

THE REACTION  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ (II). Spins of  $^{27}\text{Al}$  levelsD. M. SHEPPARD<sup>†</sup> and C. VAN DER LEUN*Fysisch Laboratorium, Rijksuniversiteit, Utrecht, Nederland*

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**Abstract** Measurements of double and triple angular correlations and gamma-ray polarizations at twenty resonances in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ , lead to the unambiguous spin and parity assignments  $J^\pi = \frac{3}{2}^-, \frac{5}{2}^+, \frac{3}{2}^+, \frac{3}{2}^+$  and  $\frac{3}{2}$  to the bound states of  $^{27}\text{Al}$  at 2.21, 2.73, 2.98, 3.00 and 4.81 MeV, respectively. The 6.48 MeV level has  $J = \frac{3}{2}(\frac{3}{2})$ . The quadrupole/dipole amplitude mixing ratios of the gamma rays de-exciting these levels are given. The spins of 15 resonance levels and the mixing ratios of the main branches in the resonance decay also follow from this experiment.

The combined evidence of the decay of the resonance levels and bound states leads to suggested spin values  $J = (\frac{1}{2}, \frac{3}{2}), \frac{3}{2}, (\frac{1}{2}, \frac{3}{2}), \frac{1}{2}, \frac{1}{2}, (\frac{3}{2}, \frac{1}{2}), \frac{3}{2}, \frac{3}{2}, \frac{3}{2}$  and  $\frac{3}{2}$  for  $^{27}\text{Al}^* = 3.68, 3.96, 4.05, 4.41, 5.25, 6.11, 6.16, 6.61, 6.65$  and  $6.78$  MeV, respectively.

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NUCLEAR REACTION  $^{26}\text{Mg}(p, \gamma)$ ,  $E = 0.3\text{--}2.8$  MeV, measured  $p, \gamma(\theta)$ ,  $p, \gamma\gamma(\theta)$ ,  $\gamma$ -ray polarization  $^{27}\text{Al}$  deduced levels,  $J, \tau$ , mixing ratios  
Enriched target

## 1. Introduction

Double and triple angular correlation measurements in radiative capture reactions provide a good means for the determination of the spins, and sometimes the parities, of bound states of the final nucleus. This paper describes angular correlation experiments in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ , which lead to unique spin and/or parity assignments to bound states of  $^{27}\text{Al}$ , in particular to the levels of the 3.0 MeV doublet.

Many resonances sufficiently strong for angular correlation measurements, have been observed<sup>1)</sup> in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ . The decay scheme of about thirty of these resonances, mostly strong ones, has been studied in detail with a  $20\text{ cm}^3$  Ge(Li) gamma-ray detector (see paper I<sup>2)</sup>). The high resolution of this detector has many advantages, especially in the determination of the characteristics of the 2.98–3.00 MeV doublet. With a Ge(Li) detector the excitation energies of these levels can be determined with a precision of about 1 keV. Since the separation is 23 keV, the designation “doublet” is hardly applicable. The problem to which of the two levels a certain resonance is decaying can be solved beyond doubt, and very low upper limits (about 1 to 2 %) can be set on the possibility of decay to the other level.

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From earlier experiments <sup>3)</sup> the spin of one of the levels of the doublet was suggested to be  $J = \frac{3}{2}$ , this suggestion was based on the unwarranted assumption that only pure dipole transitions are observed in  $(p, \gamma)$  experiments. The spin of the other level of the doublet has been proposed as  $J = \frac{9}{2}$  from  $(n, n')$  experiments <sup>4)</sup> and as  $J = \frac{7}{2}$  from  $(p, p'\gamma)$  angular correlation measurements <sup>5)</sup>. The analysis which leads to the  $J = \frac{9}{2}$  assignment relies on the unreliable  $\frac{3}{2}$  assignment mentioned above. The  $J = \frac{7}{2}$  assignment is based on measurements with NaI crystals, which have insufficient resolution. In later experiments <sup>6, 7)</sup> the  $J = \frac{3}{2}$  and  $\frac{9}{2}$  assignments usually have been accepted as well-established. For the reasons given above, however, a verification of these assignments is desirable.

Spins of several other  $^{27}\text{Al}$  levels have also been determined in this experiment. For these levels no unambiguous spin assignments have been reported earlier.

The multipole mixing ratios of many gamma rays in the decay of  $^{27}\text{Al}$ , are also reported.

## 2. Experiment

The apparatus used in the investigation has been described in paper I. For double and triple angular correlation measurements, the gamma rays are detected, not in the Ge(Li) detector but in three 10 cm thick  $\times$  10 cm diam cylindrical NaI(Tl) scintillation crystals shielded with 5 cm iron. The detectors are mounted on a horizontal turntable whose centre is directly under the beam spot on the target. Two of the crystals are placed in the horizontal plane through the proton beam. One of these detectors is positioned at  $90^\circ$  with respect to the proton beam and the other at one of the five forward angles  $\theta = 0^\circ, 30^\circ, 45^\circ, 60^\circ$  or  $90^\circ$ . The third crystal is placed vertically above the target.

The angular correlation measurements are performed with the axes of the three detectors coinciding at the target beam spot and the front surfaces at 10 cm distance from the target. This distance gives rise to solid angle attenuation factors  $Q_{21}$ , which also depend on the discriminator channel setting and the gamma-ray energy. Typical values of  $Q_2$  and  $Q_4$  range from 0.89 to 0.92 and 0.70 to 0.76, respectively.

Four standard geometries A1, A2, C1, C2 (see ref. <sup>8)</sup>) are used. All four geometries (formerly labelled I, II, V–VI in Utrecht papers, and I, II, VI, VII in Chalk River publications) can be measured simultaneously using the three NaI detectors and two differential discriminator channels per detector. In geometries A, the rotating detector, the fixed detector and the proton beam are in the same plane (the horizontal plane). In geometries C, the fixed detector is placed vertically above the plane of the rotating detector and the proton beam. If the first or second gamma ray of a cascade is detected in the moving detector the geometry is labelled by the index 1 or 2, respectively. The pulses from the discriminators are fed into four coincidence circuits with a resolution time  $2\tau = 1.5 \mu\text{s}$ . Usually the number of coincidences is counted with scalars. In some special cases, notably if the two gamma rays studied are part of a

three (or more) step cascade, coincidence spectra at four angles were measured in the four subgroups of a 400-channel RIDL analyser

In the energy ranges of both the Cockcroft-Walton generator and the Van de Graaff accelerator, at least one strong  $^{26}\text{Mg}(\text{p}, \gamma)^{27}\text{Al}$  is known to have  $J = \frac{1}{2}$ , viz  $E_p = 454$  keV (ref <sup>3</sup>) and 1409 keV (refs <sup>9,10</sup>) The isotropic radiation at these resonances provides the possibility of measuring the eccentricity of the target spot without a troublesome change of target The isotropy at these two resonances was carefully checked against that of the  $^{30}\text{Si}(\text{p}, \gamma)^{31}\text{P}$  resonance at  $E_p = 622$  keV (for results see below)

### 3. Analysis

The theoretical description of angular correlations for target nuclei with  $J = 0$  is straightforward Since only the  $m = \pm \frac{1}{2}$  magnetic substates are populated in the reaction, there is a high degree of alignment of the compound nucleus The formulation has been treated extensively in several publications <sup>8,11</sup>) In the calculations carried out for this experiment Smith's tables of coefficients <sup>11</sup>) and the sign convention given there have been used

The data taken in the angular distribution measurements and in the four geometries of the angular correlation experiments are analysed in terms of Legendre polynomials of even order For each type of measurement, a test on the significance of all possible spin combinations in the decay is carried out under the assumption that contributions of octupole radiation can be neglected For each spin combination, a value of  $Q^2$  is computed where

$$Q^2 = \sum_g \sum_i W_i^g [N_i^g - N_i^g(\text{th})]^2$$

In this expression,  $i$  labels the measuring angles for each geometry  $g$ ,  $W_i^g$  are weighting factors equal to the inverse error matrix of  $N_i^g$ ,  $N_i^g(\text{th})$  is the normalized theoretical number of counts for each measuring point that follows from the trial spin combination for the distribution and/or correlation The experimental data,  $N_i^g$  are suitably corrected for eccentricity, background, absorption and accidental coincidences Corrections for the finite solid angle of the detector are made in  $N_i^g(\text{th})$

The calculation of  $Q^2$  results in the production of a  $Q^2$  surface in those cases where quadrupole/dipole admixtures can occur in both gamma rays of the cascade studied If only one of the gamma rays has a mixed character, a  $Q^2$  curve is produced Two typical examples are given in figs 1 and 2

