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THE PHOTOPROTON DECAY OF ^{27}Al

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Abstract: Photoproton spectra from ^{27}Al were measured from 14.8 to 27.6 MeV excitation energy in 400 keV steps. From these, high resolution photoproton cross sections to low-lying states of the residual ^{26}Mg nucleus were deduced. The large integrated cross sections to these states justify the interpretation of the de-excitation γ-ray measurements which consistently indicate strong population of low-lying residual states following photodisintegration. Further, the results are discussed with reference to the particle-hole model. By examination of the microscopic configurations of the possible GDR states an explanation is proposed for the differences in the cross sections to various residual states. Finally, the results are compared with spectroscopic factors determined from pickup reactions on ^{27}Al.

E | NUCLEAR REACTIONS ^{27}Al(e, p), E = 14.8–27.6 MeV; measured proton energy spectra at θ = 90°. Deduced $\sigma(\gamma$, p) to different ^{26}Mg states, mechanism. Magnetic spectrometer, isotopically pure target.

1. Introduction

Since the advent of photonuclear physics, much interest has centred on the light 2s-1d shell nuclei. The photonuclear giant resonances of many of these nuclei have been studied in great detail and reveal a diverse range of features. Effects due to configurational splitting resulting from inner and outer shell excitations [1]), isospin splitting [2]) and possibly deformation splitting [3]) have been observed or postulated in various members of this shell.

A comprehensive theoretical description of the giant dipole resonance (GDR) of all 2s-1d shell nuclei is by no means available, however the 1p-1h model has been applied to the closed subshell nuclei ^{28}Si [ref. [4])] and ^{32}S [ref. [5])] with considerable success. The small number of possible 1p-1h configurations created by E1 photons in the 2s-1d shell nuclei encourages the belief that this model will also be applicable in the regions away from the closed subshells.

In the 1p-1h model, particle-hole pairs are created in the nuclear ground state by E1 photons. If the excited particle of a given particle-hole pair is subsequently emitted into the continuum with little further interaction the nucleus will be left in a hole state relative to the initial target nucleus. Indeed measurements of de-excitation γ-ray spectra following photodisintegration tend to support this model of the photonuclear mechanism. Both for ^{28}Si [ref. [6])] and ^{32}S [ref. [7])] good correlation was observed between spectroscopic factors of single-nucleon pickup reactions and the measured integrated photonuclear cross sections to the same residual states, thus suggesting that the photonuclear emission process is predominantly single-particle in nature.

However there is some controversy as to whether the interpretation of the de-excitation data is correct. It was suggested [8]) that the observed de-excitation strength of the low-lying states is the result not only of direct population but also enhancement by γ-ray cascades from higher excited states which may also be populated by photonucleon emission. It is possible that these high energy γ-ray cascades might not be detected because of the poor response of the Ge(Li) detectors at high energy, so that the final results could be ambiguous. This may be clarified by direct measurement of the protons emitted to the ground and various low-lying states.

^{27}Al is a light nucleus belonging to the 2s-1d shell whose photonuclear giant resonance has been investigated extensively by (γ, n) [refs. [9,10])], (γ, p) [ref. [11])] and also by (γ, $x\gamma'$) [ref. [12])] measurements. The present work describes a measurement of photoproton spectra from ^{27}Al. From these spectra, high resolution photoproton cross sections to specific states may be deduced since the low-lying ^{26}Mg states are well separated in energy [13]). Since these results are not subject to any ambiguity the validity of the de-excitation measurements can be closely scrutinized. In addition since the wave functions of the initial target nucleus and the final residual nuclear states are fairly well known, the photoproton decay mechanism can be studied in great detail.

2. Experimental details

A thin foil target (8.10 mg/cm^2) of pure ^{27}Al($>$ 99.5 %, ^{27}Al) was bombarded with the electron beam from the 300 MeV linear accelerator at Tohoku University. The charged particles emitted at 90° to the incident beam were analyzed by a broad range magnetic spectrometer of the Browne-Buechner type [14]) and detected with 100 Si(Li) solid-state detectors arranged on its focal plane. A thin Al foil was placed directly in front of these detectors so that α-particles and protons of the same energy could be distinguished on the basis of their differential energy loss in the foil.

Spectra were measured in 400 keV steps for incident electron energies ranging from 14.8 to 27.6 MeV. Over this range the momentum resolution of the incident electrons was fixed at 1.0 %, so that at 20 MeV, for example, an energy spread of 200 keV was obtained.

