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Thermal Neutron Capture Cross-section of ^{48}Ti, ^{51}V, ^{50,52,53}Cr and ^{58,60,62,64}Ni

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The thermal neutron capture cross sections of ^{48}Ti, ^{51}V, ^{50,52,53}Cr and ^{58,60,62,64}Ni were re-estimated using recent data on the thermal neutron capture cross-section of the ^{14}N. The γ-ray spectra emitted after thermal capture were studied using the IEA-R1 2 MW research reactor and a pair spectrometer with a Ge(Li) detector and two NaI(Tl) scintillators. The spectrometer efficiency calibration curve was verified by calculating the prompt γ-ray intensities from the ^{35}Cl(n,γ)^{36}Cl reaction. © 1997 Elsevier Science Ltd. All rights reserved

Introduction

The total thermal neutron capture cross-section can be determined by measuring the prompt γ-ray spectrum of a particular isotope mixed with a standard. In a previous work (Venturini and Pecequilo, 1990), the thermal neutron capture cross-sections of the ^{48}Ti, ^{51}V, ^{50,52,53}Cr and ^{58,60,62,64}Ni isotopes were calculated using ^{14}N as standard. The spectrometer efficiency calibration curve was calculated by means of the prompt γ-ray spectrum from a sample of melamine ($C_3H_6N_6$) mixed with ammonium chloride (NH_4Cl), the Islam's (Islam *et al.*, 1981) value of (77.2 ± 2.1) mb for the ^{14}N thermal neutron cross-section and the ^{35}Cl(n,γ)^{36}Cl cross-section of (43 ± 2) b compiled by Endt and Van der Leun (1978). However, Islam *et al.* (1990) re-estimated the ^{14}N thermal neutron cross section, finding a new value of (79.8 ± 1.4) mb. Also, Mughabghab *et al.* (1981) reports the value of (43.6 ± 0.46) b for the ^{35}Cl. In the present work, the spectrometer efficiency curve, in the 1.5 to 11 MeV energy range, was re-calculated considering only the ^{14}N(n,γ)^{15}N prompt γ-ray transitions and the more recent ^{14}N radiative cross-section. In order to verify the accuracy of the efficiency curve, we evaluated the ^{36}Cl prompt γ-ray transition intensities.

The net area of a peak in the γ-ray spectrum is related to the efficiency by $A = R \cdot I \cdot \varepsilon \cdot t$, where A is the net area corresponding to an energy E, R is the reaction rate, I is the intensity of the γ transition of energy E, ε is the counting efficiency at energy E and t is the counting time. For any two transitions E_1 and E_2, with corresponding efficiencies ε_1 and ε_2, from the γ-ray spectrum of the same isotope, the rate A_1/A_2 depends only on the corresponding net areas and intensities and the counting efficiency can be defined as:

$$\varepsilon = A/I \,. \tag{1}$$

The efficiency curve is to be calculated through a standard with well known prompt γ-ray energies and intensities. Melamine is appropriate since its gamma spectrum covers a large energy range in addition to the accuracy of the existing ^{14}N nuclear data.

For a composite sample, the net area of a peak in the spectrum of the target is related to a net area of a peak in the spectrum of the standard by:

$$\frac{A_t}{A_s} = \frac{n_t \cdot I_t \cdot \varepsilon_t \cdot \sigma_t}{n_s \cdot I_s \cdot \varepsilon_s \cdot \sigma_s} \tag{2}$$

where n is the number of atoms and σ is the total thermal neutron capture cross-section. The subscripts t and s stand to the target and to the standard, respectively.

Experimental Results

The measurements were carried out at the tangential irradiation facility of the IEA-R1 research reactor of IPEN. At the sample irradiation position the thermal neutron flux was of the order of 5×10^{11} n/cm^2 s^{-1}. The samples were irradiated in nuclear pure graphite capsules for its reduced background in the gamma spectra. Gamma-rays emitted following thermal neutron capture were detected by a pair spectrometer described elsewhere (Pecequilo *et al.*, 1980). Spectral analysis was achieved by means of the software Analysis (Venturini and Vandenput, 1995) which provides the centroid, net area and energy resolution of the peaks with their respective uncertainties.

