Thermal neutron capture in silicon

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The prompt gamma-rays from thermal nuteron capture in ^{28,29,30}Si have been studied and the radiative capture cross sections determined as 207±4, 120±3 and 107±2 mb, respectively. There has been a marked increase in the number of transitions observed in ^{29}Si and a complete decay scheme for this nucleus is presented. Two primary $E2$ transitions in ^{29}Si have been observed and their partial cross sections are compared with the prediction of the direct capture formalism. The measured neutron separation energies are $S_n(^{29}\mathrm{Si})=8473.61\pm0.04$ keV, $S_n(^{30}\mathrm{Si})=10\,609.21\pm0.04$ keV, and $S_n(^{31}\mathrm{Si})=6587.32\pm0.20$ keV.

There have been no recent studies on the gamma radiation following thermal neutron capture by the silicon isotopes, however, some early investigations[1-5] have been reported. A summary of information concerning levels of the silicon isotopes until 1978, is given by Endt *et al.*[6] The development of an improved detection system and the establishment of an energy standard with higher precision[7] than previously available prompted us to undertake the present study. The objective was to improve the precision of transition, level, and neutron separation energies of silicon isotopes and to ensure, through increased sensitivity, the completeness of the decay scheme.

As ≈95% of the primary gamma-ray transitions in the spectrum of natural silicon are due to ^{28}Si, emphasis was given to this isotope in the present study. Studies with enriched ^{29}Si and ^{30}Si were done in the past.[4,5] The information about the spectra of these two isotopes provided by the aforementioned aided in the assignment of the transitions observed here.

Neutron capture cross sections can be determined in a variety of ways. However, the most straightforward is that of assaying a radioactive product. In cases where neutron capture produces a stable isotope other methods are necessary. Provided the capture gamma-ray spectrum associated with the target of interest is simple, and all transitions exiting the capture state are identified, it is possible to obtain the corresponding cross section. This does require a mixed irradiation with a standard of known cross section[8,9] and absolute intensity as well as establishing the relative efficiency of the spectrometer. Since there is a significant discrepancy amongst the silicon isotopic cross sections,[5,8,10] it seemed appropriate to address this in the present study.

Recently, there has been growing interest in the possibility of direct $E2$ capture in the mass region $A\approx 20-30$.[11,12] The reactions ^{28,29}Si(n,γ) are favorable cases for investigation in which five unambiguous $E2$ transitions are possible. An effort was made to estimate the partial cross sections for these transitions in order to investigate the contribution from direct capture.[11,12]

The experiment was conducted at the tangential tube facility[13] of the McMaster University Nuclear Reactor using a pair spectrometer[14,15] with a resolution of 2.1 and 5.0 keV at 2500 and 8300 keV, respectively.

A high-purity quartz (SiO_2) rod (diameter 0.7 cm, length 15 cm) was used as the sample, thereby avoiding the need for a container. Data were accumulated for 240 h. For calibration purposes 2.7 g sample of Si_3N_4 contained in a thin-walled graphite capsule was irradiated for 120 h.

TABLE I. Energy, intensity, and placement of photon transitions observed in the ^{28}Si$(n,\gamma)^{29}$Si reaction.

Photon energy (keV)		Intensity %		Placement
1565.29	0.23	0.52	0.13	8474→6909
1793.70	0.20	0.55	0.08	3067→1273
1867.47	0.11	0.84	0.08	4934→3067
2027.99	0.09	0.80	0.05	2028→ 0
2092.98	0.05	19.67	0.20	8474→6381
2425.82	0.05	3.02	0.05	2426→ 0
2508.65	0.15	0.21	0.02	4934→2426
3539.00	0.05	69.74	0.70	8474→4934
3660.82	0.05	4.05	0.04	4934→1273
3954.45	0.05	2.40	0.03	6381→2426
4482.34	0.15	0.11	0.01	6909→2426
4840.00	0.12	0.24	0.02	4840→ 0
4879.99	0.20	0.15	0.02	6909→2028
4934.01	0.05	62.49	0.65	4934→ 0
5106.81	0.05	3.55	0.04	6381→1273
5406.46	0.66	0.02	0.003	8474→3067
5634.63	0.12	0.11	0.01	6909→1273
6046.97	0.07	0.30	0.01	8474→2426
6379.86	0.05	11.04	0.13	6381→ 0
6444.45	0.11	0.13	0.01	8474→2028
6712.18	0.45	0.04	0.005	6713→ 0
6907.34	0.29	0.04	0.004	6909→ 0
7056.99	0.12	0.15	0.01	7058→ 0
7199.25	0.05	6.81	0.07	8474→1273
7521.86	0.33	0.02	0.003	7523→ 0
7996.29	0.60	0.02	0.004	7997→ 0
8472.27	0.05	2.12	0.02	8474→ 0

TABLE II. Energy, intensity, and placement of photon transitions observed in the $^{29}Si(n,\gamma)^{30}Si$ reaction.

