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High resolution gamma-ray spectroscopy of the $^{27}Al\,(p, \gamma)\,^{28}Si$ resonance reaction

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Abstract. High resolution gamma-ray spectra have been measured from the ^{27}Al (p, γ) ^{28}Si reaction for the resonances at $E_p = 2{\cdot}482$, $2{\cdot}511$ and $2{\cdot}735$ MeV at $\theta_{p\gamma} = 0°$, $30°$, $55°$ and $90°$ using a Ge (Li) gamma spectrometer. From the spectra and the angular distributions the properties of the resonance states have been obtained. These states are the isobaric analogues of the levels at 4·69, 4·75 and 4·93MeV levels respectively in the parent nucleus $A^{28}l$.

Keywords. (p, γ) reaction; resonances; angular distributions; partial gamma transition strengths.

1. Introduction

The properties of unbound levels of ^{28}Si have been studied by many authors through proton capture reactions on ^{27}Al (Antoufiev *et al* 1964, Nordhagan and Tvetor 1965, Gibson *et al* 1968, Huang and McDaniels 1971, Meyer and Wolmarans 1969, Meyer *et al* 1970) and an up-to-date information on the resonance levels upto an excitation of 13·483 MeV has been compiled by Endt and Van der Leun (1973). This corresponds to $E_p \approx 2$ MeV. Several other works have since been reported (Neal and Leon 1973, Dalmas *et al* 1974).

Analogue states have been identified by means of the ^{27}Al (p, γ) reaction in the energy range $E_p = 0{\cdot}85 - 3{\cdot}0$ MeV, as discussed in a previous communication (Ahmed *et al* 1972). The present work is concerned with the properties of some of these resonances given by the high resolution gamma-ray spectra taken on the resonances and the angular distribution measurements of the emitted gamma rays. For this purpose three strong and isolated resonances were selected, namely at $E_p = 2{\cdot}482$, $2{\cdot}511$ and $2{\cdot}735$ MeV.

2. Experimental Procedure

The experimental measurements have been performed by using the proton beam from the 5·5 MeV Van de Graaff accelerator of the Bhabha Atomic Research Centre, Bombay. The beam was collimated by using a number of tantalum collimators of various diameters inside the beam tube. The beam energy resolution was found to be less than 1 keV by measuring the width of the 992 keV resonance having a natural width of 100 eV. The targets were prepared by vacuum evaporation of natural aluminium on tantalum backings. The target was nominally 20 μgm/cm^2 thick and was kept at an angle of 45° to the beam direction. A coaxial Ge(Li) detector (Princeton Gamma Tech) of active volume 20 cc has been used for the measurements reported here. The signal output of the detector was amplified by a Fet preamplifier and an active Filter amplifier model PA manufactured by the Electronics Corporation of India Ltd. and was analyzed by a Nuclear Data 4096 channel pulse height analyzer. The gain of the main amplifier was adjusted so as to obtain an energy dispersion (keV/channel) so that the full scale of either 2048 or 4096 channels in the pulse height analyzer covered a possible ground state transition. The low energy γ-ray background increases with proton energy and it becomes difficult to keep the dead time down to acceptable limits by adjusting only the beam current. These low energy γ-rays were attenuated by placing thin lead sheets either on the face of the detector or on the outer surface of the target chamber. The energy calibration of the Ge(Li) detector was obtained by taking a γ-ray spectrum at the 992 keV resonance. The energy dispersion was obtained from the 511 keV energy difference between the appropriate pairs of full energy, single and the double escape peaks associated with the high energy γ-rays in the spectrum of the 992 keV resonance. The relative efficiency of the detector was also obtained using the branching ratios for gamma transitions at the 992 keV resonance.

The resonances in the ^{27}Al (p, γ) reaction as determined by Ahmed *et al* (1972) at $E_p = 2\cdot482$, $2\cdot511$ and $2\cdot735$ MeV are shown in figure 1. In the present experiment, these resonances were located by using a NaI(Tl) detector of size 12·7 cm × 15·2 cm at 90° with respect to the incident beam direction. The resonances were scanned automatically in an energy range of 100 keV using the technique described by Bhalerao *et al* (1974). In this technique (illustrated in figure 2) the reference voltage for the analyzing magnet of the accelerator is varied by adding a ramp and accordingly the accelerator energy varies with the magnet current due to the corona feed-back control of the accelerator. For the (p, γ) excitation function only one detector, NaI(Tl), was used and was recorded directly on the 4096 channel pulse height analyzer. The automatic scanning preceded the manual scanning of the excitation functions and saved machine time by a quick location of the resonances under study. Setting the accelerator energy at the desired resonances, the high energy gamma spectra were obtained at the angles 0°, 30°, 55° and 90° using the Ge(Li) detector. A gamma spectrum at $E_p = 2\cdot482$ MeV is shown in figure 3. For the angular distributions, the NaI(Tl) detector served as the monitor.

