Resonance neutron capture by ^{35,37}Cl

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Neutron capture by enriched ^{37}Cl and by natural Cl was measured as a function of neutron time-of-flight over a 40 m path. Resonance peaks were fitted by least squares to Breit-Wigner parameters. The energy range covered was 4 to 225 keV for 54 ^{35}Cl resonances and 8 to 151 keV for 12 ^{37}Cl resonances. Corresponding average capture in stellar environments at $kT=30$ keV was calculated as (10.0 ± 0.3) mb for ^{35}Cl and (2.15 ± 0.08) mb for ^{37}Cl.

INTRODUCTION

Resonant neutron capture peaks were measured at the Oak Ridge Electron Linear Accelerator (ORELA) pulsed neutron time-of-flight facility for the two stable chlorine isotopes, ^{35}Cl and ^{37}Cl. Some uncertainty has persisted in the isotopic assignment of the chlorine resonances,[1-3] largely owing to the lack of direct evidence from enriched isotope studies. Most capture cross-section work for chlorine has been at low neutron energies, from thermal (0.025 eV) and epithermal neutrons to a few keV. The present study attempts to clearly assign the resonances to the correct isotope and to quantify the neutron capture probability for each resonance observed.

EXPERIMENTAL PROCEDURE

Lithium chloride was chosen as the sample material, as the lithium has negligible neutron capture, a small neutron scattering cross section, and no sharp resonance structure in the energy range studied. Although the compound is quite hygroscopic, it became dry and stable during use in the evacuated ORELA flight path. A 98.21% enriched ^{37}Cl sample was used which was 25.4 mm diam $\times$ 2.0 mm thick and weighed 2.573 g. A slab of natural lithium chloride, 26.2 mm $\times$ 51.6 mm $\times$ 3.91 mm and weighing 7.400 g, was used for the other isotope as the ^{35}Cl content is already 75.77% in terrestrial chlorine, and it was not necessary to skimp on quantity as it would have been for a second enriched sample.

The experiments were performed at the 40-m station of ORELA flight path 7. The instrumentation for this station has recently been diagramed in connection with similar measurements on four tungsten isotopes,[4] and many of the systematic uncertainties associated with the measurement technique have been previously discussed and tabulated.[5] Briefly, the experimental procedure consists in positioning the samples within the flight path and measuring the total energy of the prompt gamma rays emitted following capture of the neutrons in the sample. The neutron beam traverses the smallest dimension of a sample to minimize resonance self-protection. The capture gamma rays are detected by a pair of nonhydrogenous liquid scintillators and their total energy is calculated by pulse-height weighting.[6] The detection efficiency is determined by the saturated resonance method[7] relative to a thin ^{6}Li glass scintillator used as a neutron flux monitor.[8] The time-of-flight energy scale is calibrated with sharp aluminum resonances at 5.903 and 1094 keV and corrected for relativistic effects.

EXPERIMENTAL RUNS

The ORELA accelerator was operated at 800 pulses per second and a 0.48 g/cm^2 ^{10}B filter was used to absorb the slowest neutrons from earlier pulses which otherwise would have overlapped the events of interest in time of arrival at the sample. The natural chlorine data were taken over a 91 h period with a 4-ns burst width and 7-kW average power. For the smaller enriched sample, the power was raised to 10 kW with the burst width averaging 5 ns, and the data run was extended to 122 h.

All data were corrected for electronic dead time, measured environmental and beam-dependent backgrounds, and gamma-ray energy loss in the sample material. In a second step, apparent cross sections for ^{35}Cl and ^{37}Cl were derived, using the neutron flux monitor and calibration data. A linear subtraction matrix[9] was used to remove the yield from the minor isotope in each sample. Only for the strong 8.3 keV ^{37}Cl peak in the natural sample was it possible to see a small residual yield attributable to nonlinearity. As there has been confusion about the isotopic assignment of some of the higher energy peaks, continuous sets of data versus neutron energy for each isotope are shown: in Fig. 1 ^{35}Cl (12—420 keV), and in Fig. 2 ^{37}Cl (25—160 keV).

