GAMMA RAYS FROM THE ^{27}Al(p,γ) REACTION

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Summary

Gamma-ray spectra and angular distributions have been measured at the 759, 766, 773, and 993 keV resonances of the ^{27}Al(p,γ) reaction.

The results obtained at the lower resonance are in agreement with previous work. At the 993 keV resonance a transition to the 7·80 MeV level of ^{28}Si has been observed.

Tentative J^{π} assignments to the resonance levels of 2^-(759 keV), 4^-(766 keV), 1^+(773 keV), and 3^+(993 keV) are discussed.

I. Introduction

The present investigation was commenced in order to establish the predominant gamma-ray transitions occurring at resonances of the ^{27}Al(p,γ)^{28}Si reaction for E_p=750–1000 keV as a preliminary to a study of the resonance levels and intermediate levels of ^{28}Si by means of angular correlation measurements. Many resonances of this reaction which occur at proton energies below 750 keV have been previously studied (Casson 1953 ; Rutherglen *et al.* 1954 ; Endt and Heyligers 1960 ; Okano 1960) but, of the resonances reported at proton energies between 750 and 1000 keV, namely, 759, 766, 773, 884, 922, 936, and 993 keV (Broström, Huus, and Tangen 1947 ; Andersen *et al.*, 1959) measurements of the gamma-ray spectra have been made only at 773 and 993 keV (Gove, Litherland, and Paul, unpublished data 1957 ; Smith and Endt 1958 ; Brenner 1959). It was intended to supplement measurements at these resonances and to examine the remainder.

II. Experimental Procedure

A proton beam of up to 10 μA at the target was obtained from the Canberra 1·2 MeV Cockcroft-Walton accelerator after 90° magnetic analysis and electrostatic focusing through two tantalum defining apertures, $\frac{1}{8}$ in. in diameter, placed 2 ft apart (Fig. 1). Good energy stability and homogeneity of the beam was required to resolve the closely spaced resonances, and modifications to the accelerator input generator and the 90° magnet power supply were found to be necessary. The full width of the resonance at 773 keV, comprising target thickness, energy inhomogeneity, and the natural resonance width (less than 160 eV, Andersen *et al.* 1959), was typically 3 keV for the targets used, and measurements of the variations from maximum yield at this resonance as a function of time indicated that the energy stability was better than ±1·5 keV.

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Targets were prepared by evaporation of pure aluminium onto copper backings 0·030 in. thick which were mounted on a water-cooled holder. The target chamber (Fig. 1) was constructed of " Lucite " to minimize scattering in the vicinity of the target. Carbon deposition on the target was almost completely avoided by surrounding the target with a 0·015 in. thick copper cylinder which was maintained at liquid air temperature. For a typical run of five hours' duration, no drift of the resonance energy due to carbon build-up could be detected. The observed background from the $^{12}C(p,\gamma)$ reaction was attributed to carbon contamination during target preparation since there was no increase of the background with time.

The gamma rays were detected with a 5 in. diameter by 4 in. thick sodium iodide crystal optically coupled to a 3 in. DuMont 6363 phototube. The crystal-phototube assembly, housed in a lead shielding at least 4 in. thick in any direction, was mounted on a rotating table. Gamma rays entered the crystal through a

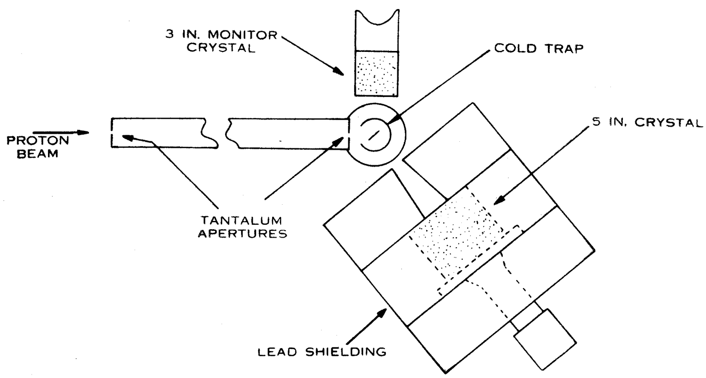

Fig. 1.—Schematic view of experimental arrangement.

