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* PHOTONEUTRON CROSS SECTIONS
OF PR¹⁴¹, O¹⁶ AND C¹²

by

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and

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*This report is based on a Ph. D. thesis submitted by John N. Bradford,
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PHOTONEUTRON CROSS SECTIONS

OF Pr^{141} , O^{16} AND C^{12}

John N. Bradford

and

Barnett C. Cook

ABSTRACT

Cross sections for the (γ, n) reaction have been determined from threshold to 65 Mev. Structure appears throughout most of the energy range in the O^{16} and C^{12} cross sections. The giant resonance is clearly split into several components in both cases. Pr^{141} shows no resolved structure. Comparison is made with the predictions of the particle-hole model. Experimental details which enhance the validity of the results are emphasized.

I. INTRODUCTION

The extensive experimental studies of the nuclear photoeffect have exhibited in nearly all nuclei a strong γ ray absorption in the vicinity of 20 MeV. This absorption peak, the so called giant resonance, has its gross features described by a collective model (1, 2) which emphasizes its electric dipole character. The model fails, however, in the region of light nuclei to explain the presence of structure within and around the giant resonance.

Attempts have been made to describe the giant resonance within the framework of the independent particle model. D. H. Wilkinson (3) was able to account for the existence of the giant resonance and obtained a reasonable width for the giant resonance, but the energy was too low. More recently, G. E. Brown and M. Bolsterli (4) have shown how the inclusion of a particle-hole interaction (i.e. an interaction between the hole left in a previously filled shell and the excited nucleon) could boost the energy of the transitions into the experimentally observed range.

Interest in the structure within the giant resonance has led quite naturally to the development of higher resolution experimental equipment and techniques. Techniques which offer comparable resolution are neutron time of flight, inverse reactions (p, γ), gamma rays generated by positron

annihilation in flight and, a posteriori, analysis of bremsstrahlung induced activation curves by the method of least structures. The latter is the technique used in this work and comparisons with the others appear in Section IV.

In the energy region, above the giant resonance but below meson threshold, little cross section work has been done. Reasons for this lack are equipment limitations, instability in energy control systems, the build up of errors in yield curve analysis, and the limited number of accelerators operating in the 30-150 MeV energy range.

Recently, these difficulties were overcome through the combined use of an energy control system developed by J. E. Griffin (5) and through the use of a new analysis technique devised by B. C. Cook (6). The method of analysis is termed "Least Structure" and hereafter referred to as CLSR. The reaction $O^{16}(\gamma, n)O^{15}$ was employed and cross sections calculated by CLSR over the energy range 15.5 MeV to 65 MeV. Half MeV steps were used. These cross section curves exhibited a sequence of high energy resonances above the giant resonance. Because the resonances appeared in a relatively unexplored energy region and because the CLSR technique involves inverting an integral equation in which oscillating solutions are characteristic, it was necessary to verify in two ways the existence of the resonances observed in that experiment.

Using an experimental arrangement similar to that in the above oxygen experiment, Pr^{141} was bombarded in .5 MeV steps from 9 to 65 MeV. For reasons discussed in Section IV one would not expect resonance structure in the $\text{Pr}^{141}(\gamma, n)$ Pr^{140} cross section at high energies. However, even if found, the resonance pattern should be distinct from the O^{16} result. Hence it was felt that a distinct result would lend credence to the measurement-analysis program used here and to the existence of the high energy structure. The results of this test appear in Section IV. A.

The second mode of verification was reproducibility. If the resonances were due to statistical fluctuations certainly one would expect not to reproduce them with new data. To this end extensive measurements of $\text{O}^{16}(\gamma, n) \text{O}^{15}$ yield curves were taken and analyzed. These results appear in Section IV. B.

The oxygen cross section is of course deserving of study from a more fundamental view. Structure is known to exist in the giant resonance and it is of interest to display this structure, as well as that occurring at higher energy. Oxygen has been subjected to considerable theoretical investigation. It is important to identify as many of the excited levels as resolution permits for comparison with such calculations. The yield curves in this work were measured in 125, 250 and 500 keV steps in an effort to resolve structure in the cross

section from threshold to 65 MeV.

In addition to the oxygen measurements, the same experimental technique and CLSR computation were applied to Carbon 12. The choice of the $C^{12}(\gamma, n)C^{11}$ reaction was dictated by it being an equally well documented reaction in the region of the giant resonance, and by virtue of carbon being a light nucleus which should have a reasonable probability of exhibiting structure above the giant resonance. The results of the carbon experiment are displayed in Section IV. C.

II. PHOTONUCLEAR YIELD CURVE ANALYSIS

A. Generation of Solutions to the Yield Equations

In a typical photonuclear yield measurement, electrons which have been accelerated to a kinetic energy E_0 strike a target and bremsstrahlung is created with a number distribution differential in photon energy, E , given by $N(E, E_0)$. The radiation then passes through and interacts with a sample whose total nuclear absorption cross section is given by $\sigma(E)$. Finally, the radiation passes through a monitoring device which has an energy response $M(E_0)$.

The number of reactions which occur when the electron energy is E_0 is then the yield given by

$$Y_*(E_0) = \frac{n}{M(E_0)} \int_0^{E_0} N(E, E_0) \sigma_*(E) dE = \frac{\text{detector count}}{\text{unit monitor response}} \quad (1)$$

where n is the number of nuclei per square centimeter exposed to the radiation.

Since the total cross section is

$$\sigma_*(E) = \sigma(\gamma, n) + \sigma(\gamma, p) + \sigma(\gamma, pn) + \dots \text{etc.} \quad (2)$$

it is necessary to eliminate the other contributions if one seeks only the cross section $\sigma(\gamma, n)$. This can be done by measuring the contributions of the extraneous activities at

several energies over the range and creating a smooth function $A(E_0)$ which, when applied to Equation 1, eliminates the effect of other reactions. Hence, Equation 1 becomes

$$Y_n(E_0) = \frac{A(E_0)n}{M(E_0)} \int_0^{E_0} N(E, E_0) \sigma_n(E) dE. \quad (3)$$

Equation 3 can then be rewritten

$$Y(E_0) = \int_0^{E_0} N(E, E_0) s(E) dE, \quad (4)$$

where $Y(E_0) = Y_n(E_0) \frac{M(E_0)}{A(E_0)}$ is the reduced yield and

$s(E) = n\sigma_n(E)$ is the reduced cross section.

In general the electron energy is stepped in equal increments over the energy range of interest. This results in a set, Y_i , of yield equations. For purposes of computation the yield equation integral may be approximated by

$$Y_i = \sum_{j=1}^i N_{ij} s_j \quad (5)$$

where s_j is the average of $s(E)$ over the j th interval

$$s_j = \frac{1}{\Delta E} \int_{E_j - \Delta E}^{E_j} s(E) dE, \quad (6)$$

and N_{ij} is the number of photons in the j th interval resulting from the i th spectrum.

$$N_{ij} = \int_{E_j - \Delta E}^{E_j} N(E, E_i) dE. \quad (7)$$

The set of Equation 5 can be solved in sequence. The value of s_1 obtained from the Y_1 equation is substituted into the y_2 equation which is then solved for s_2 , etc. This is the "Photon Difference" method of L. Katz and A. G. W. Cameron (7). The determination of successive s_i from y_i with individual errors results in a rapid build up of cumulative errors for higher energies.

A method devised by A. S. Penfold and J. E. Leiss (8) involves inversion of the N matrix to obtain an inverse operator, N^{-1} , which when applied to Equation 5 yields the s_j . Thus,

$$N_{ki}^{-1} Y_i = N_{ki}^{-1} N_{ij} s_j = \delta_{kj} s_j = s_k \quad (8)$$

where sums are taken on repeated indices.

In practice this procedure leads to wildly oscillating values for the s_j at high energies. This behavior is in response to the extreme sensitivity of the s_j on statistical or other errors in the Y_i .

B. Least Structure Analysis

In order to damp the oscillations in the s_j , smoothing must be applied. CLSR introduces smoothing into the solution, Equation 8, in a non subjective way.

Consider a true yield set, Y_i , whose value is known without error. Then

$$Y_i = \sum_{j=1}^i N_{ij} s_j \quad i = 1, 2, \dots, n \quad (9)$$

where the s_j are the corresponding true cross sections.

Then any set of s'_j constitutes a solution if the calculated yields, Y'_i , are close to the experimental yield, Y_i , at each energy. In order to insure non-subjective closeness use is made of the statistical variable χ^2 , which is defined as

$$\chi^2 = \sum_{i=1}^n \frac{(Y'_i - Y_i)^2}{(\Delta Y_i)^2} \quad (10)$$

where ΔY_i is the standard deviation. χ^2 has an average value n and most probable value $n - 2$.

In the CLSR definition the true value Y_i is taken to be the experimental measurement and ΔY_i is the error in that measurement. Equation 10 becomes

$$\chi^2 = \sum_{i=1}^n \frac{(\sum_{j=1}^i N_{ij} s'_j - Y_i)^2}{(\Delta Y_i)^2} \quad (11)$$

χ^2 is, hence, a function of the s'_j and the set s'_j constitutes an acceptable solution when $\chi^2 \leq n$.

The error, ΔY_i , in Equation 11 is defined in the following way. Each Y_i is the average of several measurements. The standard deviation is calculated in the usual way. Since one knows that the standard deviation of a count taken of a radioactive sample is equal to the square root of the number of counts, that contribution to the standard deviation of a yield point may be written explicitly,

$$\sigma_{STi}^2 = R_i^2 + \sigma_{Ci}^2 \quad (12)$$

The σ_{Ci}^2 are the counting statistics and the R_i^2 contains all of the remaining factors contributing to the error. The R_i^2 term is assumed to be a factor, ϵ , times the square of the yield average at the i th energy,

$$\sigma_{STi}^2 = \epsilon Y_i^2 + \sigma_{Ci}^2 \quad (13)$$

This is valid so long as the fractional error is not energy dependent. The square root of ϵ then is the fractional error of the experiment and represents the quality of the set, Y_i .

To evaluate ϵ , Equation 13 is summed over all energies. Once ϵ is known a new set of smoothed errors is created

from Equation 13, and these are the errors which appear in Equation 11,

$$\Delta Y_1^2 = \epsilon Y_1^2 + \sigma_{C1}^2 . \quad (14)$$

In order to determine the set s_j' which is the smoothest consistent with the experimental data, a structure function is defined as

$$S = \sum_{j=2}^{n-1} P_j (s_{j+1}' - 2s_j' + s_{j-1}')^2 . \quad (15)$$

S is the sum of the squares of the second differences and P_j are weighting factors which allow smoothing to take place in a more uniform way over the entire energy range.

In the lower energy region the s_j' are fairly well behaved and do not require the same amount of smoothing as in the high energy region. To shift the smoothing away from low energies in a consistent way a weighting function is applied. The P_j are derived from

$$P_j = \arctan \frac{\Delta s_j' \text{ unsmoothed}}{s_j' \text{ smoothed}} , \quad (16)$$

where the $\Delta s_j'$ are defined later in Equation 24. Their effect is to transfer smoothing to higher energies and to increase slightly the amount of smoothing required for solution.

From the character of Equation 15 it is clear that the

smoothest set of s'_j corresponds to a minimum value for S . The basic computation in the CLSR method is one of minimizing S subject to the constraint imposed by Equation 11.

The formalism to minimize S is taken from variational calculus. S is treated as a Lagrangian with variables s'_j and λ is a Lagrangian multiplier.