3. Analysis

The proton energies were corrected for mean energy loss in the target and nuclear recoil. The energy loss of a 10 MeV proton detected at 90° was about 200 keV. Sample photoproton spectra from ^{27}Al are displayed in fig. 1 with the corresponding electron beam energies listed above. In each case the maximum proton energy agrees within 100 keV with the theoretically expected maximum energy indicating the high resolution obtained.

Fig. 2 shows the decay of the ^{27}Al GDR to residual states of ^{26}Mg by photoproton emission. The energies of the ^{26}Mg states are taken from the compilation of Endt and Van der Leun [13]).

Since the first excited state of ^{26}Mg is located at 1.809 MeV [ref. [13])], the uppermost 1.809 MeV of each proton spectrum contains only ground state photoprotons. Thus the ^{27}Al(γ, p_0) differential cross section at 90° was readily unfolded by dividing the proton yield in this tip region by the virtual photon spectrum appropriate for each electron energy [15]). The final 400 keV of each spectrum was neglected in the analysis because of the poor statistics. Nevertheless each ^{27}Al(γ, p_0) point in the final cross section was derived independently from 3 or 4 spectra. However the top

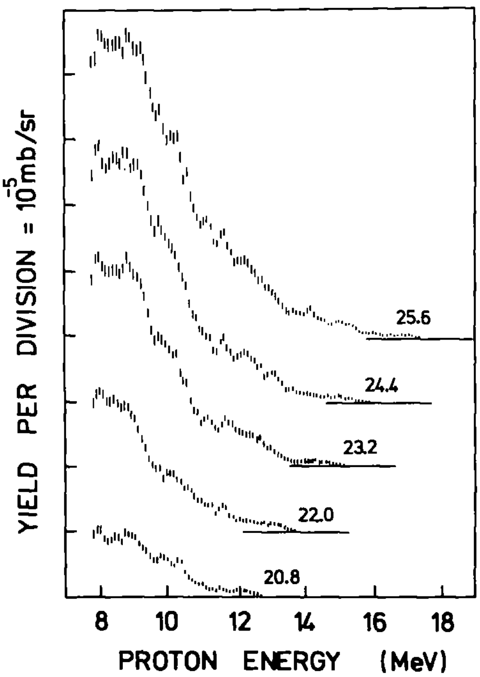

Fig. 1. Sample photoproton spectra from ^{27}Al. For each spectrum the appropriate electron energy is superposed.

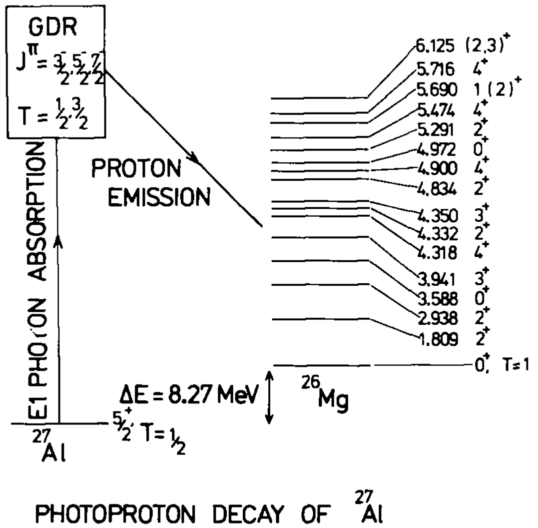

Fig. 2. The photoproton decay of ^{27}Al to residual states of ^{26}Mg. The energies of the ^{26}Mg levels are taken from ref. [13]).

400 keV or so of the cross section is not determined so well since this part of the cross section is obtained from only one spectrum.

As shown in fig. 2 the next excited states of ^{26}Mg are located at 2.938, 3.588 and 3.941 MeV followed by a triplet at 4.3 MeV (4.318, 4.332 and 4.350 MeV). Thus since the second and third excited states are clearly separated the ^{27}Al(γ, p_1) differential cross section was deduced by subtracting the ground state contribution from each spectrum and analyzing the resulting reduced spectra as for the ^{27}Al(γ, p_0) cross section. In similar fashion the ^{27}Al(γ, p_2) differential cross section was also derived though with correspondingly worse statistics since both ground and first excited state contributions were subtracted.

Above the third excited state at 3.588 MeV, the residual states of ^{26}Mg are clustered more closely. Thus it is necessary to make some assumptions as to which states of ^{26}Mg are populated by the ^{27}Al(γ, p) reaction. According to the de-excitation results of Thomson [12]), the fourth excited state at 3.941 MeV(3^+) of ^{26}Mg is not populated, and the population of the 3.588 MeV(0^+) state is in doubt because of a γ-ray cascade ambiguity. On the other hand the states around 4.3 MeV (4.318, 4.332 and 4.350 MeV) and 4.9 MeV (4.834, 4.900 and 4.972 MeV) are populated. The next higher populated state according to Thomson, is at 6.125 MeV (2^+).

