01
^{30}Si	1·00	42·0	7·83	1·00	2·07	2·23	1·00	1·00	1·00
^{31}P	1·00	1·60	6·25	1·00	3·09	1·00	1·00	1·30	1·00
^{32}S	1·00	1·01	1·00	1·00	77·9	2·05	1·00	3·18	1·00
^{33}S	1·00	1·00	1·00	0·999	3·86	1·27	1·00	1·00	1·00
^{34}S	1·00	7·43	3·33	1·00	3·61	1·01	1·00	1·00	1·00
^{36}S	1·00	124	18·3	1·00	1·00	1·00	1·00	1·00	1·01
^{35}Cl	1·00	1·00	1·01	1·00	3·65	1·00	1·00	1·10	1·00
^{37}Cl	1·00	8·73	1·45	1·00	1·00	1·00	1·00	1·00	1·00
^{36}Ar	1·00	1·00	1·00	1·00	172	3·86	1·00	2·57	1·00
^{38}Ar	1·00	9·10	1·24	1·00	8·20	1·02	1·00	1·01	1·02
^{40}Ar	1·00	107	30·1	1·00	1·08	1·00	1·00	1·00	1·01
^{39}K	1·00	1·00	1·00	1·00	3·22	1·00	1·00	1·08	1·00
^{40}K	0·893	1·71	1·62	0·739	1·30	0·859	0·888	1·06	1·01
^{41}K	1·00	7·99	2·99	1·00	1·00	1·00	1·00	1·00	1·00
^{40}Ca	1·00	1·00	1·00	1·00	393	2·98	1·00	6·98	1·00
^{42}Ca	1·00	11·0	2·19	1·00	5·10	1·02	1·00	1·04	1·00
^{43}Ca	0·992	7·05	1·08	0·997	1·45	1·18	0·991	1·00	1·02
^{44}Ca	1·00	46·9	51·2	1·00	3·69	2·31	1·00	1·00	1·00
^{46}Ca	1·00	145	200	1·00	1·02	1·58	1·00	1·00	1·00
^{48}Ca	1·00	$1\cdot12\times10^3$	$1\cdot40\times10^3$	1·00	1·00	1·00	1·00	1·00	1·00
^{45}Sc	0·867	0·848	4·66	0·988	1·49	2·18	0·775	0·874	1·05
^{46}Ti	1·00	38·6	15·0	1·00	7·09	15·1	1·00	1·17	1·00
^{47}Ti	0·934	2·36	0·973	0·981	1·52	2·50	1·00	0·997	1·14
^{48}Ti	1·00	658	33·4	1·00	34·1	7·28	1·00	1·00	1·00
^{49}Ti	1·00	1·78	3·20	1·00	1·00	1·29	1·00	1·00	1·00
^{50}Ti	1·00	404	45·7	1·00	1·54	2·38	1·00	1·00	1·04
^{50}V	0·960	9·11	8·24	0·944	1·39	1·31	0·930	1·00	1·29
^{51}V	0·988	4·70	13·7	0·996	1·08	1·10	0·987	1·01	0·995
^{50}Cr	1·00	48·1	9·90	1·00	9·13	6·73	1·00	1·39	1·00
^{52}Cr	1·00	25·2	21·3	1·00	233	7·44	1·00	1·00	1·00
^{53}Cr	1·00	14·5	1·13	1·00	1·01	5·37	1·00	1·00	1·06
^{54}Cr	1·00	$1\cdot14\times10^3$	11·4	1·00	1·16	1·24	1·00	1·00	1·43
^{55}Mn	0·915	3·44	5·28	0·988	1·01	0·959	1·01	1·21	0·940
^{54}Fe	1·00	1·04	2·43	1·00	24·1	8·45	1·00	1·02	1·00
^{56}Fe	1·00	20·4	4·03	1·00	32·0	7·48	1·00	1·12	1·09
^{57}Fe	0·813	9·78	0·923	0·979	3·03	1·28	1·60	0·951	4·29
^{58}Fe	1·00	127	15·1	1·00	2·39	1·69	1·00	1·01	1·47
^{59}Co	1·00	4·97	3·25	1·00	1·00	1·00	1·00	1·02	1·00
^{58}Ni	1·00	1·01	1·00	1·00	21·5	3·28	1·00	1·90	1·00
^{60}Ni	1·00	32·0	1·42	1·00	10·0	1·42	1·00	1·41	1·01
^{61}Ni	0·987	4·10	0·802	0·996	1·38	1·71	1·00	0·909	1·89
^{62}Ni	1·00	331	4·64	1·00	2·36	1·17	1·00	1·17	1·04
^{64}Ni	1·00	394	37·0	1·00	1·00	1·00	1·00	1·00	1·03
^{63}Cu	1·00	1·04	1·43	1·00	1·64	1·00	1·00	1·40	1·00
^{65}Cu	1·00	5·15	15·9	1·00	1·01	1·00	1·00	1·07	1·00
^{64}Zn	1·00	1·40	1·00	1·00	7·20	1·05	1·00	1·73	1·04
^{66}Zn	1·00	6·43	1·10	1·00	3·30	1·00	1·00	1·57	1·05
^{67}Zn	0·877	2·79	1·23	0·991	1·43	1·40	0·956	1·32	1·74
^{68}Zn	1·00	43·1	6·64	1·00	1·39	1·00	1·00	1·04	1·05
^{70}Zn				1·00	1·00	1·00	1·00	1·00	1·13

