

ENERGY LEVELS IN ^{28}Si FROM THE $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ REACTION

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Synopsis

The gamma-ray spectra from twelve $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ resonances in the $E_p = 500$ to 800 keV region were investigated with scintillation spectrometers. Both single and coincidence spectra were measured from which the branchings were obtained in the decay of the resonance levels and of lower levels at 1.783 ± 0.008 , 4.623 ± 0.015 , 6.28 ± 0.02 , 6.88 ± 0.05 , 7.37 ± 0.02 , 7.42 ± 0.02 , 7.93 ± 0.03 , 8.32 ± 0.05 , 8.41 ± 0.05 , 8.59 ± 0.03 , 8.92 ± 0.02 , 9.31 ± 0.02 , 9.38 ± 0.02 , 9.49 ± 0.02 , 9.76 ± 0.02 , and 10.71 ± 0.02 MeV. The levels at 9.31, 9.38, and 10.71 MeV very probably have $T = 1$ character. They would correspond to the ground-state, the 0.03 MeV and the 1.37 MeV levels in ^{28}Al with $J^\pi = 3^+$, 2^+ , and 1^+ , respectively.

From yield measurements the resonance strengths $\omega\gamma = (2J + 1)\Gamma_p\Gamma_\gamma/\Gamma_t$ were obtained for all resonance levels.

1. *Introduction.* When this investigation was started very little was known about the lower levels in ^{28}Si . The situation was summarized in the review paper by Endt and Braams ¹⁾. The excitation energies of only the lowest two levels were known with good precision from high resolution magnetic analysis experiments as 1.773 ± 0.007 and 4.617 ± 0.008 MeV, respectively ²⁾³⁾. From $^{27}\text{Al}(d, n)^{28}\text{Si}$ measurements a number of levels were found in the 4.7–10.3 MeV region with low resolution (60 to 100 keV) ⁴⁾⁵⁾⁶⁾. The information available from the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction will be compared to the results from the present experiment in section 4 of this paper.

This study was prompted by the need to obtain accurate data on the gamma-ray branching of resonance levels and lower levels as a preliminary to gamma-ray angular correlation measurements. When the experimental work was almost finished the results were received of high resolution magnetic analysis experiments by White ⁷⁾ on the $^{28}\text{Si}(p, p')^{28}\text{Si}$ reaction, and by Hinds and Middleton ⁸⁾ on the $^{27}\text{Al}(^3\text{He}, d)^{28}\text{Si}$ reaction. The levels given by White are at: 1.775 ± 0.007 , 4.612 ± 0.007 , 4.975 ± 0.007 , and 6.265 ± 0.010 MeV. In the ($^3\text{He}, d$) experiment 29 levels were found below 10.4 MeV excitation and angular distribution analysis of the corresponding deuteron groups was carried out. Their levels are at: 1.771,

4.617 ($l_p = 2$), 4.975, 6.276 ($l_p = 0$), 6.880 *), 6.889 *), 7.382, 7.415, 7.798 ($l_p = 0$), 7.932 ($l_p = 0$), 8.260 ($l_p = 2$ or 3), 8.328, 8.411 ($l_p = (3)$), 8.543, 8.587 ($l_p = 0$), 8.902 ($l_p = (2)$), 8.941, 9.167, 9.314 ($l_p = 0$), 9.379 ($l_p = 0$), 9.41, 9.491 ($l_p = 2$ or 3), 9.700 ($l_p = 3$), 9.762, 9.932 ($l_p = 2$), 10.180, 10.273, 10.308, and 10.375 MeV, all ± 0.010 MeV. This work has greatly facilitated the analysis of our measured gamma-ray spectra.

The energies of proton resonances in the $E_p = 500$ to 800 keV region ($E_x = 12.0$ to 12.3 MeV) are known quite accurately ⁹⁾¹⁰⁾.

2. *Experimental technique.* The proton beam current available from the Utrecht 850 kV Cockcroft-Walton generator has recently been improved by the installation of a high-frequency ion source and now amounts up to 150 μA (measured after magnetic analysis). It was found, however, that 70 μA is about the maximum current that oil cooled aluminium targets can stand. To obtain sufficient resolution to separate the 504 and 506 keV resonances, the magnet entrance and exit slits had to be narrowed from the usual 2 mm to $\frac{3}{4}$ mm, which reduced the maximum current at these resonances to about 30 μA .

Aluminium targets were prepared in different thickness by evaporation in vacuo onto $\frac{1}{2}$ mm copper backings. Targets can be stored for periods up to a week in a vacuum dry-box without apparent deterioration. Targets do deteriorate under bombardment, the observed resonance yield curves growing broader with time. For the measurements at the 504 and 506 keV resonances fresh targets were taken every few hours. At the other resonances targets were changed every day.

Single gamma-ray spectra were taken at all resonances both with a 2" and with a 4" NaI scintillation crystal, at an angle of 55° to the proton beam. Both these crystals provided good energy resolution yielding a full width at half maximum of 5.6 and 7.9%, respectively, for the photopeak of the strong 1.78 MeV gamma ray observed at all $^{27}\text{Al}(p, \gamma)$ resonances. The good resolution 4" crystal will be denoted in the following as the "yellow" crystal. The spectra were recorded on a R.C.L. 256-channel pulse-height analyser. At many resonances spectra were also taken with twice the usual amplifier gain to observe the low energy parts in more detail.

For the measurements of coincidence spectra an additional 4" NaI crystal was used. Its energy resolution was definitely inferior to that of the other two, amounting to 14% for the 1.78 MeV gamma ray. It will be denoted as the "blue" crystal. The yellow and the blue crystal were put at angles of $+85^\circ$ and -85° to the proton beam. Parts of the yellow and blue spectra were selected with single channel differential discriminators and then fed

*) For the unresolved groups leading to the 6.880 and 6.889 MeV levels $l_p = 2 + 3$ is found.

into a coincidence circuit with a resolving time of $2\tau = 1.2 \mu\text{sec}$. The coincidence output opened the gate of the pulse analyser recording the yellow spectrum. A delay line compensating for the time delays in the differential discriminators was placed in the signal channel. The yellow discriminator channel was always wide open, transmitting a pulse-height region of 1 to 13 MeV. Particularly good coincidence spectra are obtained if low energy lines in the 1 to 5 MeV region are observed in coincidence with high energy (5 to 12 MeV) lines picked out by the blue channel. The good resolution of the yellow crystal is used to full advantage while the bad resolution of the blue crystal matters very little.

In the beginning of this investigation quite some time was spent in trying to apply the sum-coincidence technique ¹¹⁾ to the $^{27}\text{Al}(p, \gamma)$ reaction with the 4" crystals mentioned above. It was experienced, however, that good sum-coincidence spectra can only be obtained through the use of two good resolution crystals.

The linearity of the analyser was checked carefully. No deviations from linearity could be observed above about channel 20. The drift of the zero of the analyser never amounted to more than a few tenths of a channel.

Elaborate "peeling" procedures had to be employed to analyse the often complicated observed spectra. First pulse spectra were measured for some eight standard lines in the 1.5 to 12 MeV region. For easy interpolation, curves were then drawn giving the intensity of the pulse spectrum relative to that at the pair +0.51 MeV peak, at pulse heights separated by 0.17 MeV as a function of gamma-ray energy. This had to be done separately for the 2" and the two 4" crystals. Total detection efficiencies are given in reference 11. In coincidence experiments one also has to know the efficiency for the detection of pulses with a height above a certain lower limit. These "partial" efficiencies were plotted as a function of the lower limit with the gamma-ray energy as a parameter. For any given discriminator channel cutting an arbitrary part out of the pulse spectrum the detection efficiency of a certain gamma ray can then be found as the difference of the partial efficiencies corresponding to the upper and lower channel limits. At all resonances also background measurements were performed at proton energies slightly below or above the resonance. The R.C.L. pulse analyser has a provision for automatic background subtraction. This has been used in the beginning but in later work it was found more advantageous to record the background spectra separately and then to subtract the smoothed-out background spectrum from the measured $^{27}\text{Al}(p, \gamma)$ spectrum. The automatic subtraction procedure introduces larger statistical errors and may produce bizarre "differentiated" peak shapes if the gain has shifted slightly between the two measurements.

