Investigation of the ^{27}Al$(p, \gamma)^{28}$Si Reaction in the Proton Energy Range 925-2,760 KeV*

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The ^{27}Al$(p, \gamma)^{28}$Si reaction has been studied in the proton energy range 925-2,760 keV. Seventy-four resonances were observed. Gamma-ray spectra of two new strong resonances at 2,720 and 2,748 keV, corresponding to the 14.210 and 14.237 MeV levels in ^{28}Si, were measured by a 50-cc Ge(Li) detector. Decay schemes for these two resonance levels were proposed and branching ratios of the de-excitation of gamma-rays were determined. From arguments on transition probabilities it seems to favor a spin assignment for both resonance levels to be $J^\pi = 3^+$.

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1. INTRODUCTION

IN recent years, a considerable amount of spectroscopic information on a large number of nuclei has been obtained from the analysis of the (p, γ) reaction"' . In particular, the ^{27}Al$(p, \gamma)^{28}$Si reaction has been extensively investigated[2-6]. Previously the ^{27}Al$(p, \gamma)^{28}$Si experiments have been performed, mainly with proton energies from 1.0-2.0 MeV. For $E_p = 0.2$-1.4 MeV the results available in 1967 were summarized by Endt and Leun[7]. The excitation curves obtained show many narrow resonances corresponding to compound nuclear states of ^{28}Si in the region of -13 MeV excitation. Among these resonances, de-excitation gamma-ray spectra from several strongly excited resonances, which populate a large number

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of ^{28}Si levels, in this proton energy range have been investigated, and the information on decay properties, spins and parities of the ^{28}Si levels has been obtained.

Recently Meyer et $al^{(5)}$, who have studied the $^{27}\text{Al}(p,r)^{28}\text{Si}$ reaction in the energy region $E_p = 1.01\text{-}2.00$ MeV, have observed a new resonance at $E_p = 1,683.7$ keV. Lam et $al^{(6)}$ have reported an extensive investigation on a proton resonance at $E_p = 1,724$ keV. The resonances at proton energies above 2.0 MeV have been investigated by Gibson et $al^{(3)}$, who have reported six proton resonances at energies between 1,262 keV and 2,319 keV, and by Lyons et $al^{(4)}$ who have made total yield measurements in the proton energy range 327–2,584 keV in an energy step of $\Delta E_p = 2.5$ keV. The energies of strongly excited resonances observed in the $^{27}\text{Al}(p,r)^{28}\text{Si}$ reaction have been determined to a accuracy less than 1 keV.

The present work reported herein on the $^{27}\text{Al}(p,r)^{28}\text{Si}$ reaction was carried out in an exploratory nature. The present experiment consists of yield measurements for the $^{27}\text{Al}(p,r)^{28}\text{Si}$ reaction in the proton-energy range 925-2,760 keV and of gamma-ray spectra measurement at 2,720 keV and 2,748 keV resonances. Since we have extended this work to higher energies ($E_p > 2.50$ MeV), more resonances have been observed, and the corresponding level energies of ^{28}Si have been accurately determined.

2. EXPERIMENTAL

The protons were accelerated by the 3.0 MeV Van de Graaff accelerator at Tsing Hua University. The beam current **was** 5-10 μA in the proton-energy range investigated. The energy resolution of the accelerator was about 1 keV for 2.5 MeV protons. The beam energy was determined by usual nuclear magnetic resonance method. The magnetic field was controlled by a current regulator unit supplied by the Spectra-Magnetic Industries, and was calibrated with several well-known resonances between 992 keV and 2,560 keV in the $^{27}\text{Al}(p,r)^{28}\text{Si}$ reaction[5,7].

The experimental arrangement is shown in Fig. 1. After passing through quadrupole magnetics and collimators, the beam was focused to a fine spot on the target. Targets were prepared by vacuum evaporation of aluminium (99.99 %) foil onto gold backings (of -0.4 mm thick). The thickness of the prepared targets was between a few μg/cm^2 and 20 μg/cm^2. In the course of the experiment, targets were cooled by circulating water, directly against the backings. A small target chamber was specially designed and constructed″ ′ for this experiment. Four targets can be mounted on a slowly sliding target holder driven by a small motor and they can be interchanged inside target chamber **as** desired

