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ODD PARITY LEVELS EXCITED IN THE ^{37}Cl(p, γ)^{38}Ar REACTION

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Abstract: From angular correlation and polarization measurements performed at two resonances in the ^{37}Cl(p, γ)^{38}Ar reaction, the spins and parities of levels at 4.49, 4.60, 5.67, 11.30 and 11.31 MeV have been determined to be $J^\pi = 4^-, 5^-, 5^-, 5^-$ and 5^-, respectively. The two high-energy states are very probably the (split) analogue of the first excited state in ^{38}Cl. The decay mainly proceeds, where possible, through M1 radiation, in five- and six-step cascades. The $5^- \rightarrow 5^-$ transitions are much stronger than the $5^- \rightarrow 4^-$ transitions. An explanation is suggested in terms of the predominant configurations involved. The experimental excitation energies are compared with energy values obtained in a recent shell-model calculation.

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NUCLEAR REACTION ^{37}Cl(p, γ), $E = 1.088$ and 1.092 MeV; measured E_γ, I_γ, p$\gamma(\theta)$, $\gamma\gamma(\theta)$, γ-polarization. ^{38}Ar deduced levels, J, π, multipolarity mixings. Enriched target.

1. Introduction

The ^{37}Cl(p, γ)^{38}Ar reaction shows a prodigious amount of resonances; most of them have not been investigated previously. An excitation curve for proton energies from 0.80 to 2.05 MeV has recently been reported by Simons *et al.* [1]). The study of the gamma decay is facilitated by the determination of the level energies in ^{38}Ar up to 6.88 MeV from the ^{41}K(p, α)^{38}Ar reaction by Allas *et al.* [2]). The investigation of two resonances at $E_p = 1.088$ and 1.092 MeV is reported here. Angular correlation and polarization measurements have led to the assignment of $J^\pi = 4^-$ to the 4.49 MeV level and $J^\pi = 5^-$ to the 4.60, 5.67, 11.30 and 11.31 MeV levels in ^{38}Ar. The excitation energies of these levels can be compared with recent shell-model predictions.

The decay of the resonances is strikingly similar, proceeding mainly through five- and six-step cascades. This multi-step decay considerably complicates the proof of uniqueness of the assigned spins and parities. In an investigation of triple correlations in the ^{35}Cl(p, $\gamma\gamma$)^{36}Ar reaction [3]), the analysis of multiple cascades was conclusive only if results from several pairs of transitions were combined. This procedure would entail a large amount of computation in the present case. Therefore a slightly different procedure was followed; the analysis in one least-squares fit of accurately measured polarizations and angular distributions of nearly all intense gamma rays observed at a resonance was sufficient.

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2. Experimental Procedure

The apparatus used to investigate (p, γ) reactions has been described previously by Van Rinsvelt and Smith [4]). Protons from the Utrecht 3 MV Van de Graaff accelerator pass through a 90° analysing magnet and a liquid air trap before hitting the water-cooled target. The liquid air trap has been recently described by Vuister [5]). The target consists of $BaCl_2$ enriched to 99 % ^{37}Cl, evaporated onto a tantalum or copper backing. The target thickness was about 1 keV for protons of 1.1 MeV.