conical defining aperture, 2 in. in diameter at the crystal and tapered so that the target was situated within the cone defined by the taper. Spectra were recorded on a Sunvic 100-channel pulse-height analyser. At each resonance, two spectra were recorded with the same overall gain but different analyser base-line values. In this way, the spectrum for gamma-ray energies between 1·5 and 13 MeV was contained in approximately 170 channels. The crystal response function, from which the line shape of a gamma ray of any energy between 1·5 and 13 MeV could be constructed, and energy calibrations were obtained from measurements of the gamma-ray spectra from the $^{11}B(p,\gamma)$, $^{19}F(p,\alpha\gamma)$, and $^{13}C(p,\gamma)$ reactions and ThC″ and ^{22}Na sources (Fig. 2).

An unshielded 3 in. by 3 in. sodium iodide crystal, mounted at 90° to the beam, was used for coincidence measurements and as a monitor. The output of this counter was fed to three scalers with discriminators set to count pulses corresponding to an energy loss in the crystal greater than 1·6, 4·0, and 8·0 MeV respectively. The ratios of counts thus obtained were very sensitive to the particular resonance being observed and therefore served to indicate any possible contribution from nearby resonances due to target deterioration or energy instability during the course of the measurement. For coincidence measurements, portions of the 3 in. counter output were selected with a single-channel analyser and fed to a coincidence circuit with a resolving time of $2\tau=1\cdot0$ μs. Coincidence measurements were made at the 773 and 993 keV resonances to determine the decay schemes, and, for these measurements, the front shielding of the large crystal was removed and the counter moved nearer to the target.

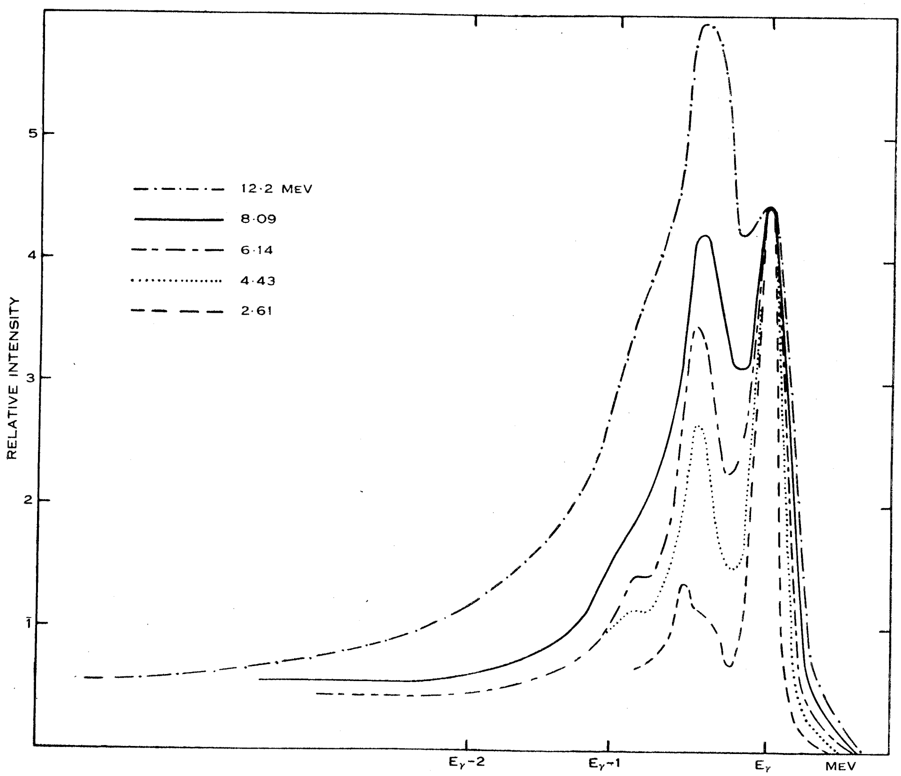

Fig. 2.—Line shapes obtained with the 5 in. by 4 in. crystal for the indicated gamma-ray energies.

A singles spectrum was recorded at each resonance at 90° to the beam and angular distributions were measured at six equal intervals of $\cos^2\theta$ between $\theta=0°$ and $\theta=90°$.

