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HIGH-RESOLUTION INVESTIGATION OF THE ^{35}Cl(d, p)^{36}Cl REACTION

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Abstract: The angular distributions of 15 proton groups from the ^{35}Cl(d, p)^{36}Cl reaction have been measured with a split-pole magnetic spectrograph at $E_d = 7$ MeV. The ^{36}Cl doublet at 1.95 MeV could be resolved in the angular distribution measurements. A DWBA analysis yields l-values and spectroscopic factors.

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NUCLEAR REACTION ^{35}Cl(d, p), $E = 7$ MeV; measured $\sigma(\theta)$. ^{36}Cl levels deduced l_n, spectroscopic factors, natural target.

1. Introduction

To test the detailed shell-model calculations of sd shell nuclei [1-4]) more experimental information relevant to the shell-model structure of $A = 16$–40 nuclei is required. Although the ^{35}Cl(d, p)^{36}Cl reaction has been studied in the past [5-8]), reliable spectroscopic factors have not yet been determined from a high-resolution experiment with a DWBA analysis.

The purpose of the present experiment was to measure proton angular distributions in this reaction with sufficient resolution to resolve e.g. the ^{36}Cl doublet at 1.95 MeV, of which the components are separated by only 8 keV.

2. Experiment

A beam of 7 MeV deuterons from the Utrecht tandem accelerator was focussed on the target (spot diameter less than 1 mm) placed in the scattering chamber of a 90 cm split-pole magnetic spectrograph [9]). After magnetic analysis the emitted protons were focussed on six 30 mm × 10 mm Nuclear Diodes position sensitive semiconductor detectors (thickness 600 μm) mounted in the focal plane of the spectrograph. The energy and position spectra from all detectors were recorded simultaneously in a 4096-channel Laben analyser by means of an electronic routing system [10]). The thickness of the detectors, corresponding to the range of 12 MeV protons, limits the maximum energy of the bombarding deuterons to about 7 MeV. For monitoring purposes a Si detector was placed in the scattering chamber at an angle of 90° respective to the

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direction of the beam, and all intensity measurements were taken relative to the deuteron elastic scattering peak in the monitor spectrum.

The targets were prepared by the evaporation of natural $BaCl_2$ onto 10 $\mu g/cm^2$ carbon foils. For a 300 nA beam there was no significant deterioration of the target (thickness 50 $\mu g/cm^2$) during the 20 h experiment.

Measurements were performed for angles of 5° to 50° in 5° steps and of 60° to 130° in 10° steps. For each angle the magnetic field of the spectrograph and the position of the detector plane were adjusted to correct for the effects of the reaction kinematics on the imaging properties of the spectrograph [9]). The total charge collected in a Faraday cup varied from 200 μC for forward angles to 1.5 mC for backward angles.

The angular distributions of 15 protons groups were measured. With six position sensitive detectors two runs had to be performed for each angle with different settings of the spectrograph magnetic field to cover the range of low and high excitation energy. In this way all proton groups corresponding to the levels up to 3.34 MeV could be covered except for those leading to the levels at 3.00 MeV and 3.10 MeV which were missed because of erroneous detector positioning.

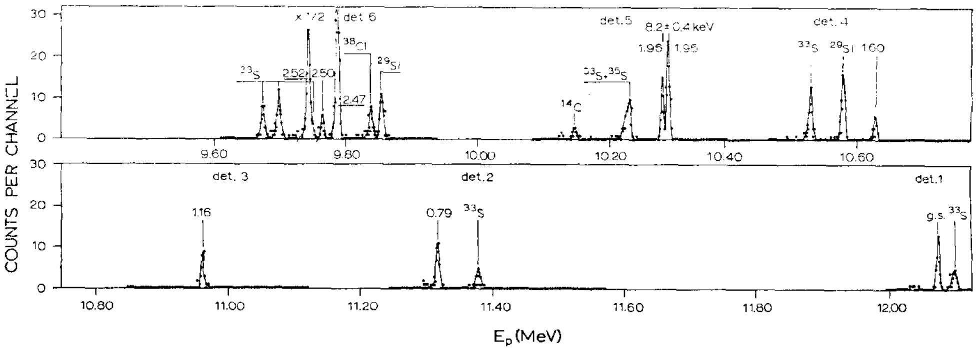

Fig. 1. Proton spectrum at $\theta = 130°$ measured with six position sensitive detectors in the focal plane of the split-pole spectrograph. The peaks corresponding to levels in ^{36}Cl are labelled with the excitation energies. For particle groups from the ^{35}Cl(d, α)^{33}S, ^{37}Cl(d, α)^{35}S, ^{13}C(d, p)^{14}C, ^{28}Si(d, p)^{29}Si and ^{37}Cl(d, p)^{38}Cl reactions only the final nuclei are indicated.