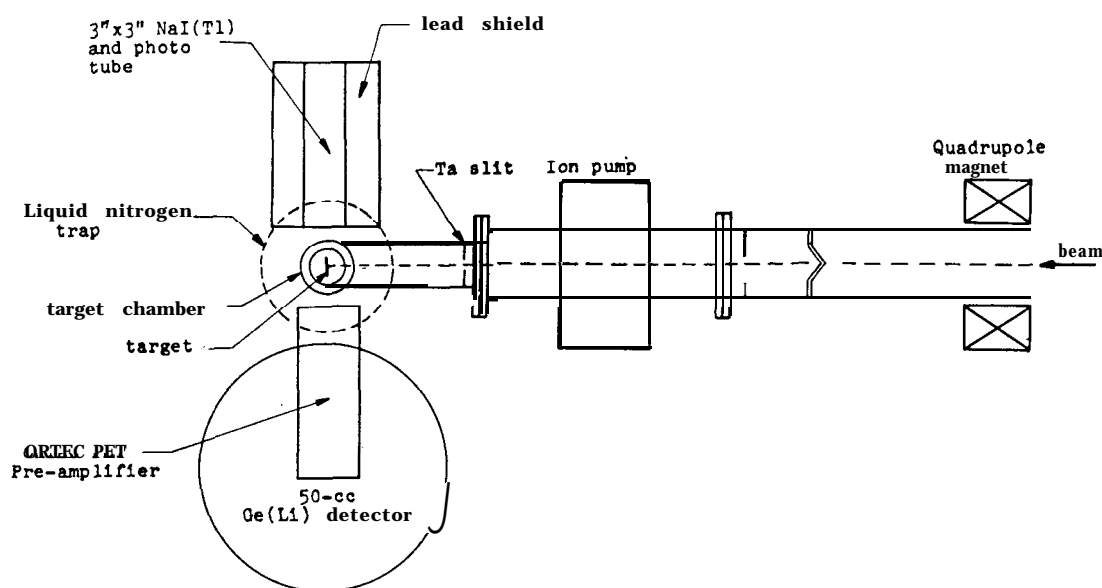(8) T. H. Hsu et **al**, to be published,

Fig. 1. Schematic view of experiment apparatus.

without breaking the vacuum. This arrangement and water cooling of the targets permitted continuously running for periods of 24 hr or longer in the gamma-ray spectra measurement without noticeable target deterioration. A liquid nitrogen cold trap was mounted near the targets to reduce contamination material buildup.

The gamma-ray were detected in a 3″ × 3″ NaI(Tl) crystal enclosed in a lead shield of the cylindrical shape, and also detected in a 50-cc Ge(Li) detector purchased from ORTEC, Oak Ridge. These two detectors were mounted oppositively at 90″ to the beam direction and were placed as close as possible to the target (at a distance 4cm from the target) in order to increase the total gamma-ray counting rate. In front of both detectors, lead absorbers of -2 mm thickness were placed in order to reduce the large amount of low-energy gamma-rays caused by bremsstrahlung and Coulomb excitation in the gold backing.

For yield measurement the NaI(Tl) crystal was used. After amplification the gamma-ray pulses were fed to three single channel analyzers which were set to accept pulses corresponding to photon energies $1,780 \pm 71$ keV, $6,880 \pm 275$ keV and above $7,500$ keV, respectively. The outputs from single channel analyzers were recorded in three scalers. The electronic arrangement is shown in Fig. 2.

About thousand points were obtained for the excitation curve, covering proton energy range 925-2,760 keV. Data were taken at an energy step of $\Delta E_p = 1$–2 keV. The integrated charges per point is 20 μC or 40 μC. Measurements were repeated at least twice for each data point in a separate day with maintaining same electronic conditions.
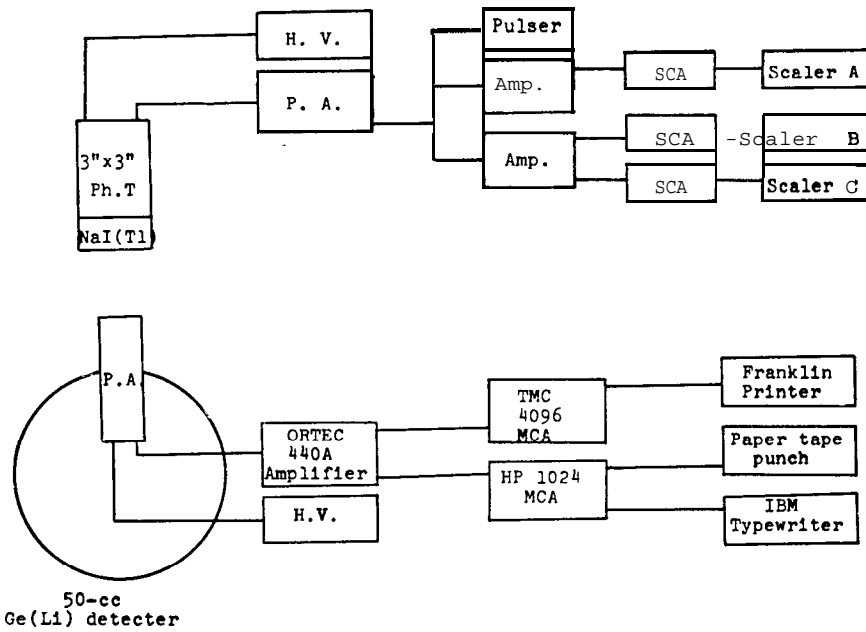
Fig. 2. Block diagram of electronic circuit used in gamma-ray spectra and yield measurements.