III. Results

The excitation functions obtained in the regions of $E_p=755$–775 keV and $E_p=990$–1010 keV are given in Figure 3. The excitation functions were recorded by applying a 20 keV sawtooth voltage to the target. The output of a gamma-ray detector triggered a pulse proportional to the instantaneous applied voltage so that the excitation function could be recorded directly on a pulse-height analyser (Carver and Waugh 1961).

(a) 759 keV Resonance (^{28}Si excitation—12·320 MeV)

The spectrum obtained at $E_p = 761$ keV is shown in Figure 4. The resonance level decays almost entirely (approximately 90%) by a transition to the first excited state of ^{28}Si at 1·78 MeV, the ground state transition being very weak ($\leqslant 3$%). The angular distribution of the 10·5 MeV gamma ray was isotropic to within 5%.

(b) 766 keV Resonance (12·327 MeV)

The spectrum is shown in Figure 4. Gamma rays of energies 7·70, 2·84, and 1·78 MeV are observed, corresponding to a transition to the second excited state at 4·62 MeV followed by a cascade through the 1·78 MeV level. This mode of decay accounts for about 75% of the gamma-ray yield. Weak gamma

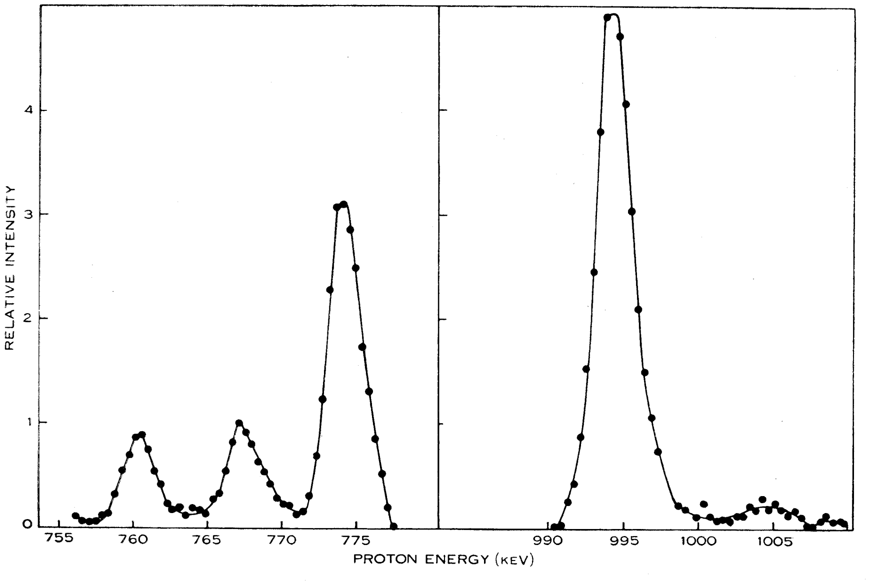

Fig. 3.—Excitation function of the $^{27}Al(p,\gamma)$ reaction in the regions of the resonances studied. The ordinate scales for the two sections of the excitation function are not related.

rays at 6·8 MeV and in the vicinity of 4 MeV are apparent in the spectrum but they were not further investigated. Endt and Heyligers (1960) have identified these gamma rays as transitions through levels at 6·28, 8·41, and 8·59 MeV.

The angular distribution of the 7·7 MeV gamma ray was found to be $W(\theta) \sim 1 + (0 \cdot 25 \pm 0 \cdot 04) \cos^2 \theta$. Small monitoring corrections, based on the monitor scaler ratios, were necessary for the angular distribution measurement to account for contamination from adjacent resonances.

(c) 773 keV Resonance (12·333 MeV)

This is the most intense of the three resonances and, as noted previously by Gove, Litherland, and Paul (unpublished data 1957) and Smith and Endt (1958), is characterized by a strong ground state transition (Fig. 4). Other gamma rays