Assuming then that neither the 3.588 nor the 3.941 MeV state of ^{26}Mg is populated the next highest populated states were taken as 4.3 MeV (the centre of gravity of the triplet), 4.9 MeV (the centre of gravity of the states at 4.834, 4.900 and 4.972 MeV) and 6.1 MeV. Thus the residual states populated by the

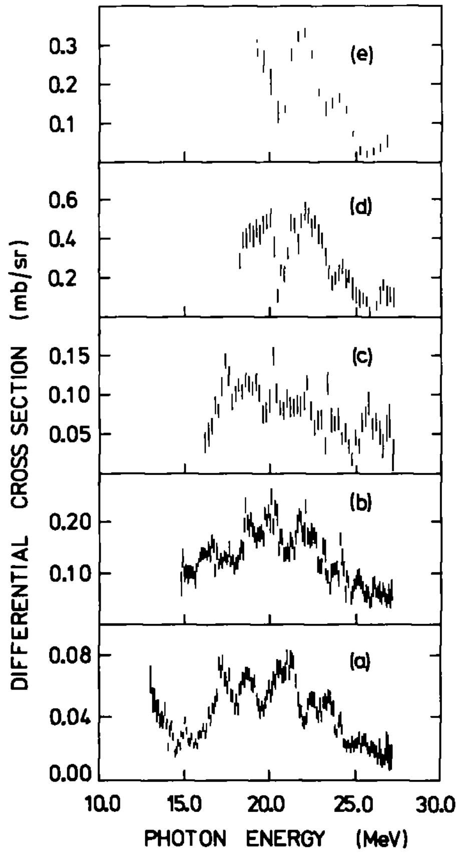

Fig. 3. Differential cross sections at 90° for the reaction $^{27}Al(\gamma, p_i)$: (a) $^{27}Al(\gamma, p_0)$, (b) $^{27}Al(\gamma, p_1)$, (c) $^{27}Al(\gamma, p_2)$, (d) $^{27}Al(\gamma, p_{“3”})$ and (e) $^{27}Al(\gamma, p_{“4”})$.

$^{27}Al(\gamma, p)^{26}Mg$ reaction are effectively located at 0, 1.81, 2.94, 4.3, 4.9 and 6.1 MeV.

Differential cross sections at 90° were thus derived to the ground, first, second, "third" and "fourth" excited states. These are displayed in fig. 3. The resolution of the cross sections to higher excited states becomes worse because of the cumulative effects involved in the analysis and because of the uncertainty in assigning a mean energy for groups of residual states. In addition the minimum energy at which the cross sections can be determined increases with the excitation energy of the residual states.

For each electron energy the magnetic spectrometer was set so that the highest energy protons were recorded. Thus, because of its operational mode, only for certain electron energies were spectra recorded which could include photoprotons decaying to residual states greater than about 5 MeV in energy. Hence cross sections to these higher energy residual states could not be derived from the present data.

4. Discussion

(a) GENERAL FEATURES

The ground and first excited state cross sections (plotted on an expanded scale in fig. 4) exhibit considerable structure. The ^{27}Al(γ, p_0) cross section has local peaks at 17.2, 18.6, 20.5, 21.3, 22.5, 23.5 and 24.0 MeV superimposed on a broad resonance centred at roughly 21 MeV. The maximum value of the differential cross section at 90° is about 0.08 mb/sr and the FWHM of the broad resonance about 7 MeV. On the other hand the ^{27}Al(γ, p_1) cross section has peaks at 16.5, 18.6, 20.1, 21.7, 24.0 and 25.2 MeV which do not correlate exactly with those in the ground state cross section. The integrated cross section to the first excited state is about 3 times that to the ground state.

The ^{27}Al(γ, p_2) cross section is less well defined and little structure is visible. The cross section rises rapidly to a value of roughly 0.15 mb/sr at 17 MeV and thereafter decreases slowly to about 0.07 mb/sr at 24 MeV.