A special study was made of summing effects which may, e.g., simulate the presence of a weak cross-over transition of a strong gamma-ray cascade.

Shape and intensity of the corresponding pulse distributions were obtained by numerically folding the pulse distributions of the two gamma rays in the cascade. The smallest summing effects are obtained, of course, by using the small (2") crystal or by putting the crystal at larger distance from the target. But even then summing effects may have to be estimated to decide on the presence or absence of a weak cross-over.

Coincidence measurements have been used to measure the branching of lower levels. As an example we take the 731 keV resonance where the 9.38 MeV level is excited by a 2.91 MeV primary and deexcited by a weak ground-state transition (not observed in single spectra) and a strong transition ($E_\gamma = 7.60$ MeV) to the first excited state. The branching is then obtained by comparing the intensities of the 2.91 MeV photopeak in the yellow spectrum in coincidence with 8.2–10.0 MeV and with 6.4–10.0 MeV blue channels. The first channel setting comprises the 9.38 MeV gamma ray while the second setting comprises both the 9.38 MeV and the 7.60 MeV gamma rays. Of course, in this case one also has to make an estimate of $7.60 + 1.78$ MeV summing effects in the blue channel.

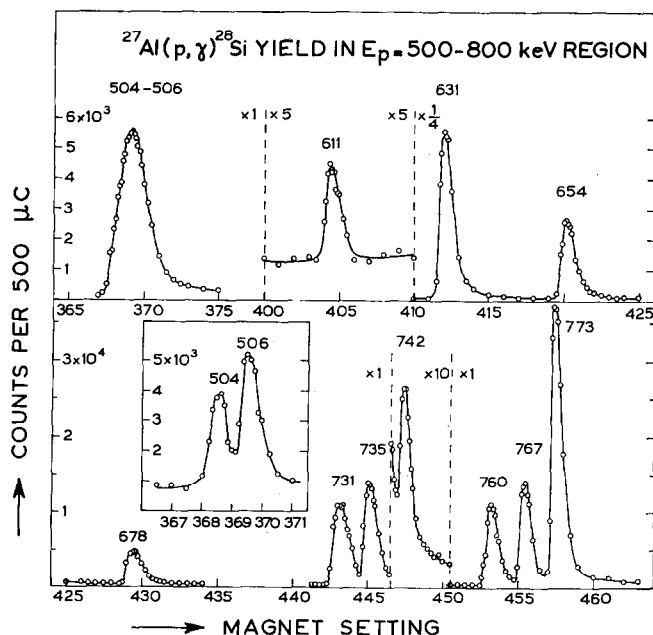


Fig. 1. Yield of the $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction in the $E_p = 500\text{--}800$ keV region as a function of the analyser magnet setting ($\theta = 55^\circ$). Target thickness 2.5 keV at 700 keV (but 0.5 keV for insert). Discriminator channel 3.0–13.0 MeV (but 1.3–10.2 MeV for insert). Magnet slits $\frac{1}{2}$ mm.

3. Results. A. Yields. In Fig. 1 the gamma-ray yield is shown as a function of the field setting of the proton analysing magnet using a target

of 2.4 keV thickness at 700 keV, magnet slits of $\frac{1}{2}$ mm width and a 3–13 MeV discriminator channel. Shown in the insert is the 504–506 keV doublet measured with a much thinner target of about 0.5 keV at 700 keV. It is seen that the doublet is unresolved with the 2.4 keV target, whereas it is almost completely resolved with the 0.5 keV target. The resonance energies are very well known from previous work ⁹⁾¹⁰⁾, and were taken as 504, 506, 611, 631, 654, 678, 731, 735, 742, 760, 767, and 773 keV.

From Fig. 1 the yields of all resonances can be obtained relative to that at 773 keV. The yield at the 773 keV resonance has been measured in absolute measure by Smith and Endt ¹³⁾. Usually yield measurements are performed with a thick target; the steps in the yield curve are then used as a measure of the resonance strengths $\omega\gamma/\{E_r(dE/dx)_{E=E_r}\}$ with $\omega\gamma = (2J_r + 1)\Gamma_p\Gamma_\gamma/\Gamma_t$ (see, e.g., reference 12). It can easily be shown, however, that the relative yields can be obtained much more accurately from the energy integrals over the different resonances. One can then conveniently make use of a target of intermediate thickness, large compared to the resonance total widths but small compared to the resonance spacing (as in Fig. 1). These energy integrals are proportional to $\omega\gamma t/E_r$, (where t is the target thickness in cm) to an excellent degree of approximation under these conditions (see reference 17). Of course, the measured yields have first to be divided by the respective counter efficiencies (differing from resonance to resonance) which were obtained by multiplying the relative intensities (given below) of all lines with $E_\gamma > 3$ MeV with the corresponding 3 MeV partial efficiencies. The $\omega\gamma$ values obtained in this way are given in Table I. The reference value taken for the 773 keV resonance was 4.7 ± 1.5 eV ¹³⁾. The errors given in Table I originate from the error in the reference value. Another error would be present if strong $P_4(\cos\theta)$ terms were to occur in the angular distributions, but this is regarded as improbable.

TABLE I

Resonance strengths of $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ resonances.			
Resonance energy (keV)	$\omega\gamma$ (eV)	Resonance energy (keV)	$\omega\gamma$ (eV)
504	0.44 ± 0.14	731	1.8 ± 0.5
506	0.44 ± 0.14	735	2.0 ± 0.6
611	0.051 ± 0.016	742	0.17 ± 0.05
631	2.5 ± 0.7	760	1.6 ± 0.5
654	1.5 ± 0.4	767	1.9 ± 0.6
678	0.47 ± 0.15	773	4.7 ± 1.5 ¹⁾

¹⁾ From ref. 13.

B. The 504 keV resonance. The gamma rays observed at this resonance from the single 4" spectrum shown in Fig. 2 are presented in Table II with their relative intensities. The experimental difficulties connected with the nearness of the 506 keV resonance prevented long coincidence measurements.

TABLE II

Gamma rays observed from the single 4" spectrum at the $E_p = 504$ keV resonance.			
E_γ (MeV) ¹⁾	relative intensity	E_γ (MeV) ¹⁾	relative intensity
12.07	100 ²⁾	5.15 ± 0.05	13
10.29	21	4.50 ± 0.06	9.4
(7.9) ³⁾	—	4.11 ± 0.06	5.9
7.46 ± 0.08	4.1	3.48 ± 0.08	3.4
6.89 ± 0.08	5.3	2.82 ± 0.03	3.8
5.80 ± 0.08	6.8	1.78	41

¹⁾ For lines which were used for energy calibrations or for which only indirect evidence exists (see e.g. section 3C) the values computed from known excitation energies were listed. No errors are indicated in these cases. For all other lines a weighted average has been taken of the energies measured in single and/or coincidence spectra.

²⁾ In this and following tables the intensity of the strongest primary has been put equal to 100.

³⁾ The presence of a 7.9 MeV gamma ray is uncertain because of the nearness of the 8.06 MeV ^{13}C contaminant gamma ray.

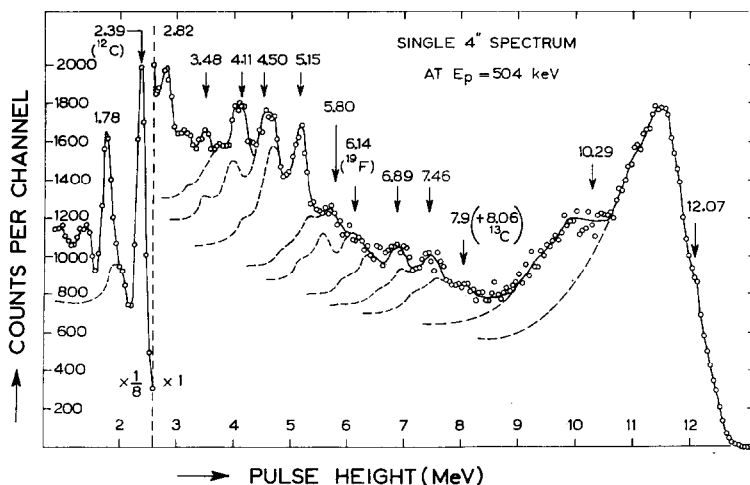


Fig. 2. Single 4" spectrum at the $E_p = 504$ keV resonance ($\theta = 55^\circ$).

