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INVESTIGATION OF THE ^{24}Mg(d, p)^{25}Mg REACTION

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Abstract: Proton angular distributions from the ^{24}Mg(d, p)^{25}Mg reaction at $E_d = 12.0$ MeV have been measured with a split-pole magnetic spectrograph for $E_x < 6$ MeV at an average resolution (FWHM) of 7 keV. New l_n values have been determined for three levels. A DWBA analysis yielded spectroscopic factors for 17 levels. A comparison has been made with shell-model and collective model results.

E NUCLEAR REACTION ^{24}Mg(d, p), $E = 12.0$ MeV; measured $\sigma(E_p, \theta)$. ^{25}Mg deduced levels, l_n and S; enriched target.

1. Introduction

The ^{24}Mg(d, p)^{25}Mg reaction has frequently been used in studies of the direct reaction mechanism, in particular for low-lying levels of ^{25}Mg. Deuteron-stripping experiments leading to ^{25}Mg and coupled-channel calculations, including indirect transitions via rotational excitation of the ^{24}Mg target nucleus and the ^{25}Mg final nucleus, are reported in refs. [1–5]).

Special attention has been paid [6–8]) to the 1.61 MeV $\frac{7}{2}^+$ state of the $K = \frac{5}{2}$ ground-state band in ^{25}Mg. Deuteron one-step stripping to this level is forbidden. Compound-nucleus cross sections have been calculated with the Hauser-Feshbach model [9,10]).

Much less attention has been focussed on spectroscopic information that can be obtained from the ^{24}Mg(d, p)^{25}Mg reaction. Only relative spectroscopic factors and l_n values are reported in refs. [11,12]). The dependence of the spectroscopic factors for some positive parity states on optical potential parameters has been studied in ref. [13]). A preliminary report on spectroscopic factors from the ^{24}Mg(α, τ)^{25}Mg reaction at $E_\alpha = 70$ MeV has appeared recently [14]).

The present investigation has mainly been performed to determine absolute spectroscopic factors. It is important to have reliable experimental spectroscopic information for a meaningful comparison with shell-model calculations which succeeded to produce generally accurate single-nucleon spectroscopic factors [15]). The present paper describes the determination of spectroscopic factors of seventeen levels of ^{25}Mg with an excitation energy below 6 MeV, populated by the ^{24}Mg(d, p)^{25}Mg reaction ($Q = 5.11$ MeV) at $E_d = 12.0$ MeV. The angular distributions of the proton groups were analysed with the DWBA theory.

2. Experiment

A deuteron beam was obtained from the 6 MV tandem Van de Graaff accelerator of the Utrecht University. The reaction protons were detected with seven position sensitive detectors placed in the focal plane of an Enge split-pole magnetic spectrograph. Teflon foils in front of the detectors were used to absorb deuterons and α-particles. For each detector coincident position (P) and energy (E) pulses were measured. The spectra of the pulse height ratios (P/E) were derived and analysed, on- and off-line, with a CDC 1700 computer [16]). The background was minimized by setting a lower threshold for the energy pulse height. Proton angular distributions have been measured in the range $\theta_{lab} = 5° - 120°$ in steps of 5°. Since the most distinctive features are observed at small angles, the differential cross section was also measured at 3°, 7.5° and 12.5°. Two different positions of the position sensitive detectors were used to detect all proton groups corresponding to excitation energies up to 6 MeV. A proton spectrum at $\theta_{lab} = 15°$ is shown in fig. 1. It is a composition of the spectra of the various detectors. The average background is less than two counts per channel and the resolution (FWHM) is typically 7 keV. Less than 3.5 keV spread in the proton energies is due to the target thickness, which consisted of about 20 μg/cm^2 ^{24}Mg, enriched to 99.9 %, evaporated onto a 10 μg/cm^2 carbon foil [17]).

As is shown in fig. 1 proton groups from the (d, p) reaction on the contaminants ^{12,13}C, ^{14}N, ^{16}O and ^{28}Si were also observed. These groups could be identified by means of their characteristic kinematical shifts and their energies [18,19]). All known ^{25}Mg levels with $E_x < 6$ MeV [see ref. [18])] were excited and, except for the 3.41 MeV doublet, the corresponding proton groups were completely separated at all angles.

