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

Yu. P. POPOV and F. L. SHAPIRO

P. N. Lebedev Physics Institute, Academy of Sciences, U.S.S.R.

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The cross section for the \textit{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.\textsuperscript{1}

INTRODUCTION

For slow neutrons, the (n, p) reaction with chlorine is energetically possible only for the isotope \textit{Cl}^{35}, whose abundance is 75.4\%. For thermal neutrons, the cross section for the reaction \textit{Cl}^{35} (n, p) is about 0.2 barns;\textsuperscript{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.\textsuperscript{1}

METHOD

The measurements were made with a spectrometer based on the slowing down of neutrons in lead.\textsuperscript{10-11} The energy resolution of the spectrometer (half-width of an isolated resonance) was \(\sim 70\%\) for \(E = 15\) keV and \(\sim 35\%\) for \(E \approx 1\) keV. The procedure for measuring a cross section using this method has been described earlier.\textsuperscript{1,8}

Attempts were made to detect the protons with gas discharge counters filled with \textit{CCl}_4. The counters were warmed to \(50^\circ\) C (vapor pressure of \textit{CCl}_4 \sim 300 \text{ mm Hg}) and operated as proportional counters. Preliminary measurements showed that the reaction \textit{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 \textit{ZnS(Ag)}, which was poured into a container filled with \textit{CCl}_4 or \textit{C}_6\text{Cl}_6. The latter are transparent liquids which served as both samples and light pipes.\textsuperscript{*} The effective sample thickness was about \(2 \times 10^{21}\) chlorine nuclei per cm\(^2\).

The electronic circuitry was set to record protons, but not \(\gamma\) rays, the adjustment being monitored by a strong \textit{Ce}^{60} source (\(E_\gamma = 1.3\) MeV). Gamma rays could arise from neutron capture in lead (\(E_\gamma = 7.4\) MeV). Other spurious reactions which could have been observed are \textit{Zn} (n, \(\alpha\)) and \textit{S} (n, \(\alpha\)). 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 \textit{CCl}_4 + \textit{ZnS} detector at 30

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{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 \textit{CCl}_4 + \textit{ZnS(Ag)} detector, Curve 2 with a \textit{CS}_2 + \textit{ZnS(Ag)} detector, and curve 3 with a \(\gamma\) ray detector. Curve 3 gives the \(\gamma\) ray background of the spectrometer. Curve 2 is normalized to agree with curve 1 at \(t = 30\) \(\mu\) sec, curve 3 is normalized to agree with curve 1 at \(t = 9\) \(\mu\) sec.}
\end{figure}

\textsuperscript{*}Other mixtures were tried, such as \textit{ZnS(Ag)} + \textit{NaCl}, \textit{CaK(Tl)} + \textit{CCl}_4, or terphenyl and toluene + \textit{NaCl}. These were considerably worse from the point of view of efficiency compared to discrimination against \(\gamma\) 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

FIG. 2. Energy dependence of the cross sections for neutron capture in chlorine. Curve 1: cross section for the reaction Cl\textsuperscript{35}(n,γ), measured with the naturally occurring mixture of isotopes and normalized to a cross section \(σ_y\) = 33.8 barns at \(E = 0.025\) ev.\textsuperscript{12} Curve 2: cross section for the reaction Cl\textsuperscript{140}(n,p)S\textsuperscript{135}, normalized so that \(a_{np}\) = 0.19 ± 0.05 barns.\textsuperscript{12} The uncertainty in the absolute cross section is essentially due to the uncertainty in the thermal cross section, which is ±26%. Figure 2 also shows the cross section for the (n,γ) reaction in chlorine.\textsuperscript{1}

According to the 1/ν law, the observed cross section falls off faster than this extrapolation, and this indicates a resonance at negative energies. This resonance occurs at \(E_b = -140\) ev according to an analysis of the total cross section\textsuperscript{5} and at \(E_b = -210\) ev from an analysis of the capture cross section.\textsuperscript{1} In the latter analysis, the relation

\[ (σ_ν)^{-1/2} = f(E) \]

was assumed, where according to the Breit-Wigner formula for a narrow resonance \((Γ \ll |E_b|\)), the function \(f\) should be given by

\[ (σν)^{-1/2} = c(E - E_b). \]  

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 \(σ_ν\) 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/ν law - i.e., (1) was replaced by the relation

\[ (σν)^{-1/2} = c(E - E_b). \]

where \((σ_ν)\)\textsuperscript{0} is the value of \(σ_ν\) at \(E = 0\).

