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LETTER TO THE EDITOR

Alpha capture to the giant quadrupole resonance

G S Foote, D Branford†, N Shikazono and D C Weisser
Nuclear Physics Department, Australian National University, Canberra, Australia

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Abstract. Angular distributions have been measured for the reaction $^{28}Si(\alpha, \gamma_0)^{32}S$ in the energy range E_x = 12–18 MeV and the cross sections for exciting 1^- and 2^+ states deduced. These data together with similar data for ^{28}Si and ^{40}Ca are compared to calculations made using Hauser–Feshbach theory. It is shown that the (α, γ) reaction most probably excites the giant quadrupole resonance.

It is well known that at high bombarding energies ($\simeq$ 200 MeV) inelastic proton scattering from light- and medium-weight nuclei excites the giant dipole resonance (GDR) (eg Tyren and Maris 1957). Recently, Lewis and Bertrand (1972) have suggested that a previously unreported giant quadrupole resonance (GQR) and giant octupole resonance are also excited. Supporting evidence for this interpretation has come largely from inelastic electron scattering data (eg Torizuka *et al* 1973).

An interesting feature of all the results is that they require the GQR to be approximately 3 MeV lower in excitation than the GDR and have a γ-ray transition strength which approximately exhausts the E2 isoscalar energy weighted sum rule (ISR). This suggests that in favourable circumstances, it should be possible to confirm the existence of the GQR using radiative capture reactions. However, measurements made by Hanna *et al* (1973), using the $^{89}Y(p, \gamma_0)^{90}Zr$ reaction, and by Ventura *et al* (1973) using the $^{20}Ne(\alpha, \gamma_0)^{24}Mg$ reaction revealed that the intensity for exciting 2^+ states is very small in these cases. On the other hand, it has been shown by Branford (1974) that the $^{36}Ar(\alpha, \gamma_0)^{40}Ca$ reaction at $E_x \simeq$ 14 MeV proceeds partially through 2^+ states and that the E2 γ-ray transition strengths associated with these levels exhaust a minimum of 20% of the ISR. It was concluded therefore that α capture most probably excites the GQR.

To investigate this possibility further, we have studied the reaction $^{28}Si(\alpha, \gamma_0)^{32}S$, which was chosen for the following reasons: (i) due to the initial and final states having $J^\pi = 0^+$, it is possible to determine the partial cross sections for exciting 2^+ (GQR) and 1^- (GDR) intermediate states unambiguously from angular distribution measurements; (ii) for $N = Z$ nuclei, excitation of 1^- intermediate states is isospin forbidden. The 1^- cross section is therefore proportional to α^2, where α is the amplitude of $J^\pi, T = 1^-,0$ states admixed into the 1^-, 1 GDR states. Since α is known to be considerably smaller for ^{32}S than several other s–d shell nuclei (Foote *et al* 1974), the 1^- cross section was expected to be sufficiently small for the 2^+ cross section to be accurately determined.

Twelve angular distributions were measured in the α energy range 6–12 MeV using the ANU EN tandem accelerator. The targets, which were placed at an angle of 45° to

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† Present address: Department of Physics, The University, Edinburgh, Scotland.

the beam direction, were 402 ± 20 μg cm^{-2} and 570 ± 30 μg cm^{-2} films of 99 % ^{28}Si enriched SiO evaporated onto 0·5 mm thick gold backings. The γ rays were detected by a collimated 23·8 cm × 25·4 cm Na(Tl) crystal with its front face 54 cm from the target and subtending a half angle of 8·7°. The detector, anti-coincidence shield and electronics have been described by Black *et al* (1971). The γ_0 yield was determined by summing over the photopeak, and normalized to take account of γ-ray absorption in the gold backing. An example of the angular distribution data is shown in the insert in figure 2.