Photon energy (keV)		Intensity %		Placement
2235.26	0.06	62.4	1.5	2235→ 0
2359.40	0.37	6.3	1.2	9104→6744
2445.82	0.09	10.5	0.8	10 609→8163
2595.32	0.21	1.9	0.6	4831→2235
2676.73	0.25	2.6	0.7	7508→4831
3101.08	0.06	29.2	0.7	10 609→7508
3252.10	0.50	1.3	0.5	5488→2235
3498.39	0.18	7.6	0.5	3499→ 0
3738.46	0.32	2.1	0.2	7508→3770
3769.26	0.11	5.9	0.3	3770→ 0
3864.96	0.04	35.6	0.5	10 609→6744
3967.84	0.09	5.2	0.3	10 609→6641
4009.27	0.17	0.8	0.3	7508→3499
4405.27	0.18	4.4	0.3	6641→2235
4508.46	0.30	1.7	0.3	6744→2235
4664.73	0.40	0.8	0.2	8163→3499
4810.31	0.50	1.2	0.4	4811→ 0
5129.44	0.08	1.9	0.1	8899→3770
5271.97	0.04	19.8	0.3	7508→2235
5538.85	0.30	1.1	0.1	9308→3770
5927.53	0.23	1.4	0.1	8163→2235
6099.58	0.50	1.2	0.2	8336→2235
6662.89	0.27	1.2	0.1	8899→2235
6743.34	0.04	37.0	0.4	6744→ 0
6821.19	0.20	0.9	0.1	10 609→3788
6838.74	0.11	4.2	0.2	10 609→3770
7109.70	0.09	5.7	0.2	10 609→3499
8161.96	0.11	3.4	0.2	8163→ 0
8372.68	0.40	0.9	0.1	10 609→2235
8896.88	0.20	0.7	0.1	8899→ 0
8952.01	0.40	0.4	0.1	8953→ 0
9618.03	0.16	1.2	0.1	9620→ 0
9790.80	0.13	1.2	0.1	9792→ 0
10 200.10	0.50	0.3	0.1	10 202→ 0
10 607.14	0.09	7.7	0.2	10 609→ 0

The energy calibration was performed using the method and transition energies of $^{14}N(n,\gamma)^{15}N$ given in Ref. 7. The transition, level, and neutron separation energies were determined by a least-squares fit[7] of transition and level energies of $^{29,30}Si$. The transition energies of ^{29}Si, ^{30}Si, and ^{31}Si are presented in Tables I–III, respectively. The energy levels of the nuclei deduced in this work are summarized in Table IV along with the previous values. The least-squares fit gave the neutron separation energies of ^{29}Si and ^{30}Si. Because of large numbers of interconnecting transitions the statistical error obtained was very low, so that the ultimate uncertainty was dictated by the nitrogen calibration. The errors include the part stemming from the calibration. The neutron separation energy of ^{31}Si was determined using the few transition and the first excited state of 752.24±0.3 keV

TABLE III. Energy, intensity, and placement of photons observed in the $^{30}Si(n,\gamma)^{31}Si$ reaction.

Photon energy (keV)		Intensity %		Level placement
2205.14	0.21	13.0	1.9	6587→4382
2780.57	0.05	69.6	1.4	3533→ 752
3054.32	0.05	71.3	1.2	6587→3533
3629.73	0.16	7.5	0.7	4382→ 752
4528.75	0.07	14.3	0.5	5281→ 752
5871.58	0.75	0.9	0.3	5872→ 0
6586.39	0.25	1.5	0.2	6587→ 0

TABLE IV. Level energies of $^{29,30,31}Si$ obtained from (n,γ) measurements.

