This thesis describes a number of experiments which were performed using the 33 MeV electron synchrotron, 12 MeV Tandem Van de Graaff and 2.0 MeV Van de Graaff accelerator facilities in the Department of Nuclear Physics of the Australian National University. Some degree of collaboration has marked all of the work described. Dr. J.H. Carver suggested and supervised the photodisintegration studies and Dr. R.B. Taylor collaborated with me in the early stages of the \( \text{Li}^7(p,\gamma)\text{Be}^8 \) experiment. The \( \text{C}^{12}(\alpha,\gamma_0)\text{O}^{16} \) reaction was examined by Dr. T.R. Ophel and myself, the experimental work and analysis being shared equally between us.

I am very grateful to all three for the guidance and encouragement they gave me during the course of this work. My thanks also go to Dr. F.C. Barker for his generous and patient help and to the technical staff for their assistance with machine operation. Dr. N.W. Tanner’s enthusiastic initiation of the \( \text{C}^{12}(\alpha,\gamma_0)\text{O}^{16} \) work is acknowledged with pleasure.

I am grateful to the Australian National University
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The results of the $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$ work have appeared in the publication:

"Proton capture $\gamma$-rays from $^{8}\text{Be}$ in the giant resonance region" (with Dr. R.B. Taylor). Nuclear Physics 44 (1963) 664.

No part of this thesis has been submitted for a degree at any other University.

[Signature]
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SECTION I
CHAPTER I

INTRODUCTION

1.1 Introduction

The phenomenon of nuclear photodisintegration was demonstrated first by Chadwick and Goldhaber (Ch 35) who ruptured the nuclear bond between the proton and neutron by irradiating deuterium with the 2.62 MeV γ-rays from a ThC² source. Later, extensive photonuclear studies, chiefly using high energy bremsstrahlung γ-ray beams, established the existence and broad characteristics of the most striking feature of nuclear absorption of electromagnetic radiation, viz. the so-called giant resonance in the absorption cross-section. Although bibliographies (e.g. To 63) and review articles (e.g. St 53, Le 54, Ti 55, Bi 57, De 57, De 59, Wi 59, Le 60, Fu 62, Ha 63) provide detailed summaries of the nuclear photo-effect and the giant resonance exhibited, a brief account of the experimental results and theoretical interpretations will prove useful to introduce the experiments described in Chapters II and III.

1.2 The Giant Resonance

Most studies were made of the partial cross-sections (γ,n), (γ,p), (γ,2n), etc. but still served to reveal the gross features of the total absorption cross-section to which they contributed. The resonance peak occurred at an energy of excitation near 22 MeV
throughout the light nuclei, decreasing with increasing mass number $A$ to about 14 MeV in the heavy nuclei, the variation being approximated closely by an $A^{-1/3}$ dependence. The resonance had a measured width at half-maximum between 3 and 8 MeV, being the more narrow in the region of closed shell nuclei and a linear dependence upon $A$ was suggested by the integrated absorption cross-section $\int \sigma \, dE$, deviations near closed shell regions reflecting the sharpening of the resonance (e.g. Ye 56). Since both the $(\gamma,n)$ and $(\gamma,p)$ cross-sections revealed similar resonance behaviour and between them accounted for almost all of the absorption up to $E_\gamma = 25$ MeV, it was clear that the giant resonance was a phenomenon of the absorption and not of the emission process. Attempts to explain the effect and its features have met with a large measure of success.

1.3 The Dipole Sum-Rule

By analogy with the Thomas-Reiche-Kuhn sum-rules for atomic absorption of electromagnetic radiation, Levinger and Bethe (Le 50) calculated the integrated total cross-section for nuclear absorption of electric dipole radiation to be

$$\int \sigma \, dE = 0.060 \frac{N_Z}{A} (1 + 0.8x) \text{ MeV-barn}$$

where $x$ was the fraction of the neutron-proton force with exchange character and took a value which depended on the potential chosen; satisfaction of the lower limit set by this rule (i.e. with $x = 0$)
was a conservation rule for summed dipole oscillator strengths, however, and therefore a strict requirement on any model which sought to explain the nuclear photoeffect. The experimentally observed near- or over-fulfilment of the lower limit confirmed the predominantly electric dipole character of the giant resonance absorption. Sum-rule estimates of E2 and M1 absorption contributions were small (Le 50, Kh 57) and when contributions from all higher order multipoles were included, Gell-Mann et al. (Ge 54) found

\[ \int_0^\infty dE = 0.060 \frac{NZ}{A} (1 + 0.1 \frac{A^2}{NZ}) \text{ MeV-barn} \]

for the total absorption cross-section integrated up to the photomeson threshold.

1.4 The Models

The models proposed to account for the giant resonance phenomena fall into two main classes comprising the collective models, in which simple, classical descriptions are given of the coherent nucleon motions excited by photon absorption (Go 48, Je 48, Da 52, Fu 56, etc.) and the independent particle or shell models, where the absorption process is described in terms of single-particle dipole transitions between shell model states (Co 51, Wi 56a, etc.). The rapprochement of the two classes is far from complete, but in one particular case, an understanding of their equivalence has been given (Br 57).
1.4.1 The Collective Models

The earliest collective model was put forward by Goldhaber and Teller (Go 48) and envisaged three possible modes of vibration of neutrons against protons. A single, collective coordinate described the absorption of incident electromagnetic radiation in terms of the oscillatory separation of the centres of mass and charge in the nuclear volume. Resonance energies $E_m$ proportional either to $A^{-1/3}$ or $A^{-1/6}$ characterized hydrodynamic dipole motion when either compressibility or incompressibility, respectively, was assumed for the neutron and proton fluids.

The extensions made to the theory by other authors (Je 48, St 50, Da 52) shared the success of the Goldhaber-Teller model in providing resonance energies and integrated cross-sections comparable with the available experimental values. Fujita (Fu 56) showed that both the resonance energy and integrated cross-section could be increased when neutron-proton exchange effects were included. No simple account could be given of the width of the giant resonance, however, and the effect was presumed to be analogous to damping by friction i.e. other modes of vibration were coupled to the dipole oscillation. A preliminary estimate of the damping and the increase it produced in the width $\Gamma$ of the giant resonance was made by Wildermuth et al. (Wi 57).

‡ Dipole oscillations "drive" the quadrupole vibrations in the unification advanced by Danos and Greiner (Da 63) of hydrodynamic dipole-oscillation and rotation-vibration models and a consequent multiple-splitting of the giant resonance is predicted.
One prediction of the model that has been substantiated by photonuclear data was the considerable broadening, and, in extreme cases, splitting of the giant resonance for nuclei strongly deformed from the spherical shape i.e. for nuclei far from the closed shell regions. Independently, Danos (Da 58) and Okamoto (Ok 58) showed that, under the assumption of constant total nucleon density, spheroidal nuclei could be expected to absorb resonantly at two discrete frequencies, corresponding to dipole fluid oscillations along each of the axes, the lower frequency being associated with the more relaxed oscillation along the major axis. An intensification of one mode was anticipated in the classical description, corresponding to dipole vibrations along each of the two equal and perpendicular axes of the nuclear ellipsoid, and verification has been provided by a number of experimental results (Fu 58a, Fu 58b, Pa 59, Fu 60, etc.). (Observation of two giant resonance peaks does not establish their correlation with the intrinsic axes of the nucleus, however, and such an identification has been secured only for Ta\(^{181}\) (Fu 58a) Ho\(^{165}\) and Er (Fu 60), the requisite tensor polarizability being demonstrated by \(\gamma\)-ray scattering experiments). The peak splitting of the giant resonance was shown to be related directly, through the nuclear deformation, to the intrinsic nuclear quadrupole moment.

While the collective models seemed to describe the photon absorption features quite well in the giant resonance region, they
provided no account of nucleon emission. The simple dipole vibration was assumed to be disordered rapidly through the coupling of other nuclear motions. Nucleons then evaporated from the excited nucleus and were expected to show an energy distribution with a typically Maxwellian tail. The yields of high energy photoprotons from heavy elements (Hi 47) were found to be small but still orders of magnitude larger than statistical model estimates, and pointed to the need for an explanation in terms of some other mechanism.

1.4.2 The Single Particle Model

Anticipated some years earlier in a suggestion by Jensen (Je 48), the first attempt to explain the anomalously large photoproton cross-section was made by Courant (Co 51). Dipole absorption was to be understood in terms of single particle E1 transitions between shell model states. The excited nucleon was emitted directly with a characteristic \( (a + b \sin^2 \theta) \) angular distribution or dispersed its energy throughout the nuclear volume by internucleon collisions i.e. a compound nucleus could be formed. Courant's analysis could not satisfy the requirements of the experimental photoproton yield, however. Shell model calculations of the Cu\(^{63}\) (Y,n) cross-section by Burkhardt (Bu 53) gave a giant resonance energy at about one half of the observed \( E_m \). Wilkinson (Wi 56a) showed that the strengths of nucleon transitions from within closed shells clustered in energy and were enhanced
several times over the strength of a single particle transition from an unfilled shell, by the presence of the remaining nucleons which close the shell. By considering ejection from specific shells, he was able to predict angular distributions of the direct photonucleons in accord with experimental observations. The relative probability of direct emission and evaporation was expressible as the ratio of the sum-rule limit width for nucleon emission to the width for absorption into the compound nucleus, this latter width being equal to twice the imaginary i.e. absorptive part W of the complex potential and contributing largely to the giant resonance width. An account was given of the increase in giant resonance width for deformed nuclei (Wi 58) but agreement with experimental values for Em (and then in the heavy nuclei) could be achieved only when an effective nucleon mass ($\sim \frac{3}{2}$ free nucleon mass) was assumed. Such an assumption received support from other studies of nuclear properties (Br 55, Ra 57, We 57) but has been challenged by measurements of single-particle transition energies in some (d,p) reactions (Co 60).

The energy elevation of an enhanced single-particle transition to the observed resonance energy was effected by the hole-particle interaction, in the analysis by Brown and Bolsterli (Br 59) of $^{16}O$ states while Carver and Peaslee (Ca 60) expressed the giant resonance energy as the sum of two terms, one showing the familiar $A^{-\frac{1}{3}}$ dependence and the other being an approximately
constant term arising from exchange forces.

1.5 Rapprochement of the Two Models

The success of both collective and shell models in predicting the main features of the photon absorption cross-section raises the question of the relationship between the two. Brink (Br 57) has shown that, for the special case of an isotropic harmonic oscillator potential, the wavefunction for the state excited by photon absorption in the giant dipole resonance can be written as a linear combination of single-particle excitations and corresponds exactly to the Goldhaber-Teller dipole oscillation i.e. the equivalence is explicit.

Since the usefulness of any collective model reflects the coherent nature of many nucleon motion, the necessity to include all nucleons in a satisfactory single-particle description is emphasized. At the present time, the mathematical difficulties associated with such calculations and the ignorance of a universally applicable expression for the nuclear force put most calculations beyond computational reach.

The limitations of the most ambitious calculations for $^{16}O$, for example, are becoming apparent as higher resolution is introduced into experimental measurement. The intermediate-coupling shell model calculations of Elliott and Flowers (El 57) predicted that all the dipole transition strength for the $^{16}O$ ground state would be exhausted by five $J = 1^-$, $T = 1$ states
Similar results were obtained from the equivalent treatment given by Brown and Bolsterli (Br 59). It is obvious from the studies made at Harwell (Fi 62a), using time-of-flight separation of neutron groups, that the resonance at ~ 24.5 MeV excitation, corresponding to one of the five "dipole" states, contains very much more structure than the configuration-mixing calculations can explain. The effect is even more marked in the "giant" resonance for absorption by $^{12}$C, as revealed through the $(\gamma,n)$ cross-section (Fi 62b).

1.6 Conclusions

The general features of the giant resonance are well understood but improved measurements in recent years pose new challenges to the theoreticians. While the advisability of even more detailed calculations is dubious, many aspects of photo-disintegration bear further experimental investigation.

The details of the emission process, and, in particular, of the competition between decay modes, can give information about the part played by compound nucleus and direct reaction mechanisms. The purpose of the experiments described in Chapter II was to assess the relative importance of the direct mechanism by measurement of the $(\gamma,n)$ and $(\gamma,2n)$ cross-sections for the two chosen nuclei.

Detailed examination of the photoproton yield curves may be made with high energy resolution by means of the inverse $(p,\gamma)$ reactions and an example is provided by the $\text{Li}^7(p,\gamma)\text{Be}^8$ reaction.
described in Chapter III.
CHAPTER II

PHOTONEUTRON REACTION STUDIES IN \textsuperscript{75}As AND \textsuperscript{133}Cs

2.1 Introduction

The suggestion made by Bohr (Bo 36) that a nuclear reaction could be envisaged as the two-stage process of formation and decay of an intermediate compound nucleus led to the development of the statistical model account of particle emission (We 37). The applicability of the statistical description rested upon the assumption that the intermediate nucleus had a sufficiently long life for the particular mode of formation to be forgotten and for the excitation energy to be distributed over all available degrees of freedom i.e. for thermodynamical equilibrium to be achieved.\footnote{In a review of \((n,n')\) \((n,p)\) and \((p,n)\) cross-sections for a large number of nuclei, Erba et al. (Er 61) concluded that the validity of a statistical model description (e.g. of level density and nuclear temperature formulae) could be secured for this group of reactions and that complete thermodynamical equilibrium was not a necessary condition for the independence of the reaction entrance and exit channels.} Under these conditions, the cross-section for a particular type of energetically permissible decay could be expressed in terms of the cross-section for the inverse reaction and the level-density of the residual nucleus. The evaporation process was more difficult to describe when emission of more than one particle became energetically possible e.g. for excitation energies in the compound nucleus above the \((\gamma,2n)\) reaction threshold. The probability of only one high energy neutron being emitted decreases rapidly in competition with
two-neutron emission, for example, and Blatt and Weisskopf (Bl 52a eq. 6.18) approximate the relative probability of two-neutron and any neutron emission events by

$$\frac{\sigma(Y,2n)}{\sigma(Y,n)} \approx 1 - (1 + \frac{E_c}{\Theta}) \exp \left[-\frac{E_c}{\Theta}\right] \quad (2.1)$$

where $E_c = E - E_{2n}$, the excess of excitation energy above the $(Y,2n)$ threshold, $\Theta = \left[(E - E_n)/a\right]^{\frac{1}{3}}$, the nuclear temperature of the intermediate residual nucleus, and $a$ is the level density parameter.

It has been suggested that a direct reaction mechanism is important in accounting for the anomalously large number of high energy photoprotons in the emission spectrum and for the asymmetry about 90° of the angular distributions, for which the statistical theory has no explanation. The possibility of testing for the participation of direct effects by a comparison of the $(Y,n)$ and $(Y,2n)$ cross-section ratios with the expression on the r.h.s. of equation 2.1 has typified studies in the nuclei Cu\textsuperscript{63} (Be 54), Nb\textsuperscript{93} (Si 58), Ni\textsuperscript{58} (Ca 59), Ta\textsuperscript{181} (Ca 58), Pr\textsuperscript{141} (Ca 59a), I\textsuperscript{127}, Au\textsuperscript{197} (Na 61) and Ga\textsuperscript{69} (Co 61a). Usually, the $(Y,2n)$ cross-section has been obtained by subtracting from a total neutron yield curve the yield curve for the $(Y,n)$ reaction as measured by the activation method and writing

$$\sigma(Y,\text{all n}) = \sigma(Y,n) + 2 \sigma(Y,2n) + \sigma(Y,pn) + 3 \sigma(Y,3n)$$
Obviously, separate determinations of the individual cross-sections are to be preferred, since no assumptions need be made about neutron multiplicity and the errors normally introduced by the subtraction of one yield from another of comparable magnitude are avoided. The activation technique is favoured when the decay properties of the radioactive nuclide permit its adoption. There is always some interest in extending the data on giant resonance systematics throughout the nuclear masses. With good beam stability, splitting may be observable in the \((\gamma,n)\) giant resonances for strongly deformed nuclei and, in favourable cases, an estimate of the intrinsic quadrupole moment may be made.

To further a series of studies begun already in this laboratory, the measurement of the \((\gamma,n)\) and \((\gamma,2n)\) cross-sections for As\(^{75}\) and Cs\(^{133}\) was undertaken. These nuclei are both mono-isotopic and the neutron-deficient daughter nuclides have radioactivities that suggested activation techniques would be applicable. In arsenic \((Z = 33, N = 42)\), the filling of the fourth major shell for protons is only half accomplished and is still far from complete in neutron numbers. Caesium has 55 protons and 78 neutrons, corresponding to an excess of 5 and a deficiency of 4 with respect to the magic numbers \(Z = 50\) and \(N = 82\) for major shell closures (Ma 55). On the basis of a simple hydrodynamic model, the ellipticity of the arsenic nucleus and near-sphericity of the caesium nucleus are expected to be reflected in the width of the
giant resonance for each.