3. Data Analysis

From the measured spectra the branching ratios for various transitions from the resonance levels at 13·980, 14·007 and 14·223 MeV in ^{28}Si corresponding to the resonances at 2·482, 2·511 and 2·735 MeV respectively have been obtained after correcting for the detector efficiency. The gamma ray strengths $(2J+1)$

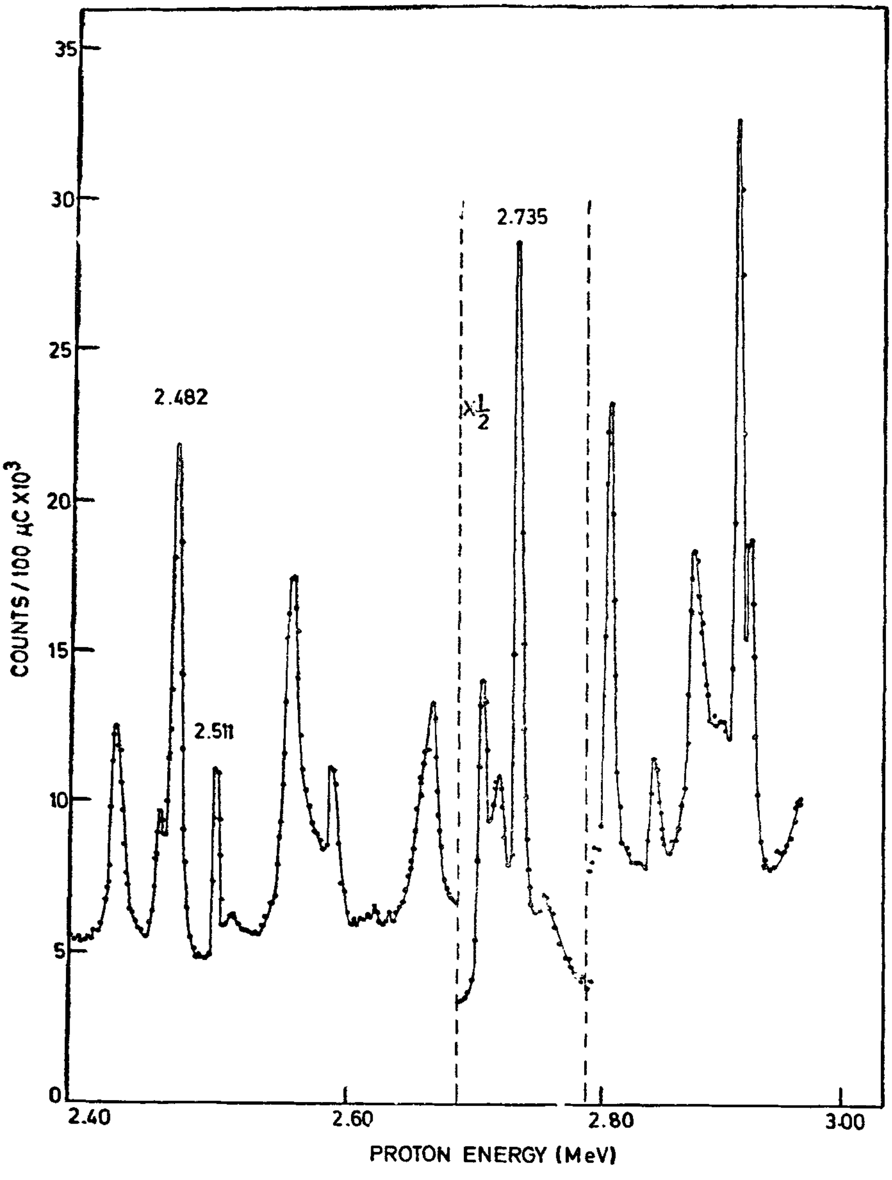

Figure 1. Excitation function for the ^{27}Al (p,γ) reaction; the resonances studied in the present work are labelled.