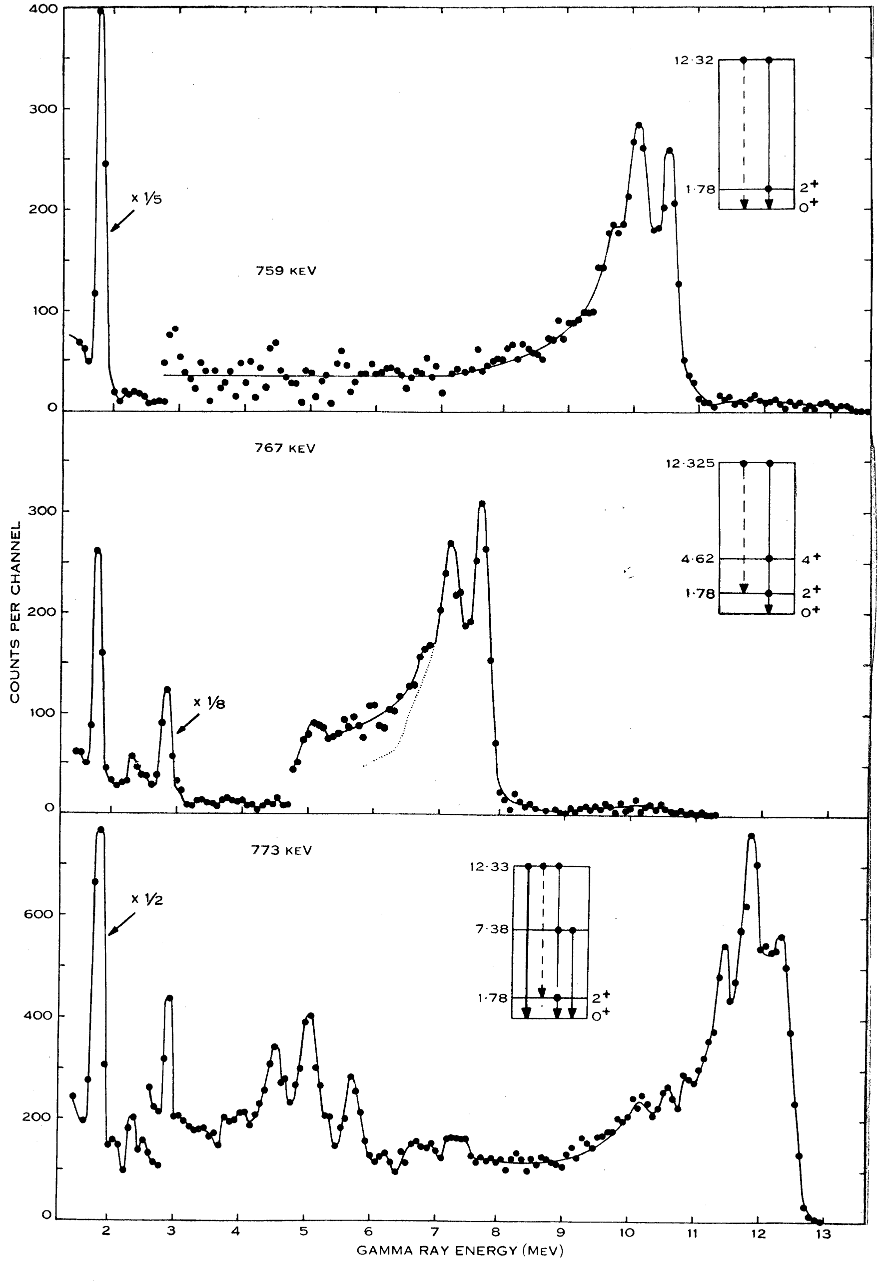

Fig. 4.—Gamma-ray spectra (measured at 90° to the beam) obtained at the 759, 766, and 773 keV resonances. Weak transitions (see text) are shown as broken lines.

are evident at 10·5, 7·4, 5·60, 5·0, 4·5, 2·85, and 1·78 MeV. The 10·5 MeV is identified as the transition to the first excited state. The 7·4 and 5·0 MeV gamma rays could result from a transition through the 4·96 MeV level or alternatively from a transition through the 7·38 MeV level. The former cascade is inconsistent with a recent assignment of 0^+ to the 4·96 MeV level of ^{28}Si

Table 1

GAMMA RAYS IN COINCIDENCE WITH SELECTED GAMMA RAYS AT THE 773 keV RESONANCE

Gate	Gamma Rays Observed in Coincidence
1·78 MeV	(10·5), 5·6, 5·0, 2·85 MeV
4–5 MeV	7·4, 5·6, 1·78 MeV
5–6 MeV	5·0, 2·85, 1·78 MeV