An additional high-resolution measurement was performed at 15° and 60° with a 1.5 cm long position sensitive detector to search for close doublets between $E_x = 2.5$ and 5.9 MeV. The resolution obtained varied from 4.0 to 5.5 keV FWHM. The 3.41 MeV doublet could only be separated partly. The 3.405 MeV level has $J^\pi = \frac{9}{2}^+$ and is weakly excited in the deuteron stripping process, whereas the 3.414 MeV $J^\pi = \frac{3}{2}^-$ level shows a very strong single-particle character. The other transitions show no doublet structure within 6 keV. This is confirmed by recent γ-ray measurements [20,21]).

Relative cross sections were obtained by normalizing the yield of reaction protons to the yield of deuterons elastically scattered from ^{24}Mg at $\theta_{lab} = 60°$, measured with a Si detector in the target chamber. Absolute cross sections at $\theta_{lab} = 15°$ and 20° were determined by comparing the yield of the ^{24}Mg(d, d$_0$)^{24}Mg reaction with that of ^{24}Mg(d, p)^{25}Mg for the lowest three states at $E_d = 12.0$ MeV. The resulting statistical error was 3 %. The elastic scattering cross sections at $\theta_{lab} = 15°$ and 20° can be calculated accurately, to within 5 %, with the optical model, as is described in the next section.

