Changes and Additions to Rate Table Since Version 86.3

• Updated tables of solar system abundances (Table 1).

• New tables of nuclear binding energies (Table 2).

• Updated tables of 30 keV neutron capture cross sections (Table 3).

• New tables of electron capture on the proton and positron capture on the neutron and their associated neutrino loss rates (Tables 4 A−E).

• New tables of reaction rates on light nuclei ($^{A}Z \leq {}^{12}C$) (Tables 5 B−E).

• New tables of thermal neutrino loss rates with individual contributions from the plasma, pair, and photo neutrino processes (Tables 6 A−D).

• New tables of the electron screening corrections to the heavy ion reactions 3α, $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$ (Tables 7 A−D).

• New neutron-induced and charged-particle strong and electromagnetic reaction rates on intermediate mass nuclei ($36 \leq Z \leq 44$).

• New tables of neutrino interaction cross sections and associated branching ratios for both charged current and neutral current reactions on intermediate mass nuclei ($^{12}C \leq ^{A} Z \leq ^{80}$ Kr).

Special Revisions to Strong and Electromagnetic Rates

• The most recent update in the Thermonuclear Reaction Rate series from Caughlan and Fowler (1988) gives revisions for 31 strong and electromagnetic rates, including modifications to the heavy ion reaction rates 3α, $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$. A list of the other 27 rate revisions follows:

$^{12}C(\alpha,\gamma)^{16}O$	$^{16}O(\alpha,\gamma)^{20}Ne$	$^{25}Mg(p,\gamma)^{26}Al$
$^{13}C(p,\gamma)^{14}N$	$^{18}O(p,\gamma)^{19}F$	$^{26}Al(n,p)^{26}Mg$
$^{14}C(\alpha,\gamma)^{18}O$	$^{18}O(p,\alpha)^{15}N$	$^{26}Al(p,\gamma)^{27}Si$
$^{13}N(p,\gamma)^{14}O$	$^{19}Ne(p,\gamma)^{20}Na$	$^{26}Al(n,\alpha)^{23}Na$
$^{14}N(p,\gamma)^{15}O$	$^{21}Ne(p,\gamma)^{22}Na$	$^{27}Al(p,\gamma)^{28}Si$
$^{15}N(\alpha,\gamma)^{19}F$	$^{21}Na(p,\gamma)^{22}Mg$	$^{27}Al(\alpha,n)^{30}P$
$^{14}O(\alpha,p)^{17}F$	$^{22}Na(n,p)^{22}Ne$	$^{27}Si(p,\gamma)^{28}P$
$^{14}O(\alpha,\gamma)^{18}Ne$	$^{22}Na(p,\gamma)^{23}Mg$	$^{29}Si(p,\gamma)^{30}P$
$^{15}O(\alpha,\gamma)^{19}Ne$	$^{22}Na(n,\alpha)^{22}Ne$	$^{30}Si(p,\gamma)^{31}P$

Entries from this survey are labeled in the strong reference matrix by "* CF".

INTRODUCTION

These tables are a compilation of current thermonuclear reaction rate information for light and intermediate mass nuclei (^{1}H to ^{134}Ru). They are intended to supplement the various works of Fowler, Caughlan, Zimmerman, and Harris especially for nuclei heavier than magnesium. Reaction rates for strong, electromagnetic, and weak interactions are tabulated in 14 sections as a function of temperature (T_9). Also presented are tables of neutral current and charged current neutrino interaction cross sections and their associated branching ratios.

Table 1 begins by listing the abundance by mass fraction of the stable isotopes as computed from the abundance data of Anders and Grevesse (1989). Also listed is the percentage [100(a-c)/a] by which each mass fraction changed compared to data from Anders 1989 (a) vs. Cameron 1983 (c) .

Table 2 lists the nuclear binding energies (in MeV) for all nuclei that have reaction rate information presented in these tables. Given are ^{A}Z, the binding energy (BE), and a flag indicating whether the binding energy was derived from a mass law (*), or a combination of experiment and mass law (**). In the later case, the mass excess used to calculate the binding energy was averaged to give a smooth transition between the adjacent experimentally measured and theoretically determined binding energies. For more inforamtion see Serino (1991). All other entries are derived from the experimentally measured nuclear mass excess data of Wapstra *et al.* (1988). The binding energies shown were used in the calculation of all strong and electromagnetic reaction rates referenced to HW or SEW in Table 8. Reaction rates drawn from the earlier works of Woosley *et al.* (1975, 1978) have not been replaced by their new counterparts in our data set.

Table 3 gives neutron capture cross-sections in millibarns at 30 keV corresponding to the (n,γ) reaction rates given in the main tables. See also eq. (41) from Woosley, Fowler, Holmes, and Zimmerman (1975; OAP-422.)

Tables 4 (A-D) list the reaction rates currently employed for electron capture on the proton and positron capture on the neutron, (in units of captures per second per particle), and their associated neutrino loss rates (in units of ergs per second per particle). These values are from an approximation formula provided by George Fuller. Also given in Table 4E is the electron degeneracy parameter Q_η, i.e the chemical potential (excluding the electrons rest mass) divided by kT. We assume symmetric neutron and proton ratios ($Y_e = 0.5$) in the evaluation the above quantities.

Table 5A shows the limits of our reaction rate data set for strong and electromagnetic rates, Table 5B lists the reactions included in our network below ^{12}C. Tables 5 (C-E) give the values of those rates in Table 5B that are not be presented in the regular reaction rate tables. All rate evaluations are from Caughlan and Fowler (1988) except as noted in table 5B.