The variation equation is then

$$\left[\lambda \sum_{j=2}^{n-1} P_i \delta_{ij} (s'_{j+1} - 2s'_j + s'_{j-1})^2 + \left(\sum_{j=1}^n \frac{(N_{jk} s'_k - Y_j)^2}{\Delta Y_j^2} - \chi^2 \right) \right] = 0 \quad (17)$$

The solution resulting from the variation is

$$Y_i = [N_{ij} + \lambda (Y_i^2 \delta_{ik} P_k \delta_{kq} N_{qp}^{-1} S_{pj})] s'_j = M_{ij} s'_j \quad (18)$$

where N_{qp}^{-1} is the inverse transpose of N_{ij} and S_{pj} is a smoothing matrix which contains, except for the first and last two rows, five non zero terms centered on the diagonal. The magnitude of λ is a measure of the amount of smoothing applied to the s'_j .

The inverse of M_{ij} is computed and the set of s'_j determined from

$$s'_j = M_{ji}^{-1} Y_i \quad (19)$$

The set s'_j is then replaced in Equation 9 and a set Y_i

is computed. The set Y' is inserted into Equation 10 and the χ^2 test is performed. That is, if the resulting χ^2 is equal to n , then the set s'_j constitutes a solution; if not, then the computation is repeated with a new value of λ .

In practice it is not possible in a reasonable time to obtain $\chi^2 = n$. As a result a range $\pm \Delta\chi^2$ is specified such that the constraint becomes $\chi^2 \pm \Delta\chi^2 = n$. $\Delta\chi^2$ is typically set at $.1\chi^2$.

In order to observe the distortion which the smoothing process creates one can consider the set

$$Y_i = \sum_{j=1}^n N_{ij} s_j \quad . \quad (20)$$

The CLSR solution would result in

$$Y'_i = \sum_{j=1}^i M_{ij} s'_j \quad . \quad (21)$$

To the extent that $Y'_i = Y_i$, which is insured by the χ^2 calculation,

$$M_{ij} s'_j = N_{ik} s_k \quad (22)$$

$$s_k = N_{ki}^{-1} M_{ij} s'_j \quad . \quad (23)$$

If $N^{-1} M$ were a unit matrix, the s_k would be identical to the s'_j . The extent to which this is not true can be seen in the

product $N^{-1} M$ which is called the resolution function, R .

For typical errors R is nearly symmetric and has a full width at half maximum, which increases from about one energy interval at low energy to a width of about 6 energy intervals at high energy. This width represents the width a narrow resonance would acquire in the smoothing process.

The Δs_j found in the defining equation, 16, are computed from

$$\Delta s_j = [M_{ji}^{-1} M_{ji}^{-1} Y_j^2]^{1/2}. \quad (24)$$

All of the above computations were performed on an I.B.M. 7040 computer. The CLSR program has λ and χ^2 as input parameters. The successive values of λ which are used in iterating to a solution are obtained from the relation

$$\lambda_{i+1} = \lambda_i + [(\lambda_i - \lambda_{i-1}) \cdot \frac{\chi^2 - \bar{\chi}_i^2}{\bar{\chi}_i^2 - \bar{\chi}_{i-1}^2}] \quad (25)$$

where χ^2 is the input value.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

A. Equipment Description and Tests

Local fluctuations in a yield curve can lead to oscillation in the solution of Equation 1. Such oscillations take on the appearance of structure in the cross section, particularly at higher energies. Numerous checks of the experimental equipment were made to rule out such sources of error. Among the effects which could result in spurious structure are:

- (1) Synchrotron beam movement
- (2) Non linearity of the synchrotron energy control
- (3) Extraneous activities
- (4) Energy dependence of dosemeter
- (5) Counting system and data statistics
- (6) Bremsstrahlung spectrum effects
- (7) Method of analysis

Great care has been taken to examine each of these and others and to rule them out as a source of structure.

1. Bombardment geometry and synchrotron beam shifts

Figure 1 displays the hardware used to bombard samples when taking these yield measurements. The accelerator used is a General Electric Model M 70 MeV electron synchrotron. The magnet is driven with a frequency of 58 cycles per second and acceleration of electrons takes place during the positive

Figure 1. Sample bombardment geometry

going quarter cycle. During acceleration the electrons are confined by the magnetic guide field to an annulus about 3 inches wide with mean radius of 11.5 inches. To avoid gas scattering at low energies the injector, beam orbit and target are housed in an evacuated ceramic doughnut which fills the annular gap between the pole pieces.

After injection into the Guide field at an energy of 60 kilovolts the electrons are accelerated for a period of 120 microseconds by betatron action. A radio frequency excited cavity provides acceleration for the remainder of the cycle.

At the desired energy, E_0 , the electron beam is caused to strike a tungsten target. The procedure for resonant excitation of the electron beam which was used in this work was developed by C. L. Hammer and A. J. Bureau (9, 10). A set of 1/8 inch copper coils wound on the ceramic doughnut are pulsed with a high current generated by the spark discharge of a capacitor. The magnetic field from the current in the coils causes the guide field gradient to take on a value which causes the electron beam to become unstable and oscillate into a collision with the tungsten target. The discharge of the capacitor is triggered at the proper time by a pulse from the energy control circuit.

The photon beam created is then collimated and passes through the sample and through the radiation monitor. The collimator is 11 inches long, with a beam hole tapered in a

cone with half angle .021 radians. Because it is located in the fringe field of the magnet it was made of lead shot to reduce eddy current heating. A lead shot-epoxy cement mixture was cast around a tapered stainless steel tube. The exit port of the collimator is 7/8 inches in diameter. Tapering the beam hole reduces scatter with the collimator walls.

Shifting of the photon beam would cause collision with and scattering from the collimator, which in turn would alter the spectrum incident on the sample and the radiation monitor. To insure against such shifts the following procedure was used. The collimator axis was aligned to the beam axis by means of bombarding and counting copper discs fixed in a cross, which was mounted on the entrance port of the collimator. Deviations of .3 millimeters between the axes could be detected by this means. The exit end of the collimator was brought into line using x-ray film photographs. Copper crosses and photographs were taken at 20, 40 and 60 MeV before, during and after these experiments. No deviation or beam swing was observed in any instance.

2. Energy control

Since yield curve measurements involve repeated measures at the same energy as well as small energy intervals between data points, it is necessary to have a highly stable and

reproducible way to determine the electron energy. Such a way has been developed by J. E. Griffin and has been described in detail in reference 5. Only the main features are presented here.

The kinetic energy of a relativistic electron is related to its momentum by

$$p^2 c^2 = T (T + 2m_0 c^2) \quad (26)$$

where p is momentum, c is the velocity of light, T is the kinetic energy and $m_0 c^2$ is the rest mass of the electron.

If the electron is moving in a magnetic field then

$$p = (2.998 \times 10^{-4}) B \rho \text{ MeV/c} \quad (27)$$

where ρ is the radius of curvature in cm, B is the magnetic field in gauss. Hence, measurement of the magnetic field with the radius fixed by the radio frequency provides a method for determining the kinetic energy.

Since the I.S.U. synchrotron is a cyclic machine, B is not fixed but is a function of time. If one inserts a closed loop in a time dependent magnetic field, then there is induced in that loop a voltage proportional to the area and the time rate of change of the field,

$$V(t) = A \dot{B}(t) . \quad (28)$$

Thus, measurement of B requires integration of the induced

voltage wave.

An annular loop is placed in the guide field external to the ceramic doughnut, lying flush against a pole piece and centered on the electron orbit. The voltage induced in the coil is integrated and compared to a preset voltage which originates in an ultrastable voltage source, a Kintrel Model 302. The output voltage from the Kintrel was compared to a standard cell and found to be correct to better than one millivolt. When the integrated voltage reaches the preset value, a pulse is triggered which fires the beam knockout circuit, causing the electron beam to strike the target.

The energy control system is calibrated against the well known break in the $O^{16}(\gamma, n) O^{15}$ activation curve at 17.28 MeV. The zero time intercept of the integrated wave was -2.7 microseconds, or 29 keV/c. The momentum of the electron then is

$$p = A V + .029 \text{ MeV/c} \quad (29)$$

where A is determined from the calibration point. An additional check of the $Cu^{63}(\gamma, n) Cu^{62}$ threshold at 10.83 MeV was made with consistent results. Measurements of the 17.28 MeV breaks in oxygen were made during the course of these experiments. The deviation in a three month period was ± 6 keV.

The response of the integrator as a function of time has

been measured using a constant DC input voltage and a Tektronix Model 545 oscilloscope with a Type Z differential comparator plug-in amplifier. The response was found to be as linear as the incremental linearity of the oscilloscope, 0.2 percent, up to slightly beyond 100 volts output. One hundred volts corresponds to an electron energy in the synchrotron of about 60 MeV.

3. Extraneous activities

The presence of reactions other than (γ, n) can contribute spurious counts to the yield measurement. To detect the presence of these reactions, samples were bombarded at energy intervals of 10 MeV and counted down to background. A semi-log plot of the count down permits the determination of the ratio of counts due to the γ, n reaction to the total number of counts including $\gamma, 2n$ and $\gamma, 3n$ which may be present. These ratios as a function of energy determine the function $A(E_0)$ in Equation 3.

In the $\text{Pr}^{141} (\gamma, n) \text{Pr}^{140}$ experiment long lived activities due to the $\text{Pr}^{141} (\gamma, 2n) \text{Pr}^{139}$ and $\text{Pr}^{141} (\gamma, 3n) \text{Pr}^{138}$ were found. The corrections to eliminate their effect were at a maximum at 65 MeV and amounted to 1.5%.

Above 25 MeV in the $\text{O}^{16} (\gamma, n) \text{O}^{15}$ experiment, detectable amounts of longer lived activities, presumably due to C^{11} and N^{13} , were observed. Elimination of these effects required a

maximum of 1.5% correction.

The $C^{12}(\gamma, n)C^{11}$ experiment required no correction for extraneous activities.

4. Dose measuring system

The ionization chamber used to monitor the radiation in these experiments is a replica of a chamber designed and calibrated at the National Bureau of Standards by J. S. Pruitt and S. R. Domen (11). Charges arising from the passage of the photon beam through the chamber are collected on a .001 micro farad polystyrene capacitor. The capacitor is part of an integrating network connected across a Cary model 31 vibrating reed electrometer.

The yield of a bombardment was measured by counting the decay of the daughter nuclei resulting from the γ, n process. Since the bombardment time of the sample is of the same order of magnitude as the half life of the daughter nuclei, many of the created daughters will have decayed by the time the bombardment ceases. The dose into the radiation monitor, however, is retained and hence does not represent the induced activity in the sample. To overcome this an activity computer was used as in Reference 5 which allowed the dose reading to build up and decay with the same time constant as the decaying daughter nuclei. Thus, with the electrometer input to the activity computer, an integrated response output

voltage was obtained which was proportional to the net induced radioactivity. The output from the activity computer was recorded on a Brown recorder whose expanded scale could be read to 1 part in 5000.

For calibration and test purposes an insert receptacle is located on the N.B.S. chamber. Repeated measurements with a Sr^{90} source in the receptacle showed wide variation throughout this experiment. It was found that the source was loose in its mounting and upon repacking the source reproducible results were obtained to $\pm .1\%$.

Since the photon beam is attenuated by interaction with the sample prior to passage through the chamber, an energy dependent correction was applied to the measured dose. The source of the correction curve was a set of doses taken at energies over the range used in the experiment with sample in and sample out. The reference dose was provided by an off beam monitor, a small ionization chamber, connected to a second electrometer circuit. In this way a set of percentage transmission values as a function of energy was obtained and a smooth curve drawn through these points provided a transmission correction at all energies.

In the case of oxygen the transmission values ranged from .85 at 15.5 MeV to .90 at 65 MeV. In the case of carbon these values were .83 at 18.5 MeV to .92 at 65 MeV. Praseodymium required no correction. All sets of transmission

values were accurate to $\pm 0.05\%$.

The N.B.S. chamber was surrounded by a lead house 6 inches thick. The frontal opening was a circular hole 2.5 inches in diameter to allow beam passage. Tests with the hole blocked gave a ratio of 3000 to 1 and the shielding was considered to be adequate. This ratio was consistent with the attenuation expected due the lead plug inserted into the beam hole.

