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$^{51}V(p, n)^{51}Cr$ reaction from E_p 1·9 to 4·5 MeV

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Abstract. The total cross-section for the reaction $^{51}V(p, n)^{51}Cr$ has been measured from E_p 1·9 to 4·5 MeV by using two different techniques: (i) by detecting the neutron using the 4π neutron counter and (ii) by measuring the activity of the residual nucleus ^{51}Cr. The two measurements are consistent with each other and together they are in good agreement with the data of Zyskind *et al.* The thermonuclear reaction rates have also been extracted starting from these cross-sections.

Keywords. (p, n) reaction; ^{51}V target; Ge(Li) and 4π neutron counter; thermonuclear reaction rates.

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1. Introduction

The $^{51}V(p, n)$ ^{51}Cr reaction has been studied systematically in the proton energy range 1·6–5 MeV notably by two groups (Sekharan *et al* 1966 and Mehta *et al* 1977; Zyskind *et al* 1980). Though the two measurements are consistent with each other for energies up to 3 MeV, there are noticeable discrepancies in $\sigma_{p,n}$ values at higher energies. With a view to resolve this problem, the total reaction cross-section was measured by two independent techniques; (i) by detecting the neutrons using a 4π geometry neutron counter and (ii) by counting the activity of the residual nucleus ^{51}Cr. The experimental procedure and results of the measurement are given in § 2. Discussion of the results and their implications to astrophysical thermonuclear reaction rates are covered in § 3. The conclusions are discussed in § 4.

2. Experimental procedure and results

2.1 *Cross-section measurement using the 4π geometry neutron counter*

Over the years we have measured systematically the total (p, n) reaction cross-sections for a large number of medium weight nuclei (Kailas and Mehta 1982), utilising the 4π geometry neutron counter developed at Trombay (Sekharan 1966). This counter has a flat response for neutrons up to about 1 MeV. The efficiency of detection ε is nearly 10%, for these neutrons (Gupta and Kerekatte 1971, unpublished) and this drops to about 6% for about 5 MeV neutrons.

The ^{51}V targets were prepared by evaporating natural vanadium metal (^{51}V abundance 99·76 %) on to thick tantalum discs. Analysed proton beam from the 5·5 MV

Van de Graaff accelerator at Trombay was collimated on the target which itself served as a Faraday cup and was situated at the centre of the neutron counter. During the present set of runs, we also monitored the performance of the neutron counter, consisting of 12 BF_3 counters, by periodically placing the Cf neutron source at the target site and counting for a fixed time interval. The target thickness was determined by the standard technique of measuring the energy shift for 2 MeV alpha particles scattered from a plain Ta face and from Ta covered with V (Balakrishnan *et al* 1974). In the present measurement the thickness varied from 8 to 15 keV for 3 MeV protons. The number of incident protons was measured by a current integrator (Gupta 1968) with an error of $\pm 1\%$.

The excitation function was measured from 1·9–4·5 MeV at several discrete energies. We calculated the nominal neutron energy E_n at each proton energy, as the one for the ground state neutron group emitted at 90° using the Q value of the $^{51}V(p, n)^{51}Cr$ reaction $-1{\cdot}534$ MeV and obtained the neutron detection efficiency for this neutron energy. This procedure where we have considered only the energy of neutrons populating the ground state of ^{51}Cr and neglected the distribution of neutrons going to various states of ^{51}Cr is reasonable as is evident from § 2·3. For E_n up to 1·5 MeV the neutron efficiency ε is uncertain by $\pm 7\%$ as measured earlier. However, the ε values are expected to be poorly determined for higher E_n values as they are obtained by interpolating the ε values at $E_n \sim 1{\cdot}5$ MeV and ~ 5 MeV (Ra-α-Be source). For $E_n \sim 3$ MeV, the maximum encountered in the present work, the ε value is estimated to be uncertain by $\pm 10\%$. We assign an error of $\pm 2\%$ for current measurement reflecting the uncertainty in the current integrater calibration constant determination. With a typical error of $\pm 10\%$ in target thickness estimation and negligible statistical error in neutron counts, the overall uncertainty in $\sigma_{p,n}$ values range from 13% at $E_p \sim 2$ MeV to 15% at $E_p \sim 4{\cdot}5$ MeV.