2.2 Arsenic

Since proton emission from $^{75}\text{As}$ leads to levels of the stable isotope $^{74}\text{Ge}$ and proton-plus-neutron emission populates levels of the stable isotope $^{73}\text{Ge}$, neither the $(\gamma, p)$ nor $(\gamma, np)$ reactions can be detected by the activation technique. No evidence for reactions other than the $^{75}(\gamma, n)$ and $^{75}(\gamma, 2n)$ was sought. The threshold for $(\gamma, n)$ and $(\gamma, 2n)$ reactions were obtained from the latest nuclear mass tables (Wa 60) as 10.2 MeV and 18.2 MeV. Decay schemes for the $^{74}\text{As}$ and $^{73}\text{As}$ nuclei are taken from the most recent entries in the Nuclear Data Sheets and are shown in figure 2.1. The 596 keV and 511 keV ($\beta^+\text{ annihilation}$) $\gamma$-rays were chosen to monitor the yield of the $^{74}\text{As}$ activity.

The $^{73}\text{As}$ decay scheme, also shown in figure 2.1, reveals only two $\gamma$-rays of 13.5 keV and 53.9 keV. The very low energy portion of the spectrum was obscured by noise and background so that detection of the $^{73}\text{As}$ activity was necessarily restricted to observation of the 54 keV $\gamma$-ray.

It was convenient to use the powder $\text{As}_2\text{O}_3$ as a target material since $(\gamma, n)$, $(\gamma, 2n)$, $(\gamma, p)$ and $(\gamma, np)$ reactions in $^{16}\text{O}$ (which has a 99.8% natural isotopic abundance) yield stable isotopes or radioactive nuclei with half-lives of two minutes or less.
Figure 2.1

The decay schemes (taken from the Nuclear Data Sheets) for the As$^{73}$ and As$^{74}$ nuclei.
2.3 Caesium

The sulphate was chosen as the least hygroscopic of the available salts and unlikely to provide embarrassing activities as a result of photodisintegration. The oxygen content is not troublesome (Chapter 2.2) while in sulphur the only likely activities that have half-lives longer than three minutes are the pure $\beta^-$ emitters originating from the ($\gamma,p$) and ($\gamma,np$) reactions in $S^{34}$, which has an abundance of only 4% in natural sulphur.

Because $Cs^{133}(\gamma,p)$ and $Cs^{133}(\gamma,np)$ reactions yield the stable isotopes $Xe^{132}$ and $Xe^{131}$, they make no contributions to the activities detected. The Q-values for the ($\gamma,n$) and ($\gamma,2n$) reactions are 9.0 MeV and 16.5 MeV (Wa 60). The decay schemes for $Cs^{132}$ and $Cs^{131}$ are shown in figure 2.2. The 673-keV level of $Xe^{132}$ is populated almost exclusively as a result of the electron capture process and this de-excitation $\gamma$-ray photopeak was selected to monitor the ($\gamma,n$) reaction yield.

It will be observed from figure 2.2 that $Cs^{131}$ decays by electron capture in every event and, therefore, is identified by the $Xe^{131}$ X-ray of 30 keV. Since the X-rays from $Xe^{131}$ and $Xe^{132}$ are indistinguishable, the yield of the ($\gamma,2n$) must be determined either by analytical separation of the two components (6.2d and 9.6d half-lives) in a decay curve of the 30 keV X-ray intensity, or by comparing the ratio of intensities of the X-ray line to the
Figure 2.2

The decay schemes (taken from the Nuclear Data Sheets) for the Cs\(^{131}\) and Cs\(^{132}\) nuclei.
673 keV photopeak below and above the \((\gamma,2n)\) threshold. The ratio below the threshold should be constant and permit the appropriate fraction of the X-ray peak to be subtracted out.

2.4 Procedure

The target powder samples were weighed and sealed into shallow cylindrical aluminium cans exposing target thicknesses of approximately 3.5 \(\text{gm cm}^{-2}\) to the bremsstrahlung flux from the 33 MeV electron synchrotron. Thin (0.010") tantalum discs were located at back and front faces of the samples to permit monitoring of the beam by means of the induced 8.1 hr activity of the 55 keV X-ray from Ta\(^{180m}\). The target sandwich was wrapped in cadmium foil to minimize activation due to slow neutron capture. The output of a thickwalled ionization chamber was used to monitor the beam intensity.

After an irradiation of 6, or, in later activations, of 24 hours duration, activities were measured by locating a sample or disc above the face of a \(\frac{3}{8}\)" diameter x 2" long NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier, the whole spectrometer assembly being well shielded by an iron, lead and concrete complex. In a conventional arrangement, pulses were fed thence through cathode-follower and non-overloading amplifier stages to a 100-channel Hutchison-Scarrot analyser. A scaling unit was operated in parallel to provide analyser dead-time correction estimates to the number of events recorded in any part of the spectrum.
Counting rates were such that the corrections did not exceed 10%. Linearity and stability of the spectrometer were checked periodically by calibration with $\gamma$-rays from standard radioactive sources.

Yields were sought for bremsstrahlung end-point energies ranging from reaction thresholds up to 32 MeV, in increments of 1 MeV. Calibration of beam energy was furnished by measurement of the thresholds for $(\gamma,n)$ reactions in $C^{12}$, $O^{16}$, $P^{31}$ and $Cu^{63}$ using the neutron separation energies listed by Geller et al. (Ge 60a).

2.5 Results

Yields were corrected for decay schemes, sample-detector geometry (by measurement), self-absorption and crystal efficiencies. By reference to the tantalum monitor activities, these were converted to yields per atom per electron employing as a standard the $Ta^{181}(\gamma,n)Ta^{180}$ yield curve (Ca 57a) which, in turn had been established by a comparison of $Ta^{181}(\gamma,n)$ and $Cu^{63}(\gamma,n)$ yield curves, the $Cu^{63}(\gamma,n)$ excitation function of Berman and Brown (Be 54) being adopted as a reference standard in this laboratory.

The yield curves were unfolded with a Silliax computer program (La 58) to provide cross-section curves, using an iterative procedure developed by Carver and Lokan (Ca 57).

2.5.1 Arsenic
2.5.1.1 The (Y,n) reaction

A typical spectrum of the 511 keV and 596 keV γ-ray peaks is shown in figure 2.3a together with a curve of the decaying intensity. The mean measured half-life was found to be $17.5 \pm 0.6$ days, in fair agreement with the value of 18d adopted in the Nuclear Data Sheets. The yield curve and cross-section are shown in figure 2.3b. A peak energy and width of 17.5 MeV and 7 MeV, respectively, are chosen to characterize the giant resonance displayed.

2.5.1.2 The (Y,2n) reaction

Identification and measurement of the intensity of the 54 MeV γ-ray were hampered by the weakness of the activity produced, large backgrounds and gross 17.5 day activities contributing to the total γ-ray spectrum at that energy. Extension of the irradiation period from 6 to 24 hours gave some improvement in intensity but pursuit of the radioactive decay of one sample at intervals over a period of 160 days failed to favour any one of the published values for the As$^{73}$ half-life. The decay scheme value of 76 days was chosen. (figure 2.4a).

Both (Y,n) and (Y,2n) cross-section measurements were handicapped by the poor performance of the synchrotron and the experiment was terminated by a major machine failure before (Y,n) activations could be repeated and before reliable (Y,2n) data could be recorded. The (Y,2n) yield curve is displayed in figure
Figure 2.3a

Portion of the γ-ray spectrum of the As$^{74}$ activity, showing the 511 keV and 596 keV lines (closed circles) and the background (open circles). A typical curve of the decaying intensity is shown, time being measured from the end of the irradiation period.

Figure 2.3b

The As$^{75}(γ, n)$As$^{74}$ activation yield curve (in arbitrary units) is shown as a solid line and the $(γ, n)$ cross-section as a dotted curve, both as a function of bremsstrahlung end-point energy. The dashed curve is the total photoneutron cross-section $Γ(γ, n) + 2Γ(γ, 2n) + ...$ measured by Montalbetti et al. (Mo 53) and has been increased in magnitude by 20% to facilitate comparison. Beyond 25 MeV the cross-section estimates are uncertain and are not included.
Figure 2.4a

The decay curve of the As$^{73}$ activity and (inset) portion of the $\gamma$-ray spectrum revealing the 54 KeV $\gamma$-ray. (Counts per channel per 300 minutes are in excess of the 4000 counts contributed by the tails of higher energy $\gamma$-rays and the background. The peak at 75 keV in this spectrum was traced to the weak radioactive poisoning of the spectrometer)

Figure 2.4b

The relative yield of the As$^{75}(\gamma,2n)$As$^{73}$ reaction ($Q = -18.2$ MeV) as a function of bremsstrahlung end-point energy.
2.4b and is thought to be too poorly determined to justify a cross-section analysis.

2.5.2 Caesium

2.5.2.1 $^{133}\text{Cs}(\gamma,n)^{132}\text{Cs}$

A typical spectrum and decay curve for the 673 keV line is shown in figure 2.5a, a mean half-life of $6.5 \pm 0.1$ days characterizing the decay. This figure compares favourably with the value reported by Whyte et al. (Wh 60) of $6.48 \pm 0.03$ days. The yield curve and cross-section are also shown, $E_m$ and $\Gamma$ for the resonance taking the values 6 MeV and 15 MeV, respectively. (figure 2.5b).

2.5.2.2 $^{133}\text{Cs}(\gamma,2n)^{131}\text{Cs}$

Both of the methods outlined in Chapter 2.3 were applied to the yield of the 30 keV line in the $\gamma$-ray spectrum but with little success. Analysis of decay curves using the method of least squares failed to identify a unique half-life or reliable yields of $^{131}\text{Cs}$, although a significant increase in the combined half-lives was observed above the $(\gamma,2n)$ threshold as shown by the points plotted in figure 2.6a. The second technique proved to be more fruitful but, again, lack of data prevented a meaningful analysis. The yield curve is shown in figure 2.6b.

2.6 Discussion

The great width of the $^{75}\text{As}(\gamma,n)$ giant resonance is presumed
Figure 2.5a

Portion of the 673-keV $\gamma$-ray spectrum and the derived decay curve.

Figure 2.5b

The $\text{Cs}^{133}(\gamma,n)\text{Cs}^{132}$ yield curve (in arbitrary units) is shown by an unbroken line and the $(\gamma,n)$ cross-section by a light, broken line.
HALF LIFE: 6.47 DAYS

GAMMA RAY ENERGY—MEV
Figure 2.6a

Half-life measurements provided by decay of the 673-keV γ-ray and 30-keV γ-ray activities. The values of the latter half-life are seen to increase for energies above the (γ,2n) threshold and testify to the contribution of the 9.6d Cs\(^{131}\) component in the 30-keV γ-ray peak.

Figure 2.6b

The approximate shape of the Cs\(^{133}\)(γ,2n)Cs\(^{131}\) yield curve, obtained by averaging yields over 3 MeV bins.
RELATIVE YIELD — DAYS

HALF LIFE FROM 673 KEV GAMMA RAY

HALF LIFE FROM 30 KEV X-RAY

GAMMA RAY ENERGY — MEV
to reflect the distortion of the arsenic nucleus from the spherical shape and compares favourably with the 8 MeV suggested by the systematic survey of giant resonance widths and nuclear ellipticities made by Okamoto (Ok 58). The results of photo-neutron studies of Montalbetti et al. (Mo 53) included an $\text{As}^{75}(\gamma,n)$ cross-section curve derived from total neutron yield measurements, and suggested values $E_m \approx 17 \text{ MeV}$, $\Gamma \approx 6 \text{ MeV}$; the width may have been underestimated since a large $(\gamma,2n)$ cross-section was invoked to explain the curious shape of the photoneutron cross-section, cf. the present results.

Similarly the 6 MeV width of the Cs$(\gamma,n)$ resonance is to be compared with the 5.5 MeV suggested by the trends of Okamoto's phenomenological curves, and reflects the proximity to double shell closure. While no claims for precision can be made for the magnitudes of observed widths, the integrated absorption cross-sections for the reactions are less sensitive to the detailed cross-section shape and useful comparisons with the sum-rule limit may be made. The values for $\int_0^{30} \sigma(\gamma,n) \, dE$ are 0.67 MeV-barn for arsenic and 1.6 MeV-barn for caesium. These are to be compared with dipole absorption sum-rule lower limits of 1.11 MeV-barn and 1.95 MeV-barn respectively. The $(\gamma,p)$ cross-section is assumed to make good a certain fraction of the deficiency in the sum-rule limit for the arsenic absorption, while a relatively less important contribution to the caesium total absorption is made by
the ($\gamma,p$) cross-section, since Coulomb barrier suppression of proton emission is much more effective.

Above the giant resonance region the cross-sections are thought to be subject to such large uncertainties that no profitable speculation can be made about direct reaction contributions to the photoneutron yield.

It is not at all clear, however, that bremsstrahlung experiments have always provided reliable cross-section estimates above the giant resonance where the yield of a reaction is large and changing little. Opinion has been divided over the interpretation of results from ($\gamma,n$), ($\gamma,2n$) studies which were designed to reveal the importance of direct reaction effects. The cross-section measurements made by Berman and Brown (Be 54) for the ($\gamma,n$) and ($\gamma,2n$) reactions in Cu$^{63}$ could be explained adequately by the statistical theory, while Silva et al. (Si 58) suggested that important contributions were made by a direct mechanism in the Nb$^{93}$($\gamma,n$) cross-section above the ($\gamma,2n$) threshold. As a result of ($\gamma,n$) and ($\gamma,2n$) cross-section determinations in Au$^{197}$ and I$^{127}$, Nascimento et al. (Na 61) concluded that the ratio (equation 3.1) was not a sensitive test of the evaporation theory. Coote (Co 61a) submitted the Ga$^{69}$ ($\gamma,n$) and ($\gamma,2n$) cross-sections as evidence for the participation of direct effects and Carver et al. (Ca 57a, Ca 58, Ca 59a) have given similar interpretations of the high-energy tails found for
the \((\gamma, n)\) cross-sections of Ta\(^{181}\) and Pr\(^{141}\). Fuller and Weiss (Fu 58a, Fu 58b) considered that in both the photoneutron and differential elastic scattering cross-sections for Ta\(^{181}\) the experimental points lay above the best-fitted Lorentz line cross-section curve by a significant amount at photon energies beyond the giant resonance region.

The recent application of nearly monochromatic \(\gamma\)-ray beams to photoneutron studies at Livermore, in particular, has furnished cross-sections of high precision. The complete disappearance of the Ta\(^{181}\)(\(\gamma, n\)) cross-section above \(E_\gamma = 17.3\) MeV (Br 63a) is in conflict with the earlier \((\gamma, n)\) cross-section results (Ca 57a etc.), for instance; the good agreement between estimates of intrinsic nuclear quadrupole moments obtained from the Livermore studies on the one hand, and from Coulomb excitation measurements on the other, argues strongly for the accuracy of the Livermore technique and analysis.

In a recent report, Bramblett et al. (Br 63b) have indicated that the ratio of the \((\gamma, 2n)\) to \((\gamma, n)\) cross-section for each of Tb\(^{159}\), Ho\(^{165}\), Ta\(^{181}\), Au\(^{197}\) and U\(^{235}\) is well described by statistical theory but suggest that some direct interaction may be required to explain the ratio in Cu. Results for other nuclei are promised and it seems that the importance of direct interaction mechanisms in photonuclear reactions will become clearer as the scope of monochromatic \(\gamma\)-ray studies is extended.
CHAPTER III

A STUDY OF THE INVERSE PHOTONUCLEAR REACTION Li\(^7\)(p,\(\gamma\))Be\(^8\)

3.1 Introduction

The advent of Tandem Van de Graaff accelerators, with the ability to provide proton beams with continuous energy variation up to 10 or 12 MeV, has made it possible to explore the giant dipole resonance region of nuclear excitation through inverse particle capture reactions. The cross-sections for the (\(\gamma\),p\(_{o}\)) and (p,\(\gamma\)_\(o\)) reactions, where p\(_{o}\) and \(\gamma\)_\(o\) denote transitions from a particular intermediate nuclear state to the ground state of the residual nucleus, are related directly by the principle of detailed balancing, so that the two cross-section curves should show similar resonance structure at any given energy of excitation in the compound system. The energy resolution that can be obtained as a result of the high stability and homogeneity of proton beam energy allows a detailed examination of the cross-section. In effect, the study of the giant resonance is made with mono-energetic \(\gamma\)-rays, i.e. without introducing the difficulties and uncertainties that attend the analysis of data from photonuclear reactions induced by radiation with a continuous energy distribution viz. bremsstrahlung radiation\(^\dagger\).

\(^\dagger\) Betatron energies can be stabilized to high precision but the resolution with which fine structure in the absorption cross-section is revealed depends quite sensitively upon the shape chosen for the bremsstrahlung spectrum, and particularly for the shape of the high energy tip (Ge 60, Ge 63).
Inverse process studies do not supersede the photonuclear reaction investigations since they cannot supply partial widths for nucleon emission to all energetically available states of the residual nucleus. However, a method is provided by the inverse process of studying photon absorption by excited states of nuclei. Measurement of the \((p,\gamma_0)\) \((p,\gamma_1)\), etc. yields, for example, can test the surmise (Fu 56, Pe 59a) that giant resonances are to be found in photon absorption cross-sections for the low-lying excited states, as well as the ground state, of a nucleus.

