THE $Cl^{35}(n,p)$ REACTION AND NEUTRON RESONANCE PARAMETERS OF CHLORINE

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The cross section for the $Cl^{35}(n,p)$ reaction has been measured as a function of energy for neutrons having energies up to 20 kev. Parameters are given for resonances at -0.21, 0.405 and 4.3 kev. The results are discussed together with the data previously obtained on the cross section for the radiative capture of neutrons by chlorine.[1]

INTRODUCTION

FOR slow neutrons, the (n,p) reaction with chlorine is energetically possible only for the isotope Cl^{35}, whose abundance is 75.4%. For thermal neutrons, the cross section for the reaction $Cl^{35}(n,p)$ is about 0.2 barns;[2-5] protons are emitted with an energy of 600 kev. We have measured the cross section for this reaction as a function of energy for neutrons having energies up to 20 kev. In this energy range, the total cross section for the interaction of neutrons with chlorine has been investigated in references 6 — 8; the cross section for radiative capture has been reported in reference 1.*

METHOD

The measurements were made with a spectrometer based on the slowing down of neutrons in lead.[10-11] The energy resolution of the spectrometer (half-width of an isolated resonance) was ~ 70% for E = 15 kev and ~ 35% for $E \lesssim 1$ kev. The procedure for measuring a cross section using this method has been described earlier.[1,9]

Attempts were made to detect the protons with gas discharge counters filled with CCl_4. The counters were warmed to 50° C (vapor pressure of CCl_4 ~ 300 mm Hg) and operated as proportional counters. Preliminary measurements showed that the reaction $Cl^{35}(n,p)$ has resonances at 405 ev and 4.3 kev. However, the poor response time of the counters made quantitative measurements impractical.

The proportional counters were replaced by scintillation detectors. The phosphor was a fine powder of ZnS(Ag), which was poured into a container filled with CCl_4 or C_3Cl_6. The latter are transparent liquids which served as both samples and light pipes.* The effective sample thickness was about 2×10^{21} chlorine nuclei per cm^2.

The electronic circuitry was set to record protons, but not γ rays, the adjustment being monitored by a strong Co^{60} source (E_γ = 1.3 Mev). Gamma rays could arise from neutron capture in lead (E_γ = 7.4 Mev). Other spurious reactions which could have been observed are Zn(n, α) and S(n, α). The possible contributions of such spurious reactions are indicated by the results shown in Fig. 1.

Even if the extreme assumption were made that the counting rate of the CCl_4 + ZnS detector at 30

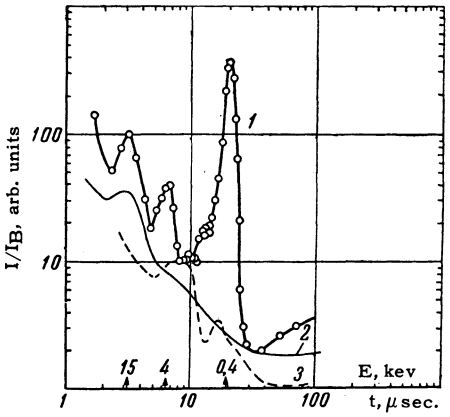

FIG. 1. This figure shows the relative detector counting rate as a function of slowing down time (t). I is the detector counting rate, I_B is the counting rate of a boron counter and is proportional to the neutron density. Curve 1 was taken with a CCl_4 + ZnS(Ag) detector, Curve 2 with a CS_2 + ZnS(Ag) detector, and curve 3 with a γ ray detector. Curve 3 gives the γ ray background of the spectrometer. Curve 2 is normalized to agree with curve 1 at t = 30 μsec, curve 3 is normalized to agree with curve 1 at t = 9 μsec.

*Preliminary results from reference 1 are quoted in reference 9.

*Other mixtures were tried, such as ZnS(Ag) + NaCl, CsI(Tl) + CCl_4, or terphenyl and toluene + NaCl. These were considerably worse from the point of view of efficiency compared to discrimination against γ rays.

μsec were entirely due to the ZnS reaction, while the counting rate at 9 μsec were entirely due to the γ background from radiative neutron capture in lead,* then the contributions of these factors to the counting rate represented by curve 1 at other energies would be negligible.