$\Gamma_p \Gamma_\gamma / \Gamma$ for many resonances in the ^{27}Al(p,γ) reaction have been listed by Endt and Van der Leun (1973) upto $E_p = 1 \cdot 968$ MeV. Using the excitation function data of Ahmed *et al* (1972) and the above compilation of Endt and Van der Leun, the strengths could also be determined for the three resonances discussed in the present work. The resonance strength at $E_p = 2 \cdot 482$ MeV is in agreement with that given by Lyons *et al* (1969).

The angular distributions were analyzed using the expression

$$W(\theta) = A_0 + A_2\, Q_2 P_2 (\cos\,\theta) + A_4 Q_4 P_4 (\cos\,\theta)$$

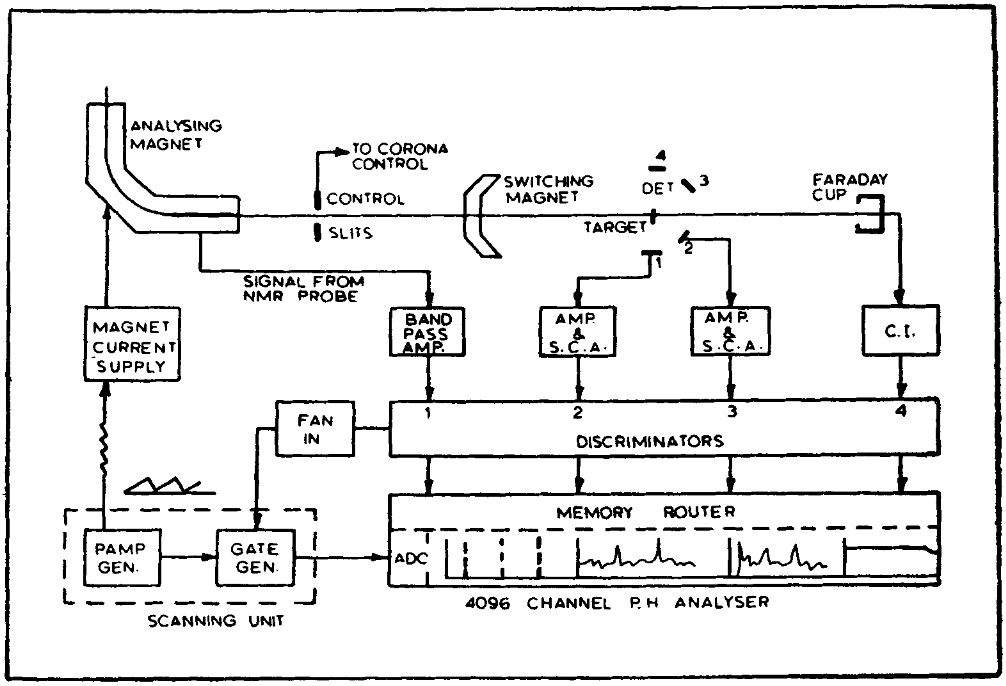

Figure 2. Schematic representation of the automatic excitation function set-up.

where $W(\theta)$ is the intensity observed at an angle θ relative to the incident beam and Q_2 and Q_4 are the attenuation factors due to the finite size of the detector (Häuser *et al* 1966). The ratios $A_2/A_0 = a_2$ and $A_4/A_0 = a_4$ depend on the spins of the initial and final states J_i and J_f and on the multipole mixing ratio δ. The analyses of the data were done in the usual way by varying arctan δ in the range $-90°$ to $+90°$ for the assumed value of J_i (J_f being known). The quality of each fit is given by the quantity χ^2 defined by

$$\chi^2 = \frac{1}{n-1} \sum_{i=1}^{n} [Y_i - W_i]^2/E_i^2$$

where n is the number of data points, Y_i and W_i are respectively the experimental and theoretical yields and E_i is the error of the experimental yield. The phase convention of Rose and Brink (1967) has been used.