The ^{27}Al(γ, $p_{\text{“}3\text{”}}$) cross section to the states centred around 4.3 MeV is dominated by two strong peaks of several MeV width at 19.6 and 22.0 MeV. The maximum value of about 0.6 mb/sr at 22.0 MeV is far greater than the maximum value of the cross section to any of the lower lying states. However the integrated cross section

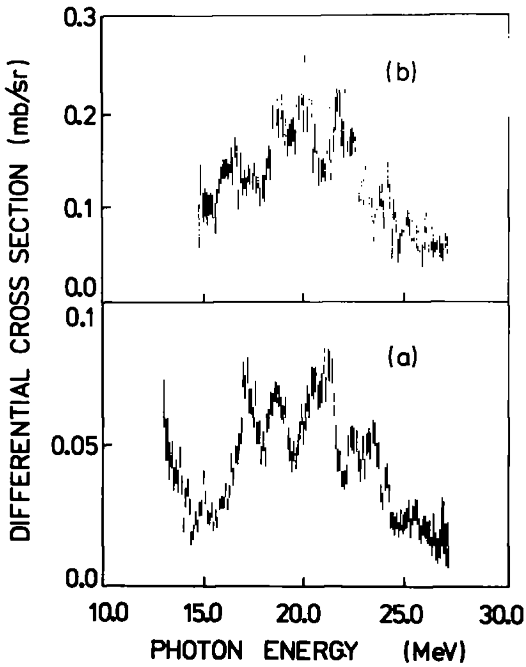

Fig. 4. Differential cross sections at 90° to the ground and first excited states: (a) ^{27}Al(γ, p_0) and (b) ^{27}Al(γ, p_1).

TABLE 1

Results and comparison with previous measurements

Residual state in ^{26}Mg [from ref. [13]] (MeV)	$\int_{14.8}^{27.6} \frac{d\sigma}{d\Omega}(\gamma, p)dE$ (at 90°) (MeV · mb/sr) [a])	$\int_{16}^{26} \frac{d\sigma}{d\Omega}(\gamma, p)dE$ (at 90°) (MeV · mb/sr) [b])	$\int_{16}^{24} \frac{d\sigma}{d\Omega}(\gamma, p\gamma')dE$ (at 150°) (MeV · mb/sr) [c])
0, 0^+	0.60 ± 0.06	0.45 ± 0.06	
1.809, 2^+	1.61 ± 0.17	0.92 ± 0.2	2.00 ± 0.5
2.938, 2^+	0.9 ± 0.2		0.74 ± 0.15
3.588, 0^+	[e])		(0.32 ± 0.1) [d])
3.941, 3^+	[e])		
4.318, 4^+ }			1.5 ± 0.2
4.332, 2^+ }	2.7 ± 0.6		< 0.25
4.350, 3^+ }			0.5 ± 0.2
4.834, 2^+ }			0.63 ± 0.15
4.900, 4^+ }	1.4 ± 0.5		< 0.2
4.972, 0^+ }			

a) Present results.
b) Results of Tsubota *et al.* [16]).
c) Results of Thomson from a de-excitation gamma-ray measurement [12]).
d) This assignment is uncertain [12]).
e) These states were assumed to be unpopulated in the present analysis (see text).

to these states is not much greater than that to the first excited state (see table 1).

The cross section to the group of states at 4.9 MeV is not well defined over the whole energy region due to limitations in the range of proton energies measured. In order to improve the statistics the cross section points have been summed in 400 keV steps. It is likely that this cross section contains decay strength to states above 4.9 MeV, such as the state at 5.474 MeV which is also strongly populated in pickup reactions [13]). Thus the large integrated cross section to the states centred at 4.9 MeV may be artificially enhanced.

As indicated previously, table 1 lists the integrated cross sections for the photoproton decay of ^{27}Al to the residual states of ^{26}Mg according to the present measurement. Of course it has been assumed in the analysis that the states at 3.588 and 3.941 MeV are not populated so that the cross section to these states is unresolved.

(b) COMPARISON WITH PREVIOUS MEASUREMENTS

A previous measurement of photoproton energy spectra from ^{27}Al was carried out at Tohoku University by Tsubota *et al.* [16]). These authors derived $^{27}Al(\gamma, p_0)$ and $^{27}Al(\gamma, p_1)$ differential cross sections at 90° and their results are quoted in table 1. The structures observed in this measurement show good correlation with the present measurement although the resolution is worse since the spectra were measured in 1 MeV rather than 400 keV steps. In agreement with the present results the fine features in the $^{27}Al(\gamma, p_0)$ and $^{27}Al(\gamma, p_1)$ cross sections are noticeably different. However the integrated cross sections to these two states are smaller since the spectra were measured only from 16 to 26 MeV excitation energy.