Open circles in the excitation function plot in figure 1 represent the neutron counter data.

2.2 *Cross-section measurement from the activity of residual nucleus ^{51}Cr*

For several E_p values, simultaneously we carried out the measurement of the activity of ^{51}Cr produced in the reaction. For $E_p \sim 2{\cdot}9$, 3·4, 3·9 and 4·1 MeV, we bombarded different freshly prepared ^{51}V samples covered with a thin gold layer (15 $\mu g/cm^2$). The gold layer is provided to prevent possible activity spills. Typical irradiation times varied from 3 hr with 100 nA beam at E_p 2·9 MeV to $1\frac{1}{2}$ hr with 70 nA beam at $E_p \sim 4{\cdot}1$ MeV. The resultant activity of ^{51}Cr was counted in a 100 cc Ge(Li) detector. We measured the yield due to 320 keV gamma ray resulting from the decay of ^{51}Cr to ^{51}V with a half life of 27·7 days. To increase the efficiency of counting we kept the ^{51}Cr sample close to the detector face, at a distance of 1 cm from the aluminium casing of the detector. To reproduce the geometry used for counting we kept the irradiated sample disc in a slotted perspex container and fixed the container on the detector. We also used a thin Pb sheet (0·8 mm thick) on the detector case to reduce the low energy background. The efficiency of the detector for this geometry was obtained using a standard ^{152}Eu source. The photo peak efficiency versus gamma energy for the detector at this geometry corrected for absorption in Pb is plotted in figure 2. The efficiency curve has been fitted with an empirical expression of the type

$$\%\ \varepsilon_{Ge(Li)} = A + B \ln E_\gamma(\text{keV}) + C[\ln E_\gamma(\text{keV})]^2 + D/E_\gamma^2(\text{keV}).$$

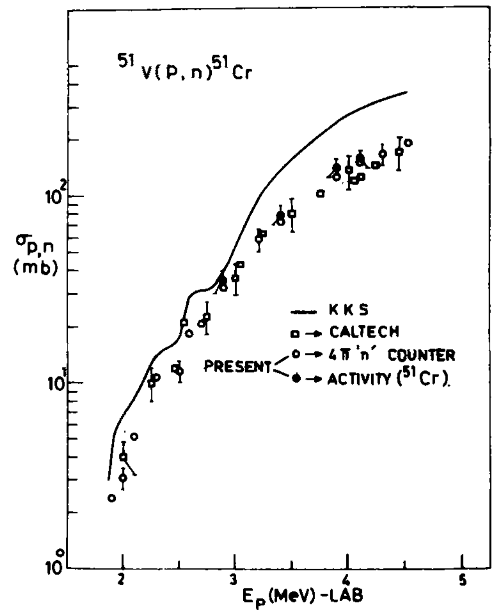

Figure 1. Excitation function for the reaction $^{51}V(p, n)\,^{51}Cr$ from E_p 1·9–4·5 MeV. The continuous line represents data (error ± 14 %) (Sekharan *et al* 1966). The squares are data from Zyskind *et al* (1980) from Caltech. The open and filled circles are data obtained in the present work.

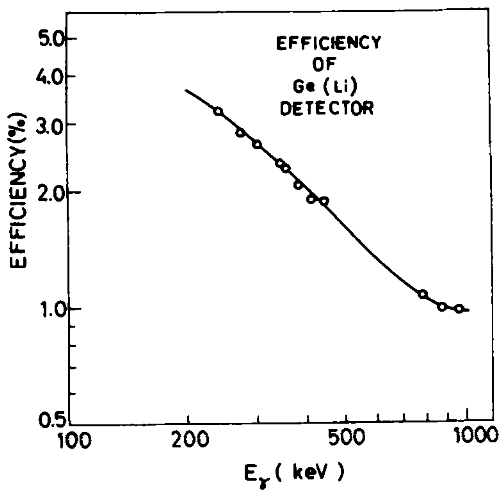

Figure 2. Percentage efficiency of 100 cc Ge(Li) detector with source at 1 cm from the cap plotted as a function of gamma energy. The continuous line is the fit using the expression,

$$73{\cdot}191 - 20{\cdot}744 \ln E_\gamma(\text{keV}) + 1{\cdot}4906\,[\ln E_\gamma(\text{keV})]^2 - 5{\cdot}9553 \times 10^4/[E_\gamma(\text{keV})]^2$$

The continuous curve in figure 2 is the best fit with $A = 73{\cdot}191$, $B = -20{\cdot}744$, $C = 1{\cdot}4906$, $D = -5{\cdot}9553 \times 10^4$. We also used a calibrated ^{133}Ba source to determine the efficiency for E_γ around 300 keV. The efficiency for the 320 keV gamma ray is 2·55 %(± 5 % uncertainty).

