

SPINS, PARITIES AND ISOSPINS OF ^{26}Al LEVELS: Shell-model aspects

P.M. ENDT, P. DE WIT and C. ALDERLIESTEN

Fysisch Laboratorium, Utrecht University, P.O. Box 80.000, 3508 TA Utrecht, The Netherlands

B.H. WILDENTHAL

Department of Physics, University of New Mexico, Albuquerque, NM 87131, USA

Received 7 April 1988

(Revised 21 June 1988)

Abstract: Two preceding papers on the $^{25}\text{Mg}(\text{p}, \gamma)^{26}\text{Al}$ reaction have presented information on the energies, γ -ray branchings, lifetimes and resonance partial widths of ^{26}Al states in the $E_x = 0$ –8.1 MeV region. These data (combined with information from other reactions) provide new J^π ; T assignments to 127 levels (of which 111 assignments are unambiguous), as discussed in the present paper.

The states obtained from a shell-model calculation in the untruncated sd-shell are found to correspond one-to-one with the 30 lowest $T = 1$ and the 42 lowest $T = 0$ even-parity states; for many higher $T = 0$ states the correspondence could also be established.

An extensive comparison has been made of experimental and calculated γ -ray strengths. On the average $E2_{\text{IS}}$ strengths are calculated correctly, whereas $M1_{\text{IV}}$ strengths are high by a factor 1.85. For many levels the decay strengths are in excellent agreement, whereas the poor agreement for some pairs of neighbouring levels with the same J^π ; T value could be ascribed to a poor description of the configuration mixing. In some cases the strength comparison has helped to establish the correspondence between calculated and experimental states.

A comparison has also been made between $T = 1$ levels of ^{26}Al and ^{26}Mg . For one (out of 44) ^{26}Al states the ^{26}Mg parent is unknown, whereas for one ^{26}Mg level the analogue in ^{26}Al has not been identified.

T	NUCLEAR STRUCTURE $^{25}\text{Mg}(\text{p}, \gamma)$, $E = 0.31$ –1.84 MeV; ^{26}Al deduced J^π , isospin.
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1. Introduction

The present paper is the last in a sequence of three. In the first paper¹⁾ the existence, yields and partial widths are discussed of $^{25}\text{Mg}(\text{p}, \gamma)^{26}\text{Al}$ and $^{25}\text{Mg}(\text{p}, \text{p}')^{25}\text{Mg}$ resonances in the $E_p = 0.31$ –1.84 MeV region. In the second paper²⁾ the energies and γ -ray branchings are given of the $^{25}\text{Mg}(\text{p}, \gamma)$ resonances and of ^{26}Al bound states, and the lifetimes of the latter as determined with the DSA method. These data serve in the present paper, together with the information from other reactions, for the assignment of spins, parities and isospins to ^{26}Al levels in the $E_x = 0$ –8.07 MeV region (sect. 2). Of the 160 states presently known in this region

141 have now obtained an unambiguous J^π ; T assignment; for another 12 states the number of J^π ; T possibilities has been restricted to two. Arguments based on γ -ray strength statistics (GRSS) are discussed in sect. 3; a short description of GRSS has already appeared as a letter⁹⁾.

The present extensive information on the level scheme makes ²⁶Al an ideal nucleus for a large-scale comparison with a shell-model calculation in the full sd-shell (sect. 4). Up to and including the 2_8^+ ; 0 level at $E_x^{\text{exp}} = 6198$ keV there is a one-to-one correspondence between calculation and experiment for the 42 lowest $\pi = +$, $T = 0$ states. For 30 $\pi = +$, $T = 1$ states such a correspondence exists up to and including the 4_7^+ ; 1 level at $E_x^{\text{exp}} = 7953$ keV. The correspondence between $T = 1$ states in ²⁶Al and ²⁶Mg is also discussed (sect. 5). A comparison between calculated and experimental γ -ray strengths in ²⁶Al is possible for many hundreds of transitions (sect. 6).

The ²⁶Al levels close to the proton binding energy determine the importance of the ²⁵Mg(p, γ)²⁶Al reaction in nucleosynthesis; this aspect has been discussed in a separate paper²⁸⁾.

2. Spins, parities, isospins

Gamma-ray angular distributions have not been measured in the present (p, γ) work, because it is a general experience that they are not very rewarding for a target spin as high as $J = \frac{5}{2}$. The possibilities of channel spin, orbital momentum, and γ -ray multipolarity mixing entail relatively small anisotropies, which generally can be fitted by several (often many) combinations of initial- and final-state J^π values.

The large sensitivity for the detection of (especially low-energy) weak transitions in the present Compton-suppressed Ge spectra has created the possibility, however, for much easier J^π ; T assignments on a large scale, from the γ -ray strengths only. In fact, resonances are observed to decay to almost all lower-energy bound states to which they possibly can decay by means of isovector dipole primaries. For example, at the $E_p = 685$ keV 3^- ; 1 resonance all 25 bound states with J ; $T = (2-4)$; 0 below $E_x = 5.6$ MeV are excited through $M1_{IV}$ or $E1_{IV}$ primaries. The low energy of many primaries has the additional advantage that it is relatively easy to prove their dipole character (with the Weisskopf estimate for quadrupole over that for dipole transitions being proportional to E_γ^2). The investigated resonances have, moreover, a great variety of J^π ; T values. All 20 $J = 1-5$, $\pi = +$ or $-$, $T = 0$ or 1 possibilities are represented and, moreover, two 6^- ; 0 resonances and (probably) a 0^- ; 1 and a 0^- ; 0 resonance. As a consequence, bound states are generally excited at several (often many) resonances with (hopefully) very different J^π ; T values. This fact, combined with the extensive information on the bound-state decay and lifetimes, at least provides stringent restrictions on J^π ; T and generally leads to unambiguous assignments for both resonances and bound states.

The γ -ray feeding and decay data are quite useful for obtaining J and T , but do not always provide π . Additional information is supplied by previous work on

proton stripping and neutron pick-up reactions ³⁻⁶), on the ²⁸Si(\vec{d} , α) reaction with tensor-polarized deuterons ^{7,13}) covering $E_x = 0$ –6.0 MeV, and on high-resolution ²⁵Mg(p, p) elastic scattering ⁸) ($E_x = 7.1$ –8.2 MeV). All these reactions are excellent for parities, but they usually yield only restrictions on J and no information on T .

The l -values from stripping ^{4,6}) and pick-up ^{3,5}) should be discussed in some more detail, in particular those which are essential for J^π assignments, and those which are in conflict with the assignments from the present (p, γ) work (see table 1). In such a discussion it should be taken into consideration that the excitation energies given in the (τ , d) paper by Betts *et al.* ⁴) are quite poor. They are the averages of their (τ , d) and (τ , α) energies ^{26,27}), but this averaging procedure does not take account of the fact that different states may be excited (and actually are excited) in stripping and pick-up reactions. The best energies can be derived directly from the (τ , d) deuteron spectrum given in fig. 1 of ref. ⁴).

The $l(p, d) = 1 + 3$ (weak deuteron group) for the 5245 keV level conflicts with $l(\tau, d) = 2$ and with the unambiguous $J^\pi = 4^+$ assignment from (p, γ) (20 decay branches observed); the explanation is probably to be found in insufficient statistics in the (p, d) work at very small angles.

The unambiguous 1^+ assignment to the 5671 keV level from (p, γ) would be invalidated by the $l(\tau, d) = 0$ component for the 5671 + 5676 keV doublet. This unstructured (τ , d) angular distribution, however, can be fitted as well by $l = 1 + 3$ (which implies that the 5676 keV 4^- level would be predominantly excited) as by $l = 0 + 2$. The $l(\tau, d) = 1 + 3$ for the 5726 keV level conflicts with the $l(p, d) = 2$ value and with our 4^+ assignment. In this case one would also say that $l(\tau, d) = 2$ fits equally well as $l = 1 + 3$.

The l -values which have been used for the J^π assignments to the levels at $E_x = 6280$, 6343 and 6399 keV all seem reasonably convincing. The $l(\tau, d) = 1$ assignment to the $E_x = 6364$ keV level, in conflict with $l(\tau, \alpha) = 0 + 2$ from ref. ⁵) and with our $J^\pi = 3^+$ assignment from (p, γ), is evidently erroneous. The very weak $l = 0$ components in the (τ , α) transitions to the 6414 and 6496 keV levels are in conflict with our 0^+ and $5^+(4^+)$ assignments, respectively. For the 6496 keV level a pure $l = 2$ fit is equally good as $l = 0 + 2$; for the 6414 keV level (weakly excited and badly resolved from $E_x = 6399$ and 6436 keV) the situation is not quite clear. The $l(\tau, d) = 1$ value for the 6816 keV level would disagree with our preferred $J^\pi = 6^+$ value; the (τ , d) transition is weak and badly resolved from the $l = 1$ transition to the 6789 keV level (see table 2).

The strengths of bound-state decay transitions are calculated from the observed branchings ²) and lifetimes ²), those of resonance primaries from the resonance branchings ²) and γ -ray widths Γ_γ . The latter are obtained ¹) from the (p, γ) resonance strengths $S = (2J + 1)\Gamma p_0 \Gamma_\gamma / \Gamma$ for resonances with known proton ground-state width Γp_0 and total width Γ . For other resonances they have been derived from S with the aid of γ -ray strength statistics, see sect. 3 and ref. ⁹).

The γ -ray strengths are used to obtain restrictions on J^π ; T values by means of recommended upper limits (RUL's). The RUL's used for E1_{IS}, M1_{IS}, E2_{IS} and E2_{IV} transitions are given in ref. ⁹⁾, those for M2_{IV} and M2_{IS} (only seven M2 transitions have been observed), E3 and M3 (none observed) are taken from ref. ¹⁰⁾.

It is appropriate to discuss the use to be made of these RUL's in this paper in which such a large number of J^π ; T assignments is presented, most of them depending on RUL's. This discussion supersedes and corrects a short remark on this point in ref. ²⁰⁾.

We assume that the distribution $f(x)$ of observed logarithmic γ -ray strengths $x = {}^{10}\log S$ for a certain transition character (e.g. E2_{IS}) has a gaussian shape with centroid s and r.m.s. spread σ :

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-s)^2/2\sigma^2}.$$

The RUL R is then defined via $r = {}^{10}\log R$ by the condition:

$$\int_r^\infty f(x) dx = \frac{1}{2} \left[1 - \Phi \left(\frac{r-s}{\sigma\sqrt{2}} \right) \right] = 0.001, \quad (1)$$

in which $\Phi(\xi) = (2/\sqrt{\pi}) \int_0^\xi e^{-x^2} dx$ represents the error integral. From eq. (1) r can be derived as $r = s + 3.10\sigma$.

We now consider a certain transition which for assumed E2_{IS} character would have a logarithmic strength $b = {}^{10}\log B = r$, and we want to investigate in the following the influence of its experimental r.m.s. error β on the possibility to exclude E2_{IS} character. We again assume a gaussian distribution:

$$g(x) = \frac{1}{\beta\sqrt{2\pi}} e^{-(x-b)^2/2\beta^2}.$$

The probability to find an E2_{IS} transition with $b \geq r$ is then given by:

$$P = \int_r^\infty db \int_{-\infty}^\infty f(x)g(x) dx.$$

Evaluation of the double integral yields:

$$P = \frac{1}{2} \left[1 - \Phi \left\{ \frac{r-s}{\sqrt{2(\sigma^2 + \beta^2)}} \right\} \right]. \quad (2)$$

One notes that eq. (2) changes into eq. (1) for $\beta \rightarrow 0$, as expected. Although P increases above $P = 0.001$ with β , the increase is quite slow. For instance, for $\beta = 0.35\sigma$ we find $P = 0.0018$ which is still very small. In ref. ⁹⁾ values of σ are given for six different transition characters; the average amounts to $\sigma = 0.70$. A value $\beta = 0.35\sigma = 0.245$ corresponds to the relative experimental error $\Delta B/B = \beta \ln 10 = 0.56$. We conclude that for B equal to the RUL, E2_{IS} character is excluded at the

0.18% probability limit if the r.m.s. error in B stays below 56%. Almost none of the transitions considered for $J^\pi; T$ assignment purposes has errors as large as this.

The eq. (2) also holds for measured values B exceeding the RUL. If the measured value $B = B_0$ is substantially larger than R , the possibility to find an $E2_{IS}$ transition with a strength $B \geq B_0$ can be calculated from eq. (2), with r replaced by b_0 . For example, for $b_0 = r + 0.30$ (equivalent to $B_0 = 2R$), we find $P = 0.0002$ (for $\beta = 0$), where P stays below 0.001 as long as β does not exceed the (exceedingly large) value $\beta = 0.55\sigma$.

In the present paper (including the discussion given above) the expression "transition character" has been used rather than "transition multipolarity". The latter only indicates the L -value of the transition, but does not differentiate between electric and magnetic, nor between isovector and isoscalar transitions.

In tables 1 and 2 the arguments are given for $J^\pi; T$ assignments to secondary states and to (p, γ) resonances, respectively. Secondary states are defined as states which are only excited in the decay of higher-lying resonances and which (for $E_x > 6306$ keV, the proton binding energy) are not observed as resonances themselves. An exception is formed by the levels at $E_x = 6496, 6551$ and 6598 keV which have been seen as extremely weak (p, γ) resonances by Elix *et al.*¹¹⁾, but of which the resonance decay has not been investigated in the present work.

Although the presentation in two tables seems to suggest that $J^\pi; T$ assignments have been obtained in an orderly fashion, first to secondary states and then to resonances, the sequence of assignments has in practice been much more haphazard, with assignments to these two groups of levels alternating rather randomly. This entails the danger that a single transition $i \rightarrow f$ is used both ways, not only to determine (or restrict) $(J^\pi; T)_f$ from $(J^\pi; T)_i$, the latter assumedly known, but also vice versa. Our assignments have been carefully checked to eliminate such cyclic reasoning.