The two coincidence spectra taken at this resonance, with 2.4–8.5 MeV and 5.7–8.5 MeV channels, have only confirmed the presence of some of the lower energy gamma rays.

The decay scheme at the 504 keV resonance is shown in Fig. 3. The resonance is characterized by a strong ground-state transition. The intensities are normalized such that the sum of all primaries is 100. The sums of the intensities of gamma rays feeding and deexciting a given level have been made equal by suitable averaging, if necessary. The energies of the levels indicated are those given by Hinds and Middleton ⁸⁾.

There is little doubt as to the position of the observed gamma rays in the ^{28}Si level scheme. At the 767 keV resonance it was found that the

8.59 MeV level decays exclusively to the first excited state. It is then necessary to assume that the observed 6.89 MeV gamma ray consists of two gamma rays with energies of 6.81 MeV ($E_x = 8.59 \rightarrow 1.78$ MeV) and of 6.88 MeV (6.88 MeV to ground). The same holds for the observed 5.15 MeV gamma ray which has to be split up in a 5.19 MeV gamma ray feeding the 6.88 MeV level, and a 5.10 MeV gamma ray ($E_x = 6.88 \rightarrow 1.78$ MeV). In this case it is uncertain, of course, whether the 6.880 MeV or the 6.889 MeV level is excited.

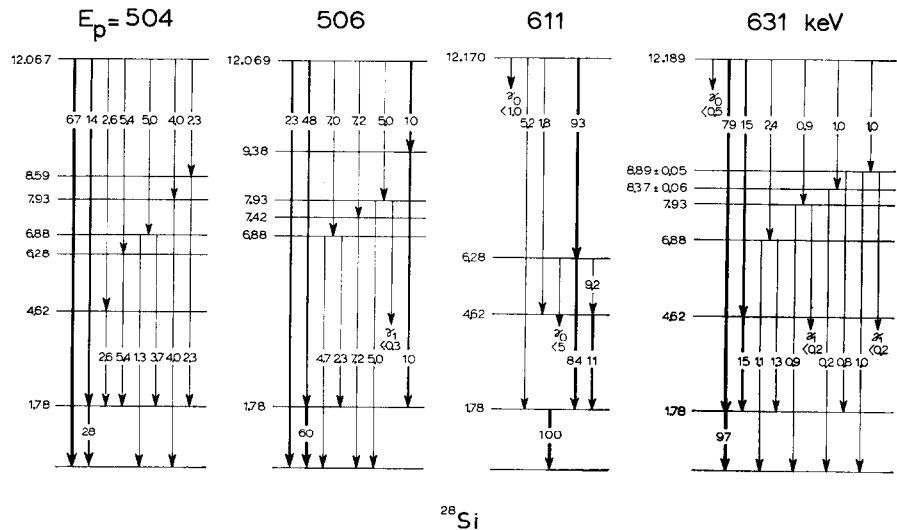


Fig. 3. Decay schemes of the four $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ resonances in the 500–640 keV region.

C. The 506 keV resonance. A single 4" spectrum is given in Fig. 4. Three coincidence spectra have been taken with 2.3–8.9 MeV, 5.5–8.5 MeV and 6.5–8.5 MeV channels, respectively. One of these is given in Fig. 5 which, in particular, clearly shows the 2.70 MeV gamma ray which is not very distinctive in Fig. 4. In Table III the observed gamma rays are listed. In the column "Method of observation" SS stands for "single spectrum",

TABLE III

Gamma rays observed at the $E_p = 506$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
12.07	48	SS	(6.15)	<0.6	CSI
10.29	100	SS	5.17 ± 0.04	19	SS
7.93	10	CSI	4.65 ± 0.03	15	SS
7.59 ± 0.08	21	SS	4.14 ± 0.03	10	SS
7.42 ± 0.08	15	SS	2.70 ± 0.02	21	SS
6.89 ± 0.06	9.8	SS	1.78	125	SS

¹⁾ For the meaning of the symbols used see section 3C.

CS for "coincidence spectrum" and CSI for "coincidence spectrum indirect". The latter applies to gamma rays which have not been observed in the SS or CS directly, but which have to be present to explain the presence and/or intensity of other gamma rays in the CS. Low energy lines listed as SS usually also appear in one or more CS spectra. The energy given in Table III

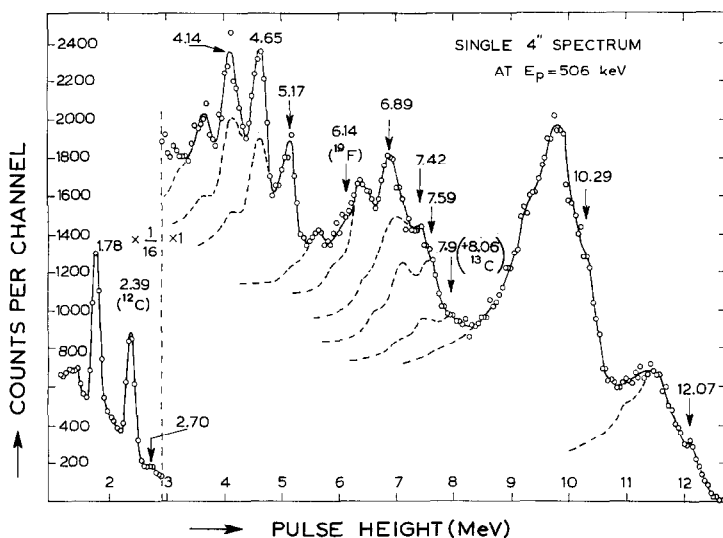


Fig. 4. Single 4" spectrum at the $E_p = 506$ keV resonance ($\theta = 55^\circ$).

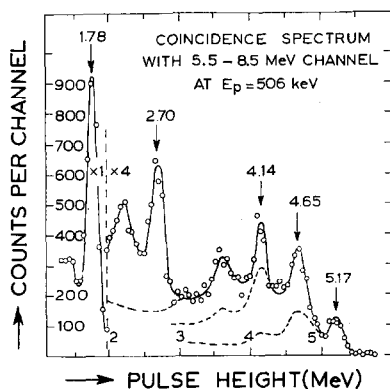


Fig. 5. Coincidence spectrum with 5.5-8.5 MeV channel at the 506 keV resonance. Counters at $\theta = +85^\circ$ and -85° .

is then a suitable average. Relative intensities of the stronger lines were determined from the SS. Intensities of the weaker lines and, of course, of the CSI lines were found more accurately from the CS, taking into account the partial detection efficiencies of coincident gamma rays in the blue channel.

The decay scheme of the resonance levels is shown in Fig. 3. Again the position of the observed gamma rays in the decay scheme can be regarded as unambiguous (except for the question as to whether the 6.880 MeV or the 6.889 MeV level is excited). The branching of the 7.42 and 9.38 MeV levels was not measured at this resonance because this was done already with appreciably higher accuracy at the 678 and 731 keV resonances, respectively.

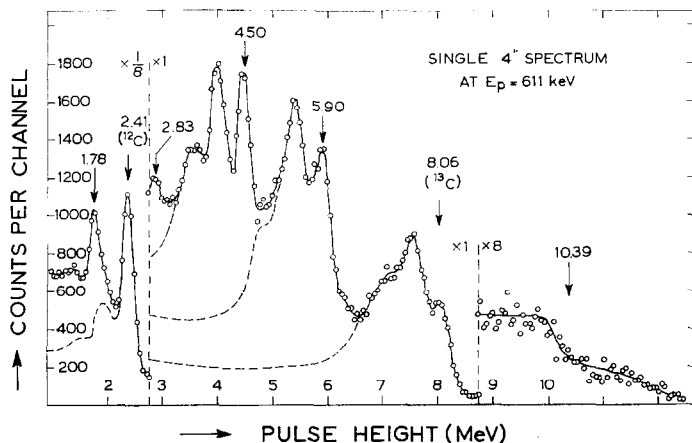


Fig. 6. Single 4'' spectrum at the $E_p = 611$ keV resonance ($\theta = 55^\circ$). The pulse distribution above 8.6 MeV is partly due to a 10.39 MeV gamma ray and partly to background and to sum pulses of the 4.50 + 5.90 MeV gamma rays.