If a spin combination is to result in a good fit to the measurement, the normalized  $\chi^2$ , defined as  $\chi^2 = Q_{\min}^2 / (N - M)$ , should be of the order of unity The value of  $Q_{\min}^2$  is the minimum value of  $Q^2$  calculated above,  $N$  is the number of data points (usually 20 for a correlation experiment) and  $M$  is the number of continuously variable parameters used in the calculation of  $N_i^g(\text{th})$ , i.e. the number of mixing ratios

The calculation of  $Q^2$  and the location of the minima,  $Q_{\min}^2$ , is carried out with an electronic computer. For each assumed spin combination that could result in de-excitation by gamma rays of mixed character, the values of  $Q^2$  are calculated for dif-

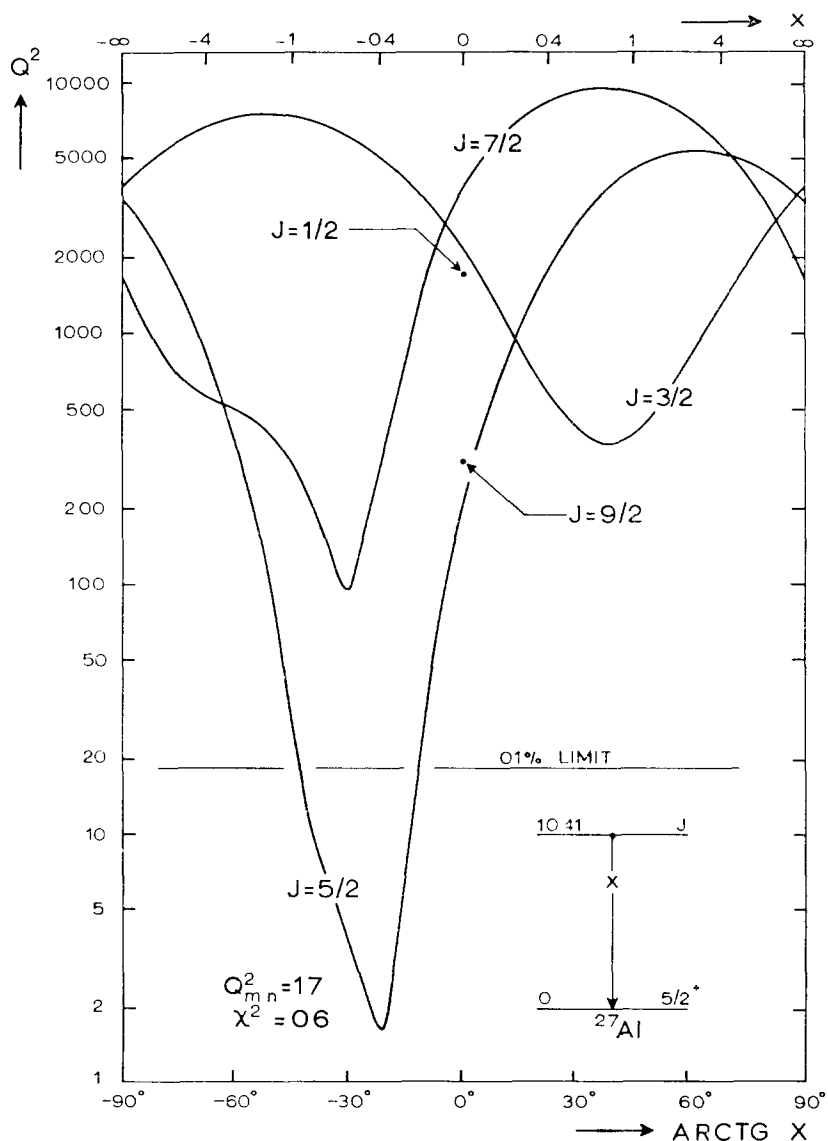


Fig. 1. The  $Q^2$  curves of the angular distribution of the 10.41  $\rightarrow$  0 MeV transition at the  $E_p = 2220$  keV resonance in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ . The values of  $Q^2$  are plotted against the amplitude mixing ratio of the ground state transition with the spin of the resonance level ( $E_\gamma = 10.41$  MeV) as a parameter. The measurement uniquely determines the resonance spin as  $J = \frac{5}{2}$ . See text for the meaning of the 0.1% probability limit.

ferences of  $10^\circ$  (from  $-90^\circ$  to  $+90^\circ$ ) in  $\arctg x$ , where  $x$  is the amplitude mixing ratio. In the cases of only one mixed decay,  $Q_{\min}^2$  is found by an iteration procedure using a parabolic fit to the calculated  $Q^2$ . In cases where both gamma-rays can be mixed, an iteration procedure using a quadratic surface in the neighbourhood of  $Q_{\min}^2$  was carried out. The choice of a  $10^\circ$  grid as the initial starting point for the iteration has prov-

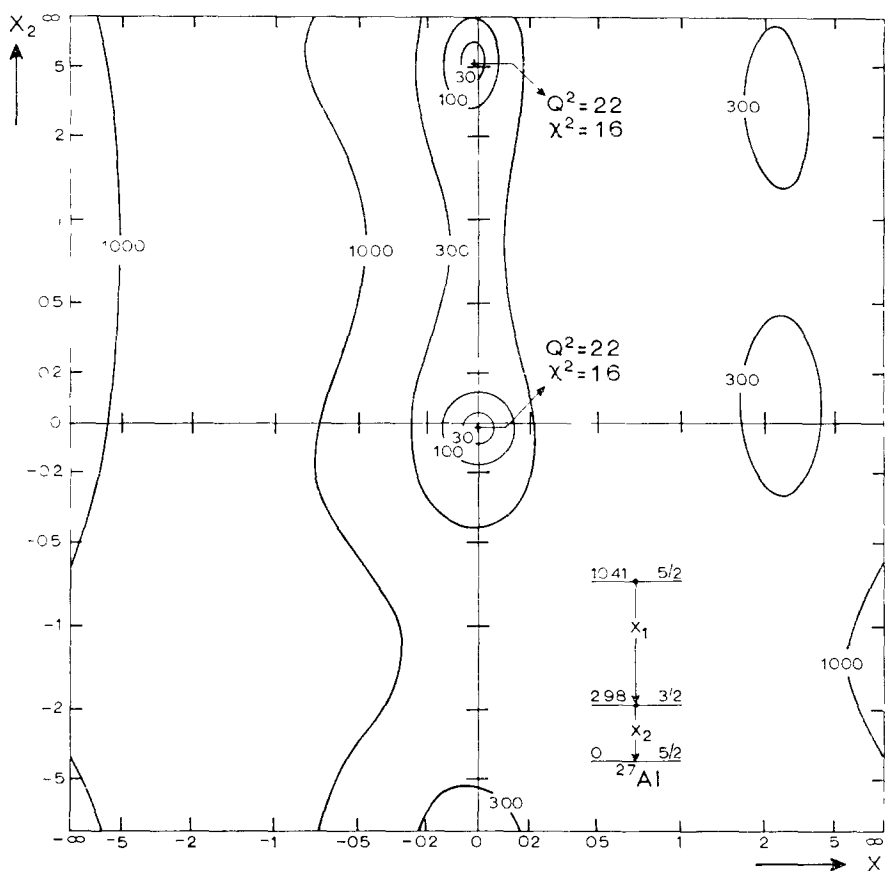


Fig. 2 The  $Q^2$  surface of the angular correlations of the  $10.41 \rightarrow 2.98 \rightarrow 0$  MeV cascade, measured at four different geometries at the  $E_p = 2220$  keV resonance in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$ . The contours give the values of  $Q^2$  as a function of the amplitude mixing ratios of the first and second gamma ray of the cascade ( $x_1$  and  $x_2$ , respectively) for the spin sequence  $\frac{5}{2} - \frac{3}{2} - \frac{5}{2}$ . The two minima with  $Q^2 = 22$  ( $\chi^2 = 1.6$ ) indicate possible solutions. The solution with  $x_2 \approx 5$  could be excluded on the basis of polarization measurements.

en satisfactory in the location of all minima in the cases investigated up to the present. All minima of  $Q^2$  which are less probable than 0.1% have been considered to be ruled out. A spin combination is considered unique if its  $\gamma^2$  value(s) is below the 0.1% limit and all other possible combinations give values of  $\gamma^2$  above the 0.1% probability limit.