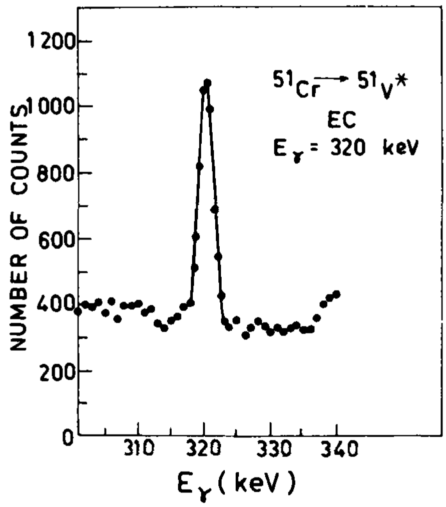

Figure 3. The gamma ray spectrum obtained from the decay of 27·7 day ^{51}Cr activity produced in the $^{51}V(p, n)^{51}Cr$ reaction.

The ^{51}Cr activity was counted for typically 8000 sec to get good statistics. A typical spectrum of 320 keV gamma ray arising from the decay of ^{51}Cr is shown in figure 3.

After correcting for the decay for the period between activity production to the actual counting and also for the absorption losses in the Pb absorber in front of the detector, the actual yield due to 320 keV gamma ray was determined. From this the $\sigma_{p,n}$ was determined using the known values of target thickness and proton current as per § 2·1

$$\sigma_{p,n} = \frac{(\mathrm{d}N/\mathrm{d}t)}{N_p N_t \lambda \varepsilon_{\mathrm{Ge(Li)}} P}, \tag{2}$$

where λ is the decay constant $= 2{\cdot}8956 \times 10^{-7}\ \mathrm{sec}^{-1}$, N_p the number of protons, $(\mathrm{d}N/\mathrm{d}t) =$ Activity (sec^{-1}), N_t the number of target atoms/cm^2 and P the decay branch from ^{51}Cr populating the first excited state of $^{51}\mathrm{V} = 9{\cdot}85\%$ (Yoshizawa *et al* 1980).

In figure 1, the filled circles represent cross-section values obtained by this technique. The errors including counting statistics on $\sigma_{p,n}$ values are $\sim 15\%$ at $E_p \sim 2{\cdot}9$ MeV and $\sim 12\%$ at $E_p \sim 4{\cdot}1$ MeV.

2·3 *Efficiency of 4π neutron counter*

By combining the two techniques discussed in §§ 2·1 and 2·2, we obtained the efficiency of the 4π counter ($\varepsilon_{4\pi}$) for various neutron energies.

$$\varepsilon_{4\pi} = \frac{N_{\mathrm{scalers}} \lambda P \varepsilon_{\mathrm{Ge(Li)}}}{(\mathrm{d}N/\mathrm{d}t)}. \tag{3}$$

($N_{\mathrm{scalers}} = 4\pi$ neutron counter)

The more realistic $\varepsilon_{4\pi}$ values obtained this way are compared with the nominal $\varepsilon_{4\pi}$ values (assuming energy of ground state neutron group) for various E_p values (table 1). The ratio for these different estimates yields a value close to one. This justifies the use of nominal values for $\sigma_{p,n}$ calculation.

