THE DECAY OF SOME $^{27}Al(p,\gamma)^{28}Si$ RESONANCES (*)

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ABSTRACT — The γ-decay of three $^{27}Al(p,\gamma)^{28}Si$ singlet resonances, at $E_p = 1262$, 1457 and 1587 keV, and three doublet resonances, at $E_p = 1363$, 1662 and 1962 keV, was studied with a 30 cm^3 Ge(Li) detector. The doublet character of the last three resonances was confirmed and the decay modes of both members were resolved.

Branching-ratios, total widths, energy spacings and relative intensities of the doublet members are reported. From the measured value of the width, a spin $J^{\pi} = 2^+$ is assigned to the lower member of the doublet at $E_p = 1662$ keV. Evidence was found for two new bound levels in the ^{28}Si nuclide, at $E_x = 10517 \pm 3$ and 9798 ± 3 keV. A possible broad resonance at $E_p \simeq 1970$ keV, with a width of $\simeq 20$ keV and decaying mainly via the α_1 channel is suggested.

1 — INTRODUCTION

The doublet resonances at $E_p = 1363$, 1662 and 1962 keV (†) were studied with Ge(Li) detectors by Meyer *et al.* (1) without resolving the decay modes of both members of each doublet. Nordhagen and Tveter (2) tentatively resolved the doublet at $E_p = 1363$ keV using a NaI(Tl) gamma spectrometer. Recent data by Tveter (3) indicate that the γ-decay of the doublet at $E_p = 1662$ keV is from the lower member only. Summaries of earlier work are found in these references and in Endt and van der Leun (4).

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(†) Doublets are identified by the energy of the lower member, as measured in this work.

In the present work an attempt was made to separate the decay modes of the doublet members. The resonances at $E_p = 1262$, 1457 and 1587 keV were also studied in the light of some discrepancies noted in recent data on their gamma transitions.

Total widths were measured for all resonances mentioned above, together with the energy spacing of doublet members.

2 — EXPERIMENTAL PROCEDURE

The present experiment was performed with the proton beam of the LFEN 2 MeV Van de Graaff accelerator. Over a long run, the standard deviation of the beam energy distribution was typically 600 eV. The absolute beam energy was determined to within 2 keV, using an electrostatic voltmeter associated to a precision Wheatstone bridge, and this was considered sufficient for resonance identification. The targets, made from 99.999 % pure ^{27}Al evaporated onto thick gold backings, were water cooled and replaced as soon as any significant carbon deposition was observed. Beam currents between 2 and 6 μA were used.

In order to obtain resonance yield curves, a sinusoidal voltage (50 Hz) with a peak to peak amplitude up to 18 kV was applied to the target, thus modulating the proton energy (5). Every time a selected pulse was detected, a sample was drawn from the applied voltage and its amplitude analysed and stored. The yield curve of the channel corresponding to the selected pulses was automatically obtained, but a correction was needed to account for the non-linear time dependence of the applied voltage. (A small fraction ($\simeq 1$ keV) of the energy window was still disregarded at each end of the spectrum, to account for the strong local non-linearity.) This was made using a radioactive source to produce a random spectrum. This system is faster than the step by step method and more reliable since it is not affected by the errors in the energy and beam current measurements, is independent of target evaporation and provides a permanent check on carbon deposition. The calibration of the amplitude in energy units was made using the well known $^{27}Al(p,\gamma)^{28}Si$ doublet resonance at $E_p = 1381$ keV. The data for the $E_p = 1962$ keV doublet, however, had to be taken step by step over an energy range of about 30 keV.

Two gamma-ray detectors were used in the experiment. The singles spectra were taken with a 30 cm³ Ge(Li) detector supplied by Ortec, with a FWHM resolution of 2.5 keV at $E_\gamma = 1$ MeV and 10 keV at $E_\gamma = 10$ MeV, which was placed at 55 degrees to the beam direction. To obtain the excitation functions, a 7.5 cm × 7.5 cm NaI(Tl) detector was generally used. However, for resonances decaying via a particle channel the Ge(Li) detector was used. In the case of the $E_p = 1662$ keV doublet the excitation function was measured also in the α_0-channel, using a silicon surface-barrier detector. Ortec spectroscopy amplifiers model 452 and a dual Northern Scientific 4096 channel ADC were used. Full gain stabilization was better than 2/4000 during data acquisition.