The coefficients A_0, a_2 and a_4 are summarized in table 1. The Ge(Li) detector has a low efficiency at the high energy gamma rays involved in the present work. The large errors in the coefficients thus arise primarily from the uncertainty in the subtraction of backgrounds for the gamma ray peak areas. The coefficients alone cannot therefore be used conclusively for the assignment of spin-parity of the resonance states studied. We have therefore used the data on the resonance strengths and the identification of the levels as isobaric analogues of the levels in ^{28}Al as well to assign the J^{π}-values and the reduced transition strengths. The reduced transition strengths were obtained by assuming $\Gamma_p \approx \Gamma \gg \Gamma_\gamma$.

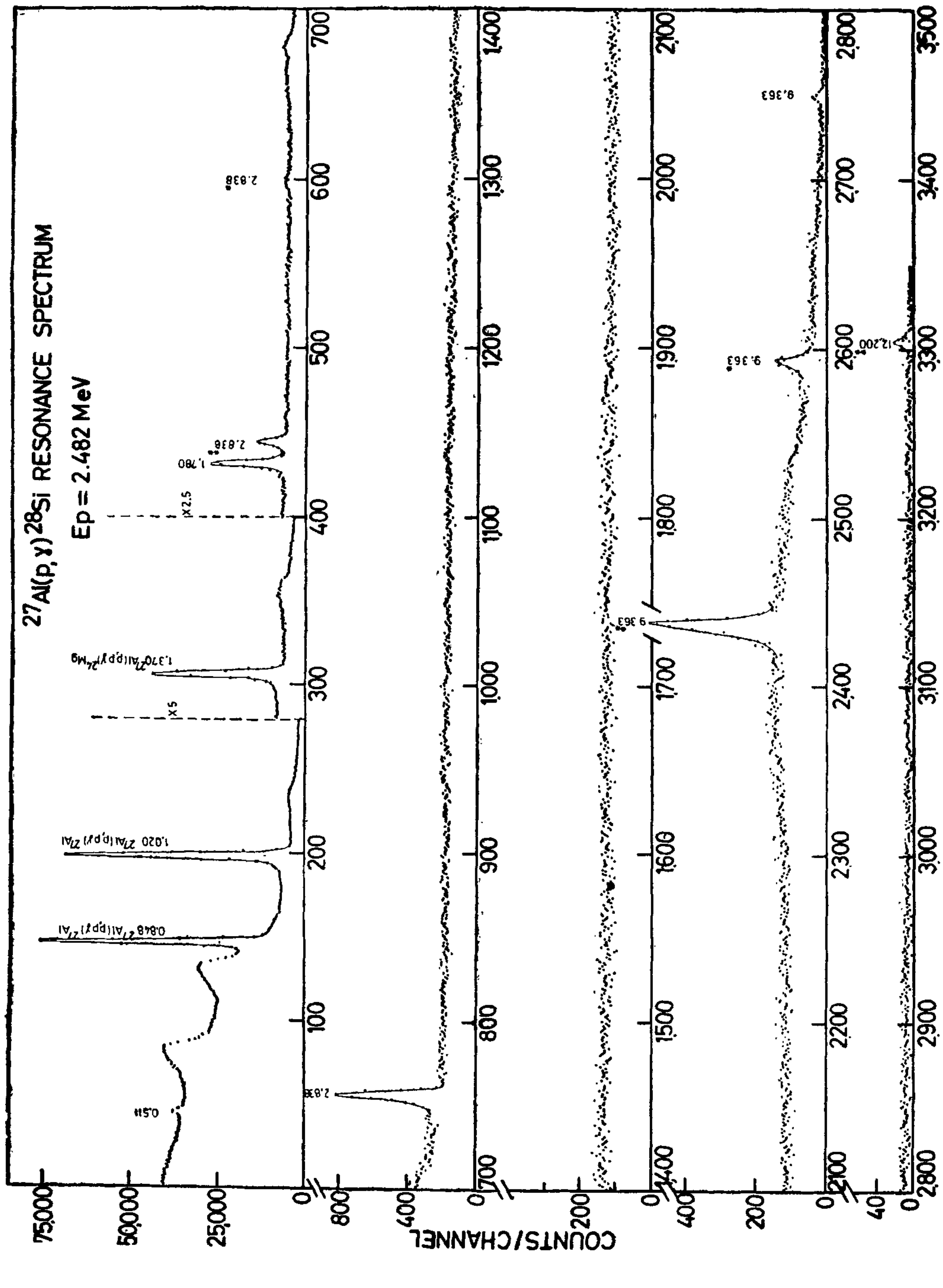

Figure 3. The gamma ray spectrum observed at $E_p = 2{\cdot}482$ MeV using the 20 cc Ge(Li) detector. The single and double asterisk marks over the gamma peaks indicate respectively the first and second escape peaks.