D. The 611 keV resonance. A single 4'' spectrum is shown in Fig. 6. Coincidence spectra were taken with 4.9–6.5 MeV, 4.9–11 MeV, and 6.5–11 MeV channels. The first of these is shown in Fig. 7. The observed gamma rays are listed in Table IV.

TABLE IV

Gamma rays observed at the $E_p = 611$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.17)	< 1.1	SS	4.50 ± 0.02	85	SS
10.39	5.6	SS	2.83 ± 0.04	12	SS
7.55	1.9	CSI	1.78	101	SS
(6.27)	< 5.4	CS	1.66 ± 0.03	8.6	CS
5.90 ± 0.03	100	SS			

¹⁾ For the meaning of the symbols used see section 3C.

This weak resonance forms the exception on the rule that all resonances show a strong transition to at least one of the three lowest ^{28}Si states. The main part of the decay proceeds with a triple cascade through the 6.27 and 1.78 MeV levels (see Fig. 3). The intensity of the 2.83 MeV gamma ray,

which at many other resonances occurs between the second and first excited states, seemed at first something of a riddle because the 7.59 MeV gamma ray, feeding the 4.62 MeV level, was found in coincidence measurements to be far too weak. The difficulty was solved by the observation that the valley beneath the 1.78 MeV photo-peak is not quite deep enough. After subtraction of the correct 1.78 MeV pulse distribution, measured through a coincidence measurement at the 760 keV resonance, a 1.66 ± 0.02 MeV gamma ray remained (see Fig. 7), which, if placed between the fourth and second excited states, just accounts for the missing intensity.

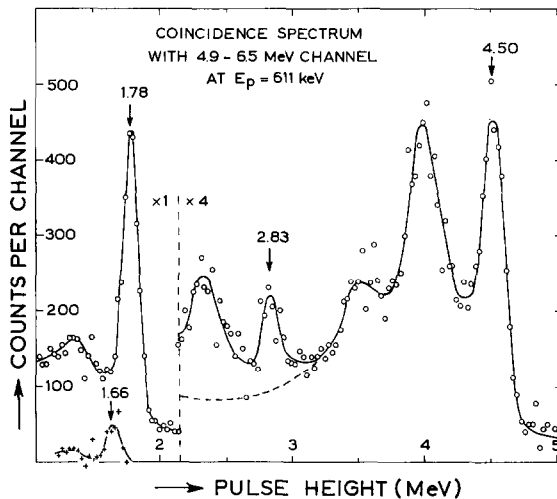


Fig. 7. Coincidence spectrum with 4.9–6.5 MeV channel at the 611 keV resonance. The bump at 2.3 MeV is partly due to $1.78 + 0.51$ MeV sum pulses. The valley below the 1.78 MeV photo-peak is partly filled by the photo-peak of a 1.66 MeV gamma ray (shown by crosses after subtraction of the correct 1.78 MeV pulse distribution).

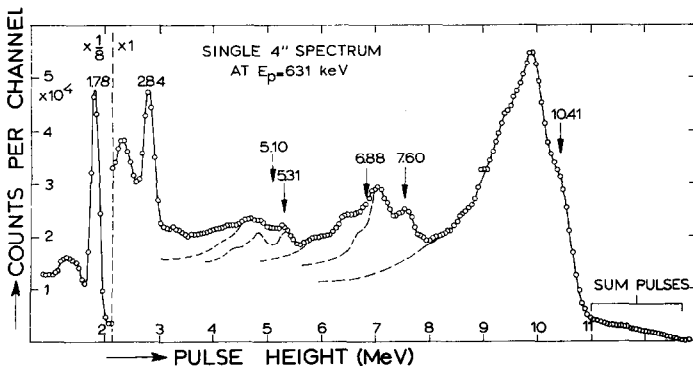


Fig. 8. Single 4'' spectrum at the $E_p = 631$ keV resonance ($\theta = 55^\circ$). Only a few of the stronger gamma rays are drawn in.

E. The 631 keV resonance. The single 4" spectrum is shown in Fig. 8 in which only the cascades through the 1.78, 4.62, and 6.88 MeV levels have been drawn in. Four coincidence spectra were taken with 4.6–11, 5.5–10, 6.6–8.5, and 7.3–8.5 MeV channels, respectively. In these, three low energy lines ($E_\gamma = 4.26 \pm 0.05$, 3.82 ± 0.06 , 3.30 ± 0.05 MeV) were found which all have to be regarded as primaries. The complete list of observed gamma rays is given in Table V. The decay scheme is shown in Fig. 3. Of course,

TABLE V

Gamma rays observed at the $E_p = 631$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.19)	< 0.6	SS	(6.15)	< 0.25	CSI
10.41	100	SS	5.31 ± 0.05	3.0	SS
8.89	1.3	CSI	5.10 ± 0.06	1.6	SS
8.37	0.25	CSI	4.26 ± 0.05	1.1	CS
7.93	1.0	CSI	3.82 ± 0.06	1.4	CS
7.60 ± 0.05	19	SS	3.30 ± 0.05	1.3	CS
(7.10)	< 0.25	CSI	2.84 ± 0.02	19	SS
6.9 ± 0.1	1.4	SS	1.78	122	SS
6.59	1.0	CSI			

¹⁾ For the meaning of the symbols used see section 3C.

it can not be decided whether the 6.880 or 6.889 MeV level is excited. Nor is the energy measurement of the weak 3.82 ± 0.06 MeV gamma ray good enough to decide between the 8.328 and 8.411 MeV levels. The same holds for the 3.30 ± 0.05 MeV gamma ray leading to a 8.89 ± 0.05 MeV level which might be either the 8.902 or the 8.941 MeV level.

F. The 654 keV resonance. The single 4" spectrum is shown in Fig. 9. Coincidence spectra were taken with 3.5–11, 7.6–11, and 8.2–11 MeV channels. The observed gamma rays are given in Table VI.

TABLE VI

Gamma rays observed at the $E_p = 654$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
12.21	7.9	SS	5.92 ± 0.07	11	SS
10.43	100	SS	5.30 ± 0.09	3.6	SS
9.38	2.8	CSI	4.48 ± 0.05	16	SS
8.30	2.8	CSI	4.28 ± 0.03	17	SS
7.90 ± 0.07	10	SS	3.91 ± 3.07	2.8	SS
7.57 ± 0.05	58	SS	2.84 ± 0.02	57	SS
6.9 ± 0.1	4.1	SS	1.78	155	SS
6.20 ± 0.07	6.5	SS			

¹⁾ For the meaning of the symbols used see section 3C.

The main problem at this resonance is the determination of the order of the 2.84 and 7.60 MeV gamma rays. In Fig. 10 giving the decay scheme at

the 654 keV resonance the 2.84 MeV gamma ray has been presented as a primary, exciting the 9.38 MeV level. At several other resonances the 2.84 MeV gamma ray occurs between the second and first excited states. The

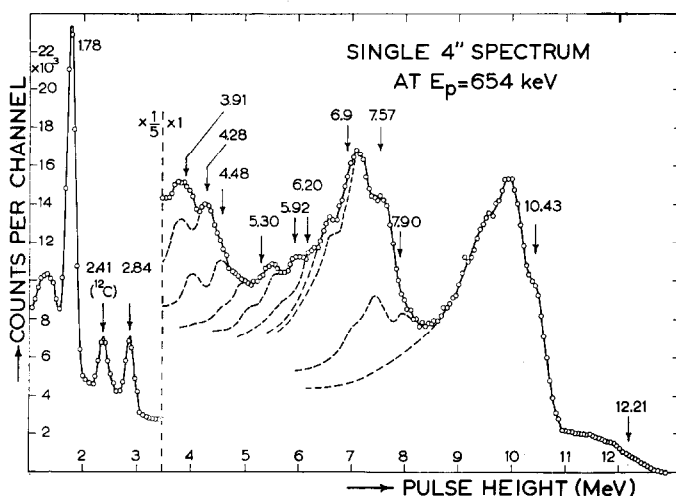


Fig. 9. Single 4'' spectrum at the $E_p = 654$ keV resonance ($\theta = 55^\circ$). The pulse distribution above 11 MeV is partly due to sum effects.