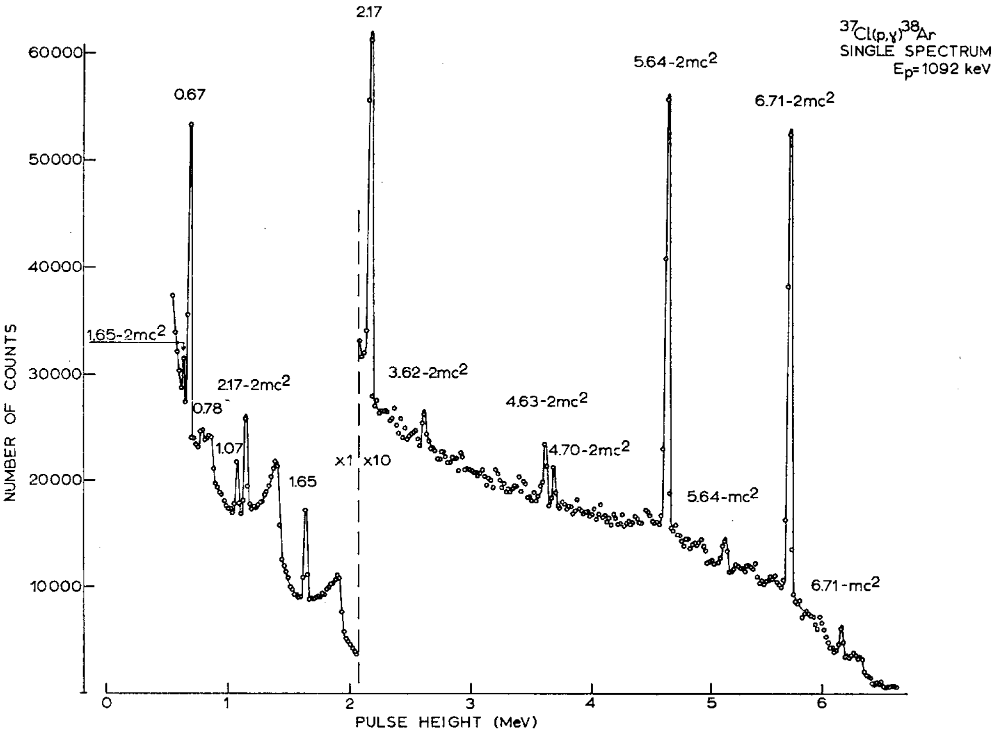

Fig. 1. Single spectrum measured at the E_p = 1092 keV resonance with a Ge(Li) detector.

The gamma rays are detected in two cylindrical NaI scintillation crystals, 10 cm thick and 10 cm in diam., and a Li-drifted germanium detector with a 3 cm^2 area and a 0.5 cm depletion depth. The detectors are mounted on a turntable and are movable in the horizontal plane; one scintillation detector can be placed in a vertical position above the target. The spectra are recorded with a 400-channel RIDL analyser. The intensities of the transitions are generally derived from a least-squares fit of standard line shapes to the recorded pulse-height distributions.

The polarization measurements are performed with the Compton-scattering method as described by Suffert, Endt and Hoogenboom [6]). The arrangement used has been recently described [3]).

3. Results

3.1. GAMMA DECAY

The single spectrum of the 1092 keV resonance is shown in fig. 1. The main decay (40 % to the 5.67 MeV and 60 % to the 4.60 MeV level) has been derived from the intensities and energies of transitions in single and coincidence spectra. The energies of the low-energy transitions from 0.11 to 2.17 MeV differed less than 0.005 MeV from the energy differences that can be derived from the level energies given by Allas *et al.* [2]).

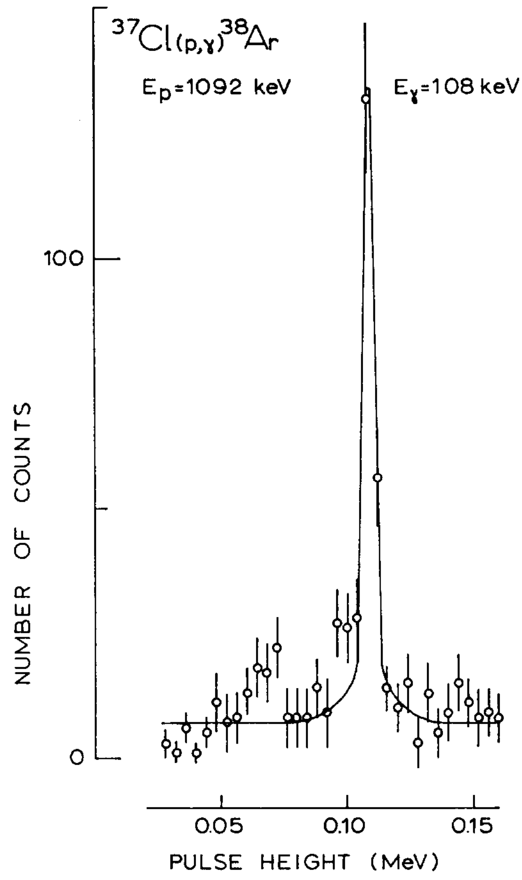

Fig. 2. Coincidence spectrum measured at the $E_p = 1092$ keV resonance. The Ge(Li) spectrum was in coincidence with pulses from a 10×10 cm scintillation detector with a gate on the 0.67 MeV γ-ray. Background as measured with a gate at a slightly higher energy setting has been subtracted.

