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$C^{12}(\gamma,n)C^{11}$ Cross Section to 65 MeV[*]

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The cross section for the reaction $C^{12}(\gamma,n)C^{11}$ has been measured from threshold to 65 MeV using least-structure analysis of yield curves. The giant resonance was resolved into a predominantly triplet structure with peaks at 22.1, 22.75, and 23.6 MeV. No structure was resolved about 40 MeV. The cross section integrated to 65 MeV is 77±6 MeV mb.

I. INTRODUCTION

Recently a computational technique has been developed which enables cross sections to be derived over an extended energy range from accurately measured yield curves.[1] The method, known as least-structure analysis (LS), gives the smoothest solutions of the yield functions consistent with experimental accuracy. Applications of LS analysis to $O^{16}(\gamma,n)O^{15}$ yield functions has shown the existence of high-energy structure in its reaction cross section.[2–4] It has been further demonstrated that the technique is capable of reasonably high resolution (100–300 keV) in the giant-resonance region.

This article reports the results of application of LS analysis to yield curves from the $C^{12}(\gamma,n)C^{11}$ reaction. Differences in experimental procedure between this work and the oxygen work were minimal but are detailed in the next section.

Carbon has been extensively studied both experimentally and theoretically. In contrast to oxygen the direct methods for studying carbon, such as the photoproton[5] and photoneutron[6] energy distributions, are in disagreement with the indirect method using the $B^{11}(p,\gamma_0)C^{12}$ reaction.[7] Photonucleon energy distributions show considerable structure in the giant resonance of carbon while the $B^{11}(p,\gamma_0)C^{12}$ reaction shows only a broad maximum near 22 MeV with no prominent structure. The assumption that only ground-state transitions are important from giant-resonance states is usually made for the interpretation of photonucleon energy distributions. This assumption has no experimental justification as yet, since the photonuclear cross section in carbon has not been measured with sufficient resolution to exhibit possible structure in the giant resonance. Experience with least-structure analysis in O^{16} has indicated that a direct measurement of the photoneutron cross section with resolution sufficient to distinguish the reported structure is possible.

The $p_{3/2}$ nucleon subshell is filled in C^{12} in the j-j coupling scheme. Using j-j coupling particle-hole calculations of the giant resonance states and higher energy configurations have been made.[8] Other coupling schemes have also been considered.[9] These calculations all indicate large $E1$ strength in the 30–35-MeV region and predict other higher energy transitions. In O^{16}, cross-section peaks have been found above the giant resonance using the least-structure technique. Motivated by these theoretical and experimental considerations, measurements in C^{12} were extended to 65 MeV.

II. EXPERIMENTAL PROCEDURE

Many details of the experimental procedure used to ensure reliable yield curves in this work have been reported previously.[2–4] For this reason only a brief description of experimental details will be presented, with emphasis on the differences between the carbon and oxygen work.

Cylinders of polystyrene $1\frac{1}{2}$ in. long and $1\frac{1}{8}$ in. in diameter were irradiated in an eclipsing geometry by the collimated bremsstrahlung beam from the Iowa State University 70-MeV synchrotron. The samples were uniform in size and weight and in yield at fixed bremsstrahlung energy to better than 0.1%, so that no correction for differing samples was required. The radiation dosage was monitored by a slightly modified version of a National Bureau of Standards P2 ionization chamber.

Following irradiation for 13 min, a 2-min time delay elapsed during which a sample was removed to a counting house. The time delay allowed all competing activities to decay to background, leaving only the 20.5-min positron decay of C^{11}. The sample was placed in the midplane between two 3-in. diameter NaI(Tl) crystals mounted in a face-to-face geometry and counted for 13 min. The annihilation spectrum of the positron

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[1] B. C. Cook, Nucl. Instr. Methods **24**, 256 (1963).

[2] D. W. Anderson, A. J. Bureau, B. C. Cook, J. E. Griffin, J. E. McConnell, and J. R. Nybø, Phys. Rev. Letters **10**, 250 (1963).

[3] J. E. Griffin and C. L. Hammer, U. S. Atomic Energy Commission Report IS-676, 1963 (unpublished).