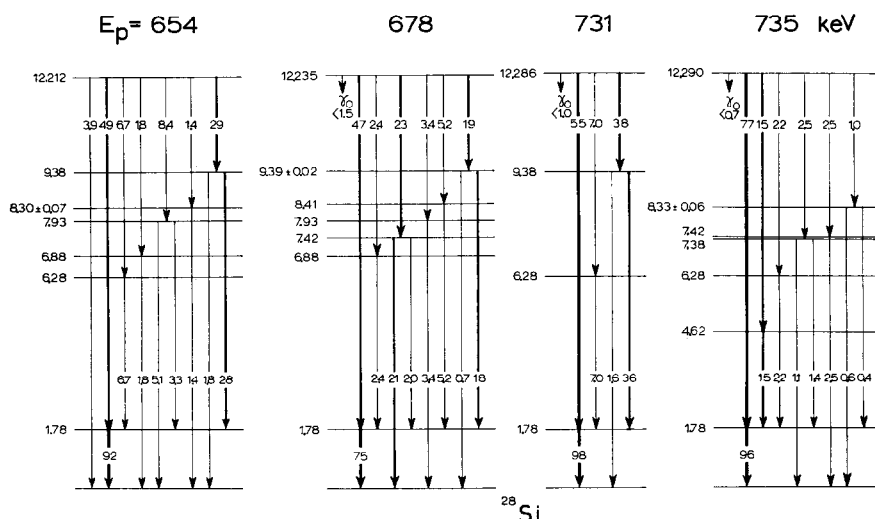


Fig. 10. Decay schemes of the four $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ resonances in the 640–740 keV region.

energy measured for the 2.84 MeV gamma ray is, within experimental errors, the same as at those other resonances (see section 3N). The argument that the 2.84 MeV gamma ray is to be regarded as a primary stems from the observation that the 2.84 MeV photo-peak as observed in the coincidence spectrum with the 8.2–11 MeV blue channel is 4.8 times more intense than

was estimated for $7.60 + 1.78$ MeV sum pulses in the blue channel. In this measurement the blue crystal was at a distance of 80 mm from the target to reduce sum effects. The conclusion is that the 2.84 MeV transition is in coincidence with a weak gamma ray of an energy appreciably above 8.2 MeV.

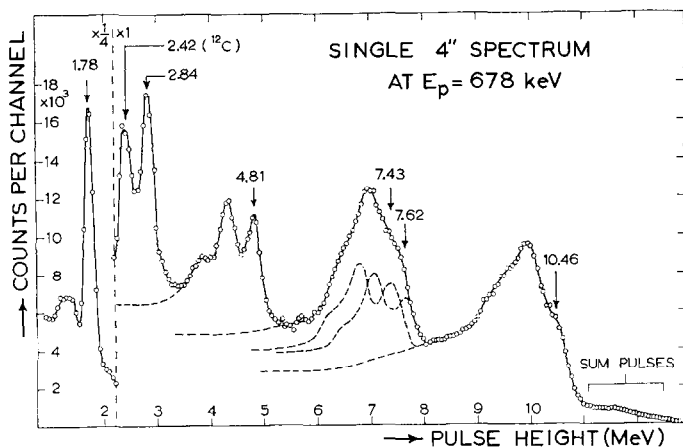


Fig. 11. Single 4'' spectrum at the 678 keV resonance ($\theta = 55^\circ$).

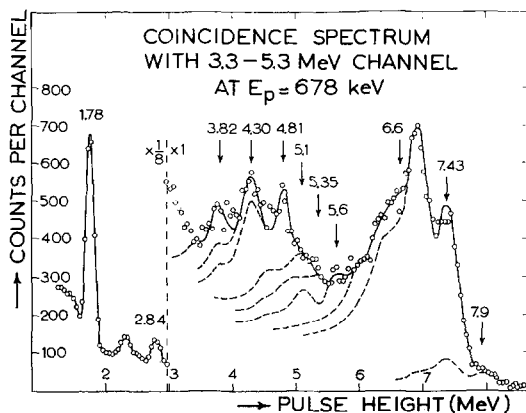


Fig. 12. Coincidence spectrum with 3.3–5.3 MeV channel at the $E_p = 678$ keV resonance, measured to determine the intensity of the 5.6 and 7.43 MeV gamma rays.

The 6.88 and 8.30 MeV levels were too weakly excited to measure their branching. It is also uncertain whether the 8.260 or the 8.328 MeV level is excited.

G. The 678 keV resonance. The single 4'' spectrum is shown in Fig. 11. Six coincidence spectra were taken with lower channel limits increasing in steps of about 1 MeV from 3.3 MeV to 8.2 MeV. One of these is given in Fig. 12. The gamma rays deduced from these measurements are listed in Table VII.

TABLE VII

Gamma rays observed at the $E_p = 678$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.23)	< 3	SS	5.35 ± 0.10	5.0	CS
10.46	100	SS	5.1 ± 0.1	5.0	CS
7.9 ± 0.1	7.2	CS	4.81 ± 0.02	48	SS
7.62 ± 0.06	40	SS	4.30 ± 0.08	7.2	CS
7.43 ± 0.05	44	SS	3.82 ± 0.05	11	CS
6.6 ± 0.1	11	CS	2.84 ± 0.02	40	SS
5.6 ± 0.1	4.2	CS	1.78	181	SS

¹⁾ For the meaning of the symbols used see section 3C.

In Fig. 10 giving the decay scheme the 2.84 MeV gamma ray has again to be regarded as a primary feeding either the 9.379 or the 9.41 MeV level. The arguments are exactly the same as those given in section 3F. In the coincidence measurement with 8.2–11 MeV blue channel (blue crystal at 80 mm distance from the target) the intensity of the 2.84 MeV line was 3.6 times that computed for $7.62 + 1.78$ MeV sum effects.

The coincidence spectrum shown in Fig. 12 served to determine the branching of the 7.42 MeV level. It is seen that the transition to the first excited state ($E_\gamma = 5.64$ MeV) is at most 10% of the 7.42 MeV ground-state transition.

The branching of the weakly excited 6.88, 7.93, and 8.41 MeV levels could not be measured accurately, but the transitions indicated in Fig. 10 certainly constitute the most prominent modes of decay.

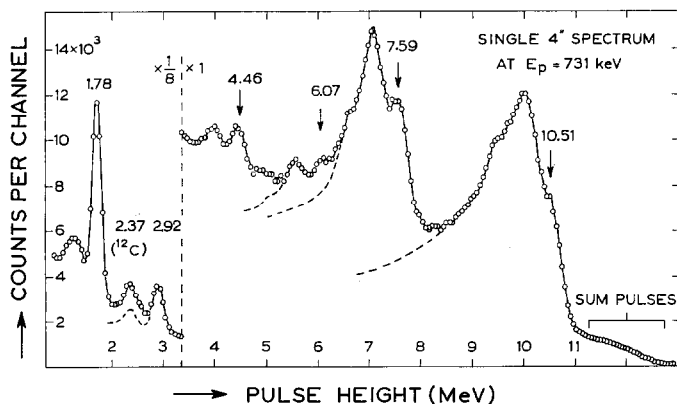


Fig. 13. Single 4'' spectrum at the $E_p = 731$ keV resonance ($\theta = 55^\circ$).