Table 1. Intensity (%) of some prompt gamma-rays from the $^{35}Cl(n,\gamma)^{36}Cl$ reaction

Energy (keV) (Kennett *et al.*, 1981)	Present work	Krusche *et al.* (1982)	Kennett *et al.* (1981)
1951.145	20.1 ± 0.6	20.2 ± 2.0	20.39 ± 0.76
1959.358	13.5 ± 0.4	12.9 ± 1.3	13.41 ± 0.58
2622.88	0.497 ± 0.017	0.633 ± 0.064	0.65
2676.300	1.59 ± 0.05	1.91 ± 0.19	2.06 ± 0.11
2800.846	0.73 ± 0.03	0.827 ± 0.086	0.61
2845.498	1.09 ± 0.03	1.27 ± 0.13	1.22 ± 0.07
2863.815	6.56 ± 0.14	6.55 ± 0.66	6.63 ± 0.21
2867.16	0.518 ± 0.023	0.615 ± 0.87	0.67
2975.235	1.19 ± 0.03	1.21 ± 0.12	1.09
2994.707	0.847 ± 0.023	0.91 ± 0.11	0.90
3001.067	0.441 ± 0.017	0.697 ± 0.036	0.71 ± 0.05
3015.985	1.17 ± 0.03	1.131 ± 0.058	1.13 ± 0.07
3061.865	3.66 ± 0.08	3.88 ± 0.20	4.01 ± 0.14
3116.216	0.970 ± 0.023	0.994 ± 0.055	1.05 ± 0.06
3250.357	0.255 ± 0.010	0.255 ± 0.015	0.26
3316.363	0.264 ± 0.009	0.257 ± 0.014	0.26
3333.09	0.783 ± 0.019	0.827 ± 0.044	0.84 ± 0.05
3374.895	0.600 ± 0.015	0.600 ± 0.033	0.64 ± 0.04
3428.856	0.813 ± 0.020	0.895 ± 0.046	0.90 ± 0.05
3589.234	0.457 ± 0.014	0.605 ± 0.034	0.48 ± 0.03
3599.251	0.502 ± 0.015	0.539 ± 0.031	0.51 ± 0.03
3634.48	0.284 ± 0.010	0.334 ± 0.021	0.31 ± 0.02
3749.905	0.285 ± 0.012	0.309 ± 0.017	0.34 ± 0.03
3821.581	1.019 ± 0.026	1.095 ± 0.058	1.08 ± 0.05
3825.53	0.792 ± 0.021	0.842 ± 0.046	0.84 ± 0.04
3962.60	0.358 ± 0.358	0.367 ± 0.036	0.41 ± 0.03
3981.064	1.031 ± 0.022	1.028 ± 0.055	1.04 ± 0.05
4082.664	0.810 ± 0.018	0.785 ± 0.041	0.73
4298.384	0.406 ± 0.011	0.389 ± 0.022	0.42 ± 0.03
4440.399	1.105 ± 0.027	1.085 ± 0.055	1.11 ± 0.05
4616.436	0.771 ± 0.019	0.682 ± 0.035	0.71 ± 0.03
4728.466	0.729 ± 0.017	0.702 ± 0.036	0.73 ± 0.03
4815.297	0.155 ± 0.008	0.154 ± 0.009	0.16
4829.064	0.199 ± 0.009	0.194 ± 0.011	0.21 ± 0.02
4979.713	3.74 ± 0.08	3.60 ± 0.18	3.95 ± 0.10
4989.96	0.188 ± 0.012	0.309 ± 0.019	0.21
5017.726	0.631 ± 0.022	0.465 ± 0.025	0.52 ± 0.03
5517.202	1.70 ± 0.04	1.707 ± 0.087	1.75 ± 0.05
5584.617	0.540 ± 0.016	0.536 ± 0.28	0.52 ± 0.02
5603.867	0.378 ± 0.013	0.358 ± 0.019	0.36 ± 0.02
5702.63	0.403 ± 0.017	0.431 ± 0.030	0.39 ± 0.02
5715.187	5.55 ± 0.11	5.60 ± 0.28	5.68 ± 0.12
5733.48	0.527 ± 0.019	0.510 ± 0.037	0.46 ± 0.02
6110.848	20.3 ± 0.4	20.2 ± 1.0	20.96 ± 0.33
6619.638	8.13 ± 0.19	7.80 ± 0.39	8.31 ± 0.16
6627.751	4.95 ± 0.13	4.83 ± 0.24	4.74 ± 0.10
6977.847	2.26 ± 0.05	2.32 ± 0.12	2.40 ± 0.06
7413.953	10.30 ± 0.22	10.36 ± 0.52	10.69 ± 0.19
7790.335	8.25 ± 0.19	8.48 ± 0.42	8.69 ± 0.16
8578.59	2.76 ± 0.07	2.78 ± 0.14	2.84 ± 0.07