Table 1 does not contain the 30^{26}Al states (including all states below $E_x = 3.75$ MeV) for which a $J^\pi; T$ assignment had already been given in the 1978 $A = 21$ –44 review¹²⁾. Exceptions are the levels at $E_x = 4206$ and 4940 keV which are members of close doublets such that the 1978 assignments could not be considered as very strong. If we exclude these, there remain 54 new secondary-state assignments, of which all except 10 are unambiguous. The majority of the new assignments have been obtained from the present (p, γ) work alone, although many of these are corroborated or strengthened through particle transfer information. For $T = 1$ assignments to five bound states from (p, γ) (in agreement with those from the present work) see also ref.²¹⁾.

For several levels in table 1 arguments are used (in particular for T -assignments) based on a comparison of the ^{26}Mg and ^{26}Al level schemes, discussed in more detail in sect. 5. These arguments get more weight by taking into account that the average absolute difference between the excitation energies of corresponding $\pi = +, T = 1$ levels of ^{26}Mg and ^{26}Al (the latter energies corrected for the 228 keV excitation

TABLE 1
Arguments for J^π ; T assignments to ²⁵Mg(p, γ)²⁶Al secondary states

E_x [keV]	I_p^+ (τ, d) ^a	I_n^- (p, d) ^b	π (\bar{d}, α) ^d	$J^\pi; T$		
				γ -decay ^c	γ -feeding ^e	resulting
3751	0+2	0+2	N	(1 ⁺ -3 ⁺); 0	$\neq (1^+, 2^-, 3^+)$	2 ⁺ ; 0
3978			0 ⁻	(0-3 ⁺)	$T=0, \neq 3^+$	0 ⁻ ; 0
4192	} 0+2	0+2	U	3; 1	$\neq 3^-$	3 ⁺ ; 1
4206		2	N	4 ⁺ ; 0 or 3 ⁺	$\neq 3^+$	4 ⁺ ; 0
4349		2	U	3 ⁺ ; 0		3 ⁺ ; 0
4480			0 ^{-g})	(0-3 ⁺)	$T=0, \neq (0^+, 3^+)$	0 ⁻ ; 0
4548		0+2	(N)	2 ⁺	$T=1$	2 ⁺ ; 1
4599	0+2	0+2	U	3; 1	$\neq 3^-$	3 ⁺ ; 1
4622			U	(1 ⁺ -3 ⁺)	$T=0, \neq (1-3)^+$	2 ⁻ ; 0
4705	2	2	(N)	(3 ⁺ , 4)	$T=1, \neq (3^+, 4^-)$	4 ⁺ ; 1
4773	2	2	N	(3, 4) ⁺ ; 0	$\neq 3^+$	4 ⁺ ; 0
4940		} 1+3		(1, 2 ⁺); 1 or 1; 0	$T=0, \neq 1^+$	1 ⁻ ; 0
4941			U	(4, 5) ⁺	$T=0, \neq 4^+$	5 ⁺ ; 0
5007		} 2		$\neq 3^-$	3 ⁻ ; 1 or 2 ⁻	2 ⁻ ; 0 ^f)
5010			U	1		1 ⁺ ; 0 ^{f,m})
5132			} N	4; 1	$\neq 4^-$	4 ⁺ ; 1
5142	0+2	0		(2, 3 ⁺)	$T=1, \neq (2^-, 3^+)$	2 ⁺ ; 1
5195			(0 ⁺)	(0-3 ⁺)	$T=1, \neq (0^-, 3^+)$	0 ⁺ ; 1 ^h)
5245	2	1+3 ⁱ)	N	4 ⁺ ; 0		4 ⁺ ; 0
5431			(N)	1; 0	$\neq 1^+$	1 ⁻ ; 0
5457	} 1			(2 ⁺ , 3); 0	$\neq (2, 3)^+$	3 ⁻ ; 0
5462				(0 ⁺ -3 ⁺)	$\neq 3^+$	0 ⁺ (1, 2); 0 ^{j,o})
5488	} 0+2	0+2	U	(3 ⁺ -5 ⁺)	$\neq (3, 4)^+$	5 ⁺ (4 ⁻); 0 ^{j,o})
5495				2		2 ⁺ ; 0 ^{f,k})
5513	2	(3)	N	(3, 4) ⁺ ; 0	$\neq 3^+$; 0	4 ⁺ ; 0
5545	2	0+2	} (U)	2 ⁺ ; 1		2 ⁺ ; 1
5569		(1+3)		(3 ⁺ -6 ⁺)	$\neq (3^+, 5^-, 6^+)$	5 ⁺ (4); 0 ^{j,o})
5585	2		} U	1; 0		1 ⁺ ; 0
5598		1+3		(1 ⁺ -4 ⁺)	$T=0, 3^-$	3 ⁻ ; 0
5671	} 0+2 ⁱ)			1 ⁺ ; 0		1 ⁺ ; 0
5676				(3 ⁺ -5 ⁺)	$T=0, \neq (3-5)^+$	4 ⁻ ; 0
5692	1	(2)	(N)	(2 ⁺ , 3); 0	$\neq (2, 3)^+$	3 ⁻ ; 0
5726	1+3 ⁱ)	2		(3 ⁺ , 4)	$T=1, \neq (3^+, 4^-)$	4 ⁺ ; 1
5849			(N)	(2, 3 ⁺); 0	$\neq (2^-, 3^+)$	2 ⁺ ; 0
5883			U	3 ⁺	$T=0$	3 ⁺ ; 0
5916	} 1+3			(1 ⁺ -3 ⁺); 0	$\neq (1-3)^+$	2 ⁻ ; 0
5924				(3 ⁺ -5 ⁺)	$T=1, \neq (3, 5)^+$	4 ⁺ ; 1 ^l)
5950			(N)	(1, 2 ⁺), $\neq 2^+$; 0	$T=0, \neq 1^+$	1 ⁻ ; 0
6028				(1, 2 ⁻); 1		1 ⁺ ; 1 ^m)
6084	} 2			(4 ⁺ , 5)	$T=0, \neq (4^+, 5^-)$	5 ⁺ ; 0
6086				(1, 2 ⁺)	$T=0, \neq 1^+$	(1 ⁻ , 2 ⁺); 0
6120				(3 ⁺ -6 ⁺)	$T=0, \neq (3^+, 5^-, 6^+)$	(4, 5 ⁺); 0
6198				1(2 ⁺)	$\neq 1$	2 ⁺ ; 0 ^j)
6238				1; 0		1; 0
6254	(1)				$T=0, 3^-$	3 ⁻ ; 0
6270	} 0+2 ⁱ)			1; 0		1 ⁺ ; 0 ^m)
6280				3; 0		3 ⁺ ; 0

TABLE 1—continued

E_x [keV]	I_p^+ (τ , d) ^{a)}	I_n^- (τ , α) ^{c)}	π (\bar{d} , α) ^{d)}	J^π ; T		
				γ -decay ^{e)}	γ -feeding ^{e)}	resulting
6343		1+3 ¹⁾		(3, 4); 0	$\neq 3^-$	4 ⁻ ; 0
6364	1 ¹⁾	0+2 ¹⁾		(2 ⁺ -4 ⁺)	$T=1$, $\neq (2^+, 3^-, 4^+)$	3 ⁺ ; 1
6399		1+3 ¹⁾			(1 ⁺ , 2)	2 ⁻ ; 0 ¹⁾
6414		0+2 ¹⁾		(0-3 ⁺)	$T=1$, $\neq 3^+$	0 ⁻ ; 1 ⁿ⁾
6436		1+3		(3, 4); 0	$\neq (3, 4^+)$	4 ⁻ ; 0
6496		0+2 ¹⁾		(3 ⁺ -5 ⁺); 0	$\neq 3^+$	5 ⁺ (4 ⁺); 0 ^{o)}
6551	2			(4, 5) ⁺		4 ⁺ (5 ⁺); 0 ^{1,o)}
6598				(3 ⁺ -5 ⁺)	$\neq (3, 4)^+$	5 ⁺ (4 ⁻); 0 ^{1,o)}
6816	1 ¹⁾			(3 ⁺ -6 ⁺)	$T=0$, $\neq 3^+$	6 ⁺ (4, 5); 0 ^{o)}

^{a)} Ref. 4). ^{b)} Ref. 3). ^{c)} Ref. 5). ^{d)} Ref. 7); N and U stand for natural and unnatural parity, respectively.

^{e)} From the application of RUL's (see text).

^{f)} With $T=0$ determined from γ -ray strength statistics; see text and ref. 9).

^{g)} Also $J^\pi=0^-$ from (\bar{d} , α) in ref. 13).

^{h)} This is the only level which can be the analogue of the ²⁶Mg level at $E_x=4972$ keV with $J^\pi=0^+$.

ⁱ⁾ For a discussion of these l -values see text.

^{j)} With $T=0$ determined on the argument that for $T=1$ there is no possible parent level in ²⁶Mg.

^{k)} With $J^\pi=5^+(4^-)$ determined for $E_x=5488$ keV, the $l=0$ component from (τ , d) and (p, d) can only apply to $E_x=5495$ keV.

^{l)} For a 4⁻; 1 assignment there is no possible parent level in ²⁶Mg.

^{m)} With $L(p, n)=0$ [ref. 33)] excluding $\pi=-$.

ⁿ⁾ This is the only level which can be the analogue of ²⁶Mg(6256 keV) with $J^\pi=0^+$.

^{o)} The preferential assignment is based on a comparison with shell-model theory (see text).

energy of the lowest 0⁺; 1 level) amounts to only 36 keV. Whether or not there exists a parent level of ²⁶Mg corresponding to a particular ²⁶Al level thus only requires a search in a region of about 200 keV.

It would evidently take too much space to discuss all the J^π ; T assignments in table 1 and 2 in detail. Instead we take the $E_x=3751$ keV level (table 1) as an example. The level with a mean life of $\tau_m=32\pm 8$ fs [ref. 2)] shows strong decay branches²⁾ to the 2⁺; 1 states at 2070 and 3160 keV, with $b(\gamma)=(64.9\pm 0.8)\%$ and $(17.7\pm 0.7)\%$, respectively. Both transitions are far too strong to have anything but M1_{IV} or E1_{IV} character which yields J ; $T(3751 \text{ keV})=(1-3); 0$. The transitions to the 417 keV 3⁺; 0 and 1058 keV 1⁺; 0 levels, with $b=(7.3\pm 0.3)\%$ and $(9.2\pm 0.3)\%$, respectively, are too strong to have M2 character, which excludes the $J^\pi=1^-$ and 3⁻ possibilities. The level is excited at the $E_p=811$ and 1800 keV resonances, both with $J^\pi=1^-$, and at the $E_p=1342$, 1587 and 1714 resonances, all with $J^\pi=4^+$. The primaries are too strong to have M2 or M3 character and thus exclude $J^\pi=1^+$, 2⁻ and 3⁺, leaving J^π ; $T(3751 \text{ keV})=2^+; 0$ as the only possibility.

The remarkable 0⁻; 0 level at $E_x=3978$ keV (the lowest odd-parity state of ²⁶Al) has already been discussed in ref. 2). The 0⁻; 0 assignment to the 4480 keV level has

TABLE 2
Arguments for J^π ; T assignments to ²⁵Mg(p, γ)²⁶Al resonances

E_p	E_x	I_p^+	$J^\pi; T$			Additional arguments and remarks
[keV]	$(\tau, d)^a)$	$(\alpha, t)^b)$	$(p, p_0)^c)$	γ -decay ^{d)}	resulting	
317	6610	1		3^-	$3^-; 0$	$T=0$ from GRSS
390	6680	0+2		$2^+; 0$	$2^+; 0$	
435	6724	1		$4^-; 0$ or 3^+	$4^-; 0$	$\neq 3^+$ from feeding
497	6784	} 1		$2^-; 0$	$2^-; 0$	
503	6789			$3^-; 0$	$3^-; 0$	
515	6801			3^+	$3^+; 0$	$T=0$ from feeding
516	6802	} 1 ^{e)}		$1^+(1^-, 2^-)$	$1^+(1^-, 2^-); 1$	$T=1$ from feeding
533	6818			$3; 0$ or 4^+	$4^+; 1$	$T=1$ from feeding
567	6852			$2^+; 1(+0)$	$2^+; 1(+0)$	
591	6874			1^+	$1^+; 0$	$T=0$ from feeding
593	6876			$2^+; 1$	$2^+; 1$	
609	6892	3		$(5^+, 6^-); 0$	$6^-; 0$	
656	6936			$1^+; 0$	$1^+; 0$	
685	6964	3		$3^+; 1$	$3^-; 1$	
723	7001			$2^+; 0$	$2^+; 0$	
738	7015			$5^+; 0$	$5^+; 0$	
775	7051			$3^+; 0$	$3^+; 0$	
811	7086			$1; 1$	$1^-; 1^f)$	
819	7093			$2^+; 0$	$2^+; 0$	
835	7109		$(1-4)^-$	$(3^+, 4^-); 0$	$4^-; 0$	
870	7142		$(1-3)^-$	$(2, 3^+); 0$	$2^-; 0(+1)$	$T=0(+1)$ from GRSS
881	7153		$(2, 3)^+$	$3^+; 0$	$3^+; 0$	
890	7161		$(1-4)^-$	$3^-; 0$	$3^-; 0$	
896	7168		$(1-3)^-$	$(3^+, 4^-)$	$4^-; 0$	$T=0$ from GRSS ^{g)}
928	7198			$1^+; 0$	$1^+; 0$	
953	7222			$5^+(4^+); 1$	$5^+; 1$	$\neq 4^+$ from feeding
969	7238		$(1-4)^-$	$(2^+, 3^-); 0$	$3^-; 0$	
986	7254		2^-	$2; 1(+0)$	$2^-; 1(+0)$	
1019	7286			$0^-(1, 2); 0$	$0^-(1, 2); 0^h)$	
1025	7291		$(2-5)^+$	$4^+(3^+); 0$	$4^+(3^+); 0$	
1043	7308			$2^+; 1$	$2^+; 1$	
1084	7348		$(3, 4)^-$	$4^-; 0+1$	$4^-; 0+1$	
1103	7366			$4^+; 0$	$4^+; 0$	
1135	7397		$(2, 3)^+$	$2^+; 0$	$2^+; 0$	
1137	7399		3^-	$3; 1$	$3^-; 1$	
1148	7410		$(2-4)^-$	$(3^+, 4^-); 0+1$	$4^-; 0+1$	
1164	7425		$(1-4)^+$	$(3, 4)^+; 0$	$3^+; 0^i)$	
1179	7440			$0(1, 2); 1$	$0(1, 2); 1$	
1184	7444		$(1-4)^-$	1^-	$1^-; 0$	$T=0$ from GRSS
1196	7455			$1^+; 0$	$1^+; 0$	
1205	7464			$3^+; 0+1$	$3^+; 0+1$	
1237	7495		3^+	$3^+; 0+1$	$3^+; 0+1$	
1239	7497		2^-	$2^-; 0(+1)$	$2^-; 0(+1)$	
1273	7529	3		$(5^+, 6^-); 0$	$6^-; 0$	
1283	7540		2^-	$2; 1$	$2^-; 1$	
1292	7548			$5^-; 0$	$5^-; 0$	
1302	7558		2^+	$2^+; 0$	$2^+; 0$	