(Gove, personal communication). Coincidence measurements, obtained by gating on various portions of the 3 in. crystal spectrum (summarized in Table 1), showed that the 5·0 MeV gamma ray was in coincidence with 7·4, 5·6, and 1·78 MeV gamma rays. Thus it can be concluded that the 5·0 MeV gamma ray is the result of a transition to the 7·38 MeV level, which decays either directly

Table 2

SUMMARY OF RESULTS OBTAINED AT THE 993 keV RESONANCE

Gamma-ray Energy (MeV)	Intensity	Coincidence with 1·78 MeV Gamma Ray	Brenner	
10·76	100	yes	10·8	100
8·98±0·15	⩽3	—		
7·95±0·05	8	yes (partially)	8·04	17
7·40±0·10	⩽2	—	7·2	
6·3 ±0·10	⩽3	—		
6·04±0·05	10	yes	6·07	20
5·12±0·10	⩽2	—		
4·78±0·075	13	yes	} 4·66	21
4·52±0·10	10	no		
3·12±0·10	⩽5	—		
2·84±0·05	10	yes	2·86	6*
1·78	124	—	1·80	100*

* Separate measurement which is not related to other intensities.

to the ground state or by a cascade through the first excited state with the emission of a 5·6 MeV gamma ray. The other weaker gamma rays were not investigated.

The angular distribution of the 12·4 MeV ground state transition was measured as $W(\theta)\sim 1-(0\cdot 18\pm 0\cdot 03)\cos^2\theta$ in good agreement with the results obtained by Gove *et al.* (1954).

(*d*) *884, 922, and 936 keV Resonances*

Strong resonances in the ^{19}F($p,\alpha\gamma$) reaction in the neighbourhood of each of these resonances were the source of a very troublesome background. No measurements were made at the 884 and 936 keV resonances, although a strong transition to the 1·78 MeV level was observed at the 884 keV resonance. The spectrum of the 922 keV resonance (not shown) closely resembled the result obtained at the 759 keV resonance in that the resonance level decayed almost entirely by a transition to the 1·78 MeV level.

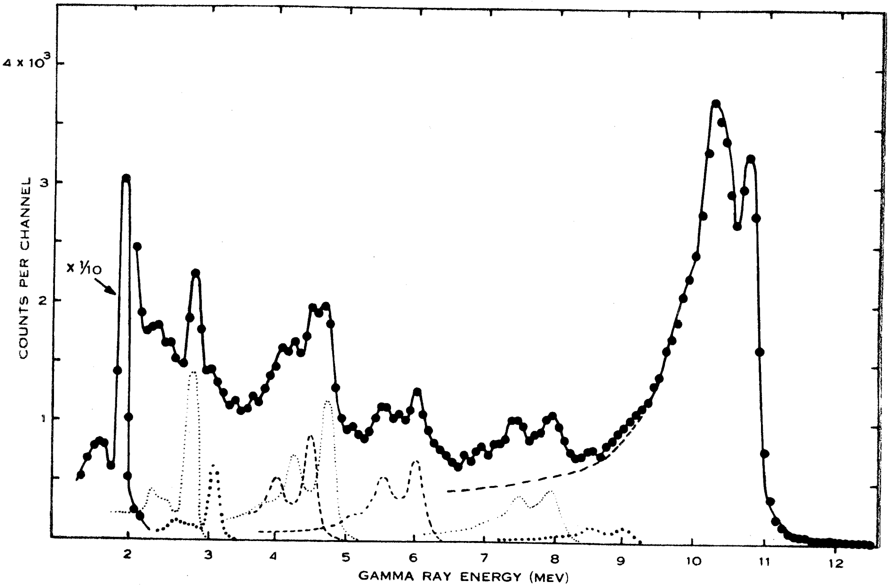

Fig. 5.—Gamma-ray spectrum of the 993 keV resonance (at 90°). The individual gamma rays, into which the spectrum was decomposed, are indicated.

(*e*) *993 keV Resonance (12·547 MeV)*

The spectrum obtained at this intense resonance is given in Figure 5 and the gamma rays identified and their relative intensities (at 90°) are listed in Table 2.