The combination of angular distribution and angular correlation experiments for a given resonance does not always lead to a unique determination of all parameters involved. It is often necessary to investigate several resonances before a unique solution is found for the spin of a bound state.

## 4. Results

### 4.1. RESONANCE LEVELS

The branching ratios of all resonance levels discussed here are given in fig. 4 of paper I. The experimental results of the angular distribution and correlation measurements are presented in tables 1 and 2, respectively. Listed in these tables are the values  $a_2$  and  $a_4$  of a Legendre polynomial decomposition of the data. Although the measured numbers and not these coefficients were used in the analysis, these coefficients present the experimental data in a concise form and enable easy comparison to be made with other data.

TABLE 1  
Angular distribution coefficients  $a_2$  and  $a_4$  of gamma rays de-exciting resonance levels in the reaction  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$

$E_p^{a)}$ (keV)	Transition $b)$	$a_2$ $c)$	$a_4$ $c)$
292	8.55 $\rightarrow$ 0.84	$-0.01 \pm 0.08$	$\pm 0.06 \pm 0.09$
338	8.60 $\rightarrow$ 0.84	$-0.74 \pm 0.06$	$\pm 0.04 \pm 0.07$
454	8.71 $\rightarrow$ (0.84 + 1.01)	$\pm 0.002 \pm 0.005$	$-0.002 \pm 0.006$
479	8.73 $\rightarrow$ 0	$-0.19 \pm 0.02$	$-0.04 \pm 0.03$
501	8.75 $\rightarrow$ 0	$\pm 0.43 \pm 0.03$	$-0.02 \pm 0.03$
522	8.77 $\rightarrow$ 0	$-0.59 \pm 0.12$	$-0.05 \pm 0.12$
650	8.90 $\rightarrow$ 0	$\pm 0.12 \pm 0.02$	$-0.01 \pm 0.02$
1249	9.48 $\rightarrow$ 0	$-0.27 \pm 0.01$	$\pm 0.04 \pm 0.02$
	9.48 $\rightarrow$ 2.21	$\pm 0.47 \pm 0.03$	$\pm 0.02 \pm 0.03$
1409	9.63 $\rightarrow$ 0	$\pm 0.01 \pm 0.01$	$-0.01 \pm 0.01$
1548	9.76 $\rightarrow$ 0	$\pm 0.66 \pm 0.01$	$-0.02 \pm 0.02$
1609	9.82 $\rightarrow$ 0	$\pm 0.12 \pm 0.06$	$\pm 0.01 \pm 0.06$
	9.82 $\rightarrow$ 1.01	$\pm 0.17 \pm 0.01$	$-0.00 \pm 0.01$
1733	9.94 $\rightarrow$ 0	$\pm 0.08 \pm 0.04$	$-0.03 \pm 0.05$
	9.94 $\rightarrow$ 3.00	$-0.20 \pm 0.03$	$-0.01 \pm 0.04$
1785	9.99 $\rightarrow$ 0	$-0.34 \pm 0.02$	$-0.02 \pm 0.02$
	9.99 $\rightarrow$ 4.81	$-0.29 \pm 0.01$	$-0.01 \pm 0.01$
1965	10.16 $\rightarrow$ 0	$\pm 0.20 \pm 0.01$	$-0.04 \pm 0.01$
2141	10.33 $\rightarrow$ 0.84	$\pm 0.46 \pm 0.09$	$-0.16 \pm 0.09$
2220	10.41 $\rightarrow$ 0	$\pm 0.67 \pm 0.02$	$-0.06 \pm 0.02$
2293	10.48 $\rightarrow$ 0	$-0.37 \pm 0.01$	$-0.03 \pm 0.01$
	10.48 $\rightarrow$ 6.48	$\pm 0.45 \pm 0.04$	$-0.02 \pm 0.05$
2323	10.51 $\rightarrow$ 0	$-0.25 \pm 0.01$	$\pm 0.01 \pm 0.01$

<sup>a)</sup> Resonance energies from ref. <sup>1)</sup>, corrected for the new recommended value <sup>44)</sup> of the  $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$  calibration resonance.

<sup>b)</sup> Excitation energies of the initial and final states (in MeV).

<sup>c)</sup> After correction for eccentricity, background and random coincidences, but without solid angle attenuation correction.

TABLE 2

Angular correlation coefficients  $a_2$  and  $a_4$  of gamma-gamma cascades de-exciting  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$  resonance levels, measured in the geometries A1, A2, C1 and C2 <sup>a)</sup>

$E_p^{b)}$ (keV)	Cascade <sup>c)</sup>	Geometry A1		Geometry A2		Geometry C1		Geometry C2	
		$a_2$	$a_4$	$a_2$	$a_4$	$a_2$	$a_4$	$a_2$	$a_4$
338	8 60→2 98→0	+0 35 ±0 06	+0 03 ±0 06	-0 03 ±0 07	-0 02 ±0 07	+0 19 ±0 06	-0 04 ±0 06	-0 11 ±0 12	+0 07 ±0 12
650	8 90→1 01→0	-0 28 ±0 05	-0 03 ±0 05	+0 26 ±0 05	+0 02 ±0 05	-0 38 ±0 04	+0 08 ±0 04	+0 00 ±0 04	-0 02 ±0 04
	8 90→2 98→0	-0 31 ±0 05	-0 07 ±0 05	-0 11 ±0 04	-0 03 ±0 04	+0 64 ±0 04	+0 07 ±0 04	+0 54 ±0 04	+0 07 ±0 04
1249	9 48→2 21→0	+0 26 ±0 03	-0 05 ±0 03	+0 19 ±0 04	-0 06 ±0 03	-0 35 ±0 06	+0 02 ±0 06	-0 03 ±0 05	-0 02 ±0 05
1380	9 60→0 84→0	-0 46 ±0 07	+0 07 ±0 07	-0 01 ±0 05	+0 05 ±0 05	+0 50 ±0 05	-0 03 ±0 05	+0 17 ±0 08	-0 02 ±0 08
	9 60→1 01→0	-0 22 ±0 04	-0 02 ±0 05	-0 01 ±0 04	+0 03 ±0 04	-0 06 ±0 04	-0 05 ±0 04	+0 30 ±0 06	+0 02 ±0 06
1548	9 76→2 21→0	+0 04 ±0 04	-0 03 ±0 03	+0 40 ±0 07	-0 09 ±0 07	+0 36 ±0 03	+0 04 ±0 03	+0 13 ±0 03	-0 06 ±0 03
1609	9 82→1 01→0	+0 15 ±0 03	+0 02 ±0 03	-0 08 ±0 03	-0 03 ±0 03	-0 32 ±0 06	-0 06 ±0 06	+0 24 ±0 05	-0 01 ±0 05
	9 82→2 73→0	+0 13 ±0 06	-0 11 ±0 06	-0 65 ±0 05	-0 09 ±0 05	-0 18 ±0 04	+0 04 ±0 04	-0 09 ±0 03	-0 01 ±0 04
	9 82→2 73→1 01	-0 26 ±0 04	+0 06 ±0 04	-0 22 ±0 03	+0 02 ±0 03	-0 24 ±0 04	-0 00 ±0 04	-0 24 ±0 04	-0 07 ±0 04
1733	9 94→3 00→0	-0 03 ±0 04	-0 01 ±0 05	-0 60 ±0 03	-0 25 ±0 03	-0 31 ±0 07 <sup>d)</sup>	-0 05 ±0 08 <sup>d)</sup>		
	9 94→3 00→2 21			-0 31 ±0 07 <sup>d)</sup>					
1785	9 99→4 81→0	-0 08 ±0 10	-0 18 ±0 10	+0 01 ±0 11	+0 11 ±0 11	-0 15 ±0 11	-0 18 ±0 12	+0 12 ±0 11	-0 03 ±0 11
	9 99→4 81→1 01	-0 31 ±0 06	-0 10 ±0 06	-0 48 ±0 06	-0 00 ±0 06	-0 30 ±0 06	-0 04 ±0 06	-0 38 ±0 07	-0 05 ±0 07
	9 99→4 81→2 21	-0 16 ±0 06	-0 02 ±0 07	-0 16 ±0 07	-0 04 ±0 07	-0 30 ±0 07	+0 14 ±0 07	-0 08 ±0 07	-0 02 ±0 08
1965	10 16→2 21→0	+0 10 ±0 05	+0 03 ±0 05	+0 38 ±0 04	-0 09 ±0 05	-0 01 ±0 05	+0 03 ±0 05	+0 27 ±0 04	+0 03 ±0 04
2141	10 33→2 98→0	-0 35 ±0 03	-0 01 ±0 04	-0 01 ±0 04	+0 10 ±0 04	+0 30 ±0 04	+0 07 ±0 04	-0 09 ±0 04	+0 03 ±0 04
2220	10 41→2 98→0	-0 40 ±0 04	+0 09 ±0 05	-0 07 ±0 06	-0 05 ±0 06	-0 28 ±0 06	-0 03 ±0 06	-0 09 ±0 04	+0 05 ±0 04
2293	10 48→6 48→0					+0 26 ±0 03	+0 01 ±0 04	-0 14 ±0 04	-0 10 ±0 04
2323	10 51→2 21→0	+0 23 ±0 06	-0 04 ±0 06	+0 03 ±0 06	+0 06 ±0 06	+0 63 ±0 07	-0 04 ±0 07	+0 39 ±0 07	+0 21 ±0 07
	10 51→3 00→0	-0 03 ±0 04	+0 03 ±0 05	+0 50 ±0 03	-0 17 ±0 03	-0 26 ±0 03	-0 04 ±0 04	+0 21 ±0 03	-0 07 ±0 03
2574	10 75→2 21→0	-0 42 ±0 04	-0 00 ±0 04	+0 51 ±0 04	+0 14 ±0 04	-0 54 ±0 03	+0 04 ±0 04	+0 20 ±0 03	+0 10 ±0 03
	10 75→3 00→0	+0 14 ±0 06	-0 04 ±0 06	-0 04 ±0 06	-0 04 ±0 07	+0 93 ±0 06	+0 01 ±0 07	+0 70 ±0 06	+0 24 ±0 06