H. The 731 keV resonance. The 4'' single spectrum is shown in Fig. 13. The coincidence spectrum (with the blue crystal at 80 mm) taken to determine the branching of the 9.38 level (already mentioned in section 2)

is given in Fig. 14. Summing effects still are responsible for 40% of the 2.92 MeV intensity in Fig. 14. Other coincidence spectra were taken with 3.3–9.2 and 6.5–9.2 MeV channels. The observed gamma rays are listed in Table VIII and the corresponding decay scheme is shown in Fig. 10. There may be several more weak gamma rays in the 3–5 MeV region but their assignment is uncertain.

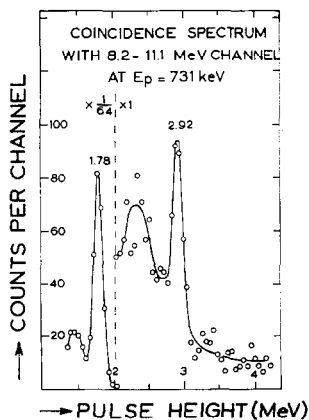


Fig. 14. Coincidence spectrum with 8.2–11.1 MeV channel at the 731 keV resonance. To reduce sum effects the blue crystal was placed at a distance of 80 mm from the target (instead of usual 40 mm).

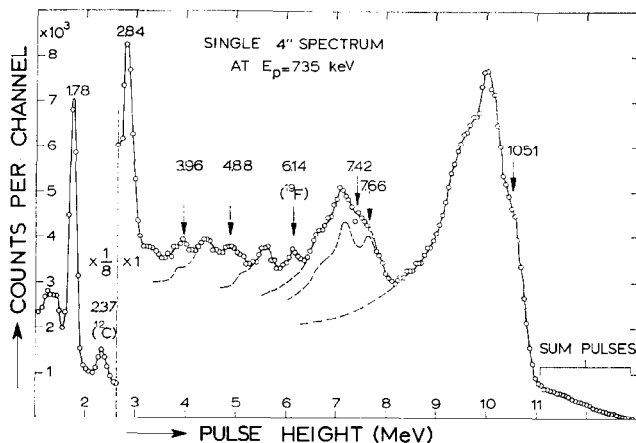


Fig. 15. Single 4'' spectrum at the $E_p = 735$ keV resonance ($\theta = 55^\circ$).

In principle the 4.46 MeV gamma ray could also have been interpreted as a primary, feeding the 7.80 MeV level. The coincidence measurement with 6.5–9.2 MeV channel, in which no 4.46 MeV gamma ray was observed, then requires that the 7.80 MeV level should decay almost exclusively to the first excited state.

I. The 735 keV resonance. The single 4'' spectrum is shown in Fig. 15.

TABLE VIII

Gamma rays observed at the $E_p = 731$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.29)	< 2.0	SS	6.07 ± 0.07	10	SS
10.51	100	SS	4.46 ± 0.03	16	SS
9.38	2.2	CSI	2.916 ± 0.015	74	SS
7.59 ± 0.05	64	SS	1.78	144	SS

TABLE IX

Gamma rays observed at the $E_p = 735$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.29)	< 0.9	SS	5.60 ± 0.07	1.8	CS
10.51	100	SS	4.88 ± 0.02	6.5	SS
8.3 ± 0.1	0.8	CS	4.47 ± 0.06	2.9	CS
7.66 ± 0.07	20	SS	3.96 ± 0.06	1.3	SS
7.42 ± 0.08	4.7	SS	2.84 ± 0.02	20	SS
6.5 ± 0.1	0.5	CS	1.78	125	SS
6.0 ± 0.1	2.9	CS			

¹⁾ For the meaning of the symbols used see section 3C.

Coincidence spectra were taken with 3.1–10 and 5.5–13 MeV channels. Observed gamma rays are listed in Table IX. The decay scheme is given in Fig. 10.

The 4.88 ± 0.02 MeV line feeds a level at 7.41 ± 0.02 MeV. Both the energy and the branching ratio of this state are intermediate between those of the 7.382 and 7.415 MeV levels. The branching of the latter two levels has been measured at the 773 and 678 keV resonances, respectively. It thus has been assumed that both levels are excited at the 735 keV resonance.

J. The 742 keV resonance. The single 4" spectrum is shown in Fig. 16. It is remarkable because of the presence of five high energy (7–11 MeV) lines of comparable intensities, while no lines are found in the middle energy (4–7 MeV) region. Coincidence spectra were taken with 5.7–13, 8.2–13, and 9.5–13 MeV channels. One of these is shown in Fig. 17 to demonstrate the presence of a 1.59 ± 0.02 MeV line remaining after subtraction of the correct 1.78 MeV pulse distribution.

The observed gamma rays are listed in Table X and the decay scheme is given in Fig. 18.

The 3.38 ± 0.02 MeV gamma ray feeds a 8.92 ± 0.02 MeV level, exactly in between the 8.902 and 8.941 MeV levels observed by Hinds and Middleton ⁸⁾. Precision measurements of the gamma-ray energy did not deviate by more than 0.01 MeV from the average value 3.38 MeV. Of course, it is possible that both levels are excited in about equal proportion. The 8.93 MeV gamma ray has to be regarded as a composite, deexciting both the 8.92 MeV doublet to ground, and the 10.71 MeV level to the first excited state.

K. The 760 keV resonance. The 4" single spectrum is given in Fig. 19. It is characterized by an extremely strong transition to the first excited state. Coincidence spectra have been taken with 2.1–7.8 and 8.2–10.0 MeV channels. Observed gamma rays are listed in Table XI and the decay scheme is given in Fig. 18.

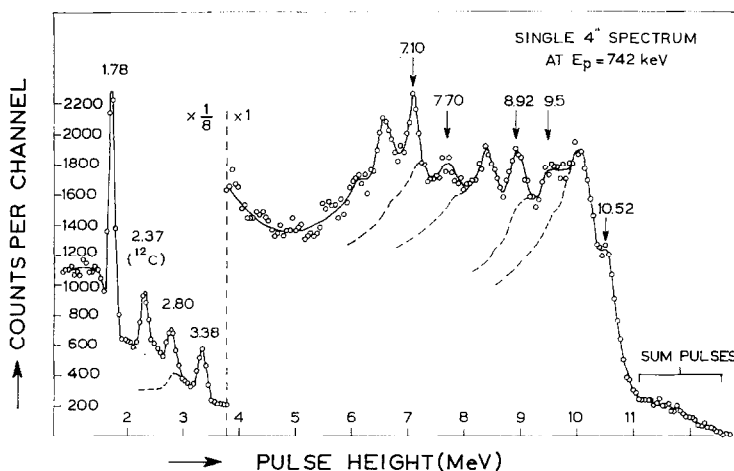


Fig. 16. Single 4" spectrum at the $E_p = 742$ keV resonance ($\theta = 85^\circ$).

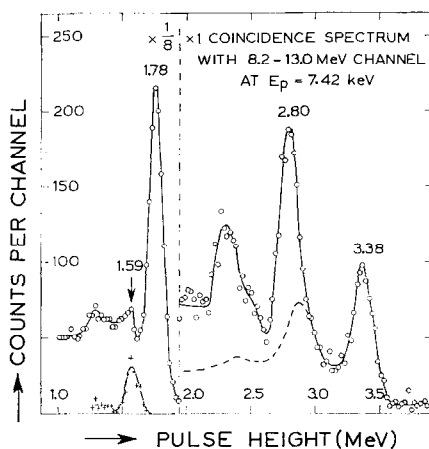


Fig. 17. Coincidence spectrum with 8.2–13.0 MeV channel at the $E_p = 742$ keV resonance. After subtraction of the correct 1.78 MeV pulse distribution a 1.59 MeV gamma ray remains (indicated by crosses).

The 2.83 MeV line is hardly visible in single spectra, but it stands out clearly in the coincidence measurement with 8.2–10.0 MeV channel proving that it is a primary feeding the 9.491 MeV level.

In the same coincidence spectrum the 2.99 MeV line was quite weak.

TABLE X

Gamma rays observed at the $E_p = 742$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
10.71	3.5	CSI	7.10 ± 0.05	28	SS
10.52	100	SS	3.38 ± 0.02	60	SS
9.5 ± 0.1	31	SS	2.80 ± 0.02	46	SS
8.92 ± 0.07	42	SS	1.78	130	SS
7.70 ± 0.09	17	SS	1.59 ± 0.02	14	CS

1) For the meaning of the symbols used see section 3C.