Table 2. Values of the ratio $\langle \sigma v \rangle^* / \langle \sigma v \rangle^0$

$T_9 = 2$

Target nucleus	(n, γ)	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(α, γ)	(α, n)	(α, p)
^{20}Ne	1·00	9·32	4·76	1·00	35·2	6·08	1·00	4·35	1·05
^{21}Ne	0·902	6·99	1·21	0·898	1·90	1·45	0·973	1·00	1·70
^{22}Ne	1·00	194	18·8	1·00	7·00	2·45	1·00	1·00	2·11
^{23}Na	0·954	5·04	7·54	0·956	2·41	0·966	0·963	1·71	0·993
^{24}Mg	1·00	39·2	5·60	1·00	141	9·82	1·00	5·13	1·00
^{25}Mg	0·993	4·38	2·56	0·989	3·29	3·36	0·994	1·00	1·02
^{26}Mg	1·00	48·7	35·7	1·00	8·19	3·25	1·00	1·00	1·04
^{27}Al	0·997	3·72	6·79	0·995	2·88	1·01	0·995	1·04	1·00
^{28}Si	0·997	5·99	5·55	1·00	129	12·3	1·00	3·49	1·00
^{29}Si	1·00	7·23	1·95	1·00	2·73	47·4	1·00	1·00	1·03
^{30}Si	1·00	51·2	12·2	1·00	2·27	3·61	1·00	1·00	1·00
^{31}P	1·00	2·10	9·73	0·996	3·40	1·00	1·00	1·49	1·00
^{32}S	1·00	1·25	1·01	1·00	83·6	3·09	1·00	3·39	1·00
^{33}S	0·997	1·10	1·00	1·00	4·14	1·69	0·995	1·00	1·00
^{34}S	1·00	10·0	5·27	1·00	5·49	1·13	1·00	1·01	1·00
^{36}S	1·00	165	33·9	1·00	1·00	1·00	1·00	1·00	1·05
^{35}Cl	1·00	1·00	1·32	1·00	4·03	1·00	1·00	1·14	1·00
^{37}Cl	1·00	12·7	2·58	1·00	1·00	1·00	1·00	1·00	1·00
^{36}Ar	1·00	1·00	1·01	1·00	184	5·66	1·00	2·74	1·00
^{38}Ar	1·00	13·4	3·04	1·00	8·23	1·45	1·00	1·01	1·03
^{40}Ar	1·00	146	51·7	1·00	1·19	1·00	1·00	1·00	1·08
^{39}K	1·00	1·00	1·00	1·00	3·51	1·00	1·00	1·11	1·00
^{40}K	0·902	2·07	1·82	0·724	1·40	0·981	0·835	1·02	0·997
^{41}K	1·00	10·0	6·83	1·00	1·00	0·999	0·997	1·01	0·997
^{40}Ca	1·00	1·00	1·00	1·00	413	5·53	1·00	7·70	1·00
^{42}Ca	1·00	18·3	11·5	1·00	7·76	1·57	1·00	1·07	1·00
^{43}Ca	0·943	7·62	2·25	0·943	1·49	1·26	0·935	1·00	1·04
^{44}Ca	1·00	68·8	89·3	0·997	4·03	3·66	0·995	1·00	1·05
^{46}Ca	1·00	210	388	0·998	1·05	2·92	1·00	1·00	1·01
