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Excitation function for the population of the 4.51 MeV state of ^{27}Al in inelastic proton scattering: Evidence for 6^- strength?

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The excitation function for emission of 2.30 MeV gamma rays from the 4.51 MeV ($\frac{11}{2}^+$) state of ^{27}Al formed in inelastic proton scattering has been measured for proton energies from 5.6 to 7.3 MeV. A resonance previously seen in both inelastic electron and proton scattering from ^{28}Si at 17.35 MeV has been observed as a resonance in the excitation function, as well as seven other resonances, all of which are narrow (i.e., less than 100 keV wide). It is suggested that these may represent fragments of 6^- strength in ^{28}Si, as calculated by Carr *et al.*

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A large-basis shell model calculation of the 6^- states of ^{28}Si by Carr *et al.* [1] predicted that a large proportion of that strength resides in a known strong state at 14.357 MeV and that there is residual strength spread over some 2 MeV of excitation centered about 17.5 MeV. Two experimental results relating to the fragmentation of that strength have since appeared. The first of these resulted from the reexamination of earlier inelastic electron scattering data at large momentum transfer, and is described by Yen *et al.* [2]. The claim of these authors is that there is a significant fraction of 6^- strength in a single peak at an excitation of 17.35±0.10 MeV. The second is included in a longer paper by Tamini *et al.* [3], which examined the ^{28}Si$(p,n)^{28}$P reaction, along with three other (p,n) reactions, and searched for structure in the neutron spectrum which would be indicative of the population of 6^- states in the residual ^{28}P. The excitations of these states can, of course, be related to the excitation energies of states of similar wave function in ^{28}Si. Reference [4] indicated that six fragments of 6^- strength occur at excitation energies in ^{28}Si between 15.44 and 17.69 MeV, as observed in a high resolution study of the ^{28}Si(p,p') reaction. The two states of interest to this study are at excitations of 17.34 MeV, in agreement with Yen *et al.* [2], and 17.69 MeV. States at excitations higher than 17.5 MeV found in this (p,p') study "were not analysed due to the spreading of the state width and the difficulties of determining an accurate quasielastic background." Tamimi *et al.* [3], however, found no 6^- strength at an excitation corresponding to the peak seen by Yen *et al.* [2] and Liu *et al.* [4], and it seemed worthwhile to seek another reaction which would, hopefully, resolve this apparent disagreement.

The reaction chosen was the proton inelastic scattering reaction on ^{27}Al, leading to a high-spin excited state in both the compound nucleus and the residual nucleus. It was hoped that a high-spin excited state in ^{27}Al could be found, which would be the final state in the inelastic scattering reaction and which also had a unique gamma ray decay. Indeed such a state exists, at 4.510 MeV excitation in ^{27}Al, and having spin and parity $\frac{11}{2}^+$. Its radiative decay takes place (77%) via a 2.300 MeV gamma ray, to the 2.211 MeV state of ^{27}Al, which then decays directly to the ground state [5]. This 2.300 MeV gamma ray is easily resolved from all other gamma rays detected in this inelastic scattering reaction at 6–7 MeV incident proton energy. A 6^- excited state in ^{28}Si will decay to this 4.51 MeV state by emission of an $l = 1$ proton. At this point it must be noted that, at these bombarding energies, the $l = 0$ and 1 emitted protons have far higher probability of penetrating the Coulomb plus angular momentum barrier than do those protons of higher angular momentum. Thus the (p,p') reaction could populate such excited final states in the target nucleus; however, because of the smallness of the (Coulomb plus angular momentum) barrier penetrability, states of excitation less than about 16.6 MeV will not be significantly populated. However, it must be noted that making such a measurement cannot, by its very nature, be angular momentum, parity, or isospin selective, for this gamma ray could arise from compound nuclear states having $J = 4$, 5, or 6, either parity, and isospin $T = 0$ or 1. It is argued that $J = 7$ states, though theoretically possible, cannot be formed in this $A = 28$ system by a $1\hbar\omega$ one-particle–one-hole (1p-1h) excitation. Furthermore, the even parity states are likely to have more complicated wave functions than the odd parity states, and certainly smaller 1p-1h excitation components. Moreover, states of the width of the peak seen by Yen *et al.* [2] (quoted as less than or equal to 70 keV, see below) will certainly not be 4^- states, which are able to decay to the ground state of ^{27}Al with the emission of an $l = 1$ proton, and are consequently expected to have much greater widths. This leaves us with the possibility of detecting the presence of 5^- and 6^- excited

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states, of $T = 0$ or 1, in ^{28}Si as resonances in the yield of the 2.300 MeV gamma ray, but without any way of distinguishing between these possibilities.

