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The Photoneutron Cross Section of ^{44}Ca

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Abstract

Measurement of the photoneutron cross section ^{44}Ca(γ, n$_s$) has been made over the photon energy range 11–26 MeV. Comparison with the ^{44}Ca(γ, p) cross section shows evidence for isospin splitting of the giant dipole resonance (GDR) in agreement with predictions. Some evidence has also been found for deformation splitting of the ^{44}Ca GDR.

1. Introduction

A measurement of the total photoneutron cross section for the reaction ^{44}Ca(γ, n$_s$) is presented here as part of a series of measurements of photonuclear cross sections made using the 35 MeV Betatron at the University of Melbourne and the Electron Linac at Tohoku University in Japan. This program involves a study of the even isotopes of calcium from ^{42}Ca to ^{48}Ca, the even isotones with $N = 28$ from ^{48}Ca to ^{54}Fe and the even titanium isotopes from ^{46}Ti to ^{50}Ti. These nuclei have been chosen to look for systematic variations due to isospin splitting of the GDR. Such effects were predicted by Fallieros and Goulard (1970). Systematic changes in the cross section due to deformation may also be observed as the 1f$_{7/2}$ shell is filled.

2. Experiment

The target sample was 3·0 g of isotopically enriched calcium metal (98·5% ^{44}Ca) in the form of a thin cylinder 25·4 mm in diameter and 3·9 mm thick. Because of its chemically active nature the sample was mounted at the centre of an evacuated aluminium tube. This tube was sufficiently long that when placed with the sample at the centre of the 4π Halpern-type neutron detector, the 1 mm thick end windows were outside the body of the detector. This reduced the background effects. Details of the neutron detector can be found in earlier publications (see e.g. Sambell and Spicer 1973).

The bremsstrahlung beam from the University of Melbourne Betatron was collimated to a diameter of 21 mm at the sample; smaller than that of the sample. This ensured that the entire dose, monitored using a thin-walled transmission ionization chamber placed before the neutron detector, was the dose incident on the sample. The transmission chamber was calibrated against a replica NBS P2 chamber (Pruitt and Domen 1962).

The Betatron energy scale was calibrated to an accuracy of 50 keV, below 20 MeV, deteriorating to 150 keV at about 29 MeV. Neutron yield curves were measured with bremsstrahlung tip energies ranging from 11 to 26 MeV, in 100 keV intervals. A total of 33 yield curves were taken with the ^{44}Ca sample in place and 15 yield curves with the sample removed, in order to determine the background effects due to the target holder. Data for each yield point were collected over a one minute interval. The energy sweeping and data collection were under computer control. This procedure was adopted to minimize the effects of drifts in detector efficiency or Betatron energy.

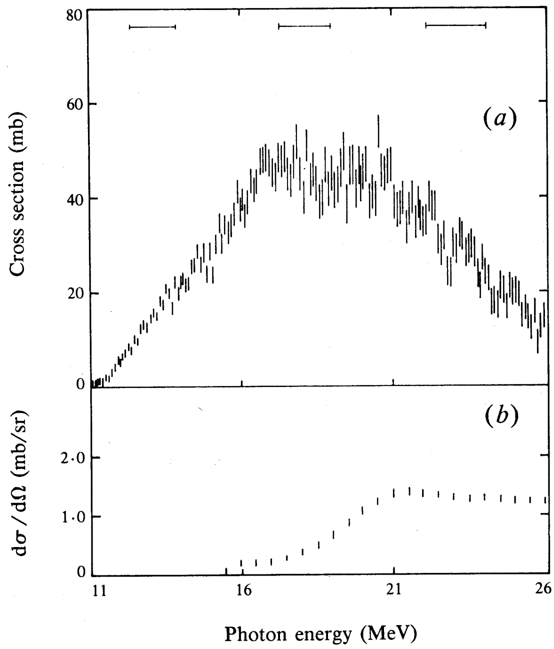

Fig. 1. (*a*) The total photoneutron cross section of ^{44}Ca, i.e.

$$\sigma(\gamma, n_s) = \sigma(\gamma, n)+\sigma(\gamma, 2n)+\sigma(\gamma, np).$$

Vertical error bars are statistical only. There is a 10% uncertainty in the absolute cross section scale. Horizontal error bars above the cross section indicate the resolution width. (*b*) The ^{44}Ca(γ, p) cross section obtained by Oikawa and Shoda (1977).