The 1088 keV resonance shows a decay nearly identical to that of the 1092 keV resonance but with a slightly different branching ratio for the transitions to the 5.67 and 4.60 MeV levels. Weaker transitions with a total intensity of at most 10 % are observed in the single spectra of both resonances; these probably belong to weak cascades via levels at 6.61, 6.68 and 7.69 (all ±0.02) MeV.

The strengths of the resonances $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$ have been obtained from relative yield measurements. The strength of the 847 keV resonance in ^{37}Cl(p, γ)^{38}Ar was used as a standard. It was determined to be 1.05±0.15 eV by Engelbertink and Endt [7]). The results for the 1088 and 1092 keV resonances are 3.5±0.5 and 6.9±1.0 eV, respectively.

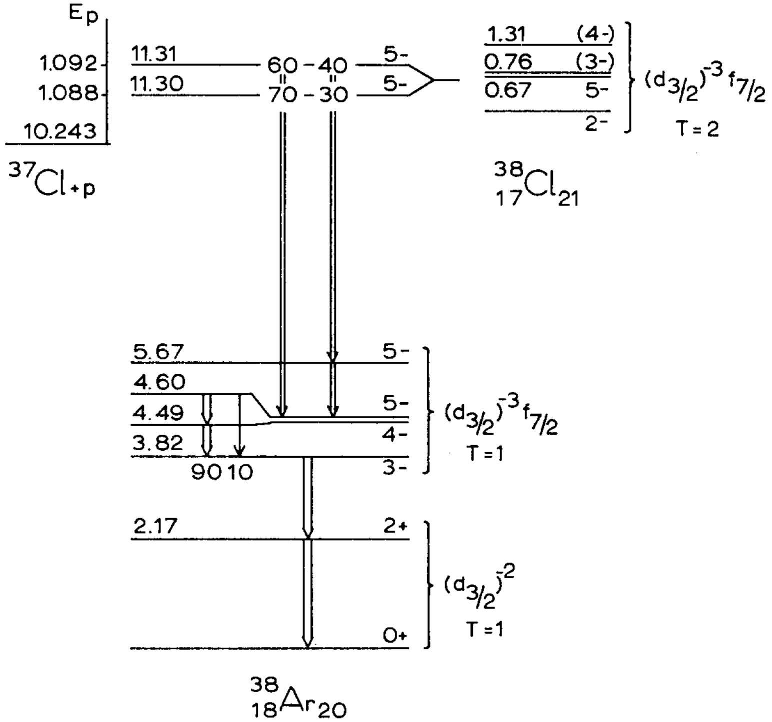

Fig. 3. Main decay of the E_p = 1088 and 1092 keV resonances. The $J^\pi = 4^-$ and 5^- assignments are derived from the present investigation.

The 5.67 MeV level decays 100 % to the 4.60 MeV level. From comparison of coincidence spectra with gates at the 6.71 and 5.64 MeV lines, an upper limit of 3 % can be set for the intensity of the 1.85 MeV transition to the 3.82 MeV level and an upper limit of 10 % for the 1.18 MeV transition to the 4.49 MeV level.

The 4.60 MeV level decays 90 % to the 4.49 MeV level through a 0.108 MeV line; 10±2 % of the decay directly proceeds to the 3.82 MeV level. A spectrum showing the 0.108 MeV line in coincidence with the 0.67 MeV transition is given in fig. 2.

The 4.49 MeV level decays 100 % to the 3^- level at 3.82 MeV. An upper limit of 2 % for the 2.32 MeV transition to the 2.17 MeV line can be derived from coincidence spectra.

The 3.82 MeV level again, decays 100 % to the 2.17 MeV level. A 0.05 % ground state transition of the level has recently been observed by Robinson [8]).

The main decay, observed at both resonances, is summarized in fig. 3. The decay is very unusual. In fact, the 0.108 MeV transition was first overlooked. The primary decays were thought to proceed to the 5.56 and 4.49 MeV levels. The weak 0.78 MeV transition could not be fitted in this interpretation, however. In spectra taken with NaI crystals, the 0.78 MeV line proved to be coincident with all other transitions except the 0.67 MeV line. It was accordingly interpreted as arising from the decay of the 4.60 MeV level. However, a primary transition to this level could not be found in the high resolution Ge(Li) spectra. The problem was solved when the energy calibration of the high-energy transitions was performed with sufficient accuracy to reveal that the primary decay proceeds to the 5.67 and 4.60 MeV levels and not to the 5.56 and 4.49 MeV levels. For the observation of the 0.108 MeV line, the tantalum backings were unsuitable because of the strong Coulomb excitation lines of ^{181}Ta. Good results were obtained with copper backings.