Integrated photoproton cross sections to excited states of ^{26}Mg were determined by Thomson [12]) from measurements of de-excitation γ-rays following photodisintegration. As table 1 shows, the integrated cross section to residual states up to and including those at 4.9 MeV is about 7.2 MeV mb/sr from the present results. The de-excitation results yield an upper limit of 6.1 MeV mb/sr for the integrated cross section to the same low-lying states (excluding the ground state cross section which cannot be determined from a de-excitation measurement). The maximum bremsstrahlung energy of 24.3 MeV used was less than the maximum electron energy of 27.6 MeV used in the present measurement. As seen in fig. 3 however, there is little cross section above 24 MeV to any of the residual states.

Hence the present measurement indicates that the low-lying states are populated very strongly following photoproton emission consistent with the conclusions of Thomson from his measurement of de-excitation γ-rays. Further, this latter measurement demonstrates clearly that the most strongly populated member of the triplet at 4.3 MeV is the 4.318 MeV state with spin 4^+. The $^{27}Al(\gamma, p_{\text{"}3\text{"}})$ cross section in fig. 3 is thus likely to reflect the photoproton decay principally to this state.

As indicated from table 1, the total decay strength to the residual states up to 4.9 MeV is about 7.2 MeV mb/sr. If the angular distribution of each partial cross section is assumed to be the same as the angular distributions of the $^{27}Al(\gamma, p_0)$ and $^{27}Al(\gamma, p_1)$ reactions [17]), the total cross section integrated over angles is obtained by multiplying the differential cross section at 90° by a factor of 11.5. Thus, integrated up to 27.6 MeV, the decay strength to these low-lying states is roughly 60–80 MeV · mb (the derived cross section to the states around 4.9 MeV is probably enhanced by decays to higher excited states and is thus uncertain).

The total integrated photoproton cross section can be estimated by subtracting the integrated photoneutron cross section from the total absorption cross section. Taking the integrated photoneutron cross section as 135 MeV · mb, the mean of the values obtained by Fultz *et al.* [9]) and Veyssiere *et al.* [10]) using quasi-monochromatic photons, and the total absorption cross section as 275 MeV · mb measured by Wyckoff *et al.* [18]) (all cross sections integrated up to 27.6 MeV) a value of roughly 140 MeV · mb is obtained for the total photoproton cross section.

The relatively low threshold for the $^{27}Al(\gamma, p)$ reaction (8.271 MeV) provides many open photoproton decay channels. At a GDR energy of 20 MeV, for instance, there are well over 100 levels in the residual ^{26}Mg nucleus [13]) which can be populated on the basis of threshold alone. Nevertheless a very large fraction (as high as 50 %) of photoproton decays is to the first 10 or so levels according to the present measurement. Such strong decay cannot be attributed to statistical proton emission and suggests an interpretation similar to that of Thomson *et al.* [6,7]) for the decay of the ^{27}Al GDR.

(c) INTERPRETATION

Since the interaction between photon and nucleus is described by a one-body operator, the initial configurations excited will be 1p-1h states based on the original nuclear ground state. These are the so-called "doorway states" of the photonuclear reaction and may either decay by emitting the excited nucleon into the continuum or may further excite more complex *np*-*n*h configurations [19]). These can decay only via their coupling to the initial 1p-1h states [20]). Thus the simple 1p-1h states created by the incoming photon should provide a reasonable basis for investigation.

Veyssiere *et al.* [10]) suggested that the structures seen in their measurement of the ^{27}Al(γ, n) cross section should be associated with 1p-1h configurations because of their widths. The resolution of their measurement was about 200 keV which was insufficient to observe the fine ($\sim$ 70 keV) structure seen, for example, in the measurement of the ^{27}Al(p, γ_0) cross section by Singh *et al.* [21]). This fine structure arises from the coupling of the 1p-1h states to the more numerous 2p-2h configurations and has the effect of fragmenting the dipole strength. The peaks observed in the present measurement of partial photoproton cross sections should thus also be associated with the basic 1p-1h states since the experimental resolution is always greater than 200 keV.

With this in mind, it is instructive to consider which 1p-1h excitations will contribute to the ^{27}Al GDR. In the simplest shell-model picture, the ground state of ^{27}Al has 11 particles in the $1d_{\frac{5}{2}}$ subshell. The 1p-1h states may be created by single-particle excitations from the $1d_{\frac{5}{2}}$ subshell to the 2p-1f shell or from the 1p shell to the unfilled levels of the 2s-1d shell. A zeroth order calculation based on the dipole transition formula [22]):

$$D^2 = \tfrac{1}{3}q^2(2j_1+1)\langle j_1 \tfrac{1}{2}\, 10 | j_2 \tfrac{1}{2}\rangle^2 \left| \int \mathrm{d}r r^3 R_1 R_2 \right|^2 \tag{1}$$

(where j_1 and j_2 are the initial and final spins of the nucleon being excited) indicates that the $1d_{\frac{5}{2}} \rightarrow 1f_{\frac{7}{2}}$ transition should be the strongest, with over one-half the absorption strength. Excitations from the 1p shell should also be significant but these will lead to population of negative-parity residual states higher in energy than the residual states considered here, which all have positive parity.