TABLE 2—continued

E_p	E_x	I_p^+	$J^\pi; T$			Additional arguments and remarks
[keV]	$(\tau, d)^a)$	$(\alpha, t)^b)$	$(p, p_0)^c)$	γ -decay ^{d)}	resulting	
1306	7561		2^+	$2^+; 1$	$2^+; 1$	
1337	7592		$(0-5)^+$	$4^+(3^+); 0$	$4^+(3^+); 0$	
1342	7596			$4^+; 0$	$4^+; 0$	
1351	7605		$2^-(3^-)$	$2; 0(+1)$	$2^-; 0(+1)$	
1370	7623			$1^+; 0$	$1^+; 0$	
1375	7628		$(0-5)^+$	$5^+; 1$	$5^+; 1$	
1396	7648			$1^+(2^+)$	$1^+(2^+); 0$	$T = 0$ from GRSS
1515	7762		3^-	3	$3^-; 0$	$T = 0$ from GRSS
1525	7772			$3^+; 0$	$3^+; 0$	
1526	7773		1^-	$T = 0$	$1^-; 0$	
1568	7814		1^+	$1^+; 0(+1)$	$1^+; 0(+1)$	
1580	7825		$4^-(3^-)$	$(3^+, 4^-)$	$4^-; 0$	$T = 0$ from GRSS
1587	7832		$(2-5)^+$	$4^+; 0$	$4^+; 0$	
1622	7865		2^+	$2^+; 0(+1)$	$2^+; 0(+1)$	
1632	7874		3^+	$3^+; 0$	$3^+; 0$	
1637	7880			$(1, 2); 1(+0)$	$1^+; 1(+0)^j)$	
1649	7891		4^+	$4^+; 1$	$4^+; 1$	
1680	7921			$5^+; 0$	$5^+; 0$	
1699	7939		3^+	$3^+; 1$	$3^+; 1$	
1714	7953		$(4, 5)^+$	$4^+; 1$	$4^+; 1$	
1744	7982		2^+	$2^+; 1$	$2^+; 1$	
1763	8001		1^-	$1^-; 1$	$1^-; 1$	
1771	8008		2^+	$2^+; 0$	$2^+; 0$	
1774	8011		$5^-(3^-, 4^-)$	$5; 1$	$5^-; 1$	
1800	8036			1	$1^-; 0$	$T = 0, \neq 1^+$ from GRSS
1811	8047		3^-	3^-	$3^-; 0$	$T = 0$ from GRSS
1829	8064		2^+	$2^+; 1$	$2^+; 1$	
1833	8067		$(5, 6)^-$	$5; 1$	$5^+; 1$	

^{a)} Ref. ⁴⁾. ^{b)} Ref. ⁶⁾. ^{c)} Ref. ⁸⁾.

^{d)} From the application of RUL's as described in the text.

^{e)} The $I(\tau, d) = 1$ assignment is presumably erroneous (the corresponding deuteron group is extremely weak).

^{f)} This is the only level which can be the analogue of ²⁶Mg(7.06 MeV, 1^-).

^{g)} The exclusion of $J^\pi = 4^-$ in the (p, p_0) work is presumably erroneous.

^{h)} The γ -decay (97.6% to $J = 1$ and 2.4% to 2^- states) strongly suggests $J^\pi = 0^-$.

ⁱ⁾ The reduced width for p_1 emission is large enough to exclude $J^\pi = 4^+$ with $I(p_1) = 4$.

^{j)} The very large width for p_1 decay only admits $I(p_1) = 0$, corresponding to $J^\pi = (0, 1)^+$.

recently been confirmed by ²⁸Si(\vec{d}, α) work of Davis *et al.* ¹³⁾. They show with a shell-model calculation that 0^- states at such low energy can not be explained by a configuration with a hole in the $1p$ shell but only by the promotion of a particle into the fp shell.

The $0^+; 1$ assignment to the 5195 keV level is supported by the decay to four out of the five low-energy $J^\pi = 1^+$ states.

The assignments to several other levels are to be discussed in sect. 4.

All J^π assignments to the $74^{25}\text{Mg}(p, \gamma)$ resonances listed in table 2 are new, except for those to the $E_p = 986, 1084$ and 1148 keV resonances¹²⁾, and to the $E_p = 317$ and 390 keV resonances²¹⁾; all T -assignments are new. All but six J^π ; T assignments are unambiguous. Most of the assignments are from the present (p, γ) investigation alone, but for the resonances at $E_p = 609, 685$ and 1273 keV where the (α, t) work⁶⁾ supplied the parity, and for 14 resonances above $E_p = 0.8$ MeV where the (p, p_0) measurements⁸⁾ provided valuable additional information (mostly parities). For the $E_p = 609$ keV resonance, see also the $^{24}\text{Mg}(\alpha, d)$ work of ref.²⁵⁾. The present $J^\pi = 4^+$ assignment to the $E_p = 1714$ keV resonance is in conflict with $J^\pi = 5^+$ deduced from γ -ray angular distribution measurements in ref.²²⁾. In the analysis of ref.²²⁾ channel-spin mixing has been neglected, however, and the M3 admixtures in several primaries would have been unacceptably strong. The latter reason also excludes a $J^\pi = 5^+$ assignment²⁹⁾ to the $E_p = 1025$ keV resonance; the 4.3%, $5^+ \rightarrow 2^+$, $r \rightarrow 3751$ keV branch e.g. would have an M3 strength of 3.1×10^6 W.u.

The $^{26}\text{Mg}(p, n)^{26}\text{Al}$ reaction³²⁾ has provided $L = 0$ states at $E_x = 6.87 \pm 0.10, 7.21 \pm 0.10$ and 7.85 ± 0.10 MeV. The first and second clearly correspond (see table 2) to the 1^+ ; 0 resonances at $E_x = 6874$ and 7198 keV, respectively, and the third either to the 7814 keV 1^+ ; 0(+1) or to the 7880 keV 1^+ ; 1(+0) resonance.

Many resonances below $E_p = 1.03$ MeV are also excited in the decay of higher-energy resonances. Such resonance-to-resonance transitions can be useful for J^π ; T assignments because their low energy generally excludes anything but isovector dipole character (see above).

For the eight T -assignments and the single π -assignment in table 2 which are based on GRSS, see ref.⁹⁾ and sect. 3.

For several high-spin J^π ; T assignments to resonances, the assumption has been made that the $E_x = 3922$ keV level has J^π ; $T = 7^+$; 0, not 5^+ ; 0, which is justified in sect. 4.

The $E_p = 1205$ and 1237 keV 3^+ resonances form a completely T -mixed doublet ($T = 0(+1)$) with almost identical γ -decay. The notation $T = 0(+1)$ or $1(+0)$ is used for resonances where the unbracketed T -value is dominant according to the γ -decay but which certainly also contain a significant component with the bracketed T -value. This significance is reserved for cases where (for assumed T -purity) either (i) the strength of one or more primaries exceeds the corresponding RUL, or (ii) one or more strength averages of primaries of a given character (e.g. $M1_{1s}$) exceed the corresponding all-state average⁹⁾ by more than three times the standard deviation of the $M1_{1s}$ strength distribution (with "all-state" referring to the decay of all ^{26}Al bound states and resonances). The T -mixing for the $\pi = +$ resonances at $E_p = 567, 593, 1205$ and 1237 keV will be discussed in sect. 4. The $E_p = 986$ keV 2^- ; 1(+0) resonance is presumably mixed with the 2^- ; 0(+1) resonance at $E_p = 870$ keV. The $E_p = 1084$ and 1148 keV 4^- ; 0+1 resonances probably form another T -mixed doublet. The γ -branchings closely resemble one another; the 4^- ; 0 resonance at

$E_p = 896$ keV seems too far away to be made responsible for the $T = 0$ admixtures. The $T = 1$ admixtures in the $2^-; 0(+1)$ resonances at $E_p = 1239$ and 1351 keV almost certainly originate from the strong and broad $E_p = 1283$ keV $2^-; 1$ resonance. Finally, the $E_p = 1637$ keV $1^+; 1(+0)$ resonance should be held responsible for the $T = 1$ admixture in the $E_p = 1568$ keV $1^+; 0(+1)$ resonance, and the very broad $E_p = 1744$ keV $2^+; 1$ resonance for that in the $E_p = 1622$ keV $2^+; 0(+1)$ resonance.

It should be mentioned that most assignments given in tables 1 and 2 are based, in one way or another, on those of the 30 low-lying bound states already listed in the 1978 compilation ¹²⁾. The latter assignments all seem correct because these states are connected by such an elaborate network of γ -ray transitions, most of known strength, to each other, to higher bound states and to resonances, that wrong assignments definitely would have shown up.

Finally we should comment on those assignments in table 1 which are based on the lifetimes or lifetime upper limits listed in table 12 of ref. ²⁾ resulting from the observed Doppler shifts derived from our $\theta = 55^\circ$ and 90° spectra. It turns out that the lifetimes in question are not very crucial. For most of the levels concerned they could have been larger by one order or even two orders of magnitude without invalidating the corresponding $J^\pi; T$ assignments.

3. Gamma-ray strength statistics (GRSS)

It has been known for a long time that on the average isovector dipole transitions are much stronger than isoscalar dipole transitions. Remarks have been made like: "The resonance decays 85% to $T = 0$ states, and thus should have $T = 1$ ". Yet resonance isovector branching, $b(\Delta T = 1)$, is not a good spectroscopic tool for the determination of resonance isospins. Of the resonances in table 2 there are 18 which have $b(\Delta T = 1) > 95\%$, but also 19 with $b(\Delta T = 1) < 50\%$; the $6^-; 0$ resonances at $E_p = 609$ and 1273 keV even have $b(\Delta T = 1) = 0$. The reason is (i) the higher density of low-lying $T = 0$ than of $T = 1$ states of ²⁶Al, and (ii) the large differences in excitation energy of yrast $T = 1$ states; there are, for instance, no $T = 1$ bound states with high spin ($J \geq 5$) nor with odd parity. The evident way to correct for these differences in level density and in transition energy, is to make use of γ -ray strength averages, with the averages taken over all resonance primaries split up according to transition character ($M1_{IV}, M1_{IS}, E1_{IV}, E1_{IS}, E2_{IS}, E2_{IV}$). A short description of the GRSS method and some examples have been given in ref. ⁹⁾.

For resonances of which the quantity $\alpha = \Gamma_{p_0}/\Gamma$ is known, e.g. from a (p, p_0) measurement, the γ -ray strengths of individual transitions can be derived from the branchings combined with the (p, γ) yield $S = (2J + 1)\Gamma_{p_0}\Gamma_\gamma/\Gamma$. For about half of the resonances in table 2 α is not known, however. If the strength averages derived from $\alpha\Gamma_\gamma = S/(2J + 1)$ then are found to be significantly lower than the all-state averages ⁹⁾ (calculated from all transitions in ²⁶Al with known strength), α can be determined from a simple least-squares calculation. The GRSS method thus not

only supplies isospins but also Γ_{p0}/Γ values. The measure of agreement for a particular resonance can be expressed in a normalized χ^2 value, based on the r.m.s. deviations of the strength averages for transitions with a certain character from the corresponding all-state character averages; the average χ^2 value then amounts to $\chi^2_{\text{av}} = 1 \pm \sqrt{2/N}$, where N is the number of transition characters (with a maximum of six) occurring in the resonance decay; for resonances where Γ_{p0}/Γ has to be considered as an unknown parameter, N has to be replaced by $N - 1$. The agreement is considered as acceptable if $|\chi^2 - 1|$ does not exceed three times the standard deviation defined above.

In fig. 1 the average logarithmic γ -ray strengths are plotted for $M1_{IV}$, $M1_{IS}$, $E1_{IV}$ and $E1_{IS}$ transitions at the resonances which have relatively pure isospin. Analogous plots of $E2_{IS}$ and $E2_{IV}$ averages are not very instructive and consequently have been omitted; because of the small number of E2 transitions the errors in the averages are quite large. It is seen in fig. 1 that apparently there is no systematic dependence of the strengths on E_p . Striking is the difference of an order of magnitude for the $M1_{IV}$ and $M1_{IS}$ averages. The $E1_{IV}$ and $E1_{IS}$ strengths also differ by an order of magnitude but the scatter of points is larger.