^{48}Ca	1·00	$1·61 \times 10^3$	$2·68 \times 10^3$	1·00	1·00	1·22	1·00	1·00	1·00
^{45}Sc	0·803	1·15	6·65	0·906	1·53	2·23	0·782	0·994	1·01
^{46}Ti	0·997	30·7	25·3	0·987	9·76	19·4	0·977	1·23	0·994
^{47}Ti	0·909	1·96	1·10	0·942	1·41	4·57	1·05	0·988	1·17
^{48}Ti	1·00	286	59·5	1·00	15·6	10·2	0·983	1·00	1·01
^{49}Ti	1·00	2·60	8·14	1·00	1·00	2·72	1·00	1·00	1·00
^{50}Ti	1·00	412	110	1·00	1·47	5·64	1·00	1·00	1·13
^{50}V	0·845	42·3	11·2	0·746	1·52	2·42	0·795	0·987	1·41
^{51}V	0·934	6·06	28·3	0·935	1·04	1·41	0·905	1·00	1·06
^{50}Cr	0·992	33·4	13·3	0·978	12·6	13·0	0·957	1·44	1·00
^{52}Cr	1·00	36·5	47·6	1·00	31·5	11·2	0·999	1·00	1·00
^{53}Cr	0·980	19·7	2·12	0·979	1·01	10·4	0·993	1·00	1·15
^{54}Cr	0·990	$1·51 \times 10^3$	31·2	0·975	1·21	4·41	0·973	1·00	1·76
^{55}Mn	0·928	4·42	10·0	1·14	0·997	1·05	1·00	1·04	0·822
^{54}Fe	1·00	1·95	12·9	1·00	65·2	17·6	0·999	1·04	1·00
^{56}Fe	0·992	27·3	7·94	0·988	20·0	11·5	0·992	1·14	1·14
^{57}Fe	0·880	7·53	1·64	0·780	1·76	1·60	2·16	0·986	1·96
^{58}Fe	0·984	188	33·7	0·993	2·30	2·86	0·960	1·01	1·78
^{59}Co	1·00	7·64	9·20	0·997	1·01	1·00	1·00	1·02	1·00
^{58}Ni	1·00	1·61	1·25	1·00	26·3	8·62	1·00	2·09	1·00
^{60}Ni	1·00	44·9	5·97	1·00	12·1	4·75	1·00	1·55	1·02
^{61}Ni	1·08	5·49	1·09	0·995	1·21	2·54	1·11	0·886	1·33
^{62}Ni	1·00	537	20·6	1·00	2·68	3·39	1·00	1·18	1·08
^{64}Ni	1·00	801	132	0·996	1·02	1·08	0·997	1·01	1·09
^{63}Cu	0·991	1·62	8·55	0·993	1·94	1·01	0·993	1·52	1·01
^{65}Cu	0·998	7·64	56·8	0·993	1·02	0·995	1·00	1·08	1·01
^{64}Zn	1·00	3·09	1·35	0·995	8·35	1·86	0·998	2·00	1·11
^{66}Zn	1·00	14·5	4·39	1·00	4·73	1·32	1·00	1·62	1·14
^{67}Zn	0·754	3·37	1·36	0·847	1·14	1·32	0·786	1·08	1·63
^{68}Zn	1·00	93·9	19·9	1·00	1·57	1·10	0·998	1·08	1·17
^{70}Zn				0·970	1·00	1·03	0·975	1·01	1·28

Table 3. Values of the ratio $\langle \sigma v \rangle^* / \langle \sigma v \rangle^0$

