THE PHOTONUCLEAR GIANT RESONANCE IN SILICON–28

By A. W. Parker,* R. R. Whitehead,* and G. G. Shute*

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Summary

The 90° yields of γ-rays from the reaction $^{27}Al(p,\gamma)^{28}Si$ have been obtained at intervals of 40 keV for proton energies between 8·02 and 10·42 MeV. The ground state γ-ray (γ_0) and the first excited state γ-ray (γ_1) were adequately resolved. The two yield curves show considerable structure and, with the present resolution, there is a strong one-way correspondence between them. The gross structure of the γ_0 yield curve is compared with data from the $^{28}Si(\gamma,n)^{27}Si$ reaction and fair agreement is found.

I. Introduction

In recent years the detailed structure of the photonuclear giant resonance in light and medium weight nuclei has been of considerable interest. This is derived, in part, from the better experimental facilities now available. The resolution obtainable in bremsstrahlung was insufficient to show much more than the broadest structure. In the last few years this difficulty has been partly overcome by the development of other techniques (nearly monochromatic annihilation radiation, time-of-flight spectroscopy of the reaction products, and study of radiative proton capture reactions). As a result it has become possible to obtain much more accurate information than formerly.

In particular, the proton capture reactions studied at Canberra (Gemmel, Morton, and Smith 1959; Gemmel, Morton, and Titterton 1959), Oxford (Tanner, Thomas, and Earle 1964*a*, 1964*b*), and Chalk River (Gove, Litherland, and Batchelor 1961) show that, at least for the light α-particle nuclei (^{8}Be, ^{12}C, ^{16}O, and others), the giant resonance contains more structure than was observed in older bremsstrahlung experiments. These results show further that there is less structure in the giant resonance regions of nuclei near major closed shells (^{16}O and ^{40}Ca) than there is in nuclei far away from these shells (^{24}Mg and ^{28}Si). The recent ^{40}Ca bremsstrahlung experiment (Baglin and Spicer 1964) shows more structure than normally revealed in such experiments.

It is possible also to obtain from proton capture experiments the distribution of those states in the compound system that may make radiative transitions directly to the first excited state of the residual nucleus. For the α-particle nuclei, all the states that can decay to the ground state can also decay to the first excited state, but not necessarily vice versa, and thus there should exist a one-way correspondence

* School of Physics, University of Melbourne.

between the peaks in the γ_0 yield and those in the γ_1 yield. Evidence of such correlations exist in the γ-ray yields from ^{12}C and ^{20}Ne (Allas *et al.* 1964; Tanner, Thomas, and Earle 1964*a*). On the other hand the measurements of γ-rays from ^{28}Si made by the Chalk River group between 8 and 10 MeV, using energy intervals of 200 keV and a thin target (20 keV), displayed little if any detailed correspondence between the yields. Similar behaviour was observed in the region below 8 MeV where the data points were closer together. Since the region from 8 to 10 MeV includes the peak of the giant resonance in ^{28}Si (Gardner 1961) and therefore is the region where one might expect the correspondence to be strongest (see Section IV), it was chosen for investigation in finer energy steps than had been used up to that time.

II. Apparatus and Experimental Procedure

The analysed proton beam from the Melbourne cyclotron was focused onto the target through two collimators. The beam spot was about $\frac{1}{4}$ in. in diameter, and its position was frequently observed with a quartz plate viewed by a television camera. The reproducibility of the results was established firstly with the 4·43 MeV γ-rays following the reaction ^{12}C(p,p′)^{12}C, $Q = -4\cdot 43$ MeV, and secondly during the runs with the reaction under investigation.

The γ-rays were detected at 90° by a shielded 5-in. diameter by 6-in. long sodium iodide crystal 10 in. from the target. The shield was a lead cylinder with a wall thickness of 4 in. Its front face was closed with a 2-in. thick lead disk with a tapered collimating aperture of 2-in. diameter at the crystal face. γ-Rays from the two collimators and the Faraday cup were shadow shielded from the crystal by at least a further 6 in. of lead.