Measurements of de-excitation gamma-ray spectra were made at two proton resonances (E_p=2,720 keV and 2,748 keV) by using a 50-cc Ge(Li) detector. The energy resolution of the employed detector was 2.1 keV. The obtained gamma-ray spectra were stored simultaneously in a TMC 4,096-channel analyser and a Hewlett Packard 1,024-channel analyser. Since the measurement was carried out in a long run (24 hr) for a accumulation of charges up to 24,000 μC in order to get sufficient number of counts, we used two multi-channel analysers to record data for a consistent check. They were used also for the ADC linearity check and for convenience of data processing. The calibration of energies of the observed gamma-ray was based on standard-source gamma-rays, the 6,129 $\pm$ 0.4 keV gamma-ray from the ^{19}F$(p,a\gamma)^{16}$O reaction originating from ^{19}F impurities and on the 511 keV energy difference between full-energy, single-escape, and double-escape peaks.

3. RESULT

3.1 Resonance energy and excitation function

The excitation function of the ^{27}Al$(p,\gamma)^{28}$Si reaction measured in the proton-energy range 925–2,760 keV is shown in Fig. 3. Fig. 3(a) shows the yields of the gamma-rays in the 1,780$\pm$71 keV region, which corresponding to the transition between the first and ground states of ^{28}Si. The yields of 6,880 $\pm$275 keV gamma-rays and gamma-rays with energies higher than 7,500 keV are shown in Figs. 3(b)

