Neutrino Astrophysics

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3.3 The pp chain

A The principal reactions

Table 3.1 summarizes the principal nuclear reactions that are important in main sequence stars like the Sun, the **proton–proton chain** (or **pp chain**). Alternative nuclear reactions are unimportant under solar conditions [see, e.g., Parker, Bahcall, and Fowler (1964), Bahcall and Wolf (1964), Parker (1972), and Hardie *et al.* (1984)]. The table also shows, for the standard solar model, in what percentage of the terminations of the pp chain each reaction occurs and what are the energies of the neutrinos, if any, that are emitted. The percentage of terminations are computed using the equilibrium equations from Section 3.3C and the neutrino fluxes from Table 6.5.

The first reaction shown is the basis for the whole pp chain (hence the name). Qualitatively, the **pp reaction** (number 1*a*) resembles the β-decay of the neutron; in this case, a proton decays in the vicinity of another proton to form a bound deuteron. The rate for this primary reaction is too slow to be measured in the laboratory at relevant energies since the transformation proceeds via the weak interaction. However, the rate can be calculated accurately using the theory of low-energy weak interactions and the measured properties of proton–proton scattering and the deuteron. In more than 99% of the terminations of the proton–proton chain in the standard solar model an electron neutrino is emitted with a maximum energy of 0.420 MeV.

Detecting the neutrinos from the pp reaction is one of the primary goals of solar neutrino astronomy. The radiochemical ^{71}Ga experiments which are discussed in Chapter 11 are sensitive to pp neutrinos, together with other neutrino sources that also contribute to the overall detector response (see Table 11.1). Some electronic experiments have been proposed that could isolate the pp neutrinos for detailed study (see the discussion of low-temperature detectors in Section 13.8 and of ^{115}In in Section 14.3).

The next reaction in Table 3.1 is known as **pep**. The pep reaction is important in principle since the ratio of pep to pp neutrinos is practically independent of solar models. Thus pep neutrinos contain essentially the same information about the rate of the basic fusion reactions as do the lower-energy pp neutrinos. Moreover, the 1.4 MeV (line) neutrinos from pep are above the threshold energy for absorption in the ^{37}Cl experiment (0.814 MeV threshold) although

Table 3.1. The pp chain in the Sun. The average number of pp neutrinos produced per termination in the Sun is 1.85. For all other neutrino sources, the average number of neutrinos produced per termination is equal to (the termination percentage/100).

Reaction	Number	Termination[†] (%)	ν energy (MeV)
$p + p \rightarrow {}^2H + e^+ + \nu_e$	1*a*	100	≤ 0.420
or			
$p + e^- + p \rightarrow {}^2H + \nu_e$	1*b* (pep)	0.4	1.442
${}^2H + p \rightarrow {}^3He + \gamma$	2	100	
${}^3He + {}^3He \rightarrow \alpha + 2p$	3	85	
or			
${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	4	15	
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	5	15	(90%) 0.861 (10%) 0.383
${}^7Li + p \rightarrow 2\alpha$	6	15	
or			
${}^7Be + p \rightarrow {}^8B + \gamma$	7	0.02	
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	8	0.02	< 15
${}^8Be^* \rightarrow 2\ \alpha$	9	0.02	
or			
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	10 (hep)	0.00002	≤ 18.77

[†] The termination percentage is the fraction of terminations of the pp chain, $4p \rightarrow \alpha + 2e^+ + 2\nu_e$, in which each reaction occurs. The results are averaged over the model of the current Sun. Since in essentially all terminations at least one pp neutrino is produced and in a few terminations one pp and one pep neutrino are created, the total of pp and pep terminations exceeds 100%.

those from the basic pp reaction are not. The rate for the pep reaction can be calculated accurately using weak interaction theory in terms of the rate of the pp reaction. Unfortunately, the reaction is sufficiently rare ($\sim 0.4\%$ of the terminations in the standard solar model) that the expected signal is comparable with the background for the ${}^{37}Cl$ experiment.