The electronics have been partially described in a previous paper (Parker and Shute 1962). About 10 min was allowed to elapse in each run before counting commenced, because it is during this time that gross gain changes are most likely to occur (Jung, Panussi, and Janecke 1960). Pile-up effects were minimized by keeping the beam current below about 0·1 μA. It thus required about half an hour to obtain a spectrum with statistics of 10% or better in each of the channels near the peak of γ_1. Finally, dead-time losses in the 256 channel pulse-height analyser were reduced by removing the low energy pulses with a discriminator. Continuous recording of live time and true time showed that dead-time losses were less than 2%.

The target was a self-supporting aluminium foil of thickness $0\cdot 75 \pm 0\cdot 05$ mg cm^{-2} (about 28 keV thick for 9 MeV protons). A yield curve is supposed to be a continuous function of energy, but if the energy intervals used are appreciably greater than the target thickness this is not so and some detail may be lost where it would otherwise be merely smeared out. In this experiment, 40 keV intervals were used in the proton range 8·02–10·42 MeV.

III. Experimental Results—Pulse-Height Spectra

Figure 1 shows a typical pulse-height spectrum obtained in this experiment. It is characterized by a prominent peak corresponding to the first excited state transition (γ_1), a fairly prominent shoulder arising from the ground state transition

(γ_0), and a very weak peak due to the second excited state transition. The steeply rising low-energy edge is caused mainly by neutron capture in the iodine of the crystal, while the flat high-energy tail is due to cosmic rays.

The spectra were analysed with the help of the line shapes for shielded and unshielded crystals experimentally determined by Gardner (1961). Using these a line shape appropriate to the present conditions could be interpolated with reasonable accuracy. Although these line shapes were obtained for 19·8 MeV γ-rays, Gardner found that the line shape is insensitive to energy variations of ± 5 MeV in this region. This is in agreement with the results of Kockum and Starfelt (1959) and Mainsbridge (1960).

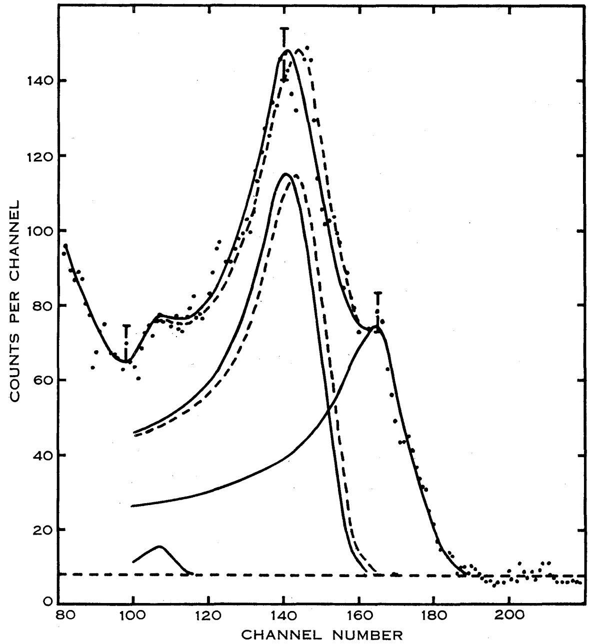

Fig. 1.—Pulse-height spectrum taken at $E_p = 8 \cdot 66$ MeV. The spectrum has been smoothed to assist in fitting the line shapes represented by the solid and dashed lines.

The results of fitting the data are given by the solid and dashed lines of Figure 1. A few comments about this fit are necessary. Firstly, the percentage resolution of both γ_0 and γ_1 has been kept constant. Secondly, the fit is relatively insensitive to the exact peak position of γ_1; the two line shapes drawn represent extreme positions separated by two channels. Thirdly, the height of γ_0 at the peak is found to be twice that beneath the peak of γ_1. By making use of these observations fairly accurate estimates of the yields could be obtained without too much labour.

To estimate the relative yields of γ_0 and γ_1, the average background per channel was found, the average heights H_0 and H_1 of spectra in the regions of the peaks of γ_0 and γ_1 were estimated, and correction factors were applied to take account of the increase of peak channel and efficiency with energy. The yields y_0 and y_1 are then given by

$$y_0 = (H_0 - B)b_0$$

and

$$y_1 = (H_1 - \tfrac{1}{2}H_0 - B)b_1,$$

where b_0 and b_1 are the correction factors mentioned above and B is the average background. The results obtained in this way are accurate to about 7%.