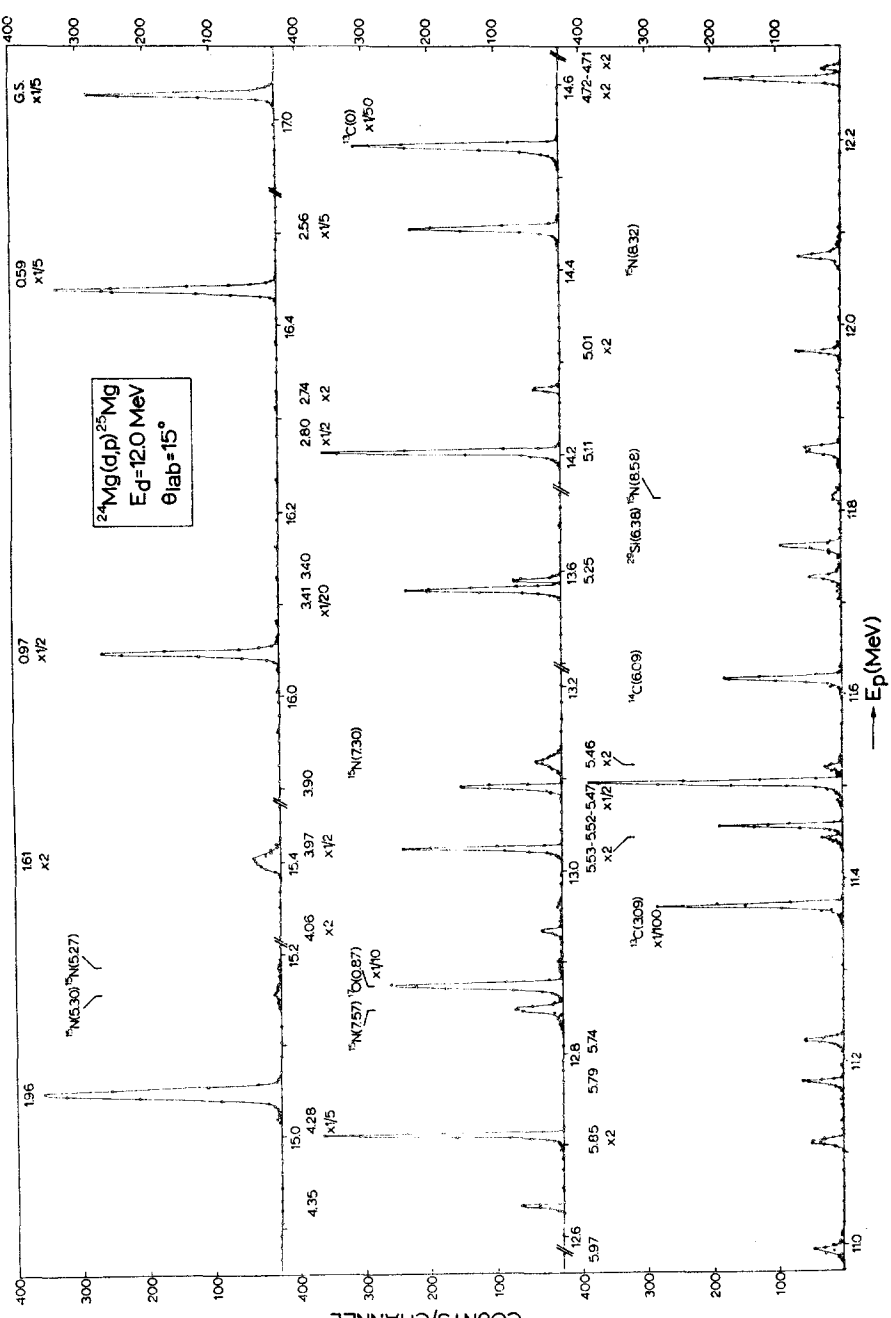

Fig. 1. Proton spectrum from the ^{24}Mg(d, p)^{25}Mg reaction at $\theta_{lab} = 15°$. The ^{25}Mg peaks are labelled with the excitation energies. The contaminant groups are indicated by final nucleus and excitation energy. Note: the rather poor resolution for the 1.61 and 1.96 MeV levels is due to bad detector performance.

3. Analysis

The theoretical direct transfer cross sections were calculated in terms of DWBA with the computer code DWUCK [22]).

The dependence of both the DWBA absolute cross section and the shape of the angular distribution on the optical model parameters in the exit channel is weak. The differences in proton energy corresponding to different excitation energies, in the present experiment $E_p = 17 \rightarrow 11$ MeV (see fig. 1), should, however, be taken into account. Two frequently used sets of overall parameters, determined by Becchetti and Greenlees [23]) and Perey [24]) are available for this purpose (see table 1). Both sets yield satisfactory results, as has been shown in ref. [25]). The calculated angular distributions for the present reaction are very similar for these sets. The resulting deviations in the spectroscopic factors were always less than 10 %. The results, given in this paper, were calculated with the Becchetti-Greenlees parameters.

TABLE 1

Proton optical model parameters

	BG [a])	Perey [b])
V_0 (MeV)	$56.6-0.32\,E_p$	$56.0-0.55\,E_p$
a_0 (fm)	0.75	0.65
r_0 (fm)	1.17	1.25
W_V (MeV)	$0.22\,E_p-2.7$ [c])	
W_d (MeV)	$12.3-0.25\,E_p$	11.6
a_W (fm)	0.54	0.47
r_W (fm)	1.32	1.25
$V_{s.o.}$ (MeV)	6.2	7.5
$a_{s.o.}$ (fm)	0.75	0.65
$r_{s.o.}$ (fm)	1.01	1.25
r_c (fm)	1.37	1.25

[a]) Ref. [23]). [b]) Ref. [24]). [c]) Only for $W_V > 0$.

Many deuteron optical model parameter sets are known for energies around 12 MeV. Optical model parameter sets determined by coupled-channel calculations, however, cannot be used for a DWBA analysis, since the coupling of the rotational states involved leads to a considerable reduction of the absorptive potential observed in the elastic channel [26]). This holds particularly for the ^{24}Mg nucleus, for which the quadrupole deformation parameter β_2 is very large [$\beta_2 = 0.47$, ref. [6])]. Table 2 lists available sets of deuteron optical model parameters for ^{24}Mg, which have been published in the literature [3, 27-31]). All these sets describe the experimental data at forward angles very accurately. The ratio of the calculated elastic cross section to the Rutherford cross section at $\theta_{lab} = 15°$ and 20° is also given in table 2. These angles have been used to determine the absolute stripping cross section, see sect. 2. In particular for $\theta_{lab} = 20°$ the calculated ratio is very stable. The resulting systematic error in the absolute cross section is less than 5 %.