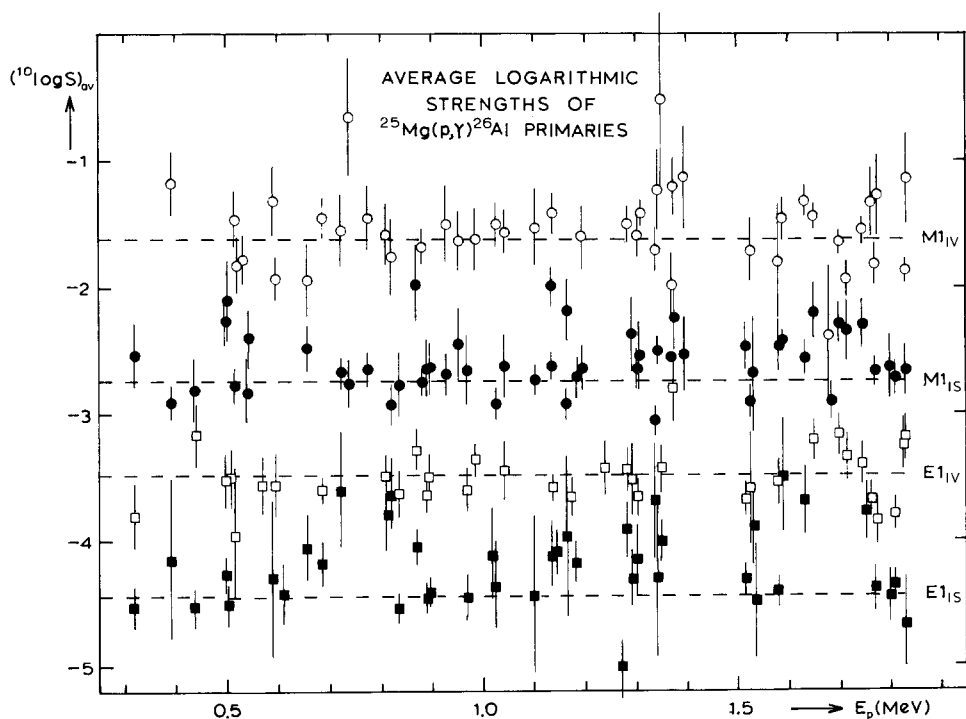


Fig. 1. Average logarithmic γ -ray strengths (in W.u.) for primaries of $M1_{IV}$, $M1_{IS}$, $E1_{IV}$ and $E1_{IS}$ character from $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$ resonances with relatively pure isospin, plotted as a function of the resonance proton energy.

In table 3 the χ^2 values for $T=0$ and $T=1$, and Γ_{p_0}/Γ values, are given for all resonances listed in table 2, except for the very weak $E_p = 1179$ keV resonance where the number of observed decay branches is too small to make GRSS meaningful. For many resonances GRSS is seen to determine T , always in agreement with the value derived in sect. 2 from considerations based on RUL's. The 12 resonances with considerable T -mixing (as shown by one or more of the averages for $M1_{IS}$, $E1_{IS}$ or $E2_{IV}$ character exceeding the corresponding all-state average by more than three times the standard deviation) have already been discussed in sect. 2. The clearest example is formed by the components of the split analogue at $E_p = 1205 + 1237$ keV, with almost equal χ^2 values for $T=0$ and $T=1$. Some T -mixing (not specifically indicated in table 3) has also been observed at the $E_p = 516, 819, 1135, 1375, 1587, 1699$ and 1763 keV resonances; the fact that one of the averages for T -retarded transitions is relatively strong causes $\chi^2 - 1$ slightly to exceed three times the standard deviation. In these cases it is easy to point out a neighbouring resonance which should be held responsible for the admixture. The small $T=0$ admixture in the $E_p = 1774$ keV resonance is not quite understood. One might speculate that the $E_p = 1774$ and 1833 keV $5^-; 1$ resonances actually form a split analogue, with the $5^-; 0$ (p, γ) component being very weak because of a *small* Γ_{p_0}/Γ value. The too large χ^2 values for $E_p = 775, 1273, 1337, 1525, 1632, 1744, 1800$ and 1829 keV are caused by one or more of the character averages being too small. This might be explained by the strength averages being to some degree dependent on the detection limit for weak transitions which varies from resonance to resonance, depending for example on bombarding time, on Γ_{p_0}/Γ , and on the Compton background in the spectrum caused by the competing ($p, p'\gamma$) reaction.

The $J^\pi = 1^+$ resonances at $E_p = 1568$ and 1637 keV should be discussed separately. Both resonate quite strongly in the (p, p') reaction, and for both we find $\Gamma_{p_0}/\Gamma \approx 1$ from GRSS. From the partial widths given in ref. ⁸⁾, however, one would derive $\Gamma_{p_0}/\Gamma = 0.24(6)$ for the 1568 keV resonance. The discrepancy can only be solved by assuming that in ref. ⁸⁾ Γ_{p_0} has been underestimated and Γ_{p_1} overestimated. For instance, values like $\Gamma_{p_0} = 1.4$ keV (instead of 0.65 keV) and $\Gamma_{p_1} = 0.6$ keV (instead of 2.0 keV) would yield $\Gamma_{p_0}/\Gamma = 0.70$ which is acceptable. For the 1637 keV resonance the quantities $\Gamma_{p_0}\Gamma_{p_1}/\Gamma = 160(33)$ eV, $\Gamma_{p_0}\Gamma_{p_2}/\Gamma = 16(3)$ eV and $\Gamma = 3700(400)$ eV have been measured ¹⁾. These yield a quadratic equation in Γ_{p_0}/Γ with the two solutions $\Gamma_{p_0}/\Gamma = 0.050(11)$ and $0.95(1)$. Only the second solution is clearly in agreement with GRSS.

4. The shell model; states and energies

A shell-model calculation ¹⁹⁾ has been performed in the untruncated sd-shell with $A=16$ active nucleons in the $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbits. The single-particle energies $\epsilon(1d_{5/2}) = -3948$ keV, $\epsilon(2s_{1/2}) = -3164$ keV and $\epsilon(1d_{3/2}) = 1647$ keV, and the 63 two-body matrix elements (the latter taken proportional to $A^{-0.3}$) have been obtained

TABLE 3

Determination of Γ_{p0}/Γ and of resonance isospins from γ -ray strength statistics (GRSS)

E_p [keV]	J^π	$^{10}\log(\Gamma_{p0}/\Gamma)$	χ^2_{g}		Resulting T -value
			$T = 0$	$T = 1$	
317	3^-	$-0.08 (12)^a)$	<u>0.7 (7)</u>	17.5 (7)	0
390	2^+	$-0.09 (2)^b)$	<u>1.6 (7)</u>	33.7 (7)	0
435	4^-	$+0.01 (11)^a)$	<u>1.2 (7)</u>	24.4 (7)	0
497	2^-	$+0.21 (10)^a)$	<u>2.0 (7)</u>	16.8 (7)	0
503	3^-	$+0.07 (12)^a)$	<u>1.2 (7)</u>	15.8 (7)	0
515	3^+	$-0.38 (12)^c)$	<u>0.4 (10)</u>	54.8 (10)	0
516	$1^+(1^-, 2^-)$	$-0.60 (19)^c)$	19.3 (10)	5.3 (10)	1
533	4^+	$-1.40 (18)^c)$	32.5 (20)	<u>3.6 (20)</u>	1
567	2^+	$+0.07 (11)^a)$	11.0 (6)	5.4 (6)	1(+0)
591	1^+	$-0.91 (16)^c)$	<u>1.0 (8)</u>	22.8 (8)	0
593	2^+	$-0.08 (12)^a)$	15.5 (7)	<u>1.7 (7)</u>	1
609	6^-	$-0.93 (23)^c)$	<u>6.4 (20)</u>	34.6 (20)	0
656	1^+	$+0.12 (13)^a)$	<u>2.3 (7)</u>	8.2 (7)	0
685	3^-	$\approx 0^d)$	72.5 (8)	<u>1.6 (8)</u>	1
723	2^+	$+0.07 (10)^a)$	<u>1.7 (6)</u>	17.3 (6)	0
738	5^+	$-0.59 (15)^c)$	<u>2.1 (8)</u>	22.9 (8)	0
775	3^+	$-0.40 (11)^c)$	5.0 (10)	42.4 (10)	0
811	1^-	$+0.12 (12)^a)$	35.4 (8)	<u>1.8 (8)</u>	1
819	2^+	$-0.50 (12)^c)$	4.3 (8)	21.5 (8)	0
835	4^-	$\approx 0^c)$	<u>0.6 (7)</u>	34.1 (7)	0
870	2^-	$\approx 0^c)$	4.3 (8)	21.4 (8)	0(+1)
881	3^+	$\approx 0^c)$	<u>1.4 (8)</u>	52.6 (8)	0
890	3^-	$\approx 0^c)$	<u>0.6 (7)</u>	34.2 (7)	0
896	4^-	$\approx 0^c)$	<u>0.2 (7)</u>	32.9 (7)	0
928	1^+	$-0.01 (14)^a)$	<u>0.7 (8)</u>	19.2 (8)	0
953	5^+	$+0.15 (16)^a)$	16.1 (6)	<u>2.0 (6)</u>	1
969	3^-	$\approx 0^c)$	<u>0.3 (7)</u>	20.2 (7)	0
986	2^-	$\approx 0^c)$	36.4 (8)	9.6 (8)	1(+0)
1019	$0^-(1, 2)$	$+0.53 (27)^a)$	<u>2.4 (8)</u>	8.4 (8)	0
1025	$4^+(3^+)$	$\approx 0^c)$	<u>1.5 (6)</u>	41.4 (6)	0
1043	2^+	$+0.01 (12)^a)$	29.8 (7)	<u>1.9 (7)</u>	1
1084	4^-	$\approx 0^c)$	12.6 (7)	8.4 (7)	0+1
1103	4^+	$+0.01 (11)^a)$	<u>0.1 (7)</u>	18.9 (7)	0
1135	2^+	$\approx 0^c)$	3.8 (7)	23.5 (7)	0
1137	3^-	$\approx 0^c)$	74.0 (8)	<u>2.1 (8)</u>	1
1148	4^-	$\approx 0^c)$	12.7 (7)	4.2 (7)	0+1
1164	3^+	$\approx 0^c)$	<u>2.2 (7)</u>	18.2 (7)	0
1184	1^-	$-0.17 (12)^c)$	<u>1.1 (7)</u>	22.0 (7)	0
1196	1^+	$+0.03 (14)^a)$	<u>0.4 (8)</u>	18.9 (8)	0
1205	3^+	$-0.25 (9)^a)$	16.1 (7)	14.6 (7)	0+1
1237	3^+	$\approx 0^c)$	12.1 (7)	17.9 (7)	0+1
1239	2^-	$\approx 0^c)$	8.0 (7)	9.5 (7)	0(+1)
1273	6^-	$-0.19 (23)^a)$	5.1 (10)	32.7 (10)	0
1283	2^-	$-0.02 (8)^c)$	62.2 (8)	<u>2.1 (8)</u>	1
1292	5^-	$+0.16 (14)^a)$	<u>0.6 (7)</u>	8.6 (7)	0
1302	2^+	$\approx 0^c)$	<u>2.6 (6)</u>	35.6 (6)	0
1306	2^+	$\approx 0^c)$	96.6 (6)	<u>1.5 (6)</u>	1

TABLE 3—continued

E_p [keV]	J^π	$^{10}\log(\Gamma_{p0}/\Gamma)$	χ^2 ^{g)}		Resulting T -value
			$T=0$	$T=1$	
1337	$4^+(3^+)$	$\approx 0^e)$	4.1 (6)	35.1 (6)	0
1342	4^+	$+0.25 (10)^a)$	<u>1.6 (6)</u>	15.0 (6)	0
1351	2^-	$\approx 0^e)$	10.2 (7)	14.7 (7)	0(+1)
1370	1^+	$-0.15 (16)^a)$	<u>2.1 (7)</u>	6.6 (7)	0
1375	5^+	$\approx 0^e)$	30.2 (6)	2.9 (6)	1
1396	$1^+(2^+)$	$-1.59 (23)^e)$	<u>1.1 (10)</u>	19.4 (10)	0
1515	3^-	$\approx 0^e)$	<u>1.7 (7)</u>	23.0 (7)	0
1525	3^+	$-0.12 (10)^a)$	3.3 (6)	21.5 (6)	0
1526	1^-	$\approx 0^e)$	<u>0.0 (8)</u>	4.0 (8)	0
1568	1^+	$\approx 0^f)$	2.9 (6)	10.0 (6)	0(+1)
1580	4^-	$\approx 0^e)$	<u>0.8 (6)</u>	22.2 (6)	0
1587	4^+	$\approx 0^e)$	3.4 (6)	33.2 (6)	0
1622	2^+	$\approx 0^e)$	5.7 (7)	14.9 (7)	0(+1)
1632	3^+	$\approx 0^e)$	8.1 (7)	78.2 (7)	0
1637	1^+	$\approx 0^f)$	4.8 (7)	4.3 (7)	1(+0)
1649	4^+	$\approx 0^e)$	83.2 (6)	<u>2.5 (6)</u>	1
1680	5^+	$-0.16 (13)^a)$	<u>1.3 (7)</u>	10.0 (7)	0
1699	3^+	$\approx 0^e)$	101.1 (7)	4.6 (7)	1
1714	4^+	$\approx 0^e)$	36.9 (6)	<u>1.5 (6)</u>	1
1744	2^+	$\approx 0^e)$	79.9 (6)	4.8 (6)	1
1763	1^-	$-0.25 (11)^e)$	20.1 (7)	3.8 (7)	1
1771	2^+	$\approx 0^e)$	<u>1.0 (7)</u>	43.5 (7)	0
1774	5^-	$\approx 0^e)$	12.2 (8)	3.9 (8)	1
1800	1^-	$-0.23 (13)^a)$	3.9 (8)	9.1 (8)	0
1811	3^-	$\approx 0^e)$	<u>1.5 (7)</u>	32.2 (7)	0
1829	2^+	$\approx 0^e)$	40.1 (6)	3.3 (6)	1
1833	5^-	$\approx 0^e)$	23.3 (7)	<u>1.5 (7)</u>	1

^{a)} As determined from GRSS; the value is taken equal to zero in the calculation of χ^2 .

^{b)} As determined from a comparison of feeding and decay γ -ray intensities.