The relative efficiency of the Ge(Li) detector was measured in the energy range 1-13 MeV using a ^{56}Co source (6) and some resonances in the $^{27}Al(p,\gamma)^{28}Si$ and $^{23}Na(p,\gamma)^{24}Mg$ reactions (7).

The singles spectra were stored in a PDP-15 on-line computer in two buffers of 4096 channels each, one containing the full spectrum up to 14 MeV and the other gamma-rays up to 7 MeV.

The yield curves were generally stored in a routed DIDAC multichannel analyser, selecting the appropriate γ-rays in single-channel analysers. The particle (p_1, p_2 and α_1) and gamma channels were studied via the associated γ-rays at $E_\gamma = 847$, 1013, 1369 and $E_\gamma > 1500$ keV, respectively. In the case of the $E_p = 1662$ keV doublet, the PDP-15 computer was used and the single-channel analysers were replaced by digital windows placed on the γ-ray Ge(Li) spectrum. Background corrections were made, using the information from windows at left and right of the γ-ray of interest.

3. METHOD OF ANALYSIS

As it was impossible to populate separately the individual members, several measurements were made in each doublet, using different bombarding energies and targets of different thickness, thus allowing a change in the relative population of the doublet members. If there are N decay modes and M experiments, the branching-ratios can be obtained from a system of NM + 2 equations, provided that $M \geqq 2(N-1)/(N-2)$ (12). Three experiments were enough to resolve each doublet studied, since $N \geqq 4$ for all of them. The experimental conditions were chosen in such a way that the resulting population ratios of the doublet members were sufficiently different to avoid ambiguities in the calculation of the system solution.

Using a non-linear least squares technique, experimental yield curves were fitted to an expression derived ([12]) under the assumptions of a gaussian beam energy spread ([8]), continuous energy loss ([9]) and negligible thermal vibrations. Since energy resolution tends to deteriorate in long runs, the corresponding parameter was adjustable in the fits, together with resonance widths and spacing.

The standard deviations of the resonance widths and doublet spacings were obtained using basically the method proposed by James *et al.* (ref. ([10]); see also ref. ([11])). Some changes had to be made and are described elsewhere ([12]).

4. RESULTS AND DISCUSSION

A typical γ-ray spectrum is shown in fig. 1. The γ-decay modes obtained for the singlets at $E_p = 1262$, 1457 and 1587 keV are in good agreement with previous work ([1, 13, 14, 15]), except for a few weak transitions as discussed below. The resonances at $E_p = 1363$, 1662 and 1962 keV exhibit a doublet character. In the present work the decay modes of these doublets were resolved as indicated in section 3. The observed γ-spectra show that some of the resonances decay by proton and or alpha emission. The relative (p,α_1), (p,p_1) and (p,p_2) strengths were estimated from the intensities of the 1.369, 0.847 and 1.013 MeV γ-rays from these reactions and from the total γ-ray intensity of the corresponding (p,γ) resonances. Corrections were made for the small contribution from the p_2 deexcitation channel to the 0.847 MeV γ-ray intensity.

The data obtaind for the γ-decay of the known bound levels populated in the present experiment are in good agreement with previous work ([1, 13-16]).

Excitation functions were obtained in the vicinity of all resonances as described in section 2, and the measured widths are shown in table 2.