The geometry of the house was altered to conform more closely to that used in the calibration at N.B.S. No variations in the dose were detected between that geometry and the house used in these experiments.

The N.B.S. chamber response curve used in processing the data was the best fit curve of Pruitt and Domen. These authors also provide extreme response curves which represent the limits of their calibration. The effect of using these extreme response curves is to raise or lower the high energy tail of the cross section but not in any way to affect structure that may be present.

5. Counting systems and data statistics

The induced activity was counted using two E.M.I. 9531 B phototubes on which were mounted three inch diameter NaI(Tl) crystals. The tubes and crystals were mounted in a face to face geometry with a gap between just wide enough to

allow the sample to be inserted in its holder. The sample was inserted with the irradiation axis midway between the crystal surfaces. In this configuration if one sums the counts in the two counters the physical displacement of the sample out of the mid-plane causes only a second order change in the sum counts. No evidence of a high-low count was observed, indicating that the sample-beam and sample-count orientations were fixed and reproducible.

Since the (γ , n) process produced reaction products which were unstable under positron decay, the annihilation radiation provided the spectrum for counting. In order to provide discrimination against low energy pulses a pick off circuit was connected between the anode and last dynode of the phototubes. This circuit is shown in Figure 2.

The electron cascade causes the tunnel diode 1N 2969 to fire if the pulse is sufficient to cause the current through the diode to rise above the peak in its characteristic curve. The 2K helipot is a bias adjust which allows the d.c. current through the diode to run at a level as near to the characteristic peak as desired, thereby providing discrimination. The tunnel diode pulse is then amplified in the 2N 643 stage and the output pulse is driven by the 2N 1986 emitter follower. These pulses were fed to Eldorado model SC-750 scaler where the counts were recorded. In order to provide temperature stability in the tunnel diode

Figure 2. Photomultiplier circuit used to count activity induced in samples.
Analog positive output provides spectrum for spectrastat power supply

circuit, a thermistor was connected in parallel with the tunnel diode and its 20 ohm load resistor. In this way the DC current, hence the bias level, of the tunnel diode was held constant.

The circuit also provides a negative analog output pulse for use in collecting spectral information. This pulse is input to a Nuclear Data 1024 channel analyzer Model 150-M. On the basis of a coincidence spectrum between this pulse and the tunnel diode pulse the discriminator level was set at approximately 100 kilovolts.

Because of the necessity for maximum stability in the counting system, Cosmic Radiation Laboratory "Spectrastat" power supplies were used. These supplies obtain their stability by monitoring with a single channel discriminator a peak in the spectrum being counted. The peak voltage is integrated and chopped on either side of center. The chopped voltages are compared and when an imbalance occurs, an error signal is developed which is fed to the high voltage in such a way as to restore the peak to the center of the discriminator window.

Short term scattering of counts as indicated by tests with a Na^{22} source was markedly reduced in comparison with conventional power supplies. Long term drifts did occur and required correction. These drifts were apparently due to drift in the discriminator window voltage and amounted to as

much as 1% during the course of the experiment.

A count rate dependence was observed in both phototube systems. To obtain a correction for this effect carbon samples were bombarded to high activities and counted down in 3 minute intervals. The resulting plot when compared to the natural decay of C^{11} provided a percentage correction at all count rates observed in these experiments.

Fluctuations in the counting system do not lead to energy dependent fluctuations in the yield curve if one randomizes the data taking energy sequence with respect to time. This procedure was followed in all activation curves. Nonetheless, statistical fluctuations could occur in the yield curve and lead to structure. For this reason at least three independent activation curves were measured. Correlation between resulting individual cross section curves is required to verify that a peak is real.

6. Bremsstrahlung spectrum effects

The function $N(E, E_0)$ in Equation 1 is approximated in analysis by a spectrum calculated by L. I. Schiff (12). To compare the effects of spectrum shape on the cross sections computations were made using a modified spectrum. The modification introduces an increased number of photons in the spectrum tip in accordance with calculations by R. T. Deck, C. J. Mullen and C. L. Hammer (13). The differences between

cross sections derived, using these two spectra, proved small and were confined in energy to the region of the giant resonance or below. No significant energy shifts in the peaks were observed and only small amplitude changes were seen. The Schiff approximation has been used extensively in photonuclear work in the past. Any distortions of the cross section due to the use of an approximate spectrum are thought to be small (8).

7. Method of analysis

To obtain the reduced yield in Equation 4 from the raw yield one multiplies by four energy dependent correction factors. These are:

- (a) The total energy in the bremsstrahlung beam at the particular energy step.
- (b) The sample transmission factor.
- (c) The extraneous activities correction.
- (d) The monitor response normalization function.

Since this collectively is an energy dependent correction, it is very important that it contain no local variations. To achieve a smooth resultant correction the product of the four factors is taken at each energy step and the resulting curve is smoothed by smoothing the first differences.

8. Samples

The oxygen and carbon samples were cylinders $1 \frac{1}{8}$ inches in diameter. Since the beam diameter was $\frac{7}{8}$ inches at the sample position the samples completely surrounded the photon beam. The oxygen samples were cylinders of boric acid, H_3BO_3 , compressed to $1 \frac{3}{8}$ inches in length. The carbon samples were cylinders cut from polystyrene rod $1 \frac{1}{2}$ inches in length. The praseodymium samples were $\frac{3}{4}$ inch in diameter and $\frac{1}{16}$ inch thick. A collimator with a smaller beam hole was used with the Pr^{141} measurement to provide eclipsing geometry.

Each set of samples was normalized to account for density differences by bombarding the set at fixed energy three times. The three counts per dose for each sample were averaged and a grand average of all samples taken. The sample normalization factors were the ratios of the grand average to the sample average. Typical sample normalization factors were from .995 to 1.005.

B. Data Acquisition and Reduction

All samples were bombarded and counted in a fixed time sequence controlled by an R.I.D.L. model 54-7 timing programmer. Pr^{141} samples were bombarded for 5 minutes followed by a one minute delay during which the sample was taken to the counting house and a new sample loaded for bombardment.

In this way the next sample was being bombarded while the previous sample was being counted.

This routine was carried out for oxygen and carbon as well. The bombardment time for O^{16} was three minutes with a one minute wait, while for carbon, the bombardment time was thirteen minutes with a two minute wait.

Thirty five oxygen samples and twenty nine carbon samples were used. Several samples were withdrawn during the course of the experiments because of chipping and breaking. The large number of samples allowed the induced activity to decay to background before the sample was used again.

In the case of Pr^{141} only fifteen samples were available. Because of the buildup of longer lived activities due to γ , $2n$ and γ , $3n$ processes it was necessary to precount these samples before bombardment and subtract that count.

Pr^{141} data were taken in .5 MeV steps. A total of three activation curves from 9 MeV to 65 MeV were taken. Oxygen data were taken in two complete sets. Each set contained three activation curves. Each activation curve was taken in .125 MeV steps from 15.5 MeV to 30.375 MeV., .250 MeV steps from 30.375 MeV to 45.250 MeV and in .5 MeV steps to 65.5 MeV. Thus in each set, the data were interlaced. Carbon data were taken in .250 MeV steps from 18.5 MeV to 48.250 MeV and in .5 MeV steps to 65.5 MeV. A separate set of

three activation curves was taken in .125 MeV steps from 18.5 MeV to 33.375 MeV. The ranges were dictated by the CLSR program being limited to 120 data points.

The energy step sequence was randomized in time to eliminate the possibility of equipment drifts inducing changes in the slope of the activation curve which would show up in the derived cross section curve.

1. Data monitors

In order to insure that the data taking proceeded satisfactorily, the activation curves were plotted as the data were taken. In the event a data point was wild it was rerun. Possible sources of such error were misread scalers, wrong energy set or recorded, misread dosage, etc.

To provide a basis for correction of the data in the event of equipment drifts, two sets of standards were taken. Two samples were set aside for use as standard points. In oxygen these samples were bombarded at 36 MeV and at least one standard point was taken each hour. The carbon standard points were run at 40 MeV, approximately one for each 8 data points. Plots of these points provided a time dependent correction. The maximum magnitude of this correction in the oxygen data was .3%. The carbon data required no correction.

In addition, the counting system was exposed to a Na^{22}

source periodically. Deviation from the natural decay of the source provided a basis for a time dependent correction to complement the standard points.

2. Corrections to the data

The data taken in these experiments was subjected to numerous, though small, correction factors. The data were so extensive, and the numerical calculations involved in applying the corrections so many, that a Fortran program called ULTIMATE was written to perform these operations. Data cards were punched during the data taking process. ULTIMATE also calculated statistics, the factor ϵ from Equation 13 and punched the yield cards and error cards for input to the CLSR program.

The input cards to ULTIMATE contain the raw data and all the information needed for indexing so that the corrections can be applied. Where useful, the program utilizes linear interpolation in applying the corrections. Table 1 lists the maximum magnitude of the corrections applied.

Curve normalization was obtained by summing all the corrected counts in each of the three activation curves and normalizing to the center value.

The ULTIMATE program also calculates standard deviations at each energy step. An additional calculation provided is the ratio of the residual to the smoothed error, Δy , at each

Table 1. Maximum corrections applied to the data

Correction	Pr^{141}	O^{16} 1st set	O^{16} 2nd set	C^{12}
Background subtraction	2700	1500	1500	5000
Count rate dependence	0	3%	4%	4%
Time dependent correction	0	.5%	1.7%	1.2%
Sample normalization	4%	1%	1%	0%
Curve normalization	.5%	.1%	.1%	.1%
Sample transmission	0	15%	15%	15%
Extraneous activities	.5%	1.5%	1.5%	0%

energy. On the basis of a plot of the corrected activation curves and the residual ratios all points with residuals greater than 2.5 times the smoothed error were thrown out if a rerun was available or, if not, adjusted toward the mean. Approximately ten points per set of three activation curves required such adjustment.

In Equation 13 it was shown that the factor $\epsilon^{1/2}$ constituted a measure of the error in the experiment. Table 2 lists the value of $\epsilon^{1/2}$ for each data set as computed by the ULTIMATE program.

Table 2. $\epsilon^{1/2}$ values for each data set

Energy step MeV	Pr ¹⁴¹ (%)	O ¹⁶ (%) First set	O ¹⁶ (%) Second set	C ¹² (%)
.125	---	.31	.37	.20
.250	---	.33	.33	.17
.500	.41	.35	.42	.19

IV. RESULTS AND COMPARISONS

A. Pr^{141} Results

The cross section for the reaction $\text{Pr}^{141}(\gamma, n)\text{Pr}^{140}$ is shown in Figure 3. It consists of a single sharp resonance at 15.2 MeV falling quickly to zero at 25 MeV but with a slowly rising tail which extends to 65 MeV. The integrated cross section to 25 MeV contains 78% of the integral to 65 MeV. The giant resonance has a full width at half maximum of 3.8 MeV. This result is in agreement with previous activation measurements by F. Ferrero, R. Malvano and E. Silva (14). The upper limit of energy in that work was 30 MeV. L. B. Rice, L. N. Bolen and W. D. Whitehead (15) have measured the Pr^{141} cross section using bremsstrahlung bombardment, neutron counters and Penfold-Leiss unfolding. Their results show the giant resonance maximum occurring at 14.8 MeV with a width of 4 MeV.

No structure was resolved above the giant resonance. The variations in the cross section at high energies have amplitudes of the order of the error bars. Further, this curve is based on the average of three independent yield curves. The cross sections derived from these three curves showed completely uncorrelated variations in the high energy region, implying that they were in response to statistical fluctuations. The cross sections derived from the individual

Figure 3. Relative cross section for the reaction $\text{Pr}^{141}(\gamma, n)\text{Pr}^{140}$. The horizontal bars represent the full width at half maximum of the resolution function

yield curves are shown in Figure 4. The horizontal error bars are the full width at half maximum of the resolution function.