The inverse photonuclear reaction also extends the study of partial photon absorption cross-sections to nuclei whose ground states are unstable, and which are therefore unsuitable for use as targets in a \((\gamma,p_0)\) reaction. The photodisintegration of \(^8\text{Be}\) may be examined viz the \(^7\text{Li} (p,\gamma)\text{Be8}\) reaction, for example.

The light nuclei with mass number \(A = 4n - 1\) recommend themselves strongly for study by a \((p,\gamma)\) reaction method. Firstly, the symmetry properties of \(A = 4n\) nuclei result in large neutron and proton binding energies, typically 12 MeV and more; Tandem proton beam energies are therefore high enough to produce compound nucleus excitations in the giant resonance region (20 - 25 MeV) and beyond. Secondly, there is frequently a sufficient energy separation of the ground from the first excited state that a reliable decomposition of the de-excitation \(\gamma\)-ray spectrum into its components is possible i.e. \((p,\gamma_0)\), \((p,\gamma_1)\) etc. contributions may be estimated individually.
The earliest application of the inverse photonuclear reaction technique to giant resonance studies in light nuclei was made by Gemmell et al. (Ge 59a, Ge 59b) using a proton beam from a 7.7 MeV cyclotron, with energy variation obtained by the use of aluminium absorbing foils. Of the target nuclei bombarded, only Li$^7$ and B$^{11}$ had sufficiently high Q-values for radiative proton capture (17.25 MeV and 12.13 MeV, respectively) for the yield measurements to extend beyond the peak of the giant resonance. The cross-section curve for the B$^{11} (p, \gamma)_0$C$^{12}$ reaction suggested possible structure within the resonance. A more recent and accurate measurement by Gove et al. (Go 61) confirmed that there was no pronounced splitting of the C$^{12}$ giant resonance.

A thick target (280 keV) Li$^7(p, \gamma)$Be$^8$ yield curve was measured at 90° by Gemmell et al. and gave no indication of structure, but resolution was considered to be no better than 300 keV. The combined yield of high energy $\gamma$-rays from this reaction showed a broad resonance with a maximum at a bombarding energy of 5.8 MeV, in agreement with the prediction by Wilkinson (Wi 54).

Two other measurements have been reported for the Li$^7(p, \gamma)$Be$^8$ reaction yield at comparable energies. Bair et al. (Ba 52), using a 20 keV target, showed that at a fixed angle the high energy $\gamma$-ray yield increased smoothly beyond $E_p = 3$ MeV. Thomas et al. (Th 60) extended the measurements from $E_p = 5$ MeV...
up to 10 MeV and claimed that broad and completely structureless resonances in yield at 90° of γ-rays to the ground and first excited states of Be⁸ displayed maxima at about 5 and 8 MeV proton energy, respectively. Few experimental details and no graphical results were given but agreement with the work of Gemmell et al. was considered to be "not good".

Remark has been made of the 2.6 MeV difference in excitation corresponding to maxima of the Be⁸ γ₀- and γ₁-ray yield curves, as quoted by Thomas et al. This is to be compared with the 2.9 MeV energy difference between the Be⁸ 0⁺ ground state and 2⁺ first excited state (Aj 59). Other workers have offered evidence for giant resonances built upon excited states of nuclei.

Penfold and Garwin (Pe 59a) extracted cross-sections for the elastic and inelastic scattering of γ-rays out of a bremsstrahlung beam incident on O¹⁶. An interpretation of the peaks at 22 MeV in the elastic scattering cross-section, and at 29 MeV in the inelastic cross-section, was given in terms of strong resonance dipole absorption by the O⁺ O¹⁶ ground state and O⁺ or 2⁺ excited state 6 or 7 MeV higher, respectively i.e. giant resonances for O¹⁶(γ,γ)O¹⁶ and O¹⁶(γ,γ')O¹⁶* were suggested.

† In fact, the data required that a number of isolated resonances be involved in the elastic scattering cross-section. Absorption at 22 MeV was particularly strong, however.
The giant resonances obtained for $^{28}(p,\gamma)_{\text{Si}}$ and $^{28}(p,\gamma_1)_{\text{Si}}$ cross-sections by Gardner and Gugelot (Ga 61) displayed a relative displacement of about 2 MeV, as did the resonance envelopes from the work of Gove et al. (Go 61). The data of Gove also suggested an energy difference of about 4 MeV in excitation for the maxima in the $^{11}(p,\gamma)_{\text{C}}$ and $^{11}(p,\gamma_1)_{\text{C}}$ yields.

Inspection of the yield curves presented by Gove et al. illustrated how much detail had been obscured, for example, in the $^{11}(p,\gamma)_{\text{C}}$ data of Gemmell et al. and the $^{27}(p,\gamma)_{\text{Si}}$ data taken by Gardner et al. It seemed quite possible that the cyclotron beam study of the $^{7}(p,\gamma)_{\text{Be}}$ reaction had smeared out structure by poor resolution. The evidence given by copious photonuclear data (To 60) for multiple splitting of the giant dipole resonances in many light nuclei posed the question of whether there really was no structure in the $^{8}$Be giant resonance, as experimental results had suggested to that time.

In summary, it is pointed out that, in favourable cases, proton radiative capture studies permit a precise investigation of the giant dipole resonance region for light nuclei. The $^{8}$Be nucleus is unstable and therefore cannot be used as a target for photodisintegration studies. The $^{7}(p,\gamma)_{\text{Be}}$ reaction is favoured by a high Q-value so that the giant resonance may be reached comfortably with available proton energies. Since agreement between available measurements of the reaction cross-section was
disputed and no structure in the curves had been found, a clarification seemed worthwhile. More precise values were desired than those tentatively quoted for the excitation energies at which $\text{Li}^7(p,\gamma_0)\text{Be}^8$ and $\text{Li}^7(p,\gamma_1)\text{Be}^{8*}$ reactions exhibited maximum yield in the giant resonance region.

The improved resolution in proton beam energy and the much lower background offered by the Tandem Van de Graaff machine encouraged a repetition and extension of the earlier work of Gemmell et al. The experiment was undertaken, therefore, to provide thin target excitation functions and angular distributions for $\gamma$-rays from the $\text{Li}^7(p,\gamma_0)\text{Be}^8$ and $\text{Li}^7(p,\gamma_1)\text{Be}^{8*}$ reactions.

3.2 Experimental Procedure

3.2.1 Target Preparation.

Thin targets of natural Lithium (92.6% Li$^7$) were evaporated from a tantalum boat onto 0.010" thick tantalum backings and mounted on a frame located axially in a cylindrical, perspex target chamber.

To confirm that excessive oxidation or nitrogenation of the Lithium target did not occur during transfer from the evaporator, the following test was performed.

A crude target chamber was constructed which could be transferred from the evaporator unit to the beam line without breaking the chamber vacuum. Targets prepared under these
conditions showed no significant difference in thickness, as measured by the \( (p,\gamma) \) yield, before and after a deliberate, short exposure to air, nor was the useful life of a target reduced noticeably. Consequently, the bulkier system was abandoned in favour of the simple perspex assembly.

Lithium was also deposited on thin, self-supporting, carbon foils. No difference could be observed in the \( \gamma \)-ray spectra recorded during proton bombardment of carbon- and tantalum-backed targets for beam energies up to 9 MeV. Most neutrons were produced in the lithium target so that the small reduction gained in background did not warrant the use of the fragile, carbon foils, at least in the range 2.5 to 9 MeV proton energy.

Targets were kept thin — approximately 10 keV for 6 MeV protons — to eliminate excessive pile-up of pulses due to neutron capture in the detecting crystals. Little could be done about the prolific yield of neutrons from the \( \text{Li}^7(p,n)\text{Be}^7 \) reaction but a real reduction could be achieved in the relative number of high energy neutrons produced in the two-stage reaction \( \text{Li}^7(p,\alpha)\text{He}^4, \text{Li}^7(\alpha,n)\text{B}^{10} \), since the latter contribution is proportional to the square of the number of target nuclei/cm\(^2\).

Fresh targets were mounted in the chamber whenever beam-spot marking or deterioration effects became apparent.
3.2.2 The Detection Equipment.

Gamma-rays from the reaction were detected by two lead-shielded 5" diameter by 4" long NaI(Tl) scintillation spectrometers. One was free to rotate in a horizontal plane about the target, while the other was fixed in position to act as a monitor during angular distribution measurements.

Pulses from the DuMont 6363 photomultipliers were fed through Franklin preamplifiers and non-overloading amplifiers and displayed by a RIDL 400-channel and RCL 512-channel pulse-height analyser.

3.2.3 Line-Shapes.

Gamma-ray line shapes for the purpose of spectrum analysis were measured under conditions of identical geometry using the proton beam of the 1.2 MeV Cockcroft-Walton accelerator. The mono-energetic γ-rays from the $^3\text{T}(p,\gamma)^4\text{He}$ ($Q = 19.8$ MeV) reaction at $E_p \sim 1$ MeV and 16 MeV γ-rays from the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction were detected and found to have similar line-shapes, confirming the findings of Mainsbridge (Ma 60a) that γ-ray line-shape changes little with γ-ray energy above about 16 MeV.

The γ-ray line-shape was considerably improved by reducing the angle of acceptance for γ-rays entering the crystal, about a factor of two reduction being observed in the low energy tail of the spectrum. The collimator was a 4" thick lead
cylinder housed in a 4" x 13" x 13" steel block, the whole assembly being interposed in the 6 1/2 inches separating the target spot from the front face of the movable crystal. The collimating aperture was tapered with a half-cone angle of 14°.

The improved tritium γ-ray line-shape was used as a standard and fitted to the γo-line in the Li\textsuperscript{7}(p,γ)Be\textsuperscript{8} (Q = 17.2 MeV) γ-spectrum obtained for Ep = 441 keV. The resultant γ\textsubscript{1} line-shape compared favourably with those obtained at higher proton energies where γ\textsubscript{1} radiation is dominant; agreement with results obtained by Mainsbridge (Ma 60a) in an earlier and similar work, was good.

3.2.4 Photomultiplier Gain Stability.

It was found that the photomultiplier gains were sensitive to count rate i.e. to the γ-ray and particularly neutron flux. The proton beam intensity was reduced, therefore, as reaction yields increased, to minimize gain changes. A close check was kept on gain drifts by frequent calibration with 2.62 MeV γ-rays from the ThC source and high-energy proton capture γ-rays from the B\textsuperscript{11}(p,γ)C\textsuperscript{12} reaction, using a B\textsuperscript{11} target. The Li\textsuperscript{7}(p,γ)Be\textsuperscript{8} γ-ray spectrum could also be used for self-calibration but was rather less reliable by virtue of the great width of the γ\textsubscript{1}-ray line.
3.2.5 Alignment of the Target.

The vertical alignment of the centres of the angular distribution table and target was checked by two methods. A set of cross-wires backed by a quartz glass was mounted on the target support strip and located at the beam-spot centre. The cross-wires and vertical axis of the table were aligned optically.

Isotropic angular distributions are required for the \( \text{Be}^9(p,\alpha\gamma)\text{Li}^6 \) (\( E_p = 2.56 \) MeV) and \( \text{C}^{13}(p,p'\gamma)\text{C}^{13} \) (\( E_p = 4.0 \) MeV) reactions (Aj 59); any measured departures from these permit appropriate corrections to be made to angular distribution data recorded for the \( \text{Li}^7(p,\gamma)\text{Be}^8 \) reaction under the same geometry. A \( \text{C}^{13} \) target was mounted for this purpose in the present experiment.

3.2.6 Procedure.

Targets were bombarded with proton beams of 0.2\( \mu \)a or less, analyser live-times being kept to higher than 90\% by control of the beam current. Use of a higher discrimination against low-level pulses than was provided at the analyser inputs was found to be unnecessary.

Spectra were recorded at intervals of approximately 50 keV over the proton energy range 2.5 to 9 MeV for the \( \gamma \)-ray yield determinations at 90\(^\circ\). Angular distribution measurements were made at a number of energies over the region of the giant resonance and for angles from 0\(^\circ\) to a maximum of 120\(^\circ\) in the
laboratory system. Observational angles greater than this were inaccessible.

3.3 Analysis.

The simple but tedious technique for separating the two component γ-rays from a spectrum was similar to the method outlined by Gove et al. (Go 61), but a number of properties of the Be⁸ nucleus introduced serious difficulties not encountered in the Chalk River work.

While no states of Be⁸ have been found between 2.9 and about 11.4 MeV excitation, the O⁺ ground state and 2⁺ first excited state are separated by only 2.9 MeV (Aj 59), representing a rather small difference in the high energies, (17.25 + \( \frac{7}{8} \) Ep) and (14.3 + \( \frac{7}{8} \) Ep) MeV, of the two proton capture γ-rays which populate them. But, it is the great width, approximately 1 MeV, of the 2⁺ state, which particularly complicated the analysis, since it is reflected in the energy spread of the Y₁-rays.

This would not be such a problem were not the Y₀ yield so weak. Reference to figure 3.1 will make the point clear. The peak of the Y₀-line lies just below channel 240 and is not resolved cleanly from the leading edge of the intense and broad Y₁-line, even though the Y₀- to - Y₁ yield ratio was found to be close to its maximum value at this proton energy viz. 5 MeV. Obviously, reliable calibrations of the spectra were required to establish the position of the Y₀-line peak at all closely.
The high energy portion of the Li$^7$(p,γ)Be$^8$ spectrum recorded at $E_p = 5.0$ MeV. Arrows labelled A and B define the $\gamma_1$ window, C and D the $\gamma_0$ window. The estimated line-shapes for the two component γ-rays are indicated, and the cosmic ray background is shown by the broken line.
Since the $^8\text{Be}^{+}$ ground state is a sharp 2.5 ev (Aj 59) it seemed reasonable to fit the experimentally determined, mono-energetic, $\gamma$-ray line-shape to the $\gamma_0$-line. This was done after a measured cosmic ray background (equal to the machine background in this energy region of the spectrum) had been subtracted. After removal of $\gamma_0$, the residual line shapes for $\gamma_1$ were found to be similar to those obtained at proton energies of less than 1 MeV, demonstrating that only cosmic ray background and $\gamma_0$ events were contributing significantly to the $\gamma_1$ spectrum in the region AB of figure 3.1. There was no method of fitting the $\gamma_1$-line shape to test the accuracy of the unfolding of a spectrum.

The windows CD and AB were chosen to define representative areas of the $\gamma_0$ and $\gamma_1$ spectra and the numbers of counts falling in these windows were used to generate the $\gamma_0$ and $\gamma_1$ yield curves. As proton, and therefore $\gamma$-ray energies were changed, each window width was adjusted to define a fixed fraction of the $\gamma$-ray spectrum.

Meaningful separation of the $\gamma_0$- and $\gamma_1$-lines became more difficult with increasing proton energy. Figure 3.2 shows a typical spectrum, recorded at a proton energy of 7.0 MeV; the $\gamma_0$ peak has merged almost completely into the broad and dominant $\gamma_1$-line. Since the $\gamma_0$ yield was found to decrease steadily thereafter, no estimate of its intensity was attempted beyond $E_p = 7$ MeV.
Figure 3.2

The $\gamma$-ray spectrum at $E_p = 7.0$ MeV. The position of the diminished $\gamma_0$ peak is indicated. Arrows A and B define a window in the $(\gamma_0 + \gamma_1)$ spectrum.
3.4 Results

3.4.1 Excitation Functions.

The excitation functions measured for $\gamma_0$ and $\gamma_1$ are shown in figure 3.3. The $\gamma_0$ yield varies smoothly with energy and exhibits a broad maximum at about 5 MeV with a width of about 5 MeV. Errors indicated are of the order of 20% and arise from the assumption that the window CD may be displaced by as much as three channels in either direction. Statistical errors on the points are typically 3 to 4%.

The $\gamma_1$ yield curve is also shown in figure 3.3. Errors are smaller, displacements of the window AB producing little change in yield estimate. The shape of the resonance suggests a "width" of about 8 MeV.

Apparent structure at about 6 and 7.3 MeV proton energy is confirmed by a comparison with the results for the $(\gamma_0 + \gamma_1)$ yield (figure 3.4). Since the $\gamma_0$ yield decreases beyond $E_p = 5$ MeV and is much weaker than the $\gamma_1$ yield, the course of the $(\gamma_0 + \gamma_1)$ excitation function should reflect the behaviour of the $\gamma_1$ yield in detail.