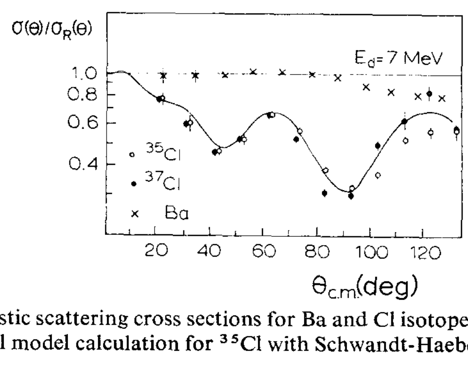

Fig. 2. Deuteron elastic scattering cross sections for Ba and Cl isotopes. The heavy solid line presents an optical model calculation for ^{35}Cl with Schwandt-Haeberli parameters [15]).

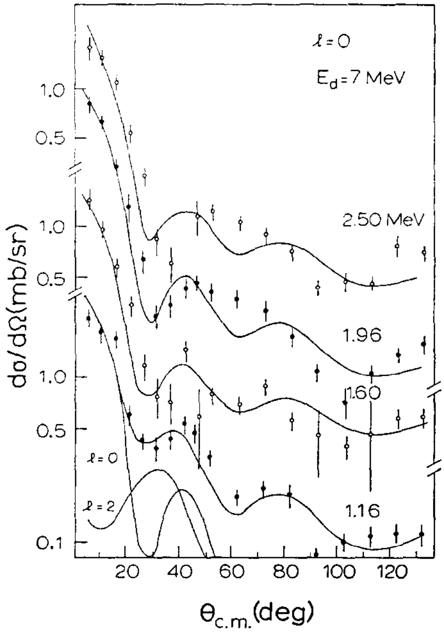

Fig. 3. Experimental differential cross sections. Solid lines present DWBA calculations for $l = 0$. The transition to the 1.16 MeV level contains an $l = 2$ admixture.

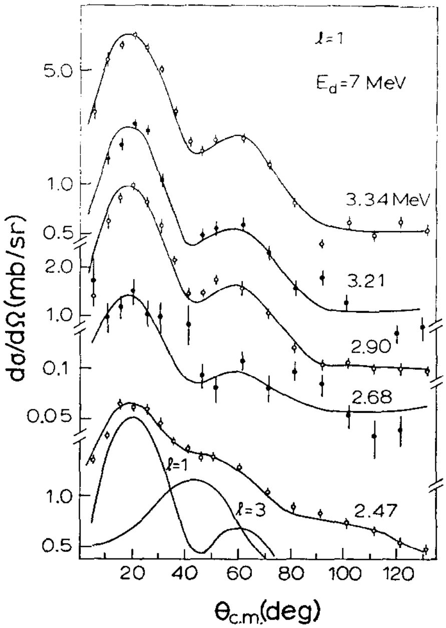

Fig. 4. Experimental differential cross sections. Solid lines present DWBA calculations for $l = 1$. The transition to the 2.47 MeV level contains a strong $l = 3$ admixture.

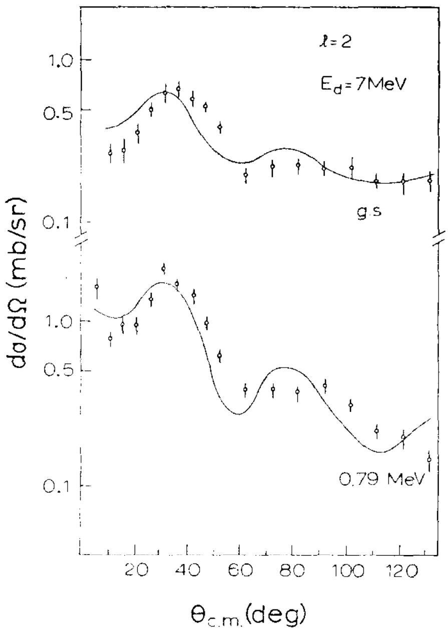

Fig. 5. Experimental differential cross sections. Solid lines present DWBA calculations for $l = 2$.