Breit-Wigner parameters were fitted to the capture peaks using the least squares program LSFIT,[10] which includes sample temperature and thickness effects such as Doppler broadening and capture after scattering. The experimental resolution function included in the code features a convolution of Gaussian and exponential shapes. Examples of the fitted curves are shown in Figs. 3—5 and the assumed and derived parameters are listed in Tables I and II. Where both $g\Gamma_n$ and Γ_γ could be determined from the present data, their correlation coefficient as found by LSFIT is tabulated. For the broadest resonances, capture parameters required a significant correction for the scattered neutron sensitivity of the apparatus. An estimated uncertainty for this correction was com-

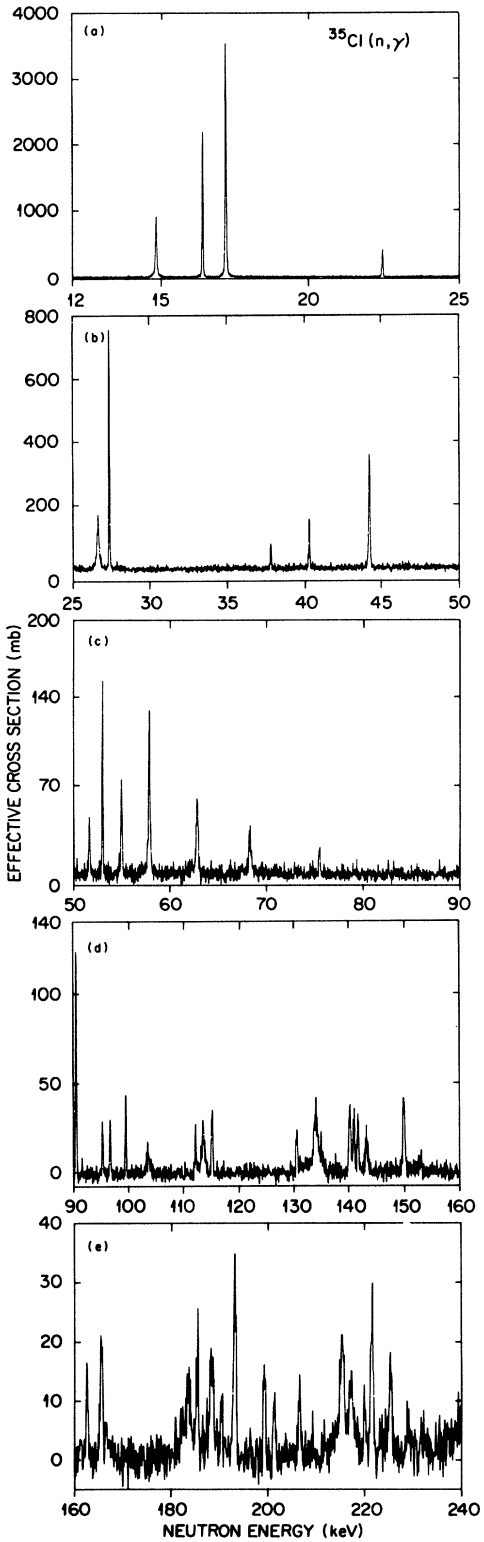

FIG. 1. (a)—(e) The neutron capture yield per nucleon of ^{35}Cl for the 7.40 g sample of natural lithium chloride. The measured ^{37}Cl yield has been subtracted.

bined in quadrature with the tabulated statistical uncertainty. The largest such correction for Table I (^{35}Cl) was 10% at 103.5 keV, and for Table II (^{37}Cl) it was 25% at 25.5 keV. Proximity to the 27 keV ^{29}F resonance in the