Not all data recorded for the $\gamma$-ray yields were analysed into $\gamma_0$ and $\gamma_1$ components, and the solid line in figure 3.4 represents the $(\gamma_0 + \gamma_1)$ yield averaged over a number of runs taken at energy intervals of about 50 keV. The hump suggested by the $\gamma_1$ data is indicated clearly in the $(\gamma_0 + \gamma_1)$ results.
Figure 3.3

The excitation functions for the $\text{Li}^7(p,\gamma_0)\text{Be}^8$ (lower curve) and $\text{Li}^7(p,\gamma_1)\text{Be}^{8\ast}$ (upper curve) reactions. Errors shown are of the order of 20% for $\gamma_0$ and 8% for $\gamma_1$ (see text). Normalized results from various measurements are distinguished by different symbols. The ordinate scale is arbitrary for both yield curves and therefore does not indicate the relative intensities of the two $\gamma$-ray components.
Figure 3.4

The \((Y_0 + Y_1)\) yield curve (unbroken line) determined by the present experiment, and the yield curve of Perry et al. (Pe 62) (heavy broken line) normalized at \(E_P = 7.3\) MeV. The suggested structure was established by careful experiment and a typical measurement is displayed in the inset (magnification \(x\) 2). The light broken line indicates the extension of the yield data recommended by Feldman (Pe 63).
A more precise determination was made in the region of energies bounded by the inset of figure 3.4. Results of one such measurement, and quite typical of three made, are displayed in the inset, confirming the change in slope of the yield curve. Thus, the structure suggested in the $\gamma_1$ yield curve is verified and seen to be the source of the structure observed in the $(\gamma_0 + \gamma_1)$ yield curve.

An independent and similar study of the $\text{Li}^7(p,\gamma_0 + \gamma_1)\text{Be}^8$ reaction was later found to have been made by Perry et al. (Pe 62) at Rice University, using a 3'' x 3'' NaI(Tl) detecting crystal. The yield curve they measured at 90° has been normalized to the present results at $E_p = 7.3$ MeV and is shown as a heavy, broken line. The agreement is remarkably good over the energy range common to both studies, and evidence of structure is again given. The very recent results of unpublished work by Feldman et al. (Fe 63) at Columbia University have extended the $\text{Li}^7(p,\gamma_1)\text{Be}^8$ measurements from 10.4 to 14.5 MeV proton energy, and are indicated by the light broken line in figure 3.4.

3.4.2 Angular Distributions.

Angular distributions were measured at a number of representative energies over the resonance and were fitted with a Legendre polynomial expansion of the form

$$W(\theta) = A_0 + A_1P_1(\cos \theta) + A_2P_2(\cos \theta)$$
Angular distributions for separated and combined $\gamma$-rays. The broken and unbroken lines are obtained for polynomial analyses with and without the inclusion of $P_1$ terms, respectively. Errors on the experimental points are estimated to be 10% for $\gamma_0$, 6% for $\gamma_1$ and $\sim 3\%$ for $(\gamma_0 + \gamma_1)$. The results of Perry et al. at $E_p = 6.73$ MeV are displayed for comparison.
using a least squares analysis programmed onto an IBM 1620 computer. The scarcity of measurements at some energies, and particularly for angles beyond 90°, made the need for inclusion of $P_1$ terms uncertain. This is shown in figure 3.5 where plots of fitted expressions are given, both with and without $P_1$ contributions assumed, indicated by the broken and unbroken lines, respectively. The expressions listed in the diagram refer to fits to the experimental data and all $P_2$ coefficients must be corrected for the finite solid angle of the detector. This correction was estimated from the curves published by Marion (Ma 60b) to increase the $P_2$ coefficients by a factor 1.09.

Both $\gamma_0$ and $\gamma_1$ angular distributions are near to isotropic and display remarkably little variation over the whole energy range explored. The same pattern of behaviour was observed by Perry et al. (Pe 62) for the $(\gamma_0 + \gamma_1)$ angular distributions and a representative measurement taken at $E_p = 6.73$ MeV is included in figure 3.5 for comparison. In both sets of data there is a persistent suggestion of a slight forward asymmetry in the $\gamma$-ray angular distributions. Errors for the $\gamma_0$ data were estimated to be 10%, for the $\gamma_1$ data 6%, and for the $(\gamma_0 + \gamma_1)$ data about 3% and purely statistical. These were generally larger than the residual r.m.s. errors arising from the polynomial analysis.
3.5 Discussion.

Crude estimates were made of the relative cross-sections for \((p, \gamma_0)\) and \((p, \gamma_1)\), the reciprocity relationship for inverse reaction cross-sections was invoked and highly dubious assumptions were made about the equalities of the \(\text{Be}^8\) and \(\text{Be}^{8\ast}\) cross-sections for photoproton and photoneutron emission to the ground and first excited states of \(\text{Li}^7\) and \(\text{Be}^7\), respectively, to show that the 120 MeV - mb. lower limits set by the dipole absorption sum-rule for \(\text{Be}^8\) and \(\text{Be}^{8\ast}\) could be met. Little importance is attached to these calculations, however, and it is rather by analogy with the characteristics of absorption cross-sections for other nuclei that the resonances seen here at about 21.6 MeV and 23.6 MeV are described as corresponding predominantly to giant dipole resonance absorption in the ground and first excited states of \(\text{Be}^8\).

It is interesting to compare the present results with those obtained in studies made for other light nuclei, since it is becoming abundantly clear that, in contrast to the \(\text{Be}^8\) results, much more structure is to be found in the various photon absorption cross-sections than had been revealed by earlier work. Indeed, they indicate that level densities in the lighter nuclei are often low enough, even at quite high excitation, that not only can total \(\gamma\)-absorption measurements supply the radiative widths of the intermediate states excited but photonucleon (i.e. partial) cross-sections reflect the individual level widths for
nucleon emission.

Excitation functions determined by Becker and Fox (Be 63) and more recently by Segel et al. (Se 63) for the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reactions have confirmed that there is definite structure but no marked splitting in the broad resonance centred at 22.6 MeV excitation. Good agreement exists among results of the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ studies (Go 61, Be 63, Se 63) and investigation of the $^{12}\text{C}(\gamma,p)^{11}\text{B}$, via the $(e,e'p)$ reaction, made by Dodge and Barber (Do 62) the latter work proposing rather more structure than did the results of Gove et al. (Go 61), as shown in figure 3.6 (from Ha 63).

Much stronger evidence of splitting is given by the $^{12}\text{C}(\gamma,n)^{11}\text{B}$ cross-section obtained by Firk et al. (Fi 62b) using time-of-flight separation of the neutron energy groups to reveal a detailed, if incomplete, energy level spectrum of $^{12}\text{C}$ in the giant resonance region of excitation; incomplete insofar as population of pure $T = 0$ states of $^{12}\text{C}$ is forbidden by the operation of the isotopic spin selection rule for E1 absorption and emission in the self-conjugate $^{12}\text{C}$ nucleus. The implication is much stronger here than in the $(p,\gamma)$ study that a number of discrete levels or states are involved in the $\gamma$-ray absorption process over this region. The dissimilarities in the $(\gamma,n)$ and $(\gamma,p)$ cross-section — most notably the correspondence of the peak in the $(\gamma,p)$ with a dip in the $(\gamma,n)$ cross-section at about 22.6 MeV excitation — argue that the ratio of neutron to proton width is
Figure 3.6

Some of the more recent measurements of $^{12}\text{C}$
photonouclear cross-sections in the giant resonance
region of excitation. The $^{12}\text{C}(\gamma,p)$ results of
Dodge and Barber (Do 62) and the $^{12}\text{C}(\gamma,n)$ results
of Firk et al. (Fi 62b) clearly display structure.
(reproduced from Ha 63).
changing from state to state i.e. that the amount of isotopic spin impurity may change from state to state.

The splitting observed in the $^{12}\text{C}(\gamma,n)^{11}\text{C}$ cross-section calls for some caution in the interpretation of the $^{12}\text{C}(\gamma,p)^{11}\text{B}$ or, equivalently, $^{11}\text{B}(p,\gamma)^{12}\text{C}$ data. Gove et al (Go 61) and Segel et al. (Se 63) found that the $\gamma_0$ angular distribution over the greater part of the giant resonance was represented closely by the $(1 - \frac{3}{4} \cos^2 \theta)$ dependence expected for a $\frac{1}{2}d - \frac{1}{2}p$ transition. The same angular distribution was observed by Penner and Leiss (Pe 59b) for photoprotons from $^{12}\text{C}$. Vinh-Mau and Brown (Vi 62) have made detailed calculations, within the particle-hole formalism, of the $J = 1^-, T = 1$ states of $^{12}\text{C}$ having large dipole transition strengths and predicted the bulk of the total dipole absorption cross-section to be split between two resonances corresponding to states of $^{12}\text{C}$ at 22.2 MeV and 34.3 MeV with the configurations \( (1p_\frac{3}{2}) (1d_\frac{5}{2}) \) and \( (1s^{-1}) (1p_{\frac{1}{2}}) \), respectively. The former resonance is well established and recently Reay et al. (Re 63) have found a small anomaly in the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ cross-section at an excitation energy of about 34 MeV, in confirmation of the predicted energy but not of the proton width or dipole transition strength required by the calculations. Segel et al. suggested that the dominant $^{11}\text{B}(p,\gamma)^{12}\text{C}$ resonance could be attributed chiefly to one state, "presumably the giant resonant state" with some incoherent
structure superimposed, or to a superposition of states of more or less equal prominence and similar properties. The latter interpretation is indicated clearly by the $^{12}(\gamma,n)^{11}$ data.

Brown et al. (Br 61) have calculated the energies and dipole transition strengths of the $J = 1^-, T = 1$ states of $^{16}O$. (The mixing of configurations through hole-particle interaction mechanism was implicitly contained in the intermediate-coupling shell model calculations of Elliott and Flowers (El 57) so that the good agreement between the two predictions is understandable.) Large dipole matrix elements were predicted for $^{16}O^-^1$ states near 22 and 25 MeV and, as in the case of $^{12}C$, a favourable comparison may be made of theory and experiment. The $^{15}(p,\gamma)^{16}O$ results of Tanner et al. (Ta 61) and $^{16}(\gamma,p_o)^{15}$ results summarized by Fuller and Hayward (Fu 62) are displayed in figure 3.7 (taken from Ha 63). Even more structure than is shown in the $^{16}(\gamma,n)^{15}$ cross-section measured by Firk et al. has been found recently. The resonance at 24.3 MeV is now thought to be the envelope of at least three resonances at energies 24.1, 24.3 and 24.5 MeV, and splitting of the resonance at 22.2 MeV is indicated also, (Fi 62a). The total absorption cross-section determined by Burgov et al. (Bu 63) is consistent with the partial absorption cross-sections, both with regard to cross-section magnitude and structure. It is obvious that little more can be expected of the theoretical calculations than a location and characterization of states that together account for the
Photonuclear reaction cross-sections for $^16O$ over the giant resonance region. The more numerous resonances seen in the total absorption measurements of Burgov et al. (Bu 63) have been verified in subsequent work by Firk et al. (Fi 62a).
EXCITATION ENERGY, MeV

RELATIVE CROSS SECTION

σ, mb

E^* = 22.5 MeV

FIRX, LOKAN & BOWEY

σ^* (N)

TANNER, THOMAS, EAGLE

σ^* (N)

σ^* (N)

σ_{tot}, mb

Excitation Energy, MeV

Burgov et al.

Elliott and Flowers
strong nuclear dipole absorption.

The considerable splitting of the "giant resonance" in light nuclei with \( A = 4n \) is a quite general feature of \((p,\gamma)\) reactions initiated in \( N^{15} \) (Co 61, Ta 61), \( P^{19} \) (Br 60a, Ta 61, Go 61), \( Na^{23} \) (Go 61), \( Al^{27} \) (Go 61, Sh 61, Se 63, Pa 63) and \( F^{31} \) (De 62). Correlation between resonances in \((p,\gamma_0)\) and \((p,\gamma_1)\) cross-sections can be made only rarely; as is to be expected, the equally numerous resonances observed in the \((p,\alpha)\) cross-sections also appear to be correlated infrequently.

In view of the structure apparent in other light nuclei, it is perhaps surprising that only a few broad levels appear to be involved in the \( Li^7(p,\gamma)Be^8 \) process. However, the cross-section behaviour of other \( Li^7 + p \) reactions, e.g. \( Li^7(p,n)Be^7 \) and \( Li^7(p,\alpha)He^4 \) display only a few broad resonances above \( E_p = 3 \) MeV (Bo 61, Ha 61, etc.). Naturally, resonances in the \((p,\alpha)\) cross-sections correspond to intermediate states with even spin and parity as required by the symmetric spatial dependence of the wavefunctions for the outgoing \( \alpha \)-particles. As such, they are unrelated to the negative parity states excited through dipole absorption of \( \gamma \)-rays by \( 0^+ \) and \( 2^+ \) states of \( Be^8 \). In fact, the resonances observed in neither the \((p,n)\) nor \((p,\alpha)\) cross-sections appear to correspond to those seen in the \((p,\gamma)\) yield curves over the giant resonance energy region. Thus, it seems that, at these excitation energies, the level density of \( Be^8 \) is not high and that the few levels present are characterized
by considerable width.

Sarma et al. (Sa 63) have interpreted the results of their Li$^7(p,α)$He$^4$ studies over the range 3.0 to 5.5 MeV proton energy to require no more than a 3% contribution from non-resonant processes at the $E_p = 3.1$ MeV resonance, i.e. the compound nucleus description seemed to be satisfactory in that energy range. Although there have been indications that triton pick-up processes are important at much higher proton energies (Ma 57a) no attempts have been made as yet to determine whether proton capture by the "triton" in the loosely (2.47 MeV) bound Li$^7$ nucleus can explain some of the observed features of the Li$^7(p,γ_o)$Be$^8$ reaction.

At present no accurate Li$^7$ shell model wavefunctions are available to provide computed cross-sections and angular distributions for comparison with experimental results. Analysis of the current $(p,γ)$ results in terms of a compound nucleus level or levels also seems to be of doubtful value for resonances as broad as these. It can be shown that s-wave proton capture, pure d-wave proton capture with channel-spin mixing, or an admixture of s- and d-wave proton capture by Li$^7$ can generate a $γ_o$ angular distribution that is isotropic, as observed in the measurements.

In view of the observed lack of structure in the present $(p,γ)$ results for Be$^8$ as compared with other light nuclei, some attention is given to the claims made by Feldman et al. (Fe 63)
The excitation function provided by Feldman (Fe 63) for the Li$^7(p,\gamma_1)$Be$^{8*}$ reaction above the giant resonance region of excitation. The results are discussed in the text.
Li$_7$(p,$\alpha$)Be$_8$

$Q_1 = 14.34$ MeV
for fluctuations in the $^{7}\text{Li}(p,\gamma)^{8}\text{Be}$ cross-section above $E_p = 10.5$ MeV. The $\gamma$-ray spectra that they obtained with a shielded and collimated $5'' \times 5''$ crystal appear to be of similar quality to those recorded in the present experiment, but for a number of reasons some caution is felt in accepting the accuracy of the excitation function produced (figure 3.8). Although $\gamma_0$-contributions to the $\gamma$-ray spectra were subtracted out, no estimates were given of the $\gamma_0$ yield or of its fluctuation, nor were errors on the $\gamma_1$ yield estimates supplied. Cyclotron beam energy resolution was not specified and lithium targets were thick (between 4 and $8 \text{ mg/m/cm}^2$), so that while the dip in the $\gamma_1$ yield curve at about $E_p = 12.6$ MeV may be real, the structure observed between 11 and 12 MeV proton energy is thought to require further substantiation.

Gamma-ray angular distributions for many of the $(p,\gamma)$ reactions display remarkably little variation throughout the many resonances traversed over a wide range of excitation energies. Mention was made of the $(1 - \frac{3}{4} \cos^2 \theta)$ $\gamma$-ray distribution measured for the $^{11}\text{B}(p,\gamma)^{12}\text{C}$ reaction (Go 61, Se 63) but nearly constant angular distributions now appear common to proton ground state capture $\gamma$-rays from the $^3\text{T}(p,\gamma)^4\text{He}$, $^{7}\text{Li}(p,\gamma)^8\text{Be}$, $^{11}\text{B}(p,\gamma)^{12}\text{C}$, $^{15}\text{N}(p,\gamma)^{16}\text{O}$, $^{19}\text{F}(p,\gamma)^{20}\text{Ne}$, $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$

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Both plastic scintillator, anti-coincidence, cosmic ray and lead shielding were employed.
and $^{31}(p,\gamma)^{32}$ reactions (Op 63). While this indicates that, in any nucleus, the states being populated have similar properties, no satisfactory explanation has been advanced for a quite generally observed and persistent forward asymmetry in the $\gamma$-ray angular distribution. Interference with an E2 component has been proposed but does not explain the persistence of the positive coefficient of the $\cos \theta$ term in the Legendre polynomial expansion of the distribution. The participation of a large number of intermediate states in the excitation might be expected to provide about as many negative as positive deviations from symmetry about $90^\circ$. No extensive distribution measurements have been taken to ascertain whether negative coefficients of $P_1(\cos \theta)$ are typical above the giant resonance region.