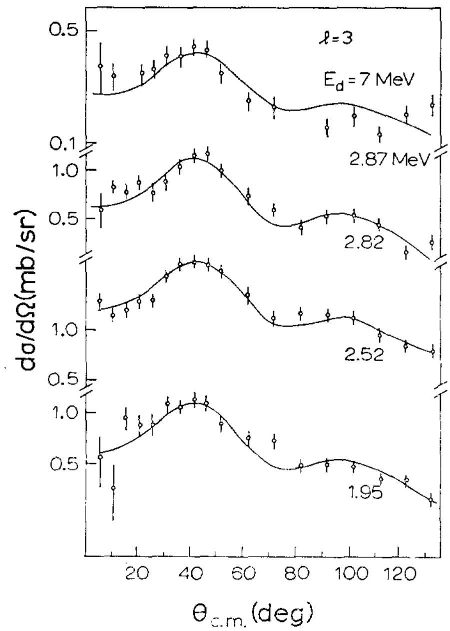

Fig. 6. Experimental differential cross sections. Solid lines present DWBA calculations for $l = 3$.

The deuteron elastic scattering angular distributions for Ba and Cl were also measured. These results were used for the cross-section normalization, and to obtain information on the Cl+d optical model parameters.

3. Results

As a typical example, the proton spectrum at 130° is shown in fig. 1. The average FWHM of the proton peaks is 4.5 keV. Peaks originating from other reactions, mainly ^{35,37}Cl(d, α)^{33,35}S, can be easily recognized from their energy variation with angle. At angles where these peaks coincided with ^{35}Cl(d, p)^{36}Cl peaks, their contribution could be estimated and subtracted by linear interpolation from the spectra taken at neighbouring angles where the peaks were well separated.

The measured angular distributions are presented in figs. 3–6. The absolute calibration of the cross section was based on the assumptions that the chemical composition of $BaCl_2$ did not change under bombardment and that the elastic scattering of 7 MeV deuterons by Ba is of Rutherford character for angles smaller than 60° [ref. [11]]. The ratio of the measured Ba scattering cross section to the Rutherford cross section was indeed constant for angles up to 90° (see fig. 2). The measured constant was taken as the cross-section normalization factor in the (d, p) experiment. During the experiment the ratio of chlorine and barium elastic peaks in the monitor spectrum was constant within the experimental error. The total error in the absolute cross-section calibration was estimated as 10 %.

No attempts were made to measure exact excitation energies because of the non-linearity of the pulses from the position sensitive detectors. Nevertheless, a good value could be obtained for the separation of the components of the doublet at E_x = 1.95 MeV [refs. [7,8,12-14]]. The non-linearity of the detector was taken into account by measuring the separation of the components at different positions on the detector. The result, 8.2±0.4 keV, is in good agreement with but more accurate than the value 8±1 keV obtained by Groshev *et al.* [14]) from the ^{35}Cl(n, γ)^{36}Cl reaction.

4. Analysis

The experimental results were compared with DWBA calculations performed on the IBM computer of the Technische Hogeschool in Delft with the use of the code DWUCK. The deuteron optical model parameters were taken from empirical expressions given by Schwandt and Haeberli [15]). The comparison between the optical model calculations and the measured elastic scattering angular distribution is shown in fig. 2. The agreement is satisfactory which implies that the average Schwandt-Haeberli parameters describe ^{35}Cl sufficiently well.

The proton and neutron parameters were taken from a paper by Becchetti and Greenlees [16]). The values of the parameters are listed in table 1. The non-locality parameters in the entrance and exit channels were chosen as 0.54 fm and 0.85 fm,

TABLE 1

Optical model parameters used in the DWBA calculations

	U_R (MeV)	r_R (fm)	a_R (fm)	W_D (MeV)	r_D (fm)	a_D (fm)	$U_{s.o.}$ (MeV)	$r_{s.o.}$ (fm)	$a_{s.o.}$ (fm)	r_{0c} (fm)
d	109.5	1.05	0.85	10.6	1.66	0.55	9.0	0.90	0.60	1.3
p	57.39–0.32 E_p (MeV)	1.17	0.75	12.47–0.25 E_p (MeV)	1.32	0.55	6.2	1.01	0.75	1.3
n	[a]	1.17	0.75	0			$\lambda_{s.o.} = 25$			

[a]) Fitted to binding energy.

respectively [17]). In the calculations a finite-range parameter of 1.24 fm was used for the n-p interaction.