To lend validity to the high energy tail, cross sections were derived using extreme monitor response functions. The N.B.S. monitor calibration of Pruitt and Domen consists of a best fit curve and two extreme curves which represent the limit of error in the calibration. One extreme curve reduced the integrated cross section above 25 MeV from 22% of the total to 12%. The other extreme increased the integrated cross section in that region from 22% to 26% of the total. Thus, the tail persisted even when using an extreme monitor response function.

Pr^{141} is magic in neutrons with 82. As has been pointed out by R. Nathans and J. Halpern (16) it is characteristic that the width of the giant resonance be small at magic numbers and large in between. This correlation was studied by K. Okamoto (17) in an effort to show that the width of the giant resonance was in response to the deformation of the nucleus. Earlier, H. Steinwedel and J. H. D. Jensen (18) had developed a relationship based on the hydrodynamical model which gave the giant resonance energy as

$$E_m^{\wedge} = [34.6 (NZ/A^2) k(\hbar^2/MR^2)]^{1/2} \quad (30)$$

where R is the nuclear radius and k is a constant from the

Figure 4. $\text{Pr}^{141}(\gamma, n) \text{Pr}^{140}$ relative cross sections derived from three independent yield curves. The fluctuations above the giant resonance are uncorrelated in energy

symmetry energy term of the Weizacker semi-empirical mass formula. A distorted nucleus has two radii, R_1 and R_2 , and the separation of the two resonances is proportional to

$\frac{1}{R_1} - \frac{1}{R_2}$. Thus, spherical nuclei such as Pr^{141} should show

a single narrow resonance.

This experiment was performed to prove that the measurement-analysis technique which produced high energy structure in the $\text{O}^{16}(\gamma, n)\text{O}^{15}$ reaction could be applied to a nucleus with a sharp giant resonance and produce a non-ringing solution as expected. This has certainly been done. As can be seen in the succeeding pages, the resolution of this method is sufficient to use 125 MeV data intervals. On the basis of the asymmetry in the Pr^{141} giant resonance in Figure 3 and noted in Reference 15, an investigation is planned using 125 keV steps over the giant resonance. This will determine if fine structure in such a heavy nucleus can be resolved by the methods used in this work.

B. O^{16} Results

A summary of the $\text{O}^{16}(\gamma, n)\text{O}^{15}$ cross section measurements is contained in Figures 5, 6, 7 and 8 and Table 3. A composite graph displaying the cross section from 15.5 to 65 MeV appears in Figure 9. Twenty three resonances or clusters of cross section were found between 15.5 MeV and 65 MeV. Of the

Figure 5. $^{16}\text{O}(\gamma, n)^{15}\text{O}$ cross section in the giant resonance region derived from the average of six independent yield curves. Data was taken in 125 keV bins

Figure 6. $^{16}\text{O}(\gamma, n)^{15}\text{O}$ cross section derived from the average of yield curves. Data was taken in 250 keV bins. Nearly all the structure of Figure 5 is resolved

Figure 7. $O^{16}(\gamma, n)O^{15}$ cross section derived from the average of six independent yield curves. Data was taken in 500 keV bins. Structure is resolved in addition to that in Figures 5 and 6 in the high energy region

Figure 8a. Resolution functions inherent to Figure 5.

Figure 8b. Resolution functions inherent to Figure 6.

Figure 8c. Resolution functions inherent to Figure 7.

Figure 9. Composite $O^{16}(\gamma, n)O^{15}$ cross section. Data bin width is 125 keV from 15.5 to 29.5 MeV, 250 keV from 29.5 to 41.5 MeV and 500 keV from 41.5 to 65 MeV. Numbered arrows indicate peaks in the cross section as referenced in the text and Tables 3 and 4

Table 3. Resonances of O^{16} observed in the present work

Peak number	E MeV	% of $\int_{15.5}^{62} \sigma dE$	Integrated cross section
1	17.30	1.2	
2	19.06	1.3	
3	19.56	1.1	
4	20.20	---	
5	21.0	3.7	
6	21.70	--	
7	22.26	15.6	
8	23.15	5	
9	24.10	20	
10	24.90	3	
11	25.55	6	
12	26.38	2	
13	27.45	4	
14	28.55	3	
15	29.60	.5	
16	31.40	4	
17	33.0	3	
18	38.75	2	
19	41.1	2	
20	43.0	2	
21	46.0	3	
22	51.0	4	
23	60.2	3	

$$\int_{15.5}^{30} \sigma dE = 49 \text{ MeV} \cdot \text{mb}$$

$$\int_{15.5}^{62} \sigma dE = 70 \text{ MeV} \cdot \text{mb}$$

cross section integrated to 60.5 MeV, 69% lies below 29.5 MeV and 89% lies below 44.25 MeV.

The resolution functions appropriate to each of the cross section curves are found in Figure 8. These plots were chosen to show the general decrease in resolution which occurs at higher energies. In the cross section curves the lower set of horizontal error bars represents full width at half maximum of the resolution function. The upper horizontal bar represents the standard deviation of the peak energy as determined from the individual yield curves which comprise the average curve. The vertical error bars are taken from computation of Equation 22. Each curve is a plot of the output of the CLSR program which has been iterated to a χ^2 solution in accordance with Equation 11.

The oxygen data was taken in two complete sets of three yield curves per set. In addition, since no beam shift or sample positioning effects were seen in the data, each phototube provided an independent set of data. The average yield curve from each phototube generated a cross section curve which is plotted in Figure 10. The stability of the peaks with respect to shifts in energy is seen to be quite good, however, for some reason the second set of curves fail to resolve the peaks at 25 MeV and 26.3 MeV. Instead, the peaks at 24.3 and 25.6 MeV are broadened compared to the first set implying poorer resolution. The average error in

Figure 10. Relative $^{16}\text{O}(\gamma, n)^{15}\text{O}$ cross sections derived from single phototube data taken in 125 keV bins. The curves show the reproducibility of the cross sections

the first set of curves is $\sqrt{\epsilon} = .31\%$ while in the second set $\sqrt{\epsilon} = .37\%$. The effects of statistics on the resolvability of such peaks is discussed in Appendix B with regard to the carbon low energy data. There it is shown that .2% error is sufficient to cause this loss of resolution. Hence, it is concluded that the 25 and 26.3 MeV peaks are real.

No correction has been made in the data for the 71 sec activity induced by the γ , 2n reaction. Measurement of the integrated cross section for this reaction to 32.5 MeV by H. Breuer and W. Pohlitz (19) yielded $.09 \pm .02$ MeV mb. The ratio of the integrated (γ , 2n) cross section to that of the (γ , n) reaction has been measured to 100 MeV by J. O'Connell, P. Dyal and J. Goldemberg (20) who show it to be .002. This small cross section, coupled with the one minute time delay before counting the samples, reduces the (γ , 2n) contribution to an inconsequential level.

1. The energy interval 15.5 to 30.375 MeV

a. Comparison with other experiments Figure 5 displays the γ , n cross section derived from the average of six independent yield curves. The energy step, ΔE_0 , was 125 keV. The widths of the peaks follow the resolution function widths of Figure 8a. The peaks could be more narrow, particularly at the higher energies, hence the peak height is not too meaningful. However, the integrated cross sections can be

compared with other techniques. Figures 11 and 12 are presented for comparison of this work with other recent experiments.

Figure 11a shows the cross section curve measured by R. L. Bramblett, J. T. Caldwell, R. R. Harvey and S. C. Fultz (21). The curve was obtained by counting neutrons from the $O^{16}(\gamma, n)O^{15}$ reaction and using annihilation radiation from high energy positrons as a source. Their energy calibration is quoted as 1%. There, as in this work, no correction was made for $(\gamma, 2n)$ contribution. Figure 11b displays the present work for comparison. The resolution of the present work is clearly better up to about 23 Mev. Over the rest of the energy range the two techniques have comparable resolutions.

Figure 12a displays the relative cross section from 17 MeV to 25 MeV as measured by F. W. K. Firk (22) using neutron time-of-flight techniques. Non ground state transitions have been subtracted off by the author but no correction for background has been made. The resolution in Firk's experiment is somewhat better than this work. The quoted resolution follows an $E^{3/2}$ dependence on neutron energy with a value of 32 keV at 4 MeV. This yields approximately a resolution of 250 keV at 25 MeV compared with about 375 keV in the present work.

Figure 12b shows a synopsis of six runs between 16 MeV

Figure 11a. $^{16}\text{O}(\gamma, n)^{15}\text{O}$ cross section from Bramblett, Harvey and Fultz by the use of positron annihilation radiation

Figure 11b. The 125 keV bin results of the present work

Figure 12a. $^{16}\text{O}(\gamma, n)^{15}\text{O}$ relative yield from Firk by the method of neutron time of flight

Figure 12b. Relative yield of the reaction $^{15}\text{N}(p, \gamma_0)^{16}\text{O}$ from the experiment by Tanner, Thomas and Earle

and 26 MeV taken by N. W. Tanner, G. C. Thomas and E. D. Earle (23) using the inverse reaction $N^{15}(p, \gamma)O^{16}$. All counts were recorded at 90° to the beam direction. The resolution of this work is about 25 keV, hence, the width of the peaks tends to be the true width of the states.

The reaction $O^{16}(e, e'p)N^{15}$ has been employed by W. R. Dodge and W. C. Barber (24) to observe γ , p structure in O^{16} . The protons were momentum analyzed at 78° and the assumption of 100% ground state transitions was made. The results are listed in Table 4.

A composite of the $O^{16}(\gamma, n)O^{15}$ cross section from 15.5 to 65 MeV is displayed in Figure 9. The peaks have been numbered in sequence for comparison to the above experiments. Table 4 contains the results from Figure 9 and these experiments.

The peak at 16.1 MeV seen in the work of Bramblett et al. and Tanner et al. lies in a region of insufficient bremsstrahlung intensity from the I.S.U. synchrotron. This peak has been identified by the latter as an M1 transition. The remaining peaks are,

- (1) The 17.3 MeV peak is used as an energy calibration point for the I.S.U. synchrotron. It is closely verified by all but Bramblett who is 200 keV low. The 17.1 MeV peak resolved by Firk and by Tanner is much smaller and not seen in the

Table 4. Resonances observed in O^{16}

Peak number Figure	Present work (γ, n) E MeV	Bramblett et al. (γ, n) E MeV	Firk (γ, n) E MeV	Tanner et al. (p, γ_0) E MeV	Barber and Dodge (e, pe') E MeV	Griffin (γ, n) E MeV
1	17.30	16.0, 17.1	17.1, 17.3	16.18, 17.13, 17.29	17.27	
2	19.06	19.0	19.0	19.05	18.07, 18.99	
3	19.56	19.3	19.4	19.56	19.57	
4	20.20		20.1			
5	21.0	20.8	20.9	21.0	20.65	
6	21.7	21.8	21.6			
7	22.26	22.1	22.1, 22.3	22.2	22.3	
8	23.15	23.1	23.1	23.0	23.1	
9	24.1	24.0	24.1, 24.3	24.3	24.35	
10	24.9	25.0				
11	25.55			25.2		
12	26.38	26.2				
13	27.45	27.3				
14	28.55	28.9				
15	29.6					
16	31.4					
17	33.0					33.0
18	38.75					39.7
19	41.1					
20	43.0					
21	46.0					45.9
22	51.0					51.6
23	60.2					58.4

present work. Tanner et al. found evidence at about 17 MeV of a broad set of states whose integrated strength is of the order of the two well resolved states at 17.13 MeV and 17.29 MeV.