The existence of transitions from the $E_p = 1262$ keV resonance to states at $E_x = 6.89$, 10.91 and 11.08 MeV, unsucessfully searched for by Meyer *et al.* ([1]), has been confirmed. However, the present

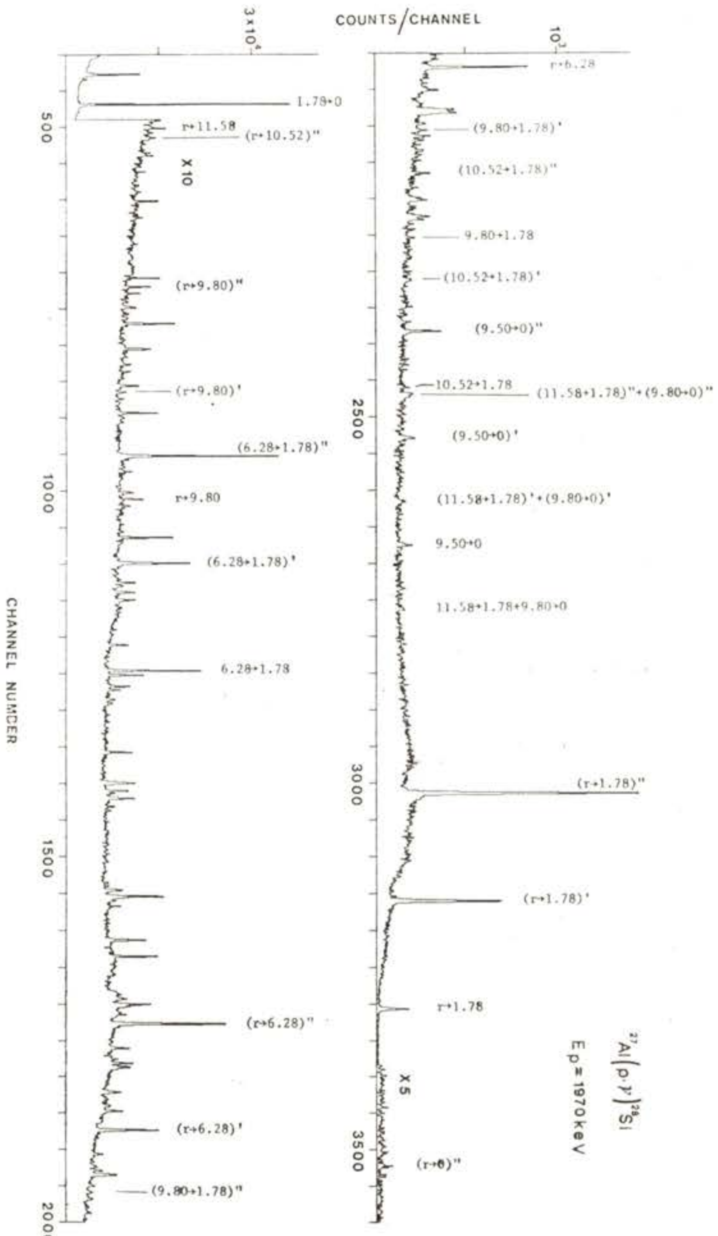

Fig. 1 — Gamma-ray spectrum taken at $E_p = 1970$ keV. The labelled peaks are those relevant to the discussion of section 4 and also some prominent lines used in the calibration procedure.

data do not support the presence of 0.5 °/₀ transitions to the levels at $E_x = 7.94$ and 9.42 MeV, reported respectively by Gibson *et al.* (13) and by Meyer *et al.* (1); an upper limit of 0.3 °/₀ could be put on these branches. This resonance was seen to decay by α-emission to the first excited state of ^{24}Mg with a relative intensity $\Gamma_{\alpha_1}/\Gamma_\gamma$ of the order of 0.03.

The results obtained for the $E_p = 1457$ keV resonance are in good agreement with those of Forsblom (14), confirming (1) that the transition $r \rightarrow 1.78$ MeV is much weaker than reported by Gibson *et al.* (13). This resonance was seen to decay via the p_1 channel with a relative intensity of $\Gamma_{p_1}/\Gamma_\gamma \simeq 0.14$, which is significantly greater than reported by Meyer *et al.* (1).