$T_9 = 3{\cdot}5$

Target nucleus	Reaction (n, γ)	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(α, γ)	(α, n)	(α, p)
^{20}Ne	0·992	10·5	5·33	0·990	36·1	6·65	0·981	4·81	1·17
^{21}Ne	0·828	6·40	1·14	0·837	1·81	1·61	0·961	0·995	1·46
^{22}Ne	0·972	186	22·0	1·00	6·12	2·74	0·988	1·00	2·46
^{23}Na	0·910	4·91	8·69	0·908	2·32	0·938	0·880	1·44	0·956
^{24}Mg	0·983	26·8	6·93	0·972	141	13·3	0·950	5·09	1·02
^{25}Mg	0·956	4·86	2·98	0·940	3·45	4·39	0·979	0·992	1·06
^{26}Mg	0·994	60·7	46·3	0·993	7·73	4·29	1·00	1·00	1·20
^{27}Al	0·974	3·92	9·09	0·967	3·10	1·07	0·961	1·09	0·987
^{28}Si	0·993	6·38	6·49	0·989	137	18·2	0·987	3·62	1·00
^{29}Si	0·987	8·21	2·73	0·973	3·00	50·5	0·984	0·991	1·11
^{30}Si	1·00	68·8	19·8	0·996	2·62	5·21	0·997	1·00	1·02
^{31}P	0·992	2·44	14·7	0·972	3·74	1·03	0·991	1·64	0·996
^{32}S	0·998	1·85	1·20	0·996	89·3	5·04	0·997	3·69	1·00
^{33}S	0·977	1·30	1·03	0·969	4·48	2·47	0·970	1·00	1·00
^{34}S	1·00	16·5	9·15	0·993	7·01	1·54	0·996	1·02	1·01
^{36}S	1·00	274	62·1	1·00	1·00	1·00	1·00	1·00	1·26
^{35}Cl	0·991	1·08	2·15	0·988	4·40	1·02	0·987	1·19	1·00
^{37}Cl	1·00	19·1	6·58	1·00	1·00	1·00	1·00	1·00	1·00
^{36}Ar	0·997	1·34	1·38	0·995	195	9·31	0·995	2·96	1·00
^{38}Ar	1·00	24·2	5·20	0·997	0·878	2·35	0·996	1·04	1·08
^{40}Ar	0·994	232	89·8	0·961	1·41	1·00	0·963	1·00	1·31
^{39}K	1·00	1·01	1·20	1·00	3·90	1·01	1·00	1·20	1·00
^{40}K	0·894	2·42	1·88	0·705	1·47	1·17	0·801	1·03	0·972
^{41}K	0·966	12·2	14·5	0·939	1·02	0·973	0·940	1·01	0·971
^{40}Ca	1·00	1·05	1·04	1·00	434	11·1	1·00	8·40	1·00
^{42}Ca	1·00	28·9	23·4	0·979	16·2	2·89	0·966	1·10	0·989
^{43}Ca	0·849	7·77	4·30	0·843	1·43	1·44	0·882	0·991	1·05
^{44}Ca	0·983	114	153	0·965	4·51	4·71	0·924	1·00	1·15
^{46}Ca	1·00	356	732	0·944	1·12	10·4	0·982	1·00	1·05
^{48}Ca	1·00	$2{\cdot}83 \times 10^{3}$	$5{\cdot}13 \times 10^{3}$	1·00	1·00	3·78	1·00	1·00	1·06
^{45}Sc	0·692	1·48	10·4	0·746	1·42	2·08	0·801	1·00	0·975
^{46}Ti	0·980	29·9	30·2	0·921	17·3	25·0	0·885	1·19	0·937
^{47}Ti	0·936	2·11	1·98	0·926	1·37	7·75	1·05	0·973	1·11
^{48}Ti	1·00	195	99·8	0·957	9·39	18·1	0·873	0·996	1·10
^{49}Ti	0·986	4·11	17·2	0·978	1·00	7·21	0·990	1·00	1·05
^{50}Ti	0·997	480	246	0·981	1·59	12·1	0·985	1·00	1·35
^{50}V	0·732	45·7	17·4	0·541	1·37	3·54	0·716	0·952	1·29
^{51}V	0·879	8·21	58·4	0·847	1·02	1·95	0·848	1·00	1·08
^{50}Cr	0·971	22·6	22·1	0·906	14·9	22·3	0·824	1·35	0·957
^{52}Cr	1·00	54·2	101	0·981	16·4	22·3	0·959	1·00	1·10
^{53}Cr	0·927	25·8	3·83	0·856	1·01	17·4	0·970	0·997	1·28
^{54}Cr	0·942	$1{\cdot}58 \times 10^{3}$	70·2	0·785	1·17	6·35	1·03	1·00	1·88
^{55}Mn	0·985	6·69	21·4	1·39	0·979	1·08	0·994	1·01	0·809
^{54}Fe	0·992	3·89	32·4	0·976	111	36·3	0·954	1·04	0·990
^{56}Fe	0·945	35·5	18·7	0·964	13·0	12·2	0·831	1·08	1·14
^{57}Fe	1·07	7·87	2·90	0·566	1·38	2·23	1·72	0·994	1·50
^{58}Fe	0·927	282	72·9	0·916	1·97	3·84	0·783	1·00	1·85
^{59}Co	0·962	11·2	24·5	0·953	1·02	1·02	0·948	1·05	0·963
^{58}Ni	0·987	4·02	3·35	0·972	39·2	18·8	0·967	2·53	1·01
^{60}Ni	0·991	70·3	19·2	0·969	15·6	12·4	0·963	1·71	1·04
^{61}Ni	1·13	6·89	2·35	0·957	1·15	4·05	1·32	0·959	1·26
^{62}Ni	0·990	688	68·6	0·978	2·98	7·45	0·943	1·19	1·01
^{64}Ni	1·00	$1{\cdot}81 \times 10^{3}$	472	0·943	1·05	3·29	0·943	1·01	1·23
^{63}Cu	0·944	2·76	26·8	0·904	2·12	1·02	0·938	1·64	0·986
^{65}Cu	0·961	13·0	160	0·903	1·02	0·923	0·928	1·09	0·932
^{64}Zn	1·02	5·73	3·82	0·948	11·5	3·45	0·920	2·68	1·13
^{66}Zn	1·02	37·1	13·2	0·982	7·12	2·30	0·953	1·58	1·07
^{67}Zn	0·696	4·54	1·70	0·700	0·986	1·80	0·624	0·965	1·52
^{68}Zn	1·01	329	57·6	0·955	1·71	1·18	0·891	1·07	1·33
^{70}Zn				0·762	0·992	1·41	0·805	0·991	1·43