The experimental data are fitted best by \(α = 0\) and \(E_b = -210\) ev, although experimental errors are such that \(α\) could be less than \(4 \times 10^{-2}\), which corresponds to \(|E_b| > 175\) ev.* The (n,p) results do not contradict the resonance energy obtained from analysis of the (n,γ) data. However, the value of \(E_b\) 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\textsuperscript{35}, as was noted above, all the resonances refer to this isotope. In the total cross section measurements, Cl\textsuperscript{35} resonances have been observed at 405 ev,\textsuperscript{3} 15 kev and 17 kev.\textsuperscript{14}

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

*Capture by the Cl\textsuperscript{37} isotope gives \(α = 0.5 \times 10^{-4}\), while resonances with positive energy give \(α < 0.1 \times 10^{-4}\). The direct capture of neutrons must follow the 1/ν law, but there are no data on the magnitude of direct capture for chlorine.
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 of the level of 120 \(\pm\) 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 \(\times\) \(10^4\) ev the resonance integral 
\[
R = \int \sigma dE/E \quad \text{for the Cl}\(^{35}\) (n, p)
\]
reaction is equal to \(R_p = 0.074 \pm 0.025\). For the (n, \(\gamma\)) 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 \(\pm\) 0.8 b, which is in satisfactory agreement with results obtained by other authors (12 barns\(^{17}\) and 12.7 \(\pm\) 1.7 barns\(^{18}\)).

### Table I. Parameters of neutron resonances in Cl\(^{35}\) as a function of the statistical factor
\[
g = (2J + 1)/(2J + 1)
\]

| Parameter | \(E_0\), ev | \(10^4 \sigma\) | \(10^3 \Gamma\) | \(\Gamma\), ev | \(\sigma\delta\), barn-ev | \(a_n\), \(\sigma_n\)
<table>
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<tbody>
<tr>
<td>(-210\pm10)</td>
<td>0.5±0.01</td>
<td>0.5±0.01</td>
<td>0.5±0.01</td>
<td>(-210\pm10)</td>
<td>(10^4 \sigma)</td>
<td>(10^3 \Gamma)</td>
</tr>
<tr>
<td>(405)</td>
<td>120±10</td>
<td>120±10</td>
<td>120±10</td>
<td>120±10</td>
<td>(10^4 \sigma)</td>
<td>(10^3 \Gamma)</td>
</tr>
<tr>
<td>(1100\pm500)</td>
<td>0.5±0.01</td>
<td>0.5±0.01</td>
<td>0.5±0.01</td>
<td>0.5±0.01</td>
<td>(10^4 \sigma)</td>
<td>(10^3 \Gamma)</td>
</tr>
<tr>
<td>(4300\pm500)</td>
<td>4.3±0.3</td>
<td>4.3±0.3</td>
<td>4.3±0.3</td>
<td>4.3±0.3</td>
<td>(10^4 \sigma)</td>
<td>(10^3 \Gamma)</td>
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*The values \(g = 1/8\) 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 \((n, \gamma)\) cross section.

\(^{1}\)The reduced partial widths \(\gamma_p\) were calculated by dividing the measured partial widths \(\Gamma_l\) by twice the penetrability \(P_l\); \(\gamma_p = \Gamma_l/2P_l\), where \(P_l = kR/F_1 + \Gamma_1^2\) (for further details, see reference 15). The calculations were carried out using the tables in reference 16 and the formula \(R = 1.3 A^{1/3} \times 10^{-11}\) cm.

\(^{2}\)The radiation widths are taken to be equal to the radiation width of the level at \(-210\) ev.

\(^{3}\)The magnitude of \(\Gamma_0\) depends on the assumption made about the spin of the compound nucleus Cl\(^{35}\) (see Table II).
The authors would like to thank Yan I-min, who was very helpful in the early stages of this work.

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