The sum of the pp and pep contributions in column 3 of Table 3.1 exceeds 100% of the terminations. In essentially all of the terminations, at least one pp neutrino is produced. Most often, two pp neutrinos are created. In about 0.4% of the terminations, one pep

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Sun is 1.85. For all other
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Termination† (%)	ν energy (MeV)
100	≤ 0.420
0.4	1.442
100	
85	
15	
1[illegible]	(90%) 0.861
	(10%) 0.383
15	
0.02	
0.02	< 15
0.02	
0.00002	≤ 18.77

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neutrino and one pp neutrino are produced. About twenty terminations in a million produce two pep neutrinos and no pp neutrinos.

The ^{2}H+p reaction (reaction 2 in Table 3.1) is so fast that its rate is unimportant. It always occurs, but with no observable signature.

Historically, the rate of the ^{3}He+^{3}He reaction (reaction 3 of Table 3.1) constituted the principal uncertainty in the initial prediction of the solar neutrino fluxes (see the discussion of Figure 1.2 in Chapter 1). Fortunately, the reaction has by now been well studied and its rate at thermal energies is rather accurately known. This reaction completes the pp chain in about 85% of the terminations in the standard solar model, with no additional neutrino emission.

The ^{3}He+^{4}He reaction (reaction 4 of Table 3.1) leads to the two important neutrino-producing reactions involving ^{7}Be. The cross section for the ^{3}He+^{4}He reaction was first measured by Holmgren and Johnston (1958, 1959) and found to be much larger than was expected. Fowler (1958) immediately pointed out the importance of the Holmgren–Johnston result for solar neutrino astronomy. The reaction has been studied extensively in the past few years and the rate is now well determined (see Table 3.2).

In the Sun, ^{7}Be is almost always destroyed by electron capture (reaction 5 of Table 3.1), usually from free electrons in the solar plasma. The rate for this process can be calculated accurately using weak interaction theory.

The ^{7}Be+p reaction (reaction 7 of Table 3.1) occurs only rarely in the standard solar model, in about 1 out of every 5000 terminations of the pp chain. (The ^{7}Be electron capture reaction is about a thousand times more probable.) Nevertheless, the ^{7}Be+p reaction is of crucial importance since it leads to ^{8}B neutrinos with energies as high as 14 MeV that are more easily detected than the more abundant lower-energy (pp, pep, and ^{7}Be) neutrinos. Despite their rarity, neutrinos from ^{8}B decay dominate the predicted capture rate in the ^{37}Cl experiment and in most of the other proposed solar neutrino experiments (see Table 1.3 and Chapters 10 to 14). Unfortunately, there are still significant uncertainties in the low-energy cross section for this reaction [see Parker (1986), Bahcall and Ulrich (1988), and the references in Section 7.2A].

The final reaction in Table 3.1 is the hep reaction, which produces the highest-energy solar neutrinos. The neutrinos from this reaction are extremely rare, but they may be measurable in some of the electronic experiments that are discussed in Chapter 14 (e.g., with the D_2O and liquid argon detectors).

B The reaction parameters

Table 3.2 presents the reaction parameters for the most important reactions in the pp chain. For each reaction, the table lists the total thermal energy release – **Q-value** – including the $2m_ec^2$ following positron annihilation, exclusive of neutrino energy losses. The average neutrino energy loss, $\langle q \rangle$, is also shown; this quantity was computed by averaging over the spectrum of neutrinos that are emitted. To measure one of the low-energy cross section factors, S_0, usually requires years of work by expert nuclear experimentalists. The final column in Table 3.2 is the calculated lifetime in the solar interior of the target (first-listed) nucleus.

The caption to the table contains references to some of the principal work on each reaction. More complete references to this research can be found in Fowler, Caughlan, and Zimmerman (1967, 1975), Kavanagh (1972), Rolfs and Trautvetter (1978), Barnes (1981), Bahcall *et al.* (1982), Fowler (1984), Parker (1986), Bahcall and Ulrich (1988), and Rolfs and Rodney (1988). The reader should consult especially the discussion in Bahcall *et al.* (1982) and Parker (1986) for a critical analysis of the rates and their uncertainties.