The present data for the singlet at $E_p = 1587$ keV are in quite good agreement with Meyer *et al.* (1), except for a 1 °/₀ transition $r \rightarrow 8.59$ MeV, seen in this work. Several weak transitions, reported by Gibson *et al.* (13), Forsblom (14) and Gonidec (15), were also not observed. The width of this resonance was measured to be 90^{+60}_{-30} eV.

4.1. *The $E_p = 1363$ keV doublet*

The lower member has an intensity in the γ-channel that is approximately twice that of the upper member, as can be inferred from the measured excitation function (fig. 3) and from the fitted populations to the observed γ-spectra at the three bombarding energies used. This observation contradicts clearly the suggestion by Nordhagen and Tveter (2) that the upper member would have a γ-strength 50 times smaller. The analysis shows that the γ-decay of both members is very similar (table 1) in contrast with the scheme suggested by Nordhagen and Tveter (2). Several weak transitions are reported wich were not observed by those authors and by Meyer *et al.* (1). A significant feature of this doublet is the strong α-decay of the upper member (2,3). From the interpretation of the γ-spectra discussed above, we have measured a relative intensity $\Gamma_{\alpha_1}/\Gamma_\gamma \simeq 0.44$ for the upper member. A very weak proton decay was observed ($\Gamma_{p_1}/\Gamma_\gamma \simeq 0.007$), with an yield curve following that of the 1.369 MeV γ-ray and has been interpreted as due only to the upper member.

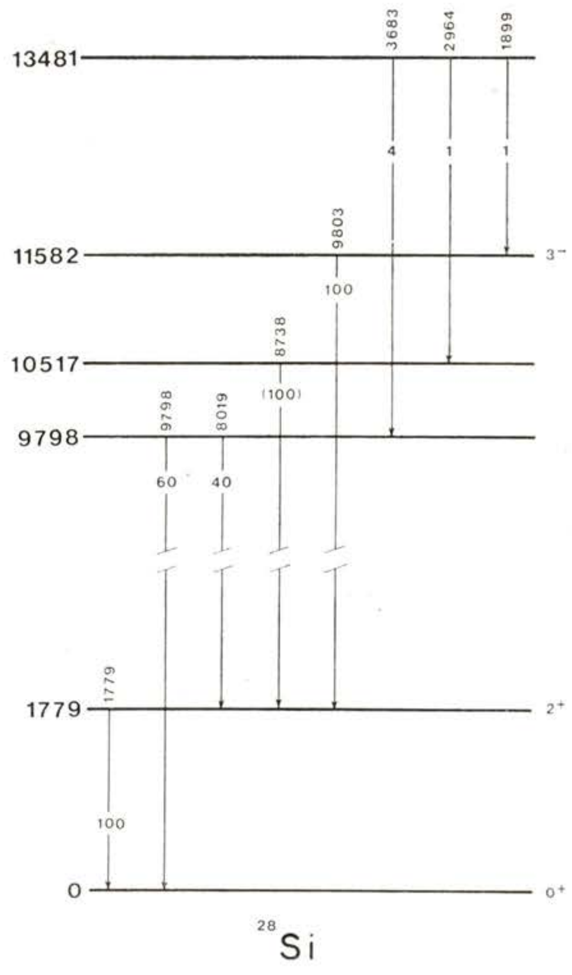

Fig. 2 — Partial level diagram for the γ-decay of the upper member of the $E_p = 1962$ keV doublet, showing the observed transitions involving new levels in ^{28}Si (see subsection 4.3).

4.2. *The $E_p = 1662$ keV doublet*

The γ-decay of this doublet was found to be essentially due to the lower member, while only the upper memper has p_1 and p_2-decays, in agreement with Tveter (3). A very weak α_0-decay was observed for the lower member, confirming the result quoted by Tveter (3) and suggesting that this $T=1$ state must have a $T=0$ contamination. The measured branching-ratios for the γ-decay agree well with those given by Meyer *et al.* (1) for the unresolved doublet; however, a 0.4 % transition to ground state was observed in this work. The total widths were measured to be 1700 ± 110 and 690 ± 60 eV, respectively for the lower and upper members. Tveter (3) studied the lower member by elastic proton scattering and obtained acceptable fits for the spins $J^\pi = 2^+$ or 3^+ with widths respectively 1650 ± 100 and 970 ± 100 eV. Thus, the width measured in this work allows a spin assignment $J^\pi = 2^+$ for this member.