Fig. 3. Yield curves from the $^{27}Al(p, \gamma)^{28}Si$ reaction (a) Yield (a) Yield of 1,780±71 keV gamma-rays, (b) Yield of 6,880±275 keV gamma-rays, (c) Yield of gamma-rays with energies higher than 7,500 keV. Numbers over peaks refer to resonant energy.
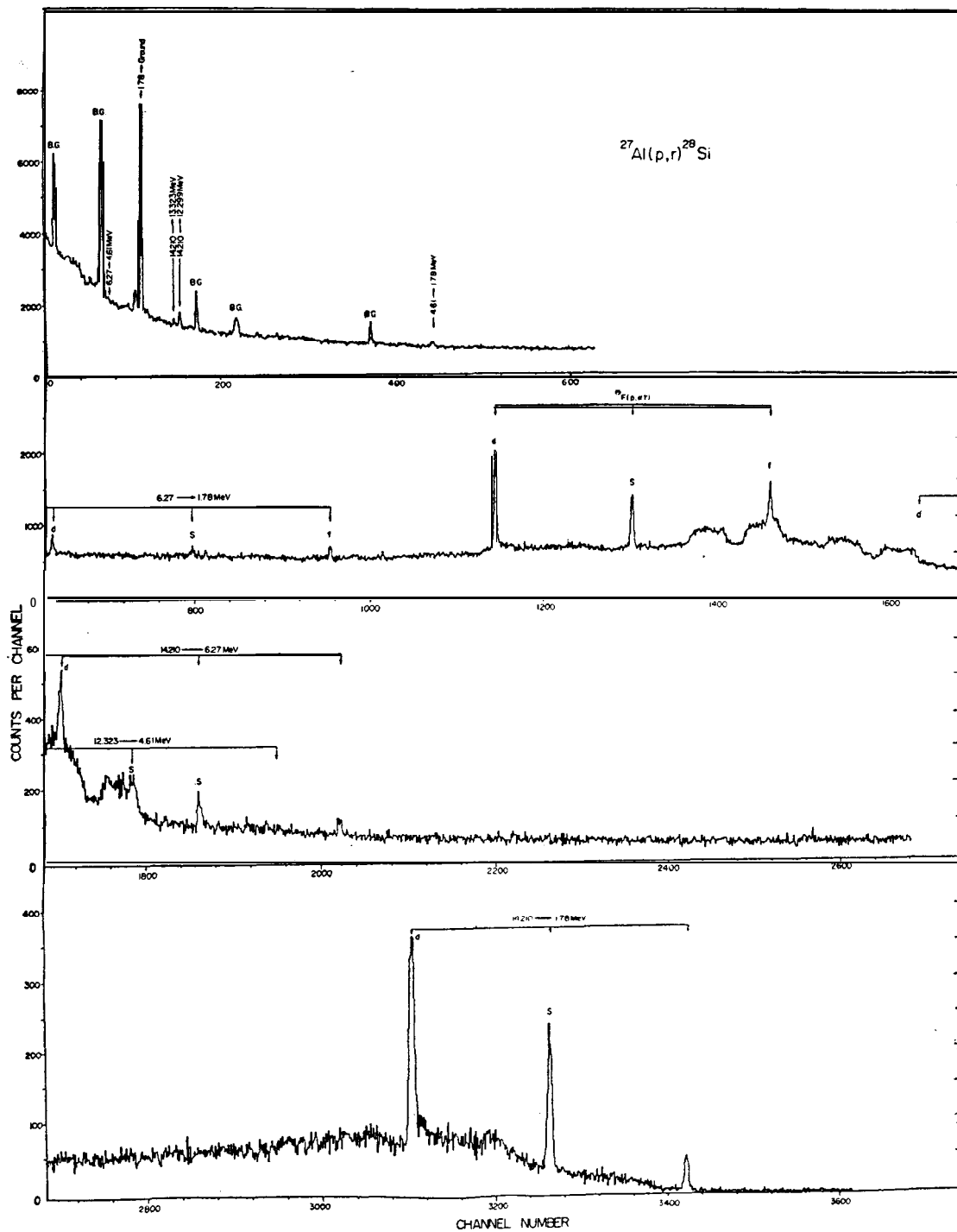
Fig. 4. A gamma-ray spectrum of the ^{27}Al$(p,\gamma)^{28}$Si reaction at $E_p = 2{,}720$ keV, B.C., background.

Table 1. Summary of $^{27}\mathrm{Al}(p,\gamma)^{28}\mathrm{Si}$ yield data

E_p (keV) Present Work	ref.[4]	ref.[5]	E_{exc} (MeV)	Half Width (keV)
935	937		12.489	2.9
992*	992		12.543	1.3
1,002	1,002		12.554	12
1,025*	1,025	1,025	12.576	1.3
1,089	1,090	1,090	12.638	4
1,096	1,098	1,098	12.645	6
1,118*	1,118	1,118	12.666	1.48
1,171	1,172	1,172	12.716	3.4
1,183	1,183	1,183	12.728	5.8
1,200	1,200	1,199	12.745	5.6
1,213*	1,213	1,213	12.757	2.9
1,262*	1,262	1,262	12.805	3.2
1.277	1,276	1,278	12.819	3.2
1,317*	1.317	1,317	12.858	1
1,329	1,328	1,328	12.669	3.6
	1,364	1,364	12.903	1.2
1,364	1,365	1,365		
1,381*	1,381	1,381	12.919	2.0
1,388'	1,388	1388	12.926	1.7
	1,435			
1,455	1,451	1,457	12.991	4.2
1,502	1,499	1,502	13.036	5.9
1,518	1.514	1,520	13.051	4 . 5
1,563	1,568	1,566	13.095	2.7
1,577	1,579	1,578	13.108	5.2
1,588*	1,589	1,588	13.119	3.6
1,647	1,647	1,647	13.176	4.1
1,663		1,662	13.191	4.0
	1,669	1,663		
	1,680	1,680		
1,682		1,684	13.209	4.0
1,706	1,709	1,706	13.232	4.3
1,724*	1,726	1,724	13.250	4.3
1,747	1,746	1,749	13.272	11
1,800*	1,797	1,800	13.323	3.4
1,843	1,838	1,842	13.365	3.6
1,902	1,909	1,899	13.421	2.5
1,911	1,917	1,910	13.430	4
1,922			13.441	3.2
1,970	1,976	1,969	13.487	4.2
	1,978			
2,035	2,041		13,550	5.9