<sup>a)</sup> Solid angle attenuation corrections have not been applied

<sup>b)</sup> Energies from ref <sup>1)</sup> with small corrections for a more recent calibration energy <sup>4)</sup>

<sup>c)</sup> Excitation energies (in MeV) of the levels involved in the cascades

<sup>d)</sup> Deduced from coincidence spectra measured at four instead of the usual five angles

In the double and triple angular correlation analyses, the spins and parities of the ground state, the 0.84 MeV level and the 1.01 MeV level were assumed to be well established as  $\frac{5}{2}^+$ ,  $\frac{1}{2}^+$  and  $\frac{3}{2}^+$ , respectively<sup>12)</sup> Using this as a starting point the analyses of the angular distributions from the resonance decay to one of these levels led

TABLE 3  
Spins of resonance levels in the reaction  $^{26}\text{Mg}+p$

$E_p$ (keV)	$J\pi$				
	this work <sup>a)</sup>	ref. <sup>a)</sup>	ref. <sup>10)</sup>	others	conclusion
292	$(\frac{1}{2}, \frac{3}{2})$			$(\frac{1}{2}, \frac{3}{2})$ <sup>b)</sup>	$(\frac{1}{2}, \frac{3}{2})$
338	$\frac{1}{2}^-$			$\frac{3}{2}$ <sup>c)</sup>	$\frac{1}{2}^-$
454	$(\frac{1}{2}, \frac{3}{2})$			$\frac{1}{2}$ <sup>c)</sup>	$\frac{1}{2}$
479	$(\frac{3}{2}, \frac{3}{2}, \frac{3}{2})$				$\frac{1}{2}$
501	$\frac{5}{2}$				$\frac{3}{2}$
522	$\frac{5}{2}$				$\frac{3}{2}$
650	$\frac{1}{2}$			$\frac{5}{2}$ <sup>d)</sup>	$\frac{5}{2}$
662	$[\frac{1}{2}, \frac{3}{2}]$			$\frac{1}{2}(\frac{1}{2})$ <sup>e)</sup>	$\frac{1}{2}(\frac{1}{2})$
719	$[\frac{3}{2}, \frac{1}{2}]$			$\frac{3}{2}(\frac{1}{2})$ <sup>e, c)</sup>	$\frac{1}{2}(\frac{1}{2})$
1001	$[\frac{1}{2}, \frac{1}{2}]$	$\frac{1}{2}^+$			$\frac{1}{2}^+$
1249	$\frac{3}{2}$				$\frac{3}{2}$
1287	$[\frac{3}{2}, \frac{5}{2}]$				$[\frac{3}{2}, \frac{5}{2}]$
1380	$\frac{1}{2}$				$\frac{1}{2}^-$
1409	$(\frac{1}{2}, \frac{3}{2})$	$\frac{1}{2}^-$	$\frac{1}{2}^-$		$\frac{1}{2}^-$
1548	$\frac{5}{2}(\frac{1}{2})$	$\frac{3}{2}^+$	$(\frac{1}{2}, \frac{1}{2})^+$		$\frac{1}{2}^+$
1609	$\frac{1}{2}(\frac{1}{2})$	$\frac{1}{2}(\frac{3}{2})^+$			$\frac{1}{2}^+$
1733	$\frac{7}{2}$				$\frac{7}{2}$
1753	$[\frac{3}{2}, \frac{3}{2}]$	$\frac{3}{2}(\frac{1}{2})^-$			$\frac{1}{2}^-$
1756	$[\frac{1}{2}, \frac{5}{2}]$	$(\frac{3}{2}, \frac{5}{2})^-$			$(\frac{3}{2}, \frac{5}{2})^+$
1785	$\frac{7}{2}$	$(\frac{3}{2}, \frac{3}{2})^-$			$\frac{7}{2}^-$
1820	$[\frac{1}{2}, \frac{3}{2}]$	$\frac{5}{2}^+$			$\frac{3}{2}^-$
1965	$\frac{5}{2}(\frac{1}{2})$	$(\frac{3}{2}, \frac{1}{2})^-$			$\frac{3}{2}^-$
2048	$[\frac{3}{2}]$				$[\frac{3}{2}]$
2141	$\frac{3}{2}(\frac{1}{2})$		$\frac{1}{2}^+$		$\frac{3}{2}(\frac{1}{2})$
2182	$[\frac{1}{2}]$		$(\frac{3}{2}, \frac{3}{2})^+$		$(\frac{1}{2})^+$
2220	$\frac{3}{2}(\frac{1}{2})$		$(\frac{1}{2}, \frac{3}{2})^+$		$\frac{3}{2}$
2234	$[\frac{3}{2}]$				$[\frac{3}{2}]$
2293	$\frac{3}{2}^-$		$(\frac{3}{2}, \frac{3}{2})^-$		$\frac{7}{2}^-$
2323	$\frac{7}{2}$		$(\frac{3}{2}, \frac{3}{2})^-$		$\frac{7}{2}^-$
2574	$\frac{9}{2}$				$\frac{9}{2}$
2761	$[\frac{1}{2}]$		$(\frac{1}{2}, \frac{3}{2})^+$		$(\frac{1}{2})^-$

<sup>a)</sup> Deduced from angular correlation measurements except for the values in square brackets, which are suggestions based on intensity considerations only

<sup>b)</sup> Ref.<sup>41)</sup>

<sup>c)</sup> Ref.<sup>3)</sup>

<sup>d)</sup> Ref.<sup>42)</sup>

<sup>e)</sup> Ref.<sup>43)</sup>

to unique spin assignments for several of the resonances. For most of the other resonances only two values for the resonance spin remained in consideration. The triple angular correlation experiments then usually lead to the rejection of one of the two remaining possibilities.