In conclusion, it may be said that an inspection of the $(p,Y_0)$ and $(p,Y_1)$ cross-sections, to determine whether giant dipole absorption resonances exist for excited states of nuclei, seems rather more profitable when only the gross features of the absorption cross-section are evident. Poor resolution studies – total absorption, thick target and low beam energy resolution experiments – are therefore often more useful. A good example is provided by the $^{27}(p,\gamma)^{28}$ data of Gardner and Gugelot (Ga 61) where an apparent displacement of about 1.8 MeV may be observed in the maxima of the $(p,Y_0)$ and $(p,Y_1)$ resonance envelopes (figure 3.9), while the more detailed structure in the results of Gove et al. (Go 61) obscures the effect. In this
In the upper diagram a separation of about 1.8 MeV is suggested between the peaks of the envelopes of the resonances in the differential cross-sections for the $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ and $^{27}\text{Al}(p,\gamma_1)^{28}\text{Si}_{1.8}^*$ reactions. The results of Becker and Fox (Be 63) are presented in the lower diagram and suggest a displacement of about 4.5 MeV (C.M.) in the resonance envelopes for the $^{11}\text{B}(p,\gamma_0)^{12}\text{C}$ and $^{11}\text{B}(p,\gamma_1)^{12}\text{C}_{4.43}^*$ reaction cross-sections at $\theta = 90^\circ$. 
respect the \( \text{Li}^7(p,\gamma)\text{Be}^8 \) and \( \text{B}^{11}(p,\gamma)\text{C}^{12} \) studies have proved exceptional; a separation of about 4 MeV is still suggested between the envelopes of the \( \text{B}^{11}(p,\gamma_0)\text{C}^{12} \) and \( \text{B}^{11}(p,\gamma_1)\text{C}^{12} \) cross-section resonances obtained by Becker and Fox (Be 63) as shown in figure 3.9, and no confusing structure has appeared in the \( \text{Li}^7(p,\gamma)\text{Be}^8 \) excitation functions.

Calculations by Barker (Ba 57), using very approximate shell model wavefunctions, have provided harmonic mean energies \( W_H \) for dipole absorption in nuclei with mass number \( A \leq 40 \) in good agreement with experimental values, and further suggested that the \( W_H \) were insensitive to the details of the ground state wavefunctions chosen. These findings may be taken to confirm the view that this characteristic of the giant resonance reflects the gross size and shape of the nucleus rather than nuclear details. Since the size of a particular nucleus is not expected to alter very much for low energy excitations, a similar value \( W_H \) can be anticipated for dipole transitions out of the low-lying excited states. The observed trend of a displacement in \( (p,\gamma_0) \) and \( (p,\gamma_1) \) resonance maxima by about the separation of the ground and first excited states (Chapter 3.1) therefore has some foundation. The peaks observed in the present \( \text{Li}^7(p,\gamma)\text{Be}^8 \) results are in fact separated by about the appropriate energy but the widths of the peaks prohibit an accurate estimate. Indeed, this difficulty is common to all similar measurements made for other nuclei.
SECTION II
4.1 Introduction

In the simplest single-particle picture of $^{17}_{17}O$, in which the valence neutron is coupled to an inert $^{16}_{16}O$ core, the $^{17}_{17}O$ quadrupole moment and the matrix element for the E2 transition between the 0.871 MeV $\frac{1}{2}^+$ first excited state and $\frac{5}{2}^+$ ground state of $^{17}_{17}O$ (Aj 59) are both zero. This result follows immediately from Weisskopf's formulae for single-particle transition rates (We 51), since the neutron carries no charge and the contribution arising from the magnetic moment of the neutron may be ignored, to a good approximation.

The earliest measurement of the lifetime of the 0.871 MeV state of $^{17}_{17}O$ was made by Thirion and Telegdi (Th 53) and yielded a value $(2.5 \pm 1) \times 10^{-10}$ sec., thus indicating that core effects were involved. Since these authors were unable to explain their experimental value purely in terms of core recoil, they proposed a departure from the extreme independent particle model by mixing into both the ground state and first excited state wavefunctions of $^{17}_{17}O$ small contributions from an $^{16}_{16}O$ core $2^+$ "collectively" excited state. (This state was collective in the sense that it had to have a large E2 matrix element for the ground state transition).
In a number of different approaches, authors (Am 57, Ba 59a, Ba 59b, Fa 59, Ra 60) were able to obtain fair agreement with experiment for the values of the $^{17}\text{O}$ quadrupole moment and lifetimes of the first excited states of $^{17}\text{O}$ and $^{17}\text{F}$ (the 0.871 MeV $^{1+}/2$ and 0.500 MeV $^{1+}/2$ states, respectively).

If a single $2^+$ "collective" state, which exhausted the $T = 0$ E2 sum-rule limit (Ge 53) for the $^{16}\text{O}$ ground state, were assumed to account for the whole $^{17}\text{O}$ quadrupole effect, estimates (Am 57, Ba 59b, Fa 59) of its maximum energy varied from 12 - 18 MeV. Results of an analysis by Thomas and Tanner (Th 62), using improved single-particle wavefunctions, indicated that although the quadrupole properties of $^{17}\text{O}$ could be accounted for in terms of the known $T = 0$ 2$^+$ states in $^{16}\text{O}$ (Aj 59) the magnitude of the $^{17}\text{F}$ lifetime could only be matched by changing the single-particle matrix element by about 30%, or by postulating a new $2^+ T = 1$ state in $^{16}\text{O}$ which would make a large E2 matrix element contribution.

Matthies et al. (Ma 62) carried through an analysis of the $^{17}\text{O}$ problem in terms of weak-coupling between the valence neutron and an $\alpha$-model core, and obtained good agreement with experiment for their calculated values of the $^{17}\text{O}$ quadrupole moment and lifetime of the $^{1+}/2$ state. They concluded that the 6.92 MeV $2^+$ state of $^{16}\text{O}$ contributed almost all the enhancement, so that no new $2^+ 0^{16}$ state was required by them to make core contributions.
However, they did not quote their estimate for the lifetime of the 6.92 MeV state of \( ^{16}O \) (for comparison with the experimental value \((1.2 \pm 0.3) \times 10^{-14}\) sec. (Aj 59)) to permit a test of the accuracy of their model.

It should be remarked that all previous calculations have ignored contributions from recoil effects. This has been shown by Fallieros and Ferrell (Fa 59) to be accurate for oscillator potential wavefunctions but it is possible that more reasonable forms for the potential will give rise to non-zero recoil contributions which may partly account for the observed \( ^{17}O \) and \( ^{17}F \) quadrupole properties.

Thus, while the relative importance of a hypothetical collective state is debatable, and, therefore, the need for contributions from \( 2^+ \) states of \( ^{16}O \) besides those already known, there exist other theoretical predictions which encourage a search for \( ^{16}O \) \( 2^+ \) states. Two rather different shell model calculations of the even parity states of \( ^{16}O \) have each predicted a \( 2^+ \) state with a large E2 matrix element for the ground state transition;

\[ U(r) = \frac{\hbar^2}{2Ma^2} \frac{1}{\alpha} \left(1 - e^{-\frac{r^2}{a^2}}\right) \]

which tends towards the oscillator form as \( \alpha \to 0 \), suggested that contributions might be appreciable. The estimates were unreliable, however, because they were expressed as power series in \( \alpha \) and convergence was not assured (F.C. Barker, private communication).
Gillet (Gi 62) requires a specific $T = 0$ state at 13.7 MeV and Brink and Nash (Br 63) predict a $T = 0$ state in the energy range 15 - 20 MeV. Both states make large contributions to the quadrupole sum-rule limit and have large widths for $\alpha$-particle decay. As such, they should be observable in the $^{12}_C(\alpha,\gamma_0)^{16}_O$ reaction.

The spectroscopic evidence from $^{15}_N + p$ and $^{12}_C + \alpha$ studies indicates that even parity levels of $^{16}_O$, including a $2^+$ level, are to be found at an excitation energy of about 13 MeV, and these data are discussed in the following section.

4.2 Spectroscopic evidence

The known energy levels of $^{16}_O$ over the range of excitation energy 8.88 - 13.26 MeV are shown schematically in figure 4.1 (taken from the latest compilation of Lauritsen et al. (La 62)). Although this energy region has been explored in considerable detail, notable discrepancies exist in the data provided by a variety of $^{12}_C + \alpha$ and $^{15}_N + p$ reaction studies.

Particular attention is paid in this summary to the resonance anomalies associated with the 13.10 MeV level, and the explanations that have been offered for them. To simplify identification in the following discussion, the excitation energy of a level in $^{16}_O$ will be given by the value listed in figure 4.1, except where an author has specified its value to be otherwise.
Section of the energy level scheme for $^{16}$O (La 62).
4.2.1 The $^{12}$C + α Reactions

It is to be recalled that the requirement of conservation of isotopic spin $T$ is satisfied by the $^{12}$C ($T = 0$) capture of α-particles ($T = 0$) only into states of $^{16}$O with $T = 0$ i.e. the reactions $^{12}$C($α,α_0$)$^{12}$C and $^{12}$C($α,α^*$)$^{12}$C$^*$ (for all excited states of $^{12}$C (see La 62) below the 15.1 MeV $T = 1$ level) proceed via $T = 0$ states in $^{16}$O. However, operation of the selection rule (Ra 52, Ge 53) $ΔT = ± 1$ for electric dipole γ-ray transitions in self-conjugate ($N = Z$) nuclei will inhibit the de-excitation of $J = 1^−$, $T = 0$ states of $^{16}$O by radiative transitions to the $J = 0^+$, $T = 0$ ground state. Resonances in the $^{12}$C($α,γ_0$)$^{16}$O cross-section corresponding to intermediate $1^−$ states of $^{16}$O are then to be understood in terms of the isotopic spin impurity of these states; the radiative and α-particle widths of such a $1^−$ level will reflect the proportions of $T = 1$ and $T = 0$ configurations mixed into the resonant state.

4.2.1.1 The $^{12}$C($α,α_0$)$^{12}$C Reaction

One of the properties of the elastic scattering of a zero-spin particle from a zero-spin target nucleus, e.g. the $^{12}$C($α,α_0$)$^{12}$C event, is that the pure resonant scattering amplitude contains only one Legendre polynomial, $P_\ell (\cos θ)$, as a factor, where $\ell$ is the orbital angular momentum of the scattered wave. Specifically (equation (7.11) of Blatt and Biedenharn, (Bl 52)
\[ |f_{R\ell}|^2 = \pi \alpha^2 (2\ell + 1) \frac{(\frac{\Gamma_{\ell}}{\alpha_{\ell}})^2}{(E - E_0)^2 + (\frac{2}{\hbar})^2} |Y_{\ell,0}(\theta)|^2 \]

where \( Y_{\ell,0}(\theta) = \left( \frac{2\ell + 1}{4\pi} \right)^{\frac{1}{2}} P_{\ell}(\cos \theta) \)

At an angle of scattering corresponding to a zero of \( P_{\ell}(\cos \theta) \), the resonant yield will be zero and this is often sufficient to identify the angular momentum \( \ell \) and thus the spin, \( J = \ell \), and parity, \( \Pi = (-)^\ell \), of the resonant state of the compound nuclear system. Clearly, such identification is made most reliably for isolated resonances.

Bittner and Moffat (Bi 54) measured the differential elastic scattering cross-section of carbon for \( \alpha \)-particles for bombarding energies \( 3.8 \leq E_\alpha \leq 7.6 \text{ MeV} \), and at angles \( \theta_{\text{C.M.}} = 147.9^0 \), \( 140.8^0 \), \( 123.2^0 \) and \( 90.0^0 \), corresponding to zeros of the Legendre polynomials, \( P_{\ell}(\cos \theta) \), of order \( \ell = 4 \), \( 3 \), \( 2 \) and \( 1 \) and \( 3 \), respectively. A fifth measurement was made at \( \theta_{\text{C.M.}} = 171.2^0 \), where all \( P_{\ell} \) contribute.

Reference to figure 4.2, a reproduction of the experimental results, demonstrates the usefulness of the qualitative method described above. The assignment-by-inspection of values \( J^\pi = 4^+ \),

\[ ^* \text{Bittner and Moffat quote these values instead of the correct } 149.4^0 \text{ and } 125.3^0. \text{ Note the disappearance of the } E_\alpha = 4.28 \text{ MeV resonance in the inset, } \theta_{\text{C.M.}} = 149.5^0, \text{ of figure 4.2.} \]
Figure 4.2

The differential elastic scattering cross-section for $\alpha$-particles from carbon, measured by Bittner and Moffat (64). Excellent account (solid curves) has been given of the experimental data (points). The disappearance at zeros of $P_j(\cos \theta)$ of the resonance, corresponding to an $O^{16}$ level of spin $J$, is well exhibited.
2\(^+\) and 1\(^-\) to the resonances at \(E_\alpha = 4.28, 5.82\) and 7.04 MeV, respectively, was confirmed by detailed phase-shift analysis. Further, the analysis showed that, at the upper energy limit of the experiment (\(E_\alpha^{16^*} = 12.5\) MeV), the \(\ell = 0\) and \(\ell = 2\) phase-shifts were increasing, strongly suggesting the existence of a 0\(^+\) and 2\(^+\) level at slightly higher energies.

A study of the same reaction by Ferguson and McCallum (Fe 61) at Chalk River extended the measurements of Bittner et al. to an \(\alpha\)-particle energy of \(\sim 11\) MeV. The differential cross-sections obtained are shown in figure 4.3. Again, the disappearance of resonances at a particular energy, for angles of observation corresponding (or nearly so) to zeros of \(P_\ell (\cos \theta)\), point to the appropriate \(J^n\) values for a number of discrete resonances. Clearly, assignments 3\(^-\) and 4\(^+\) for the levels at \(E_\alpha = 8.15\) and 9.0 MeV are indicated. Similarly, \(J^n = 1^-\) is implied for the resonance at \(\sim 7.04\) MeV. Much the same angular dependence of apparent resonance energy was displayed in both studies for this level, but in a detailed analysis of the Chalk River results Ferguson required a value of \(E_\alpha = 7.065\) MeV to characterize this level cf. Bittner's 7.04 MeV. A C.M. width for this resonance was given as 173 keV by Bittner et al. but as 80 keV by Ferguson. This represents a real discrepancy in the data, since high resolution was claimed for each experiment.

At first, the appearance at all angles of the "resonance"
The $^{12}_3(a,a_0)^{12}$ and $^{12}_3(a,a_1')^{12*}$ data of Ferguson and McCallum. It is suggested in the text that the two resonances appearing at $E_\alpha \approx 7.9$ MeV and $E_\alpha \approx 8.15$ MeV in the $124^\circ$ C.M. and $146.8^\circ$ C.M. cross-section curves, and absent in the $88.5^\circ$ C.M. and $139.6^\circ$ C.M. cross-section curves, may correspond to two $J^\pi = 3^-$ levels of $0^{16}$. 
at 13.1 MeV excitation energy was taken as evidence for an $^{16}_0$ level ($P_0 (\cos \theta) = 1$) but no successful Eisenbud-Wigner fit could be made for such an assignment. Ferguson (private communication to D.F. Hebbard) has since indicated that the assumption of two close-lying levels, $J^\pi = 1^-$ and $2^+$ of almost identical width and energy, most nearly explain the $^{12}_C(\alpha, \alpha_0)^{12}_C$ data in this region, but can not account for the yields convincingly. Both above and below this resonance the yields are well-explained.

If the naive, qualitative assignment-by-inspection of the differential cross-sections is adopted for the curves in figure 4.3, it would seem possible to postulate a $3^-$ level at $E_\alpha \sim 7.9$ MeV, but no such easy description can be applied to the other resonance anomalies appearing at slightly lower energy.

The analyses of these two studies of the elastic scattering of $\alpha$-particles from $^{12}_C$ both strongly suggest the existence of a $2^+$ state in the vicinity of 13 MeV excitation in $^{16}_O$.

4.2.1.2 The $^{12}_C(\alpha, \alpha_1)C_{4.43}^{12*}$ and $^{12}_C(\alpha, \alpha_1')C_{4.43}^{12}$ Reactions

Incomplete information has been given by Ferguson and McCallum concerning the $^{12}_C(\alpha, \alpha')C_{4.43}^{12}$ inelastic scattering cross-sections † in this energy region; they remark, however, that the $^{12}_C(\alpha, \alpha_0)C_{4.43}^{12}$ and $^{12}_C(\alpha, \alpha_1')C_{4.43}^{12*}$ reactions exhibit the same

† Ferguson et al. detected the inelastically scattered $\alpha$-particles directly.
resonances except at the energy corresponding to the $1^-$ level at 12.44 MeV. Only the elastic scattering is resonant, i.e.

$$\Gamma_{a_1} \ll \Gamma_{a_0}$$

for this level.

At Florida State University, Mitchell et al. (Mi 61) have measured the excitation function of the $4.43$ MeV $\gamma$-rays from the $^{12}\text{C}(\alpha,\alpha'\gamma)^{12}\text{C}$ reaction, over the energy range $7.3 \leq E_\alpha \leq 17.0$ MeV. Of the several resonances observed, the two lowest in energy appeared at $0^{16}$ excitations of 13.10 and 13.25 MeV. Angular distributions, measured at a number of energies over these two resonances, were "consistent" with $J^\pi = 3^-$ assignments for both. Following Ferguson, Mitchell et al. pointed out that contributions from a $1^-$ and $2^+$ level could, if suitably mixed, generate an angular distribution of $4.43$ MeV $\gamma$-rays identical with that from a single $3^-$ level in $0^{16}$. This point is discussed later. Neither the Florida nor the Chalk River group has suggested that the "7.9 MeV" resonance seen in $^{12}\text{C}(\alpha,\alpha_0)^{12}\text{C}$ on the one hand and in $^{12}\text{C}(\alpha,\alpha'\gamma)^{12}\text{C}$ and $^{12}\text{C}(\alpha,\alpha'\gamma)^{12}\text{C}$ on the other, might correspond to different levels in $0^{16}$; an explanation has been sought purely in terms of a $1^- - 2^+$ level complex.