2,067	2,054		13.561	2.4
	2,067			
2,100	2,084		13.612	2.9
2,106	2,106		13.618	3.0
	2,114			
2,127	2,120		13.638	3.4
	2,140			
2,154	2,144		13.664	2.5
2,159			13.669	2.5
2,162	2,168		13.672	4.9
2,172	2,171		13.682	3.7
2,183	2,190		13.692	3.7
2,205	2,212		13.713	4.2
2,222	2,221		13.730	3.5
2,238	2,249		13.746	3.2
2,289	2,296		13,794	3.8
2.306	2512		13.811	3.3
2,315	2,320		13.820	2.5
2,334	2,334		13.838	6.3
2,360	2,365		13.663	2.6
2,374	2,375		13.877	7.7
2,404	2,407		13.905	3.3
2,415			13.916	2.1
2,449	2,447		13.949	7.8
2,488	2,481		13.987	3.7
2,493	2,489		13.991	1.6
2,522	2,522		14.019	2.4
2,537	2,537		14.034	4.0
2.541			14.037	2.6
	2.560		14.050	3.2
2,554				
2,583	2,584		14.078	2.7
2,593			14.088	4.0
2,612			14.106	1.6
2,641			14.134	5.4
2,683			14.174	3.8
2,720			14.210	2.2
2.729			14.218	2.1
2,733			14.222	2.1
2,748			14.237	3.6

* Resonances were used for the energy calibration in the present work.

and 3(c), respectively. The yield curve of Fig. 3(a) shows many distinct and well-isolated resonances. There appears a total of seventy-four resonances belonging to the ^{27}Al$(p,r)^{28}$Si reaction. A summary of the determinations of resonance energies and widths from the present investigation is presented in Table I. As

can be seen in Table I, our data regarding to the resonance energies obtained in the proton-energy range 925-2,106 keV are overall in good agreement with earlier data reported by Lyons et al[4] and Meyer et al[5]. The resonance energies given in Table I are assumed to be corrected within ±1 keV relative to the 992 keV resonance, except some resonances which are very weak and their data are meager. At proton energies higher than 2.58 MeV, we observed several new resonances. In the proton-energy range 2,583-2,760 keV, there appears several strongly excited resonances. The relative intensity of resonances can be estimated from Fig. 3. The contribution due to gold background was found to be rather small. In the course of the experiment, background measurements were performed by bombarding gold foil several time over long periods. The results are shown by the dash line in Fig. 3(b).

3.2 De-excitation of gamma-rays at 2,720 KeV and 2,748 KeV resonances

It is seen from the yield curves as shown in Fig. 3 that several distinct resonances appear at proton energies above 2.70 MeV. We have measured gamma-ray spectra at two of these resonances, the 2,720 keV and 2,748 keV resonances, which corresponding to the excitation energies of ^{28}Si at 14.210 MeV and 14.237 MeV, respectively. There are no previous data on the decay of these two levels.

The result of one of the above two measurements is shown in Fig. 4, which presents a typical gamma-ray spectrum recorded at 2,720 keV resonance. The characteristic of the spectrum is that there exhibits a prominent gamma-ray at 12.432 MeV and most of others are weaker. The observed 12.432 MeV transition indicates that the decay of resonance feeds the first excited level of ^{28}Si at 1.78 MeV. Similar feature was observed in the measured gamma-ray spectrum at 2,748 keV resonance. This means that the 14.210 MeV and 14.237 MeV resonance

Table II. Relative strength of gamma-rays in the decay of the 14.210 MeV resonance

E_x (MeV)	14.210	12.323	12.299	6.27	4.62	1.78
12.323	10±4					
12.299	35±4					
6.27	61±6					
4.61		7±5		5±4		
1.78	315±31		(16)	4546	13±2	
g. s.						397±40

The errors include the statistical measurement and the uncertainty of the efficiency for Ge-detector. The number in parenthesis is taken from the previous data of Endt and Heyligers.[10]

Table III. Relative strength of gamma-rays in the decay of the 14.237 MeV resonance

E_x (MeV)	14.237	12.323	12.173	11.974	11.898	6.27	4.62	1.78
12.323	32±5	12.323						
12.173	10 12		12.173					
11.974	15±2			11.974				
11.898	10±2				11.898			
6.27	29±5		10±3			6.27		
4.61	13±2	26±4		11±2	7±3	5±3	4.62	
1.78	97±10					42±6	70±11	1.78
g. s.								210±21

The errors include the statistical measurement and the uncertainty of the efficiency for Ge-detector.