Two reactions that are important in the pp chain do not involve nuclear fusion, but instead electron capture. These electron capture reactions are (numbers 2 and 6) the pep and $^7\text{Be–e}^-$ reactions. The rates for these reactions can be calculated accurately using weak interaction theory and the local physical conditions of the solar plasma. The results are:[†]

$$R_{\mathrm{p+e+p}} \cong 1.102 \times 10^{-4} (\rho/\mu_e) T_6^{-1/2} (1 + 0.02 T_6) R_{\mathrm{pp}}, \qquad (3.17)$$

and

$$R_{(^7\mathrm{Be+e^-})} = 5.54 \times 10^{-9} (\rho/\mu_e) T_6^{-1/2} [1 + 0.004(T_6 - 16)]\,\mathrm{s}^{-1}. \quad (3.18)$$

Here $\mu_e \simeq [2/(1+X)]$ is the mean molecular weight per electron.

[†] The evaluation of the ^{7}Be electron capture rate was the first calculation the author did in solar neutrino theory, see Bahcall (1962b). R. Davis, Jr., at the suggestion of W.A. Fowler, wrote Bahcall about the possibility of calculating the rate.

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$$[1+0.004(T_6-16)]\,\mathrm{s}^{-1}. \quad (3.18)$$

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Table 3.2. Reaction parameters for the proton–proton chain. The uncertainties for the cross section factors are indicated in parentheses; they correspond to 3σ errors and have been calculated using the data given in the original experimental papers [see Parker (1986) and Bahcall and Ulrich (1988) for discussions]. Some of the principal references are given below for each numbered reaction.

Reaction	No.	Q (MeV)	$<q_{\nu_e}>$ (MeV)	S_0 (keV barns)	dS/dE (barns)	t (yr)
^{1}H(p,e$^+\nu_e$)^{2}H	1	1.442	0.265	4.07(1±0.051)E−22	4.52E−24	10^{10}
^{1}H(p,e$^-$,ν_e)H	2	1.442	1.442	[see Eq. (3.17)]		10^{12}
^{2}H(p,γ)^{3}He	3	5.494		2.5E−04	7.9E−06	10^{-8}
^{3}He(^{3}He,2p)^{4}He	4	12.860		5.15(1±0.17)E+03	−0.9	10^5
^{3}He(^{4}He,γ)^{7}Be	5	1.586		0.54(1±0.06)	−3.1E−04	10^6
^{7}Be(e$^-$,ν_e)^{7}Li	6	0.862	0.862	[see Eq. (3.18)]		10^{-1}
		0.384	0.384			
^{7}Li(p,α)^{4}He	7	17.347		52(1 ± 0.5)	0	10^{-5}
^{7}Be(p,γ)^{8}B	8	0.137		0.0243(1 ± 0.22)	−3E−05	10^2
^{8}B(e$^+\nu_e$)^{8}4Be*	9	17.980	6.710			10^{-8}
^{8}Be*(α)^{4}He						
^{3}He(p,e$^+\nu_e$)^{4}He	10	19.795	9.625	8E−20		10^{12}

References: (1) Bahcall and May (1969) and Bahcall *et al.* (1982); (2) Bahcall and May (1969); (3) Griffiths, Lal, and Scarfe (1963); (4) Bahcall and Ulrich (1988) and Krauss, Becker, Trautvetter, and Rolfs (1987); (5) Alexander, Ball, Lennard, Geissel, and Mak (1984), Parker (1986), and Hilgemeier *et al.* (1988); (6) Bahcall and Moeller (1969); (7) Rolfs and Kavanagh (1986); Fowler (1987); (8) Filippone, Elwyn, Davids, and Koetke (1983) and Parker (1986); (9) Wilkinson and Alburger (1971) and Warburton (1986); (10) Werntz and Brennan (1973) and Tegner and Bargholtz (1983).

Note that the rate of the pep reaction is proportional to the rate of the pp reaction. Tests with a number of solar models have shown that the proportionality factor is practically independent of the details of the stellar model; the variation in the proportionality constant from one stellar model to another is $\lesssim 10\%$.

3.4 Neutrino fluxes and terminations of the pp chain

The basic process in the pp chain is the burning of four protons to form an α-particle, two positrons, and two neutrinos. The isotopes