The values of the resonance spins which lead to  $\gamma^2$  values below the 0.1% probability limit are listed in column 2 of table 3. The spin values given in square brackets are not deduced from correlation measurements. They are based on intensity considerations only, and should therefore be considered as suggested values. The spins reported

TABLE 4  
Quadrupole/dipole amplitude mixing ratios of primary gamma rays de-exciting  $^{27}\text{Al}$  resonances

$E_p$ (keV)	Transition ( $E_x$ in MeV)	$J_i^\pi \rightarrow J_f^\pi$	Mixing ratio
338	8.60 $\rightarrow$ 0.84	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$+0.10 \pm 0.03$
	8.60 $\rightarrow$ 2.98	$\frac{3}{2}^- \rightarrow \frac{1}{2}^+$	$+0.02 \pm 0.03$
501	8.75 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$-0.00 \pm 0.03$ (or $-1.3 \pm 0.3$ )
522	8.77 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.18 \pm 0.18$ (or $-0.9 \pm 0.4$ )
650	8.90 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^-$	$+0.29 \pm 0.08$
	8.90 $\rightarrow$ 1.01	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.06 \pm 0.07$
	8.90 $\rightarrow$ 2.98	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$+0.00 \pm 0.01$
1249	9.47 $\rightarrow$ 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$-0.07 \pm 0.02$
	9.47 $\rightarrow$ 2.21	$\frac{3}{2}^- \rightarrow \frac{1}{2}^-$	$+0.04 \pm 0.02$
1548	9.76 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^-$	$-0.16 \pm 0.02$
	9.76 $\rightarrow$ 2.21	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^-$	$+0.06 \pm 0.02$
1609	9.82 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^-$	$+0.21 \pm 0.06$ (or $+2.2 \pm 0.3$ )
	9.82 $\rightarrow$ 1.01	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	$+0.14 \pm 0.01$ (or $-8.9 \pm 0.3$ )
	9.82 $\rightarrow$ 2.73	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.13 \pm 0.03$
1733	9.94 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.20 \pm 0.02$
	9.94 $\rightarrow$ 3.00	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.02 \pm 0.01$
1785	9.99 $\rightarrow$ 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$+0.00 \pm 0.02$
	9.99 $\rightarrow$ 4.81	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$-0.02 \pm 0.02$
1965	10.16 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.23 \pm 0.01$
	10.16 $\rightarrow$ 2.21	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.12 \pm 0.01$
2141	10.33 $\rightarrow$ 0.84	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	$-0.55 \pm 0.07$ (or $+50 \pm 20$ )
	10.33 $\rightarrow$ 2.98	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.02 \pm 0.02$ (or $-4.3 \pm 0.3$ )
2220	10.41 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.39 \pm 0.07$
	10.41 $\rightarrow$ 2.98	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$-0.03 \pm 0.02$
2293	10.48 $\rightarrow$ 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$+0.03 \pm 0.01$
	10.48 $\rightarrow$ 6.48	$\frac{3}{2}^- \rightarrow (\frac{7}{2})$	$+0.01 \pm 0.03$
2323	10.51 $\rightarrow$ 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	$-0.04 \pm 0.01$
	10.51 $\rightarrow$ 2.21	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	$+0.06 \pm 0.04$
	10.51 $\rightarrow$ 3.00	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	$+0.00 \pm 0.02$
2574	10.75 $\rightarrow$ 2.21	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.10 \pm 0.04$
	10.75 $\rightarrow$ 3.00	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^+$	$+0.05 \pm 0.07$

here are compared with literature data in table 3. They are in excellent mutual agreement, except for the 2141 keV resonance. The last column of table 3 (conclusion) gives the spin and parity values used in the decay schemes of paper I.

The corresponding multipole mixing ratios of the gamma rays de-exciting the resonances are listed in table 4. Some of these mixing ratios were used for parity assignments. The tentative even parity assignments given in column 2 of table 3 indicate that an assumed odd parity leads to M2 transitions with a strength of more than one

Weisskopf unit. The odd parities of the  $E_p = 338$  and 2293 keV resonances are deduced from polarization measurements with photographic plates soaked in heavy water, this will be described later.

## 4.2 BOUND STATES

The conclusions drawn from the angular correlation measurements at different resonances are summarized in table 5. A short discussion for each level is given below.

TABLE 5  
Quadrupole/dipole amplitude mixing ratios of gamma transitions between bound states of  $^{27}\text{Al}$

Transition ( $E_\gamma$ in MeV)	$J_i^\pi \rightarrow J_f^\pi$	Resonance investigated ( $E_p$ in keV)	Mixing ratio	Average
1.01 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	650	$+0.40 \pm 0.08$	$+0.37 \pm 0.03$
		1380	$+0.39 \pm 0.05$	
		1609	$+0.33 \pm 0.05$	
1.01 $\rightarrow$ 0.84	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	338	$-0.05 \pm 0.06^a)$	$-0.40 \pm 0.01$
2.21 $\rightarrow$ 0	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$	1249	$-0.42 \pm 0.02$	
		1548	$-0.41 \pm 0.04$	
		1965	$-0.40 \pm 0.02$	
		2323	$-0.36 \pm 0.03$	
		2574	$-0.40 \pm 0.02$	$-0.01 \pm 0.01$
2.73 $\rightarrow$ 0	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^-$	1609	$-0.09 \pm 0.03$	
2.73 $\rightarrow$ 1.01	$\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$	1609	$-0.09 \pm 0.03$	
2.98 $\rightarrow$ 0	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$	338	$0.04 \pm 0.05$	
		650	$-0.08 \pm 0.09$	
		2141	$-0.02 \pm 0.02$	$-0.00 \pm 0.02$
		2220	$+0.00 \pm 0.02$	
3.00 $\rightarrow$ 0	$\frac{9}{2}^- \rightarrow \frac{1}{2}^-$	1733	$\infty$	
		2323	$\infty$	
		2574	$\infty$	$-0.00 \pm 0.03$
3.00 $\rightarrow$ 2.21	$\frac{9}{2}^- \rightarrow \frac{5}{2}^-$	1733	$-0.00 \pm 0.03$	
4.81 $\rightarrow$ 0	$\frac{7}{2}^- \rightarrow \frac{1}{2}^-$	1785	$+0.29 \pm 0.03$ (or $2.7 \pm 1.0$ )	$-0.06 \pm 0.02$
4.81 $\rightarrow$ 1.01	$\frac{7}{2}^- \rightarrow \frac{3}{2}^-$	1785	$-0.06 \pm 0.02$	
4.81 $\rightarrow$ 2.21	$\frac{7}{2}^- \rightarrow \frac{5}{2}^-$	1785	$+0.05 \pm 0.02$ (or $5.5 \pm 1.0$ )	

<sup>a)</sup> See subsect. 4.2.2

**4.2.1 The 0.84 MeV level** In general a unique spin determination for a  $J = \frac{1}{2}$  level is quite difficult from  $(p, \gamma\gamma)$  angular correlation measurements alone<sup>13)</sup>. In this respect the investigation of the  $^{26}\text{Mg}(d, n)^{27}\text{Al}$  reaction<sup>14)</sup> complements the experiments described here, since it leads to unambiguous  $I_n = 0$  assignments. The  $J^\pi = \frac{1}{2}^+$  assignment to the 0.84 MeV level from the  $(d, n)$  experiments is consistent with our measurements.

**4.2.2 The 1.01 MeV level** In the analysis the spin and parity of the second excited state were assumed<sup>12)</sup> to be  $J^\pi = \frac{3}{2}^+$ . As in the case of the 0.84 MeV level, our meas-

urements are all in agreement with this value. The average of the quadrupole/dipole amplitude mixing ratio of the 1.01 MeV gamma ray, determined at three resonances, is  $\lambda = +0.37 \pm 0.03$  or  $x = 1.5 \pm 0.2$ . The high value of  $x$  can be excluded since combined with the mean life of the level,  $\tau_m = 2.2 \pm 0.3$  ps (ref. <sup>15</sup>), it would lead to an unacceptably <sup>16</sup>) high E2 transition strength of about 100 W u. Moreover, with  $\lambda = 0.37 \pm 0.03$ , one calculates from the mean life of the level a partial E2 mean life in agreement with the experimental <sup>17</sup>) value  $\tau_m(\text{E2}) = 13 \pm 4$  ps. The lower value of the mixing ratio given above is in agreement with the results of an  $^{27}\text{Al}(p, p'\gamma)^{27}\text{Al}$  experiment <sup>18</sup>), yielding  $x = 0.32 \pm 0.14$ . The relative E2/M1 amplitude ratios of the  $1.01 \rightarrow 0.84$  and  $1.01 \rightarrow 0$  gamma transitions measured by Almqvist *et al.* (see fig. 2 of ref. <sup>19</sup>) and note the different sign conventions), combined with the value of  $x(1.01 \rightarrow 0)$  reported here, lead to  $x(1.01 \rightarrow 0.84) = -0.05 \pm 0.06$  or  $2.0 \pm 0.3$ . The higher value can be disregarded since it would lead to an impossibly high E2 transition strength.

**4.2.3 The 2.21 MeV level** The spin and parity of this level,  $J^\pi = \frac{7}{2}^+$ , have been reported earlier <sup>20</sup>). The data reported there have been reanalysed using the directly measured data, instead of the coefficients of the Legendre polynomial expansion. Cascades through this level have been studied at two additional resonances, to determine the resonance spins. The quadrupole/dipole amplitude mixing ratio of the 2.21 MeV gamma ray, averaged from the values found at five resonances, is  $x = -0.40 \pm 0.01$ , in agreement with the earlier results. For a discussion of other experiments on the 2.21 MeV level, see ref. <sup>20</sup>).