A 14.25 g melamine sample was run in the reactor to calculate the spectrometer efficiency curve. The γ spectrum was measured for two energy ranges: from 1.5 to 6.1 MeV and from 5.0 to 11 MeV. In order to have a calibration curve for the 1.5 to 11 MeV interval, a correction factor was used to take into account the neutron flux variation and the counting time of each measurement. This correction factor was calculated by dividing the net areas of the 5269, 5297, 5533 and 5562 keV transitions in the first energy range by their respective net areas in the second one, and averaging the resulting values. The efficiency data were fitted to the function $\ln(\varepsilon) = a_0 \ln(E) + a_1 \ln(E) + a_2 \ln^2(E)$, where E is the γ-ray energy and ε is given by equation (1). Since the fractional error of the γ-ray energies used (Kennett *et al.*, 1986) are less than 10^{-5}, the experimental data fit was done by supposing exact independent variables. The variance of $\ln(\varepsilon)$ is $\mathrm{var}(\ln \varepsilon) = \mathrm{var}(A)/A^2 + \mathrm{var}(I)/I^2 + d^2$, where $d = 1.0\%$ is the estimated systematic error in the sample preparation, $\mathrm{var}(I)$ was taken from Kennett *et al.* (1986) and $\mathrm{var}(A)$ was obtained from the spectral analysis. The fitted efficiency curve was used to

Table 2. Sample characteristics

Target	Isotope	Isotopic fraction (%)	Natural element content (g)	Melamine content (g)
Titanium	48	73.80	1.0332	11.0994
Vanadium	51	99.75	4.0196	10.2166
Chromium	50, 52, 53	4.35; 83.79; 9.50	4.0566	11.5445
Nickel	58, 60, 62, 64	67.88; 26.23; 3.66; 1.08	4.1726	11.0994

Table 3. Thermal neutron capture cross-section (barn)

Isotope	This work	Venturini and Pecequilo (1990)	Mughabghab *et al.* (1981)
^{50}Cr	14.2 ± 0.5	13.4 ± 0.7	15.9 ± 0.2
^{52}Cr	0.86 ± 0.03	0.79 ± 0.02	0.79 ± 0.06
^{53}Cr	18.6 ± 0.6	18.1 ± 0.7	18.2 ± 1.5
^{51}V	4.6 ± 0.2	4.9 ± 0.2	4.9 ± 0.1
^{48}Ti	8.5 ± 0.2	8.4 ± 0.1	7.84 ± 0.25
^{58}Ni	4.4 ± 0.2	4.41 ± 0.08	4.6 ± 0.3
^{60}Ni	2.55 ± 0.09	2.54 ± 0.07	2.9 ± 0.2
^{62}Ni	15.5 ± 0.7	15.2 ± 0.5	14.5 ± 0.3
^{64}Ni	1.6 ± 0.1	1.6 ± 0.1	1.52 ± 0.03
^{35}Cl	43.4 ± 0.9	—	43.6 ± 0.46

determine the intensities of the prompt γ-rays from the ^{35}Cl(n,γ)^{36}Cl reaction which were measured by irradiating a composite sample of melamine and ammonium chloride. The intensity of each chlorine line was calculated using equation (2) and averaging the values obtained for the strongest nitrogen lines. The results for some chlorine transitions are shown in Table 1.

In order to calculate the uncertainty of the average intensity, we first calculated the uncertainty of each individual value (of the set to be averaged) by error propagation using equation (2) and including the systematic error of 1.0% of the sample preparation. All variables in equation (2) were considered to be independent. The weighted average intensity is given by the least squares method as $I_{av} = (\mathbf{Z}^t \mathbf{W}^{-1} \mathbf{Z})^{-1} \mathbf{Z}^t \mathbf{W}^{-1} \mathbf{I}$, with variance $(\mathbf{Z}^t \mathbf{W}^{-1} \mathbf{Z})^{-1}$, where $\mathbf{Z} = \mathbf{1}$ = unity vector, $\mathbf{I}$ is the individual intensity vector and $\mathbf{W}$ is variance matrix corresponding to $\mathbf{I}$.