The cross sections for exciting 2^+ (σ_2) and 1^- (σ_1) states were determined explicitly using the formula for two overlapping levels,

$$W(\theta) = \frac{1}{4\pi}\left|\sigma_1(1-P_2)+\sigma_2(1+0{\cdot}71P_2-1{\cdot}71P_4)-2{\cdot}68(\sigma_1\sigma_2)^{1/2}\cos\theta_{12}(P_1-P_3)\right|, \qquad (1)$$

where θ_{12} is the difference in phase angle of the $l = 1$ and $l = 2$ partial waves. The results are presented in figure 1.

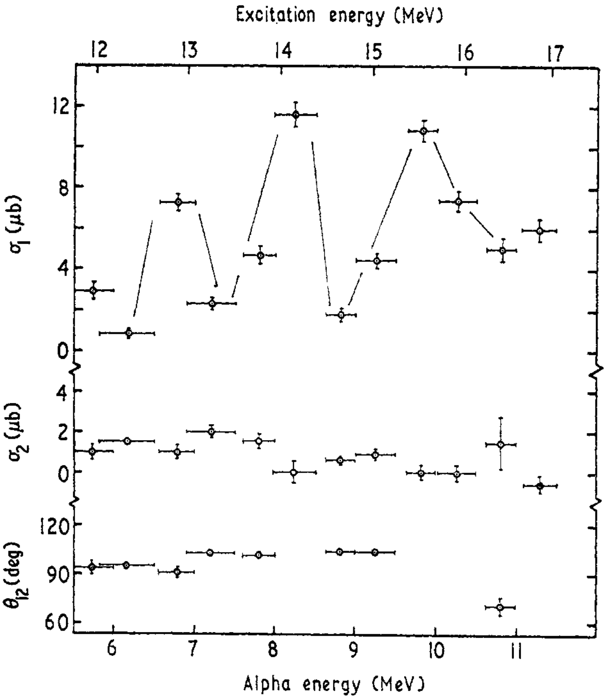

Figure 1. The ^{28}Si(α, γ_0)^{32}S absolute cross sections for exciting 1^- and 2^+ states and the interference angle θ_{12} plotted as functions of excitation energy. The error bars represent relative statistical errors. The horizontal lines indicate the energy loss in the target. The absolute error in the scale is ± 30 %.

Figure 1 shows that below $E_x \simeq 15$ MeV, σ_2 is almost constant with an average value of approximately 20 % of the total (α, γ_0) cross section. Above $E_x \simeq 15$ MeV it is much smaller. The fact that the values of θ_{12} are all approximately equal to 90° is probably due to the simultaneous excitation of many levels in the energy interval corresponding to a target thickness of about 400 keV. Under these circumstances, the interference terms would probably cancel to zero which corresponds to $\theta_{12} = 90°$ (Watson *et al* 1973).

The ${}^{28}\mathrm{Si}(\alpha, \gamma_0){}^{32}\mathrm{S}$ cross sections for exciting 2^+ intermediate states were converted to those for the (γ, α_0) reaction using the principle of detailed balance. The results are shown in figure 2 together with those for ${}^{40}\mathrm{Ca}(\gamma, \alpha_0)$ (Branford 1974) and those for