Table 4. Values of the ratio $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$

$T_9 = 5$

Target nucleus	(n, γ)	(n, p)	(n, α)	(p, γ)	(p, n)	(p, α)	(α, γ)	(α, n)	(α, p)
				Reaction					
^{20}Ne	0·959	12·2	4·98	0·954	34·1	6·86	0·907	4·90	1·29
^{21}Ne	0·808	6·15	1·13	0·818	1·78	1·95	0·943	0·985	1·37
^{22}Ne	0·917	159	22·1	0·895	5·11	2·72	0·968	0·996	2·46
^{23}Na	0·897	4·95	9·70	0·890	2·27	0·944	0·826	1·30	0·918
^{24}Mg	0·939	20·4	7·30	0·924	120	15·0	0·835	4·70	1·04
^{25}Mg	0·905	5·05	3·18	0·862	3·48	5·02	0·958	0·973	1·10
^{26}Mg	0·968	71·4	53·8	0·958	8·05	4·92	0·974	1·00	1·41
^{27}Al	0·934	4·12	10·9	0·913	3·22	1·14	0·905	1·13	0·972
^{28}Si	0·976	6·51	7·26	0·950	140	23·5	0·933	3·55	1·02
^{29}Si	0·943	8·67	3·34	0·907	3·18	50·1	0·927	0·964	1·18
^{30}Si	0·989	89·4	28·6	0·982	2·99	6·63	0·973	1·01	1·09
^{31}P	0·972	2·63	18·4	0·901	3·77	1·11	0·969	1·70	0·978
^{32}S	0·988	2·33	1·57	0·980	90·1	7·35	0·975	3·79	1·00
^{33}S	0·943	1·46	1·06	0·920	4·73	3·24	0·916	0·995	1·01
^{34}S	1·00	25·8	13·1	0·979	8·02	2·02	0·964	1·05	1·02
^{36}S	0·998	428	95·9	1·00	1·00	1·02	0·995	1·00	1·68
^{35}Cl	0·972	1·19	3·06	0·948	4·48	1·05	0·945	1·23	0·992
^{37}Cl	0·994	26·0	13·7	0·987	1·00	1·00	0·985	1·00	0·995
^{36}Ar	0·978	1·80	1·92	0·963	195	13·2	0·981	2·98	0·996
^{38}Ar	1·01	39·6	7·78	0·975	9·41	3·16	0·969	1·07	1·17
^{40}Ar	0·964	315	120	0·833	1·57	0·966	0·884	0·995	1·52
^{39}K	1·00	1·08	1·74	0·995	4·14	1·05	0·995	1·30	1·00
^{40}K	0·860	2·62	1·88	0·673	1·47	1·26	0·754	1·00	0·971
^{41}K	0·873	12·5	22·1	0·772	1·04	0·893	0·814	1·00	0·946
^{40}Ca	0·998	1·33	1·28	0·996	440	18·6	0·994	8·77	1·00
^{42}Ca	0·955	35·8	30·2	0·897	22·1	3·76	0·833	1·10	0·948
^{43}Ca	0·772	8·31	5·35	0·738	1·37	1·83	0·848	0·974	1·05
^{44}Ca	0·933	156	190	0·897	4·44	6·26	0·860	0·982	1·16
^{46}Ca	0·990	515	$1·01\times10^3$	0·789	1·15	10·9	0·921	0·992	1·10