There is reasonable agreement with Brenner (1959) so far as the energies of the most intense gamma rays are concerned, although a considerable difference of the relative intensities of the 7·95 and 6·04 MeV gamma rays is to be noted. It is perhaps significant that possible contaminant reactions ^{13}C(p,γ) and ^{19}F($p,\alpha\gamma$) yield gamma rays of approximately these energies.

The present spectrum is better resolved than that obtained by Brenner and shows an important difference in that two gamma rays are resolved in the vicinity of 4·6 MeV, whereas Brenner identified only one gamma ray at 4·66 MeV. The decay scheme proposed (Fig. 6) is consistent with the observed energies and intensities and the present coincidence measurements as well as with the 8 and 4·6 MeV cascade observed by Gove, Litherland, and Paul (unpublished data 1957).

De-excitation of the various levels involved is in agreement with the scheme proposed by Endt and Heyligers (1960), although they did not observe the excitation of the level at 7·80 MeV at any of the resonances between E_p=500 and 800 keV. A transition to this level, followed by a cascade through the 1·78 MeV level, would result in gamma rays of energies 4·74 and 6·02 MeV as compared to the observed energies of 4·78 and 6·04 MeV. The only other level which could account for gamma rays of approximately these energies is the 7·93 MeV level. However, the energy discrepancy is in excess of 0·1 MeV for

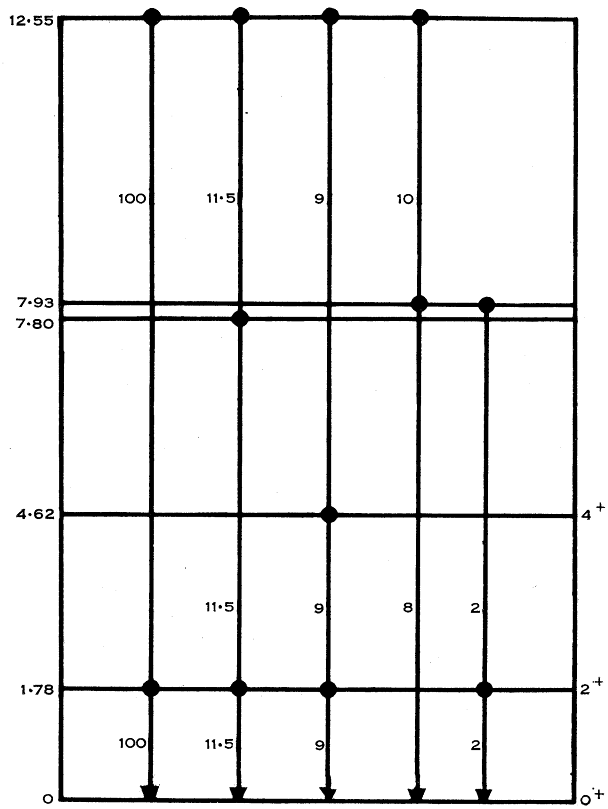

Fig. 6.—Proposed decay scheme of the 993 keV resonance level showing relative intensities of the gamma-ray transitions.

each gamma ray and, since 80% of the de-excitation of the 7·93 MeV level proceeds directly to the ground state (Endt and Heyligers 1960), an excess intensity of the 6·04 MeV gamma ray is observed. The intensity difficulty could arise from the angular distributions of the gamma rays but the energy discrepancy is considered to be too large, since the 4·78 MeV gamma ray was further calibrated by means of comparison with the spectrum obtained at 773 keV. The energy assigned to the 4·52 MeV gamma ray is less accurate since it is more dependent on analysis of the spectrum.

The $8 \cdot 98$ MeV gamma ray could result from excitation of either the $10 \cdot 71$ or $8 \cdot 91$ MeV levels.

The angular distribution of the $10 \cdot 76$ MeV gamma ray was measured as $W(\theta) \sim 1+(0 \cdot 10 \pm 0 \cdot 03) \cos^2 \theta$ as compared to the other measurements of $\sim 1+0 \cdot 16 \cos^2 \theta$ (Brenner 1959) and $\sim 1+0 \cdot 076 \cos^2 \theta$ (Gove *et al.* 1954). The $1 \cdot 78$ MeV gamma ray was found to be isotropic to within 2% and the triple correlation of these two gamma rays ($10 \cdot 76$ MeV variable) was $\sim 1+(0 \cdot 20 \pm 0 \cdot 03) \cos^2 \theta$.

