J. Astrophys. Astr. (1986) **7,** 53–57

Thermonuclear Reaction Rates from (*p*, *n*) Reactions on Targets with *A* = 92–122

S. Kailas *Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Bombay 400085*

Received 1985 May 8; accepted 1985 December 3

Abstract. From the experimentally measured (*p,n*) cross-sections for ^{92,94}Zr, ^{93}Nb, ^{95,96,98}Mo, ^{103}Rh, ^{107,109}Ag, ^{110}Pd, ^{115}In, ^{117,122}Sn nuclides, for proton energies below 7 MeV, thermonuclear reaction rates in the temperature range $1 \leqslant T_9 \leqslant 5$($T_9$=$10^9$ K) have been extracted. These reaction rates have been fitted to a three parameter empirical expression proposed by Fowler.

Key words: (*p,n*) reaction: *A* = 92122 targets—thermonuclear reaction rates

1. Introduction

The astrophysical calculations concerning the synthesis of elements require as input temperature-dependent expressions for thermonuclear reaction rates (TNRR). These TNRR values are obtained starting from the cross-section data of interest, measured experimentally or calculated theoretically. Recently, an excellent review on the topic of charged particle reaction cross-section and nucleosynthesis has been published (Sargood 1982,1983). Extensive tabulations of the TNRRs have been made for proton induced reactions covering the nuclei with Z up to 36. (Woosley *et al.* 1975,1978). These TNRRs have been obtained employing theoretical models for the calculation of the cross-sections. Experimentally only 5060 per cent of these cross-sections have been measured so far. For nuclei with $Z > 36$, TNRRs have been determined recently from measured (*p,n*) and (*p,y*) cross-sections (Roughton *et al.* 1979). In the present work, starting from the recently measured (*p,n*) cross-section data for nuclei with *A* = 92–122, the TNRRs have been computed. Most of the nuclei considered here have not been included in the work of Roughton *et al.* (1979). In Section 2, the procedure for the calculation of TNRR is discussed. In Section 3, the results obtained are given. General conclusions are given in Section 4.

2. Procedure

The TNRR is the rate at which a specific nuclear reaction takes place in the stellar environment. The factors contributing to this rate are the cross-section for the reaction and the temperature of the stellar environment which determines the energy

distribution of the colliding particles. Excellent reviews are available on this topic. (Burbidge *et al.* 1957; Clayton 1968). The reaction rate between two different nuclei 1 and 2 in a high temperature (T) environment depends upon the densities of 1 and 2, the temperature, and the appropriate nuclear properties of the system. It is given by the expression

$$P_{12} = n_1 n_2 \langle \sigma v \rangle \text{ reactions cm}^{-3}\text{s}^{-1}, \tag{1}$$

where n_1, n_2 are the number densities of nuclei 1 and 2. Generally, the nuclei are assumed to possess a Maxwell-Boltzmann distribution of velocities at T and hence $\langle \sigma v \rangle$ is averaged over this distribution. Converting to energy space,

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} (kT)^{-3/2} \int_{|Q|}^{\infty} E\sigma(E) \exp(-E/kT)\, \mathrm{d}E \text{ cm}^3\text{s}^{-1} \tag{2}$$

where k is the Boltzmann constant, μ the reduced mass, E the centre of mass energy, Q is the Q value of the reaction. A more usual form of quoting the TNRR is as follows:

$$P_{12} = N_A \langle \sigma v \rangle \text{ cm}^3 \text{ mole}^{-1}\text{s}^{-1} \tag{3}$$

where N_A is the Avogadro number.