Tables 6 (A-D) give the neutrino energy loss rate (erg g^{-1} s^{-1}) due to thermal processes and the contributions to this rate from the pair, plasma, and photo neutrino processes tabulated for a grid of temperatures and densities. Symmetric neutron and proton ratios have been assumed for their evaluation, *i.e.* $Y_e = 0.5$. The rates are from Beaudet, Petrosian, and Salpeter (1967) as modified by Munakata *et al.* (1985) to include the effects of weak neutral currents.

Tables 7 (A-D) lists the electron screening corrections for the heavy ion reactions: 3α, $^{12}C + ^{12}C$, $^{12}C + ^{16}O$, and $^{16}O + ^{16}O$. For each rate, the screening corrections were evaluated using a composition appropriate to the stellar environment in which that rate dominates during hydrostatic burning phases. Each composition is characterized by the parameters $X(^AZ)$ (the mass fraction(s) of isotope ^AZ), $\bar{A}$ (the average atomic weight), $\bar{Z}$ (the average atomic number), and Y_e (the electron mole number).

Tables 8 and 9 show the reaction rate reference matrices which provide a complete bibliography coded to the principal authors for each reaction rate. The main tables are broken into two ranges, $0.03 \leq T_9 \leq 1.5$, which gives rate information only for nuclei with $Z \leq 26$, and $2.0 \leq T_9 \leq 10.0$, which covers the entire range $Z \leq 44$. References to rates on nuclei in Table 8 that are *italicized* (e.g. ^{43}S) are presented only in the sections with $T_9 \geq 2.0$. Entries in the matrices that are preceeded by a * indicate rates that have been experimentally measured, all others are theoretical estimates. Entries of 0. indicate that no rate is tabulated.

Table 10 gives the ground state weak decay rate (in units of s−1) for beta decay (β^-) *out of nucleus* ^AZ, and the sum of positron decay plus electron capture (β^- + E.C.) *into nucleus* ^AZ. These rates are taken as a lower bound to the weak decay rate, subject to replacement by the temperature dependent weak decay rates from Fuller *et al.* provided in the main reaction rate tables. (See also Table 11).

STRONG, ELECTROMAGNETIC, AND WEAK INTERACTION TABLES

Each of the 14 sections detailing the strong, electromagnetic, and weak reaction rates begins by listing for each isotope (^AZ), the temperature dependent partition function (W), and the ratio (G) of that partition function at a temperature T_9 to the statistical weight for the ground state $(2J_0 + 1)$. For a further description, see WFHZ (1978), page 374.

Special heavy ion reactions are then tabulated (taken from Caughlan and Fowler 1988), giving the total and reverse rates for each reaction, as well as the temperature dependent branching ratios where applicable. The 3α reaction rate has been divided by 6, while the $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ rates have both been divided by 2 to account for identical reactants.

Next, strong and electromagnetic reaction rates are tabulated in 12 columns. For each isotope listed, 6 of the columns are defined as "Forward Rates", the others are defined as “Reverse Rates” as follows:

Forward Rates	Forward Rates	Reverse Rates	Reverse Rates
(n,γ)	(α,p)	(γ,n)	(p,α)
(p,n)	(α,n)	(n,p)	(n,α)
(p,γ)	(α,γ)	(γ,p)	(γ,α)

A forward rate increases the charge and/or the atomic number of the target nuclei. The rate for reaction $I(j,k)L$ on target I producing species L, is found by choosing the row in the table corresponding to the isotope (I or L) with the lowest Z value, then moving over to the entry labeled under column (j,k).

For example, consider the “Forward Rate” ^{12}C(α,γ)^{16}O. Choose the row in the table corresponding to the reaction isotope with the lowest Z value (^{12}C), then move over to the value listed under the column labeled (α,γ). The choice of the correct row for a reaction given in terms of a “Forward Rate” will be given by the target nuclei. The corresponding inverse reaction ^{16}O(γ,α)^{12}C, is found by choosing the isotope with the lowest Z value (^{12}C), and moving over to the value listed under column (γ,α). The appropriate inverse rate for any reaction given in terms of a “Forward Rate” will be the number directly to the right of its “Forward Rate”.

As an example of a reaction given in terms of a “Reverse Rate”, consider the reaction ^{41}K(p,α)^{38}Ar. This rate is found by choosing the row corresponding to the isotope with the lowest Z value (^{38}Ar), and moving over to the value listed under the column labeled (p,α).

Next, weak interaction rates are tabulated. For $T_9 < 1.0$ or $\rho < 10^6$ gm cm^{-3}, a mean ground state weak decay rate (s^{-1}) has been calculated from the nuclides half-life, and taken as a lower limit to the weak decay rate. These are provided in a separate table (Table 10) following the reaction reference bibliography. Given are the beta decay rate (β^-) *out of* the isotope, and the sum of positron decay plus electron capture (β^++EC) *into* the isotope. Table 11 gives the temperature dependent β^+ rate into nucleus ^AZ that includes contributions from the ground state plus first excited isomeric state (assumed in thermal equilibrium) for 35 nuclei in Table 10. For $T_9 \geq 1.0$, the temperature dependent rates from Fuller *et al.* are given. The weak rates are given in 12 columns for 6 values of density between $6 \leq \log_{10}(\rho) \leq 11$. For each isotope at a specified density two columns are listed, the first column gives the beta decay rate (β^-) *out of* the isotope, the second column gives the sum of positron decay plus electron capture ($\beta^+ + \mathrm{EC}$) *into* the isotope.