(a) E_p = 2720 keV   (b) E_p = 2746 keV

Decay scheme (a): 14.210 MeV → levels 12.323, 12.299 (2$^+$), branching 8, 3; 75, 14, (44), 70; 6.27 (3$^+$), 10; 4.62 (4$^+$); 90, 100; 1.78 (2$^+$); 100; g.s. (0$^+$). ^{28}Si

Decay scheme (b): 14.237 MeV → levels 12.323, 12.173 (5$^+$), 11.974 (4$^+$), 11.898 (4$^+$), branching 5, 7, 5, 16; 47, 6, 14, 70, 73, 100, 81; 6.27 (3$^+$), 1; 4.62 (4$^+$); 90, 100; 1.78 (2); 100; g.s. (0$^+$). ^{28}Si
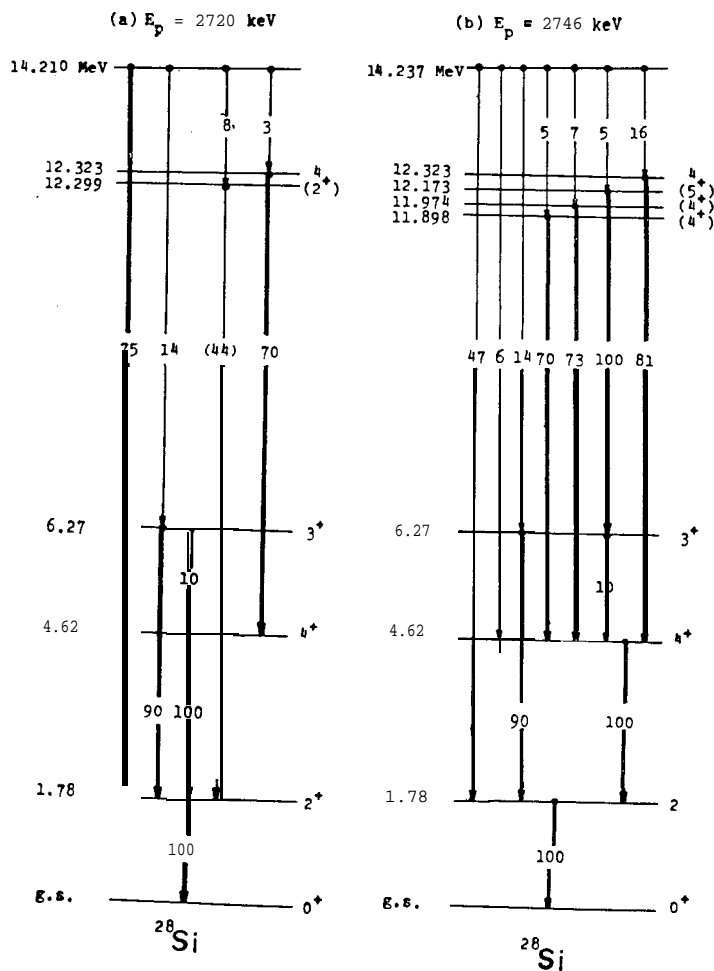
Fig. 5. Gamma-ray decay scheme for the levels populated in ^{28}Si at (a) the 2,720 keV resonance and (b) the 2,748 keV resonance. The number in parenthesis is taken from ref. 10.

levels decay mainly to the 1.75 MeV level.

Tables II and III show the relative strength of gamma-rays in the decay of resonant states at 14.210 MeV and 14.237 MeV, respectively. Considering the intensity of the $r{\rightarrow}1.78$ MeV transition as 100 per cent, gamma-ray decay schemes for above two levels populated in ^{28}Si are proposed and presented in Figs. 5(a) and 5(b).

4. DISCUSSION

Most of proton resonances found previously have been observed in the present experiment. The doublets 1,364–1,365 keV and 1,976–1,978 keV peaks were not resolved. Several weak resonances reported[4] by the CIT group were confirmed here, except the 1,435 keV, 2,067 keV, 2,084 keV and 2,144 keV resonances. New resonance at 1,684 keV found by Meyer et *al*[5] appears to be weakly excited in our measured spectra. We observed a weak resonance at 2,127 keV, while the **2,120** keV and 2,140 keV resonances as reported in ref. 4 were not observed. The weak resonances at 1,922 keV, 2,127 keV, 2,159 keV and 2,541 keV have not been previously reported. The 2,541 keV resonance was resolved from the 2,537 keV resonance.