[4] J. N. Bradford and B. C. Cook, U. S. Atomic Energy Commission Report IS-1086, 1965 (unpublished).

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[6] F. W. K. Firk, K. H. Lokan, and E. M. Bowey, in *Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962*, edited by E. Clementel and C. Villi (Gordon and Breach Science Publishers, Inc., New York, 1963).

[7] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. **58**, 122 (1964).

[8] N. Vinh Mau and G. E. Brown, Nucl. Phys. **29**, 89 (1962).

[9] G. F. Nash, Nuovo Cimento **32**, 727 (1964).

decay was counted with a discrimination level of 100 keV. To provide a basis for correction against counter drift, the counting system was exposed periodically to a Na^{22} source and the results corrected for the natural decay of Na^{22}. Throughout the course of the experiment this correction attained a maximum value of 1.2%.

Three independent yield curves were taken from 18.5 to 65.5 MeV. The energy interval used was 125 keV for energies to 33.375 MeV, 250 keV as far as 48.250 MeV, and 500 keV up to 65.5 MeV. Approximately three million counts were recorded for data points above the giant resonance. The reproducibility of the yield points at constant excitation energy was 0.21% except where counting statistics dominate. Thus, an error of 0.12% was achieved for the average yield function.

The energy control circuit was calibrated by reference to the 17.28-MeV break in the $O^{16}(\gamma,n)O^{15}$ yield curve, and was constant during the experiment within ±6 keV as determined by repeated measurements.

The absolute cross section was obtained by irradiating a sample at 50 MeV and counting in a 4-in.×4-in. well-type NaI(Tl) crystal, whose efficiency was known to about 2%. For this measurement correction was applied to the Pruitt and Domen[10] calibration of the ionization chamber for 3.63 lb overpressure, N_2 atmosphere and temperature.

III. RESULTS

The (γ,n) cross section of C^{12} is displayed in Figs. 1, 2, and 3. The vertical error bar is the error as computed by LS. The lower horizontal bar is the resolution function full width at half-maximum and the upper horizontal bar is the rms deviation of the peak energy as determined from cross sections derived from the individual yield curves. The width of the peaks, as one goes to higher energies in general, reflects the width of the resolution function. Table I contains a tabulation of all structure seen in the present work and a comparison of the energies of some previously reported results.

TABLE I. Comparison of energies of peaks found in $C^{12}(\gamma,n)C^{11}$ cross section with recent photonucleon spectra results and with yield-curve "break" analysis.

Present work (γ,n) E (MeV)	Error (keV)	Thorson and Katz[a] (γ,n) E (MeV)	Firk *et al.*[b] (γ,n) E (MeV)	Dodge and Barber[c] (γ,p) E (MeV)
19.80	50	19.9		
20.10	20	20.13		
20.35	30	20.29		
20.60	120	20.6		
20.90	150	20.9		
21.30	150	21.08, 21.22		21.2
21.65	150	21.58	21.7	
22.10	200	22.02	22.1	22.5
22.75	150	22.88	23.1	23.3
23.60	200		23.7	23.85
25.35	250		25.5	24.8
26.00	310			25.7
27.55	320		27.8	26.7
29.50	360			27.2, 27.9
32.70	250			
36.40	300			

[a] Reference 11.
[b] Reference 6.
[c] Reference 5.