Proton pickup experiments on ^{27}Al demonstrate that the ground state (0^+), first excited state (1.809 MeV, 2_1^+), second excited state (2.938 MeV, 2_2^+) and the states around 4.3 MeV are strongly populated by $d_{\frac{5}{2}}$ proton pickup [23-25]). It is likely that the pickup strength of this latter level can be mostly attributed to the

4.318 MeV, 4^+ state. In addition, according to Wagner *et al.* [23]), the 2^+ strength is split between the first and second excited states because of $(d_{\frac{5}{2}})^8(2s_{\frac{1}{2}})^2$ admixtures.

Thus these states all have the basic configuration of $2d_{\frac{5}{2}}$ holes relative to the "closed" ^{28}Si nucleus. Photon induced excitation and emission of a $1d_{\frac{5}{2}}$ proton from the $1d_{\frac{5}{2}}$ subshell will leave 2 holes in this subshell. These 2 holes will recouple to 0^+, 2^+ or 4^+ only and will form the residual states (with spins 0^+, 2^+ and 4^+) just mentioned.

Pursuing this simple model one stage further it should be noted that if the $d_{\frac{5}{2}}$ proton subshell in the ^{27}Al ground state has 4 paired protons and one unpaired proton, excitation and emission of the unpaired proton will result in formation of the ^{26}Mg ground state with spin 0^+. Removal of one of the paired protons will leave the nucleus in a non-zero magnetic quantum substate because of the Pauli principle so that the residual nucleus cannot be in a 0^+ state. The two unpaired protons must then couple to 2^+ or 4^+ and these residual states will be more strongly populated than the ground state, with spin 0^+, by simple weighting arguments.

Furthermore, since the ground state of ^{27}Al has spin $\frac{5}{2}^+$ the E1 selection rules permit giant resonance states of spins ($\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$) to be excited. If these states, represented as an excited nucleon coupled to a residual core, decay by emitting the excited nucleon with little further interaction, then the GDR states which can decay to the 0^+, 2^+ and 4^+ states of ^{26}Mg are listed in table 2. It is immediately apparent that decay to the 2^+ and 4^+ states is far more complicated than decay to the ground state (0^+). The 2^+ state may be populated by proton emission from 9 possible GDR configurations while the ground state can be populated from 3 only.

Thus, a combination of the two effects mentioned in the preceding paragraphs may explain qualitatively why the $^{27}Al(\gamma, p_0)$ and $^{27}Al(\gamma, p_1)$ cross sections have different strength and structure. Excitation of the unpaired proton leaves the residual

TABLE 2

Configurations of the GDR states of ^{27}Al (expressed as a ^{26}Mg core coupled to an excited nucleon) which can decay to the 0^+, 2^+ and 4^+ states of the residual ^{26}Mg nucleus

Residual state spin	GDR state spin	Possible GDR configurations (^{26}Mg core ⊗ particle)
0^+	$\frac{3}{2}^-$	$0^+ \otimes 2p_{3/2}$
	$\frac{5}{2}^-$	$0^+ \otimes 1f_{5/2}$
	$\frac{7}{2}^-$	$0^+ \otimes 1f_{7/2}$
2^+	$\frac{3}{2}^-$	$2^+ \otimes (2p_{3/2}, 1f_{5/2}, 1f_{7/2})$
	$\frac{5}{2}^-$	$2^+ \otimes (2p_{3/2}, 1f_{5/2}, 1f_{7/2})$
	$\frac{7}{2}^-$	$2^+ \otimes (1p_{3/2}, 1f_{5/2}, 1f_{7/2})$
4^+	$\frac{3}{2}^-$	$4^+ \otimes (1f_{5/2}, 1f_{7/2})$
	$\frac{5}{2}^-$	$4^+ \otimes (2p_{3/2}, 1f_{5/2}, 1f_{7/2})$
	$\frac{7}{2}^-$	$4^+ \otimes (2p_{3/2}, 1f_{5/2}, 1f_{7/2})$

nucleus in a 0^+ state which can couple only in one way to the excited nucleon to form a GDR state. Conversely excitation of a paired proton leaves the core in a 2^+ or 4^+ state which can couple to the excited nucleon to form a multiplicity of possible GDR states.