4.2.1.3 The $^{12}\text{C}(\alpha,\gamma_0)0^{16}$ Reaction

Larson and Spear (La 61) at California Institute of Technology have investigated this energy region through a study of the $^{12}\text{C}(\alpha,\gamma_0)0^{16}$ reaction.

The excitation function, measured at $\theta = 45^0$, (figure 4.4)
The $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$ excitation function recorded at $\theta = 45^\circ$ by Larson and Spear (La 61).
$^{12}\text{C}(\alpha,\gamma_0)\,^{16}\text{O}$ Excitation Function
(Corrected for background)

LARSON and SPEAR

Yield (Arbitrary units)

$^{12}\text{C}(\alpha,\gamma_0)\,^{16}\text{O}$ Excitation Function

Alpha Particle Energy - MeV

9.85; 2+
10.36; 4+
11.52; 2+
12.47; 1−
13.09; 1−
13.25; 3−
confirmed the data of Meads and McIlwrie (Me 60) at low energies and did not identify any new states between 11 and 14 MeV excitation. Resonances found at \( E_\alpha = 7.08, 7.89 \) and 8.11 MeV were associated with the 12.44 \((1^-)\), 13.10 \((1^-)\) and 13.26 \((3^-)\) MeV levels of \(^{16}\text{O}\). The experiment was performed under conditions of poor geometry and the peak at \( E_\alpha = 8.11 \) MeV was thought to be due largely to summing in the crystal of the cascade \( \gamma \)-rays. A similar explanation was given for the peak at 4.26 MeV.

The ratio of the peak yields at the resonances labelled 12.47 and 13.09 MeV is 0.65 : 1. The implication that this value might be explained in terms of a \( 2^+ \) level at \( \sim 13 \) MeV is left until Chapter 4.2.3, where the necessary parameters are presented.

As a by-product of their work, Larson et al. measured the \( ^{12}\text{C}(\alpha, \alpha' \gamma)^{12}\text{C} \) excitation function at an angle \( \theta = 45^0 \) for \( \alpha \)-energies from 7.5 to 10.5 MeV, corroborating the data of Mitchell et al. to within 20 keV for the energy of each resonance. In particular, they quoted \( E_\alpha = 7.96 \) and 8.14 MeV for the peak energies of the two low-lying resonances. No explanation was given for the 70 keV difference in peak energy revealed by the ground state and 4.43 MeV \( \gamma \)-ray measurements at the lower of the two resonances.

4.2.2 \(^{15}\text{N} + p \) Reactions

Since the same region of excitation in \(^{16}\text{O}\) is accessible through bombardment of \(^{15}\text{N} \) by \( \sim 1 \) MeV protons \( (Q = 12.126 \) MeV)
and of $^{12}\text{C}$ by $\sim 7$ MeV $\alpha$-particles ($Q = 7.162$ MeV), the literature on $^{15}\text{N} + \text{p}$ reactions at low proton energy is relevant to this survey. These reactions are characterized by two possible values, 0 and 1, of the entrance channel spin $s^+$ and may therefore proceed via $^{16}\text{O}$ states which are strictly forbidden to the $s = 0$ ($^{12}\text{C} + \alpha$) system viz the "unnatural-parity" states $0^-, 1^+$, $2^-$, etc. Consequently, these are of no concern to this discussion. Both $T = 0$ and $T = 1$ states of $^{16}\text{O}$ can be populated in the proton-induced reactions cf. the predominantly $T = 0$ intermediate states formed in the $^{12}\text{C} + \alpha$ reactions. Thus, $^{15}\text{N} + \text{p}$ reaction studies can be expected to reveal strongly radiating dipole states ($T = 1$, $J = 1^-$) not easily available to a $^{12}\text{C} + \alpha$ system.

4.2.2.1 The $^{15}\text{N}(p,\alpha_0)^{12}\text{C}$ Reaction

Resonances have been observed by many workers (Sc 52, Co 53, Ne 53, Ha 57a, Ba 59c) in the $^{15}\text{N}(p,\alpha_0)^{12}\text{C}$ reaction at or near to proton energies of 338, 1010 and 1210 keV, corresponding to the $^{16}\text{O}$ levels at 12.44, 13.10 and 13.26 MeV.

An isotropic angular distribution of the long-range $\alpha$-particles has been measured below 400 keV, consistent with either a $0^+$ or $1^-$ assignment. The former was proposed by Cohen and French (Co 53) and interference with the 13.10 MeV $1^-$ level invoked

$^+$ The channel spin is defined as the sum of the intrinsic spins of incident and target nucleus: $s = \frac{1}{2} + I$. The spins of $^{15}\text{N}$, $^{12}\text{C}$, $^{4}\text{He}$ and $^{1}\text{H}$ are $\frac{3}{2}$, 0, 0 and $\frac{1}{2}$ respectively (Aj 59).
to explain the appearance of an increasing $\cos \theta$ term in the 
$\alpha$-particle distribution for proton energies greater than 400 keV. 
Hagedorn and Marion (Ha 57a) found $1^{-}$ to be the more satisfactory 
possibility, and their observation of terms in $\cos \theta$ up to the 
fourth power in the distribution at higher proton energies implied 
an interfering participation by a state of positive parity and 
higher $J$ value. Bashkin et al. (Ba 59c) interpreted their data 
in the neighbourhood of 1010 keV to involve a single ($1^{-}$) state 
$\mathrm{C}^{16}_{1}$ in the $(p,\alpha_{0})$, $(p,\alpha_{1} \gamma)$ and $(p,\gamma_{0})$ processes. Again, 
interference effects were suggested.

In a comprehensive analysis of the published data, Hebbard 
(He 60) has given a description of the $\mathrm{N}^{15}(p,\alpha_{0})\mathrm{C}^{12}$ cross-section 
from threshold up to 1200 keV in terms of the $338^{-}$ and 1010-keV 
$1^{-}$ resonances and their constructive interference. However, his 
analysis of the angular distributions of long-range $\alpha$-particles 
over this energy region strongly suggested that two further levels, 
a $0^{+}$ level at $\sim$ 500 keV and a $2^{+}$ level at $\sim$ 1000 keV proton 
energy, were contributing. To account for their appearance only 
in the $\mathrm{C}^{12}(\alpha,\alpha_{0})\mathrm{C}^{12}$ reaction (Chapter 4.2.1.1) and through the 
angular distribution of the $\mathrm{N}^{15}(p,\alpha_{0})\mathrm{C}^{12}$ reaction, Hebbard has 
postulated large $\alpha$-particle and small proton widths for these two 
levels.

The angular distributions of long range $\alpha$-particles at the 
1210-keV resonance favour a $3^{-}$ over a $4^{+}$ assignment, Hagedorn et
al. (Ha 57a) and the work of Bashkin et al. (Ba 59c) has confirmed this preference. The question of this assignment is raised again in the next section, however.

4.2.2.2 The \( N^{15}(p,\alpha_1 \gamma)C^{12} \) and \( N^{15}(p,\alpha_1')C^{12*} \) Reactions

No resonance has been observed for this reaction at 338 keV and its absence in the \( C^{12}(\alpha,\alpha_1')C^{12*} \) reaction (Chapter 4.2.1.1) indicates an extremely small width \( \Gamma_{\alpha_1} \) for the level. The resonance at 1010 keV is weak and suffers a displacement towards higher energies (e.g. Schardt et al. (Sc 52)) an effect attributed to the penetration factor for the short range \( \alpha \)-particles. The identification of this resonance with the 13.10 MeV \( 1^- \) level is accepted, however.

Likewise, the identity of the resonance at 1210 keV is not disputed, but the spin-and-parity assignment for this resonance has proved curiously ambivalent. The \( (\alpha_1 - \gamma) \) angular correlation measured by Hagedorn indicated \( J = 3^- \), while the angular distributions of the 4.43 MeV \( \gamma \)-rays (Ha 57b, Ba 57a) proved compatible with either \( 3^- \) or \( 4^+ \) assignments. The short-range \( \alpha \)-particle angular distribution recorded by Kraus et al. (Kr 53) and by Hagedorn (Ha 57b) excluded the \( 3^- \) assignment, but a similar measurement by Bashkin et al. (Ba 59c) favoured this value.

4.2.2.3 The \( N^{15}(p,\gamma_0)O^{16} \) Reaction

Observation by Hebbard (He 60) of the weak ground-state \( \gamma \)-radiation from the 12.44 MeV level has established definitely
the $^1$ character of this level. The resonance observed (Sc 52, Kr 54, Ba 59c, He 60) at $\sim$ 1010 keV has been found to radiate isotropically (Kr 54) to the ground state in accord with the $^1$ assignment. The great strength of this electric dipole transition has led to an interpretation (Wi 56) of the level as the $T = 1$ analogue of the 392-keV, $^1$ level of $^{16}$N (Aj 59). A small $T = 0$ admixture is required to explain the considerable $\alpha$-particle width implied by the $^{12}$C $+ \alpha$ results. Destructive interference between the two $^1$ resonances adequately explained the integrated cross-section for the $(p, \gamma)$ reaction in Hebbard's description of this energy region. G.M. Bailey (of this laboratory) has made careful measurements (to be published) of the $\gamma$-ray angular distributions from this reaction at proton energies from 800 to 1080 keV and found no evidence for odd order Legendre polynomial terms, i.e. no evidence of interference between the $^1$ level and another of positive parity. Both this result and Hebbard's analysis imply a very small proton width for the $2^+$ level believed to exist near 1000 keV proton energy.

4.2.2.4 The $^{15}$N$^1(p,p)$N$^{15}$ Reaction

The elastic scattering of protons (Ha 57b, Ba 59c) by $^{15}$N has confirmed the spin-parity assignments $^1$ and $^3$ for the 1010-keV and 1210-keV resonances. Hagedorn (Ha 57b) claimed that the 1010-keV anomaly was sufficiently well fitted to exclude the possibility of two states being involved at this resonance.
The small proton width of the 338 keV resonance explains the non-appearance of a scattering anomaly at this energy.

4.2.3 Discussion

The parameters which describe the three levels of interest are taken from Hebbard (He 60) and are displayed in tabular form below:

<table>
<thead>
<tr>
<th>Ep (keV)</th>
<th>J^π</th>
<th>T</th>
<th>( \Gamma_p ) (keV)</th>
<th>( \Gamma_{\alpha_o} ) (keV)</th>
<th>( \Gamma_{\alpha_1} ) (keV)</th>
<th>( \Gamma_{\gamma_o} ) (eV)</th>
<th>( \Gamma ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>338</td>
<td>1^-</td>
<td>0</td>
<td>1.1</td>
<td>93</td>
<td>0.025</td>
<td>12.8</td>
<td>94</td>
</tr>
<tr>
<td>1010</td>
<td>1^- (2^+?)</td>
<td>1</td>
<td>100</td>
<td>40</td>
<td>( \approx 1 )</td>
<td>88</td>
<td>140</td>
</tr>
<tr>
<td>1210</td>
<td>3^-</td>
<td>1</td>
<td>4.5</td>
<td>10.5</td>
<td>7.5</td>
<td>22.5</td>
<td></td>
</tr>
</tbody>
</table>

The identification of a single level, \( J^\pi = 1^- \), with the resonances seen at 338-keV proton energy in \( N^{15} + p \) reactions and at about 7.05 MeV \( \alpha \)-particle energy in \( C^{12} + \alpha \) reactions seems to be unavoidable. A \( T = 1 \) admixture of about 15% is estimated (He 60) to contaminate this \( T = 0 \) state. Fair agreement exists in the estimates of the width of this resonance with the exception of the value given by Bittner and Moffat (Bi 54) as was noted in Chapter 4.2.1.1.

* Similarly, about a 15% \( T = 0 \) admixture from this state into the \( T = 1 \) state at 13.10 MeV is proposed.
The resonances observed at the 1210-keV proton energy and 8.15 MeV α-particle energy are similarly identified with a single level of $^{16}\text{O}$ at 13.26 MeV. There is powerful support for the assignment $J^\pi = 3^-$, and the $4^+$ assignment suggested by some of the $^{15}\text{N} + p$ work may have its origin in experimental inaccuracies. This level is believed to be the $T = 1$ analogue of the 295-keV $3^-$ level (Aj 59) of $^{16}\text{O}$.

The experimental evidence is strongly indicative of a companion level to the $J^\pi = 1^-$, $T = 1$ 13.10 MeV level of $^{16}\text{O}$. Both α-particle elastic scattering studies (Bi 54, Fe 61) have pointed to the existence of a $2^+$ state in the vicinity of 13 MeV excitation, and a similar indication is given by the analysis of the $^{15}\text{N}(p,\alpha)^{12}\text{C}$ angular distribution on and near the resonance. Ferguson has recommended an energy close to 13 MeV for this level and favours a total width $\Gamma_{\text{lab}}$ for it comparable with the 140 keV of the $1^-$ level. The isotropy of the ground-state radiation from the $^{15}\text{N}(p,\gamma)^{16}\text{O}$ reaction implies a very small proton width for the proposed $2^+$ level; such an assumption would also explain why no effects are seen in the $^{15}\text{N}(p,p)^{15}\text{N}$ reaction, corresponding to such a level.

Use of the parameters given in table 4.1 can provide a crude argument for another level at 13.10 MeV, when applied to the data of Larson and Spear (La 61). If the resonances labelled 12.47 MeV and 13.09 MeV (figure 4.4) are assumed to be due
entirely to the $J^\pi = 1^-$ 12.44 and 13.10 MeV levels, then, on the peak of each resonance, the integrated cross-section $\sigma(\alpha, \gamma_0)$ may be approximated by the single-level, Breit-Wigner formula

$$
\sigma = 4\pi \lambda^2 \frac{(2J + 1)}{(2I + 1)(2i + 1)} \frac{\Gamma\alpha_0}{\Gamma} \frac{\Gamma\gamma}{\Gamma}.
$$

Substitution of the appropriate values into this expression produces a ratio 0.85 for the relative yields at the lower and upper resonance, at any given angle. This ratio is to be compared with the value 0.65 given in Chapter 4.2.1.3. The discrepancy was taken as a further indication of the presence of another level.

It is certain that the $1^-$ level at 13.10 MeV cannot alone explain the angular distribution of 4.43 MeV $\gamma$-rays observed in the $^{12}\text{C}(\alpha, \alpha' \gamma)^{12}\text{C}$ reaction at about 7.95 MeV alpha-particle energy.

One attractive possibility is that the known $1^-$ level and the postulated $2^+$ level together generate the intensity distribution characteristic of a $3^-$ level. Some explanation would then be necessary for the displacement (La 61) of the resonance for this reaction to an energy some 50 keV higher than the $^{12}\text{C}(\alpha, \gamma_0)^{16}\text{O}$ reaction resonance.

Alternatively, the $3^-$ type anomalies in the alpha-particle elastic scattering data of Ferguson, appearing at an alpha-energy just below the 8.15 MeV resonance anomalies, and also the observed displacement of the $^{12}\text{C}(\alpha, \alpha' \gamma)^{12}\text{C}$ resonance may argue for
another $3^-$ level in $^{16}O$. Lack of an analogue ($A_j 59$) in $^{16}N$
would require a $T = 0$ assignment to the level and its non-
appearance in the $^{15}N(p,\alpha_o)^{12}C$ reaction would demand that it
have a very small proton width.

There is no detailed information about the angular
distribution of the inelastically scattered $\alpha$-particles to test
these speculations.

In the foregoing, mention has been made both of the
importance of $2^+$ states of $^{16}O$ to the description of core effects
in the $^{17}O$ and $^{17}F$ nuclei, and of the predictions of a specific
$T = 0$, $J = 2^+$ state of $^{16}O$ above 13 MeV excitation energy.
Further, it has been shown that the experimental evidence is
strongly suggestive of a $2^+$, $T = 0$ level at about 13.1 MeV.

The primary purpose of the present experiment was to
establish the existence of this level through the effects of its
interference with the $1^-$ level at 13.10 MeV and, since a small
proton width has been indicated, the $^{12}C(\alpha,\gamma)^{16}O$ reaction was
chosen for the study. It was hoped that some clarification of
the other anomalies in the existing data would prove possible,
and in particular, that the identity of the $^{12}C(\alpha,\alpha_1',\gamma)^{12}C$
resonance at about 7.95 MeV $\alpha$-particle energy would be revealed.
4.3 Experimental Method

4.3.1 The Beam

The 2.0 MeV Van de Graaff injector provided a beam of about 120\(^\alpha\) of \(^4\text{He}^+\) ions at 600 keV energy which was then neutralized in an adder canal and allowed to drift to the stripper canal at the terminal of the 12 MeV Tandem Van de Graaff accelerator. The emergent \(^4\text{He}^{++}\) beam was accelerated to the required energy (\(E_\alpha = 2 \times \text{terminal voltage} + 600 \text{ keV}\)) and analysed by a 90\(^\circ\) magnet, some 0.5\(^\alpha\) of \(\alpha\)-particles being delivered to the target area. The same target chamber was used in both the \(\text{Li}^7(p,\gamma)\text{Be}^8\) (Chapter 3) and the present experiment (figure 4.5).