The previous parity assignment was based on lifetimes considerations. In this experiment the parity of the 2.21 MeV level has been measured at the  $E_p = 2323$  and  $2574$  keV resonances, using the Compton scattering method <sup>32</sup>). The polarization of the 2.21 MeV gamma ray, calculated using mixing ratios of the gammas in the  $r \rightarrow 2.21 \rightarrow 0$  cascades given in the tables, is  $P = \pm 0.75$  and  $\pm 1.00$  at the two resonances, respectively. The plus sign holds for E2/M1 mixing, the minus sign for M2/E1 mixing.

The polarization efficiency  $p$  is 0.18. The measured effects are  $pP = +0.13 \pm 0.07$  and  $+0.19 \pm 0.04$ , respectively. The parity of the 2.21 MeV level is thus uniquely determined to be even.

**4.2.4 The 2.73 MeV level** This level has been investigated at the  $E_p = 1609$  keV resonance. A combined analysis of the angular correlations of the  $r \rightarrow 2.73 \rightarrow 0$  and  $r \rightarrow 2.73 \rightarrow 1.01$  cascades, which have a common primary gamma ray, leads to the unique assignment  $J(2.73) = \frac{5}{2}$ . This value has been suggested earlier <sup>3</sup>) on the basis of angular distribution measurements only.

The mixing ratios of the  $2.73 \rightarrow 0$  and  $2.73 \rightarrow 1.01$  transitions, both  $x = -0.09 \pm 0.03$ , are in disagreement with the values  $x = +0.04 \pm 0.06$  and  $+0.23 \pm 0.06$ , respectively, found <sup>21</sup>) from an investigation of the  $^{27}\text{Al}(p, p'\gamma)$  reaction.

**4.2.5 The 2.98 MeV level** The spin of this level turned out to be an evasive quantity. At the 338 keV resonance ( $J^\pi = \frac{3}{2}^-$ ) all four possible spins  $J(2.98) = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$

and  $\frac{7}{2}$  lead to  $\chi^2$  values below the 0.1 % limit. At the 650 and 2220 keV resonance (both  $J = \frac{5}{2}$ ) the spin assumptions  $J(298) = \frac{3}{2}$  and  $\frac{7}{2}$  each lead to acceptable  $\gamma^2$  values and mutually consistent mixing ratios for the  $298 \rightarrow 0$  transition. In many cases exclusion of a spin value differing by  $\Delta J = 2$  from the actual value is rather difficult. At the 2141 keV resonance ( $J = \frac{3}{2}$ ) the assignments  $J(298) = \frac{1}{2}, \frac{3}{2}$  and  $\frac{5}{2}$  are allowed. Combination of the results obtained at the different resonances then leads to the unique assignment  $J(298) = \frac{3}{2}$ . No unique spin assignment for this level has been reported earlier (see introduction).

The values of mixing ratio of the  $298 \rightarrow 0$  transition for this  $J = \frac{3}{2}$  assignment, found at the four resonances, agree within the experimental errors (see table 5). The average value is  $\alpha = +0.01 \pm 0.01$  or  $4.9 \pm 0.5$ . The higher value can be excluded again considering the mean life  $\tau_m = 5.9 \pm 0.4$  fs (see e.g. refs <sup>22, 23</sup>). See also subject 4.2.9.

**4.2.6 The 3.00 MeV level** The angular correlation measurements at the  $E_p = 2323$  and 2574 keV resonances both lead to the assignment  $J(300) = \frac{9}{2}$  or  $\frac{5}{2}$ . The latter value, however, implies an improbably large mixing ratio  $\alpha(300 \rightarrow 0) = -1.7$ . A unique solution was found at the 1733 keV resonance. The two angular distribution measurements (see table 1) only exclude  $J_{\text{res}} = \frac{1}{2}$  and  $\frac{9}{2}$ . The angular correlation data were compared with the theoretical values for all possible spin combinations with  $J_{\text{res}} = \frac{3}{2}, \frac{5}{2}$  and  $\frac{7}{2}$ ,  $J(300) = \frac{1}{2}$  through  $\frac{9}{2}$ , and  $J(0) = \frac{5}{2}$ . Only the sequence  $\frac{7}{2} \rightarrow \frac{9}{2} \rightarrow \frac{5}{2}$  gives a  $\chi^2$  value below the 0.1 % limit. It should be noted that here again the next-best solution is  $J(300) = \frac{5}{2}$ , but here this assignment can be excluded on the basis of the 0.1 % criterion.

The  $J(300) = \frac{9}{2}$  assignment is in agreement with the value proposed from  $^{27}\text{Al}(n, n')^{27}\text{Al}$  experiments <sup>4</sup>), but in disagreement with results from an investigation of the  $^{27}\text{Al}(p, p'\gamma)^{27}\text{Al}$  reaction <sup>5</sup>) (see introduction).

The mixing ratio of the  $300 \rightarrow 221$  transition was determined from an  $r \rightarrow 300 \rightarrow 221$  angular correlation measurement in geometry A2 at the 1733 keV resonance, using the relevant spins and mixing ratio of the primary transition found above. The unique solution is  $\alpha(300 \rightarrow 221) = -0.00 \pm 0.03$ , in agreement with an earlier reported <sup>7</sup>) value  $\alpha = +0.03 \pm 0.03$ .

**4.2.7 The 4.81 and 6.48 MeV levels** In the analysis of the angular correlations of cascades through these levels, use had been made of information on the relevant resonances from elastic proton scattering experiments, to arrive at unique solutions. The 4.81 MeV level was investigated at the 1785 keV resonance. The ground-state angular distribution yields  $J_{\text{res}} = \frac{3}{2}$  or  $\frac{7}{2}$ , elastic scattering <sup>9</sup>) gives  $J_{\text{res}} = \frac{7}{2}^-$  or  $\frac{5}{2}^-$ , and thus  $J_{\text{res}} = \frac{7}{2}^-$ . Angular correlation measurements of the cascades  $r \rightarrow 481 \rightarrow 0$ ,  $r \rightarrow 481 \rightarrow 101$ , and  $r \rightarrow 481 \rightarrow 221$ , then lead to the unique solution  $J(481) = \frac{5}{2}$ , and to the mixing ratios given in table 5. This spin assignment is consistent with inelastic proton scattering data <sup>24</sup>).

At the 2293 keV resonance, the ground-state angular distribution gives  $J_{\text{res}} = \frac{3}{2}$  or  $\frac{7}{2}$ , elastic scattering <sup>10</sup>) yields  $J_{\text{res}} = \frac{5}{2}^-$  or  $\frac{7}{2}^-$ , and thus  $J_{\text{res}} = \frac{7}{2}^-$ . Angular cor-

relations on the  $r \rightarrow 6.48 \rightarrow 0$  cascade allow two values for the spin of the 6.48 MeV level,  $J = \frac{7}{2}$  and  $\frac{5}{2}$ . The probability ratio for these two assignments favours  $J = \frac{7}{2}$  by a factor of 30.

**4.2.8 Other levels** In this subsection a few suggestions are given for the spins of bound states entirely on branching ratio arguments. These values are given in square brackets in the figures and should be considered as preliminary at most.

The decay of the resonance levels with known spin (see fig. 4 of paper I) proceeds primarily to bound states whose spins differ at most by  $\Delta J = 1$  from the resonance spin. Transitions between levels with  $\Delta J = 2$  have an intensity  $\leq 2\%$ . This rule leads to the suggestion that e.g. the 3.96 MeV level has  $J = \frac{3}{2}$ , since direct transitions to this level have been observed from resonances with  $J = \frac{1}{2}, \frac{3}{2}$  and  $\frac{5}{2}$ . This assignment is consistent with the decay of this level to the  $J = \frac{5}{2}$  ground state.

Similar reasoning leads to the suggestions  $J = (\frac{1}{2}, \frac{3}{2}), (\frac{1}{2}, \frac{3}{2}), \frac{5}{2}, \frac{5}{2}, (\frac{3}{2}, \frac{5}{2}), \frac{3}{2}, \frac{3}{2}, \frac{3}{2}$  and  $\frac{3}{2}$  for  $^{27}\text{Al}^* = 3.68, 4.05, 4.41, 5.25, 6.11, 6.16, 6.61, 6.65$  and  $6.78$  MeV, respectively. The assignment  $J(3.68) = (\frac{1}{2}, \frac{3}{2})$  is consistent with the known  $^{11,21})$  spin and parity of this level,  $J^\pi = \frac{1}{2}^+$ . The suggestion  $J(3.96) = \frac{3}{2}$  is consistent with the assignment  $J = (\frac{1}{2}, \frac{3}{2})$  deduced from angular distributions of inelastically scattered protons<sup>24)</sup>, but inconsistent with tentative assignments from other experiments<sup>14)</sup>. The  $J^\pi(3.96) = \frac{7}{2}^+$  assignment given in ref.<sup>33)</sup> is based on an erroneous interpretation of the decay scheme of the  $E_p = 2293$  keV resonance.