Moreover, it might be expected that the cross sections to the 2^+ and 4^+ states should be similar since the configurations which can populate each state are similar apart from the spin of the core. The resolution of the ^{27}Al(γ, p"$_3$") cross section (which is expected to reflect decay mainly to the 4^+ state at 4.318 MeV) is not good enough to make a detailed comparison. However the two regions of strength at around 19.5 and 22.0 MeV resemble the structure in the ^{27}Al(γ, p_1) cross section at (18.6, 20.1 MeV) and (21.7, 22.0 MeV) respectively (refer to fig. 3).

The cross section to the states at 3.588 MeV (0^+) and 3.941 MeV (3^+) cannot be resolved from the present measurement. According to Wagner *et al.* [23]) the weak proton pickup strength to these states is consistent with principal shell-model configurations of $(d_{\frac{5}{2}})^8(2s_{\frac{1}{2}})^2$ and $(d_{\frac{5}{2}})^9 2s_{\frac{1}{2}}$ respectively (relative to the closed ^{16}O core). Such states cannot be populated by single-nucleon excitation and emission from the ^{27}Al ground state assumed so far to have 11 nucleons in the $d_{\frac{5}{2}}$ subshell.

However, thorough shell-model calculations by Wildenthal and McGrory [26]) (in a $1d_{\frac{5}{2}}-2s_{\frac{1}{2}}-1d_{\frac{3}{2}}$ basis space) reveal that the ground state $d_{\frac{5}{2}}$ occupancy of ^{27}Al is 9.9 (rather than 11) and that there are significant admixtures of configurations which include $1d_{\frac{3}{2}}$ and $2s_{\frac{1}{2}}$ nucleons. Hence these two states may be populated via such admixtures. Interestingly, the de-excitation measurement of Thomson (see table 1) indicates that the 3.588 MeV state is populated weakly if at all whereas the 3.941 MeV state is not populated. From this it may be inferred that removal of a nucleon from one of these admixtures either by direct particle pickup or by photoproton emission is far less likely than removal of a $d_{\frac{5}{2}}$ proton from the principal ^{27}Al ground state configuration.

On the other hand, the present measurement shows that higher excited states around 4.9 MeV (the ^{27}Al(γ, p"$_4$") cross section in fig. 3 possibly also includes decay strength to the state at 5.474 MeV as well) are strongly populated following photoproton decay. These states are also populated by direct pickup of $d_{\frac{5}{2}}$ protons from ^{27}Al [ref. [23])]. No shell-model wave functions have been published for these states, however it is probable that they have very complex structure without having a single dominant configuration like the lower-lying states. Thus they may include *np-nh* admixtures raising them in energy above the states with simple configurations. For the case of ^{32}S, Varlamov *et al.* [27]) attributed the photoproton decay to residual states of ^{31}P greater than 3 MeV to be partially due to the decay of the more complicated *np-nh* configurations in the GDR. Similarly the strength of the integrated cross section to the states at 4.9 MeV could be caused in part by decay of *np-nh* configurations in the ^{27}Al GDR.

So far the discussion has concerned photoproton decay only to the positive-parity residual states of ^{26}Mg. Brady *et al.* [25]) found that the strength with which the 7.86

MeV (2^-) and the 9.16 MeV (3^-) states are populated by $1p_{\frac{1}{2}}$ proton pickup more than exhausts the sum rule limit. Thus it would be expected that these states be strongly populated via decay of 1p-1h excitations formed by exciting 1p shell nucleons to the 2s-1d shell. This decay strength cannot be resolved from the present data, however for the neighbouring nucleus ^{26}Mg Ishkhanov *et al.* [28]) found that up to an excitation energy of 27 MeV, over 35 % of the (γ, p) channel goes to negative-parity residual states of ^{25}Na. Consequently photoproton decay to negative-parity residual states may well be significant for the ^{27}Al case.

Photoproton decay to higher excited states, as mentioned previously, may involve contributions from the more complicated np-nh configurations of the ^{27}Al GDR. The present measurement has shown that about 50 % of the photoproton decay is to states below about 4.9 MeV. It is thus reasonable to assume that the remaining strength arises both from 1p shell excitations and the decay of these more complicated np-nh GDR configurations.