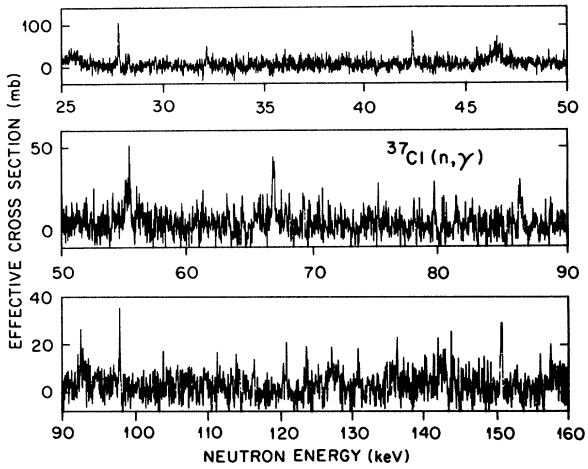

FIG. 2. The neutron capture yield per nucleon of ^{37}Cl measured with the 2.573 g sample of lithium chloride enriched to 98.21% in ^{37}Cl. The ^{35}Cl minor isotope yield has been subtracted.

C_6F_6 detector material makes this last correction exceptionally large.

DISCUSSION

Statistical uncertainties in the data as reflected in the fitted parameters are indicated in the tables. For the ^{37}Cl resonances these are as large as 31% of the capture area, although the analysis could be extended only to 160 keV. With the better looking data (Fig. 1) for ^{35}Cl(n,γ) the analysis was extended as far as the transmission data of Singh *et al.*[2] extended. Cross section normalization uncertainties are estimated at 2.4% standard deviation with flux shape uncertainties increasing with energy from 0.1% to 2.8%. Detailed estimates based on the neutron flux monitor calibration procedure[11] are given in Table 3

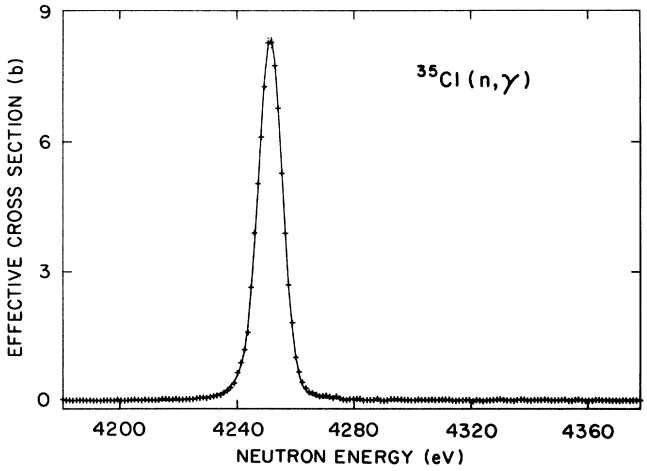

FIG. 3. An example of the parametric least squares fit to a well-defined ^{35}Cl neutron capture resonance. The parameters are included in Table I and determine the solid line in combination with Doppler broadening and the experimental resolution function.

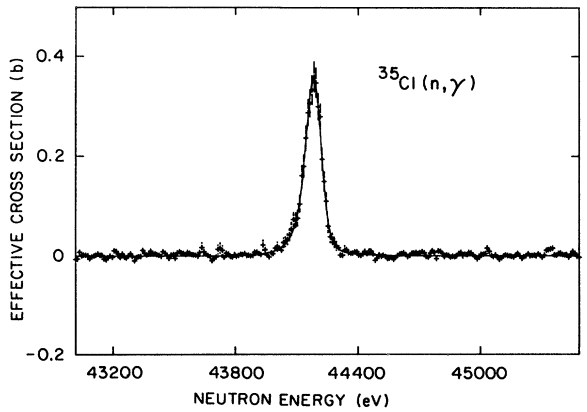

FIG. 4. A ^{35}Cl(n,γ) peak at 44 keV. This peak shows no evidence of doublet structure (Ref. 1), although the statistical uncertainties of the data points are relatively larger and therefore define the resonance peak less well than, for example, the data at lower energy shown in Fig. 3.