Table 1. Summary of the γ-ray angular distribution coefficients

E_p (lab) (MeV)	Primary transition E_γ (MeV)	A_0	$a_2 = A_2/A_0$	$a_4 = A_4/A_0$
	9·363	2182±52	0·35±0·50	0·10±0·10
2·482	12·200	46±8	0·50±0·33	0·20±0·65
2·511	9·390	2855±54	−0·11±0·04	0·05±0·07
	5·275	228±30	−0·49±0·26	0·01±0·49
2·735	7·335	122±20	−0·49±0·33	−0·14±0·63
	9·606	422±24	−0·13±0·13	0·13±0·24
	12·442	40±7	−0·33±0·31	0·08±0·70

4. Results and Discussion

The angular distributions of γ-rays which are emitted by the resonance levels 13·980, 14·007 and 14·223 MeV of ^{28}Si at E_p = 2·482, 2·511 and 2·735 MeV respectively are discussed below. Some of the angular distributions with the theoretical fits and the χ^2 as a function of arctan δ are shown in figures 4 and 5. The results are summarized in table 2.

The $E_p = 2 \cdot 482$ *MeV resonance*

The resonance level 13·980 MeV of ^{28}Si emits the 9·363 and 12·200 MeV γ-rays populating the 4·618 ($J^\pi = 4^+$) and the 1·779 ($J^\pi = 2^+$) MeV levels respectively. The gamma ray spectra at $E_p = 2 \cdot 482$ MeV were studied by Antoufiev *et al* (1972) and the level was found to be de-excited through the 4·618 MeV level without branching. On the basis of the angular distributions of the γ-rays, the $J^\pi = 4^-$ is the best assignment. But this assignment leads to an $M2$ multipolarity for the 12·200 MeV transition. If the transition is assumed to be such a character, the reduced gamma transition strength for it is ~19 W.u., which is rather unreasonably high. Hence adopting the next best J^π-value of 3^-, we have calculated the transition strengths and found them to be reasonable. This assignment is also consistent with that of the 4·685 MeV level in the parent nucleus ^{28}Al [$J^\pi = (1–4)^-$] (Endt and Van der Leun 1973).

The $E_p = 2 \cdot 511$ *MeV resonance*

The 4·618 MeV level ($J^\pi=4^+$) of ^{28}Si is populated by the de-excitation of the 9·390 MeV γ-rays from the resonance level 14·007 MeV. The spin of this level is found to be 4, which is again consistent with that of the parent level in ^{28}Al [E_x = 4·741 MeV, $J^\pi = (0–5)^+$, Endt and Van der Leun 1973].

The $E_p = 2 \cdot 735$ *MeV resonance*

The de-excitation of the resonance level 14·223 MeV takes place through the emission of the 5·275, 7·335, 9·606 and 12·442 MeV γ-rays and the levels 8·945, 6·889 ($J^\pi = 4^+$), 4·618 ($J^\pi = 4^+$) and 1·779 ($J^\pi = 2^+$) MeV of ^{28}Si are respec-