Table 1 Efficiency of 4π geometry neutron counter at Trombay.

	a	*b*	
En (MeV)	$\varepsilon_{4\pi}(\%)$ *A*	$\varepsilon_{4\pi}(\%)$ *B*	Ratio (*A*/*B*)
1·3	9·47	10·15	0·93 ± 0·09
1·8	8·69	9·40	0·92 ± 0·09
2·3	7·90	8·90	0·89 ± 0·10
2·5	8·44	8·70	0·97 ± 0·10

(*a*) Determination from the activation data of the present work (±6%).
(*b*) Previous value (±8–10%) based on $^7Li(p, n)$ cross-section and Ra-Be source

3. Discussion

The (*p*, *n*) cross-sections measured by the two independent techniques, agree with each other very well. Our new measurements up to $E_p = 3$ MeV closely follow the earlier results (Sekharan 1966 (unpublished) continuous line in figure 1) within the respective experimental errors. However, above this energy there are noticeable differences between the present and the old measurements. As the earlier data were measured almost two decades back, it is not possible at this stage to assign definite reasons for this discrepancy. However, our present results are in good agreement with those of the Caltech group (Zyskind *et al* 1980) (squares in figure 1) for the whole energy range.

Having obtained the revised $\sigma_{p,n}$ values we computed the thermonuclear reaction rates as per the procedure discussed by Kailas and Mehta (1976). By first fitting $\sigma_{p,n}$ from the threshold to the highest energy measured, with an expression,

$$\sigma_{p,n}(E) = \frac{1}{E} \sum_{i=1}^{5} a_i \exp\left(-\frac{22{\cdot}5}{\sqrt{E}} \right) E^{i-1}. \tag{4}$$

(E in cm system (MeV))

and using this in the expression for thermonuclear reaction rate (TNRR)

$$N_A \langle \sigma v \rangle = N_A (8/\pi\mu)^{1/2} (kT)^{-3/2} \int_{|Q|}^{\infty} E\,\sigma(E) \exp - (E/kT)\,\mathrm{d}E$$
$$= \frac{6{\cdot}023 \times 6{\cdot}20 \times 10^6}{T_9^{3/2}} \left(\frac{A_T + 1}{A_T} \right)^{1/2} \int_{|Q|}^{\infty} E\,\sigma(E) \exp$$
$$- (E/kT)\,\mathrm{d}E \tag{5}$$

where N_A is the Avogadro number, μ the reduced mass, $kT = 0{\cdot}08617\, T_9$ (MeV), T_9 the temperature in 10^9 K, A_T the target mass number, $\sigma = \sigma_{p,n}$ in mb and Q the Q value. TNRR values were computed for $T_9 = 1$ to 5. The numerical integration was done only up to 4·5 MeV in steps of 0·05 MeV in (5) using Simpson's rule.

Table 2. Thermonuclear reaction rates (TNRR) from $^{51}V(p, n)\,^{51}Cr$ reaction.

T_9 (10^9 K)	$N_A \langle \sigma v \rangle$ cm^3/(mole sec) Present^a(A)	Past^b (B)	Ratio ((A/B)
1	0·312 (−1)	0·619 (−1)	1·98
2	0·647 (+3)	1·048 (+3)	1·62
3	2·610 (+4)	4·396 (+4)	1·68
4	2·018 (+5)	3·668 (+5)	1·82
5	7·576 (+5)	1·476 (+6)	1·95

(a) Based on present measurement.
(b) Based on past measurement (Kailas and Mehta 1976).
The number in the parenthesis is the power to which ten has to be raised *e.g.* (−1) means 10^{-1}.
In the present work, cross-sections were measured from E_p 1·9 MeV and cross-sections between threshold (1·56 MeV) and 1·9 MeV were obtained by interpolation and fit to the data up to 4·5 MeV as per expression 4. This may lead to larger uncertainty for cross-section and hence reaction rate in this region.

The results are tabulated in table 2. We also fitted TNRR values, as

$$N_A \langle \sigma v \rangle = (\alpha + \beta T_9^{\gamma}) \exp\left(-\frac{|Q|}{kT_9}\right), \tag{6}$$

with $\alpha = 7{\cdot}887 \times 10^5$, $\beta = 1{\cdot}014 \times 10^6$ and $\gamma = 2{\cdot}022$. The new TNRR values are considerably smaller than the earlier ones, reflecting the fact that the cross-sections from the present work are considerably smaller as compared to the earlier measurement (Sekharan *et al* 1966), (table 2).

4. Conclusion

We have reported new measurements, by two independent techniques for the $^{51}V(p, n)\,^{51}Cr$ reaction cross-sections. Our present results are in good accord with the data of the Caltech group. It may be mentioned that the present measurements are much more accurate ($\sim$ 12–15% uncertainty) as compared to the Caltech work ($\pm$20% error).

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