It is assumed that the target nucleus is in the ground state; otherwise nuclear partition functions must be included. Once the cross-section σ (E) is given as a function of E, it is easy to compute P_{12}. For the convenience of the calculation, the σ (E) values measured experimentally are fitted with an expression (Vlieks, Morgan & Blatt 1974)

$$\sigma(E) = \frac{1}{E} \sum_{i=1}^{5} a_i \exp(-b/\sqrt{E}) E^{i-1}. \tag{4}$$

This expression is introduced in Equation (3) to determine P_{12}. In the present work, we have kept the parameter $b = Z - 0.5$ where Z is the atomic number of the target. Earlier, we have reported TNRR calculation for several medium-weight nuclei using the above technique (Kailas & Mehta 1976). Starting from the experimentally measured (p,n) reaction cross-sections (Johnson *et al.* 1977; Johnson, Galonsky & Kernell 1979, Hershberger *et al.* 1980; Flynn, Hershberger & Gabbard 1979) for nuclei with A in the range 92 to 122 and for proton energies below 7 MeV, the TNRRs have now been calculated in the temperature range $1 \leqslant T_9 \leqslant 5$,where $T_9 = T/10^9$ **K.**

3. Results

The TNRRs have been calculated by the procedure discussed in Section 2. The upper limit of integration (expression 3) has been kept equal to ~7 MeV, the highest energy up to which cross-section data are available. The TNRRs are listed in Table 1. The TNRR is estimated to have an uncertainty of ±10 per cent, mainly due to error on $\sigma_{p,n}$ For comparison, we have included the values obtained by Roughton *et al.* (1979) from thick target activation measurements. They have also made measurements for ^{95,96} Mo and ^{117,122} Sn targets. For Mo targets, they have listed two sets of cross-sections, one where the final state is the ground state and the other where the low-lying isomer, is the final state. For^{95,96} Mo targets the TNRR values obtained by Roughton *et al.* (1979)—the ground state or the isomer—agree reasonably well with the present results within their respective uncertainties. Similarly, the TNRR values from both these works for

Table 1. Thermonuclear reaction rates from (p,n) reactions.

		P^{c}_{12} (cm^3 mole^{-1} s^{-1})				
Reaction	Q value (MeV) .	$T_9 =$ 1	2	3	4	5
^{92}Zr$(p,n)^{92}$Nb	−2.789	0.13(−7)	3.42(−1)	1.46(+2)	3.64(+3)	2.82(+4)
^{94}Zr$(p,n)^{94}$Nb	−1.704	0.49(−4)	3.99(+0)	4.36(+2)	6.92(+3)	4.36(+4)
^{93}Nb$(p,n)^{93}$Mo	−1.202	0.80(−4)	2.11(+0)	2.32(+2)	3.88(+3)	2.47(+4)
^{95}Mo$(p,n)^{95}$Tc	−2.441	0.74(−7)	0.36(+0)	1.13(+2)	2.76(+3)	2.20(+4)
^{95}Mo$(p,n)^{95}$Tc[a]	−2.441[a]			1.03(+2)	1.98(+3)	1.23(+4)
^{95}Mo$(p,n)^{95}$Tc[b]	Lowest isomer[b]			2.20(+2)	4.27(+3)	2.57(+4)
^{96}Mo$(p,n)^{96}$Tc	−3.717		0.70(−2)	1.74(+1)	1.03(+3)	1.27(+4)
^{96}Mo$(p,n)^{96}$Tc[a]	−3.717[a]		1.83(−2)	3.14(+1)	1.30(+3)	1.18(+4)
^{96}Mo$(p,n)^{96}$Tc[b]	Lowest isomer[b]		0.85(−2)	1.51(+1)	6.34(+2)	5.75(+3)
^{98}Mo$(p,n)^{98}$Tc	−2.372	0.72(−7)	0.32(+0)	1.20(+2)	3.36(+3)	2.88(+4)
^{103}Rh$(p,n)^{103}$Pd	−1.337	0.16(−4)	0.77(+0)	1.09(+2)	2.17(+3)	1.62(+4)
^{110}Pd$(p,n)^{110}$Ag	−1.650	0.17(−4)	0.86(+0)	9.66(+1)	1.91(+3)	1.44(+4)
^{107}Ag$(p,n)^{107}$Cd	−2.199	0.18(−6)	0.20(+0)	5.09(+1)	1.25(+3)	1.04(+4)
^{109}Ag$(p,n)^{109}$Cd	−0.951	0.99(−5)	0.44(+0)	6.69(+1)	1.43(+3)	1.11(+4)
^{115}In$(p,n)^{115}$Sn	−0.293	0.24(−5)	0.17(+0)	3.41(+1)	8.60(+2)	7.83(+3)
^{117}Sn$(p,n)^{117}$Sb	−2.603	0.33(−8)	0.39(−1)	1.92(+1)	6.37(+2)	6.34(+3)
^{117}Sn$(p,n)^{117}$Sb[a]	−2.603[a]		1.76(−1)	5.56(+1)	1.49(+3)	1.32(+4)
^{122}Sn$(p,n)^{122}$Sb	−2.405	0.24(−7)	0.93(−1)	3.22(+1)	9.02(+2)	8.29(+3)
^{122}Sn$(p,n)^{122}$Sb	−2.405[a]				9.96(+2)	9.07(+3)