The excitation function for production of this 2.300 MeV gamma ray has been measured as a function of incident proton energy. The experiment was done at the tandem accelerator facility of the Australian Nuclear Science and Technology Organization, at Lucas Heights, New South Wales. The energy calibration of the proton beam was made using the results of Overley, Parker, and Bromley [6] for the ^{27}Al(p,n) reaction, using the threshold and the sharp peak observed in the excitation function at a laboratory proton energy of 6.000 MeV as the two calibration points. These are adequate for the proton energies used in this study. The aluminum target was 600 μg/cm^2 thick, and the beam energy loss in it approximately 35 keV. The Ge(Li) detector used for the gamma ray measurements was placed as close as possible to the target ($d = 10$ cm, approximately), and was at an angle of about 60° to the beam direction.

The results of the measurements are presented in Figs. 1 and 2. Figure 1 shows the gamma ray spectrum between 2.0 and 3.1 gamma ray energy; the two outstanding peaks arise from 2.211 and 3.004 MeV gamma rays. These gamma rays are very well known in ^{27}Al as gamma rays from excited states of those excitation energies to the ground state. Figure 2 shows the excitation function for production of the 2.300 MeV gamma ray. In that figure, vertical arrows mark the locations of peaks expected using the results of Tamimi *et al.* [3].

At the lowest proton energies used, two comments are in order. First, the isolated peak seen at an incident proton energy of 5.970 MeV laboratory proton energy is almost certainly to be identified with the 17.35 MeV peak of Yen *et al.* [2]. The excitation energy determined in this experiment is 17.325±0.020 MeV, when allowance is made for the effect of target thickness on the resonance energy. The width of the peak, as given in the plotted excitation function, is 30±5 keV. There is no sign of a peak at proton energy 5.78 MeV, which corresponds to an excitation energy of 17.16 MeV in ^{28}Si (or 7.8 MeV in ^{28}P); this is the location of one of the strongest peaks claimed by Tamimi *et al.* [3]. This disagreement could only be resolved if there were an error of the order of 200 keV in the neutron energies given by Tamimi *et al.*, or by a mismatch in excitation energies of the analog 6^- states in ^{28}P [from the (p,n) reaction] and ^{28}Si (the other three reactions). However, there is no indication given in Ref. [3] regarding the precision of the energy measurements of the neutron groups, only that the resolution of the measurement was about 320 keV for two time-of-flight paths, and 450 keV for the third.

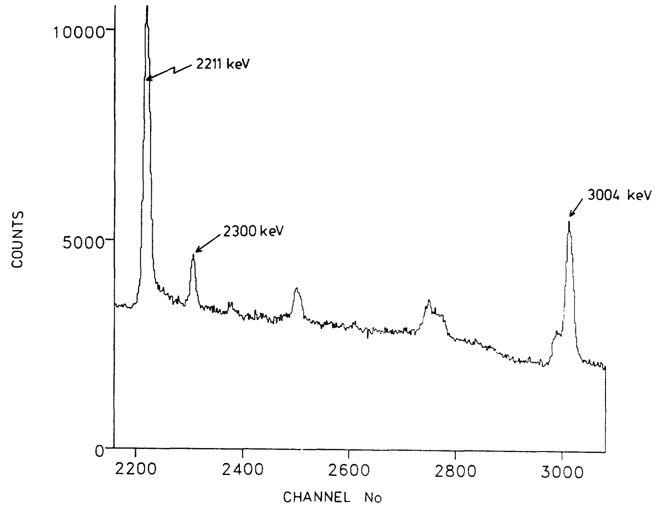

FIG. 1. Spectrum of gamma rays, of energy between 2.0 and 3.1 MeV, obtained with proton bombarding energy of 6.99 MeV. The 2.300 MeV gamma ray peak, whose excitation function was measured, is clearly shown.