One of the early evidences for structure in the giant resonance region were breaks in the (γ, n) yield curves. H. King and L. Katz (25) and A. S. Penfold and E. L. Garwin (26) found breaks corresponding to the now resolved peaks at 16.1, 17.13 and 17.3 MeV.

(2) This peak is verified by all experiments within a 70 keV span. The peak at 18.07 MeV seen by Barber and Dodge is not seen in any of the compared works. K. N. Geller and E. G. Muirhead (27) have found a peak in the (γ, n) reaction at this energy as well as numerous others in the low energy region. However, some of their results seem to be unsupported by comparison to the p, γ work of Tanner et al. and the present work. W. C. Barber, J. Goldemberg, G. A. Peterson and Y. Torizuka (28) have measured magnetic transitions in many nuclei and ascribe an M1 transition to the 19.06 MeV peak. D. B. Isabelle and G. R. Bishop (29) using electron scattering techniques give this transition an E2 assignment. Both measurements, however, carry

approximately 40% error bars.

(3,4,5,6) The 20.2 MeV peak is seen only by Firk. The 21.7 MeV peak which is not completely resolved in any work fails to appear in the experiments of Tanner and of Barber and Dodge.

(7) Firk finds evidence of splitting at 22.1 and 22.3 MeV. Angular distribution work by Isabelle and Bishop leads them to assign an E1 transition to this peak.

(8) The peak of Tanner at 23.0 MeV is reduced in comparison with the γ , n reactions at that energy implying a greater width for the neutron reaction.

(9) Firk again finds evidence for splitting this peak into 24.1 and 24.3 MeV peaks. The transition is assigned E2 by Isabelle and Bishop.

(10, 11, 12, 13, 14, 15) One runs out of comparative evidence here. The Bramblett data deviates from the present work by 350 keV at 28.9 MeV. The reason for this is not known. Isabelle and Bishop find a peak at 25.7 MeV corresponding to an E1 transition.

The peak for peak corroboration between the present work and the current experiments which have been referenced lends genuine credence to the experimental technique used and to CLSR computation. Extension of these methods to higher

energies is fully justified and the validity of the results achieved there is enhanced.

The detailed agreement between the cross sections from $O^{16}(\gamma, n)O^{15}$ and from $N^{15}(p, \gamma_0)O^{16}$ suggest that isotopic spin is a good quantum number. Electric dipole transitions in self conjugate nuclei (0^+ ground states) require angular momentum change of one and parity change. Thus the transitions go to $J^\pi = 1^-$ states. Self conjugate nuclei have the third component of isotopic spin, T_3 , equal to zero. The selection rule for isotopic spin change accompanying electromagnetic transitions have been described by M. Gell-Mann and V. L. Telegdi (30). The selection rule requires $T - T' = 0, \pm 1$ with no $0 \rightarrow 0$ change allowed for E1 transitions. The selection rule is not exact since a wave length long with respect to the nuclear size has been assumed and because of Coulomb perturbation effects. Failures of the selection rule are frequently attributed to a mixing of $T = 0$ and $T = 1$ states. The mixture ratio has been computed by Tanner et al. (23) by comparing peak ratios from Figure 12a and by detailed balance from Figure 12b. The results show that the square of the wave function amplitude ratio a_0^2/a_1^2 , is less than 2.5×10^{-3} . Hence, the states are essentially pure $T = 1$ states.

b. Comparison with theory The most successful theoretical calculations which lead to a prediction of

several of the dipole states observed have come from the shell model employing $j - j$ coupling. When a nucleon in a filled shell is elevated into an excited state by E1 photon absorption, the hole that is left can be treated in many ways as a particle. The effect of the particle-hole interaction on the odd parity states of O^{16} has been calculated with some success by J. P. Elliott and B. H. Flowers (31). A similar but more extensive calculation has been made by G. E. Brown, L. Castillejo and J. A. Evans (32). The procedure has been to determine empirically the unperturbed particle-hole interaction energy from the ground and first few excited states of O^{17} and O^{15} respectively. The introductions of a residual two-body interaction modifies the unperturbed energy such as to boost $T = 1$ states to still higher energies. In this way a set of collective states is derived from the single particle shell model states.

Oxygen 16 is doubly magic. The $1s_{1/2}$, $1p_{3/2}$ and $1p_{1/2}$ levels are filled. Under E1 photon absorption the excited nucleon is promoted to a $1d_{5/2}$, $1d_{3/2}$, or $2s_{1/2}$ level in accordance with angular momentum conservation. A total of 5 transitions is available and gives rise to $1p_{3/2}^{-1} 2s_{1/2}$, $1p_{3/2}^{-1} d_{5/2}$, $1p_{1/2}^{-1} d_{3/2}$, $1p_{1/2}^{-1} 2s_{1/2}$ and $1p_{3/2}^{-1} d_{3/2}$ configurations. The two body residual interaction causes configuration mixing among these five single particle-single hole states. The resulting E1 levels are then linear

combinations of these five lp-lh electric dipole levels.

The exchange force used by Elliott and Flowers was $\frac{1}{3} V_c T_i \cdot T_j (.3 + .7 \sigma_i \cdot \sigma_j) \times e^{-r/a} / r/a$ where $V_c = 43$ MeV and $a = 1.4 \times 10^{-13}$ cm. Brown et al. used a Soper exchange force, $(.3 + .43 P_m + .27 P_B) V(\bar{r}_1 - \bar{r}_2)$ where P_M and P_B are the Majorana and Bartlett exchange operators.

V. Gillet and N. Vinh Mau (33) have made extensive calculations of the particle-hole states under two separate approximations. Approximation I corresponds to diagonalization of the two body interaction in a subspace restricted to lp-lh configurations. This was also the assumption of Elliott and Flowers. Approximation II is equivalent to linearization of the equations of motion in a Hartree-Fock time dependent theory. The effective interaction used was derived from the most general two nucleon force subject to the assumptions of neglect of the tensor force, central force approximation and the same radial dependence for all exchange terms. To obtain the interaction the exchange parameters M, B, H, W, the well depth and the range were varied simultaneously subject to the constraint $M + W + B + H = 1$. Energy levels of O^{16} were calculated and the parameters chosen were those yielding minimum error with respect to the known levels using approximation II.

The results of the calculations for the $1^- T = 1$ and $2^- T = 1$ states are presented in Table 5. The values

Table 5. Calculated energies, dipole strengths, and level widths for El
T=1 transitions in O^{16}

Elliott and Flowers			Brown, Castillejo, Evans				Gillet and Vinh Mau			
			Ordinary force		Soper mixture		Approxima- tion I		Approxima- tion II	
Energy MeV	% Dip. str.	MeV	Energy MeV	% Dip. str.	Energy MeV	% Dip. str.	Energy MeV	% Dip. str.	Energy MeV	% Dip. str.
25.2	32	5.8	25.6	15	25.0	29	25.4	19.8	25.3	34.1
22.6	67	12.0	21.5	81	22.2	68	22.5	75.6	22.8	62.5
20.4	0	0.02	19.9	1	20.0	1	19.9	0.8	20.2	0.4
17.3	1	0.14	17.7	2	17.6	1	17.8	1.6	17.7	1.2
13.1	0	0.06	13.9	1	13.7	1	13.4	2.2	13.3	1.8

obtained for the 1^- levels correspond closely to those obtained by Elliott and Flowers and by Brown et al.

Electric quadrupole states of O^{16} are shown in Table 6 as a function of the energy of the $1f_{7/2}$ and $2p_{3/2}$ particle energies. The lowest $2^+ T = 1$ states are composed primarily of $1 p_{3/2}^{-1} 1f_{7/2}$ and $1 p_{1/2}^{-1} 1f_{5/2}$ transitions. The highest values occurring are pure $1 s_{1/2}^{-1} d_{3/2}$ and $1 d_{5/2}$ respectively. The energy differences between the latter two should reflect the $1 d_{3/2} - 1 d_{5/2}$ spin orbit splitting. The values in Column 3 were considered by Vinh Mau and Gillet to be the most realistic.

The predictions when compared to Figure 5 show good correspondence. The 25.4, 22.7 and 19.6 MeV $1^- T = 1$ states are clearly evident. The first two of these have been verified by Bishop and Isabelle as E1 transitions. The $2^+ T = 0$ state in Column 3 at 25.9 MeV and the $2^+ T = 1$ state in Column 1 at 23.5 MeV are both in a region where electric quadrupole transitions have been measured.

The cross section integrated to 26 MeV as measured in Figure 5 contains 30% of its strength in levels other than those predicted in Table 5. In spite of the fact that the predictions are made for total absorption, the similarity of the (γ, n) and (γ, p) cross sections allows ratio comparisons such as this to be made. The peak predicted at 22.7, 22.2 MeV is given 70% of the dipole strength whereas

Table 6. Calculated energies and relative strengths of E2 T=0 and T=1 transitions in O^{16} (Energies of $1f_{7/2}$ level are referred to ground level for O^{16})

	$1f_{7/2} = -0.3 \text{ MeV}$		$1f_{7/2} = 6.7 \text{ MeV}$		$1f_{7/2} = 13.7 \text{ MeV}$	
	Energy MeV	% Relative strength	Energy MeV	% Relative strength	Energy MeV	% Relative strength
2^+ T=0	12.6	89	19.3	91	25.9	93
	53.2	11	53.3	12	53.3	14
2^+ T=1	48.2	10	48.3	11	48.4	13
	23.7	40	30.7	47	37.6	46

Figure 5 shows it to be approximately 40%.

At photon energies above 22 MeV, nonground state transitions can take place to the first excited state of O^{15} . This is a $3/2^-$ level at 6.2 MeV excitation. Very recently, N. W. Tanner and E. D. Earle (34) have compared the 1963 data of Bramblett et al. with the neutron time-of-flight data of P. F. Yergin et al. (35). Tanner and Earle show that the neutron spectrum of Yergin et al. can be obtained from ground state, $1p_{1/2}^-$ hole, and first excited state, $1p_{3/2}^{-1}$ hole, transitions only. It is further shown that, between 23 and 26 MeV, 50% of the transitions go to excited states in O^{15} . Thus, the high energy portion of Figure 5 must also be composed of a similar proportion of nonground state transitions.

2. The energy interval 30.375 to 65 MeV

a. Comparison with other experiments Figure 6 displays the $O^{16}(\gamma, n)O^{15}$ cross section from 15.5 MeV to 45.25 MeV. This curve is again the average of six independent yield curves. The data was taken in 250 keV steps beyond 30.500 MeV and is interlaced with the 125 keV data below 30.5 MeV. All of the structure observed in the 125 keV data remains resolved in this curve. The peak at 29.6 MeV verifies that the partial peak at 29.9 MeV in Figure 5 is real.

Additional structure appears, some of which is previously unreported in the literature. Peaks occur at energies of

29.6, 31.4, 33.0, 39.75, 41.1 and 43.0 MeV. The peaks at 31.4 and 33.0 were reported by Griffin in Reference 5 as a single, broad peak at 33.0 MeV. The peak at 39.75 was reported at $38.9 \pm .5$ MeV by the same. A fairly large peak occurs between 34 and 37 MeV but is uncorrelated in the individual runs and hence our results are inconclusive. Small peaks at 31 and 33 MeV are seen in the data of Isabelle and Bishop (29). They also display a broad peak extending from 35 to 41 MeV ending sharply at 41.1 MeV. This could easily be a combination of the 39.75 and 41.1 peaks seen in Figure 6. There is no comparative evidence for the peak at 43 MeV. Both Griffin and Isabelle show a valley in the cross section at this energy. Hence, despite the fact that the 43 MeV peak was found in each of the independent cross sections which comprise the average, its validity remains uncorroborated.

Figure 7 displays the $O^{16}(\gamma, n)O^{15}$ cross section from 15.5 to 65 MeV. It is also derived from the average of six independent yield curves. The data step, E_0 , is 500 keV. The resolution function appropriate to Figure 7 is found in Figure 8c. Many of the low energy resonances are unresolved in this curve. Structure appears at 46, 51 and 60.2 MeV in addition to that found in Figure 4. The peaks at 51 MeV is nearly split into two smaller peaks. The energy at 51 MeV is just the centroid of the combination.