[a] Roughton *et al.* 1979 'ground state'
[b] Roughton *et al.* 1979 'isomer'
[c] The number in the parenthesis is the power to which ten has to be raised *e.g.* (−1) means 10^{-1}

Table 2. Parameters fittings the TNRR data ($1 \leqslant T_9 \leqslant 5$).

Reaction	α	β	γ
$^{92}Zr(p,n)$	7.609(+5)	7.394(+5)	1.963
$^{94}Zr(p,n)$	1.402(+4)	4.120(+3)	3.914
$^{95}Mo(p,n)$	9.610(+4)	5.100(+4)	2.980
$^{98}Mo(p,n)$	4.232(+4)	2.107(+4)	3.613
$^{107}Ag(p,n)$	1.855(+4)	3.548(+3)	3.831
$^{117}Sn(p,n)$	3.377(+4)	8.949(+3)	3.518
$^{122}Sn(p,n)$	2.720(+4)	6.605(+3)	3.596

the ^{122}Sn target agree with each other. However, the results of Roughton *et al.* for the ^{117}Sn target differ considerably from that of the present work. Roughton's (1979) values are a factor of 2 to 3 higher as compared to the present results. The reason for this discrepancy is not clear and it needs to be explored. It may be noted that the TNRR rates given by Roughton *et al.* (1979) and calculated here refer to only 'laboratory' rates. Thus at high temperatures they do not include the effect of having a thermal population of accessible excited states in the target nucleus.

In order to enhance the usefulness of these TNRR values in astrophysical calculations, we have fitted them to an empirical form suggested by Fowler (1973). The TNRR is given as

$$P_{12} = (\alpha + \beta T_9^{\gamma}) \exp(-11.605\,|Q|/T_9) \tag{5}$$

where α, β and γ are constants to be found by fitting the P_{12} values at various T_9 values for each target. Even though the above functional form was tried for all the nuclides discussed in the present work, only half the number of them could be adequately fitted by expression (5) to yield α, β and γ values. The results are listed in Table 2. A careful examination of these parameters (Table 2) or the TNRR values (Table 1) does not reveal any systematic behaviour as a function of A or Z of the targets considered here.

4. Conclusion

Starting from the measured (p,n) cross-sections, we have computed the TNRR values for 13 nuclides in the mass range A = 92122. The TNRR values extracted in the present work agree with those obtained by Roughton *et al.* (1979)in the case of^{95,96}Mo and ^{122}Sn nuclei. The two results differ considerably for ^{117}Sn target. Roughton *et al.* (1979) have quoted the TNRR values with errors ranging from 15 to 50 per cent. The present results are estimated to have uncertainties of not more than 10 per cent. The compilation of the TNRR values for A = 92–122 does not seem to indicate the presence of any kind of simple systematics. It is hoped that the experimentally determined values of TNRR will be helpful in improving the theoretical models developed to compute them, so that these theoretical calculations can be extended with greater confidence to many other nuclei for which measurements do not exist.

Acknowledgement

The author thanks Professor Ramadurai for his helpful comments.

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