The energies of the peaks in the excitation function

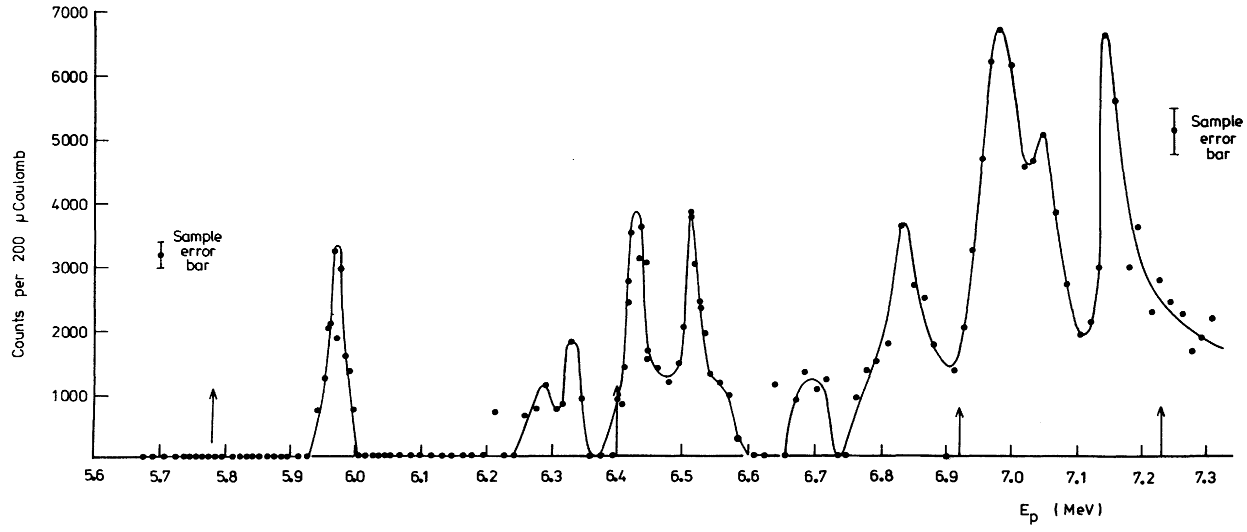

FIG. 2. Excitation function for production of the 2.300 MeV gamma ray from 5.60 to 7.30 MeV proton energy. The equivalent excitations of the four peaks seen by Tamimi *et al.* [3] in the ^{28}Si(p,n) reaction study are shown as arrowed vertical lines.

TABLE I. Energies of peaks in the ^{27}Al(p,p') excitation function equivalent.

Proton energy (MeV)	Excitation in ^{28}Si(MeV)	Excitation in ^{28}Si (Ref. [3]) (MeV)	Excitation in ^{28}Si (Ref. [4]) (MeV)
		15.26	15.44
			15.92
			16.41
			16.96
5.97	17.34	17.16	17.34
(6.29)	(17.65)		
6.33	17.69		17.69
6.43	17.79	17.76	
6.515	17.87		
6.835	18.18	18.26	
6.99	18.33		
7.055	18.39		
7.15	18.48	18.56	
		19.56	
		20.56	

are given in Table I. It is to be noted that all the peaks observed are narrow ($\leq$ 100 keV) and, on the basis of the argument given above, they are most probably evidence for states of angular momentum and parity 5^- or 6^- in ^{28}Si. In the excitation region in ^{28}Si from 17.7 to 18.5 MeV we find seven peaks. Tamimi *et al.* [3] quote three energies in this range at which the 6^- strength is concentrated; their excitation energies in ^{28}P are in acceptable agreement, when comparing excitations of analog states, with those in ^{28}Si which are quoted in Table I; the several possibilities noted above exist for the interpretation of the others that are seen in our experiment. The overlaps between the different experiments are very small, but, where they do occur, the excitation energies are in fairly good agreement.

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