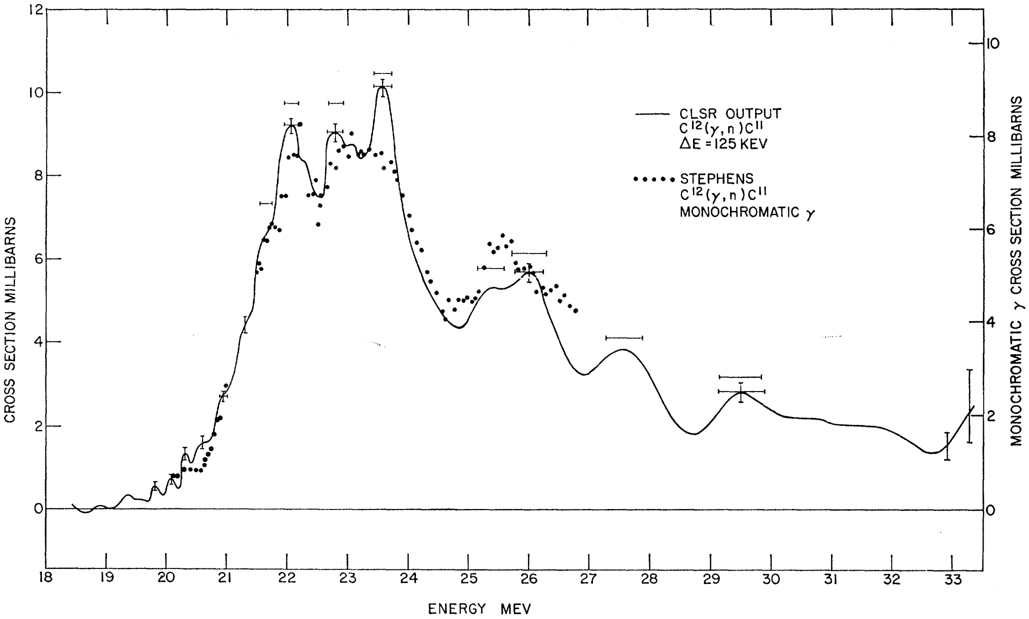

FIG. 1. Comparison of the present results for the $C^{12}(\gamma,n)C^{11}$ cross section with a recent monochromatic-γ-ray result. Error bars have the meaning given in the text in Sec. III. CLSR refers to the least-structure computer routine.

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[10] J. S. Pruitt and S. R. Domen, Natl. Bur. Std. Monograph 48, 1962.

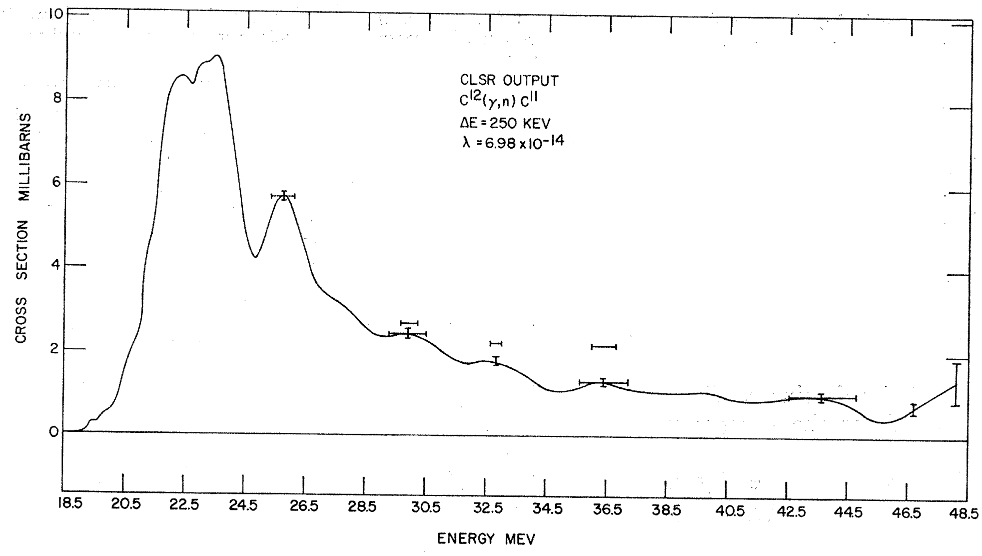

FIG. 2. $C^{12}(\gamma,n)C^{11}$ cross section derived from data taken in 250-keV intervals.

Figure 1 shows the cross section derived from the average yield curve with data taken in 125-keV intervals. The giant resonance is split into three major peaks at 22.1, 22.75, and 23.6 MeV. Numerous partially resolved peaks appear on the ascending side of the giant resonance. These are in close agreement with the breaks reported in the carbon (γ,n) yield curve by Thorson and Katz.[11] Three of the peaks (20.6, 20.9, and 21.3) also agree well with the (γ,p_0) work of Shin and Stephens[12] using monochromatic γ rays over a restricted energy range.