The 1,381 keV and 1,388 keV resonances and the 2,488 keV and 2,493 keV resonances are well-resolved here. Fig. 6 show the yield curves of these resonances measured with thin target at a step of proton energy $\Delta E_p = 0.50$ keV. The corresponding half widths of them are 2.0 keV and 1.7 keV for the 1,381 keV and 1,388 keV resonances, and 3.7 keV and 1.6 keV for the 2,488 keV and 2,493 keV resonances. The resonances found in this measurement at proton energies higher than 2,583 keV are new, the observed gamma-rays for these resonances are quite intense. In this energy region a broad peak was observed, which might consist of several resonances; we identified three resonances at 2,583 keV, 2,593 keV, and 2,612 keV. It is interesting to see from yield curve in Fig. 3(a) the steep rise at E_p above 2.70 MeV, where there appears several strong resonances. Since these resonances were also observed in the yields of gamma-rays with energies higher than 6,880 keV, as shown in Figs. 3(b) and 3(c), it is believed that these resonances do belong to the ^{27}Al$(p,r)^{28}$Si reaction.

The gamma-ray transitions for the 2,720 keV and 2,748 keV resonances, as shown in Figs. 5(a) and 5(b), were obtained from the analysis of the measured gamma-ray spectra. The numbers in Figs. 5(a) and 5(b) are the percentage of the branching ratio. These were determined with uncertainty, which includes the experimental errors and the uncertainty of the effeciency of the Ge(Li) detector, of about 12 per cent for strong transitions and about 50 per cent for weak transitions. The effeciency of the 50-cc Ge(Li) detector was taken from ref. 9.
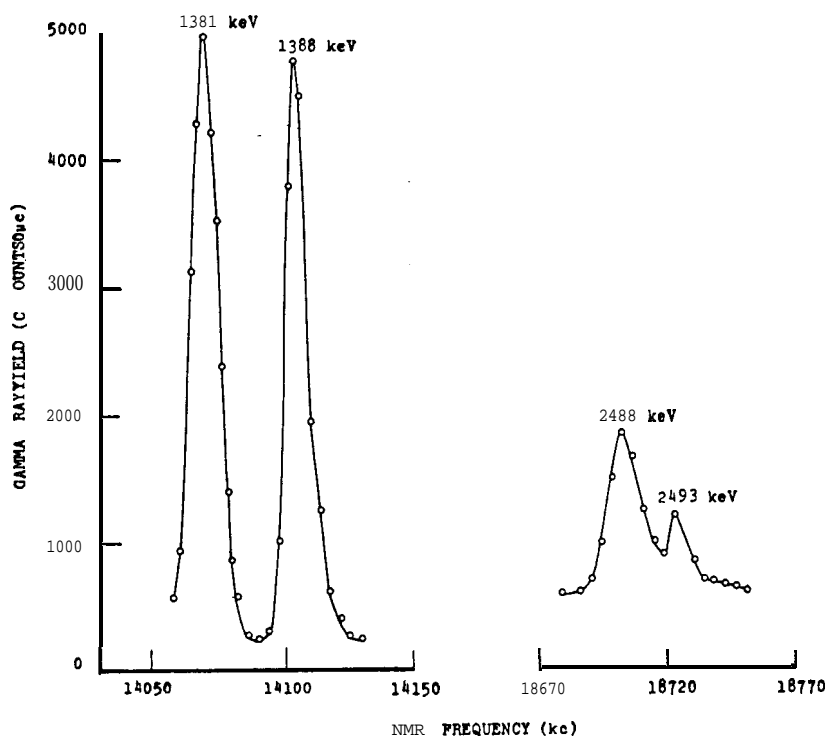
Fig. 6. Yield curves for the 1,381 keV and 1,388 keV resonances, and for the 2,488 keV and 2,493 keV resonances.

Some individual discussion of the decay data follows :

4.1 The 2,720 KeV resonance

The decay from the 14.210 MeV level feeds to four lower energy levels at 12.323 MeV, 12.299 MeV, 6.27 MeV and 1.78 MeV. The $r\rightarrow$1.78 MeV transition is predominant with a branching ratio of 75 per cent. The branching ratio for the $r\rightarrow$6.27 MeV transition is 14 per cent. The r-+12.323 MeV and r-+12.299 MeV transitions are quite weak, the branching ratio was estimated to be about 3 per cent and 8 per cent, respectively. No ground state transition from the resonance level was observed.