TABLE 2
Deuteron optical model parameters

	I [a])	II [b])	III [c])	IV [d])	V [e])	VI [f])
E_d (MeV) [g])	11.8	13.0	15.0	12.0	13.5	14.0
V_0 (MeV)	93.8	77.7	101.3	99.8	78.0	81.2
a_0 (fm)	0.87	0.80	0.90	0.85	0.77	0.84
r_0 (fm)	1.00	1.05	1.00	1.05	1.25	1.05
W_d (MeV)	29.2	21.3	28.9	13.0	21.5	25.9
a_W (fm)	0.61	0.70	0.50	0.63	0.43	0.70
r_W (fm)	1.36	1.28	1.44	1.50	1.67	1.28
$V_{s.o.}$ (MeV)	12.0			11.0		
$a_{s.o.}$ (fm)	0.87			0.46		
$r_{s.o.}$ (fm)	1.00			0.84		
r_c (fm)	1.30	1.20	1.30	1.30	1.30	1.30
σ/σ_R ($\theta_{lab} = 15°$ [h])	0.81	0.81	0.75	0.77	0.80	0.82
σ/σ_R ($\theta_{lab} = 20°$)	0.98	0.98	0.95	0.96	0.98	0.98

[a]) Ref. [27]). [b]) Ref. [28]). [c]) Ref. [29]).
[d]) Global formulas from ref. [30]) applied for $E_d = 12.0$ MeV.
[e]) Ref. [3]). [f]) Ref. [31]). [g]) Deuteron energy.
[h]) The ratio of the optical model to the Rutherford cross section at $E_d = 12.0$ MeV for $\theta_{lab} = 15°$ and 20°, see sect. 3.

All six deuteron optical model parameter sets of table 2 were used to calculate the proton angular distributions of the $1d_{\frac{5}{2}}$ neutron transfer leading to the ^{25}Mg ground state and the $2s_{\frac{1}{2}}$, $1d_{\frac{3}{2}}$, $2p_{\frac{3}{2}}$ and $1f_{\frac{7}{2}}$ neutron transfers to the 0.59, 0.98, 3.41 and 3.97 MeV excited states, respectively. The calculated height of the first maximum in the differential cross section, which strongly determines the value of the spectroscopic factor, shows a spread of less than 20 % for all these transitions for the different parameter sets. Since set I of table 2 yielded the best fits to the experimental angular distributions this parameter set was used to obtain the final results. Only minor differences in the shapes of the angular distributions were found, however, for the different parameter sets.

The DWBA calculations were carried out with a non-locality parameter of 0.54 fm for the deuterons and 0.85 fm for the protons [32, 33]). A spherical Woods-Saxon potential with a radius parameter $r_0 = 1.25$ fm and diffuseness $a_0 = 0.65$ fm was used to generate the bound-state wave function of the transferred neutron. The depth of this potential was adjusted to obtain the proper binding energy. A Thomas-type spin-orbit potential with $\lambda = 25$ ($r_{s.o.} = 1.25$ fm, $a_{s.o.} = 0.65$ fm) was used [22]). The finite-range effect was included by means of a radial correction function with a range parameter of 0.62 fm [ref. [34])]. The normalization constant was taken as $N = 1.53$ [ref. [22])].

Angular distributions were calculated only for the transitions which show a stripping pattern (see fig. 2). The experimental cross section may be, however, partially due to compound nucleus formation. This contribution can be estimated from the cross