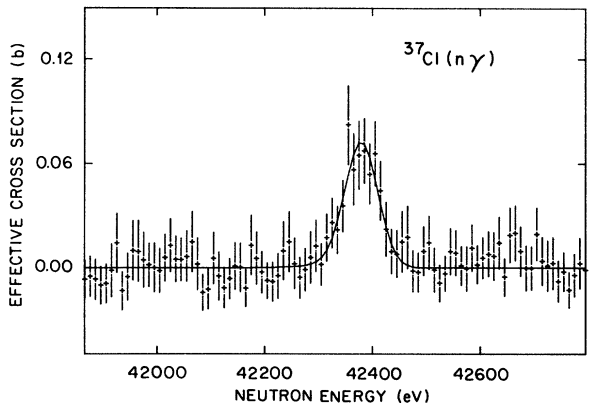

FIG. 5. A ^{37}Cl(n,γ) peak at 42.38 keV. This peak which was not seen in previous work is too narrow to allow determination of the neutron or total width. Only the capture area proportional to $g\Gamma_n\Gamma_\gamma/\Gamma$ is fitted by the solid line.

TABLE I. ^{35}Cl(n,γ) resonance parameters.

E_{res} (lab keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Standard deviation (meV)	$g\Gamma_n$ (eV)	Standard deviation (eV)	Γ_γ (meV)	Standard deviation (meV)	Correlation $(g\Gamma_n,\Gamma_\gamma)$ $\times 100$	J adopted
(0.398)								
(1.1)								
4.252	99.0	0.4	0.25[a]		437	3		1
5.492	1.9	0.1						
14.803	253.5	3.3	19.2	0.4	410	5	+13	2[a]
16.359	365.5	4.4	4.9	0.1	632[b]	9	−66	
17.137	830.8	5.6	9.4	0.1	1458	11	−52	
22.40	89.1	1.9	0.10	0.03	1000[b]			
26.61	237	9	79.7	3.3	380[b]	14	+28	
27.35	268	9	28.4	0.1	475[b]	19	−88	
37.78	53	3						
40.28	118	5						
44.19	450	12	9.7	0.4	1259	36	−62	1
51.63	63	5	1.6[a]		105[b]	9		
53.00	207	8						
54.96	168	11	22.9	2.3	452	29	−34	1
57.84	398	15	54.5	3.3	642	24	−17	2
62.80	260	13	46.0	3.9	697	36	+6	1
68.29	195	14	87.6	9.9	522	36	+29	1
75.51	65	7						
90.50	655	20						
95.28	149	11						
96.67	162	10						
99.48	238	14						
103.53	220	22	159	26	587	65	+42	1
112.12	164	16						
113.53	543	33	245	25	872	52	+29	2
115.15	289	20						
130.6	271	24						
134.0[c]	1453	93						
135.0	106	36	66[a]		283	97		1
140.2	485	38						
140.9	413	36	59[a]		665	59		2
141.7	353	32						
143.2[c]	412	40						

TABLE I. (*Continued*).

E_{res} (lab keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Standard deviation (meV)	$g\Gamma_n$ (eV)	Standard deviation (eV)	Γ_γ (meV)	Standard deviation (meV)	Correlation $(g\Gamma_n,\Gamma_\gamma)$ $\times 100$	J adopted
150.0[c]	804	58	66	7				1
153.0	159	27						
162.7	262	34						
165.5	601	61	106	18	1612	165	−18	1
180.9	67	31						
182.5	328	135	583[a,d]		524[b]	217		
183.6	821	139	607[e]	160	1316[b]	222	+70	
185.4	417	49						
188.3	947	93	375[e]	60	1520[b]	150	+27	
189.3	88	36						
190.4	234	41						
193.1	1130	80	116[e]	14	1825[b]	132	−46	
199.2	413	51						
201.3	303	77	64[e]	24	487[b]	125	−75	
206.5	329	41						
215.3	1268	171	384[e]	65	2036[b]	274	+60	
216.0	522	554	3000[e]					
217.3	697	139	356[e]	88	1117[b]	223	+60	
220.0	229	44						
221.5	866	62						
225.4	763	74	198[e]	30	1226[b]	120	−13	

[a]Adopted from Ref. 2 or Ref. 3.
[b]Value equals $\frac{8}{5}g\Gamma_x$.
[c]Probable doublet or multiplet.
[d]Value reported (a) minus fitted $g\Gamma_n$ of the 183.6 keV resonance.
[e]Value equals $\frac{5}{8}\Gamma_n$.

of Ref. 12. The neutron energy scale uncertainty is estimated as about half the resolution width, or $E_n/1300$.