^{c)} As determined from GRSS.

^{d)} Assumed because the level is strongly excited in the (α, t) reaction ⁶⁾.

^{e)} As determined from the ²⁵Mg(p, p₀) and (p, p') reactions ^{1,8)}.

^{f)} See text.

^{g)} The χ^2 values with $|\chi^2 - 1| < 3.4\chi^2$ are underlined.

from a fit to the experimental energies of 440 states in the $A=17$ –39 region. For most J ; T values the lowest 10 eigenvalues have been calculated, for some the lowest 20. For the calculation of $B(E2)$ values effective charges have been used of $1.35e$ for the proton and $0.35e$ for the neutron, and bare-nucleon g -factors for the calculation of M1 strengths.

A comparison of calculated and experimental $\pi = +$ states is given in table 4. For the 30 lowest $T=1$ states there is a one-to-one correspondence. The 2^+ ; 1 states at $E_x^{\text{exp}} = 7982$ and 8064 keV should be considered as intruders, because the next higher

TABLE 4
Comparison of experimental and calculated $\pi = +$ states of ²⁶Al^{a)}

Experiment		Calculated		Experiment		Calculated	
E_x [keV]	$J^\pi; T$	ΔE_x [keV] ^{b)}	$J_n^\pi; T$	E_x [keV]	$J^\pi; T$	ΔE_x [keV] ^{b)}	$J_n^\pi; T$
0	5 ⁺ ; 0	+139	5 ⁺ ; 0	5671	1 ⁺ ; 0	+136	1 ⁺ ; 0
228	0 ⁺ ; 1	-8	0 ⁺ ; 1	5726	4 ⁺ ; 1	-33	4 ⁺ ; 1
417	3 ⁺ ; 0	+434	3 ⁺ ; 0	5849	2 ⁺ ; 0	-257	2 ⁺ ; 0
1058	1 ⁺ ; 0	-101	1 ⁺ ; 0	5883	3 ⁺ ; 0	+489	3 ⁺ ; 0
1759	2 ⁺ ; 0	-294	2 ⁺ ; 0	5924	4 ⁺ ; 1	+305	4 ⁺ ; 1
1851	1 ⁺ ; 0	+25	1 ⁺ ; 0	6028	1 ⁺ (1 ⁻); 1	(+25	1 ⁺ ; 1)
2069	4 ⁺ ; 0	+373	4 ⁺ ; 0	6084	5 ⁺ ; 0	+124	5 ⁺ ; 0
2070	2 ⁺ ; 1	+80	2 ⁺ ; 1	6086	1 ⁻ (2 ⁺); 0	(+56	2 ⁺ ; 0)
2072	1 ⁺ ; 0	+71	1 ⁺ ; 0	6120	(4, 5 ⁺); 0	(+50	4 ⁺ ; 0)
2365	3 ⁺ ; 0	+99	3 ⁺ ; 0 ^c	6198	1(2 ⁺); 0	(+90	2 ⁺ ; 0)
2545	3 ⁺ ; 0	-285	3 ⁺ ; 0 ^c	6238	1; 0		
2661	2 ⁺ ; 0	+66	2 ⁺ ; 0	6270	1 ⁽⁺⁾ ; 0	(-187	1 ⁺ ; 0)
2740	1 ⁺ ; 0	+298	1 ⁺ ; 0	6280	3 ⁺ ; 0	+448	3 ⁺ ; 0
2913	2 ⁺ ; 0	-25	2 ⁺ ; 0	[6315]		-	6 ⁺ ; 0
3074	3 ⁺ ; 0	+134	3 ⁺ ; 0	6364	3 ⁺ ; 1	+124	3 ⁺ ; 1
3160	2 ⁺ ; 1	+213	2 ⁺ ; 1	[6382]		-	7 ⁺ ; 0
3403	5 ⁺ ; 0	+158	5 ⁺ ; 0	6414	0 ⁺ ; 1	-132	0 ⁺ ; 1
3508	6 ⁺ ; 0	-34	6 ⁺ ; 0	6496	5 ⁺ (4 ⁺); 0	(-36	5 ⁺ ; 0)
3596	3 ⁺ ; 0	-100	3 ⁺ ; 0	6551	4 ⁺ (5 ⁺); 0	(+245	4 ⁺ ; 0)
3675	4 ⁺ ; 0	-227	4 ⁺ ; 0	6598	(4, 5 ⁺); 0	(+11	5 ⁺ ; 0)
3681	3 ⁺ ; 0	+113	3 ⁺ ; 0	6680	2 ⁺ ; 0	+147	2 ⁺ ; 0
3724	1 ⁺ ; 0	+100	1 ⁺ ; 0	6801	3 ⁺ ; 0	+35	3 ⁺ ; 0
3751	2 ⁺ ; 0	+311	2 ⁺ ; 0	6802	1 ⁺ (1 ⁻ , 2 ⁻); 1	(+232	1 ⁺ ; 1)
3754	0 ⁺ ; 1	+147	0 ⁺ ; 1	6816	6 ⁺ (5, 4); 0	(-157	6 ⁺ ; 0)
3922	7 ⁺ (5 ⁺); 0	(-34	7 ⁺ ; 0)	6818	4 ⁺ ; 1	+179	4 ⁺ ; 1
3963	3 ⁺ ; 0	+279	3 ⁺ ; 0	6852	2 ⁺ ; 1(+0)	+15	2 ⁺ ; 1
4192	3 ⁺ ; 1	-51	3 ⁺ ; 1	6874	1 ⁺ ; 0	-77	1 ⁺ ; 0
4206	4 ⁺ ; 0	-15	4 ⁺ ; 0	6876	2 ⁺ ; 1	+187	2 ⁺ ; 1
4349	3 ⁺ ; 0	+170	3 ⁺ ; 0	6936	1 ⁺ ; 0	+144	1 ⁺ ; 0
4548	2 ⁺ ; 1	+213	2 ⁺ ; 1	7001	2 ⁺ ; 0	+252	2 ⁺ ; 0
4599	3 ⁺ ; 1	+132	3 ⁺ ; 1	7015	5 ⁺ ; 0	+141	5 ⁺ ; 0
4705	4 ⁺ ; 1	+48	4 ⁺ ; 1	7051	3 ⁺ ; 0	+216	3 ⁺ ; 0
4773	4 ⁺ ; 0	+87	4 ⁺ ; 0	7093	2 ⁺ ; 0		
4941	5 ⁺ ; 0	-321	5 ⁺ ; 0	7153	3 ⁺ ; 0	+180	3 ⁺ ; 0
4952	3 ⁺ ; 0	+201	3 ⁺ ; 0	7198	1 ⁺ ; 0	+221	1 ⁺ ; 0
5010	1 ⁺ ; 0	+67	1 ⁺ ; 0	7222	5 ⁺ ; 1	+52	5 ⁺ ; 1
5132	4 ⁺ ; 1	+20	4 ⁺ ; 1	7286	0 ⁻ (1, 2); 0		
5142	2 ⁺ ; 1	+78	2 ⁺ ; 1	7291	4 ⁺ (3 ⁺); 0	(+113	4 ⁺ ; 0)
5195	0 ⁺ ; 1	+229	0 ⁺ ; 1	[7306]		-	5 ⁺ ; 0
5245	4 ⁺ ; 0	+105	4 ⁺ ; 0	7308	2 ⁺ ; 1	+21	2 ⁺ ; 1
5462	0 ⁺ (1, 2); 0	(-625	0 ⁺ ; 0)	7366	4 ⁺ ; 0	+175	4 ⁺ ; 0
5488	5 ⁺ (4 ⁻); 0	(+184	5 ⁺ ; 0)	7397	2 ⁺ ; 0	+211	2 ⁺ ; 0
5495	2 ⁺ ; 0	-67	2 ⁺ ; 0	7425	3 ⁺ ; 0	+163	3 ⁺ ; 0
5513	4 ⁺ ; 0	-26	4 ⁺ ; 0	[7430]		-	5 ⁺ ; 0
5545	2 ⁺ ; 1	+79	2 ⁺ ; 1	7440	0(1, 2); 1		
5569	5 ⁺ (4, 3 ⁺); 0	(+149	5 ⁺ ; 0)	[7451]		-	8 ⁺ ; 0
5585	1 ⁺ ; 0	-292	1 ⁺ ; 0	7455	1 ⁺ ; 0		

TABLE 4—continued

Experiment				Calculated			
E_x [keV]	$J^\pi; T$	ΔE_x [keV] ^{b)}	$J^\pi; T$	E_x [keV]	$J^\pi; T$	ΔE_x [keV] ^{b)}	$J^\pi; T$
7464	$3^+; 0+1$	} +38	$3_4^+; 1$	7832	$4^+; 0$	+453	$4_{13}^+; 0$
7495	$3^+; 0+1$			[7848]		–	$7_3^+; 0$
7558	$2^+; 0$			7865	$2^+; 0(+1)$	+313	$2_{14}^+; 0$
7561	$2^+; 1$	+232	$2_3^+; 1$	7874	$3^+; 0$	+291	$3_{17}^+; 0$
7592	$4^+(3^+); 0$	(+105	$4_{11}^+; 0$	7880	$1^+; 1(+0)$	+77	$1_3^+; 1$
7596	$4^+; 0$	+194	$4_{12}^+; 0$	7891	$4^+; 1$	–260	$4_6^+; 1$
[7618]		–	$6_4^+; 0$	7921	$5^+; 0$	+104	$5_{12}^+; 0$
7623	$1^+; 0$	+149	$1_{13}^+; 0$	7939	$3^+; 1$	–117	$3_5^+; 1$
7628	$5^+; 1$	+57	$5_4^+; 1$	7953	$4^+; 1$	+208	$4_7^+; 1$
7648	$1^+(2^+); 0(1)$	(+177	$2_{13}^+; 0$	7982	$2^+; 1$		
7772	$3^+; 0$	+250	$3_{16}^+; 0$	8008	$2^+; 0$		
7814	$1^+; 0(+1)$	+447	$1_{14}^+; 0$	8064	$2^+; 1$		

^{a)} All calculated states are listed up to $E_x=8.07$ MeV, and all experimental states which certainly or possibly have $\pi=+$. Entries in square brackets in the first column relate to the calculated energies of states not observed experimentally.

^{b)} $\Delta E_x = E_x(\text{calc}) - E_x(\text{exp})$.

^{c)} For the inversion of the $3_2^+; 0$ and $3_3^+; 0$ states, see text.

calculated $2^+; 1$ state ($2_{10}^+; 1$) is at $E_x^{\text{th}} = 8627$ keV. The $E_x^{\text{exp}} = 7440$ keV level with $J; T = 0(1, 2); 1$ presumably has $\pi = -$, because all calculated $0^+; 1, 1^+; 1$ and $2^+; 1$ states up to $E_x^{\text{th}} = 8.1$ MeV already correspond to known ²⁶Al states.

The almost identical γ -decay²⁾ of the $2^+; 1(+0)$ 6852 keV and $2^+; 1$ 6876 keV levels (resonances at $E_p = 567$ and 593 keV, respectively) would make plausible their interpretation as a T -mixed split analogue. The calculation then should provide one $2^+; 1$ and one $2^+; 0$ state in the region. Instead there are two $2^+; 1$ states (at $E_x^{\text{th}} = 6786$ and 6982 keV), and not a single “free” $2^+; 0$ state. We thus can only conclude to two strongly configuration mixed $T = 1$ states. The $T = 0$ admixture in the 6852 keV level could originate from mixing with either of the $2^+; 0$ levels at $E_x = 6680$ or 7001 keV.

The clearest case of a split analogue would seem to be the $3^+; 0+1$ doublet at $E_x = 7464$ and 7495 keV (the $E_p = 1205$ and 1237 keV resonances) also with closely analogous γ -decay. Theoretically there is only one $3^+; 1$ state available (the $3_4^+; 1$ at $E_x^{\text{th}} = 7518$ keV), but again there is no “free” calculated $3^+; 0$ state (the $3_{14}^+; 0$ and $3_{15}^+; 0$ already have experimental partners).

On the average the $T = 1$ calculated energies seem to be slightly higher than the experimental values: $(E_x^{\text{th}} - E_x^{\text{exp}})_{\text{av}} = +80$ keV. There does not seem to be any systematic dependence on E_x . After correction for this difference, the average absolute deviation between theory and experiment amounts to $|E_x^{\text{th}} - E_x^{\text{exp}}|_{\text{av}} = 100$ keV for $T = 1$ states.

For the 42 lowest $T=0$ states (up to and including the $2_8^+; 0$ level at $E_x^{\text{exp}} = 6198$ keV) there is also a one-to-one correspondence between calculation and experiment. The region above this energy, in which also many corresponding pairs of states can be established, is shown in fig. 2.