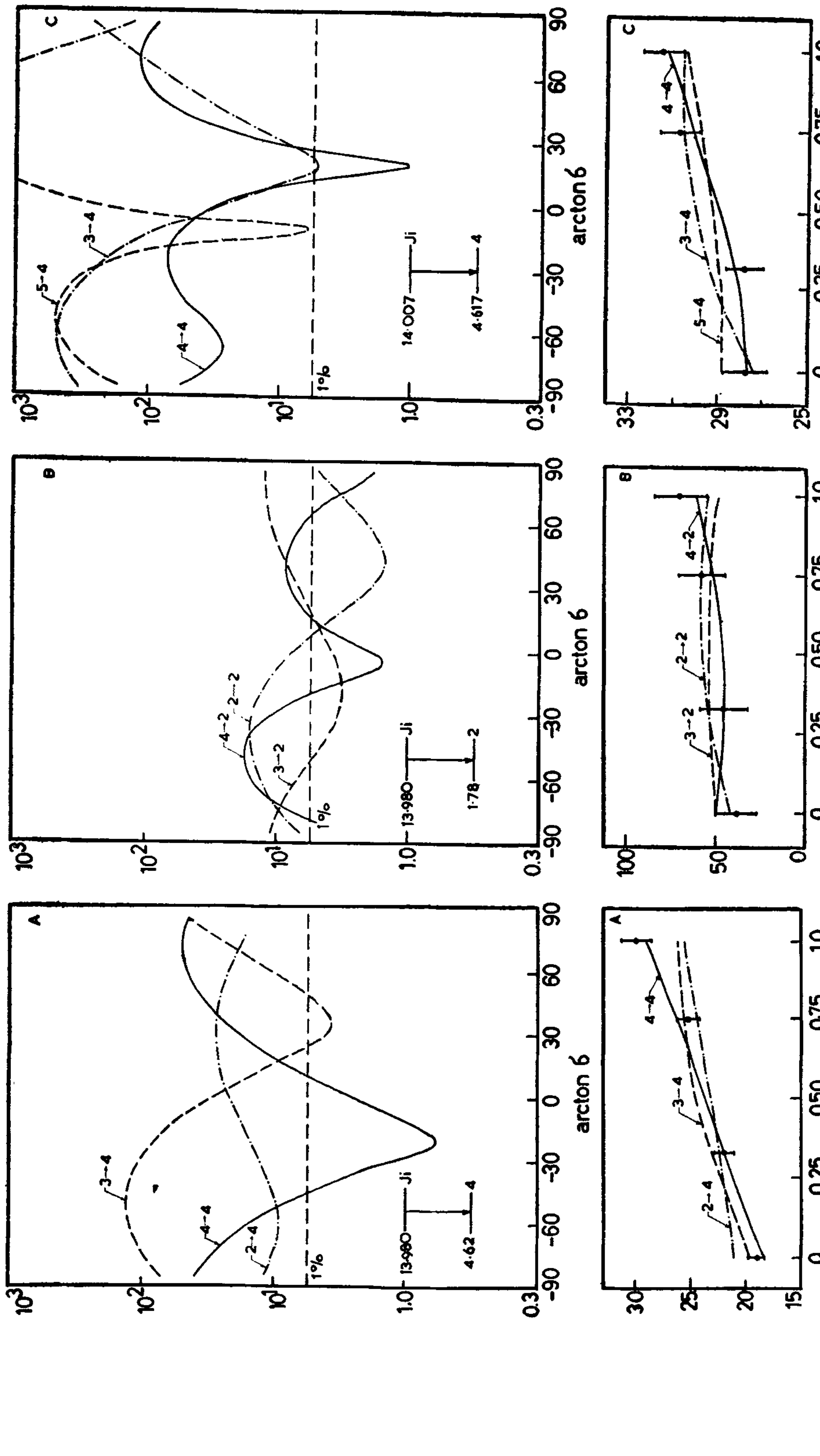

Figure 4. The angular distribution and the χ^2 plots for the (A) 9·363 and (B) 12·200 MeV gamma rays produced at the $E_p = 2{\cdot}482$ MeV resonance and (C) 9·390 MeV gamma ray produced at the $E_p = 2{\cdot}511$ MeV resonance.