The results of the DWBA calculations are presented in figs. 3–6 as solid lines. The odd-A target implies the possibility of a mixture of two l-values differing by 2. This mixture is incoherent [18]). The least-squares method was used to fit the weighted sum of two DWBA curves to the experimental points. In the fitting also the possibility of an isotropic compound nucleus contribution was included. The spectroscopic factors

TABLE 2

Spectroscopic factors for the $^{35}Cl(d, p)^{36}Cl$ reaction

E_x [a]) (keV)	J^π [a])	$(2J_f+1)S$ Experiment $l = 0$	$l = 1$	$l = 2$	$l = 3$	Theory [b]) $l = 0$	$l = 2$, $j = \frac{3}{2}$	$l = 2$, $j = \frac{5}{2}$
0	2^+	$\leqq 0.05$		3.12		0.03	3.35	0.02
788±2	3^+ [c])			0.77			1.26	0.11
1164±2	$(1)^+$	0.25		0.39		0.22	0.39	0.03
1598±3	$(1, 2)^+$	0.11						
1949±3	2^- [d])				0.81			
1957±3	2^+ [d])	0.40						
2469±3	3^-		0.29		1.02			
2497±5	$(1, 2)^+$	0.12						
2522±5	$\pi = -$				1.77			
2681±5	$\pi = (-)$		(0.02)					
2818±5	$\pi = -$				0.78			
2870±5	3^- [e])				0.22			
2902±5	$\pi = -$		0.55					
3213±6	$\pi = -$		0.19					
3339±5	$\pi = -$		0.68					

[a]) Ref. [19]), unless indicated otherwise.
[b]) Ref. [23]).
[c]) Ref. [21]).
[d]) See text.
[e]) In ref. [21]) $J\pi = 3^-$ and 4^- are left as possibilities. The relatively strong, 6.1 %, transition from the $J^\pi = 2^+$ (n, γ) capture state to this level [14]) excludes the latter possibility.

were extracted from the fitted intensities with the expression

$$\sigma(\theta) = 1.53\frac{2J_f+1}{2J_i+1} S\sigma_{\mathrm{DWBA}},$$

where J_i and J_f are the spins of the target nucleus and the final state, respectively. The values $(2J_f+1)S$ are presented in table 2 and in fig. 7.

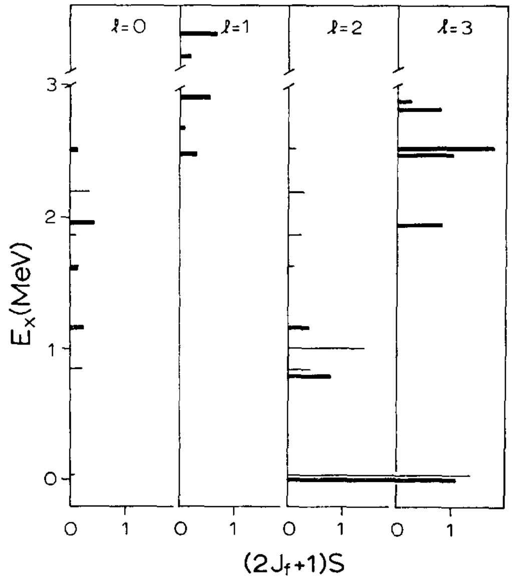

Fig. 7. Spectroscopic factors for the ^{35}Cl(d, p)^{36}Cl reaction. Heavy and thin lines present the experimental results and the calculated values (for $l = 0$ and 2 only) [22], respectively.

5. Discussion

All the l-assignments in the present work are in good agreement with the results of Hoogenboom *et al.* [8]. The angular distribution of the group to the 2.47 MeV level shows both $l = 1$ and $l = 3$ contributions (see fig. 3). This limits the J^π value to $J^\pi = 1^-$, 2^- or 3^-, consistent with an angular correlation assignment $J^\pi = 3^-$ [refs. [20,21]]. The weakly excited 2.68 MeV level seems to exhibit an $l = 1$ pattern (fig. 3). If it can be identified with the 2.68 MeV level strongly excited in the pick-up reaction [22] the present l-assignment is in contradiction with the previously assigned even parity [22]. The measured angular distributions for both components of the doublet at 1.95 MeV show that the upper level has even and the lower odd parity. This fact is in contradiction with ref. [20] in which the opposite parity order is suggested.

The compound nucleus contribution estimated in the present analysis from the least-squares fit does not exceed 5 % for $l = 0$, 1 and 2 transitions except for the 0.79 and 2.68 MeV levels where it reaches a value of 20 %. For all $l = 3$ transitions this contribution is about 15 %.