The $0^+(1, 2); 0$ level at $E_x^{\text{exp}} = 5462$ keV is the only state which possibly can correspond to the single calculated $0^+; 0$ level ($E_x^{\text{th}} = 4837$ keV) in the $E_x = 0-8.2$ MeV

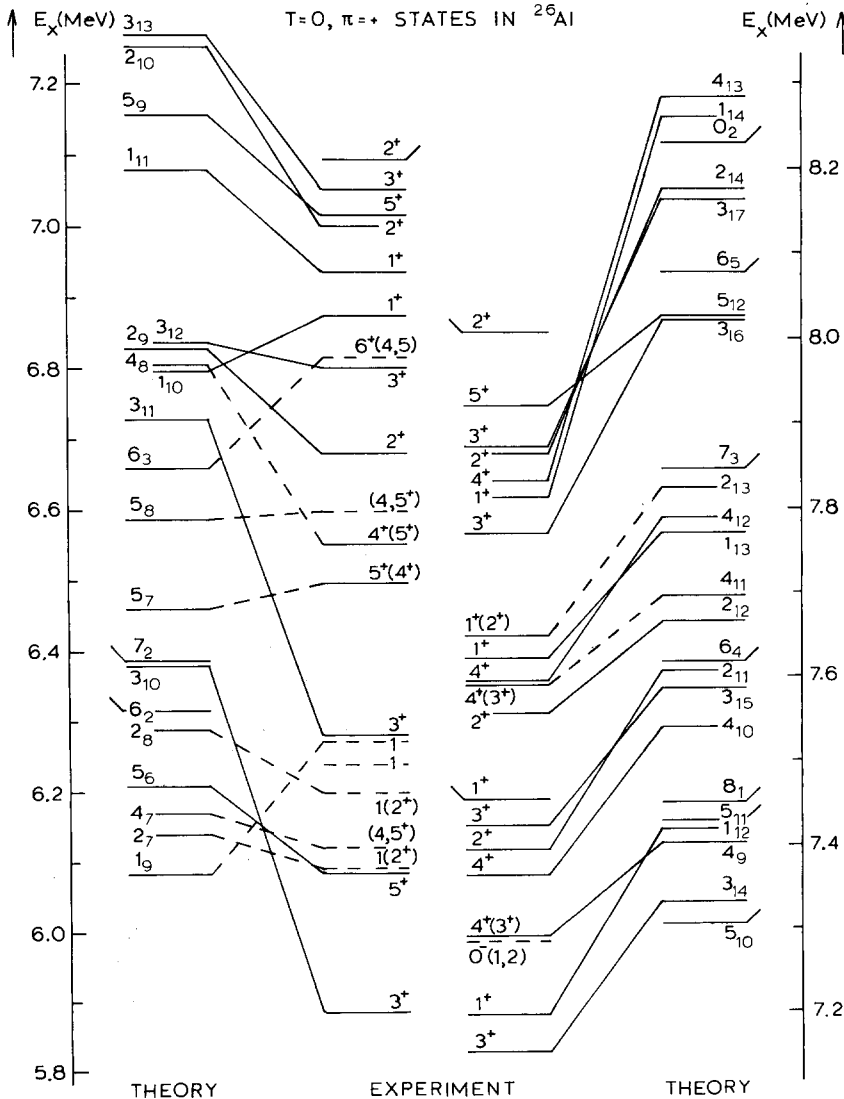


Fig. 2. Comparison of experimental and calculated $\pi=+$, $T=0$ states of ^{26}Al above $E_x^{\text{exp}} = 5.88$ MeV. Experimental states with unknown parity are indicated as dashed lines. The lines connecting calculated and experimental states with non-unique J^π values are also dashed. Theoretical (experimental) states for which no experimental (calculated) counterpart is present are indicated with a flag.

region. It shows the required γ -decay characteristics, with the main decay proceeding to $1^+; 0$ and $2^+; 0$ states. Our decision to identify this level with the $0_1^+; 0$ came rather late because of the exceptionally poor agreement between calculated and experimental energies: $E_x^{\text{th}} - E_x^{\text{ex}} = -625$ keV.

The lowest 12 calculated $1^+; 0$ states have all been located. For the correspondence of the $1_9^+; 0$ with the $J; T = 1; 0$ level at $E_x = 6270$ keV we refer to sect. 6. If we assume that one of the $1^+; 0$ levels at $E_x^{\text{exp}} = 7455$ and 7623 keV corresponds to the $1_{13}^+; 0$, the other has to be regarded as an intruder. The $1^+; 0(+1)$ level at $E_x^{\text{exp}} = 7814$ keV might well be identified with the $1_{14}^+; 0$.

The location of the six lowest $2^+; 0$ levels and the $2_9^+; 0$, $2_{11}^+; 0$ and $2_{12}^+; 0$ offers no difficulties. The $2_7^+; 0$ and $2_8^+; 0$ might correspond to the levels at $E_x^{\text{exp}} = 6068$ and 6198 keV with $J^\pi; T = 1^-(2^+); 0$ and $1(2^+); 0$, respectively, but the γ -decay of both, with a strong branch to the $0_1^+; 1$ at $E_x = 228$ keV, is indicative of $1; 0$ rather than $2^+; 0$. For the $2_{10}^+; 0$ there are $2^+; 0$ candidates at $E_x^{\text{exp}} = 7001$ and 7093 keV; one of these two levels presumably has to be regarded as an intruder. The identification of the $1^+(2^+); 0(1)$ level at $E_x^{\text{exp}} = 7648$ keV as the $2_{13}^+; 0$ is possible but questionable because of the badly known γ -decay. If the $2^+; 0(+1)$ level at $E_x^{\text{exp}} = 7865$ keV corresponds to the $2_{14}^+; 0$, the $2^+; 0$ level at $E_x^{\text{exp}} = 8008$ keV should be regarded as an intruder because the $2_{15}^+; 0$ appears at very much higher energy ($E_x^{\text{th}} = 8817$ keV).

For $3^+; 0$ there is a very beautiful unbroken series of pairs of corresponding experimental and calculated levels up to and including the $3_{17}^+; 0$, with the only shadow (already mentioned above) being the theoretically missing $3^+; 0$ component to be mixed into the $3^+; 0+1$ $E_x^{\text{exp}} = 7464 + 7495$ keV split analogue. The problem is solved, of course, if this missing $3^+; 0$ component or one of the experimental $3^+; 0$ states (preferably that at $E_x^{\text{exp}} = 7425$ keV) is regarded as an intruder.

The $4^+; 0$ levels also form such a series, up to and including the $4_{13}^+; 0$. The identification of the $4_8^+; 0$ with the $E_x = 6551$ keV $(4, 5)^+; 0$ level is based on the γ -decay (see sect. 6).

For the lowest six $5^+; 0$ levels and the $5_{12}^+; 0$ the correspondence with experimental levels is clear. The locations of the $5_7^+; 0$, $5_8^+; 0$ and $5_9^+; 0$ are discussed in sect. 6. The $5_{10}^+; 0$ and $5_{11}^+; 0$ are missing experimentally. These two states are expected as d-wave (p, γ) resonances in the $E_p \approx 800$ – 1000 keV region and it is difficult to explain why they have not been observed.

Of the $\pi = +, T = 0$ levels with $J > 5$, the $6_1^+; 0$ at $E_x^{\text{exp}} = 3508$ keV has been known for a long time, and we think to have found (from the decay of high-spin resonances) a good candidate for the $6_3^+; 0$ at $E_x^{\text{exp}} = 6816$ keV. For the $7^+(5^+); 0$ level at $E_x^{\text{exp}} = 3922$ keV we have not been able to eliminate experimentally the $5^+; 0$ possibility, but there is no shadow of doubt about its identification as the $7_1^+; 0$, because there are no “free” calculated $5^+; 0$ states in the neighbourhood. Furthermore, the level is not excited at any of the 15 $J = 4$ resonances. The $6_2^+; 0$ has been missed experimentally, and the higher $6^+; 0$ and $7^+; 0$ calculated states would

correspond to g-wave resonances which prevents their observation. This holds a fortiori for the 8_1^+ ; 0 state (i-wave resonance).

The agreement between experimental and calculated energies is certainly not as good for $T=0$ as for $T=1$. First there is a tendency for the experimental $T=0$ levels at higher E_x to be increasingly depressed relative to the calculated values (see fig. 2). This compression of the level scheme might be explained by the increasing number of intruder states at higher energies. For $E_x < 6$ MeV this effect is not yet noticeable. For this region we find $(E_x^{\text{th}} - E_x^{\text{exp}})_{\text{av}} = +39$ keV and, after correction for this systematic difference, $|E_x^{\text{th}} - E_x^{\text{exp}}|_{\text{av}} = 163$ keV.

In addition to the energy, the γ -ray strengths can be an effective aid in establishing the correspondence between experimental and calculated levels. This aspect is discussed in sect. 6.

5. The $T=1$ states of ²⁶Al and ²⁶Mg

The correspondence between the $T=1$ levels of ²⁶Al and ²⁶Mg is shown in fig. 3, with the ²⁶Mg ground state lined up with the 0^+ ; 1 level of ²⁶Al at $E_x = 228$ keV. Before discussing fig. 3 we should comment on the J^π assignments to ²⁶Mg levels not yet given in ref. ¹²).

The $E_x = 6125$ keV level with $J^\pi = (2, 3)^+$ listed in ref. ¹²) has unnatural parity (and thus $J^\pi = 3^+$) as shown with the ²⁶Mg(α, α') reaction ¹⁴). The $J^\pi = 3^-$ and 5^- assignments to the levels at $E_x = 7350$ and 7953 keV, respectively, follow from the ²⁴Mg(t, p) reaction ¹⁵). The ²⁵Mg(d, p) work of ref. ¹⁶) has provided parities and spin restrictions for the levels at $E_x = 7261, 7350, 7543, 7725, 7773, 7816$ and 7953 keV. Strong excitation ¹⁷) of the $E_x = 7694$ keV level in ²⁶Mg(γ, γ') limits the J^π value to $(1, 2^+)$. The ²³Na($\alpha, p\gamma$) work of ref. ²³) has yielded excitation energies (± 1 or 2 keV), a.o. of the previously unobserved level at $6634(1)$ keV, the J^π values of the levels at 6623 (4^+), 6978 (5^+), 7281 (4^-), 7395 (5^+) and 7840 keV (2^+), and J^π restrictions (from the measured γ -ray branchings and lifetimes) for several other levels.

On the whole the agreement between $T=1$ states of ²⁶Al (44 levels) and ²⁶Mg is excellent (see fig. 3). The fact that the p-states of ²⁶Al, with $J^\pi = (1-4)^-$, are appreciably depressed (on the average $\Delta E_x = -171$ keV) relative to their ²⁶Mg parents is well explained in ref. ¹⁸).

The assumption that the pairs of ²⁵Mg(p, γ) resonances at $E_p = 1084$ and 1148 keV (both with $J^\pi = 4^-$), 1205 and 1237 keV ($J^\pi = 3^+$), and 1774 and 1833 keV ($J^\pi = 5^-$) have to be regarded as split analogues, seems to be justified because for each of these pairs there is only one ²⁶Mg parent present with the correct J^π value.

In ²⁶Mg one state in the $E_x = 6.5-6.7$ MeV region is still missing. We assume that this is the parent of the $E_p = 516$ keV ²⁵Mg(p, γ) resonance with $J^\pi = 1^+(1^-, 2^-)$ (presumably corresponding to the 1_2^+ ; 1, see table 4), since the ²³Na($\alpha, p\gamma$) reaction ²³) excites almost all ²⁶Mg states but for those with spin $J = 1$ or 0 . Of the four

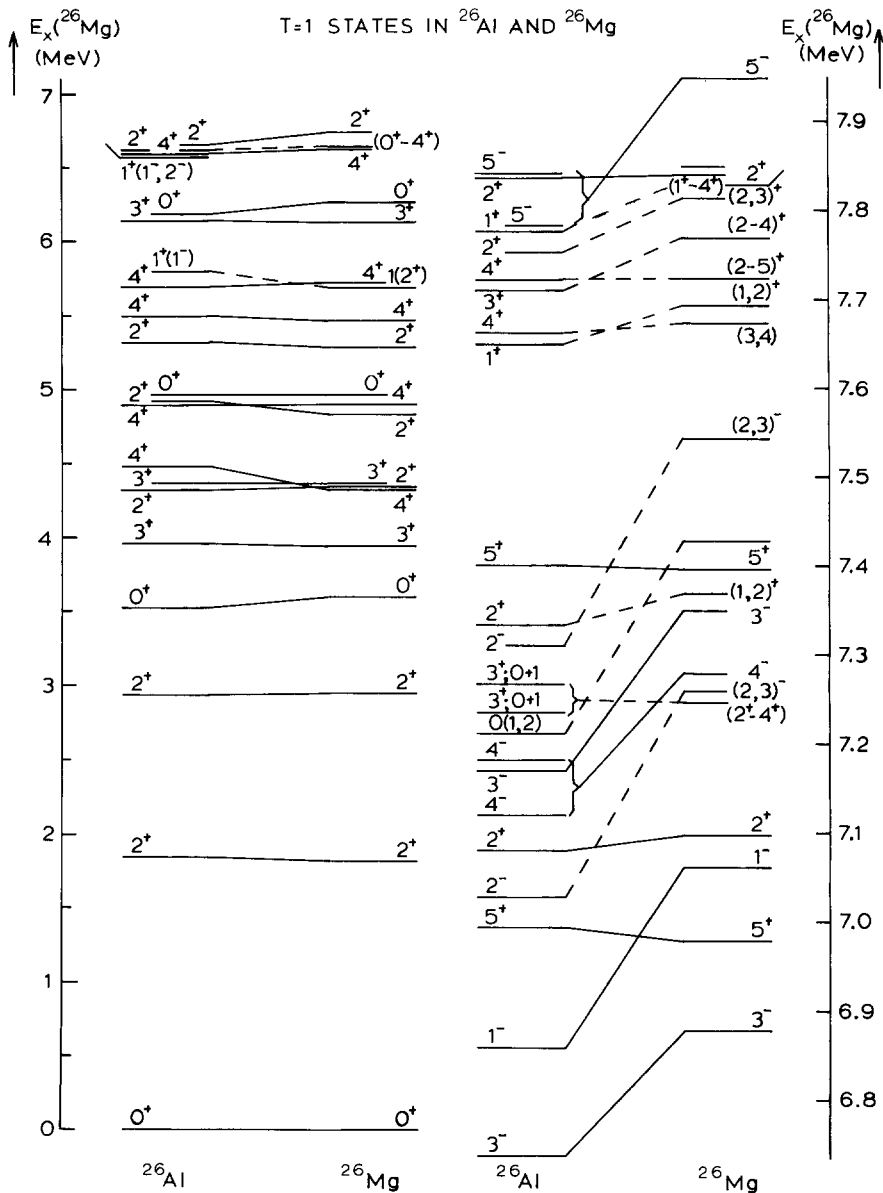


Fig. 3. Comparison of $T=1$ states of ^{26}Al and ^{26}Mg , with the ^{26}Al first excited state at $E_x=228$ keV lined up with the ^{26}Mg ground state. Levels of ^{26}Al (^{26}Mg) which have no corresponding level in ^{26}Mg (^{26}Al) are indicated with a flag. Note the large difference in energy scales for the left- and right-hand parts of the figure.

other $J = 1$ states (see fig. 3) only that at $E_x = 7063$ keV is (weakly) excited in this reaction, and none of the four $J = 0$ states.