The recent monochromatic (γ,n) work of Lochstet and Stephens[13] has been superimposed on Fig. 1. Except for a difference in absolute scale, the general shape of each curve is quite similar. The dominant characteristic of both curves in the giant resonance is the dip at 22.5 MeV. The less prominent dip at 23.5 MeV in the present work is not found in the monochromatic gamma work but the shape in the latter curve is inconsistent with a single Lorentz shape, perhaps indicating further structure. The well-known structure near 26 MeV is clearly resolved in both curves.

Figure 2 shows the cross section derived from the average yield curve taken in 250-keV intervals to 48.25 MeV. The loss of resolution associated with the larger bin width eliminates all but the strongest structural features of the giant resonance. Two additional features appear at 32.7 and 36.5 MeV. It is emphasized

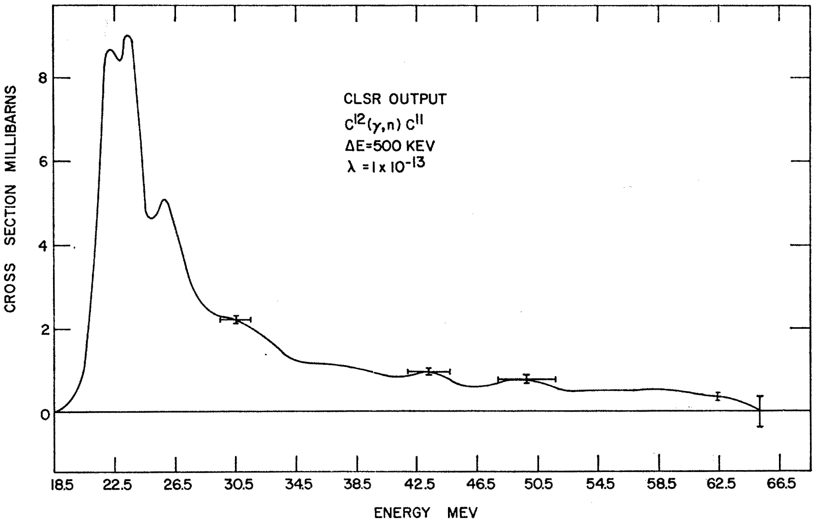

FIG. 3. $C^{12}(\gamma,n)C^{11}$ cross section derived from data taken in 500-keV intervals. No high-energy structure was observed.

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[11] I. M. Thorson and L. Katz, Proc. Phys. Soc. (London) **77**, 166 (1961).

[12] Y. M. Shin and W. E. Stephens, Phys. Rev. **136**, B660 (1964).

[13] W. A. Lochstet and W. E. Stephens, Phys. Rev. **141**, 1002 (1966).