Figure 13 shows a comparison between the present work and the cross section derived by Griffin and Cook in 1963 using similar techniques. There is detailed difference in the results from 31 to 42 MeV. The broad shoulder at 33 MeV in Figure 13b is split up in Figure 13a. The single peak at 39 MeV in Figure 13b would seem to be a collection of the peaks at 36.6 and 41.5 MeV in Figure 13a. On the basis of the comparison one would conclude that Figure 13b is quite a bit over smoothed. The three highest energy peaks repeat in both curves, however, indicating their validity. The better resolution of the current work is due to the smaller error involved in the data which resulted in less smoothing of the cross section. This is reflected in the resolution functions of the two works. At 25 MeV in the present work Γ , the full width at half maximum, is 1 MeV and at 60 MeV Γ is 2 MeV. The corresponding widths for Figure 13b are 1.5 and 3 MeV respectively. Figure 13b shows 28% of the cross section integrated to 60 MeV to be above 30 MeV. Figure 13a has 30% of the cross section in this region.

Isabelle and Bishop have found strong peaks in their inelastic electron scattering data at 44.8 and 49.3 MeV. A lesser peak is seen at 53 MeV. Angular distribution measurements showed the former to be a mixture of E1 and E2 transitions. Later analysis by the authors using different form factors showed the distribution to correspond to E_0

Figure 13a. The 500 keV bin results of the present work

Figure 13b. $^{16}\text{O}(\gamma, n)^{15}\text{O}$ relative cross section from Griffin. Derived by a technique very similar to the present work

excitation which would not be excited in this experiment.

b. Comparison with theory Shell model calculations which predict energy levels in the region above 30 MeV are not in abundance. The 2^+ states calculated by Gillet and Vinh Mau, which are listed in Table 6, span the range of possibilities based on the unknown $1f_{7/2}$ and $2p_{3/2}$ excited levels. The values which appear in the third column are reasonably close to the levels observed in Figure 9a. These levels have further justification, as mentioned above, in the inelastic electron scattering peaks at 44.8 and 49.3 MeV.

The collective model, which has predicted only the envelope of the giant resonance, also predicts overtones which occur in the region above the giant resonance. J. H. Carver and D. C. Peaslee (36, 37) have examined the basis for the shift in the giant resonance energy with respect to simple shell model expectations. They conclude that the shift is ~ 7.5 MeV, is constant over mass number and is generated by the two nucleon interaction.

They obtain for the E1 giant resonance energy

$$E_m = 40A^{-1/3} + 7.5 \text{ MeV} \quad . \quad (31)$$

The first harmonic available to E1 excitation is $3\hbar\omega$, hence, the first E1 overtone would be given by

$$E_{3m} = 115 A^{-1/3} + 3 \text{ MeV} . \quad (32)$$

The changes in parameter values are given slight justification by Carver and Peaslee. The 5hw, overtone would be beyond the energy range of the present data.

M. Danos (38) has shown that one can expect E1 overtones at $2.86 E_m$ based on hydrodynamical considerations. This yields a value very close to the prediction of Equation 28. Danos further predicts E2 collective transitions beginning at $1.6 E_m$. For O^{16} these imply a giant resonance energy of 23.5 MeV. If the energies of the two main peaks in the giant resonance are used, E1 overtones should occur at 45.7 and 51.7 MeV. These values correspond well with the observed peaks. Inserting the giant resonance values into the E2 relation gives 35.5 and 38.4 MeV. These values are not well correlated to the peaks observed in Figure 13a.

c. Integrated cross sections The difference in resolution of the various experimental techniques makes comparison of the cross sections on the basis of peak heights nonmeaningful. The integrated cross sections are subject to comparison, however, and a calculation has been made to predict the electric dipole integrated cross section. E. G. Fuller and E. Hayward (39) have described the sum rule calculations which follow.

In the long wave length approximation, the photon-nucleus

interaction can be treated as the interaction of a static external electric field, $\bar{E}$, and the induced dipole moment, $\bar{D}$, according to a theorem due to A. J. F. Siegert (40). Thus,

$$H_1 = \bar{E} \cdot \bar{D} = E_0 e \sum_{i=1}^Z \bar{r}_i \cdot \bar{\mu} \quad (33)$$

where E_0 is the magnitude of the electric field, $\bar{\mu}$ is its polarization vector and $\bar{r}_i$ is the proton coordinate with respect to the mass center. When the transformation to relative coordinates, $\rho_i = R_i - r_i$, is made, where R_i is the recoil nucleus displacement, the protons can be thought of as having charge Ne/A and the neutrons charge $-\frac{Z}{A}e$.

The Thomas-Reiche-Kuhn sum rule states that the total electric dipole oscillator strength summed over discrete levels and integrated over the continuum is equal to the number of charges in the system. When applied to nuclei, modification must be made to take into account the relative motion of the excited nucleon and the recoil nucleus and to include the effects of the nuclear force.

The oscillator strength of the k -th level at energy E_k is defined as

$$f_k = \frac{2ME_k}{\hbar^2} \left| \int \psi_k^* z \psi_0 d\tau \right|^2 = \frac{2ME_k}{\hbar^2} |z_{ok}|^2 \quad (34)$$

where z_{ok} is the matrix element of the dipole operator, z , and M is the nucleon mass. The integrated absorption cross

section for the transition described by Equation 34 is given by

$$\int \sigma_k dE = \frac{2\pi^2 e^2}{MC} q_k^2 f_k \quad (35)$$

where q_k is the effective charge on the nucleon in units of e . Integration over all dipole transitions yields

$$\int \sigma dE = \frac{2\pi^2 e^2}{MC} \sum_k q_k^2 f_k \quad (36)$$

Introduction of the effective charges N/A and $-Z/A$ for the proton and neutron gives

$$\int \sigma dE = \frac{2\pi^2 e^2}{MC} \frac{NZ}{A} \quad (37)$$

This relation is based on the independent motion of the nucleons. If the nucleon-nucleon interactions are included Equation 37 is modified to give

$$\int \sigma dE = \frac{2\pi^2 e^2}{MC} \frac{NZ}{A} \beta = .06 \frac{NZ}{A} \beta \text{ MeV} \cdot \text{mb} \quad (38)$$

where $\text{lmb} = 1 \text{ millibarn} = 10^{-27} \text{ cm}^2$. J. S. Levinger and H. A. Bethe (41) have evaluated β for an equal mixture of ordinary and exchange forces and find $\beta = 1.4$. Equation 38 evaluated for O^{16} yields $336 \text{ MeV} \cdot \text{mb}$.

Absolute calibration of the present work is described in Appendix A. The result is $70 \text{ MeV} \cdot \text{mb}$ integrated from 15.5 to 62 MeV . The Dodge and Barber (24) result of $\int_{16}^{27} \sigma(\gamma, p) dE = 56 \pm 11 \text{ MeV} \cdot \text{mb}$ compares to $41.5 \text{ MeV} \cdot \text{mb}$ for the (γ, n)

integrated cross section. This is 30% larger and if maintained to 62 MeV should yield about 92 MeV·mb. Thus the sum of the partial cross section gives 162 MeV·mb or about half the sum rule prediction.

A. N. Gorbunov and V. A. Osipova (42) have determined the integrated cross sections up to 170 MeV using a cloud chamber in a magnetic field. Their results for (γ, n) are 65 ± 2 MeV·mb to 30 MeV and 86 ± 3 MeV·mb to 170 MeV. For (γ, p) they find 100 ± 4 MeV·mb to 30 MeV and 117 ± 5 MeV·mb to 170 MeV. Also measured were (γ, pN) and (γ, α) which contribute an additional 65 MeV·mb. These combine to a total of about 270 MeV·mb leaving about 70 MeV·mb to be made up by spallation reactions to reach the sum rule prediction.

The present work compares favorably with other measurements of the (γ, n) integrated cross section. Bramblett et al. (21) obtain 46 ± 5 MeV·mb to 30 MeV and the present work gives 49 ± 7 MeV·mb. Breuer and Pohlitz (19) have measured the integrated cross section to 32.5 MeV to be 53 ± 4.7 MeV·mb compared to 53 ± 7 MeV·mb in the present work. Some authors (43, 44) have reported results about 10% larger than these values.

C. C^{12} Results

The cross sections for the (γ, n) reaction in C^{12} are displayed in Figures 14, 15, 16, 17 and Table 7. A composite

Figure 14. $\text{Cl}^{12}(\gamma, n)\text{Cl}^{11}$ cross section derived from the average of three independent yield curves. Data was taken in 125 keV bins

Figure 15. $\text{Cl}^{35}(\gamma, n) \text{Cl}^{36}$ cross section derived from the average of three independent yield curves. Data was taken in 250 keV bins

Figure 16. $C^{12}(\gamma, n)C^{11}$ cross section derived from the average of three independent yield curves. Data was taken in 500 keV bins. No high energy structure comparable to that in oxygen is observed

Figure 17a. Resolution functions inherent in Figure 14.

Figure 17b. Resolution functions inherent in Figure 15.

Figure 17c. Resolution functions inherent in Figure 16.

Table 7. Resonance energies of Cl^{35} observed in the present work

Peak number Figure 18	Peak energy MeV	% of $\int_{18.5}^{65} \sigma(\gamma, n) dE$	Integrated cross section
1	19.8		
2	20.1		
3	20.3	.4	$\int_{18.5}^{31} \sigma(\gamma, n) dE = 44 \text{ MeV} \cdot \text{mb}$
4	20.6		
5	20.9		
6	21.3		
7	21.7		
8	22.1	18	$\int_{18.5}^{40} \sigma(\gamma, n) dE = 55 \text{ MeV} \cdot \text{mb}$
9	22.3		
10	22.7		
11	23.1		
12	23.6	14	
13	24.25		
14	25.3	11	$\int_{18.5}^{65} \sigma(\gamma, n) dE = 69 \text{ MeV} \cdot \text{mb}$
15	26.1		
16	27.5	8	
17	29.5	4	
18	32.9		
19	36.4		

graph showing the cross section from 18.5 to 65 MeV appears in Figure 18. The data for the 125 keV step cross section was taken from three yield curves measured independently of the 250 and 500 keV step data. The experimental error contained in this data is approximately .2% and represents the limit of the current experimental technique. The error bars in the figures have the same meaning as given in Section IV B.

Nineteen peaks in the cross section were observed. All of these lie below 37 MeV. Thus, no high energy structure was resolved comparable to that observed in O^{16} . Of the cross section integrated to 65 MeV, 68% lies below 32.5 MeV. The cross section integrated to 65 MeV is 69 MeV·mb. The absolute calibration of the cross sections is described in Appendix A.

In examining the cross sections derived from each of the yield curves taken in 125 keV steps, two features were noticed and examined in detail. These were (1) a shifting in the peak energy values in the giant resonance and (2) inconsistent splitting of the peak at about 26 MeV. The effect of statistical fluctuations which cause this are described in Appendix B.

The reproducibility of the 125 keV step results can be seen in Figure 19. Each curve was derived from the sum of the counts recorded by the two phototubes. The smoothing

Figure 18. Composite $C^{12}(\gamma, n)C^{11}$ cross section. Data bin width is 125 keV from 18.5 to 31.5 MeV, 250 keV from 31.5 to 44.5 MeV and 500 keV from 44.5 to 65.5 MeV. Numbered arrows indicate peaks in the cross section as referenced in Tables 7 and 8

Figure 19. Relative $C^{12}(\gamma, n)C^{11}$ cross sections derived from three independent yield curves. Data taken in 125 keV bins. Curves 1, 2, and 3 show the reproducibility of the results

applied to each curve is the same, $\lambda = 3.53 \times 10^{-15}$. The lack of correlation in the fluctuations at higher energies causes the average curve, Figure 14, to be relatively smooth in this region.