The 7428 keV ²⁶Mg level which only has been observed in the ²⁶Mg(p, p') reaction²⁴), can only be the parent of the $E_p = 1179$ keV resonance with $J; T = 0(1, 2); 1$. We presume that this level has $J^\pi = 0^-$ (the calculation provides no 0^+ ; 1 level in the neighbourhood) but do not understand the relatively large energy depression ($\Delta E_x = -216$ keV).

In the region $E_x(^{26}\text{Mg}) > 7.6$ MeV several uncertainties remain. It is not clear whether the levels observed at 7828(3) keV with the ²⁶Mg(p, p') reaction²⁴) and at 7822(2) keV with ²³Na(α , p γ) [ref. ²³)] are one and the same level (as we assume), or whether they are different. The parents of the 1^+ level at $E_x(^{26}\text{Al}) = 7880$ keV and of the 5^- split analogue with components at $E_x(^{26}\text{Al}) = 8011$ and 8067 keV can be indicated with reasonable certainty, but for the other ²⁶Al and ²⁶Mg levels in this region the correspondence is ambiguous. If levels correspond as suggested in fig. 3, the $E_x = 7822$ keV ($1^+ - 4^+$) level of ²⁶Mg remains without an analogue, and the energy depression for the 1^- level of ²⁶Al ($E_x = 8001$ keV) seems very small ($\Delta E_x = -78$ keV).

6. The shell model: γ -ray strengths

In figs. 4 and 5 experimental and calculated γ -ray strengths are compared for $E2_{IS}$ and $M1_{IV}$ transitions between $\pi = +$ bound states of ²⁶Al. The comparison does not include very weak transitions ($S < 0.1$ W.u. for $E2_{IS}$, < 0.01 W.u. for $M1_{IV}$), nor does it include transitions from or to states with badly described configuration mixing to be discussed below. For most transitions the multipolarity mixing ratios are unknown, but considerations based on RUL's show that such admixtures ($M3_{IS}$ mixed into $E2_{IS}$, $E2_{IV}$ into $M1_{IV}$) are negligible.

Inspection of fig. 4 shows that the average (logarithmic) experimental and calculated $E2_{IS}$ strengths are very closely the same ($S_{av}^{exp} = 1.02 S_{av}^{th}$). Apparently the effective charge of $0.35e$ used in the calculation for the whole sd-shell is a happy choice. The average absolute deviation between logarithmic experimental and calculated $E2_{IS}$ strengths amounts to 0.29, corresponding to a factor 1.9.

The $M1_{IV}$ strengths (see fig. 5) are definitely overestimated theoretically, on the average by a factor 1.85. Even after correction for this systematic difference, the average absolute deviation between calculation and experiment is somewhat worse than for $E2_{IS}$, amounting to a factor 2.5. The calculated overestimate of $M1$ strengths, a common feature in shell-model calculations (to be formally remedied by the use of effective g -factors), is elaborately discussed in ref. ¹⁹).

The same sort of comparison for the (T -retarded) $E2_{IV}$ and $M1_{IS}$ transitions does not make much sense, because they can be speeded up appreciably by small (and unknown) T -admixtures. Most $M1_{IS}$ transitions have the additional disadvantage

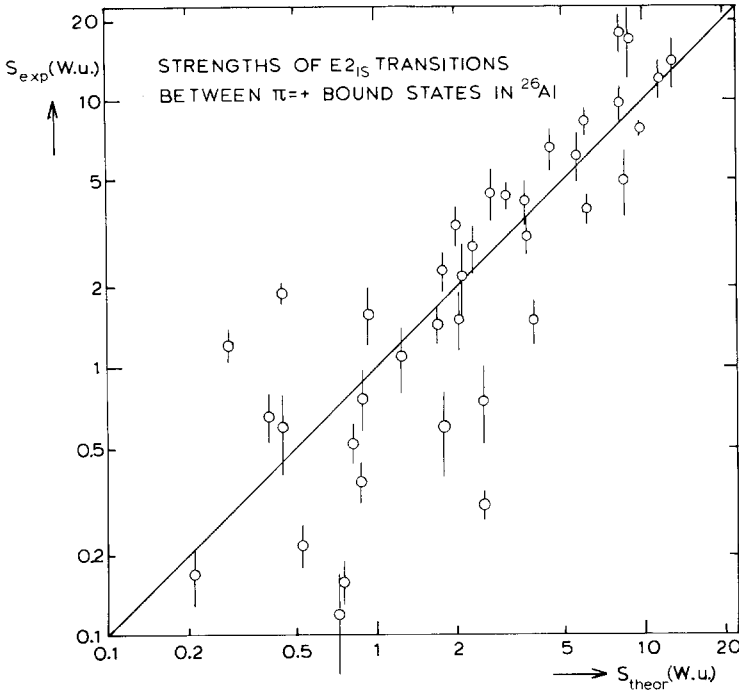


Fig. 4. Comparison of experimental and calculated $E2_{IS}$ strengths (in W.u.), S_{exp} and S_{theor} , respectively, of relatively strong transitions ($S > 0.1$ W.u.) between $\pi = +$ bound states of ^{26}Al . Transitions from or to states with badly described configuration mixing (see text) are not included.

that the $E2_{IS}/M1_{IS}$ mixing ratios have not been determined experimentally, whereas theoretically these can have very large values.

We now turn to a comparison of experimental and calculated γ -ray strengths of the transitions from individual ^{26}Al levels. Calculated $M1$ strengths have been divided by a factor 1.85 (see above). Weak transitions (defined as above) were not included in the comparison. Because many bound states have short mean lives (of the order of a few fs), which are difficult to determine accurately from DSA measurements, the lifetime has been considered as an adjustable parameter. The measure of agreement for the decay of a particular level can then be expressed in a (normalized) χ^2 value (with the help of the $E2_{IS}$ and $M1_{IV}$ deviations found from figs. 4 and 5). The average χ^2 value then amounts to $\chi^2_{av} = 1 \pm \sqrt{2/(N-1)}$, where N is the number of decay branches taken into account. The agreement is considered as acceptable if $|\chi^2 - 1|$ does not exceed three times the standard deviation. It should be noted that acceptable agreement only means that the differences between experimental and calculated (logarithmic) strengths are about as large as the differences for the transitions in figs. 4 and 5. That such χ^2 considerations make sense is based on the fact that the range in both experimental and calculated strengths of a particular

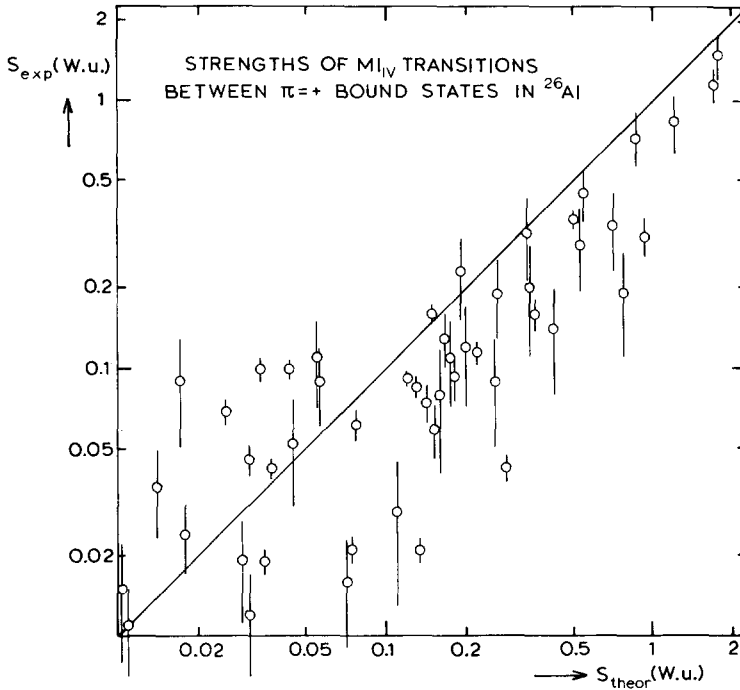


Fig. 5. Comparison of experimental and calculated $M1_{IV}$ strengths (in W.u.), S_{exp} and S_{theor} , respectively, of relatively strong transitions ($S > 0.01$ W.u.) between $\pi=+$ bound states of ²⁶Al. Transitions from or to states with badly described configuration mixing are not included.

transition character, amounting to about an order of magnitude, is much larger than the experimental and calculated errors.

Although for most levels the main decay is of $M1_{IV}$ character, there are also quite a few for which a considerable fraction of the decay proceeds by means of mixed $M1_{IS} + E2_{IS}$ transitions. This holds in particular for relatively low-lying $4^+; 0$ and $5^+; 0$ levels because the lowest $3^+; 1$ and $4^+; 1$ states are at relatively high energy ($E_x = 4192$ and 4705 keV, respectively). Such $M1_{IS} + E2_{IS}$ transitions (with δ unknown experimentally) were taken along by using the calculated value of $|\delta|$.

The results are shown in table 5. For many levels the agreement is seen to be excellent. For several other levels the large χ^2 values are thought to be due to badly described configuration mixing with nearby levels with the same $J^\pi; T$ value. Ten such pairs of levels are listed in table 6. A good example is the pair of levels at $E_x = 3596$ and 3681 keV, both with $J^\pi; T = 3^+; 0$ and both with large χ^2 values, where the calculated level separation exceeds the experimental value by a factor 3.5. The $3^+; 0$ pair at $E_x = 2365$ and 2545 keV is remarkable because the agreement becomes somewhat better (but remains poor), also for transitions feeding these levels from higher levels, if $3_3^+; 0$ is assigned to the 2365 keV level and $3_2^+; 0$ to that

TABLE 5
Comparison of experimental and calculated γ -rays strengths ^{a)}

E_x [keV]	$J^\pi; T$	τ_m or Γ_γ		χ^2	E_x [keV]	$J^\pi; T$	τ_m or Γ_γ		χ^2
		exp.	calc. ^{c)}				exp.	calc. ^{c)}	
5462	(0 ₁ ⁺); 0	<30	66 fs	1.88	6120	(4 ₇ ⁺); 0	153	250 fs	1.410
1058	1 ₁ ⁺ ; 0	367	55 fs		6551	(4 ₈ ⁺); 0		100 fs	2.46
1851	1 ₂ ⁺ ; 0	465	30 fs	0.114	7291 ^{b)}	(4 ₉ ⁺); 0	34535	(140) meV	6.45
2072	1 ₃ ⁺ ; 0	530100	390 fs	0.914	7366 ^{b)}	4 ₁₀ ⁺ ; 0	31035	(85) meV	4.87
2740	1 ₄ ⁺ ; 0	435	59 fs	0.914	7592 ^{b)}	(4 ₁₁ ⁺); 0	11035	(145) meV	4.86
3724	1 ₅ ⁺ ; 0	62	25 fs		7596 ^{b)}	4 ₁₂ ⁺ ; 0	33530	(95) meV	11.77
5010	1 ₆ ⁺ ; 0	<9	7.9 fs	0.014	7832	4 ₁₃ ⁺ ; 0	910110	(275) meV	11.96
5585	1 ₇ ⁺ ; 0	<8	4.5 fs	2.16	3403	5 ₁ ⁺ ; 0	9618	105 fs	0.914
5671 ^{b)}	1 ₈ ⁺ ; 0	<40	(17) fs	18.47	4941	5 ₂ ⁺ ; 0	356	37 fs	0.76
6270	(1 ₉ ⁺); 0	<13	5.2 fs	0.110	5488	(5 ₃ ⁺); 0	258	165 fs	1.38
6874 ^{b)}	1 ₁₀ ⁺ ; 0	4720	(65) meV	16.05	5569 ^{b)}	(5 ₄ ⁺); 0		(310) fs	5.310
1759	2 ₁ ⁺ ; 0	6.05	6.7 ps	0.014	6084 ^{b)}	5 ₅ ⁺ ; 0	13015	(122) fs	9.68
2661 ^{b)}	2 ₂ ⁺ ; 0	3.04	(4.8) ps	7.46	6496	(5 ₆ ⁺); 0	<12	62 fs	0.37
2913 ^{b)}	2 ₃ ⁺ ; 0	986	(71) fs	5.77	6598	(5 ₈ ⁺); 0		86 fs	
3751	2 ₄ ⁺ ; 0	328	34 fs	1.46	7015	5 ₉ ⁺ ; 0	13020	46 meV	1.65
5495	2 ₅ ⁺ ; 0	<7	4.6 fs	0.610	3508	6 ₁ ⁺ ; 0	245	25 fs	
5849	2 ₆ ⁺ ; 0	148	(57) fs	2.96	3922	(7 ₁ ⁺); 0	286	31 fs	
6086	(2 ₇ ⁺); 0	2016	59 fs	3.410	3754	0 ₂ ⁺ ; 1	73	13 fs	1.58
6680	2 ₉ ⁺ ; 0	22020	(55) meV	5.64	5195	0 ₃ ⁺ ; 1	<35	4.3 fs	0.38
7001	2 ₁₀ ⁺ ; 0	44040	(77) meV	4.06	2070	2 ₁ ⁺ ; 1	203	20 fs	0.18
417	3 ₁ ⁺ ; 0	1.805	1.4 ns		3160	2 ₂ ⁺ ; 1	62	6.6 fs	0.96
2545 ^{b)}	3 ₂ ⁺ ; 0	1.0025	(1.05) ps	9.56	4548	2 ₃ ⁺ ; 1	<15	5.2 fs	1.45
2365	3 ₃ ⁺ ; 0	1.43	2.6 ps	1.17	5142	2 ₄ ⁺ ; 1	<6	2.9 fs	1.86
3074	3 ₄ ⁺ ; 0	28045	245 fs	0.56	5545	2 ₅ ⁺ ; 1	2219	4.6 fs	0.85
3596 ^{b)}	3 ₅ ⁺ ; 0	264	(60) fs	1231	6852	2 ₆ ⁺ ; 1	22020	340 meV	2.04
3681 ^{b)}	3 ₆ ⁺ ; 0	122	(74) fs	6.35	4192	3 ₁ ⁺ ; 1	73	10 fs	1.76
3963	3 ₇ ⁺ ; 0	547	(113) fs	3.06	4599	3 ₂ ⁺ ; 1	73	5.0 fs	1.94
4349	3 ₈ ⁺ ; 0	134	22 fs	3.07	6364	3 ₃ ⁺ ; 1	3215	3.3 fs	0.45
4952	3 ₉ ⁺ ; 0	144	(39) fs	2.85	7939	3 ₅ ⁺ ; 1	3.64	(2.9) eV	2.34
5883	3 ₁₀ ⁺ ; 0	<17	(81) fs	11.84	4705	4 ₁ ⁺ ; 1	<5	3.5 fs	1.96
2069	4 ₁ ⁺ ; 0	45070	530 fs	0.414	5132	4 ₂ ⁺ ; 1	<5	(1.5) fs	2.75
3675	4 ₂ ⁺ ; 0	22530	305 fs	1.66	5726	4 ₃ ⁺ ; 1	<7	3.1 fs	1.15
4206	4 ₃ ⁺ ; 0	9015	97 fs	0.85	5924	4 ₄ ⁺ ; 1	<17	0.8 fs	1.57
4773	4 ₄ ⁺ ; 0	11817	205 fs	1.64	6818	4 ₅ ⁺ ; 1	4017	26 meV	1.94
5245 ^{b)}	4 ₅ ⁺ ; 0	174	(135) fs	8.24	7891 ^{b)}	4 ₆ ⁺ ; 1	3.9035	2.0 eV	2.44
5513 ^{b)}	4 ₆ ⁺ ; 0	516	(100) fs	4.74					