4.3.2 Spectrometers

The \(\gamma\)-ray line-shapes obtained with a 3\(^\prime\) diameter x 3\(^\prime\) NaI(Tl) scintillation spectrometer for 4.43 MeV and \sim 13 MeV \(\gamma\)-rays (figure 4.6) compared favourably with those produced by a 5\(^\prime\) diameter x 4\(^\prime\) crystal system. The smaller crystal was chosen, therefore, permitting a closer source-detector geometry at angles greater than about 120 degrees with respect to the beam direction. To provide additional attenuation of low-energy \(\gamma\)-rays from the collimators and some shielding from cosmic rays, the crystal was set rigidly in a precisely-machined steel block, the "beam-line" edge being bevelled (figure 4.5). The assembly was mounted upon a rotating table which enabled \(\gamma\)-ray detection
Figure 4.5

Schematic representation of the experimental lay-out.
A typical γ-ray spectrum showing the three groups of γ-rays: the 4.43 MeV γ-rays (from the $^{12}C(α,α'γ)^{12}C$ reaction) the 6.14 MeV and ~7 MeV γ-rays (from the $^{13}C(α,νγ)^{16}O$ reaction) and (inset) the ~13 MeV γ-rays (from the $^{12}C(α,γ_0)^{16}O$ reaction).
over the angular range 0° to 135°. A 5" diameter x 4" crystal was located at 90° (opposite the smaller spectrometer) and was supported independently of the table to serve as a monitor for angular distribution measurements and to provide independent excitation functions. No shielding was employed for this crystal.

Pulses were routed from the photomultipliers to four Franklin A8 amplifiers, the pulses being fed thence to two pulse-height analysers and two single-channel analysers. The single-channel analyser outputs were fed to scaling units to record the number of events corresponding to any selected portion of a spectrum. The use of four, instead of two, amplifiers assisted in the identification of gain changes and faulty behaviour of the electronics. Gamma-ray energy calibrations were secured and spectrometer gain stabilities monitored chiefly with spectra of the 4.43 MeV γ-rays.

4.3.3 Targets

Harwell mass-separated C¹² targets, of a nominal 144 μ-gm/cm² thickness deposited onto 0.005" gold backings, were used but some degree of C¹³ contamination was evidenced in all γ-ray spectra.

4.3.4 Target Alignments

As described in Chapter 3, provision was made for eliminating systematic asymmetries in the alignment achieved by optical methods; a C¹³ target was included in the target array to take advantage of
the isotropy of the γ-rays emitted in the \( ^{13}\text{C}(p,p'\gamma)^{13}\text{C} \) reaction at \( E_p = 4.0 \) MeV (Aj 59). The forward—backward symmetry of the 4.43 MeV γ-rays from the \( ^{12}\text{C}(\alpha,\alpha'\gamma)^{12}\text{C} \) reaction provided another check and the freedom to rotate the spectrometer from one side of the target, through the \( \theta = 0^\circ \) position, to the other quadrants guaranteed the comprehensiveness of the test.

4.3.5 Backgrounds

Identical γ-ray background spectra were obtained by α-bombardment of clean platinum and the reverse side of the target. No measurable difference above \( \sim 8 \) MeV γ-ray energy existed in background spectra recorded with the beam on and with the machine off. It was concluded that only cosmic rays contributed to the background above this energy. A large crystal was located vertically above the 3" x 3" spectrometer and operated in an anticoincidence arrangement to assess its usefulness in reducing the cosmic-ray background but the improvement was thought to be too small to warrant retention of the system.

Background contributions from a pair of beam position defining slits, approximately 12 feet away, were negligible but γ-ray production was observed from the \( \frac{3}{8} \)" diameter beam apertures in two, co-axial, tantalum collimators located approximately 18" and 20" from the target (figure 4.5). Deposits of natural carbon i.e. 99% \( ^{12}\text{C} \) and 1% \( ^{13}\text{C} \) were found to be the most troublesome contaminants, the former producing the 4.43 MeV γ-rays characteristic
of the inelastic scattering of the incident \( \alpha \)-particles \((E_\alpha > 5.9 \text{ MeV})\) and the latter responsible for 6 and 7 MeV \( \gamma \)-rays from the \(^{13}\text{C}(\alpha,n^*\gamma)^{16}\) reaction \((Q = 2.215 \text{ MeV}, (\text{La 62}))\). The standard installation of mercury diffusion pumps on all beam lines of the Canberra machine obviated the need for sophisticated vapour trapping such as Larson et al. \((\text{La 63})\) found necessary with an oil diffusion pumping system and the incipient problem of hydrocarbon vapour cracking at the target. The few O-rings in the target chamber were smeared with silicone vacuum grease to minimize release of carbon-rich compounds into the target volume. No evidence was found for a significant carbon build-up on the targets, even after extended periods of bombardment and, for the majority of measurements, a single target was used.

The perspex target chamber was lined with 0.005" tantalum to prevent scattered \( \alpha \)-particles from initiating reactions in its walls, a precaution that gave a measurable reduction in the \( \gamma \)-ray spectra observed for \( \alpha \)-bombardment of clean gold. Similarly, the intensity of \( \gamma \)-rays (predominantly of 4.43 MeV energy) produced at the collimating apertures was reduced considerably by shielding the beam tube with a lead sleeve approximately 2" thick and 4" long (figure 4.5). The reproducibility of target and machine background yields indicated that carbon accumulation at the target and beam apertures was of a very slow and long-term nature.
4.3.6 Spectrum Analysis

For the full energy $\gamma$-ray, yields were estimated by summing all the pulses recorded in the spectrum between channels corresponding to approximately $0.8 \, E_x$ and $1.10 \, E_x$, where $E_x$ is the excitation energy in $^{16}O$ relevant to the particular $\alpha$-particle incident energy. Allowance was made for the small energy-dependent changes in the spectrum over the 300 keV range of bombarding energy to which the study was limited. Windows in the single-channel analysers were usually adjusted to span the photopeak and two escape peaks of the 4.43 MeV $\gamma$-ray from the $^{12}C(\alpha,\alpha'\gamma)^{12}C$ reaction.

4.3.7 Procedure

The target was bombarded with 0.1-1 $\mu$A beams of $\alpha$-particles over the energy range 6.9 MeV to 8.2 MeV, to furnish $^{12}C(\alpha,\gamma)^{16}O$ and $^{12}C(\alpha,\alpha'\gamma)^{12}C$ excitation functions at $\theta = 90^\circ$. Beam current integration was provided by collecting the charge incident on the target. Measurements of the $\gamma_0$ yield at $\theta = 45^\circ$ and $\theta = 135^\circ$ were made with the target normal to the beam direction, attenuation of both 4.43 MeV and 13 MeV $\gamma$-rays in the target backing proving to be small and constant. For angular distributions the target was inclined at $45^\circ$ or $135^\circ$ to the beam direction as required, to eliminate the problem of attenuation in the target edges. The specific precautions taken in particular measurements are discussed where the appropriate results are presented.
4.4 Results

4.4.1 Excitation Functions

The excitation function (figure 4.7) for the $^{12}_C(\alpha, \gamma_0)^{16}\alpha$ reaction, measured at $\theta = 90^\circ$, reveals resonances at bombarding energies of 7.04 MeV and 7.87 MeV, while a small anomaly is suggested in the curve at $E_\alpha = 8.15$ MeV. The excitation function for the $^{12}_C(\alpha, \alpha'\gamma)^{12}_C$ reaction determined at the same angle (figure 4.8) exhibits two prominent resonances at 7.95(5) MeV and 8.14 MeV alpha-particle energy. An 80 keV separation (i.e. 60 keV in $^{16}\alpha$ excitation energy) of the "7.9 MeV" ($\alpha, \gamma_0$) and ($\alpha, \alpha'\gamma$) resonance peaks is indicated.

Excitation functions for $\gamma_0$ at $\theta = 45^\circ$ and $135^\circ$ were derived and are displayed in figure 4.9. Results of the yield determination repeated recently by Larson (La 63a) have been included and agree well with the present data, at the cost of a simple shift of energy scales. The two dominant $^{12}_C(\alpha, \gamma_0)^{16}\alpha$ resonances were observed to be displaced consistently to energies lower than the Caltech values by 20 keV. The good agreement obtained in this present and other studies for the energies which identify the $^{12}_C(\alpha, \alpha'\gamma)^{12}_C$ resonances encourages retention of the present values. To facilitate comparison, the Canberra curves for the $45^\circ$ and $135^\circ$ yields have been displaced upwards by 20 keV. Since the source-to-3" x 3" detector distance was at no time less than 3.5", cf. the 3/4" and use of a 4" x 4" crystal in the geometry adopted by Larson.
The curve of the relative yield of the $^{12}\text{C}(\alpha,\gamma)\text{O}^{16}$ reaction measured at $\theta = 90^\circ$ as a function of laboratory alpha-particle energy in MeV.
The excitation function of the $^{12}\text{C}(\alpha,\alpha'\gamma)^{12}\text{C}$ reaction, measured at $\theta = 90^\circ$ by detection of the 4.43 MeV $\gamma$-rays.
Figure 4.9

The $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ yields measured at $\theta = 45^\circ$ and $\theta = 135^\circ$, both displaced upward in alpha-particle energy by 20 keV to allow a comparison with the $(\alpha,\gamma)$ yield measured by Larson and Spear at $\theta = 45^\circ$. The peak at $E_\alpha = 3.14$ MeV in the Caltech curve is thought to be due to summing effects in the crystal.

The ratio of yields measured at $\theta = 45^\circ$ and $135^\circ$ are shown below, together with the simultaneously measured ratios for the 4.43 MeV $\gamma$-ray. The asymmetry in the $\gamma$ distribution is invoked as evidence of two $^{16}\text{O}$ levels of opposite parity. (Chapter 4.4.2.4).
et al., fewer spurious \((\alpha,\gamma_0)\) resonance effects would be anticipated from energy summing in the crystal of cascade \(\gamma\)-rays from \(C^{12}(\alpha,\gamma\gamma)O^{16}\) reactions. It is to be expected that such effects are more important where cascade de-excitation competes strongly with a single, multipolarity-inhibited, \(\gamma\)-ray transition. The similarity of the Caltech and present yield curves between 7 and 8 MeV bombarding energies suggests that the peak observed by Larson at \(E_\alpha \approx 8.14\) MeV, and attributed to the \(13.26\) MeV, \(J^\pi = 3^-\) level of \(O^{16}\) (La 62) is due largely to such summing effects. A comparison with the early data of Larson and Spear (figure 4.4) reveals the considerable revision in relative yield estimates. A much closer approach is made to the ratio 0.85 expected of the \(\gamma\)-ray yields on the basis of the two \(J^\pi = 1^-\) levels of \(O^{16}\) at 12.44 MeV and 13.10 MeV, as discussed in Chapter 4.2.3. An appreciable reduction in the yield between the resonances is also evident. Both 45° yield curves exhibit the same width

\[
\Gamma_{\text{lab}} \approx 140\text{ keV for the } E_\alpha = 7.04\text{ MeV resonance.}
\]

No measurable discrepancies existed amongst the available excitation function data for the \(C^{12}(\alpha,\alpha'\gamma)C^{12}\) reaction (Mi 61, La 61).

4.4.2 Angular Distributions

4.4.2.1 Theoretical Distributions

As a preface to the experimental results, the theoretical
angular distributions of the $\gamma$-rays emitted in the $^{12}\text{C} (\alpha, \gamma_0) ^{16}\text{O}$ and $^{12}\text{C} (\alpha, \alpha' \gamma) ^{12}\text{C}$ reactions are presented.

The former process is described schematically in figure 4.10a where, following closely the notation of Sharp et al. (Sh 53),

the channel spin, is the vector sum of the intrinsic spins $i, I$ of the projectile and target nuclei $s = i + I$;

$L$ is the relative orbital angular momentum of the components in the colliding system;

$J$ is the total angular momentum of the intermediate compound state: $J = L + s$;

$L, \pi$ are the multipolarity and intrinsic parity of the emitted $\gamma$-ray. $\pi$ takes the value $0$ or $1$ according to whether the transition is of electric or magnetic character, respectively, and,

$I$ is the spin of the residual nucleus.

In the $^{12}\text{C} (\alpha, \gamma_0) ^{16}\text{O}$ reaction $i = I = 0$, so that the channel spin is zero. The condition of even spin- even parity that this imposes on the intermediate states implies that all radiative transitions to the $^{16}\text{O}^+$ ground state are electric multipole, i.e. $L = J, \pi = 0$.

The inelastic process is shown schematically in figure
Figure 4.10a

Schematic representation of an \((\alpha, \gamma_0)\) reaction.

Figure 4.10b

Schematic representation of an \((\alpha, \alpha'\gamma)\) reaction.
4.10b where

\( l_1 s_1 J_1 \) correspond to the \( lsJ \) of figure 4.10a;

\( L_{12} \) is the relative angular momentum of the outgoing particle and residual nucleus;

\( J_2 \) is the spin of the excited state of the residual nucleus;

\( L_2 \) is the multipolarity of the \( \gamma \)-ray, and

\( I_2 \) is the spin of the residual nucleus in its ground state.

Specifically, for the \( ^{12}C \) nucleus, \( I_2 = 0 \), \( J_2 = 2 \) and \( L_2 = 2 \) i.e. the first excited state of \( ^{12}C \) de-excites by an E2 \( \gamma \)-ray transition. Conservation of momentum requires \( J_1 = L_{12} + J_2 \) and conservation of parity restricts the possible values of \( L_{12} \) to \( J_1 + 2 \), \( J_1 \) and \( J_1 - 2 \).

The angular distribution function may be written conveniently in the form

\[
W(\theta, \varphi, \ldots) = \sum_{tt'} W_{tt'}(\theta, \varphi, \ldots) S_t^* S_{t'}
\]

where the \( S_t \) are the matrix elements which are independent of angles and magnetic quantum numbers, and \( t \) and \( t' \) label the interfering transitions. Selection of the beam direction as the coordinate z-axis then permits the expansion of \( W_{tt'} \) as a Legendre polynomial series in \( \cos \theta \). For the angular distribution of the ground state \( \gamma \)-rays
\[ W_{tt'} = \sum_k (-1)^{s-I} Z(\ell J_{1}\ell' J'_{1},sk) Z_1(\ell J_{1}' J'_{1},\ell I_k) P_k (\cos \theta) \]

and for the 4.43 MeV \( \gamma \)-rays with the inelastic \( \alpha \)-particles unobserved,

\[ W_{tt'} = \sum_k (-1)^{s_1+i_{12}-I_{2}+J_{2}'-J_{2}+L_{2}'+L_{2}} Z(\ell_{1} J_{1} \ell_{1}' J_{1}',s_{1}k) W(J_{1} J_{2} J_{1}' J_{2}',L_{12}k) \]
\[ \times Z_1(L_{2} J_{2} L_{2}' J_{2}',I_{2} k) P_k (\cos \theta) \]

The \( Z, Z_1 \) are the angular distribution coefficients defined by Biedenharn, Blatt and Rose (Bi 52) and the \( W \) are the Racah coefficients. Again, primes are used to indicate interfering transitions. The summations are made over all \( k \)-values compatible with the conservation laws for the nuclear process and the "triangular conditions" for the coefficients.

Tables for \( W_{tt'} \) are given for the ground-state \( \gamma \)-rays in Table 4.2 and 4.43 MeV \( \gamma \)-rays in Table 4.3. No higher values than \( J = 3 \) have been considered in the former table, and contributions from values of \( L_{12} \) greater than 3 have been suppressed from the latter.
TABLE 4.2

Coefficients of $P_k (\cos \theta)$ in $W_{tt}$, for the ground-state $\gamma$-ray.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
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TABLE 4.3

Coefficients of \( P_k (\cos \theta) \) in \( W_{tt'} \)
for the 4.43 MeV γ-ray.

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4.4.2.2 Solid Angle Corrections

It is necessary to correct the measured angular distributions for the smoothing effects of the large solid angle subtended at the beam spot by the detecting crystal. If the observed angular distribution be expressed as a Legendre polynomial series

\[ W'(\theta) = \sum_n B_n P_n(\cos \theta) \]

it is related to the true distribution

\[ W(\theta) = \sum_n A_n P_n(\cos \theta) \]

through \( B_n = \frac{J_n}{J_0} A_n \) \( (Ro\ 53) \).