The statistical error in the extracted spectroscopic factors is not larger than 10 %. A more important source of uncertainties is the choice of the optical parameters used in the DWBA analysis. For example the calculations with Perey's proton parameters [ref. [24])] give results which are lower by about 5 %, 15 %, 30 % and 30–40 % for $l = 0$, 1, 2 and 3 transitions, respectively. An additional uncertainty appears if the compound nucleus contribution is large, i.e. for the $l = 2$ transitions to the 0.79 and 2.68 MeV levels and for all $l = 3$ transitions. Taking into account the 10 % uncertainty in the absolute calibration one can conclude that the total error in the obtained spectroscopic factors is 20–30 % for $l = 0$ or $l = 1$ transitions and can reach 50–60 % for $l = 2$ or 3 transitions. These errors are typical for DWBA analyses [see e.g. ref. [25])].

The measured spectroscopic factors are compared (fig. 7 and last columns of table 2) with values calculated by Wildenthal [23]) for even-parity states. In these calculations ^{16}O is assumed to be an inert core and the Kuo-Hamada-Johnston interaction is applied for particles in the $2s_{\frac{1}{2}}$, $1d_{\frac{3}{2}}$ and $1d_{\frac{5}{2}}$ orbitals. The calculated spectroscopic factors for the three lowest levels agree well with the experimental values (see table 2).

The energy difference between the unperturbed $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ orbitals obtained by weighting the energies with the spectroscopic factors is 1.3–1.4 MeV (this result is dependent on the assumed spins for the $l = 0$ levels). This is in good agreement with the value of 1.22 MeV calculated for this mass region [1]).

The $l = 3$ levels are grouped in the $E_x = 2.5$ MeV region and lie on the average about 2.1 MeV above the unperturbed $d_{\frac{3}{2}}$ level. This is in not too bad agreement with the value of 2.9 MeV calculated by Erné [26]) for the separation between the $f_{\frac{7}{2}}$ and $d_{\frac{3}{2}}$ single-particle levels in this mass region.

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References

1) P. W. M. Glaudemans, G. Wiechers and P. J. Brussaard, Nucl. Phys. **56** (1964) 548
2) B. H. Wildenthal and P. W. M. Glaudemans, Nucl. Phys. **A108** (1968) 49
3) A. E. L. Dieperink and P. J. Brussaard, Nucl. Phys. **A128** (1969) 34
4) B. H. Wildenthal, E. C. Halbert, J. B. McGrory and T. T. S. Kuo, Phys. Lett. **32B** (1970) 339
5) C. H. Paris, W. W. Buechner and P. M. Endt, Phys. Rev. **100** (1955) 1317
6) J. S. King and E. H. Beach, Phys. Rev. **90** (1953) 381
7) I. B. Teplov, ZhETF (USSR) **31** (1956) 25; JETP (Sov. Phys.) **4** (1957) 31
8) A. M. Hoogenboom, E. Kashy and W. W. Buechner, Phys. Rev. **128** (1962) 305
9) J. E. Spencer and H. A. Enge, Nucl. Instr. **49** (1967) 181
10) A. C. Wolff and H. G. Leighton, Nucl. Phys. **A140** (1970) 319
11) J. Rapaport and A. K. Kerman, Nucl. Phys. **A119** (1968) 641
12) J. E. Draper and A. A. Fleischer, Phys. Rev. **122** (1961) 1585
13) R. E. Segel, Phys. Rev. **113** (1959) 844

14) L. V. Groshev, A. M. Demidov and V. N. Lutsenko, Izv. Akad. Nauk USSR (ser. fiz.) **24** (1960) 833
15) P. Schwandt and W. Haeberli, Nucl. Phys. **A123** (1969) 401
16) F. D. Becchetti and G. W. Greenlees, Phys. Rev. **182** (1969) 1190
17) K. K. Seth, J. Picard and G. R. Satchler, Nucl. Phys. **A140** (1970) 577
18) G. R. Satchler, Nucl. Phys. **55** (1964) 1
19) P. M. Endt and C. van der Leun, Nucl. Phys. **A105** (1967) 1
20) G. van Middelkoop and P. Spilling, Nucl. Phys. **77** (1966) 267
21) J. Kopecky and E. Warming, Nucl. Phys. **A127** (1969) 385
22) L. Broman, C. M. Fou and B. Rosner, Nucl. Phys. **A112** (1968) 195
23) B. H. Wildenthal (East Lansing, Michigan) private communication
24) F. G. Perey, Phys. Rev. **131** (1963) 745
25) M. Fazio, S. Micheletti, M. Pignanelli and L. Zetta, Nuovo Cim. **51B** (1967) 459
26) F. C. Erné, Nucl. Phys. **84** (1966) 91