The weak gamma-ray at 7.71 MeV is due to the de-excitation of the 12.323 MeV level to the 4.62 MeV level, the branching ratio for this transition was obtained to be 70 per cent which is in agreement within the experimental error with the pervious data of Endt and Heyligers[10]. The subsequent decay from the 6.27 MeV level goes mainly to the 1.78 MeV level and partly to the 4.62 MeV level. The branching ratio was obtained to be 90 per cent for the 6.27 MeV→ 1.78 MeV transition and 10 per cent for the 6.27 MeV→4.62 MeV transition. These

(9)   F. C. Young, A. S. Figuera and G. Pfenfer (University of Maryland), unpublished (1970).

(10) P.M. Endt and A. Heyligers, Physica **26**, 230 (1960).

values agree very well with the earlier measurements by Endt and Heyligers[10], and Jacobs and Engelbertink[11]. Also, the sum of measured intensities for these two transitions is consistent with the strength of the $r \to 6.27$ MeV transition.

The 4.62 MeV level decays to the 1.78 MeV level with 100 per cent of the intensity of the transitions from the resonance level to the 4.62 MeV level and from the 6.27 MeV level to the 4.62 MeV level. For the transition from the 1.78 MeV level to the ground state, the observed intensity is consistent with the sum of strengths of those transitions feeding to the 1.78 MeV level, where the branching ratio for the 12.299 MeV $\to$ 1.78 MeV transition given in ref. 7 is taken into consideration.

4.2 The 2,748 KeV resonance

At the 2,748 keV resonance seven levels at 12.323 MeV, 12.173 MeV, 11.974 MeV, 11.398 MeV, 6.27 MeV, 4.62 MeV, and 1.78 MeV were fed from the 14.237 MeV resonance level. The branching ratios for the decay of these low lying levels are given in Fig. 5(b). No ground state transition directly from the resonance level was observed.

In the subsequent decay from the 12.323 MeV level 81 per cent of the total decay was found to feed the 4.62 MeV level. The obtained branching ratio for the 12.323 MeV $\to$ 4.62 MeV transition is in agreement with the value reported by Endt and Heyligers[10]. The 12.173 MeV level decays to the 6.27 MeV with 100 per cent of the intensity of the $r \to 12.173$ MeV transition. Although the observed gamma-rays at 5.90 MeV is rather weak, the 12.173 MeV $\to$ 6.27 MeV transition presented in ref. 7 is confirmed in the present work.

About same branching ratio ($\sim 70\%$) was found for the transitions from the 11.974 MeV and 11.898 MeV to the 4.62 Mev levels. The obtained values agree fairly well with the previous data of Okano[12]. The 6.27 MeV $\to$ 4.62 MeV transition is rather weak as compared to the 6.27 MeV $\to$ 1.78 MeV transition. The intensity of the transitions feeding to the 6.27 MeV level is seen to be somewhat smaller than that of transition outgoing from the 6.27 MeV level. It is apparent that some weak transitions from highly populated levels to the 6.27 MeV level are likely missed. We were not able to observe the corresponding gamma-ray lines in the measured spectra. For the 4.62 MeV $\to$ 1.78 MeV and 1.78-g. s. transitions the obtained strength of gamma-ray are consistent with the decay scheme.

It is seen that the decay scheme for two resonances at $E_b = 2,720$ and 2,748 keV are somewhat similar. As discussed above, the $r \to 1.78$ MeV transition was observed about three to five times stronger than the $r \to 12.323$ MeV and $r \to 6.27$ MeV transitions. The 1.78 MeV, 6.27 MeV and 12.323 MeV levels are known(') to

(11) Jacobs and Engelbertink (Utrecht), unpublished (1965).

(12) Kotoyuki Okano, J. Phys. Soc. Japan 15, 28 (1960).

be $J^{\pi} = 2^+$, $3'$ and 4, respectively. From arguments on transition probabilities and taking the fact that the ground state of ^{28}Si is $0'$ into consideration, it is favorable to suggust two resonance levels to be $J^{\pi} = 3^+$. This assignment gives a consistency in relative transition probabilities between present data and calculations of Weisskopf [13]. However, for the 14.237 MeV resonance, as the strengths of the $\gamma \to$ 12.323 MeV and $\gamma \to$ 6.27 MeV transitions are comparable, it may indicate that the 14.238 MeV level would be 3^+ with possible higher spin admixture. In order to give a definite spin assignment, it would require a more extensive study of the ^{27}Al(p, γ)^{28}Si reaction with angular correlation measurements.

ACKNOWLEDGMENTS

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