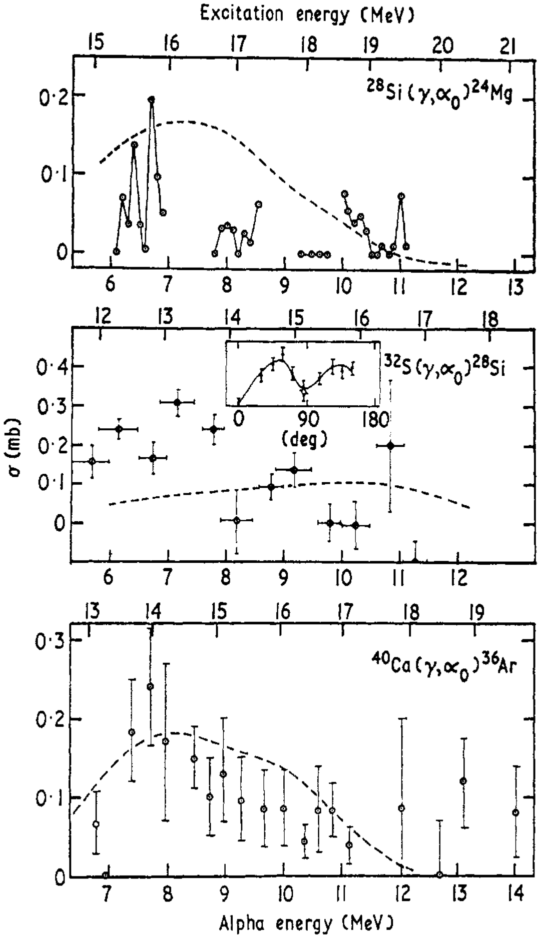

Figure 2. Cross sections for exciting 2^+ states obtained by the (α, γ_0) reaction and inverted using the principle of detailed balance. The bars indicate the relative errors where known. The ${}^{24}\mathrm{Mg}(\gamma, \alpha_0){}^{28}\mathrm{Si}$ points were calculated from angular distributions measured by Meyer-Schutzmeister *et al* (1968). The ${}^{40}\mathrm{Ca}(\gamma, \alpha_0){}^{36}\mathrm{Ar}$ data are taken from Watson *et al* (1973). The absolute errors in the cross section scales are ±30%. The insert shows an angular distribution measured at $E_\alpha = 6{\cdot}5$ MeV. The full curve represents the fit obtained using equation (1). The broken curves are calculated cross sections using a γ-ray strength that exhausts 100% of the ISR(2^+).

${}^{28}\mathrm{S}(\gamma, \alpha_0)$ which were extracted from the data of Meyer-Shutzmeister *et al* (1968) using equation (1). From these data we determined that the energy weighted cross sections $\int(\sigma/E^2)\,\mathrm{d}E$ for ${}^{40}\mathrm{Ca}$, ${}^{32}\mathrm{S}$ and ${}^{28}\mathrm{Si}$ exhaust 20%, 17% and 12% of ISR respectively. Since $\Gamma\alpha_0$ for the 2^+ states is undoubtedly less than Γ_{total}, it follows that the γ-ray transition strengths associated with these states exhaust a considerable fraction of ISR. These results strongly suggest therefore that the α capture reaction proceeds partly through the GQR proposed by Lewis and Bertrand (1972). However, the fact that σ_2 is a maximum below 16 MeV for these nuclei (see figure 2), whereas the GQR is expected to be at $E_x \simeq 17$ MeV (discussed later), appears to be inconsistent with this interpretation.

A plausible explanation of this fact is suggested by the recent calculations of Foote *et al* (1974) using Hauser–Feshbach theory. These show that the shape of the (γ, α_0) cross section for exciting 1^- states depends on the energy variation of $\Gamma\alpha/\Gamma$ to a greater extent than the energy variation of the γ-ray strength function. We have therefore made similar calculations to estimate the cross sections for (γ, α_0) reactions proceeding through 2^+ states. In this case, the cross section may be written as

$$\sigma(\gamma, \alpha_0) = \sigma_{\mathrm{CN}}(2^+) \frac{T\alpha_0}{\Sigma T_i}, \tag{2}$$

where $\sigma_{\mathrm{CN}}(2^+)$ is the total absorption cross section for isoscalar quadrupole radiation. The T_i are transmission coefficients which were calculated as described by Foote *et al* (1974).