IV. Discussion

During the course of the experiment, it was found that Endt and Heyligers (1960), as a means of establishing the energy levels of ^{28}Si, had already determined the gamma-ray scheme in detail at each resonance in the region $E_p = 500$–800 keV. As has been indicated in Section III, the present results for the 759, 766, and 773 keV resonances are in agreement with the measurements of Endt and Heyligers.

Assignment of J^π values to the resonance levels by means of correlation measurements is complicated, since the ground state spin of the target nucleus is $5/2^+$. Considering s,p, and d-wave proton capture, the possible resonance states are as follows:

l_p	Channel Spin $s=2$	Channel Spin $s=3$
$l=0$	2^+	3^+
$l=1$	1^-, 2^-, 3^-	2^-, 3^-, 4^-
$l=2$	0^+, 1^+, 2^+, 3^+, 4^+	1^+, 2^+, 3^+, 4^+, 5^+

Even with the restriction of l_p, the angular correlations for most possible J^π values involve parameters for either or both channel spin mixing (t) and orbital angular momentum mixing (δ and a relative phase factor $\cos \varphi$) as well as a multipole mixing parameter (x) of the gamma-ray transition.

The reaction $^{27}Al(p,\alpha)^{24}Mg$ does not provide any definite simplification of the possible spins since the alpha-particle yield (to the ground state of ^{24}Mg) is non-resonant at each of the four resonances under study (Shoemaker *et al.* 1951; Kuperus and Smith 1960). Non-emission of alpha particles implies that the spins of the resonance levels are in the sequence 1^+, 2^-, 3^+, 4^-, etc., but such an interpretation is not rigorous, since alpha-particle emission may be forbidden by isotopic spin selection rules.

In the following discussion, the observed correlations are compared with the theoretical predictions (Sharp *et al.* 1954; Ferguson and Rutledge 1957) with the assumptions that (i) the gamma-ray transitions are pure multipole of the lowest allowed order except that mixing is considered for possible ($M1$, $E2$) transitions (it is to be noted that $E1$ transitions may be inhibited since ^{28}Si is a self-conjugate nucleus) and (ii) proton capture is restricted to s, p, and d-wave capture. The inhibition of electric dipole radiation will depend on isotopic spin being a good quantum number at the excitations in question. Smulder, Smith, and Endt (personal communication 1961) have demonstrated, by examination of a number of resonances of the $^{24}Mg(\alpha,\gamma)^{28}Si$ reaction, that isotopic spin is a good quantum number at excitation energies of 12 MeV.

(a) *759 keV* (^{28}*Si excitation—12·320 MeV*)

The presence of a ground state transition indicates that $J\leqslant 2$ and eliminates $J=0\pm$. The assignment of 1^+ or 1^- is not consistent with the relative intensity of the ground state transition. The observed distribution of the transition to the first excited state, $W(\theta)\sim 1+(0\cdot 0\pm 0\cdot 05)\cos^2\theta$ could result from either a spin of 2^+, which would be produced predominantly by s-capture, or a spin of 2^- with channel spin mixing $(s=3)/(s=2)$ in the range $2\leqslant t\leqslant 8$. Non-emission of alpha particles from the level favours a 2^- assignment.

The properties of this resonance are very similar to those of the 226 keV resonance which de-excites almost entirely via the 1·78 MeV level, and the angular distribution of the transition is very nearly isotropic (Okano 1960).

(b) *766 keV* (*12·327 MeV*)

At this resonance, no ground state transition is observed and the transition to the first excited state is very weak compared to the transition to the second excited state. Thus the spin is most probably $\geqslant 3$. The assignment of either 3^+ or 3^- is unlikely since, for 3^+, the transitions to both levels would be $(M1, E2)$ and, for 3^-, both $(E1, M2)$. In each case, the higher energy transition to the first excited state would be expected to be the more intense. The observed anisotropy is a further argument against a spin of 3^+ which would result predominately from s-wave capture.