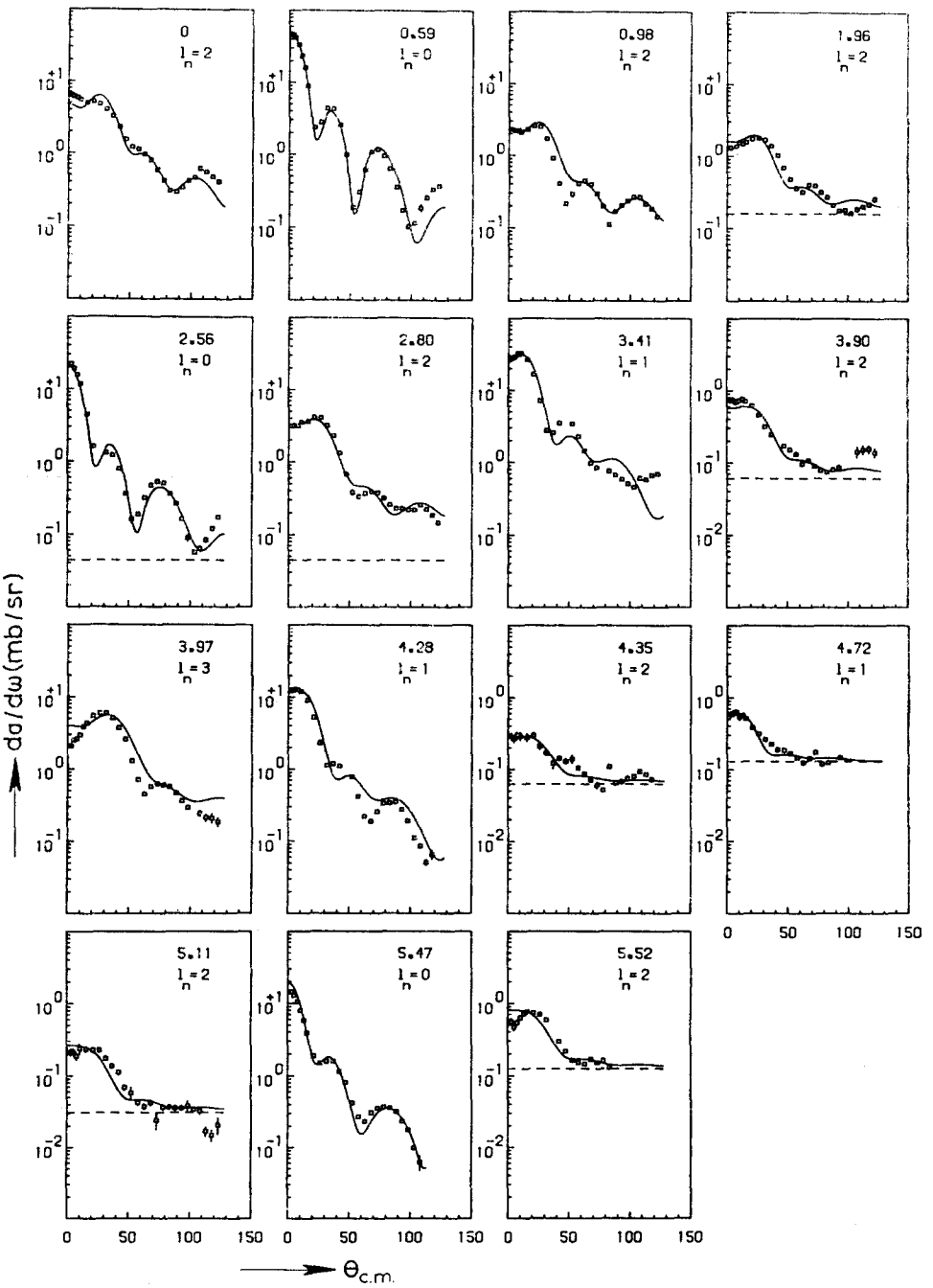

Fig. 2. Proton angular distributions from the ^{24}Mg(d, p)^{25}Mg reaction at E_d = 12.0 MeV. The full lines give the total calculated cross sections which consist of a DWBA contribution and a compound nucleus contribution (horizontal dotted line). Only the levels which show a stripping pattern are displayed.

TABLE 3

K^2 values for weak transitions in the ^{24}Mg(d, p)^{25}Mg reaction [a])

E_x (MeV)	K^2			
	$l_n = 0$	1	2	3
3.90	2.61	0.74	0.44	2.73
4.35	1.69	0.78	0.38	1.41
4.72	1.16	0.22	0.40	2.00
5.11	2.78	1.84	0.79	1.41
5.52	4.13	1.51	1.22	1.30

[a]) $K^2 = \Sigma_{\theta \leq 60^\circ} [(\sigma_{th}(\theta) - \sigma_{exp}(\theta))/\sigma_{exp}(\theta)]^2$, normalized at 12 angles [25]).