4.3. *The $E_p = 1962$ keV doublet*

Excitation functions were measured in the region $E_p = 1949$ to 1978 keV for the p_1, p_2 (fig. 3), γ and α_1 channels. The yield curve for α_1-decay appears to originate mainly in a very wide resonance ($\Gamma \simeq 20$ keV) at a bombarding energy somewhat above the second member of the doublet. Unfortunately, it was not possible to extend the measurements any further. However, the present yield curve suggests that the lower member at $E_p = 1962$ keV also decays via the α_1-channel and this is compatible with the intensities of the 1369 keV γ-ray, observed at the three bombarding energies where γ-ray spectra were taken. The remaining channels do not show any evidence for the presence of the wide resonance and are compatible with a doublet having an energy spacing of 5.6 ± 0.5 keV. The lower member, at $E_p = 1962$ keV, has a width of 6.9 ± 0.6 keV and decays strongly via proton emission ($\Gamma_{p_1}/\Gamma_\gamma \simeq 75$ and $\Gamma_{p_2}/\Gamma_\gamma \simeq 60$); the upper one, at $E_p = 1967$ keV, has a width of 2180 ± 100 eV and relative proton intensities $\Gamma_{p_1}/\Gamma_\gamma \simeq 5$ and $\Gamma_{p_2}/\Gamma_\gamma \simeq 120$.

The γ-spectra were analysed in terms of the decay of the two members referred above, which were seen to have similar intensity. Several weak γ-transitions were seen, that were not reported by

TABLE 1. Gamma-decay of $^{27}Al(p,\gamma)^{28}Si$ résonances from spectra taken at 55°.

Final levels		E_p (keV)																					
E_x (MeV)	J^π a)	1262 b)	1262 c)	1262 d)	1363 b)	1363 e)	1365 b)	1365 e)	Unr. c)	1457 b)	1457 c)	1457 d)	1587 b)	1587 c)	1587 d)	1587 f)	1662 b)	1664 b)	Unr. c)	1962 b)	1967 b)	Unres. c)	Unres. d)
0	0^+				—	—	5⩽30		—								0.4	This member of the doublet does not have any appreciable γ-decay	—	—	0.3	—	—
1.78	2^+	43	43	43	24	35	32	20	25	6	3	15	45	45	45	48	79		82	47	28	40	41
4.62	4^+	5	5	6	11	12	8	—	10	11	13	11	21	22	22	22				2	2	—	—
6.28	3^+	1	1	1.6	41	35	23	—	42	2	1	2	3	3	3.2	3.2	3		3	15	19	17	21
6.88	3^-	37	41	32						2	4	—	4	6	6	1.6				3	8	10	14
6.89	4^+	1	—	1.8	10	9	6	—	15				< 0.4	—	—	1.8							
7.38	2^+												8	9	7	7.2	4		5	1	5	4	4
7.42	2^+	6	6	7	—	—	2	—	—				3	2	1.7	1.6				—	5	5	4
7 80	3^+				5	—	4	—	—	8	9	8	< 0.3	—	1.0	1	3		2	3	—	—	—
7.94	2^+	< 0 3	—	0.5	—	—	1	—	—				< 0.2	—	—	0.5	3		2	5	4	4	2
8 26	2^+												2	1	1.6	1.5	2		1				
8.33	1^+																			—	3	1	—
8.41	4^-	2	2	1.8	—	—	1	—	—	5	5	3	4	3	2.4	2.6							
8.59	3^+				3	—	2	—	2	9	8	12	1	—	0 8	0.8				3	6	7	6
8.90	1^-				—	1.5	—	—	—														
8 94	π = nat.				2	—	—	—	—														
9.16	$(2^+, 3^-, 4^+)$												4	3	3.4	2.9				—	< 0.5	—	4
9.32	3^+	1	0.5	1.3	3	5	6	—	3	56	57	49	< 0.4	—	0.9	—				11	3	3	< 3
9.38	2^+	2	1	0.7	1	—	10	50	3											7	—	2	—
9.42	$(2^+, 3^-, 4^+)$	< 0.3	0.5	—																			
9.50	$(1,2)^+$																6		5	1	4	4	—
9.76													< 0.2	—	—	0.3				1	1	—	—
(9.80)																				—	4	—	—
10.21	$(2^+, 3, 4^+)$												5	6	5	4.7				1	4	3	4
(10.52)																				—	3	—	—
10.54										1	—	< 0.5											
10.59	1^+				—	2.5	—	—	—														
10.91	π = nat.	1	—	1.4																			
11.08		1	—	2.9																			
11.58	3^-																			—	1	—	—