Present Values energy (keV)			From Ref. 6 energy (keV)	
		^{29}Si		
1273.35	0.04		1273.1	0.1
2028.19	0.07		2028.2	0.3
2425.91	0.04		2425.6	0.2
3066.95	0.10		3067.1	0.3
4840.43	0.12		4839.9	0.5
4934.43	0.04		4933.6	0.5
6380.54	0.04		6380.7	0.4
6713.01	0.44		6711	2
6908.12	0.45		6908.1	0.7
7057.91	0.12		7057.8	0.5
7522.91	0.32		7522	4
7997.47	0.36		7994	4
8473.61	0.04			
		^{30}Si		
2235.40	0.04		2235.37	0.13
3498.53	0.08		3498.7	0.2
3769.52	0.06		3769.7	0.2
3787.12	0.22		3787.9	0.2
4810.72	0.50		4809.2	0.3
4830.94	0.16		4830.7	0.3
5487.7	0.5		5487.5	0.4
6641.07	0.08		6641.1	0.5
6744.07	0.04		6744.1	0.4
7507.93	0.04		7507.8	0.5
8163.27	0.07		8163.1	0.5
8335.7	0.5		8333.0	0.6
8899.40	0.08		8898.0	0.6
8953.45	0.40		8954.3	0.6
9103.6	0.4		9103.8	0.6
9308.9	0.3		9308.3	0.6
9619.69	0.16		9619.9	0.6
9792.52	0.13		9792.4	0.6
10 201.96	0.50		10 202.1	0.8
10 609.21	0.04			
		^{31}Si		
5872.18	0.75		5874	1
5281.25	0.20		5282.0	0.4
4382.11	0.30		4382.9	0.4
3532.84	0.20		3533.7	0.2
752.14	0.30		752.43	0.10

TABLE V. Primary $E2$ transitions in $^{29,30}Si$.

Final nucleus	Spins of capture state	Energy of levels with spin $\frac{5}{2}^+$	Energy of levels with spin 4^+	Energy of primary $E2$ transitions (keV)	Absolute[a] intensity (%)
		2028		6445	0.13
^{29}Si	$\frac{1}{2}^+$	3067		5407	0.02
		4895		3579	<0.031[b]
^{30}Si	$1^+,2^+$		5280	5329	<0.11[b]
			5950	4659	<0.39[b]

[a]Photons per 100 n capture in target nucleus.
[b]With 68% confidence.

obtained from beta decay.[16] The deduced neutron separation energies of ^{29}Si, ^{30}Si, and ^{31}Si are 8473.61±0.04, 10 609.21±0.04, and 6587.32±0.20, respectively. These are based upon a ^{15}N Q value of 10 833.302±0.012 keV.[17] The values are in general agreement with those previously reported,[3,18] but there has been a significant improvement in the precision.

We observe 27 γ-ray transitions in ^{29}Si of which eight were not previously observed. The decay scheme presented in Table I includes all the new transitions at 4483, 4880, 5407, 5635, 6713, 6909, 7523, and 7997 keV. The two transitions at 1565 and 7058 stated to be doubtful[3] are confirmed in the present study. The energy levels at 7997.47±0.60, 7522.91±0.33, and 6713.01±0.45 keV are observed by (n,γ) for the first time although they were previously detected in (d,p) reaction studies.[19,20] The average values of the levels reported in the literature are 7994±4, 7522±4, and 6711±2 keV. Although our measurements agree within error with these values, there has been an improvement in precision.

The efficiency calibration was performed using the intensities[7] of transitions in $^{14}N(n,\gamma)^{15}N$. The absolute intensities of transitions in $^{29,30,31}Si$ were determined in the present study on the basis of their complete decay schemes.

Using the percentage abundances of the silicon isotopes[8] and the absolute intensities from the present work, the ratio of the radiative capture cross sections for the three nuclides, after a 16% correction for the resonance integral of ^{30}Si are found to be 1:0.580:0.518.