RESULTS

Figure 2 shows the cross section for the reaction $Cl^{35}(n,p)$, measured as a function of energy. The curve is normalized to the thermal cross section $\sigma_{np} = 0.19 \pm 0.05$ barn.[12] The uncertainty in the absolute cross section is essentially due to the uncertainty in the thermal cross section, which is $\pm 26\%$. Figure 2 also shows the cross section for the (n,γ) reaction in chlorine.[1]

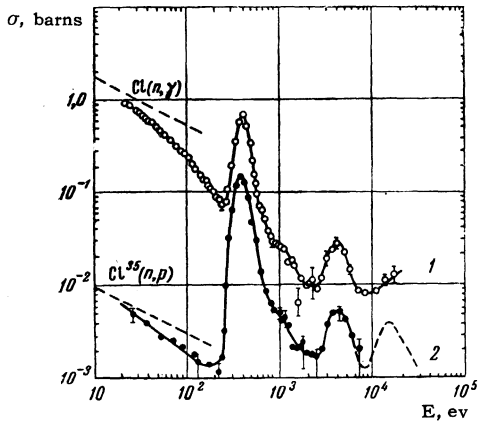

FIG. 2. Energy dependence of the cross sections for neutron capture in chlorine. Curve 1: cross section for the reaction $Cl(n,\gamma)$, measured with the naturally occurring mixture of isotopes and normalized to a cross section $\sigma_\gamma = 33.8$ barns at $E = 0.025$ ev.[12] Curve 2: cross section for the reaction $Cl^{35}(n,p)S^{35}$, normalized so that $\sigma(n,p) = 0.19 \pm 0.05$ barns at $E = 0.025$ ev.[12] The errors shown on the curve are statistical; an error also arises because the normalization is uncertain. Taking errors associated with the background also into account, this amounts to $\sim 30\%$. At energies near 2 kev, the cross section might be a factor 2 less than that shown (because of inadequate corrections for background).

DISCUSSION OF THE RESULTS

1. Negative energy resonance. The dotted straight lines on Fig. 2 represent extrapolations of the thermal (n,γ) and (n,p) cross sections according to the 1/v law. The observed cross section falls off faster than this extrapolation, and this indicates a resonance at negative energies. This resonance occurs at $E_0 = -140$ ev according to an analysis of the total cross section[8] and at $E_0 = -210$ ev from an analysis of the capture cross section.[1] In the latter analysis, the relation $(\sigma_\gamma v)^{-1/2} = f(E)$ was assumed, where according to the Breit-Wigner formula for a narrow resonance ($\Gamma \ll |E_0|$) the function f should be given by

$$(\sigma_\gamma v)^{-1/2} = c(E - E_0). \quad (1)$$

In the work being reported upon here, the analysis of reference 1 was improved in two ways. In the first place, the experimental values of $\sigma_\gamma v$ were corrected for the presence of the resonance at 405 ev, taking the instrumental resolution into account. The resolution of the apparatus was obtained from measurements of the (n,p) reaction, which showed that the baseline of the peak at 405 ev was very small. In the second place, the capture cross section was corrected for, assuming a 1/v law — i.e., (1) was replaced by the relation

$$[\sigma_\gamma v - \alpha(\sigma_\gamma v)_0]^{-1/2} = c(E - E_0), \quad (2)$$

where $(\sigma_\gamma v)_0$ is the value of $\sigma_\gamma v$ at $E = 0$.

The experimental data are fitted best by $\alpha = 0$ and $E_0 = -210$ ev, although experimental errors are such that α could be less than 4×10^{-2}, which corresponds to $|E_0| > 175$ ev.* The (n,p) results do not contradict the resonance energy obtained from analysis of the (n,γ) data. However, the value of E_0 obtained from the (n,p) data is unreliable, since it is strongly dependent on the assumptions made about the background due to (n,α) and (n,γ) reactions.

2. Positive energy resonances. Both curves of Fig. 2 clearly show resonances at 405 ev and at 4.3 ± 0.3 kev. There is also a bump near 1 kev which may be due to a resonance at 1.1 ± 0.2 kev. The cross section for the (n,p) reaction showed a peak at ~ 15 kev; in this energy range, measurements are not reliable because of the large background due to the zinc and sulphur reactions. Since the (n,p) reaction is possible only for Cl^{35}, as was noted above, all the resonances refer to this isotope. In the total cross section measurements, Cl^{35} resonances have been observed at 405 ev,[8] 15 kev and 17 kev.[14]

Tables I and II show the level parameters calculated from the data on the (n,γ) and (n,p) re-

*The γ background due to capture of neutrons in the chlorine sample was small compared to γ-background from neutron capture in lead.

*Capture by the Cl^{37} isotope gives $\alpha = 0.5 \times 10^{-2}$, while resonances with positive energy give $\alpha < 0.1 \times 10^{-2}$. The direct capture of neutrons must follow the 1/v law,[13] but there are no data on the magnitude of direct capture for chlorine.