A further check on the above fit may be obtained by analysing the spectrum into two peaks of equal line shape. This may be done fairly easily by starting with the high-energy leading edge of γ_0 which is given uniquely by the data. This is substituted for the leading edge of γ_1 and part of the trailing edge of γ_0 is then found by subtraction. The process is continued and the intensities and shapes are adjusted until at the conclusion the line shapes are the same. Line shapes and fits obtained in this way are indistinguishable from the ones above.

The differential cross-section scales shown in Figure 2 were obtained with the help of the line shapes given in Figure 1. Since these shapes are identical to those interpolated from Gardner's (1961) results, the ratio of counts in the peak, defined to include all the counts above the point where the line shape reaches half height, to the total number of counts was found to be $0 \cdot 35 \pm 0 \cdot 02$. This assumes, as Gardner did, that the tail remains flat from 8 MeV to zero energy. The detection efficiency of the crystal ranged between 0·89 and 0·92 and the solid angle subtended by the collimator at the target was 0·039 sr. Corrections have been made for several complicating factors. These include absorption of the γ-rays in the target holder and the chamber wall, and the increased effective solid angle due to penetration of the collimator by some of the γ-rays. The effect of these corrections is to increase the apparent cross section by about 12% and to increase the absolute error to about 15%.

IV. Discussion

It may be seen from Figure 2 that the one-way correspondence in the peak positions mentioned in Section I does in fact exist under the present conditions of resolution—provided allowance is made for the small shift in position when one peak sits on the side of another. A more recent experiment performed at Argonne National Laboratory (Allas *et al.* 1963) with even smaller energy intervals indicates that the correspondence still holds when the resolution is as small as 15 keV. It is further apparent that the average yield of γ_1 is higher than that for γ_0.

These observations are quite consistent with the known electric dipole character of the giant resonance. Assuming $E1$ transitions, the 0^+ ground state of ^{28}Si can be fed only from 1^- states, whereas the 2^+ first excited state may be fed by 1^-, 2^-, or 3^- states. The additional peaks and higher average cross section for γ_1 could then be due to transitions from the 2^- and 3^- states.

It must be pointed out here that the correspondence between γ_0 and γ_1 observed in these reactions has nothing to do with the validity of Ericson's (1963) cross-section fluctuation theory, which predicts that under certain conditions the cross sections for different exit channels from the same compound system should be uncorrelated. This lack of correlation arises ultimately from the smallness of the coherent part of the reaction amplitude of the overlapping resonances. In photonuclear reactions in the giant resonance region the coherent part of the amplitude must be large because of the very special collective nature of the giant resonance. Under these conditions the fluctuating part of the cross section becomes very small. At lower energies, where, even though there is little dipole strength, (p,γ) reactions may have quite high cross sections, fluctuations of the Ericson kind may be important if the theory is correct. Moreover, as noted by Tanner (personal communication), a correlation of the type found here does not invalidate a statistical interpretation, for Brink and Stephen (1963)

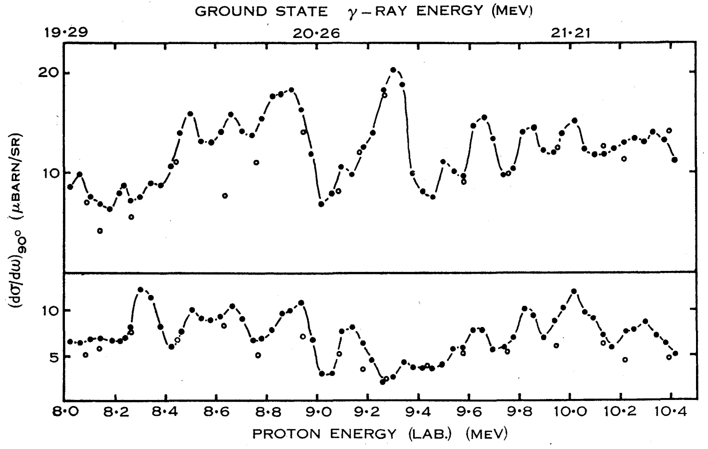

Fig. 2.—Yield curves of ground state γ-rays (lower curve) and first excited state γ-rays (upper curve). The full circles are the present results, and the open circles are the results of Gove, Litherland, and Batchelor (1961). The target-thickness correction ($\sim$ 14 keV) to the energy scale has not been applied.