The correction coefficients \( \frac{J_n}{J_0} \) for the two target-detector distances employed with the 3" x 3" crystal viz. 8.57 cm and 23.0 cm were evaluated by numerical integration of the quantities

\[ J_n = \int_0^{\beta_1} P_n(\cos \beta) \left( 1 - e^{-\lambda X(\beta)} \right) \sin \beta d\beta \quad n = 0, 1, 2, 3, 4. \]

where \( \beta \) is the angle between the \( \gamma \)-ray direction and the crystal axis and \( X(\beta) \) is the \( \gamma \)-ray path length in the crystal for the \( \beta \)-direction. The upper limit \( \beta_1 \) of the integration is provided by the grazing angle at the front face of the crystal. Favourable comparisons were made between calculated values and those obtained by interpolation in the curves supplied by Marion \( (Ma\ 60b) \).

For \( d = 8.57 \) cms, the calculated correction factors were
\[ \frac{J_1}{J_0} = 0.970 \quad \frac{J_2}{J_0} = 0.910 \]
\[ \frac{J_3}{J_0} = 0.826 \quad \frac{J_4}{J_0} = 0.740 \]

### 4.4.2.3 The 4.43 MeV \( \gamma \)-ray Angular Distributions

Numerous angular distributions of the 4.43 MeV \( \gamma \)-rays were recorded at each of four energies over the region of the two resonances, viz. \( E_\alpha = 7.90, 7.95, 8.01 \) and 8.14 MeV. (Manual control of the 90° beam-analysing magnet current permitted better than 3 keV beam energy stability.) Measurements were made for two source-detector geometries, \( d = 8.57 \) cm and \( d = 23.0 \) cm and, as a precaution against possible contributions from the 3.68 MeV and 3.86 MeV \( \gamma \)-rays produced by \( ^{13}\text{C}(\alpha,\alpha'\gamma)^{13}\text{C} \) reactions, the single-channel analyser windows were reduced to select only the photopeak of the 4.43 MeV \( \gamma \)-ray spectrum. A window was placed above the 4.43 MeV peak to indicate the magnitude and variation of the contribution made by 6 and 7 MeV \( \gamma \)-rays from \( ^{13}\text{C}(\alpha,n\gamma)^{16}\text{O} \) reactions. They were responsible for less than 1% of the yield in the 4.43 MeV window and appeared to originate at the collimators i.e. they were most pronounced in the forward (\( \theta = 0^\circ \)) direction. Reproducibility of data and agreement between measurements for the two geometries was very good. Representative results are shown by the points in figure 4.11. Statistical errors on the points are everywhere less than 2%. The data were fitted with a Legendre polynomial series by the method of least squares, the analysis being carried through on an IBM 1620 computer. No polynomials of
Figure 4.11

Observed angular distributions of the 4.43 MeV $\gamma$-rays from the $^{12}C(a, a'\gamma)^{12}C$ reaction measured at three bombarding energies are expressed:

$(E_a = 7.00$ MeV) \hspace{1cm} $P_0 + (0.56 \pm 0.02)P_2 - (0.51 \pm 0.03)P_4$

$(E_a = 7.95$ MeV) \hspace{1cm} $P_0 + (0.55 \pm 0.05)P_2 - (0.50 \pm 0.05)P_4$

$(E_a = 8.14$ MeV) \hspace{1cm} $P_0 + (0.56 \pm 0.01)P_2 - (0.47 \pm 0.01)P_4$
odd order or of higher than the fourth order were found to be required in the expansion of any measured distribution.

Typical results are indicated by the solid curves of figure 4.11, the corresponding expressions being listed in the figure captions.

Solid angle smoothing corrections were applied to the angular distributions measured for the 4.43 MeV γ-rays emitted at $E^\alpha = 8.14$ MeV, furnishing

$$W(\theta) \propto P_0 + (0.61 \pm 0.01)P_2 - (0.64 \pm 0.02)P_4$$

The coefficients listed in Table 4.3 provide the γ-ray distributions expected following p-wave α-emission from an intermediate state of $^{16}O$ with $J^\pi = 3^-$,

$$W(\theta) \propto (P_0 + 0.571 P_2 - 0.571 P_4)$$

and for a $J^\pi = 4^+$ level, with d-wave emission,

$$W(\theta) \propto (P_0 + 0.510 P_2 - 0.367 P_4)$$

Clearly, the $3^-$ assignment is preferred, verifying the known properties of the level.

A representative 4.43 MeV γ-ray angular distribution measured at the lower resonance, $E^\alpha = 7.95$ MeV, was found to be

$$W(\theta) \propto (P_0 + (0.60 \pm 0.05)P_2 - (0.68 \pm 0.06)P_4)$$
The similarity of the angular distributions at both resonances suggests that the corresponding levels are both of $J^\pi = 3^-$ character.

It has been remarked (Chapter 4.2.1.2) that the superposition of 4.43 MeV γ-ray distributions following alpha-particle emission from a closely lying $1^-$ and $2^+$ level can simulate the distribution characteristic of a $3^-$ level. In fact, it is seen immediately that one possible solution is found if contributions from $W_{11}(L_1 = 1)$ and $W_{22}(L_1 = 0)$ are in the ratio 2 : 1 (imposing this algebraic condition on the ratio of the matrix elements for the two levels).

No evidence for such a description has been found in results of $N^{15} + p$ studies, nor have Ferguson et al. been able to satisfy the requirements of the $C^{12}(\alpha,\alpha')C^{12}$ data with such an assumption (Chapter 4.2.1.1).

The simplest and quite adequate explanation for the $C^{12}(\alpha,\alpha'\gamma)C^{12}$ resonance at $E_{\alpha} = 7.95(5)\text{ MeV}$ is found by proposing a $J^\pi = 3^-$ level of $O^{16}$ at about $13.13\text{ MeV}$ excitation energy. It follows that the $3^-$-type anomaly at this energy in the elastic alpha-scattering data of Ferguson et al. (figure 4.3) may be provided with a satisfactory interpretation, previously lacking.

The coefficients of $P_2$ and $P_4$ in the fitted distributions exceed the magnitude of the theoretical values by an amount well in excess of the errors quoted. The result is manifestly real, the mean of eighteen separate angular distribution measurements
over the energy range providing

\[ W(\theta) \propto (P_0 + 0.61 P_2 - 0.66 P_4) \] .

Further, while the discrepancy in the \( P_2 \) coefficient remains essentially constant over the 250 keV range of bombarding energy, the \( P_4 \) coefficient appears to decrease from approximately 0.70 at \( E_\alpha = 7.90 \) MeV to 0.64 at \( E_\alpha = 8.14 \) MeV. Contributions to the \( \gamma \)-ray angular distributions following \( f \)-wave emission of short-range alpha-particles from a \( 3^- \) state of \( O^{16} \) are expected to be inhibited (due to the low penetrability of \( L_{12} = 3 \) alpha-particles) and, in any case, increase the discrepancy in the \( P_2 \) coefficient if an attempt is made to fit the \( P_4 \) coefficient. Interference of a \( 1^- \) and a \( 3^- \) level, with \( W_{13}(L_{12} = 1) \) and \( W_{13}(L_{12} = 3) \) contributions in about the ratio 5 : 4, can account for the anomalous coefficients in a qualitative way. The participating \( 1^- \) level presumably would be identified with the \( O^{16} \) level at 13.10 MeV excitation, and therefore would contribute negligibly in \( W_{11} \) by virtue of the small widths, \( \Gamma_{\alpha_0} = 40 \) keV and \( \Gamma_{\alpha_1} \approx 1 \) keV, (Table 4.1) for this level.

While a more exhaustive experimental examination is required to secure a quantitative account of the anomalous magnitudes of \( P_2 \) and \( P_4 \) coefficients in the 4.43 MeV \( \gamma \)-ray angular distribution, the identification of both \( C^{12}(\alpha,\alpha'\gamma)C^{12} \) resonances with two \( J^{\pi} = 3^- \) levels of \( O^{16} \) at excitation energies of 13.13 MeV and 13.26 MeV
seems reasonably certain.

4.4.2.4 The $^{12}\mathrm{C}(\alpha,\gamma)$0$^{16}$ Angular Distributions

The average ratio of the $\gamma$-ray yields measured at $\theta = 45^\circ$ and $\theta = 90^\circ$ for alpha-particle energies of 6.98, 7.03 and 7.13 MeV was found to be $2.08 \pm 0.08$ and a ratio of $0.93 \pm 0.07$ was obtained for the $\theta = 45^\circ$ and $\theta = 135^\circ$ yields at $E_\alpha = 7.04$ MeV, in accord with the $(P_0 - P_2) = \sin^2 \theta$ $\gamma$-ray angular distribution (Table 4.2) which typifies the $J^K = 1^-$ assignment for the $0^{16}$ level. The uniqueness and identity of the level excited in both the $\mathrm{N}^{15}(\mathrm{p},\gamma)0^{16}$ and $\mathrm{C}^{12}(\alpha,\gamma)0^{16}$ reactions at, or near, to 12.44 MeV excitation energy in $0^{16}$ seems indisputable, the 230 keV width quoted by Bittner and Moffat (Bi 54) providing the only exceptional estimate for the laboratory width of the resonance.

The contents of Table 4.2 show that excitation of $0^{16}$ levels with $J^K = 1^-$ and $J^K = 2^+$ via the $\mathrm{C}^{12} + \alpha$ reaction may furnish $\gamma$-ray angular distributions of the form

$$W(\theta) \propto P_0 - P_2$$

and

$$W(\theta) \propto P_0 + \frac{5}{7} P_2 - \frac{12}{7} P_4$$

respectively. Interference of the two levels results in angular distributions

$$W(\theta) \propto P_1 - P_3$$
so that we may write for the combined effect

\[ W(\beta) = 3A_1^2 (P_0 - P_2) + 5A_2^2 (P_0 + \frac{5}{7} P_2 - \frac{12}{7} P_4) \]

\[ + 6\sqrt{3} A_1 A_2 (P_1 - P_3) \cos \delta_{12} \]  

(4.1)

where \( A_1, A_2 \) are the energy-dependent resonance amplitudes and \( \delta_{12} \) the phase difference. Observation of an asymmetry about 90° in the intensity of \( \gamma_0 \) would indicate the presence of odd-order Legendre polynomial terms in the expansion of the angular distribution and therefore imply the existence of two \( ^{16}O \) levels of opposite parity.

Measurement of the ratio of the relative yields \( Y(45^\circ) \) and \( Y(135^\circ) \) provided a direct test. Since \( \gamma \)-ray yields were very low, it was essential to eliminate spurious contributions and experimental asymmetries. Satisfaction of the requirement for symmetry about 90° of the 4.43 MeV \( \gamma \)-ray angular distribution was checked simultaneously. The \( Y(45^\circ)/ Y(135^\circ) \) ratio of 0.93 ± 0.07 at \( E_a = 7.04 \) MeV resonance served to check the experimental symmetry for \( (a, \gamma_0) \) yield measurements, also. Constancy of yield and, incidentally, the reliability of the current integration, was assured by maintaining constant monitoring. Any one yield ratio value was obtained from a series of at least two 45° yield and two 135° yield measurements taken alternately, to minimize the effects of beam energy or detector gain drifts. Backgrounds were measured for the same beam and integrated charge between every target yield measurement.
The evidence for interference is unambiguous as is seen by the plotted values for yield ratios in figure 4.9 and implies that a $J^\pi = 2^+$ level of $0^{16}$ is to be found in the vicinity of the 13.10 MeV $1^-$ level.

To test the prediction more thoroughly, an angular distribution was measured at $E_a = 7.90$ MeV over the angular range $0^\circ$ to $135^\circ$. Data were fitted by a Legendre polynomial series up to $P_6 (\cos \theta)$. However, no orders beyond the fourth were found to be necessary and the solid curve shown in figure 4.12 was generated from the (resultant) expansion listed in the figure caption. When solid angle corrections appropriate to the "8.57 cm" geometry were applied, the distribution became

$$W(\theta) \propto P_0 + (0.379 \pm 0.053)P_1 - (0.927 \pm 0.052)P_2$$

$$- (0.344 \pm 0.057)P_3 - (0.134 \pm 0.053)P_4$$

Now, two conditions are imposed upon the angular distribution coefficients. Equation 4.1 shows firstly, that the coefficients of the odd order polynomials are of equal magnitude and opposite sign and secondly, that the sum of the coefficients of $P_1$ and $P_3$ is $(0.035 \pm 0.078)$ while the corresponding sum for $P_2$ and $P_4$ is $(-1.061 \pm 0.074)$ cf. the value $(-1)$ required by the theoretical distribution.
The angular distribution of $\gamma$-rays emitted in the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction at $E_\alpha = 7.90\text{ MeV}$. The solid curve corresponds to the fitted distribution

$$P_0 + (0.375 \pm 0.052)P_1 - (0.844 \pm 0.047)P_2$$

$$- (0.284 \pm 0.047)P_3 - (0.099 \pm 0.039)P_4$$

$Q_1$, $Q_2$ represent the first ($0^\circ \leq \theta < 90^\circ$) and second ($90^\circ \leq \theta < 180^\circ$) quadrants, respectively.
4.5 Discussion

An attempt was made to extract the $A_1^2$ and $A_2^2$ resonance parameters by an analysis of the yield curves measured at $\theta = 45^\circ$, $90^\circ$ and $135^\circ$. By introducing the appropriate geometrical factors and evaluating the $P_n(\cos \theta)$ it is possible to relate the $A_1^2$, $A_2^2$ to the measured yields via

$$4.111 A_1^2 = 1.005 Y(90^\circ) - \frac{Y(45^\circ) + Y(135^\circ)}{16.8}$$

$$A_2^2 = 1.005 Y(90^\circ) - 4.387 A_1^2$$

While values of $A_1^2$ are extracted which reproduce the resonance shape quite well, a meaningful analysis of the energy dependence of the small resonance-like $A_2^2$ variation is impossible. The $(\alpha, \gamma_o)$ yield at $\theta = 90^\circ$ is considered to be established to an accuracy of 5% which is reflected as a 50% uncertainty in $A_2^2$.

The $^{12}\alpha(\alpha, \gamma_o)^{16}O$ reaction study proves valuable in demonstrating the existence of a $2^+$ level of $^{16}O$ at about 13.1 MeV excitation energy but, while it reveals a strong asymmetry in the $\gamma_o$-ray angular distribution, nevertheless it cannot provide the requisite accuracy for a more quantitative account of the levels of $^{16}O$ in the region of excitation around 13 MeV than the present description.

Two other methods of extracting information about the $^{16}O$ levels are suggested.

A preliminary investigation in this laboratory has shown
that a measurement of the angular distributions of α-particles from the $^{12}_C(\alpha,\alpha')^{12}_C$ reaction is feasible at alpha bombarding energies of 8 MeV and less. The measurement is made difficult by the extremely low energies of the inelastically scattered α-particle at backward angles, which, presumably, accounts for the paucity of the $^{12}_C(\alpha,\alpha')^{12}_C$ data provided by Ferguson et al. (Figure 4.3). Effects of interference between $1^-$ and $2^+$ and $2^+$ and $3^-$ levels of $^{16}O$ should be clearly apparent as backward-forward asymmetries in the measured angular distributions of the short-range α-particles. Commencement of this work is proposed soon.

Although it involves considerable technical problems, the powerful technique developed by Eidson et al. (Ei 63) offers an intriguing possibility of establishing the spins of the $^{16}O$ levels in question.

A measurement is taken of the angular correlation $W(\theta,\phi)$ between α-particles scattered inelastically from an even-even nucleus, and the α-particles emitted by the excited state of the recoiling nucleus to a $0^+$ state of the daughter fragment. (Necessarily, the recoiling nucleus excited state must be at sufficiently high excitation to permit α-particle decay.) For an appropriate choice of the polar angle of observation $\theta$, the $\phi$-dependence of the correlation function becomes particularly simple, and can provide an unambiguous spin-parity assignment of
the $\alpha$-emitting level.

Eidson et al. scattered 22.5 MeV $\alpha$-particles inelastically from a C$^{12}$ target and recorded coincidences between these and the $\alpha$-particles emitted from the 3$^-$ 9.64 MeV level of C$^{12}$ to the 0$^+$ Be$^8$ ground state. Well-established by previous work (Aj 59), the $J = 3$ assignment was demanded specifically under the stringent conditions of the $\alpha' - \alpha_0$ correlation.

The immediate problems of adapting the technique to the 0$^{16}$ level study are several. An alpha energy of at least 17 MeV is required if the incident beam is to excite the 0$^{16}$ states at 13 MeV by the inelastic process. Energy discrimination between $\alpha$-particle groups from the 13.26 and 13.10 MeV levels might become difficult, particularly if an O$^{16}$ gas target were being used and straggling losses were important. A thin, self-supporting, organic or oxide target could prove satisfactory, provided that $\alpha$-groups from the target contaminant made calculable or no spurious contributions to the coincidence yield.

Investment in an experiment of the kind outlined above carries no guarantee of success, and it would seem that the less sophisticated C$^{12}(\alpha,\alpha')C^{12*}$ study promises more reward, particularly as it can be expected to provide width parameters $\Gamma_{\alpha'}$, $\Gamma_{\alpha'}$ of the 0$^{16}$ levels of interest, as well as their spin assignments.
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