The N.B.S. monitor calibration of Pruitt and Domen (11) consists of a best fit curve and two extreme curves which represent the limit of error in the calibration. The effect of using these extreme monitor response curves when applied to the 500 keV step data is seen in Figure 20a. No appreciable effects occur at low energies. At high energies the cross section tail is caused to ride higher or lower than the best fit response. No effect on the structure is seen.

The effect of introducing the P(I) factors from Equation 16 can be seen in Figure 20b. It is clear that their presence does not contribute false peaks in the data or alter the integrated cross section significantly. The effect as described earlier is to remove smoothing from the giant resonance region and apply it to the higher energy region. Many of the statistical fluctuations at higher energies are seen reduced by this method.

1. The energy interval 18.5 to 31.0 MeV

a. Comparison with other experiments In the region from 18.5 MeV to the first giant resonance peak at 22.1 MeV many small peaks are seen. Those appearing on the ascending

Figure 20a. Cross section response to extreme monitor response function

Figure 20b. Cross section response to smoothing function P(I). The transfer of smoothing to higher energy is evident from the increased resolution in the giant resonance peak

side of the giant resonance are not completely resolved. Nearly all of these peaks show energy correspondence to the activation curve work of I. M. Thorson and L. Katz (45). In that work the existence of cross section peaks is inferred from breaks in the activation curve of C^{11} . Eighteen breaks were measured by Thorson and Katz and the eleven highest in energy are listed in Table 8. With the exception of the peak at 21.08 MeV there exists an excellent correspondence over this energy range. Their cross section integrated from 18.73 to 23 MeV is 14 MeV·mb. This compares to 14 MeV·mb from the present data. It is concluded that this sequence of peaks in the present work represents real structure and is not the result of data fluctuations.

V. Emma, C. Milone and A. Rubbino (46) have measured the $C^{12}(\gamma, n)C^{11}$ cross section using proton recoil in emulsions for detection. A plot of their results is shown in Figure 21b. Figure 21a is the present work reproduced for comparison. The resolution quoted by Emma et al. was 200 keV. Their results are listed in Table 8. The agreement is seen to be generally good. Their peaks at 20.9 and 21.4 MeV have relative intensities well in excess of those observed in the present work. Emma et al. ascribe the 20.9 MeV peak as being due to the 22.9 MeV peak branching to the first excited state of C^{11} at 2 MeV. If this were true one would expect their 22.9 peak to be depleted to some extent

Table 8. Resonances observed in C^{12}

Peak number Figure 18	Present work (γ, n) E MeV	Thorson and Katz (γ, n) E MeV	Emma et al. (γ, n) E MeV	Firk et al. (γ, n) E MeV	Fuchs et al. (γ, n) E MeV	Barber and Dodge (e, pe') E MeV	Cohen et al. (γ, p) E MeV
1	19.8	19.9					
2	20.1	20.13					
3	20.3	20.29					
4	20.6	20.6					
5	20.9	20.9	20.9				20.8
6	21.3	21.08, 21.22	21.4			21.2	
7	21.7	21.58		21.7			21.5
8	22.1	22.02	22.2	22.1	22.1		
9	22.3				23.0	22.5	
10	22.7	22.88	22.9				22.6
11	23.1			23.1		23.3	23.1
12	23.6		23.6	23.7	23.6	23.85	
13	24.3		24.3			24.8	
14	25.3		24.8, 25.6	25.5	25.5	25.7	
15	26.1					26.7	
16	27.5			27.8	27.5	27.2, 27.9	
17	29.5						
18	32.9						
19	36.4						

Figure 21a. $C^{12}(\gamma, n)C^{11}$ cross section derived from 125 keV bin data in the present work

Figure 21b. $C^{12}(\gamma, n)C^{11}$ relative yield from the nuclear emulsion experiment of Emma, Milone and Rubbino.

and it is not. Similarly, their peak at 21.4 MeV is very high and must also be made by neutrons leaving the C^{11} nucleus in either the 2 MeV or the 4.26 MeV excited state. The peak at 23.6 is seen to be depleted and probably is responsible for feeding the first C^{11} excited state and producing the 21.4 MeV peak. The 20.9 MeV peak can be made in a similar way by transition from the 25.3 MeV peak to the 4.26 MeV second excited state of C^{11} . The angular distributions of neutrons with energies greater than 3 MeV (corresponding to $E_\gamma = 22$ MeV) were measured and observed to have a $2 + 3 \sin^2\theta$ dependence. This is the distribution predicted by D. H. Wilkinson (3) for a direct electric dipole interaction. Their integrated cross section to 31 MeV was given as 42 ± 7 MeV·mb. This is in good agreement with the 44 ± 6 MeV·mb measured in the present work.

The cross section in this energy range has been measured with somewhat less resolution by V. Fuchs, D. Haag, K. Lindenberger and V. Meyer-Berkhout (47) using proton recoil in a stilbene crystal for detection. These authors see fit to draw a smooth curve through their results rather than face up to the structure that is evident. The peaks taken from their data are listed in Table 8. Absolute calibration was made and shows a giant resonance peak height of 8 mb.

Figure 22a shows the relative yield of the $C^{12}(\gamma, n)C^{11}$ reaction measured by F. W. K. Firk, K. H. Lokan and E. M.

Figure 22a. $C^{12}(\gamma, n)C^{11}$ relative yield from neutron time of flight experiment by Firk, Lokan and Bowey

Figure 22b. $C^{12}(e, e')B^{11}$ differential cross section from experiment of Dodge and Barber

Bowey (48) using neutron time of flight techniques. The peak energies are listed in Table 8. The correspondence is good with the exception of the large peak at 21.7 MeV. The magnitude of this peak is not in agreement with the present work but agrees with the peak seen by Emma et al. The conclusion is the same, i.e., that the peak is generated by a nonground state transition. An alternate explanation could be that the peak is really much smaller but is riding on a large background.

Figure 22b displays the $C^{12}(e,pe')B^{11}$ differential cross section measured by Dodge and Barber (24) using electron bombardment and magnetic analysis of the protons. The peaks of this curve are seen to be shifted upwards between 200 and 400 keV with respect to the present (γ, n) curve. The integrated cross section from 20.3 to 29.3 MeV is given as 50 ± 8 MeV·mb. This is 20% larger than the 41 MeV·mb obtained in the present work in the same energy span. Their data was taken at 76° and 100% ground state transitions were assumed.

W. C. Barber, W. D. George and D. D. Reagan (49) have measured the absolute cross section for the (γ, n) reaction by electron bombardment and counting the induced C^{11} activity. The cross section peaks at 22.5 MeV with a value of 8.3 mb. The cross section integrated to 38 MeV is 56 ± 3 MeV·mb and integrated to 250 MeV is 80 ± 10 MeV·mb. The corresponding

values in the present work are 53 MeV·mb to 38 MeV and 69 MeV·mb to 65 MeV.

L. Cohen et al. (50) have measured the (γ, p) cross section to 24 MeV and find peaks in essentially the same sequence as Barber and Dodge. Their peak at 23.1 MeV has a cross section of 20 mb. and the cross section integrated to 24 MeV is 56 MeV·mb. Nonground state transitions were included. Their results are listed in Table 8.

S. Penner and J. E. Leiss (51) have studied the (γ, p) reaction and measured the angular distribution of the protons. They find a peak in the cross section at 22.1 MeV with magnitude 8.13 mb. $7 \pm 16\%$ of the transitions below 30 MeV go to nonground states of B^{11} but at higher energies nonground state transitions acquire a major portion of the transition strength. The angular distributions show the $2 + 3 \sin^2\theta$ dependence at 22 MeV but considerable forward peaking at higher energies. This implies that contributions from other than E1 transitions become important at those energies.

The (γ, p) integrated cross section has also been measured by V. J. Vanhuyse and W. C. Barber (52) who obtained a peak at 22.6 MeV with magnitude $12.7 \pm$ mb. The cross section integrated to 24 MeV was 41 ± 9 MeV·mb. and 77 ± 18 MeV·mb. integrated to 40 MeV. More recently, N. W. Reay, N. M. Hintz and L. L. Lee (53) have obtained from detailed balance applied to the $B^{11}(p, \gamma_0)C^{12}$ reaction, an integrated

cross section to 40 MeV of 55 ± 13 MeV·mb.

Very recently Y. M. Shin and W. E. Stephens (54) have measured the (γ, p_0) cross section using monochromatic gamma rays from the ${}^3(p, \gamma) \text{He}^4$ reaction. Peaks were found at 20.57, 20.95 and 21.38 MeV, in close agreement with the present work.

From the above comparisons one can conclude that all the structure observed in Figure 10 is real, with the possible exception of the small peak at 22.3 MeV. The correspondence of the (γ, n) levels to those seen in (γ, p) cross sections is good with the exception of the energy shifts seen in the work of Barber and Dodge (24).

b. Comparison with theory The C^{12} nucleus consists of 6 neutrons and 6 protons occupying closed $1s_{1/2}$ and $1p_{3/2}$ levels. The ground state J^π , T is 0^+ , 0. Excitation by E1 radiation promotes the nucleus to J^π , T = 1^- , 1 states represented by the configurations $1p_{3/2}^{-1}2s_{1/2}$, $1p_{3/2}^{-1}1d_{3/2}$, $1p_{3/2}^{-1}1d_{5/2}$, $1s_{1/2}^{-1}1p_{1/2}$. Neutron emission from these excited states will leave the residual nucleus, C^{11} , in its $3/2^-$ ground state or if energetically possible some of the decays will leave the C^{11} nucleus in its first $1/2^-$ and $3/2^-$ excited states. Threshold for the $\text{C}^{12}(\gamma, n)\text{C}^{11}$ reaction is 18.7 MeV and the first excited states of C^{11} are at 1.99, 4.26 and 4.75 MeV. Consequently, one can expect nonground state transitions to appear above $E_\gamma = 21$ MeV.

The overall agreement obtained by Gillet and Vinh Mau in ^{16}O is not obtained for ^{12}C . The energies of the 1^- , 1 and 2^- , 1 states and their predicted strengths are given in Table 9. The predicted strength of the 21.9 MeV state, which corresponds to the peak at 22.1 MeV in the present work, is 73%, whereas it is seen in Figure 14 to contain about 20% of the strength. Neglect of the 2p-2h configurations and difficulty in fitting the low lying even parity states are among the reasons given by Gillet and Vinh Mau for the failure.

N. Vinh Mau and G. E. Brown (55) have obtained a better agreement using the Brown and Bolsterli model and a short range force. Their results are listed in Table 8. The 2^+ level at 27.9 MeV carries 41% of the oscillator strength, and is close to the observed peak at 27.5 MeV in Figure 14. The 1^- peak predicted at 34.3 MeV as carrying 18% of the dipole strength has been detected by Reay et al. (53) but with an observed strength of 2%.