Branching-ratios given in %. Typical errors are of the order of 50% of the value given for values less than 2, 20% for values between 2 and 10 and 10% for values greater than 10.

a) Ref. (4). b) Present work. c) Ref. (1). d) Ref. (13). e) Ref. (2). f) Ref. (14).

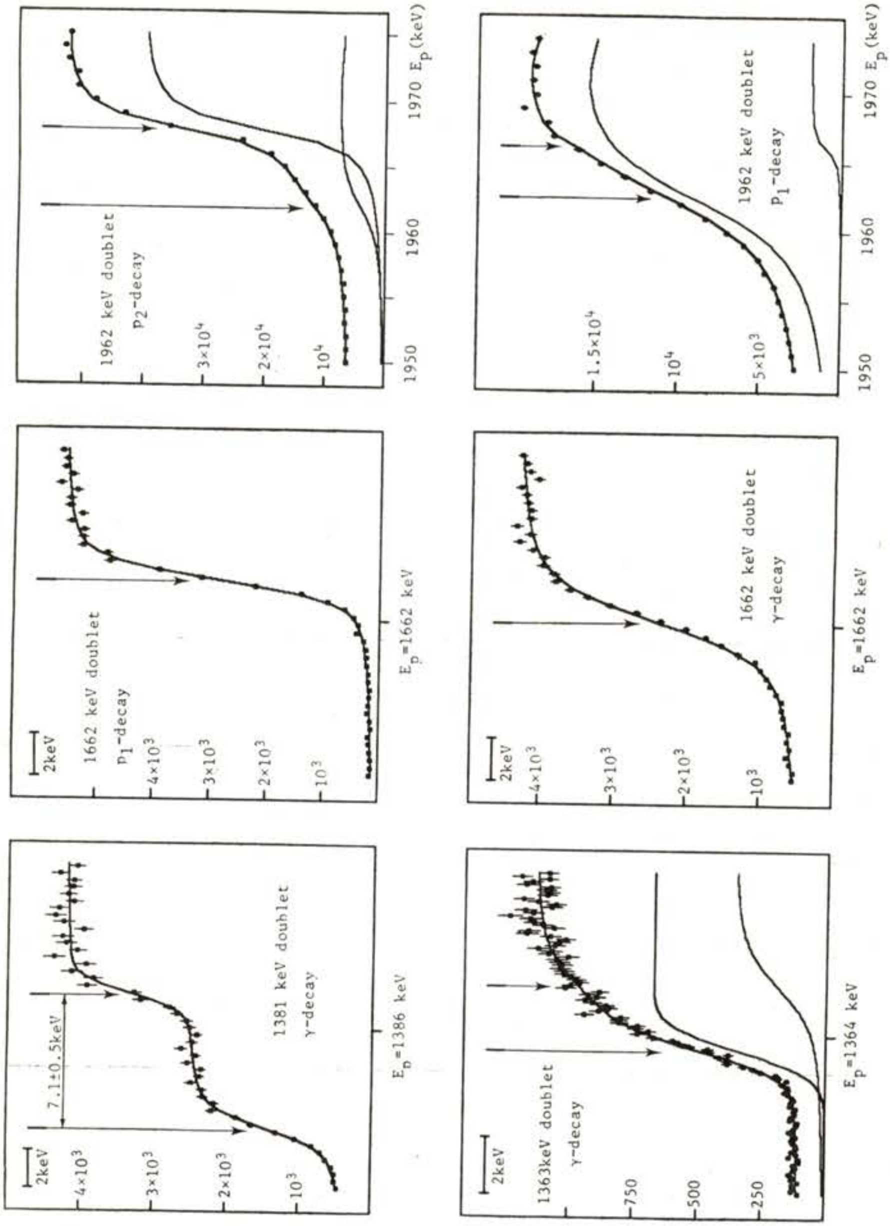

Fig. 3 — Excitation functions taken over the doublet resonances studied. The doublet at $E_p = 1381$ keV, used in the energy calibration of the modulator, is also shown. Experimental points are represented with error bars and the solid line is the best fit obtained, as explained in section 3. The shape of each doublet member, as found by the computer, is also drawn. The excitation functions labelled p_1-decay include a small contamination from the p_2-channel, as referred in the text.

TABLE 2. Resonance widths and energy gaps of doublet members

E_p (keV)	J^π	Γ (eV) Present	Γ (eV) Previous	Energy gap (keV) Present	Energy gap (keV) Previous
Sing. 1262	3^- a)	<50 (γ ch.)	100±40 a)		
Doub. 1363	(4^+) a, b)	<100 (γ ch.)	70±40 a)	2. 0±0. 3	1.1±0.6 a)
Doub. 1365	2^+ a, b, c)	1630±220 (γ ch.)	1100 a, b) 2000±500 a) 1400±200 c)		
Sing. 1457	3^- c)	2200±600 (γ ch.)	3000 d) 2000±100 c)		
Sing. 1587	$(2^+, 3^-, 4^+)$ e)	90^{+60}_{-30} (γ ch.)	<1000 a)		
Doub. 1662	2^+ c, f)	1700±110 (γ ch.)	2000 d) 1650±100 c) or 970±100 c)	1.67±0.15	1.8±0.9 c)
Doub. 1664		690±60 (p_1, p_2 chs.)			
Doub. 1962		6900±600 (p_1, p_2 chs.)	12000 d)	5. 6±0. 5	2 d)
Doub. 1967		2180±100 (p_1, p_2 chs.)	<2000 d)		

a) Ref. (4). b) Ref. (2).
c) Ref. (3). d) Ref. (17).