predict such correlations when the two final states are closely related, e.g. members of the same rotational band. The temptation to try to get a numerical estimate of the degree of correlation by using a cross-correlation function has been resisted in this paper. Such functions are not suited to the sort of data obtained here because they assume a flat underlying background (a condition that is clearly not valid in the present work).

It is of interest to see whether isotopic spin is still a good quantum number in this region. In self-conjugate nuclei, $E1$ transitions change the isotopic spin by either $+1$ or -1. This predicts that both the ground state and first excited state will be fed from $T = 1$ states, as they are $T = 0$. On the other hand, as α-particle emission involves no change in isotopic spin, only $T = 0$ should contribute to the corresponding (p,γ_0) reaction. Comparison of the present (p,γ_0) with the ^{27}Al(p,α_0) results from Oxford (Allardyce, Graham, and Hall 1964) was inconclusive because of the very fine structure in the α-particle yields.

Conservation of isotopic spin also implies that (γ,n_0) and (γ,p_0) total cross sections will differ only by known penetrability and isotopic-spin-space factors

(Barker and Mann 1957). Experiments which separate out the ground state transitions are difficult to perform but monochromatic radiation from positron annihilation-in-flight has been used (Caldwell *et al.* 1963) to measure the total cross section for the reaction $^{28}Si(\gamma,n)^{27}Si$ in which, if T is a good quantum number, only 1^-, $T = 1$ states are selected as in this experiment. They found two prominent peaks of comparable cross section at 19·8 and 20·9 MeV. These clearly correspond to the gross structure in the (p,γ_0) yield curve. The ratios of the dipole strengths of the higher to the lower peak are approximately 3 : 1 in the (γ,n) data and 1 : 1 in the (p,γ_0) data. This is not surprising since one is a total cross section, for which a simple collective model with a nucleus of prolate shape predicts a ratio of about 2 : 1, and the other is a partial cross section. The recent particle–hole calculations of Bolen and Eisenberg (1964) predict the ratio of the strengths to be 3 : 1; thus this shell-model calculation adequately accounts for the gross structure.

Recent experiments on $^{27}Al(p,n)^{27}Si$ by the time-of-flight group in this laboratory indicate that preferential feeding of the ground state seems to occur in this giant resonance region and we would not be greatly in error if we assumed, say, that approximately half of the neutrons were ground state neutrons and so assumed that $\sigma(\gamma,n_0)$ was half of $\sigma(\gamma,n)$. However, we must be careful of extrapolating from proton-induced neutron emission to γ-induced neutron emission because of the coherent dipole nature of the γ-resonance. Nevertheless we can still draw some useful conclusions as follows. As $\sigma(\gamma,p_0)$ is about twice $\sigma(\gamma,n)$, our assumption leads to $\sigma(\gamma,p_0)/\sigma(\gamma,n_0) \sim 4$. The relative proton to neutron penetrability for p-wave emission is 1·35 and we obtain a 6% $T = 0$ impurity in the $T = 1$ intermediate system. Irrespective of the validity of our ground state neutron fraction, we are sure that the impurity must be at least 1% if the theory of Barker and Mann (1957) is of general applicability.

It appears from considerations such as the above that accurate (γ,p) and (γ,n) experiments are important and that full angular and energy distributions of the outgoing particle groups must be established throughout the giant resonance region. The experiment reported here has been repeated at smaller energy intervals, and angular distributions have been obtained (Allas *et al.* 1963). It will be interesting to see the results of precision (γ,p) and (γ,n) experiments on silicon, now under way in this laboratory, when they become available.

V. Acknowledgments

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