TABLE 4

Spectroscopic data

E_x [a]) (keV)	J^π [b])	l_n [c])	S					
			experiment				theory	
			(d, p)		(d, n)	(τ, d)		
			[c])	[d])	[e])	[f])	[g])	[h])
0	$\frac{5}{2}^+$	2	0.53	0.26	0.58	0.25	0.32	0.33
585	$\frac{1}{2}^+$	0	0.49	0.50	0.85	0.37	0.44	0.17
975	$\frac{3}{2}^+$	2	0.37	0.27	0.45	0.32	0.22	0.29
1965	$\frac{5}{2}^+$	2	0.10	0.09	0.20	0.05	0.08	0.08
2564	$\frac{1}{2}^+$	0	0.16	0.12		0.14	0.16	0.56
2801	$\frac{3}{2}^+$	2	0.31	0.27		0.34	0.27	0.17
3414	$\frac{3}{2}^-$	1	0.30					0.22
3901	$(\frac{3}{2}, \frac{5}{2})^+$ [c, i])	2	0.017 [j, k])				0.0001 [j])	0.029 [j])
3968	$\frac{7}{2}^-$	3	0.43					0.14
4277	$\frac{1}{2}^-$ [f])	1	0.21					0.05 [m])
4354	$\frac{3}{2}^+$	2	0.011				0.005	
4715		1, (2)	0.004 [n])					
5108	$\frac{3}{2}^+$ [c])	2	0.004				0.005	
5465	$\frac{1}{2}^+$	0	0.17				0.05	
5515	$\frac{5}{2}$ [o])	(2)	(0.006)				(0.003)	
5742	$\frac{5}{2}^+$ [f, o])		< 0.004					
5853	$\frac{5}{2}^+$ [o])		< 0.001					

[a]) Ref. [18]). [b]) Ref. [18]), if not indicated otherwise. [c]) Present work, see text.
[d]) Results of ref. [13]) with the best proton optical model parameters for each transition and the correct normalization ($N = 1.00 \rightarrow 1.53$).
[e]) Ref. [41]). [f]) Ref. [42]). [g]) Shell model calculations, ref. [15]).
[h]) Nilsson model with $\beta = 0.45$, see sect. 4 and ref. [6]). [i]) Ref. [35]).
[j]) Calculated for $1d_{\frac{5}{2}}$ transfer. [k]) For $1d_{\frac{3}{2}}$ transfer one obtains $S_n = 0.031$. [l]) Ref. [21]).
[m]) Calculated for $\beta = 0.3$, ref. [6]).
[n]) Calculated for $2p_{\frac{1}{2}}$ transfer; for $2p_{\frac{3}{2}}$ one obtains $S_n = 0.008$.
[o]) Ref. [40]).

the calculated angular distributions are almost identical in shape. The resulting spectroscopic factors would, however, be more than a factor of two larger and thus unrealistically high. No significant stripping pattern was observed for the 5.74 and 5.84 MeV levels, to which recently $J^\pi = \frac{5}{2}^+$ has been assigned [21, 40]). For the spectroscopic factors only an upper limit can be given.

For some low-lying levels a comparison with other experimental spectroscopic factors can be made. Spectroscopic factors have been determined for ^{25}Mg levels with the ^{24}Mg(d, p)^{25}Mg reaction at E_d = 10 MeV [ref. [13])] (see table 4). Proton transfer spectroscopic factors for the mirror states in ^{25}Al, deduced from the ^{24}Mg (d, n)^{25}Al reaction [41]) and the ^{24}Mg(τ, d)^{25}Al reaction [42]), are also listed in table 4. No comparison is made with the ^{24}Mg(α, τ)^{25}Mg results of ref. [14]) since the normalization for the (α, τ) reaction is unclear. The deuteron stripping values of ref. [13]) and the ^{24}Mg(τ, d)^{25}Al results [42]) agree reasonably well with the spectroscopic factors deduced in this work, as is shown in table 4. The values obtained with the ^{24}Mg (d, n)^{25}Al reaction [41]) are relatively high. For the ground-state transition the agreement is poor. The spectroscopic factor for the inverse transition in the ^{25}Mg(p, d)^{24}Mg reaction has been determined as 0.23 [ref. [43])], which is in agreement with the values from refs. [13, 42]).

Table 4 also gives theoretical values for the spectroscopic factors. The shell model results have been obtained with an adjusted surface-delta interaction (ASDI) in a $1d_{\frac{3}{2}}2s_{\frac{1}{2}}1d_{\frac{5}{2}}$ configuration space, truncated by means of the diagonal energy truncation method [44]).