e) Ref. (1). f) Present work.

Gibson *et al.* [13] and Meyer *et al.* [1]. A weak transition was observed to the level at $E_x = 11.58$ MeV which lies at the proton separation energy. This level had already been observed as an (α, γ) resonance by Smulders and Endt [18] and the present data support the previously indicated 100 % decay to the first excited state.

The observed intensity of the 9.803 MeV γ-ray is about three times that of the 1 % transition $r \rightarrow 11.582$ MeV and can not correspond only to the reported [18] 100 % decay of this level to the first excited state. The remaining is accounted for (fig. 2) assuming a previously unreported level at $E_x = 9798 \pm 3$ keV, decaying to the ground state and this is supported by the observation of the 4 % transition $r \rightarrow 9.798$ MeV, followed by the 9.798 MeV $\rightarrow$ g. s. transition referred above and by the clear transition 9.798 MeV $\rightarrow$ 1.779 MeV. The intensities of the γ-rays involved agree quite well.

Two other γ-rays are seen in the spectrum, which can not be explained by transitions between known levels. Their energies together with that of the first excited state sum quite well to the energy of the upper member, at $E_p = 1967$ keV. Also the observed intensities are of the same magnitude and this suggests the presence of a new level at $E_x = 10517 \pm 3$ keV.

We wish to express our special gratitude to Mr. L. A. Cunha for his assistance during the experiment and in the analysis of single spectra.

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