^{48}Ca	1·00	$4·75\times10^3$	$8·20\times10^3$	0·997	1·00	11·6	0·999	1·00	1·25
^{45}Sc	0·611	1·65	14·1	0·615	1·29	1·91	0·792	0·978	0·969
^{46}Ti	0·975	27·1	32·2	0·855	22·6	27·2	0·843	1·13	0·901
^{47}Ti	0·939	2·38	3·22	0·887	1·33	10·8	1·01	0·966	1·07
^{48}Ti	1·00	156	125	0·918	7·06	22·8	0·858	0·985	1·13
^{49}Ti	0·934	5·46	28·5	0·901	0·989	13·3	0·949	0·986	1·12
^{50}Ti	0·974	553	375	0·880	1·68	20·1	0·957	0·995	1·53
^{50}V	0·637	22·2	23·9	0·417	1·25	4·09	0·665	0·914	1·20
^{51}V	0·840	10·6	93·5	0·765	1·00	2·41	0·863	0·990	1·10
^{50}Cr	0·968	17·7	29·6	0·859	16·7	28·8	0·770	1·21	0·931
^{52}Cr	0·963	67·6	151	0·925	13·5	32·7	0·825	0·982	1·25
^{53}Cr	0·847	28·2	5·61	0·672	0·982	21·7	0·905	0·966	1·32
^{54}Cr	0·902	$1·47\times10^3$	95·0	0·568	1·10	7·10	0·992	0·992	1·79
^{55}Mn	1·00	9·14	35·9	1·49	0·967	1·27	1·03	0·992	0·821
^{54}Fe	0·944	5·70	46·7	0·869	124	51·3	0·811	0·953	1·02
^{56}Fe	0·917	41·7	29·6	0·957	9·31	14·5	0·661	1·01	1·34
^{57}Fe	1·24	9·44	4·38	0·457	1·21	2·93	1·16	0·977	1·33
^{58}Fe	0·885	365	114	0·745	1·66	5·45	0·748	0·993	1·73
^{59}Co	0·864	13·6	45·0	0·806	1·02	1·27	0·803	1·02	0·889
^{58}Ni	0·916	6·47	6·98	0·871	51·2	28·7	0·843	2·84	1·00
^{60}Ni	0·934	87·4	36·1	0·868	17·2	18·4	0·811	1·68	0·939
^{61}Ni	1·09	7·69	3·88	0·862	1·10	5·11	1·21	0·951	1·23
^{62}Ni	0·951	778	133	0·912	3·00	9·45	0·752	1·12	0·901
^{64}Ni	0·971	$3·20\times10^3$	$1·08\times10^3$	0·765	1·04	6·76	0·769	0·986	1·34
^{63}Cu	0·857	3·49	46·3	0·746	2·00	0·939	0·773	1·54	0·827
^{65}Cu	0·879	16·0	291	0·702	1·00	0·824	0·720	1·03	0·745
^{64}Zn	1·01	8·32	6·67	0·864	26·8	4·83	0·745	2·90	1·06
^{66}Zn	1·01	63·9	25·2	0·926	8·28	2·65	0·749	1·41	0·880
^{67}Zn	0·636	5·80	2·27	0·596	0·893	2·31	0·476	0·867	1·42
^{68}Zn	0·961	662	103	0·759	1·64	0·980	0·646	1·01	1·43
^{70}Zn				0·512	0·933	1·74	0·684	0·914	1·47