^{a)} No transitions have been used which are either very weak, or which proceed to states with badly described configuration mixing (see table 6). Errors are underlined.

^{b)} Large χ^2 value because of badly described configuration mixing (see table 6).

^{c)} In the calculation of theoretical Γ_γ (or τ_m) values the contribution of E1 transitions has been taken as observed experimentally. The values for large χ^2 have been bracketed.

TABLE 6
Pairs of states of ²⁶Al with badly described configuration mixing

E_x [keV]	$J^\pi; T$	ΔE_x [keV] ^{a)}	
		exp.	calc.
2365 + 2545	$3_3^+; 0 + 3_2^+; 0$	180	204
2661 + 2913	$2_2^+; 0 + 2_3^+; 0$	252	161
3596 + 3681	$3_5^+; 0 + 3_6^+; 0$	85	298
5245 + 5513	$4_5^+; 0 + 4_6^+; 0$	268	137
5488 + 5569	$(5_4^+); 0 + (5_5^+); 0$	81	46
5585 + 5671	$1_7^+; 0 + 1_8^+; 0$	86	523
6084 + 6496	$5_6^+; 0 + (5_7^+); 0$	412	252
7291 + 7366	$(4_9^+); 0 + 4_{10}^+; 0$	75	137
7592 + 7596	$(4_{11}^+); 0 + 4_{12}^+; 0$	4	94
7891 + 7953	$4_6^+; 1 + 4_7^+; 1$	62	530

^{a)} With ΔE_x denoting the level separation.

at 2545 keV. For “normal” levels the transitions feeding the states listed in table 6 have not been taken along in the χ^2 value.

If the states given in table 6 are left out of consideration we find good agreement for all 38 levels below $E_x = 5.8$ MeV (except for the $3_7^+; 0$, $3_9^+; 0$ and $4_2^+; 1$ states, all with $\chi^2 - 1$ values between three and four times the standard deviation).

For some higher levels with large χ^2 values the lack of agreement is not quite unexpected because of poor calculated E_x values. For instance, for the $3_{10}^+; 0$ and $4_{13}^+; 0$ levels at $E_x^{\text{exp}} = 5883$ and 7832 keV we have $E_x^{\text{th}} = 6372$ and 8285 keV, respectively. For the poor agreement for the levels at $E_x^{\text{exp}} = 6680, 6874, 7001$ and 7939 keV we have no ready explanation.

For most levels the agreement between experimental and calculated lifetimes is also reasonably good. The disagreement for some very weakly excited levels in the $E_x = 5.4$ – 6.6 MeV region might well be of experimental origin (poor branchings and/or lifetimes). For the strongly excited levels at e.g. $E_x = 3724$ and 4773 keV the discrepancy remains unexplained. For high-energy levels good agreement can hardly be expected. In ref. ¹⁵⁾ it is maintained that fits to $^{24}\text{Mg}(t, p)^{26}\text{Mg}$ differential cross sections are appreciably improved for $E_x > 7$ MeV if admixtures of $(sd)^8(fp)^2$ character are taken along. Such admixtures should also be expected for ²⁶Al.

It was mentioned already in sect. 4 that γ -ray strengths can help in establishing the correspondence between experimental and calculated levels. Some clear examples are given in table 7.

For the $1; 0$ levels at $E_x = 6238$ and 6270 keV the parity has remained undetermined. Although in principle either of the two could be identified with the $1_9^+; 0$, it is seen in table 7 that only the 6270 keV level produces an acceptable γ -decay χ^2 value for this assignment; the 6238 keV level presumably has odd parity.

TABLE 7

Examples of identification ambiguities solved by the analysis of γ -ray strengths

E_x [keV]	$(J^\pi; T)^{\text{exp}}$	$(J^\pi; T)^{\text{calc}}$ assumed	χ^2
6238	1; 0	$1_9^+; 0$	6.65
6270	$1^{(+)}; 0$	$1_9^+; 0$	0.110
6496	$5^+(4^+); 0$	$5_7^+; 0$	0.37
		$5_8^+; 0$	13.37
		$4_8^+; 0$	1.67
6551	$4^+(5^+); 0$	$5_7^+; 0$	20.66
		$5_8^+; 0$	29.96
		$4_8^+; 0$	2.46
7015	$5^+; 0$	$5_8^+; 0$	5.75
		$5_9^+; 0$	1.65
		$5_{10}^+; 0$	10.15

For the $4_8^+; 0$ and $5_7^+; 0$ states there are experimental candidates, both with $J^\pi; T = (4, 5)^+; 0$, at $E_x = 6496$ and 6551 keV. Table 7 shows that apparently the 6551 keV level can only be identified with the $4_8^+; 0$. The 6496 keV level agrees both with $5_7^+; 0$ and $4_8^+; 0$ but with the latter possibility already taken up only the $5_7^+; 0$ assignment remains. The $5_8^+; 0$ possibility which has also been tried is clearly unacceptable for both levels; it should be assigned to the 6598 keV level with $J^\pi; T = 5^+(4^-); 0$ of which the decay is too badly known experimentally for a χ^2 test.

Energetically the $5^+; 0$ level at $E_x = 7015$ keV would be a good candidate for the $5_9^+; 0$, but because the identification of the $5_8^+; 0$ is slightly uncertain (see above) whereas the $5_{10}^+; 0$ has not been located at all, these possibilities have also been considered. Table 7 shows unambiguously that only for $5_9^+; 0$ an acceptable χ^2 value is obtained.

In preceding sections several pairs of resonances have been discussed with pairwise the same J^π value and with very similar γ -decay, the latter caused either by T -mixing or by configuration mixing. The similarity of the decay strengths can be expressed quantitatively by means of a correlation coefficient

$$\rho(x, y) = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{[\sum_i (x_i - \bar{x})^2 \sum_i (y_i - \bar{y})^2]^{1/2}},$$

where $x_i = \log S_i$ denotes the logarithmic strengths of the primaries of one resonance of a pair and y_i the logarithmic strengths of the other resonance. The \bar{x} and \bar{y} values stand for the all-state average logarithmic strengths for M1, E1 or E2, which were taken as the average of the averages for IV and IS transitions. The sum is taken over all corresponding primaries. The value $\rho = 1$ corresponds to identical decay strengths, and a small value of ρ to uncorrelated decay.

The values of ρ thus calculated agree very closely with the qualitative discussion in preceding sections. For the highly T -mixed resonance pairs at $E_p = 1205$ and

1237 keV ($J^\pi; T = 3^+; 0+1$) and at $E_p = 1048$ and 1148 keV ($J^\pi; T = 4^-; 0+1$) we find the large values $\rho = 0.89$ and 0.82, respectively. The T -mixing for the pair at $E_p = 1774$ and 1833 keV ($J^\pi; T = 5^-; 1$) has remained unclear and the correlation coefficient, $\rho = 0.63$, is correspondingly smaller. The strong configuration mixing for the pair at $E_p = 567$ keV with $J^\pi; T = 2^+; 1(+0)$ and $E_p = 593$ keV ($J^\pi; T = 2^+; 1$) is borne out by the high correlation coefficient of $\rho = 0.90$. As a test, also two resonances have been chosen almost at random, only with the requirement that they have the same $J^\pi; T$ value and are not too far apart. For the $E_p = 890$ and 969 keV resonances ($J^\pi; T = 3^-; 0$) we find $\rho = -0.08$ showing that the decay is highly uncorrelated.

7. Concluding remarks

The present extensive new information has made ²⁶Al one of the very best investigated nuclei. Thanks to the very detailed shell-model calculation, it is also one of the nuclei which are best understood theoretically.

The information has been obtained by conventional means, from (p, γ) spectra without measurements of γ -ray angular distributions, $\gamma\gamma$ -coincidence spectra or angular correlations. A number of factors have contributed to the success of this simple method. The use of Compton suppression has made it possible to observe relatively weak γ -rays, in particular at relatively low γ -ray energy. The Mg targets used withstand high proton currents for many hours, such that spectra could be obtained with very good statistics. In the measurements at many resonances, with widely different $J^\pi; T$ values, almost all secondary states are excited at least once, whatever the $J^\pi; T$ value. Gamma-ray energies could be measured to high accuracy by means of simple internal calibration, based on preceding precision measurements³⁰). The good energies facilitate the placement of γ -rays and the unraveling of composite γ -ray structures, and have reduced the number of unplaced lines to insignificance.

The present measurements have yielded the strengths of some 2000 γ -ray transitions, an ideal set for the application of strength statistics. Statistical strength arguments have proved useful for $J^\pi; T$ assignments, for an understanding of resonance T -mixing, and for the determination of resonance Γ_{p0}/Γ values.

The elaborate shell-model calculations for even-parity states (level scheme and transition probabilities) have substantially furthered the interpretation of the experimental data. Even-parity intruder states in ²⁶Al are only observed above $E_x \approx 7$ MeV. The present data have shown that the effective charge used in the calculations is correct, and they have provided an accurate measure of the attenuation factor for M1 transitions. The main defect of the calculation seems to be the fact that calculated excitation energies are not accurate enough to provide a good description of the configuration mixing between close-lying states with the same J^π value.

One may ask whether the present experimental and analytical methods can profitably be extended to other (p, γ) reactions. This question encompasses a.o. considerations regarding the suitability of the target material, the Q -value, the spin of the initial nucleus, the height of the Coulomb-barrier, and the presence of competing (p, p'), (p, α) or (p, n) reactions. For low Q -values the number of interesting secondary states is too small, whereas for high Q -values and correspondingly high E_γ the large Weisskopf estimate for $\Gamma_\gamma(E2)$ makes it generally impossible to exclude E2 character. A low value of the initial spin restricts the investigation to low- or medium-spin resonances, such that high-spin secondary states cannot be excited.

We limit the discussion to the (p, γ) reactions leading to self-conjugated nuclei (in the sd-shell), in which because of the presence of both $T=0$ and $T=1$ states the strength differences between IV and IS γ -transitions can be fully exploited spectroscopically. The $^{17}\text{O}(p, \gamma)^{18}\text{F}$ reaction has already been investigated very well³¹⁾. The (p, γ) reactions on ^{19}F , ^{23}Na and ^{27}Al are unattractive because of the high Q -values of 12.8, 11.7 and 11.6 MeV, respectively, those on ^{29}Si and ^{31}P because of the low initial spin $J=\frac{1}{2}$. Of the remaining (p, γ) reactions, on ^{21}Ne , ^{33}S , ^{35}Cl and ^{39}K , all with $J_i=\frac{3}{2}$ (rather low), and with $Q=6.7, 5.1, 8.5$ and 8.3 MeV (the latter two rather high), one might select the $^{33}\text{S}(p, \gamma)^{34}\text{Cl}$ reaction from target stability considerations.

It should be concluded that investigations of other (p, γ) reactions along the lines of the present work all have certain drawbacks compared to $^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$. In addition, ^{26}Al was favoured because solid spectroscopic information existed from previous work, as obtained e.g. from single-nucleon transfer and the $^{28}\text{Si}(\bar{d}, \alpha)$ and $^{25}\text{Mg}(p, p_0)$ reactions, and from precision measurements of γ -ray energies (see preceding sections).

The present work has also shown²⁸⁾ that it is possible to obtain unique information on the levels close to the proton binding energy, important for nuclear synthesis in stars. In fact, ^{26}Al is now one of the very nuclei in which the knowledge on important spectroscopic quantities like branching ratios, lifetimes, spins, parities and isospins extends continuously from the ground state far up into the resonance region. This result might provide the strongest argument to start analogous (p, γ) work on other nuclei, notwithstanding the difficulties mentioned above.

We are much indebted to the many Utrecht colleagues and students who contributed in one way or another to our work. Of our foreign colleagues we thank in particular G.E. Mitchell, C. Rolfs and H.T. Fortune for preprints of their work, and for very useful discussions and correspondence on our results.

This investigation was performed as part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie" (FOM) with financial support of the "Nederlandse Organisatie voor Zuiver-Wetenschappelijk Onderzoek" (ZWO).

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