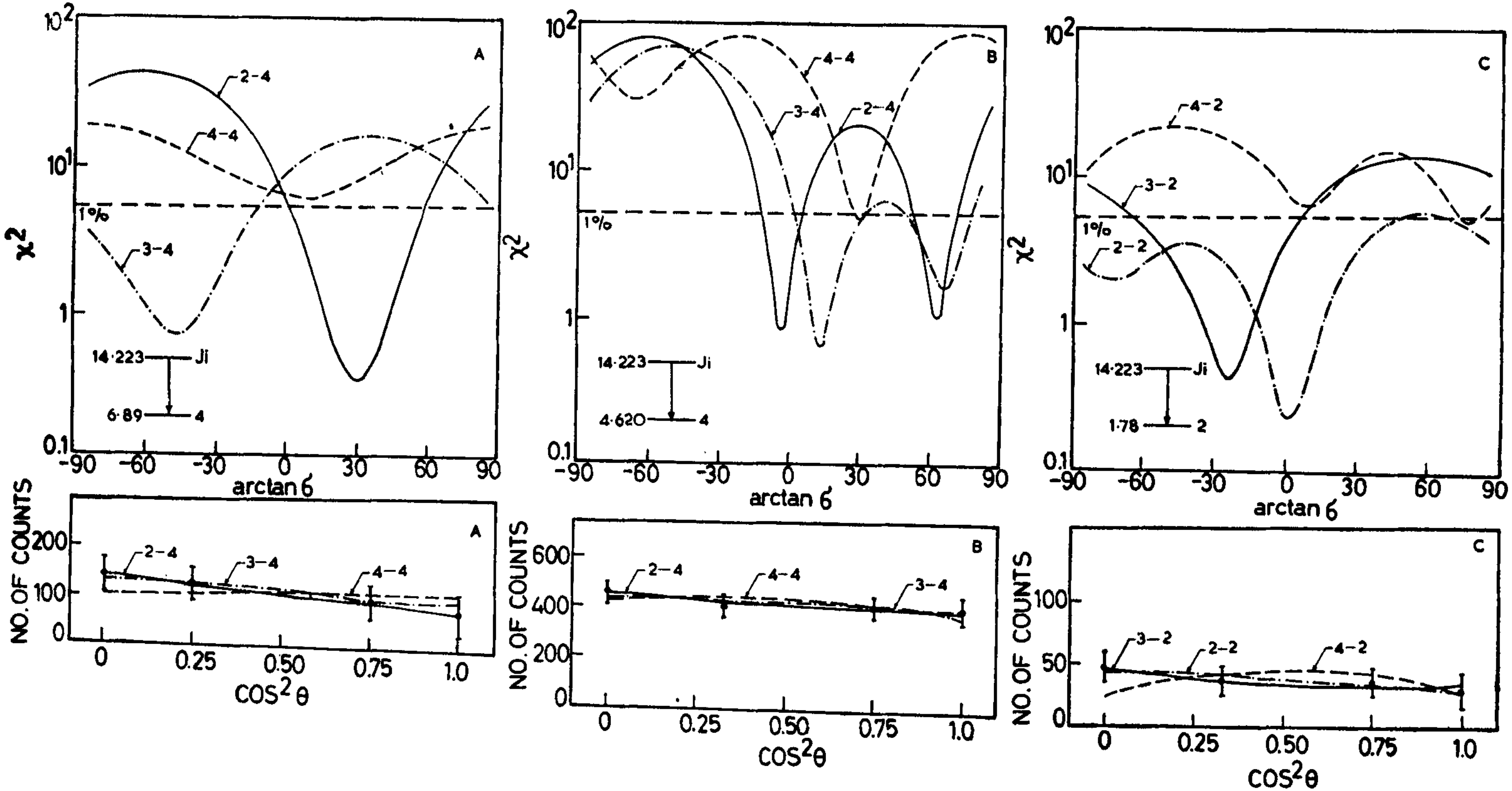

Figure 5. The angular distribution and the χ^2 plots for the (A) 7·355, (B) 9·606 and (C) 12·442 MeV gamma rays produced at the E_p = 2·735 MeV resonance.

Table 2. Reduced transition strengths

E_p (lab) (MeV)	Primary transition energy (MeV)	Branching ratio (%)	Spin sequence J_i^π	J_f^π	$(2J+1)$ $\Gamma_p\Gamma_\gamma/\Gamma$ $\pm 20\%$ (eV)	Multipolarity	Reduced transition strength $\pm 20\%$ (m.W.u.)
	9·363	95	3^-	4^+	40	$E1$	33·9
2·482	12·200	5	3^-	2^+	2	$E1$	0·8
2·511	9·390	100	4^+	4^+	15	$M1$	37·5
	5·275	13	3^+	4^+	14·6	$M1$	690
2·735	7·335	7	3^+	4^+	7·8	$M1$	136
	9·606	66	3^+	4^+	73·9	$M1$	570
	12·442	14	3^+	2^+	16·0	$M1$	57

tively populated by them. The spin of the resonance level has been assigned to be 3, (2) from the latter three angular distributions; the spin 3 is favoured because 66·7% branching of the 9·606 MeV γ-rays takes place by decaying to the 4·618 MeV level ($J^\pi = 4^+$). The spin value is consistent with that of the parent level in ^{28}Al.

The angular distribution of the 5·275 MeV γ-rays, populating the 8·945 MeV level of ^{28}Si, was analysed with the above spin assignment ($J = 3$); this leads to the $J = 4$ for the latter level. This level decays to the $J^\pi = 4^+$ level at $E_x = 4{\cdot}618$ MeV without branching which is consistent with the above spin assignment. The other spin value (2) does not lead to any satisfactory fit. The data on the reduced gamma transition strengths are listed in table 2.