3.2. ANGULAR CORRELATION AND POLARIZATION MEASUREMENTS

The angular distributions of most of the observed gamma rays were measured with a scintillation detector at 10 cm from the target. Corrections for eccentricity of the target were measured with radiation from the isotropic decay of the 622 keV resonance in $^{30}Si(p, \gamma)^{32}P$. The angular distribution of the 0.11 MeV line was measured at a distance of 2.6 cm from the target with the Ge(Li) detector. Corrections for absorption of radiation in the copper backing and the target holder were accurately determined for the 0.11 MeV line. For this purpose, angular distributions were measured with and without an additional copper plate of 1.5 mm thickness between target and detector and parallel to the target.

The angular distributions are expanded in a Legendre polynomial series $W(\theta) \propto 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$, where θ is the angle between the gamma ray and the proton beam direction. The results are given in table 1. Most results for low-energy gamma rays had to be corrected for intensity losses due to coincident summing, since the intensities were mainly determined from the areas under the photopeaks. Effects from summing in five- and six-step cascades cannot be neglected, since the detector efficiency at 10 cm is about 3 %. In a previous paper [3]) a simple expression was given for angular distributions of sum pulses. If spins and multipolarities are unknown, the sum distribution of two radiations with angular distributions $W_1(\theta)$ and $W_2(\theta)$ can be approximated by $W_{\text{sum}}(\theta) \cong W_1(\theta)W_2(\theta)$. The intensity loss for γ_1 due to summing with γ_2 is $etW_{\text{sum}}(\theta)$, where e is the detector efficiency and t the fraction of γ_2 which is coincident with γ_1. The corrections applied to the A_2 coefficients were of the order of 0.00 to 0.04. The corrections to the A_4 coefficients were negligible.

Additional triple correlation measurements were performed at the 1092 keV resonance, in the geometries I, II, V and VI (see ref. [3])). They were measured in the form of coincidence spectra at several combinations of angles. The results are shown in

TABLE 1

Results from angular distribution and polarization measurements at the 1088 and 1092 keV resonances

E_γ (MeV)	Angular distributions A_2	A_4	Polarization effect pP	Polarization efficiency p
1088 keV resonance				
6.71	$+0.38\pm0.03$	-0.03 ± 0.03 }	$+0.06\pm0.03$	0.10
5.64	$+0.30\pm0.03$	-0.02 ± 0.03 }		
2.17	$+0.30\pm0.02$	-0.09 ± 0.02		
1.65	-0.23 ± 0.02	-0.01 ± 0.02		
1.07	$+0.30\pm0.07$	-0.03 ± 0.07		
0.67	-0.22 ± 0.02	-0.02 ± 0.02		
1092 keV resonance				
6.71	$+0.38\pm0.03$	-0.04 ± 0.03 }	$+0.05\pm0.02$	0.10
5.64	$+0.33\pm0.03$	-0.02 ± 0.03 }		
2.17	$+0.32\pm0.02$	-0.05 ± 0.02	$+0.14\pm0.03$	0.25
1.65	-0.19 ± 0.02	$+0.00\pm0.02$	$+0.12\pm0.02$	0.32
1.07	$+0.30\pm0.04$	-0.02 ± 0.04	$+0.29\pm0.06$	0.44
0.78	$+0.29\pm0.02$	-0.09 ± 0.02	$+0.19\pm0.09$	0.52
0.67	-0.18 ± 0.02	-0.02 ± 0.02	-0.17 ± 0.02	0.56
0.11	-0.24 ± 0.03	$+0.01\pm0.04$		