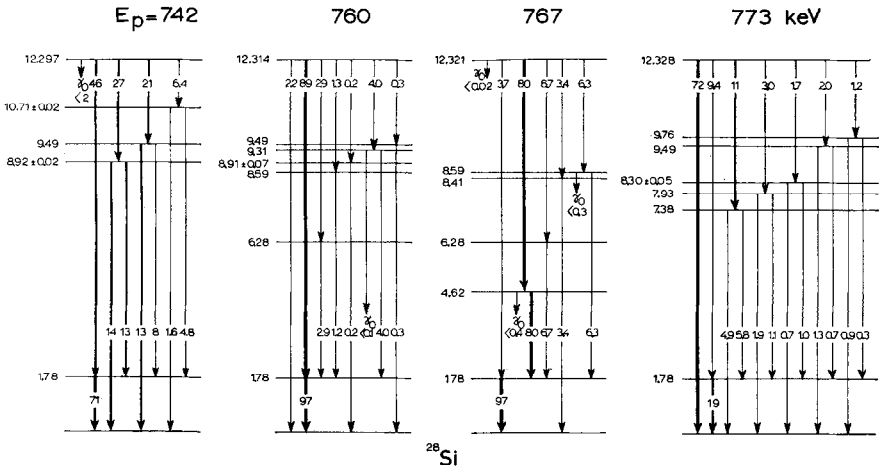


Fig. 18. Decay schemes of the four $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ resonances in the 740–800 keV region.

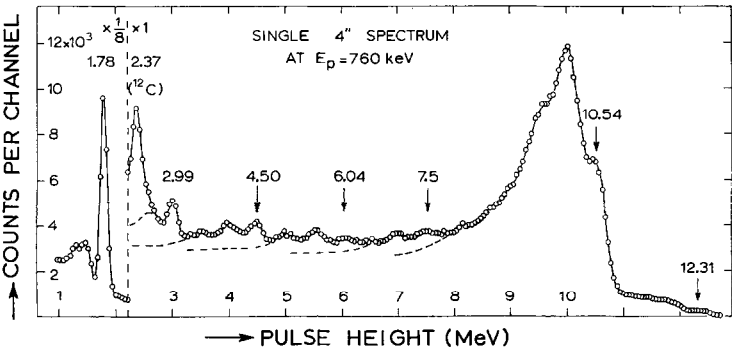


Fig. 19. Single 4'' spectrum at the $E_p = 760$ keV resonance ($\theta = 55^\circ$).

Its intensity could completely be explained by $7.53 + 1.78$ MeV sum effects. The upper limit for the intensity of the 9.31 MeV line given in Table XI is based on the assumption that it contributes at most half of the observed 2.99 MeV intensity.

TABLE XI

Gamma rays observed at the $E_p = 760$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
12.31	2.5	SS	6.04 ± 0.07	4.1	SS
10.53	100	SS	4.50 ± 0.02	2.6	SS
9.49	0.3	CSI	3.72 ± 0.05	1.5	CS
(9.31)	< 0.09	CSI	3.40 ± 0.07	0.2	CS
8.90	0.2	CSI	2.99 ± 0.02	5.3	SS
7.5 ± 0.1	3.8	SS	2.83 ± 0.05	1.0	CS
6.81	1.4	CSI	1.78	95	SS

¹⁾ For the meaning of the symbols used see section 3C.

L. The 767 keV resonance. Here the main transition from the resonance level occurs to the 4.62 MeV level, as shown in Fig. 20 giving the 4" single spectrum. Coincidence spectra were taken with 4.8–7.1, 6.7–8.5, 7.4–9.1, and 8.2–12.0 MeV channels. Observed gamma rays are listed in Table XII and the decay scheme is shown in Fig. 18. The fitting of the lines into the decay scheme presented no special problems. This resonance was especially useful to obtain low upper limits for possible ground-state transitions from the 4.62 and 8.59 MeV levels.

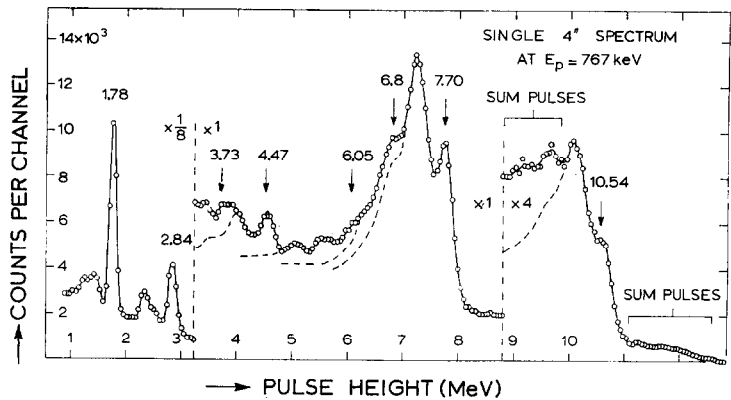


Fig. 20. Single 4" spectrum at the $E_p = 767$ keV resonance ($\theta = 55^\circ$).

TABLE XII

Gamma rays observed at the $E_p = 767$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
(12.32)	< 0.02	SS	(4.62)	< 0.5	CS
10.54	4.7	SS	4.47 ± 0.03	10	SS
(8.59)	< 0.4	CSI	3.93 ± 0.06	4.3	CS
8.41	4.3	CSI	3.73 ± 0.03	7.0	SS
7.70	100	SS	2.84 ± 0.02	105	SS
6.8 ± 0.1	9.0	SS	1.78	116	SS
6.05 ± 0.08	7.3	SS			

¹⁾ For the meaning of the symbols used see section 3C.

M. The 773 keV resonance. This resonance is quite strong and has a relatively strong ground-state transition (see Fig. 21). In coincidence spectra taken with 3.1–10.0, 4.9–8.0 (see Fig. 22), 5.4–10.0, 7.5–8.5, and 8.6–10.0 MeV channels several weak lines were observed not found in the single spectra. The observed gamma rays are given in Table XIII and the decay scheme in Fig. 18.

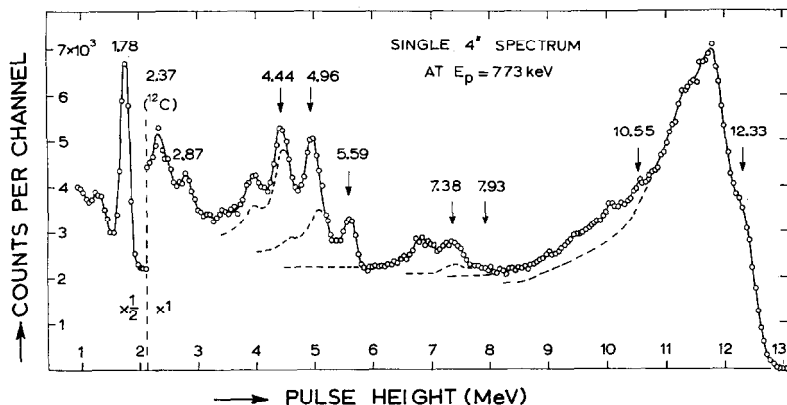


Fig. 21. Single 4'' spectrum at the $E_p = 773$ keV resonance ($\theta = 55^\circ$).

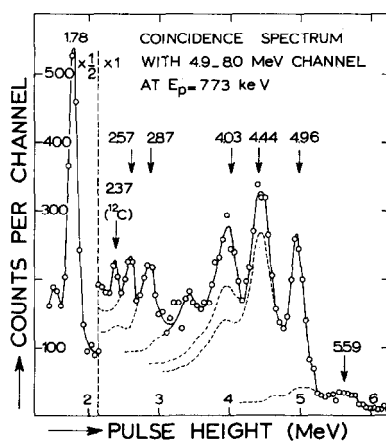


Fig. 22. Coincidence spectrum with a 4.9–8.0 MeV channel at the $E_p = 773$ keV resonance.