In order to evaluate the thermal neutron capture cross-section of the titanium, vanadium, chromium and nickel isotopes, samples of the natural elements well mixed with melamine were irradiated. The characteristics of each sample are presented in Table 2. The mass uncertainties are estimated to be 1%. Equation (2) was used for every strong γ-ray emitted following thermal neutron capture in each isotope (Aube, 1977; Ishaq *et al.*, 1977; Aube, 1978; Verheul and Aube, 1987; Ruyl and Endt, 1983 and Michaelson *et al.*, 1991) and several ^{14}N(n,γ)^{15}N transitions. The cross-section of ^{35}Cl was calculated using the energies and intensities from Krusche *et al.* (1982) and the same spectral data used for the

Table 4. Prompt gamma-ray intensities (%) from (n,γ) reaction in nickel and chromium isotopes

Isotope	Energy (keV) (see text)	This work	Published data (see text)
^{58}Ni	4859.18	1.43 ± 0.06	1.53 ± 0.11
	5213.18	1.84 ± 0.07	1.74 ± 0.10
	5817.99	3.42 ± 0.13	3.70 ± 0.24
	5974.40	0.90 ± 0.04	0.87 ± 0.08
	6106.03	2.30 ± 0.09	2.39 ± 0.17
	6584.61	2.44 ± 0.10	2.74 ± 0.16
	7698.40	1.22 ± 0.05	1.28 ± 0.09
	8121.76	4.36 ± 0.17	4.65 ± 0.25
	8534.14	25.0 ± 1.0	25.6 ± 1.4
	8999.91	52.8 ± 2.1	52.7 ± 3.5
^{60}Ni	5696.03	5.62 ± 0.23	6.31 ± 0.29
	6720.36	2.23 ± 0.10	2.30 ± 0.11
	7537.29	27.5 ± 1.1	32.0 ± 2.2
	7820.25	49.2 ± 2.0	54.8 ± 2.5
^{62}Ni	5514.64	1.28 ± 0.08	1.70 ± 0.10
	5837.03	6.86 ± 0.17	6.52 ± 0.42
	6682.63	1.50 ± 0.06	1.47 ± 0.08
	8638.16	94.1 ± 2.0	85.9 ± 5.9
^{64}Ni	6034.85	67.4 ± 2.5	66.5 ± 3.5
^{50}Cr	6137.7	7.6 ± 0.16	7.6 ± 0.8
	6370.9	4.23 ± 0.10	4.0 ± 0.4
	7392.0	13.1 ± 0.3	13.7 ± 1.4
	8484.0	22.2 ± 0.5	26 ± 3
	8512.1	31.0 ± 0.7	37 ± 4
^{52}Cr	5618.23	18.7 ± 0.7	14.4 ± 1.2
	7374.58	11.9 ± 0.5	11.4 ± 0.2
	7938.58	62.0 ± 2.4	58.4 ± 0.8
^{53}Cr	5706.56	1.23 ± 0.06	1.3 ± 0.1
	5858.59	1.15 ± 0.05	1.1 ± 0.1
	5999.52	4.62 ± 0.20	4.3 ± 0.4
	6282.66	1.92 ± 0.09	1.8 ± 0.2
	6645.34	9.6 ± 0.4	9.5 ± 0.9
	6890.01	2.20 ± 0.10	2.0 ± 0.2
	7099.71	7.8 ± 0.3	7.8 ± 0.7
	8884.12	46.3 ± 1.9	46.2 ± 7.9
	9718.83	16.3 ± 0.7	15.0 ± 2.6

efficiency curve check. For ^{51}V we used the data from Michaelson *et al.* (1991) instead of the previous ones (Benne, 1978). The weighted average values are presented in Table 3. The uncertainty calculation was achieved in the same way as for the chlorine γ-ray intensities.

Conclusion

Table 1 shows that the measured intensities of the strongest γ-rays from the $^{35}Cl(n,\gamma)^{36}Cl$ reaction are in good agreement with the literature data (Krusche *et al.*, 1982 and Kennett *et al.*, 1981). The discrepancies for some weak transitions can be attributed to the complexity of the $^{35}Cl(n,\gamma)$ γ-ray spectrum.

As we can see from Table 3, the actual cross-sections are in good agreement with the previous work, except for ^{51}V and $^{50,52}Cr$. However, if compared to Mughabghab *et al.* (1981) data, they show no good agreement for most of the isotopes.

This way, it is interesting to use the Mughabghab cross-sections and the more recent nitrogen data to recalculate the intensity of the prompt γ-rays emitted following thermal capture in some of the studied isotopes. Table 4 shows this calculation for several γ-rays emitted following capture in $^{58,60,62,64}Ni$ and $^{50,52,53}Cr$.

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