Abstract. Some weak interaction processes which are important in stars whose central temperatures and densities exceed $10^9 \text{K}$ and $10^6 \text{gm/cm}^3$ are discussed. Simple analytic expressions for reaction rates which are convenient for computer studies of the late stages of stellar evolution are given.

1. Introduction

It has been pointed out by numerous authors that weak interaction processes may have a profound influence on both the evolutionary structure and the rate of evolution of stars whose nuclear burning phases have progressed beyond carbon or oxygen burning. It is the purpose of this paper to review briefly the most important of these processes and to give simple analytic approximations reproducing their effects with a reasonable degree of accuracy and entailing a minimum of computation.

We will divide the interactions to be considered into two categories: neutrino-producing interactions (Section 2); and neutrino-absorbing or -scattering interactions (Section 3).

2. Neutrino-Producing Reactions

A. ELECTRON-NEUTRINO REACTIONS

Stars which have evolved to the point of burning carbon or oxygen generally have central densities exceeding about $10^4 \text{gm cm}^{-3}$ and central temperatures of more than a few $\times 10^8 \text{K}$. A reasonable run of temperatures and densities that may obtain during the evolution of such stars is illustrated in the recent paper of Rakavy et al. (1967).

If we assume that the "universal Fermi interaction" of Feynman and Gell-Mann (1958), which predicts a direct electron-neutrino coupling, is valid, then under the above conditions one or more of the following processes can be expected to proceed rapidly: pair annihilation (Chiu and Morrison, 1960; Chiu, 1961; Chiu and Stabler, 1961), photoneutrino emission (Pontercorvo, 1959; Chiu and Stabler, 1961; Levine, 1963; Ritus, 1962; Petrosian et al., 1967) and plasmon decay (Adams et al., 1963; Inman and Ruderman, 1964; Zaïdi, 1965).

These three reactions have been reviewed in a paper by Beaudet et al. (1967) where analytic expressions for the rate of energy lost in neutrinos are given which reproduce "exact" results to within an error of at most 15%. This accuracy is achieved

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only by using rather complicated expressions, and it may be argued that such accuracy is not necessary considering the other uncertainties encountered in models for highly evolved stars and that a penalty is paid for it in computing time. If we allow a maximum error of about 30% for the combined neutrino loss rate, then the following expressions are simple and adequate for \( \rho/\mu_e \) (density in \( \text{gm cm}^{-3} \)/mean molecular weight of electrons) \( \geq 10^5 \text{ gm cm}^{-3} \) and \( T_9 \) (temperature in units of \( 10^9 \) K) \( \geq 0.7 \):

Let \( L \), the total neutrino luminosity in \( \text{ergs cm}^{-3} \text{ sec}^{-1} \), be

\[
L = L_{pl} + L_p, \tag{1}
\]

where \( L_{pl} \) is the plasmon decay luminosity, and \( L_p \) is the pair annihilation luminosity. (For \( \rho/\mu_e \geq 10^5, T_9 \geq 0.7 \) the photoneutrino rate can be ignored.)

\( L_{pl} \) is given by

\[
L_{pl} = 3.1 \times 10^{21} y^9 F(x) + 7.9 \times 10^{19} y^9 (e^x - 1)^{-1}, \tag{2}
\]

which includes both longitudinal and transverse plasmons, where

\[
x = 3.35 \times 10^{-4} \left( \frac{\rho/\mu_e}{2} T_9^{1/2} \right) + 1.018 \times 10^{-4} \left( \frac{\rho/\mu_e}{2} T_9^{1/2} \right)^{-1/4}, \tag{3}
\]

and

\[
y = 0.169 \times T_9. \tag{4}
\]

The function \( F(x) \) is determined by

\[
F (x) = 2.4 x^{-3}, \quad x \leq 0.2; \tag{4a}
\]

\[
F (x) = 2 x^{-3} + 0.443 x^{-3/2} e^{-2x} (1 + 0.94/x + 0.45 x^{-2}), \quad 0.2 < x < 1; \tag{4b}
\]

\[
F (x) = 1.253 x^{-3/2} e^{-x} (1 + 1.88/x + 0.9 x^{-2}), \quad x \geq 1. \tag{4c}
\]

These expressions for \( F(x) \) may be derived as approximations to expansions given by INMAN and RUDERMAN (1964).

For \( L_p \) we have

\[
L_p = 5.1 \times 10^{18} T_9^3 \left[1 + T_9 + 0.3 T_9^2 \right] \exp \left(- 0.703 u^2 T_9^{-2} \right) \exp \left(- 11.85/T_9 \right), \tag{5a}
\]

provided that 0.7 \( \leq T_9 \leq 1 \).

For \( T_9 \geq 1 \),

\[
L_p = 4.3 \times 10^{15} T_9^9 \exp \left(- (1.054 u^2 + 3.76) T_9^{-2} \right). \tag{5b}
\]

The quantity \( u \) denotes the electron chemical potential (including rest mass energy) divided by \( m(\text{electron}) c^2 \) of the electron gas when pair-created electrons are included (see CHIU, 1961). An approximation to \( u \) which must be used here is

\[
u = \text{lesser of } \left( \frac{\rho/\mu_e}{2} \right)^{1/3} 10^{-2}, 6 \times 10^{-6} \left( \frac{\rho/\mu_e}{2} \right) T_9^{-2}. \tag{6}
\]

The \( \sim 30\% \) accuracy assigned to \( L \) refers only to the sum of \( L_p \) and \( L_{pl} \). The individual contributions may be off by far more than this in some instances.