The suggested  $J$  values for the 4.05 and 5.25 MeV levels are again consistent with the results from inelastic proton scattering<sup>24)</sup>. An investigation of the  $^{26}\text{Mg}(d, n)^{27}\text{Al}$  reaction leads to the suggestion  $J(4.41) = \frac{3}{2}$ , whereas gamma-ray resonant scattering experiments<sup>25)</sup> result in an assignment  $J^\pi(4.41) = \frac{5}{2}^+$  or  $\frac{7}{2}^+$ , of which  $J^\pi = \frac{5}{2}^+$  is the most probable value. This latter assignment is in agreement with the value reported here. No earlier spin assignments have been published for the five highest-energy levels mentioned above.

**4.2.9 Parities** The analysis of the angular distributions of inelastically scattered deuterons<sup>26,27)</sup> and electrons<sup>46)</sup> yields even parity for the levels  $^{27}\text{Al}^* = 2.21, 2.73$  and  $2.98 + 3.00$  MeV. Another investigation of the first mentioned reaction, however, leads to an odd parity for the 2.21 MeV level<sup>28)</sup>. Studies of the  $^{26}\text{Mg}(d, n)^{27}\text{Al}$  and  $^{24}\text{Mg}(\alpha, p)^{27}\text{Al}$  reactions suggest even parities for the 2.73 and 2.98 MeV level<sup>14)</sup> and for the 2.21 MeV level<sup>29)</sup>, respectively.

Gamma-ray polarization measurements have been performed to check these assignments, and also to remove some ambiguities in the mixing ratio determinations discussed above. The results for the 2.21 MeV level are given in subsection 4.2.3. Similar measurements on the 2.73, 2.98 and 3.00 MeV levels, that will be presented in detail later<sup>30)</sup>, lead to unambiguous even parity assignments to these three levels. They also exclude the high mixing ratio for the ground-state transition from the 2.98 MeV level given in subsection 4.2.5.

It might be noted that if indeed the 6.48 MeV level is the lowest  $1f_{7/2}$  state (see sub-

sect 5.3), one does not expect any odd-parity levels in  $^{27}\text{Al}$  below this excitation energy. Though several experiments suggest odd parities for lower levels<sup>14, 24</sup>), none of these assignments can be considered as unique.

4.2.10 *Conclusions* The spins, parities and mixing ratios which follow from the present experiment, are summarized in fig. 3 for the levels with  $E_x \leq 3.00$  MeV.

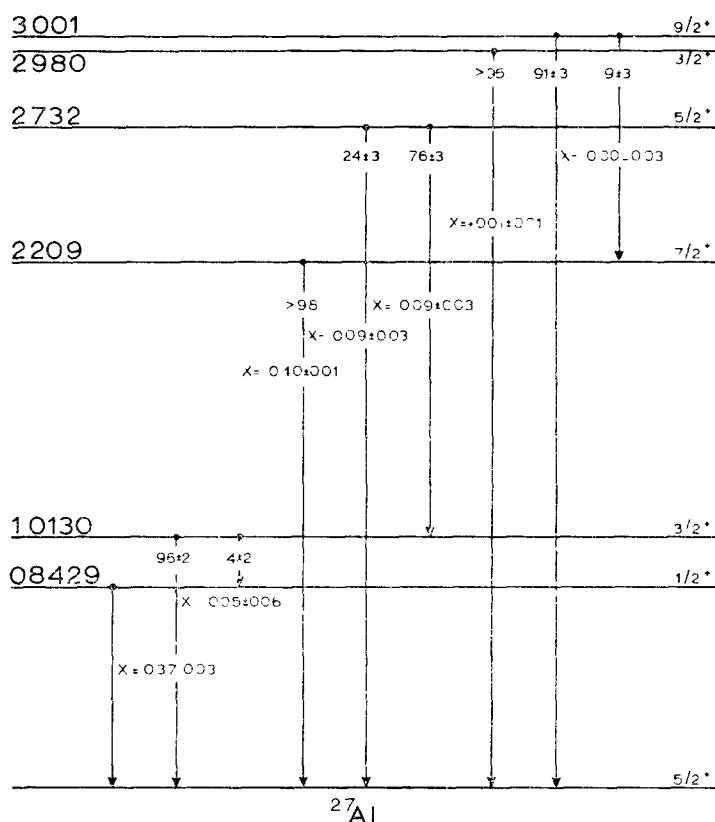


Fig. 3. Summary of the data on the six lowest excited states of  $^{27}\text{Al}$  found in the present experiment.

## 5. Discussion

### 5.1 THE $^{27}\text{Al}$ MODEL

A detailed discussion of the results will be postponed until the polarization measurements<sup>30</sup>) are finished. Recently, extensive discussions of the  $^{27}\text{Al}$  level scheme have been published<sup>14, 15, 31, 46</sup>). Comparison of the theoretical calculations<sup>15</sup>) with the present experimental results, indicates that it will be difficult to explain the decay properties of the 2.73 MeV level in terms of the excited-core model. This same level also presents problems in the explanation of the cross sections of inelastically scat-

tered deuterons <sup>27)</sup> and alpha particles <sup>34)</sup> A probably less serious problem is the discrepancy between the calculated <sup>15)</sup> and measured mixing ratio of the 2.98 MeV gamma ray The excited-core model also does not explain the data from the

TABLE 6  
Transition strengths of gamma rays de-exciting  $^{26}\text{Mg}(\text{p}, \gamma)^{27}\text{Al}$  resonance levels

Transition ( $E_\gamma$ in MeV)	$J_1^\pi \rightarrow J_2^\pi$	$\Gamma_\gamma^{\text{a)}}$ (meV)	$ M ^2 \times 10^3$			
			E1	M1	E2	M2
9.76 $\rightarrow$ 0	$\frac{5}{2}^+ \rightarrow \frac{5}{2}^+$	100		5	7	
9.76 $\rightarrow$ 2.21	$\frac{3}{2}^- \rightarrow \frac{7}{2}^+$	135		15	5	
9.82 $\rightarrow$ 2.73	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$	130		17	30	
9.99 $\rightarrow$ 0	$\frac{7}{2}^- \rightarrow \frac{1}{2}^-$	280	0.45			
10.16 $\rightarrow$ 0	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^-$	620		25	70	
10.16 $\rightarrow$ 2.21	$\frac{3}{2}^+ \rightarrow \frac{7}{2}^-$	190		18	20	
10.41 $\rightarrow$ 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^-$	130		5	35	
10.41 $\rightarrow$ 2.98	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^+$	150		17	(2)	
10.48 $\rightarrow$ 0	$\frac{7}{2}^- \rightarrow \frac{5}{2}^+$	1000 <sup>b)</sup>	1.7			50
10.51 $\rightarrow$ 0	$\frac{5}{2}^- \rightarrow \frac{3}{2}^+$	530 <sup>b)</sup>	0.75			45
10.51 $\rightarrow$ 2.21	$\frac{3}{2}^- \rightarrow \frac{7}{2}^-$	230 <sup>b)</sup>	0.65			150
10.51 $\rightarrow$ 3.00	$\frac{7}{2}^- \rightarrow \frac{9}{2}^+$	150	0.60			

<sup>a)</sup> Calculated using the resonance strength of ref <sup>1)</sup> (as corrected in refs <sup>39,40)</sup>) and the branching ratios of ref <sup>2)</sup>

<sup>b)</sup> For resonance strengths, see sect. 5.3

TABLE 7  
Strengths of gamma transitions between bound states of  $^{27}\text{Al}$