(d) COMPARISON WITH PICKUP DATA

In the preceding section reference was made to single-nucleon pickup reactions on ^{27}Al to ascertain the nature of the ^{26}Mg residual states. Direct proton [23-25]) and neutron [29,30]) pickup studies on ^{27}Al indicate that the majority of the pickup strength results from $l = 2$ nucleon transfer. It is reasonable to assume that this has resulted from the pickup of a $d_{\frac{5}{2}}$ nucleon from the ^{27}Al ground state. Since it was shown in the previous section that the low-lying states of ^{26}Mg are most likely populated by the excitation and subsequent emission of a $d_{\frac{5}{2}}$ proton, it is of interest to compare the spectroscopic factors determined in pickup with the residual state populations following photoproton emission.

Table 3 shows a comparison between the integrated cross sections for photoproton emission and the spectroscopic factors deduced from (d, τ) [refs. [23,24])] and (n, d) [ref. [25])] reactions on ^{27}Al. The photoproton data have been arbitrarily normalized to the spectroscopic factor for the first excited state determined by Wagner *et al.* [23]). Considering that the spectroscopic factors are only accurate to about 30 % the overall agreement is good. Not only are the same states populated, but there is also fair agreement in their relative population strengths. Carrying this correlation further it should be noted that the 3.588 and 3.941 MeV states which were assumed to be unpopulated by photoproton decay in the present analysis are populated only very weakly in pickup reactions.

Table 3 also includes the spectroscopic factors for proton pickup as calculated by Wildenthal *et al.* [31]) using the many-particle shell model. This calculation predicts the spectroscopic factors for the strongly populated states better than either the simple weak coupling model or the simple rotational model [see ref. [25])] and indicates that a 4^+ level at about 4.3 MeV should be very strongly populated. The pickup data cannot resolve the strength to the triplet at 4.3 MeV but it is expected that the 4^+ state at 4.318 MeV is by far the most strongly populated.

TABLE 3

Comparison between residual state populations following photoproton emission and spectroscopic factors from proton pickup on ^{27}Al

Residual state in ^{26}Mg (MeV)	$\int_{14.8}^{27.6} \frac{d\sigma}{d\Omega_{90°}}(\gamma, p)dE$ (relative) [a]	^{27}Al(d, τ) C^2S [b]	^{27}Al(d, τ) C^2S [c]	^{27}Al(n, d) C^2S [d]	Shell model C^2S [e]
0, 0^+	0.34	0.27	0.26	0.24	0.29
1.809, 2^+	0.92	0.92	0.85	0.72	0.75
2.938, 2^+	0.51	0.19	0.29		0.29
3.588, 0^+		0.01			
3.941, 3^+		0.01			
4.318, 4^+ } 4.332, 2^+ } 4.350, 3^+ }	1.51	1.92	2.1	1.87	1.8(4^+)
4.834, 2^+ } 4.900, 4^+ } 4.972, 0^+ }	0.81	0.36			0.02

[a]) Present results.
[b]) From Wagner et al. [23]).
[c]) From Arditi et al. [24]).
[d]) From Brady et al. [25]).
[e]) From Wildenthal et al. [31]).

The agreement between the residual state populations following photoproton emission and the spectroscopic factors from pickup reactions is remarkably good. This further strengthens the contention that the dominant mechanism for photoproton reactions in ^{27}Al is the excitation of a proton from the $1d_{\frac{5}{2}}$ subshell to the 2p-1f shell forming an intermediate dipole state. This is followed by the emission of that excited nucleon with little further interaction with the nucleus.

5. Conclusion

Photoproton spectra from ^{27}Al were measured over the GDR energy region. From these spectra photoproton cross sections to specific low-lying states of the residual nucleus ^{26}Mg were deduced. The strong population of these low-lying states is at variance with statistical decay theory but is consistent with de-excitation measurements which also showed that these states are populated strongly. This good agreement tends to justify the use of the de-excitation γ-ray technique to study the decay of the GDR in light nuclei.

To a first approximation the low-lying residual states of ^{26}Mg are populated by decay of 1p-1h states formed by exciting 2s-1d shell nucleons into the 2p-1f shell. The GDR states which can decay to the 2^+ and 4^+ states, in this simple model, are far more numerous than those which can decay to the ground state (0^+) and have different microscopic configuration. This may qualitatively account for the differences in the measured cross sections to these states.

The remainder of the strength in the photoproton decay channel must be due both to decay of 1p-1h states formed by 1p shell excitations and decay of the *n*p-*n*h configurations in the ^{27}Al GDR. Both these mechanisms lead to residual states of high energy so their cross sections cannot generally be determined by the present measurement. However the positive-parity states around 4.9 MeV could well be populated in part via the latter mechanism.

Finally, the good correlation between the present results and spectroscopic pickup factors further supports the hypothesis that the low-lying states of ^{26}Mg are populated by excitation of 2s-1d shell protons to the 2p-1f shell followed by their subsequent emission.

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