The theoretical distribution for the transition $4^-(E1)4^+(l=1,\ s=3)$ is $\sim 1+0\cdot 46\cos^2\theta$, whereas the predicted distribution for the transition $4^+(M1\ E2)4^+(l=2,\ s=2,\ 3)$ can be fitted to the observed distribution for the ranges $0\leqslant t\leqslant 8\cdot 1$ and $-0\cdot 23\leqslant x\leqslant 1\cdot 66$ (where x is the $E2/M1$ ratio). Thus the level is almost certainly 4^+ and consequently a $T=1$ state since it is not an alpha-emitting level $(2Jr+1)\Gamma\alpha\Gamma p/\Gamma<0\cdot 38$ eV. Some confirmation of the assignment can be found in a comparison of the resonance with the 326 and 405 keV resonances to which 4^- assignments have been made (Okano 1960).

The three resonances are similar in that the predominant transition is to the second excited state but the lower resonances show a fairly strong transition to one of the levels of the 6·88 MeV doublet. The absence of this transition at the 766 keV resonance is consistent with a spin assignment of 2^- to the 6·88 MeV level so that the transition would be $M2$ at the 766 keV resonance (and therefore weak) but $E2$ at the lower resonances.

(c) *773 keV* (*12·333 MeV*)

This resonance has been discussed previously by Smith and Endt (1958). The strong ground state transition indicates that $J\leqslant 2$. A spin of 2^- is unlikely because of the weak transition to the first excited state and the observed anisotropy, $W(\theta)\sim 1-(0\cdot 18\pm 0\cdot 03)\cos^2\theta$ rules out 2^+ which would result mainly from s-wave capture. The theoretical distribution for the transition

$1^+(M1)0^+(s=3, l=2)$ is $\sim 1-0\cdot 20\cos^2\theta$, in good agreement with the observed distribution. However, the transition $1^-(E1)0^+(s=2, l=1)$ is by no means precluded since the predicted distribution is then $\sim 1-0\cdot 14\cos^2\theta$.

(*d*) *993 keV (12·547 MeV)*

The spin of the 993 keV resonance level is likely to be $\geqslant 3$, since no ground state transition is observed and a triple correlation of the 8 and 4·66 MeV gamma rays measured at this resonance (Gove *et al.*, unpublished data 1957) is consistent with the sequence $3^+(M1)2^+(E2)0^+$. Previous measurements (Brenner 1959) do not exclude the possibility of 2^- and consequently the present three correlations have been analysed considering possible compound state spins of 2^-, 3^+, and 3^-.

The results for spins 2^- and 3^- are summarized in Table 3.

TABLE 3

CORRELATION COEFFICIENTS OF P_2 (cos θ) FOR GAMMA RAYS AT THE 993 KEV RESONANCE

Sequence	First Gamma Ray	Second Gamma Ray	Triple Correlation
	$(a_2)_{\text{obs}}=0\cdot 065\pm 0\cdot 025$	$(a_2)_{\text{obs}}=0\pm 0\cdot 02$	$(a_2)_{\text{obs}}=0\cdot 12\pm 0\cdot 02$
$2^-(E1)2^+(E2)0^+$ $s=2, 3$ $l=1$	Yes $3\cdot 74\leqslant t\leqslant 3\cdot 95$	Yes $0\cdot 61\leqslant t\leqslant 1\cdot 24$	No $a_2<0$ for $0\leqslant t\leqslant\infty$
$3^-(E1)2^+(E2)0^+$ $s=2, 3$ $l=1$	Yes $1\cdot 05\leqslant t\leqslant 1\cdot 52$	Yes $0\cdot 72\leqslant t\leqslant 0\cdot 89$	Yes $1\cdot 35\leqslant t\leqslant 2\cdot 13$

The analysis of the $3^+(M1\ E2)2^+(E2)0^+$ sequence is complicated, since the small anisotropy of the first gamma ray indicates that some *d*-wave capture must be taken into account. The data were analysed graphically for the possible values of the mixing parameters assuming the amount of *d*-wave admixture to be small, i.e. $0<\delta\ll 1$. The measurements were found to be consistent with the predicted correlations for wide overlapping ranges of the parameters. Thus, the assignment 3^+ can be made with fair certainty since 2^- is eliminated and the various values of channel spin mixing required to fit the data for 3^- do not overlap. Some uncertainty concerning a spin of 3^- remains, since approximately 20% of the second gamma-ray intensity arises from other cascades.

V. ACKNOWLEDGMENTS

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