TABLE 2

Results from triple angular correlation measurements at the 1092 keV resonance

Transitions (MeV)	Geometry	A_2	A_4
6.71−0.67	I	$+0.41\pm0.04$	$+0.01\pm0.04$
6.71−0.67	II	-0.12 ± 0.05	-0.02 ± 0.06
6.71−0.67	V	$+0.27\pm0.04$	-0.01 ± 0.05
6.71−0.67	VI	-0.24 ± 0.04	-0.03 ± 0.04
5.64−1.07	I	$+0.13\pm0.06$	-0.06 ± 0.06
5.64−1.07	II	$+0.17\pm0.05$	$+0.01\pm0.05$
5.64−1.07	V	$+0.70\pm0.08$	$+0.04\pm0.08$
5.64−1.07	VI	$+0.72\pm0.07$	$+0.01\pm0.07$
5.64−0.67	I	$+0.39\pm0.05$	$+0.03\pm0.06$
5.64−0.67	II	-0.13 ± 0.05	$+0.00\pm0.06$
5.64−0.67	V	$+0.27\pm0.05$	-0.05 ± 0.05
5.64−0.67	VI	-0.24 ± 0.05	$+0.01\pm0.05$

table 2. These measurements are not corrected for coincident summing. In the subsequent analysis, all double and triple correlations measurements are still to be corrected for solid angle attenuation [3]).

An outline of the χ^2 methods used for the analysis of double and triple correlations in multiple cascades has recently been given in ref. [3]). Possible solutions are generally excluded if the χ^2 value is above the 0.1 % limit.

Measurements of the polarizations P were performed with the Compton-scattering method [3,6]. The measured effect is expressed in the quantity $pP = (N_{90}-N_0)/(N_{90}+N_0)$, where N_{90} and N_0 are the intensities observed at 90° and 0°. The 90° direction lies in the plane perpendicular to the proton beam. The results are given in table 1. The polarization efficiencies p of the polarimeter, calculated as in ref. [6], are listed in the last column of table 1.

3.3. DETERMINATION OF SPINS AND PARITIES

As the angular distribution and polarization data for similar transitions at both resonances are identical within the errors, conclusions derived from these data for one resonance also apply to the other resonance.

The analysis proceeds in steps, starting with the lowest levels. The spins of the 3.82 and 2.17 MeV levels are known to be 3^- and 2^+, respectively [9]. The mixing ratio of the 3.82 → 2.17 MeV transition can be determined from the angular distributions and polarizations of the 1.65 and 2.17 MeV transitions, since the resonance decay proceeds 100 % via the 3.82 and 2.17 MeV levels. The ratios $A_{2(1.65)}/A_{2(2.17)}$, $A_{4(1.65)}/A_{4(2.17)}$ and $P_{(1.65)}/P_{(2.17)}$ depend on the mixing ratio of the 1.65 MeV transition only. A least-squares fit to data from both resonances gives the result $x_{1.65} = -0.01 \pm 0.02$. Here x is the amplitude ratio of quadrupole to dipole radiation.

As a second step, the angular distribution and polarization of the 4.49 → 3.82 MeV transition are included in a similar analysis together with the data for the 1.65 and 2.17 MeV transitions. The resonance decay proceeds 90 % via the 4.49 MeV level. The small effects from the 10 % 4.60 → 3.82 MeV transition on the angular distributions of the 1.65 and 2.17 MeV transitions are neglected at this stage. Corrections in the A_2 and A_4 coefficients in the ultimate analysis, with the known spin values inserted, proved to be smaller than 1 %. A least-squares analysis for data from both resonances proves $J^{\pi}_{4.49}$ to be 4^-; the value of the E2/M1 mixing ratio for the 4.49 → 3.82 MeV transition is $x_{0.67} = -0.01 \pm 0.02$. All other possible solutions $J^{\pi} = 1^{\pm}, 2^{\pm}, 3^{\pm}, 4^+$ and $5^{\pm}$ have values of χ^2 higher than the 0.1 % limit.

Next, the spin and parity of the 4.60 MeV level are determined. To this end the angular distribution of the 0.11 MeV line is included into the analysis. The spin possibilities $J_{4.60} = 2$ or 4 can be rejected. For $J_{4.60} = 5$ a good fit is obtained with $x_{0.11} = +0.02 \pm 0.03$, and for $J_{4.60} = 3$ with $x_{0.11} = -0.11 \pm 0.03$. For these solutions the analysis is continued by including in the calculations the angular distribution and polarization measurements of the (intensity 10 %) 0.78 MeV transition. A good fit is obtained for $J^{\pi}_{4.60} = 5^-$ with pure electric quadrupole radiation for the 0.78 MeV line and for $J^{\pi}_{4.60} = 3^+$ with $x_{0.78} = -1.5 \pm 0.2$. The M2/E1 mixings of the 0.11 and 0.78 MeV transitions found for $J^{\pi}_{4.60} = 3^+$ are very improbable. The radiation mixing of the 0.11 MeV line would entail a measurable lifetime for the 4.60 MeV level. The lifetime was checked to be smaller than 5 ns with a conventional combination of fast and slow coincidence circuits with a 50 ns resolution time. This measurement limits the mixing ratio $x_{0.11}$ to at most 0.01 if M2 radiation with a strength of 6 Weisskopf units is admitted. The possibility $J^\pi = 3^+$ can therefore be rejected.