The sheer magnitude of these ratios has important implications for nucleosynthesis calculations. In many cases the compound nucleus level density is not sufficiently high to satisfy the basic assumption of the statistical model yet, apart from a difficult and time-consuming technique based on measurements of compound elastic and inelastic scattering from individual resonances (Bahcall and Fowler 1969; Fowler *et al.* 1975), the only method currently available for determining the ratio $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$ depends on the use of this model. It is therefore clear that, in such cases, deducing stellar reaction rates from even the most carefully collected experimental data may be quite hazardous, since it involves applying a significant correction factor which is highly suspect. Correction factors such as those presented here should therefore be used with due caution. However, the correction factor is a ratio of calculated reaction rates and some of the weaknesses in the model which may arise for a given reaction will largely cancel. For that wide range of reactions and temperatures for which the experimental data in the literature have shown the statistical model to be substantially reliable, it should be possible to use with confidence the $\langle\sigma v\rangle^*/\langle\sigma v\rangle^0$ ratios calculated from statistical model cross sections to determine $\langle\sigma v\rangle^*$ from experimentally based values of $\langle\sigma v\rangle^0$.

The statistical model development by Woosley *et al.* (1975) has been published by Holmes *et al.* (1976). A discussion of the role of excited states and the assumption of a thermal distribution of states, and also parametrization of the data on which the present paper is based, are given by Woosley *et al.* (1978).

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References

Anderson, M. R., Kennett, S. R., Mitchell, L. W., and Sargood, D. G. (1980). *Nucl. Phys.* A **349**, 154.
Anderson, M. R., Kennett, S. R., Sevior, M. E., and Sargood, D. G. (1981). *Aust. J. Phys.* **34**, 105.
Arnett, W. D. (1977). *Astrophys. J. Suppl. Ser.* **35**, 145.
Arnett, W. D., and Truran, J. W. (1969). *Astrophys. J.* **157**, 339.
Bahcall, N. A., and Fowler, W. A. (1969). *Astrophys. J.* **157**, 645.
Fowler, W. A., Caughlan, G. R., and Zimmerman, B. A. (1967). *Ann. Rev. Astron. Astrophys.* **5**, 525.
Fowler, W. A., Caughlan, G. R., and Zimmerman, B. A. (1975). *Ann. Rev. Astron. Astrophys.* **13**, 69.
Holmes, J. A., Woosley, S. E., Fowler, W. A., and Zimmerman, B. A. (1976). *At. Data Nucl. Data Tables* **18**, 305.
Pardo, R. C., Couch, R. G., and Arnett, W. D. (1974). *Astrophys. J.* **191**, 711.
Solomon, S. B., and Sargood, D. G. (1978). *Astrophys. J.* **223**, 697.
Ward, R. A., and Fowler, W. A. (1980). *Astrophys. J.* **238**, 266.
Woosley, S. E., Arnett, W. D., and Clayton, D. D. (1972). *Astrophys. J.* **175**, 131.
Woosley, S. E., Arnett, W. D., and Clayton, D. D. (1973). *Astrophys. J. Suppl. Ser.* **26**, 231.
Woosley, S. E., Fowler, W. A., Holmes, J. A., and Zimmerman, B. A. (1975). Caltech Preprint No. OAP-422.
Woosley, S. E., Fowler, W. A., Holmes, J. A., and Zimmerman, B. A. (1978). *At. Data Nucl. Data Tables* **22**, 371.

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