In choosing $\sigma_{\mathrm{CN}}(2^+)$ we considered the data of Torizuka *et al* (1973) which suggest that for nuclei with $A \gtrsim 40$, the energy dependence of the GQR is given by $E_x \simeq 58\ A^{-1/3}$ MeV. It is not known however whether this is reasonable for nuclei with $A \lesssim 40$, since it has been shown for example that the energies of the GDR fall below $70\ A^{-1/3}$ MeV, the formula for $A \gtrsim 40$. In view of this, we chose $E_x = 17$ MeV which is about 3 MeV lower than the GDR in these nuclei. As very few data are available on the widths of GQR, we used a lorentzian shape for $\sigma_{\mathrm{CN}}(2^+)$ with $\Gamma = 4$ MeV which is the width of ^{40}Ca GQR (Lewis 1972). With regard to the strength of GQR there is good evidence that it approximately exhausts ISR, although estimates range from 70% (Lewis 1972) to 150% (Torizuka *et al* 1973). We therefore used a strength of 100% ISR which may be in error by up to 50%.

The results of the calculations are presented in figure 2 and show that the absolute magnitudes of the calculated cross sections are in reasonable agreement with experimental data. Also the shape of the ^{40}Ca data is well reproduced. In the case of ^{32}S and ^{28}Si there is poor agreement between the detailed shapes. However, this is to be expected for the following reason.

It is well known that photonuclear reactions involving the GDR of nuclei with $A \lesssim 40$ do not have cross sections that exhibit a simple resonance shape. For example, the data on p capture and α capture to the ^{28}Si and ^{32}S GDR (Meyer-Schutzmeister *et al* 1968) exhibit intermediate structure with a width of about 1 MeV. It is quite plausible that a similar situation will also hold for the GQR. One would not therefore expect detailed agreement with our calculations which are based on smoothly varying $\sigma_{\mathrm{CN}}(2^+)$.

Another feature of the results is that better overall agreement can be obtained between experimental and calculated cross sections if the GQR of ^{32}S has $E_x \simeq 14$ MeV. This is considerably lower in energy than expected since the ^{40}Ca GQR has $E_x \simeq 17$ MeV and the energy of the GQR should increase smoothly with decreasing A. It should be emphasized however that the agreement may be fortuitous because of the effects of intermediate structure mentioned above.

In view of all the considerations presented here and the fact that the (α, γ_0) E2 transition strength exhausts a large fraction of ISR, we conclude that it is most plausible that α capture excites the GQR. This supports the idea of Lewis and Bertrand (1972) that there are low-lying giant resonances in nuclei other than the GDR. Also, it would appear that the ^{36}Ar(α, γ_0)^{40}Ca reaction is mainly statistical in nature and can be explained using Hauser–Feshbach theory.

References

Black J L, Caelli W J, Watson R B 1971 *Australian National University Report* ANU-P/540

Branford D 1974 *Part. Nucl.* to be published

Foote G S, Branford D, Weisser D C, Shikazono N and Huang F C P 1974 *J. Phys.* A: *Math., Nucl. Gen.* 7 L4–7

Hanna S S, Glavish H F, Avida R, Calarco J R, Fisher G A, Kuhlmann E and LaCanna R 1973 private communication

Lewis M B 1972 *Phys. Rev. Lett.* **29** 1257–60

Lewis M B and Bertrand F E 1972 *Bull. Am. Phys. Soc.* **17** 462

Meyer-Schutzmeister L, Vager Z, Segel R E and Singh P P 1968 *Nucl. Phys.* A **108** 180–208

Torizuka Y, Kojima Y, Saito T, Itoh K, Nakada A, Nitsunobo S, Nagao M, Hosoyama K, Fikuda S and Miura H 1973 *Proc. Int. Conf. on Photonuclear Reactions and Applications, Asilomar* (Livermore, California: Lawrence Livermore Laboratory) pp 675–83

Tyren H and Maris Th A J 1957 *Nucl. Phys.* **4** 637–42

Ventura E, Kuhlmann E, Mavis D, Calarco J R and Hanna S S 1973 private communication

Watson R B, Branford D, Black J L and Caelli W J 1973 *Nucl. Phys.* A **203** 209–20