Agreement with the isotopic assignments accepted by Singh *et al.*,[2] which in some cases are based on still older work, is complete except for the 27.35- and 68.29-keV resonances which are now assigned to ^{35}Cl + n. The analysis of the present data yielded 56 resonances between 4 and 191 keV, compared to 34 analyzed in the transmission study.[2] An additional ten ^{35}Cl capture peaks from 191 to 225 keV were analyzed, five of which can be seen in the transmission plots.

The strong difference in number of levels and their neutron capture strength can be partially attributed to the smaller binding energy of ^{37}Cl and the negative parity of

TABLE II. ^{37}Cl(n,γ) resonance parameters.

E_{res} (lab keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Standard deviation (meV)	$g\Gamma_n$ (eV)	Standard deviation (eV)	Γ_γ (meV)	Standard deviation (meV)	Correlation $(g\Gamma_n,\Gamma_\gamma)$ $\times 100$	J adopted
8.303	155	4	58	2	248	6	49	2
25.53	174	29	289	32	510	67	79	1
27.83	39	2	2.5[a]		63[b]	4		
42.38	58	4						
46.49	222	38	268[a]		355	61		2
55.13	43	8	10[c]		69[b]	13		
55.40	92	17	64[c]		148[b]	20		
66.84	132	14	33[a]		212[b]	22		
86.24	96	14						
92.81	172	53	404[a]		275[b]	84		
127.3	222	55	215[a]		355[b]	88		
150.7	317	53						

[a]Adopted from Ref. 2.
[b]Value given is $\frac{8}{5}g\Gamma_\gamma$.
[c]The sum of the $g\Gamma_n$ values for this close doublet adopted as in a.

the levels below 1.9 MeV excitation in ^{38}Cl. The capture cross section averaged over a 30 keV kT Maxwellian spectrum is (10.0±0.3) mb for ^{35}Cl and (2.15±0.08) mb for ^{37}Cl.

CONCLUSIONS

Neutron capture resonances for the stable isotopes of chlorine were measured and parametrized; 54 resonances were observed for ^{35}Cl between 4 and 225 keV, and 12 were observed for ^{37}Cl between 8 and 151 keV.

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[1]S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross Sections* (Academic, New York, 1983), Vol. 1.
[2]U. N. Singh *et al.*, Phys. Rev. C 10, 2138 (1974).
[3]R. N. Alves *et al.*, Nucl. Phys. A134, 118 (1969).
[4]R. L. Macklin, D. M. Drake, and E. D. Arthur, Nucl. Sci. Eng. 84, 98 (1983).
[5]H. Beer and R. L. Macklin, Phys. Rev. C 26, 1404 (1982).
[6]J. H. Gibbons and R. L. Macklin, Phys. Rev. 159, 1007 (1967); also R. L. Macklin, in *Neutron Capture Gamma Ray Spectroscopy,* edited by R. E. Chrien and W. R. Kane (Plenum, New York, 1979).
[7]R. L. Macklin, J. Halperin, and R. R. Winters, Nucl. Instrum. Methods 164, 213 (1979).
[8]R. L. Macklin, N. W. Hill, and B. J. Allen, Nucl. Instrum. Methods 96, 509 (1971).
[9]R. L. Macklin, Nucl. Sci. Eng. 71, 182 (1979).
[10]R. L. Macklin, Nucl. Sci. Eng. 59, 12 (1976).
[11]R. L. Macklin, R. W. Ingle, and J. Halperin, Nucl. Sci. Eng. 71, 205 (1979).
[12]R. L. Macklin, Nucl. Sci. Eng. 86, 362 (1984).