Table I. Parameters of neutron resonances in Cl^{35}

Parameter	E_0, ev				
	−210±10	405	1100±200	4300±300	(15 and 17)×10³
Γ_γ, ev	0.50±0.01	0.5*	0.5*	0.5*	
$\sigma_0\Gamma_\gamma$, barn-ev		120±10	~8	80±27	
$\sigma_0\Gamma_p$, barn-ev		16±5	~0.8	5.6±2.0	~10
$10^3\Gamma_p$, ev	2.4±0.8	70±22	~50	35±15	~100
γ^2_{0p}, ev**	70	[2.10³]	[~10³]	[8.10²]	~2·10³
γ^2_{1p}, ev**		9·10³	~6·10³	3.8.10³	
$10^3\Gamma_n$, ev***		26—65	4—30	250—700	(30+35)·10³[14]
γ^2_{0n}, ev**	7.4·10²	[1.0—1.7]	[0,1—0,2]	[3.3—5.8]	(1.2+1.4)·10²
γ^2_{1n}, ev**		(2—4.9).10³	(1—5)·10²	(5.6—16)·10²	
l	0 ($g=5/8$)	1	1	1	0

*The radiation widths are taken to be equal to the radiation width of the level at $E_0 = -210$ ev.

**γ^2_{0p} and γ^2_{0n} are the reduced proton and neutron widths calculated on the assumption that the resonance corresponds to orbital angular momentum $l = 0$; similarly, γ^2_{1p} and γ^2_{1n} correspond to the assumption $l = 1$.

***The magnitude of Γ_n depends on the assumption made about the spin of the compound nucleus Cl^{36} (see Table II).

Table II. Parameters of the resonances at 405 ev and 4.3 kev in Cl^{35} as a function of the statistical factor $g = (2J+1)/2(2l+1)$

E_0	g*	$10^3\Gamma_n$, ev	$10^3 g\Gamma_n$, ev	Γ, ev	$\sigma_0\Gamma$, barn-ev	σ_0, бн
405 ev	3/8	65±5	25±2	0,64	155±15	240±25
	5/8	38±3	24±2	0,61	147±15	240±25
	7/8	26±2	22±2	0,60	144±15	240±25
4,3 kev	3/8	>700	>260	>1,2	>160	~140
	5/8	410±150	260±80	0,95	155±40	164±40
	7/8	250± 50	220±50	0,78	130±27	167±40

*The value g = 1/8 for the 405 ev level is inconsistent with the measured cross section for absorption, while for the 4.3 kev level it does not accord with measurements of the (n, γ) cross section.

actions. In the calculations the radiation widths of the various levels were taken equal to the radiation width of the level at −210 ev, i.e., equal to 0.5 ev.[1] Supplementary measurements of self-absorption were carried out for the resonance at 405 ev. These gave a value for the strength $\sigma_0\Gamma$ of the level of 120 ± 30 barn-ev per Cl^{35} nucleus, which agrees with the data of reference 1 (see Table II).

3. The negative energy resonance in Cl^{35} determines the cross section for capture of thermal neutrons and hence must be an s-resonance, i.e., corresponds to capture of a neutron with orbital angular momentum $l = 0$. If the resonances at 405 ev, 1.1 kev and 4.3 kev were also taken to correspond to $l = 0$, then the reduced neutron widths of these resonances* would come out to be two to three orders of magnitude smaller than the reduced neutron widths for the resonances at −210 ev and 17 kev (the last is an s-resonance[14]). Hence the resonances at 405 ev, 1.1 kev and 4.3 kev must have $l = 1$. For the 405 ev resonance, this conclusion contradicts the data quoted in reference 14; the 1.1 kev and 4.3 kev resonances are not noted in reference 14.

It should be noted that the reduced proton width for the negative energy resonance is very small.

In the energy range 0.5 to 2×10^4 ev the resonance integral $R = \int_{E_1}^{E_2} \sigma dE/E$ for the $Cl^{35}(n,p)$ reaction is equal to $R_p = 0.074 \pm 0.025$. For the (n, γ) reaction this integral is $R_\gamma = 14.0 \pm 0.8$ b.[1] The total resonance integral for absorption is thus equal to 14.1 ± 0.8 b, which is in satisfactory agreement with results obtained by other authors (12 barns[17] and 12.7 ± 1.7 barns[18]).

*The reduced partial widths γ^2_{li} were calculated by dividing the measured partial widths Γ_i by twice the penetrability P_l: $\gamma^2_{li} = \Gamma_i/2P_l$, where $P_l = kR/F^2_l + G^2_l$ (for further details, see reference 15). The calculations were carried out using the tables in reference 16 and the formula $R = 1.3\,A^{1/3} \times 10^{-13}$ cm.

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