Nitrogen, whose intensities and capture cross section are precisely known,[7,9] was employed as a standard for determining the cross section for ^{28}Si. Using 79.8±1.4 mb as the σ_γ value of nitrogen, the capture cross section for ^{28}Si was found to be 207±4 mb and the cross sections for ^{29}Si and ^{30}Si were 120±3 and 107±2 mb, respectively. The cross section determined for ^{30}Si agrees well with the values of 110±10,[21] 103±3,[22] and 107±2 mb,[8] found earlier. Because the product of the $^{30}Si(n,\gamma)$ reaction is radioactive, $\sigma(^{30}Si)$ has been evaluated via the activation method. The fact that agreement is achieved through different methods lends credence to the present study in which all three cross section values are linked in fixed ratio. The $\sigma(^{28}Si)=207\pm4$ mb is higher than the values of 80±30 mb,[10] 160±18 mb,[5] and 177±5 mb,[8] reported earlier. Among these, the work of Ref. 5 was similar to the present study. Their 29% lower value seems to be due to the combined effect of their greater intensities of high-energy transitions in $^{28}Si(n,\gamma)^{29}Si$ and the lower intensity of transitions in the standard ^{28}Al. The isotopic cross sections observed in the present work lead to an elemental cross section of 200±4 mb. Scattering length and transmission measurements[23] performed at 510 μeV yield a capture cross section of 1.22±0.04 b. If one assumes a $1/v$ variation this would imply a thermal cross section of 172±6 mb. Our result indicates a small departure from a $1/v$ variation. It is to be noted that for ^{28}Si, the sum of the resonance contribution and estimated direct capture cross section is 217 mb.[8] Thus these two contributions are consistent with the value 207±4 mb obtained in the present study. The value for $\sigma(^{29}Si)=120\pm2.5$ mb is to be compared with 280±90 mb (Ref. 10) and 101±14 mb (Ref. 5).

Since the spin of the target nucleus ^{28}Si is 0^+, s-wave neutron capture produces only $\frac{1}{2}^+$ states. Thus a primary transition populating a $\frac{5}{2}^+$ level will be a pure $E2$ transition, provided that the p-wave capture contribution is negligible. Using the data of Ref. 8, the p-wave contribution has been found to be less than 0.5% in the present instance. A list of three $\frac{5}{2}^+$ levels in ^{29}Si along with the energy of the corresponding primary $E2$ transitions is given in Table V. The intensities (or its upper limits) of the transitions are also tabulated. The capture state of ^{30}Si, on the other hand, can have possible spins 1^+ or 2^+. The unambiguous $E2$ primary transition only obtainable from 2^+ capture state, therefore populates a level with spin 4^+. Data for two such $E2$ transitions are also given in the Table.

In order to compare the partial cross sections for $E2$ transitions with the prediction of direct capture, a theoretical calculation is done. The direct cross section is calculated using the formula[11,24]

$$\sigma^J_{n\gamma f}=\frac{(2J_f+1)S}{2(2J_t+1)}\frac{\pi\bar{e}^2}{300\hbar v_n}\left[\frac{A+1}{A}\right]^5\frac{\lambda_c^5}{R^3}y^6\left[\frac{y^2+7y+15}{y^2+3y+3}+(R-A_{\rm coh})\frac{y^2+5y+8}{y^2+3y+3}\right]^2 . \tag{1}$$

The term $(2J_f+1)S$ is the $l=2$ spectroscopic factor for the (d,p) reaction populating the final state. These factors for the $^{28}Si(d,p)^{29}Si$ reaction for the excitation energies 2028 keV and 3067 keV are 1.74 and 0.60, respectively.[6] In Eq. (1), J_t is the spin of the target nucleus, λ_c the Compton wavelength of the neutron, v_n the neutron velocity, and A the target mass number. The channel radius R is taken to equal $1.35A^{1/3}$ fm. The effective neutron charge factor $\bar{e}/e$ used for ^{28}Si is 0.6.[12] The term y is given by

$$y=k_fR \ ,$$

where the neutron wave number

$$k_f=\frac{\sqrt{2m(S_n-E_x)}}{\hbar} \ ,$$

S_n being the neutron separation energy. The cross section that results from the first term in the parentheses of Eq. (1), is the hard-sphere scattering contribution. The contribution from resonances is given by the second term in the parentheses. The term $A_{\rm coh}$ is the coherent scattering length. This is related to the bound coherent scattering length by the relation[8]

$$A_{\rm coh}=b_{\rm coh}\left[\frac{A}{A+1}\right]+2\times1.38\times10^{-3}\left[\frac{A}{A+1}\right] . \qquad (2)$$

The value of $b_{\rm coh}$ used for ^{28}Si is 4.106 ± 0.006 fm.[8]

The calculated direct capture cross sections for $E2$ transitions at 8445 keV and 5407 keV are 203 μb and 44 μb, respectively, and the experimentally observed cross sections are 26 ± 22 μb and 41 ± 5 μb. The cross sections may almost fully be accounted for by the direct capture contribution.

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