S. G. Nilsson, J. Sawicki and N. K. Glendenning (56) also have applied the random phase approximation treatment to the residual interactions in a deformed nucleus. ^{12}C is considered to be an oblate nucleus in the Nilsson scheme. Two separate modes of excitation are then available corresponding to the rotational quantum numbers $K = 0$ and $K = 1$. The two body force used in the calculation was due to Ferrell

Table 9. Calculated energies and strengths for transitions in Cl^{12}

Gillet and Vin Mau			Vin Mau and Brown			Goswami and Pal			Nilsson et al.		
J^π, T	E MeV	%	J^π, T	E MeV	%	J^π, T	E MeV	%	K	E MeV	M ²
$1^-, 1$	33.8	19	$1^-, 1$	34.3	18	$1^-, 1$	37.37	19.88	0	31.91	3.52
	24.2	3		23.9	.5		26.30	12.35		26.31	1.26
	21.9	73		22.2	75		25.08	52.42		23.74	1.08
	17.7	23		18.7	6.5		20.86	1.63		20.85	.08
$2^-, 1$	23.2		$2^-, 1$	22.9	24						
	19.4			19.2	86						
	18.2			18.1	7						
$2^+, 1$	16.4		$2^+, 1$	41.5	16	$2^+, 0$	33.1	1	1	29.5	1.04
				36.6	13		28.24	1.1		24.7	1.04
				35.2	1		24.09	9.8		22.97	1.08
				35.0	19		18.85	46.1.		22.21	3.66
				28.1	1					19.74	.08
				27.9	41						

and Vischer. Those states which carry a majority of the oscillator strength are listed in Table 9. The agreement is much improved in comparison to the single particle-hole calculations.

A. Goswami and M. K. Pal (57) have extended the particle-hole calculations to include some of the 2p-2h configurations. The two body interaction used was Soper exchange mixture with a finite range Yukawa force. The agreement with the present work is not especially good, although these calculations manage to spread the oscillator strength more uniformly over the states than do the single particle-hole calculations.

2. The energy interval 31.0 to 65.0 MeV

The cross section in this region is displayed in Figures 15 and 16. Structure in the curves above the giant resonance is limited to two small peaks at 32.9 and 36.4 MeV. The curves tail off toward zero at high energy but still contain some 32% of the integrated cross section above the giant resonance.

The peak at 32.9 MeV is of interest despite its size, since it lies near an energy predicted by the particle-hole calculations. The peak was first seen by Reay et al. (53) at $34.5 \pm .5$ MeV using the $B^{11}(p, \gamma_0)C^{12}$ reaction. The peak was observed to be a factor of ten reduced in strength, compared to the prediction in agreement with the magnitude

seen in the present work.

The dipole sum rule prediction for C^{12} yields

$$.06 \frac{NZ}{A} (\beta) = .06 \frac{36}{12} (1.4) = 252 \text{ MeV}\cdot\text{mb} . \quad (39)$$

Accepting the Barber et al. (49) result for the (γ, n) cross section to 250 MeV as 80 MeV $\cdot$ mb. and the Dodge and Barber (24) result of 50 ± 8 MeV $\cdot$ mb. for the (γ, p) cross to 24.3 MeV, one can estimate that the sum of the partial cross sections is of the order of 180 MeV $\cdot$ mb. to 250 MeV. The remainder of the dipole sum is attributed to many particle reactions.

V. CONCLUSIONS

The cross sections for the reactions $O^{16}(\gamma, n)O^{15}$ and $C^{12}(\gamma, n)C^{11}$ have been measured in the energy range from threshold to 65 MeV. The experimental technique coupled with CLSR computation have produced cross section curves with resolution comparable to techniques that do not require bremsstrahlung unfolding. Thus, a valid procedure has been determined for deriving cross sections over an extended energy range.

The O^{16} results reproduced in large measure the earlier work of Anderson et al. (58) in the region above the giant resonance and resolved a peak at 31.4 MeV which was not seen in that work. The cross sections derived in the giant resonance region provide detailed agreement with current data. The good agreement with the $O^{16}(\gamma, p)N^{15}$ cross section implies that isotopic spin is a good quantum number in O^{16} .

The particle-hole formalism advanced by Brown and Bolsterli (4) has had partial success in providing some of the details of the observed structure. It is clear, however, that there is more structure than theory at the present time. Extensive measurements of angular distributions are needed to provide spin and parity assignments to all the levels observed. The presence of multipolarities other than dipole have been established by several investigators (28, 59) but

the full extent of their contributions to the cross sections has not been determined. The interpretation of their work is further complicated at higher energies by the presence of nonground state transitions. These have been shown by Tanner and Earle (23) to contribute 50% of the yield between 23 and 26 MeV in O^{16} .

The shortage of integrated cross section compared to sum rule predictions is frequently attributed to many particle break up reactions such as (γ, np) , $(\gamma, 2n)$ etc. The cross sections for these reactions need to be measured to determine the validity of the sum rule. The $O^{16}(\gamma, n)O^{15}$ cross section integrated to 62 MeV is 70 ± 10 MeV·mb.

Much of the structure in the giant resonance of carbon is unresolved. The level spacing is not wide as in O^{16} and will require a truly high resolution technique to display the structure clearly. Three peaks previously unreported for the (γ, n) reaction were found at 29.5, 32.9 and 36.4 MeV. The 32.9 MeV peak is presumably associated with the 33.8 MeV prediction of Gillet and Vinh Mau (33) and found by Reay et al. (53) at 34.5 MeV using the $B^{11}(p, \gamma_1)C^{12}$ reaction. Additional structure in the giant resonance was resolved. The splitting of the three main component peaks into the five peaks shown has not been seen previously.

The region above the giant resonance in carbon is devoid of resolvable structure in contrast to that observed in O^{16} .

Even the undersmoothed versions of Figure 16 fail to display any structural character. Thus, transitions at these energies would seem to go to a true continuum or else too much unresolved structure exists.

The single particle-hole calculations fail to predict all the structure seen in carbon. The random phase approximation treatment of the two body interaction as applied to an oblate C^{12} nucleus has proved very fruitful. The results of Nilsson et al. (56) predict half of the major peaks observed in the C^{12} cross section.

The basic problem of photonuclear physics is to determine why certain of the many states available are selected by the electromagnetic interaction. It is clear that to attack the problem further the multipolarities of the transitions to these chosen states must be determined. The branching ratios from these levels to excited states of the residual nucleus need to be measured, since these have been shown to comprise of the order of 50% of the transitions above the giant resonance.

The present technique is not capable of producing these measurements. New methods which allow particle detection and coincidence measurements are required. The present technique can, however, be applied to nearly all nuclei for purposes of displaying structure in the cross section over an extended energy range.

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VII. APPENDIX A

A. Absolute Calibration
of the Cross Sections

The number of counts recorded by a detector following bombardment of a sample by a bremsstrahlung beam is given by

$$\text{Counts } (E_0) = \int_0^{E_0} dk \int_0^{w_s} dw N_e N_T \sigma_{\text{brem}} I(w) \rho_s \sigma(k) \epsilon \quad (40)$$

where E_0 is the energy of electrons which produce bremsstrahlung

w_s is the solid angle subtended by the sample

N_e is the number of electrons in the beam

N_T is the number of target atoms/cm²

$I(w)$ is the angular distribution function of the bremsstrahlung

ρ_s is the number of sample atoms/cm²

σ_{brem} is the bremsstrahlung production cross section

$\sigma(k)$ is the reaction cross section

ϵ is the efficiency of the counter.

When taking data one normalizes to unit monitor response and Equation 40 becomes

$$\frac{\text{Counts } (E_0)}{\text{Dose to monitor}} = \frac{C}{D} = \frac{\int_0^{E_0} dk \int_0^{w_s} dw N_e N_T \sigma_{\text{brem}} I(w) \rho_s \sigma(k) \epsilon}{\int_0^{E_0} dk \int_0^{w_c} dw N_e N_T \sigma_{\text{brem}} I(w) k \alpha} \quad (41)$$

where w_c is the solid angle subtended by the collimator, k is the photon energy and α is the transmission coefficient of the sample.

The relation derived by Schiff (12) for σ_{brem} can be written

$$\sigma_{\text{brem}} = A f(k) = 16A \frac{\theta_p}{k} = 16A \psi \quad (42)$$

where θ_p is the reduced brem cross section used by A. S. Penfold and J. E. Leiss (60) in calculating the bremsstrahlung energy integrals and ψ is the Schiff function as programmed in CLSR. Penfold and Leiss have computed $\int_0^{E_0} \theta_p dk$. Multiplying through Equation 41 by this integral and replacing for σ_{brem} in terms of ψ yields

$$y(E_0) = \frac{C}{D} \int_0^{E_0} \psi k dk \quad (43)$$

$$= \frac{\int_0^{E_0} dk \int_0^{w_s} dw N_e N_T 16 A \psi I(w) \rho_s \sigma(k) \int_0^{E_0} \psi k dk}{\int_0^{E_0} dk N_e N_T 16 A \psi k \int_0^{w_c} I(w) dw \alpha}$$

where $y(E_0)$ is called the reduced yield. Cancellation leaves

$$y(E_0) = \int_0^{E_0} dk \psi(k) \sigma(k) \frac{\int_0^{w_s} I(w) dw}{\int_0^{w_c} I(w) dw} \frac{\rho_s \epsilon}{\alpha}. \quad (44)$$

The calculations performed in CLSR result in an inverse operator M^{-1} . Applying this operator to Equation 44 gives

$$M^{-1}y(E_0) = s = \frac{\sigma}{\alpha} \frac{\int_0^{w_s} I(s) dw}{\int_0^{w_c} I(w) dw} \rho \epsilon. \quad (45)$$

The correspondence between this s value and one previously computed on a relative basis by CLSR is,

$$\frac{s}{y(E_0)} = \frac{s'}{y'(E_0)}, \quad (46)$$

since the inverse operators are identical. Finally,

$$\sigma_{E_0} = y(E_0) \frac{s'}{y'} \frac{\alpha}{\rho_s \epsilon} \frac{\int_0^{w_c} I(w) dw}{\int_0^{w_s} I(w) dw} \quad (47)$$

Hence, once the relative cross section at E_0 is evaluated absolutely, the remainder of the cross section curve is also calibrated.

The integrals over solid angle were obtained from $I(w) = I_0 e^{-kr}$ where r is measured normal to the photon beam axis. The value for k was determined from semi-log plots of copper cross activations. The cross was centered on the collimator and bombarded. The resulting activity was then plotted as a function of r . In this way k was found to be 1.132/cm.

The counter used was a 4 X 4 inch sodium iodide well type crystal. The efficiency for counting was determined by computation utilizing a fortran program written by R. S. Dingus and M. G. Stewart (61). The efficiencies proved to be 92% for the carbon samples and 88% for the oxygen samples.

The results for carbon were .499 mb at 54 MeV. The results for oxygen were .0221 mb at 54 MeV. An error estimate of 15% is assigned to these values based on possible differences between the dose monitor used and the one calibrated by Pruitt and Domen, 5%, error in the efficiency calculation, 3%, error in transmission coefficient and that inherent in the CLSR computation, 7%.

IX. APPENDIX B

A. Effect of Statistical Fluctuations
on Carbon Low Energy Data

The carbon cross section curves in the interval 18.5 to 33.375 MeV showed variations in the splitting of the peaks at 26 MeV. To verify that such variations were due to statistics a set of simulated carbon data was processed through CLSR. To obtain the yield curve use was made of a fortran program called Gauss-3.

The function of this program is to calculate gaussian peaks at prescribed energies and create a simulated cross section. The cross section is then operated on by N_{ij} from Equation 9 and produces a yield curve. Then, corresponding to a prescribed input amplitude, a random number generator provides a set of statistical errors which are superimposed on the yield curve. A number of such curves were analyzed by CLSR to see the effect of the statistics.

Figure 23a shows the simulated cross section as calculated by Gauss-3. Figures 23b and 23c are two curves as analyzed by CLSR from the yield curve based on Figure 23a plus .2% statistics. This value was chosen in accordance with the value of ϵ obtained from the raw data. The splitting is unresolved in Figure 23b but resolved in 23c. Both curves were run with the same value of the smoothing

parameter, λ . Shifting of the peaks in the giant resonance region is less than 100 kilovolts. The shifts in the higher energy peaks is of the order of 250 kilovolts.

It is of interest to observe the set of small peaks near the base line above 28.5 MeV. There is no input basis for these and they are generated by the errors in the data. The error bars have the same amplitude as the peaks, however. The mere presence of such peaks, none the less, makes verification of small amplitude structure difficult.