The average neutron yield curve of the reaction ^{44}Ca(γ, n_s) was determined from the individual yield curves mentioned above, and reduced to a cross section using the variable bin Penfold–Leiss method of Bramanis *et al.* (1972). Above the ^{44}Ca(γ, 2n) threshold at 19·1 MeV, determination of the cross section is complicated by double counting of neutrons. Allowance for this neutron multiplicity was made on the basis of a statistical model, along the lines described by Sambell and Spicer (1973). The resulting ^{44}Ca(γ, n_s) cross section is shown in Fig. 1*a*.

The ^{44}Ca(γ, p) cross section reported by Oikawa and Shoda (1977) is shown for comparison in Fig. 1*b*.

3. Discussion

No previous measurement of the ^{44}Ca(γ, n_s) cross section has been reported and hence the structure seen in Fig. 1*a* is of particular interest. The main strength is seen to occur as two peaks centred at 17·2 and 19·7 MeV.

Isospin Effects

Fallieros and Goulard (1970) predicted that the GDR in non-self-conjugate nuclei will consist of two isospin components. These are a consequence of the population of states with isospin T_0 and T_0+1 via E1 photo-absorption (the $T_<$ and $T_>$ components respectively). According to Akyüz and Fallieros (1971) the energy separation of these isospin components is given by

$$\Delta E = 60(T_0+1)/A \quad (\mathrm{MeV}), \tag{1}$$

and the relative energy-weighted integrated cross sections are given by

$$\int \sigma_>/E\,\mathrm{d}E \Big/ \int \sigma_</E\,\mathrm{d}E = \frac{1}{T_0}\frac{1-1\cdot 5T_0/A^{2/3}}{1+1\cdot 5/A^{2/3}-4T_0(T_0+1)/A^2}. \tag{2}$$

In the case of ^{44}Ca ($T_0 = 2$) the relevant values are $\Delta E = 4\cdot 1$ MeV and $0\cdot 34$ for the relative strength.

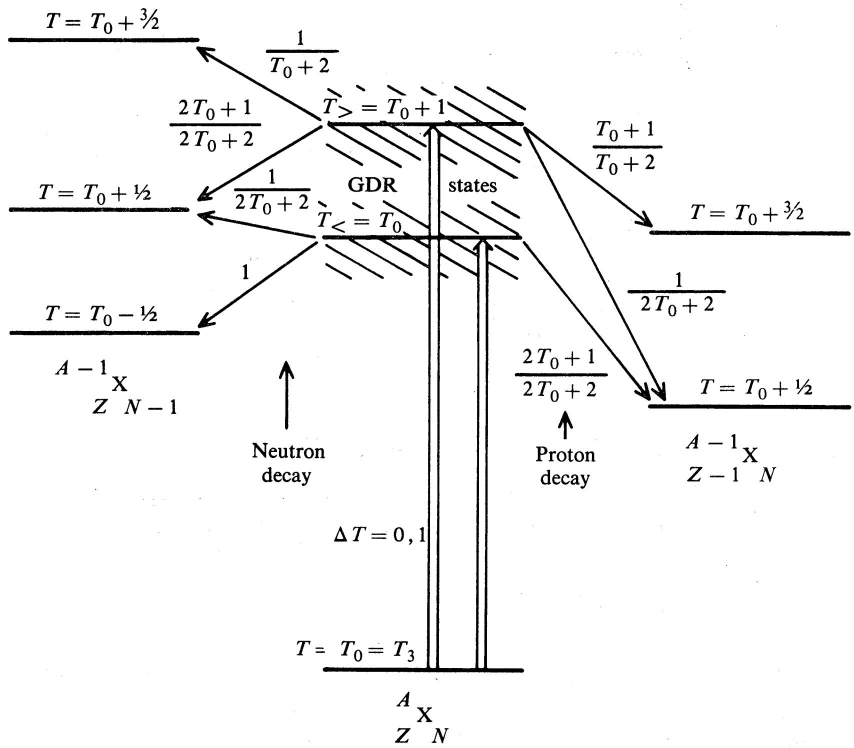

Fig. 2. Isospin decay scheme for the two components of the GDR of a non-self-conjugate nucleus. The isospin Clebsch–Gordan coefficients are shown for each decay.