5. Conclusion

The decay scheme of the resonance levels 13·980, 14·007 and 14·223 MeV as assigned in this experiment is shown in figure 6. These resonance levels are identified as analogues from a consideration of the Coulomb displacement energy in the pair of nuclei ^{28}Al–^{28}Si. A comparison with the properties of the corresponding parent levels derived from the (d, p) stripping reaction on ^{27}Al (Carola and Van der Baan 1971, Chen *et al* 1972) is made in table 3. The spin values are found to be consistent with those of the parent levels in ^{28}Al. Since the ground state spin of the target nucleus is $5/2^+$, the possible channel spins are 2 and 3. This fact was taken into account in the process of analyses of the data. Large $M1$ strengths as carried out by the 5·275 and 9·606 MeV transitions from the 14·223 MeV level are noteworthy.

The most likely proton configurations of the resonance levels are suggested as follows:

13·980 MeV level ($J^\pi = 3^-$, $T = 1$): $[(d_{5/2})^{-1}\ (f_{7/2})^1]$

14·007 MeV level ($J^\pi = 4^+$, $T = 1$): $[(d_{5/2})^{-1}\ (d_{3/2})^1]$

14·223 MeV level ($J^\pi = 3^+$, $T = 1$): $[(d_{5/2})^{-1}\ (d_{3/2})^1]$

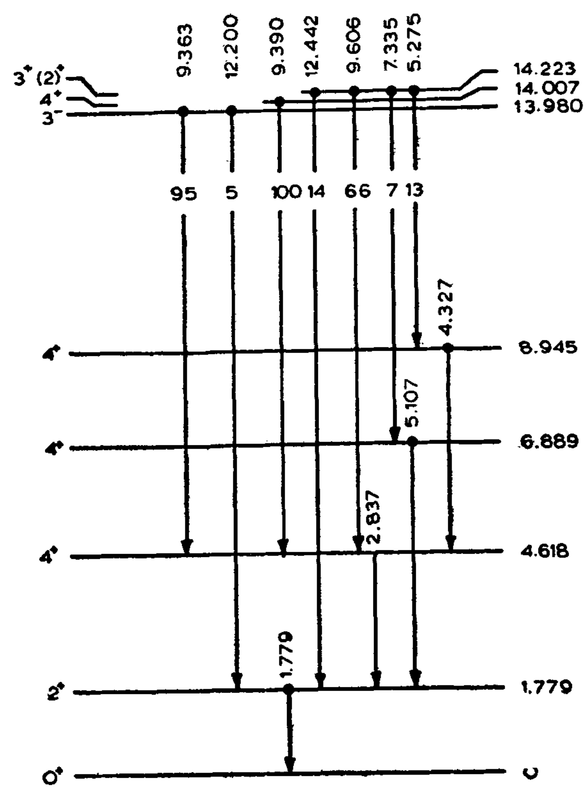

Figure 6. The decay scheme of the levels measured in the present experiment for the nucleus ^{28}Si.

Table 3. Properties of the analogue resonances

$^{27}Al(p,\gamma)^{28}Si$				$^{27}Al(d,p)^{28}Al$			
E_p (lab) (MeV)	E_x (MeV)	J^π	E_x (MeV)	l_n		J^π	
				Carola and Van der Baan (1971)	Chen *et al* (1972)	Carola and Van der Baan (1971)	Chen *et al* (1972)
2·482	13·980	3^-	4·685	1+3	1+3	$(1-4)^-$	$(1-4)^-$
2·511	14·007	4^+	4·741	(0)+2	2	$(0-5)^+$	$(0-5)^+$
2·735	14·223	3^+, $(2)^+$	4·928	(0+2)		$(0-5)^+$	

It may be mentioned here that the energy levels and the electromagnetic transition rates in ^{28}Si have been calculated by Farris and Eisenberg (1966) in the framework of the particle-hole description and a number of odd parity levels with both $T = 0$ and $T = 1$ have been predicted at $E_x > 10$ MeV; for the lack of experimental data the even parity levels were not calculated. It would be of interest to calculate such levels with the availability of more data (present work; Huang and McDaniels 1970, Neal and Leon 1973, Dalmas *et al* 1974).

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