Spectroscopic factors were also calculated in the Nilsson model from Satchler's expression [45]) $S = 2(2I_i+1)/(2I_f+1)\langle I_i K_i j\Omega | I_f K_f\rangle^2 C_{lj}^2$. The Nilsson coefficients in the lj representation, C_{lj}, were taken from ref. [6]) with $\beta_2 = 0.45$.

Except for the first $\frac{5}{2}^+$ and $\frac{3}{2}^+$ states the agreement between the experimental values and the shell model calculations is satisfactory. The $2s_{\frac{1}{2}}$ transfer to the 0.59 and 2.56 MeV levels is much better described by the shell model than by the Nilsson model. The agreement between the experimental and collective model results for negative parity states is poor. Unfortunately, however, shell model spectroscopic factors are not available for these levels.

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section for transitions which show no direct transfer process and was found to be of the order of 100 μb/sr. The angular dependence is small. For each transition the spectroscopic factor and the intensity of a constant compound nucleus cross section were used as free parameters in a least-squares fit to the experimental data. A compound nucleus contribution was omitted, however, in cases where it worsened the fit at forward angles and in cases where the intensity was calculated unrealistically high. The l_n values were deduced from the quality of the fits by means of the K^2 criterion [25]). For each transition an l_n value is believed to be assigned unambiguously if the corresponding K^2 value (defined in table 3) is at least a factor of 2 lower than the K^2 values for the other l_n possibilities.

4. Results and discussion

For fifteen levels the measured proton angular distributions show a stripping pattern, see fig. 2. For strong transitions the deduced l_n values (see table 4) are in agreement with known J^π values [18]). The transitions to the 3.90, 4.35, 4.72, 5.11 and 5.52 MeV levels in ^{25}Mg show only a weak stripping pattern. The K^2 values for these levels are listed in table 3.

Since the 3.90 MeV level has positive parity [35]) the transition to this state should have $l_n = 2$, as table 3 shows. This result affirms the tentative $l_n = 2$ assignment by neutron pick-up from ^{26}Mg [refs. [36-38])]. The transition to the 4.35 MeV level unambiguously has $l_n = 2$ which is in agreement with $J^\pi = \frac{3}{2}^+$ from ref. [18]). For the transition to the 4.72 MeV level in ^{25}Mg the next best K^2 value is less than a factor of two higher than the minimum value. Possible $l_n = 2$ transfer cannot be completely ruled out. The $l_n = 1$ value for this transition would disagree with a tentative $l_n = 2$ assignment from the ^{26}Mg(τ, α)^{25}Mg reaction [37]). In the latter experiment the 4.715 MeV level could not be resolved from the 4.708 MeV level, whereas the corresponding proton groups were completely separated in the present experiment. From fig. 2 and table 3 it is clear that the 5.11 MeV level is not populated by $l_n = 1$ transfer, as has been assumed in ref. [36]). An angular correlation measurement of the ^{24}Mg (d, pγ)^{25}Mg reaction [39]) has limited the spin of this level to $\frac{1}{2}$ or $\frac{3}{2}$. One may thus conclude that the 5.11 MeV level has $J^\pi = \frac{3}{2}^+$. The 5.52 MeV level, which has $J = \frac{5}{2}$ [ref. [40])], is probably populated by $l_n = 2$ transfer, but $l_n = 3$ is not excluded.

As is shown in fig. 2 the DWBA calculations describe the experimental angular distributions fairly well. In particular the $l_n = 0$ transfers to the 0.59, 2.56 and 5.47 MeV levels are very well reproduced by the DWBA curves. The difference in the experimental $l_n = 2$ distributions for the transitions to the $J^\pi = \frac{5}{2}^+$ ground state and the $J^\pi = \frac{3}{2}^+$ 0.98 MeV level cannot be explained by DWBA, as is commonly known. The inclusion of collective excitations is required to describe these transitions [2, 5, 6]). This also affects the spectroscopic factors for the one-step transfer.

The spectroscopic factors deduced in this work are listed in table 4. For $l_n = 1$ the spectroscopic factor is given for either $2p_{\frac{1}{2}}$ or $2p_{\frac{3}{2}}$ neutron transfer. For $1p_{\frac{1}{2}}$ or $1p_{\frac{3}{2}}$