The decay of the GDR from these two components by proton or neutron emission is governed, amongst other factors, by isospin conservation laws. The particle decay scheme from the GDR, showing isospin branching ratios, is presented in Fig. 2.

Decay via neutron emission from $T_>$ ($T = 3$) GDR states of ^{44}Ca to the $T = \frac{3}{2}$ states of the residual ^{43}Ca nucleus is isospin forbidden. Furthermore, since the

$T = \frac{5}{2}$ state in ^{43}Ca lies 7·9 MeV above the ground state, neutron decay from the $T_>$ states of ^{44}Ca is not expected to contribute significantly to the (γ, n_s) cross section. Consequently it is expected that neutron decay from the $T_<$ states should form the dominant component of the (γ, n_s) cross section.

Decay via proton emission from the $T_<$ GDR states of ^{44}Ca to the $T = \frac{5}{2}$ states of the residual nucleus is expected to be inhibited by the Coulomb barrier and by competition from neutron decay. The (γ, p) cross section should therefore largely reflect the $T_>$ resonance.

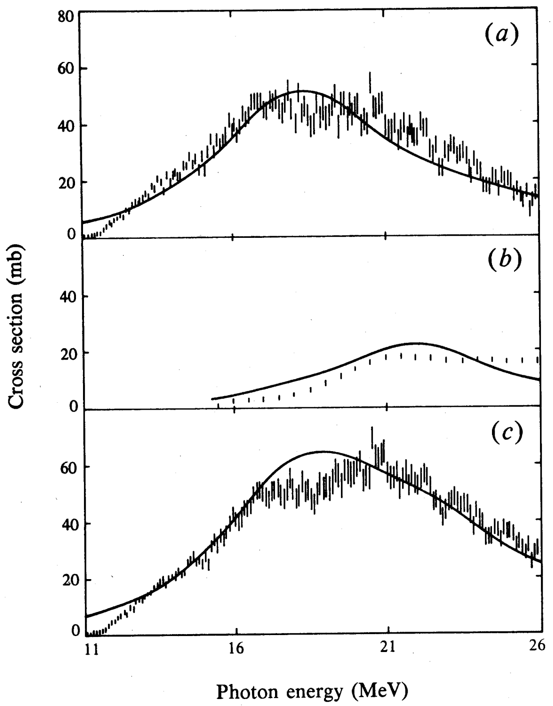

Fig. 3. Statistical calculations for the shapes of the photonuclear cross sections of ^{44}Ca (solid lines) compared with the measured cross sections (*a*) ^{44}Ca(γ, n_s) and (*b*) ^{44}Ca(γ, p) and (*c*) the approximation to the total absorption cross section.

On a simplified model the total photo-absorption cross section is assumed to be composed of two isospin components, which may be taken as Lorentzians, whose energy separation and relative strength are given by equations (1) and (2). An experimental measure of the total absorption cross section, to which this sum of isospin components is normalized, is not available. However, it can be well approximated by the sum of the measured ^{44}Ca(γ, n_s) (Fig. 1*a*) and ^{44}Ca(γ, p) (Fig. 1*b*) cross sections, since these are the dominant decay modes.

This estimate of the photo-absorption cross section was fitted with the sum of the two isospin GDR components in the form of Lorentzians consistent with the limitations of equations (1) and (2). Decay of these two isospin components by neutron and proton decay was now considered in the same way as described in detail by Pywell and Thompson (1979). As in that paper, decay was assumed to be evaporative with a 10% direct decay to low lying residual states. The residual level densities were again taken to be given by the back-shifted Fermi-gas model (Dilg *et al.* 1973).

The calculated (γ, n_s) and (γ, p) cross sections resulting and their sum are shown in Fig. 3, with the relevant measured cross sections. Apart from the fine structure in the (γ, n_s) cross section, the overall shapes and relative strengths of the calculated cross sections are in good agreement with experiment. No such agreement is possible if isospin considerations are ignored.