The spins and parities of the resonances and the 5.67 MeV level are determined by a least-squares fit of the resonance formation parameters and the mixing ratios of the 6.71, 5.64 and 1.07 MeV transitions to (i) the angular distributions of the 6.71, 5.64 and 1.07 MeV lines, (ii) the polarization of the 1.07 MeV line, (iii) the average branching ratio for the 6.71 and 5.64 MeV transitions at both resonances, (iv) the tensor parameters $\rho_{20}(JJ)$ and $\rho_{40}(JJ)$ derived for the 4.60 MeV level from the previous analysis. The least-squares fit has been performed for the 30 spin and parity combinations that allow for radiation mixtures up to pure quadrupole radiation and proton orbital momenta up to $l = 4$. Two solutions give values of χ^2 below the 0.1 % limit. For these solutions the resonance parity is determined from the polarization measurement of the 6.71 and 5.64 MeV transitions together. One solution is found for $J^\pi_{\text{res}} = 4^+$, $J^\pi_{5.67} = 5^-$, $x_{6.71} = +0.61 \pm 0.15$, $x_{5.64} = +0.47 \pm 0.15$ and $x_{1.07} = +0.1 \pm 0.1$. This solution can be rejected as it would entail magnetic quadrupole components in the 6.71 and 5.64 MeV transitions of at least 20 and 40 Weisskopf units for the 1088 and 1092 keV resonance, respectively. The other solution is obtained for $J^\pi = 5^-$ for both the resonances and the 5.67 MeV level. This result is confirmed for the 1092 keV resonance by the analysis of the triple correlation measurements performed (see sect. 4). The spin and parity assignments made are summarized in fig. 3.

TABLE 3
Gamma-ray mixing ratios derived from the present experiment

Transition (MeV)	Mixing ratio x	
1.65	-0.01 ± 0.02	
1.07	$+0.10 \pm 0.09$	
0.67	-0.01 ± 0.02	
0.11	$+0.02 \pm 0.03$	
6.71	$+0.03 \pm 0.06$	1088 keV resonance
5.64	$+0.19 \pm 0.06$	1088 keV resonance
6.71	$+0.03 \pm 0.06$	1092 keV resonance
5.64	$+0.13 \pm 0.06$	1092 keV resonance

The values for the tensor parameters of the resonance level, $\rho_{20}(JJ)/\rho_{00}(JJ) = -0.92 \pm 0.05$ and $\rho_{40}(JJ)/\rho_{00}(JJ) = +0.8 \pm 0.2$ fit reasonably well to values of these parameters for f-capture via channel spin 2, which are $\rho_{20}(JJ)/\rho_{00}(JJ) = -0.98$ and $\rho_{40}(JJ)/\rho_{00}(JJ) = +0.70$. From the measured yield at the 1092 keV resonance a lower limit can be obtained for the proton width. It accounts for at least 2.5 % of the Wigner limit for f-capture.

The best values for the radiation mixing ratios at both resonances are given in table 3. The mixing ratios of the 6.71, 5.64 and 1.07 MeV transitions have been computed under the assumption that the resonances are formed by pure f-capture.

4. Discussion

The combined analysis of angular distribution and polarization measurements as presented here is thought to be an economic way of obtaining definite evidence for the spins involved in the case investigated. The analysis of the triple correlation measurements performed (see table 2) does not lead to a unique result. The measurement and the analysis of more of these data would be inacceptably lengthy. Another difficulty in the triple correlation measurements is the correction for coincident summing effects. Crude estimates indicate that these amount to 15 % in some of the geometries. The correct calculation of these effects is by no means so easy as for the angular distribution measurements. If the radiation were detected at larger distances from the target, the summing effects would be reduced. However, the statistics would be so much worse that no advantage is obtained in this way. Within the limitations mentioned, the triple correlation results are in good agreement with those from the angular distribution and polarization measurements, but they do not aid to the accuracy in the determination of radiation mixing ratios.