Transition ( $E_\gamma$ in MeV)	$J_1^\pi \rightarrow J_2^\pi$	$\Gamma_\gamma^{\text{a)}}$ (meV)	$ M ^2(\text{M1})$ ( $\times 10^3$ )	$ M ^2(\text{E2})$
0.84 $\rightarrow$ 0	$\frac{1}{2}^+ \rightarrow \frac{3}{2}^-$	0.02 <sup>b)</sup>		13
1.01 $\rightarrow$ 0	$\frac{3}{2}^+ \rightarrow \frac{3}{2}^-$	0.3 <sup>c)</sup>		9
1.01 $\rightarrow$ 0.84	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	0.01	12	
2.21 $\rightarrow$ 0	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$	17 <sup>d)</sup>	100	
2.73 $\rightarrow$ 0	$\frac{5}{2}^- \rightarrow \frac{1}{2}^+$	15 <sup>e)</sup>	65	11
2.73 $\rightarrow$ 1.01	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	45 <sup>c)</sup>	35	0.2
2.98 $\rightarrow$ 0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^+$	110 <sup>f)</sup>	430	6
3.00 $\rightarrow$ 0	$\frac{9}{2}^- \rightarrow \frac{3}{2}^+$	6 <sup>g)</sup>	200	< 0.05
3.00 $\rightarrow$ 2.21	$\frac{3}{2}^- \rightarrow \frac{7}{2}^+$	0.6 <sup>h)</sup>	60	6
				< 0.5

<sup>a)</sup> Widths based on the averages of the lifetimes reported in the literature (for a few typical references, see below) and the branchings reported in this article

<sup>b)</sup> Ref <sup>17)</sup>

<sup>c)</sup> Ref <sup>15)</sup>

<sup>d)</sup> Ref <sup>22)</sup>

<sup>e)</sup> Ref <sup>23)</sup>, the lifetime reported in ref <sup>47)</sup>, however, leads to widths that are about a factor of 25 lower than the values listed here

<sup>f)</sup> Refs <sup>22,23)</sup>

<sup>g)</sup> Refs <sup>46,47)</sup>

$^{26}\text{Mg}(d, n)^{27}\text{Al}$  reaction. These experiments favour a description of the  $^{27}\text{Al}$  level scheme in terms of the strong or weak coupling collective model<sup>14)</sup>

## 5.2 RADIATIVE WIDTHS

From the data given above, a number of gamma transition strengths can be deduced without any assumptions about what has to be considered a "normal" transition strength.

If a resonance has been observed both in the  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$  and  $^{26}\text{Mg}(p, p)^{26}\text{Mg}$  reaction, a comparison of the resonance strengths practically always leads to the conclusion  $\Gamma_\gamma \ll \Gamma_p$ . The  $(p, \gamma)$  resonance strength,  $(2J_r + 1)\Gamma_p\Gamma_\gamma/\Gamma$ , then equals  $(2J_r + 1)\Gamma_\gamma$  and thus determines the radiative width of the resonance level. The resonance branching then immediately gives the partial radiative widths. Comparison with the Weisskopf estimates is possible when the character of the gamma rays (E1, M1, E2, M2) is known from the spins and parities of the initial and final states and from the measured mixing ratio. Twelve transitions for which all the required information is available are listed in table 6. The transition strengths are expressed in Weisskopf units  $|M|^2 = \Gamma_\gamma/\Gamma_w$ , where  $\Gamma_w$  is the Weisskopf estimate<sup>45)</sup>. In the calculation a nuclear radius  $R = 1.2A^{1/3}$  fm has been used. None of the listed strengths deviates strongly from previously measured transition strengths in sd-shell nuclei<sup>16)</sup>. It might be noted, however, that most of the E2 transitions are relatively weak.

The results of similar calculations for transitions between bound states of  $^{27}\text{Al}$  are listed in table 7. The mixing and branching ratios deduced from this experiment, combined with lifetimes averaged from the literature, lead to M1 strengths that are slightly above normal. The enhancement factor of the low-energy E2 transitions centers around the normal value  $|M|^2 = 10$ , except for the  $2.73 \rightarrow 0$ ,  $2.98 \rightarrow 0$ , and  $3.00 \rightarrow 2.21$  MeV transitions where one finds the unusually low values  $|M|^2 = 0.2$ ,  $< 0.05$  and  $< 0.5$ , respectively.

## 5.3 ANALOGUE STATES

The  $^{27}\text{Al}$  level at 6.81 MeV, with  $J^\pi = \frac{1}{2}^+$ , has been identified<sup>15)</sup> as the  $T = \frac{3}{2}$  analogue of the  $^{27}\text{Mg}$  ground state. Since the proton binding energy in  $^{27}\text{Al}$  is 8.27 MeV, the analogues of the second and higher excited states of  $^{27}\text{Mg}$  could appear as resonances in the  $^{26}\text{Mg} + p$  reactions. Unfortunately, the spectroscopic factors are not known for all relevant levels of  $^{27}\text{Mg}$ . A few of these levels, however, are known to have a relatively pure single-particle character and are therefore expected to correspond to strong  $^{26}\text{Mg} + p$  resonances.

The analogues of the second and third excited states of  $^{27}\text{Mg}$  at 1.69 and 1.94 MeV, which both have  $J^\pi = \frac{5}{2}^+$  (ref.<sup>35)</sup>), are expected to correspond to  $^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$  resonance levels at  $E_x \approx 8.50$  and 8.75 MeV, respectively. A level at  $E_x = 8.50$  MeV corresponds to a resonance with  $E_p \approx 250$  keV. At this low energy the penetration of  $l_p = 2$  protons ( $J^\pi = \frac{5}{2}^+$ ) will be prohibitively low. At  $E_x \approx 8.75$  MeV, three  $J = \frac{5}{2}$  resonance levels have been observed ( $E_p = 501, 522$  and 650 keV) and it might be



noted that the next resonance whose spin is known to be  $J = \frac{5}{2}$  occurs at a proton energy which is about 1 MeV higher ( $E_p = 1548$  keV). This large gap suggests isospin enhancement of the three resonances mentioned above.

Two other resonances, which very likely are analogue states of  $^{27}\text{Mg}^* = 3.47$  and  $3.56$  MeV (with  $J^\pi = \frac{1}{2}^+$  and  $\frac{3}{2}^-$ ), respectively (refs. <sup>35,36</sup>) are the very broad  $^{26}\text{Mg}(p, p)^{26}\text{Mg}$  resonances observed by Mertz <sup>10</sup>) at  $E_x = 2021$  ( $J^\pi = \frac{3}{2}^-$ ,  $\theta_p^2 = 0.22$ ) and  $2046$  keV ( $J^\pi = \frac{1}{2}^+$ ,  $\theta_p^2 = 0.14$ ). These resonances have not been investigated in this experiment.

The next odd-parity state of  $^{27}\text{Mg}$  is the  $I_n = 3$  level at  $3.76$  MeV (ref. <sup>37</sup>). The expected excitation energy of its analogue state in  $^{27}\text{Al}$  is  $E_x \approx 10.57$  MeV. Two  $J^\pi = \frac{7}{2}^-$  resonances have been observed in this experiment at  $E_p = 2293$  and  $2323$  keV ( $E_x = 10.48$  and  $10.51$  MeV, respectively). The reduced proton widths of these resonances reported by Mertz <sup>10</sup>),  $\theta_p^2 = 0.18$  and  $0.02$ , respectively, are in agreement with the identification of these two levels as split analogues of the  $3.76$  MeV level of  $^{27}\text{Mg}$ . With the appropriate isospin Clebsch-Gordan coefficient one finds the spectroscopic factor  $S_n(3.76) = 3\theta_p^2 = 0.60$ . This calculated value is slightly lower than, but within the errors in agreement with the experimental value  $S_n = 0.9$ . Several strong  $J^\pi = \frac{7}{2}^-$ ,  $T = \frac{3}{2} \rightarrow J^\pi = \frac{7}{2}^-$ ,  $T = \frac{1}{2}$  gamma transitions have been observed in neighbouring nuclei <sup>38</sup>). Both resonances discussed here strongly decay to the  $J = \frac{7}{2}(\frac{5}{2})$  level at  $6.48$  MeV. If  $^{27}\text{Al}(6.48)$  is indeed the anti-analogue level with  $J^\pi = \frac{7}{2}^-$  (this assumption still has to be confirmed experimentally), the strengths of the two  $(p) \rightarrow 6.48$  MeV transitions is  $|M|^2(\text{M1}) = 0.5$  and  $0.3$ , respectively. These values are based on measurements of the strengths of the  $2293$  and  $2323$  keV resonances relative to the well-known strength of the  $1965$  keV resonance <sup>39,40</sup>), which yield  $(2J+1)\Gamma_p\Gamma_\gamma/\Gamma = 15$  and  $12$  eV, respectively. Similar enhancements over the normal M1 transition strengths,  $|M|^2(\text{M1}) \approx 0.03$ , have been observed in neighbouring nuclei <sup>38</sup>).

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