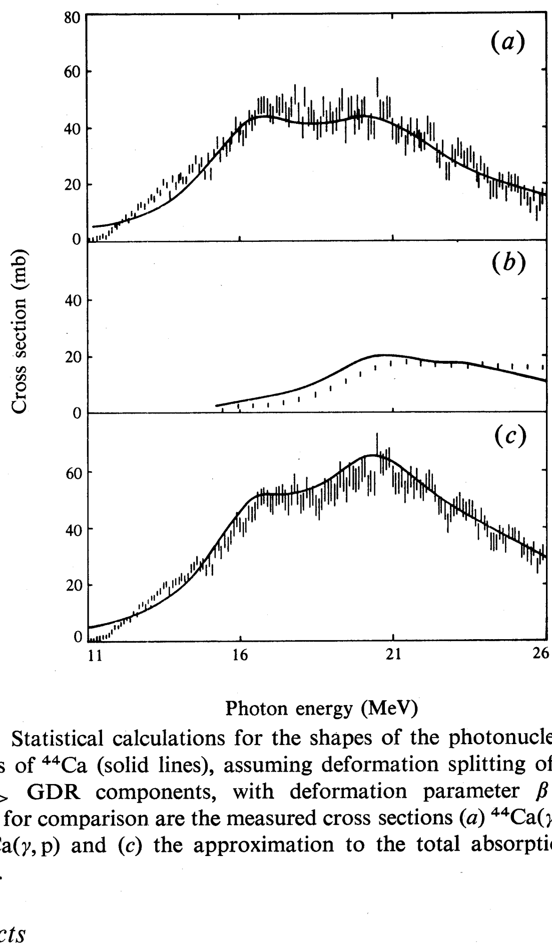

Fig. 4. Statistical calculations for the shapes of the photonuclear cross sections of ^{44}Ca (solid lines), assuming deformation splitting of the $T_<$ and $T_>$ GDR components, with deformation parameter $\beta = 0 \cdot 24$. Shown for comparison are the measured cross sections (*a*) ^{44}Ca(γ, n_s) and (*b*) ^{44}Ca(γ, p) and (*c*) the approximation to the total absorption cross section.

Deformation Effects

According to the collective model of Danos (1958), the GDR for deformed heavy nuclei is split into two components such that

$$2\sigma_a \Gamma_a = \sigma_b \Gamma_b, \tag{3}$$

$$E_b/E_a = 0 \cdot 911\, a/b + 0 \cdot 089, \tag{4}$$

where $E_{a,b}$, $\sigma_{a,b}$ and $\Gamma_{a,b}$ are the energy, strength and width parameters of the Lorentzians *a* and *b*. The ratio of the major to minor axis is given by a/b.

Whether such a model can be applied to light nuclei, such as ^{44}Ca, has been questioned before (Diener *et al.* 1971). Nonetheless, deformation effects have been calculated in light nuclei using shell model techniques (Nilsson *et al.* 1962) and so are certainly expected.

Unfortunately there is no experimental precedent as to how deformation effects might affect the individual isospin components of the GDR, particularly the $T_>$ component. Most previous studies of deformation splitting have been of heavy nuclei, with subsequent large values of ground-state isospin, so that according to equation (2), the $T_>$ components are very small.

The assumption was made that deformation splitting would be reflected equally in in both isospin components of ^{44}Ca. On the basis of equations (3) and (4), isospin components split by deformation were fitted to the total absorption cross section (approximated as before by the sum of the (γ, n_s) and (γ, p) cross sections). The value of a/b in equation (4) is related to the nuclear deformation parameter β, which was estimated from B(E2) transition rates in ^{44}Ca (Stelson and Grodzins 1965) to have a value of $0 \cdot 24$. Decay of these isospin components by proton and neutron emission was calculated using the model described above.

The calculated (γ, n_s) and (γ, p) cross sections resulting and their sum are shown in Fig. 4, together with the measured cross sections. This figure shows better agreement between the calculated and measured (γ, n_s) cross sections. The total absorption cross section is then also better fitted by the isospin components split by deformation.

However, the agreement for ^{44}Ca(γ, p) is not as good. Nevertheless, in view of the assumptions made regarding the mode of deformation splitting of the isospin components, there is some evidence to support the inclusion of deformation effects in the separate isospin components of the GDR.

4. Conclusions

The ^{44}Ca(γ, n_s) cross section presented here in conjunction with the ^{44}Ca(γ, p) cross section provides evidence for isospin splitting of the ^{44}Ca GDR, consistent with the predictions of Fallieros and Goulard (1970). The data also provide some evidence that each of the GDR isospin components suffers a deformation splitting. However, further study into deformation effects in nuclei with large isospin effects is required.

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