The excitation energies of the odd parity levels excited in the present investigation can be compared with values that have been recently predicted from a shell-model calculation [10]). In this calculation a closed-shell ^{32}S core was assumed with extra nucleons in the $1d_{\frac{3}{2}}$ shell and one nucleon in the $1f_{\frac{7}{2}}$ shell. The excitation energies were calculated with the effective parameter method [11]). A total of 14 energy parameters were fitted with a least-squares procedure to the energies of 60 nuclear levels. A $2^-, 3^-, 4^-, 5^-$ quadruplet of mainly seniority $v = 2$ was predicted at excitation energies 4.78, 3.68, 4.12 and 4.59 MeV, respectively. This is in good agreement with the present experiment, where 3^-, 4^- and 5^- levels are excited at 3.82, 4.49 and 4.60 MeV, respectively. A second quadruplet was predicted, with a 5^- level at 5.51 MeV; the experimental value is 5.67 MeV.

The 5^- resonances probably correspond to the same configuration, but with isospin $T = 2$. They can thus be considered as the split analogue of the 5^- level at 0.67 MeV in ^{38}Cl. After correction for Coulomb energy and proton-neutron energy mass difference, the energies of the resonances and the ^{38}Cl level differ by about 70 keV. An indication for the isospin assignment is also the relatively large reduced proton width of the resonances. From the (p, γ) yield one finds that for both resonances together it amounts to at least 0.04. This can be compared with the pure single-particle value of 0.25, if the isospin is taken into account. Recently, Rapaport and Buechner (ref. [12])) have performed a DWBA analysis of ^{37}Cl(d, p)^{38}Cl differential cross-section measurements. They found a reduced neutron width for the 0.67 MeV level close to the single-particle value. From comparison one might expect $\Gamma_p > \Gamma_\gamma$ in the case investigated here, such that Γ_γ can be obtained approximately from the yield of the $^{37}Cl(p, \gamma)^{38}Ar$ reaction. The splitting may be due to the presence of a $J^\pi = 5^-$, $T = 1$ resonance of a different configuration. Coulomb interaction might appreciably mix the isospins of these levels.

Another feature of the 5^- resonances is the preferential decay to bound 5^- states. One can try to understand this qualitatively by considering the shell-model configurations involved. The main components of the configurations of the odd parity levels with spin J and isospin T would be $|(1d_{\frac{3}{2}})jt,\ 1f_{\frac{7}{2}};\ JT\rangle$. Here, the five nucleons in the $1d_{\frac{3}{2}}$ shell are coupled to $j = \frac{3}{2}$ with isospin $t = \frac{1}{2}$ or $\frac{3}{2}$. If the dominating part of the M1 operator operates on the particle in the $1f_{\frac{7}{2}}$ shell, the dependence of the transition strength on the initial spin J_i and the final spin J_f is expressed by the factor

$$(2J_i+1)(2J_f+1)\begin{Bmatrix} J_i & J_f & 1 \\ \frac{7}{2} & \frac{7}{2} & \frac{3}{2} \end{Bmatrix}^2 .$$

Here, the expression in curly brackets is a 6-j symbol.

This factor favours $J_i \rightarrow J_f = J_i$ transitions over $J_i \rightarrow J_f = J_i \pm 1$ transitions by an order of magnitude. In the case that $J_i = 5$, the transition to $J_f = 5$ would be favoured by a factor 14 over the transition to $J_f = 4$. This argument could also apply to the decay of the 5.67 MeV level, see fig. 3.

A complete calculation in which anomalous g-factors are used and the value $t = \frac{3}{2}$ inserted in the expressions for the wave functions of the initial and final states gives transition strengths of 9.7 Weisskopf units for the resonance decay to the 5^- level and 0.6 Weisskopf units for the decay to the 4^- level. The contribution from the part of the M1 operator that operates on the nucleons in the $1d_{\frac{3}{2}}$ shell appears to be small in this calculation. In the case that $t = \frac{1}{2}$ is inserted in the expression for the wave function of the final state, the transition strength is due to this part only. From the experiment, approximate values can be derived for the strengths of the transitions to the 5.67 and 4.60 MeV levels, if the assumption $\Gamma_p > \Gamma_\gamma$ is used. These are much smaller than the calculated values; moreover the strength is almost equally divided between the two transitions. However, the qualitative argument given above may remain valid for the relative strengths of transitions to levels with different spins.

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