The 7.36 and 4.96 MeV lines cannot be explained as a cascade through the 4.975 MeV level 13). The presence of the 5.59 MeV line, in coincidence with the 4.96 MeV line, shows that the 4.96 MeV line is a primary feeding the 7.382 MeV level which is decayed through the 7.38 and 5.59 MeV lines to the ^{28}Si ground state and first excited state, respectively. The fact that the 4.44, 4.03, 2.87, and 2.57 MeV lines are primaries was also shown through coincidence measurements. The energy of the 4.03 MeV line could

TABLE XIII

Gamma rays observed at the $E_p = 773$ keV resonance.					
E_γ (MeV)	relative intensity	method of observation ¹⁾	E_γ (MeV)	relative intensity	method of observation ¹⁾
12.33	100	SS	6.52	1.4	CSI
10.55	13	SS	6.15	1.5	CSI
9.76	1.2	CSI	5.59 ± 0.04	8.0	SS
9.49	1.8	CSI	4.96 ± 0.02	15	SS
8.30	1.0	CSI	4.44 ± 0.04	4.2	SS
7.98	0.4	CSI	4.03 ± 0.05	2.4	CS
7.93 ± 0.08	2.6	SS	2.87 ± 0.02	2.8	SS
7.71	1.0	CSI	2.57 ± 0.02	1.7	CS
7.38 ± 0.05	6.8	SS	1.78	26	SS

¹⁾ For the meaning of the symbols used see section 3C.

not be measured with sufficient accuracy to determine whether the 8.260 or the 8.328 MeV level is excited.

N. Gamma rays in the $E_\gamma = 2.8\text{--}3.0$ MeV region. At many resonances gamma rays have been observed with energies in the 2.8–3.0 MeV

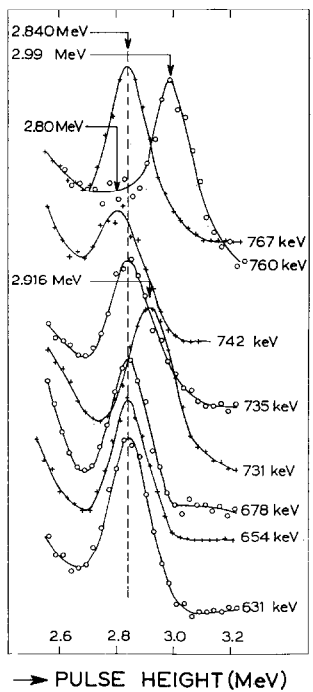


Fig. 23. The 2.6–3.2 MeV region measured with enlarged amplifier gain at eight different resonances. Shown are single $4''$ spectra ($\theta = 85^\circ$), except that at the 760 keV resonance which is a $4''\text{--}4''$ coincidence spectrum ($\theta = +85^\circ$ and -85°) with 2.7–8.4 MeV channel. Background and contributions from higher energy lines have not been subtracted except at the 742 keV resonance.

region. An accurate determination of the energy helps to determine whether the gamma ray occurs as a primary or as a transition between the second and first excited states. The results of these measurements are shown in Fig. 23. In one afternoon single 4" spectra were measured at the 631, 653, 678, 731, 735, 742, and 766 keV resonances, and a coincidence spectrum with 2.7–8.4 MeV channel at the 760 keV resonance. During this run a small gain shift (1.5%) occurred determined by also observing the position of the 1.78 MeV gamma ray, present in all spectra. In Fig. 23 all spectra have been reduced to the same gain.

It is seen in Fig. 23 that the measured energies at the 731, 742, and 760 keV resonances are distinctly different from those at the other resonances. If an energy of 1.773 ± 0.006 MeV (weighted average of the values given in references 2, 3, 7, and 8) is taken for the transition deexciting the first level one finds 2.916 ± 0.015 , 2.80 ± 0.02 , and 2.99 ± 0.02 MeV, respectively. These gamma rays are certainly primaries. The average of the energies observed at the 631, 735, and 767 keV resonances is 2.840 ± 0.014 MeV, which is in very good agreement with the weighted average 2.841 ± 0.009 MeV of the values given in references 3, 7, and 8 for the energy difference between the second and first levels. For the interpretation of the 2.84 MeV gamma ray observed at the 654 and 678 keV resonances, see sections 3F and 3G.

The best value obtained for the energy of the gamma ray deexciting the first excited state is 1.783 ± 0.008 MeV, in reasonable agreement with the average result (1.773 ± 0.006 MeV, see above) of other experimenters.

4. *Conclusions.* The weighted averages of the excitation energies and branching ratios of ^{28}Si lower levels observed at different resonances are presented in Fig. 24. All measured spectra could be explained by assuming that lower levels decay only to the ground state and/or first excited state. Only the 6.276 MeV level shows a detectable transition to the second excited state. The excitation energies measured by Hinds and Middleton⁸⁾ have been indicated at the right hand side of Fig. 24. Spins and parities have been indicated resulting from other investigations discussed below.

No branching ratios have been indicated for the 6.88 MeV doublet and for the 8.41 MeV level. These levels are only weakly excited, and measured branching ratios scatter appreciably. The 8.92 MeV doublet is strongly excited at the 742 keV resonance but the branching ratio indicated is probably an average of those for the 8.902 and 8.941 MeV levels.

Very little about spins and parities can be deduced only from the branching ratios. If, however, also the $^{27}\text{Al}(^3\text{He}, d)^{28}\text{Si}$ angular distribution measurements⁸⁾ are taken into account one can assign $J = 2^+$ to the 7.932 and 9.379 MeV levels. The corresponding deuteron groups show $l_p = 0$ angular distributions, limiting the J^π possibilities to 2^+ and 3^+ . Both levels are

9.314 and 9.379 MeV levels show both $l_p = 0$ angular distributions with exceptionally large reduced widths. It is tempting to identify these as the $T = 1$ states corresponding to the ^{28}Al ground-state doublet. Once this is assumed, the observation that the 9.379 level has $J = 2^+$ (see above) then decides that the order of the doublet components in ^{28}Si is the same as in ^{28}Al . This checks with the relative intensities⁸⁾ of the corresponding $^{27}\text{Al}(^3\text{He}, d)$ groups. That the 9.314 MeV level has $J = 3^+$ is strengthened by the fact that it does not decay to the ^{28}Si ground state (upper limit 2%). The 10.71 MeV level in ^{28}Si could well be the analogue of the 1^+ level at 1.37 MeV in ^{28}Al . The fact that the 10.71 MeV level partially decays to the ground state limits the J^π possibilities to 1^\pm and 2^+ .

Remarkable is the fact that at none of the twelve resonance transitions are observed to or from the 4.975 MeV third excited state. In ^{24}Mg and ^{32}S , 3^- states with a collective character¹⁴⁾ have been observed at about this energy. In ^{28}Si the 4.975 MeV level would be the most probable candidate for this 3^- assignment, because it has been shown⁸⁾ that the 4.62 and 6.27 MeV levels have even parity. The assumed collective character of the 4.975 MeV level would provide a natural explanation of the observed weakness of the transitions to this level.

Finally one can compare the present results with other $^{27}\text{Al}(p, \gamma)$ work. The 1954 measurements of Rutherglen, Grant, Flack, and Deuchars¹⁵⁾ are in rough agreement with our observations although the better knowledge of the ^{28}Si level scheme would change at present some of their conclusions. They investigated the 404, 504 + 506, 631, 654 and 678 keV resonances. Recently Okano¹⁶⁾ has measured single spectra, coincidence spectra, and angular distributions at the 226, 294, 326, and 404 keV resonances. They find that the 4.62 and 8.59 MeV levels only decay to the first excited state, and assign $J^\pi = 4^{(+)}$ and 3^+ , respectively, to these levels. The work by Hinds and Middleton⁸⁾ removes the doubt about the positive parity of the 4.62 MeV level.

The present knowledge of spins and parities of several ^{28}Si lower levels makes it tempting to speculate on spins and parities of the twelve resonance levels investigated in the present work. Such a discussion, however, can be more fruitful if the outcome of the planned angular correlation measurements is awaited.

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