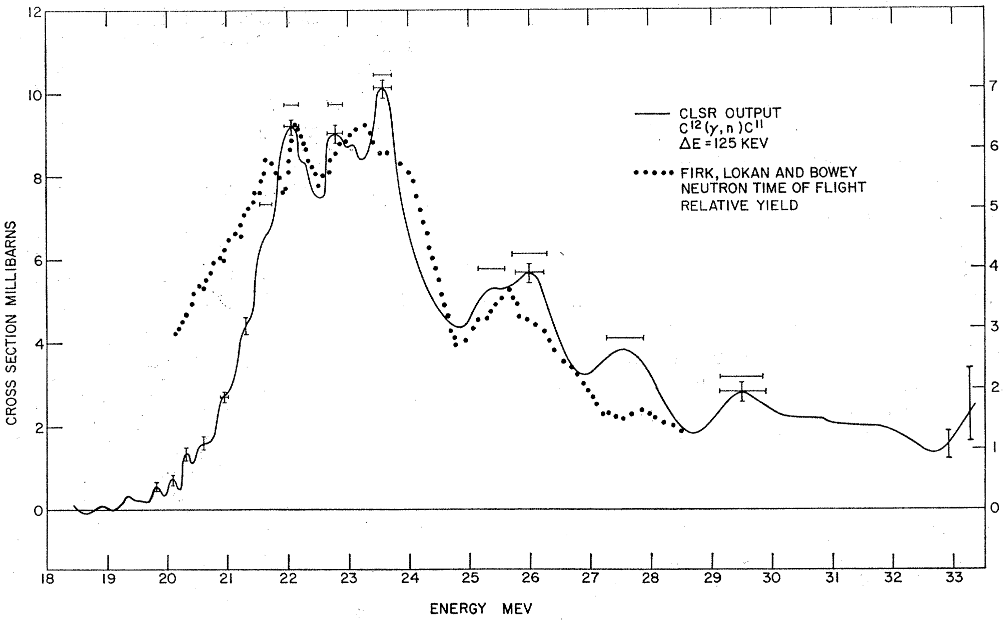

FIG. 4. Comparison of present work with neutron energy spectrum of Firk *et al.* The enhancement of the neutron spectrum at 21.7 MeV is probably due to an excited-state transition.

that the choice of character in the cross section considered to be true structure is based upon its reproducibility in the cross sections derived from individual yield curves. The structure at 32.7 MeV is in the region of a peak found by Reay, Hintz, and Lee[14] in a (p,γ) experiment on B^{11}.

Figure 3 displays the cross section derived from the average yield curve taken in 500-keV steps from 18.5 to 65.5 MeV. No structure appears in the cross section at higher energies in contrast to the result found in the $O^{16}(\gamma,n)O^{15}$ reaction.

The integrated cross section based on absolute calibration of the 50-MeV point is 77±6 MeV mb to 65 MeV. This is 23.4% of the classical sum-rule value, $60N(Z/A)=180$ Mev mb. The cross section integrated to 35 MeV is 56 MeV mb in good agreement with the recent NBS[15] value of 57.6 MeV mb. The cross section integrated between 20.5 and 26.5 MeV is 40.5 MeV mb in the present work and 33.0 MeV mb in Stephens monochromatic-photon measurement. The older value for the cross section integrated to 38 MeV obtained by Barber, George, and Reagan[16] using bremsstrahlung was 56±3 MeV mb compared to 59±5 MeV mb in this work. Thus, the 15–20% discrepancy between absolute cross sections measured using bremsstrahlung, and values measured using monochromatic photons, noted for the $O^{16}(\gamma,n)O^{15}$ cross section is also true for carbon.

IV. DISCUSSION

The experimental evidence in the giant resonance in carbon has presented a confused picture about possible structure. Measurements of photoneutron and photoproton energy distributions have shown definite structure usually attributed to transitions from the giant resonance, whereas $B^{11}(p,\gamma_0)C^{12}$ measurements show only one peak at 22.5 MeV with little evidence of structure in the giant resonance itself. The resolution of the (p,γ_0) experiments is sufficient to resolve all reported structure,[7] so that the differences are significant. In the interpretation of energy-distribution data, the unjustified assumption that only ground-state transitions to C^{11} or B^{11} occur has been made. A possible explanation for the discrepancy between the experiments is that all the observed structure in the energy distributions of photonucleons is due to non-ground-state transitions, and thus the giant resonance itself is structureless. In this experiment the total photoneutron cross section is measured in the giant resonance since the (γ,pn) threshold is at 27.4 MeV and the $(\gamma,2n)$ threshold is at 31.8 MeV. Thus, all structure in the cross section relates directly to states in C^{12} unambiguously.

Three partially resolved peaks corresponding to state at 22.1, 22.75, and 23.6 MeV are found. The strength of each transition is approximately equal and the integrated cross section over the three peaks amounts to 44% of the cross section integrated to 30 MeV. A comparison between the photoneutron-energy-distribution work of Firk, Lokan, and Bowey[6] and the present measurements is exhibited in Fig. 4. Four strong transitions are found in the photoneutron energy dis-

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[14] N. W. Reay, N. M. Hintz, and L. L. Lee, Nucl. Phys. **44**, 338 (1963).

[15] J. M. Wyckoff, B. Ziegler, H. W. Koch, and R. Uhlig, Phys. Rev. **137**, B576 (1965).

[16] W. C. Barber, W. D. George, and D. D. Reagan, Phys. Rev. **98**, 73 (1955).

tributions, corresponding to four states in C^{12} if only ground-state transitions are involved. However, in C^{11} there is a known state at 2 MeV as well as many more highly excited states. The transition interpreted as a state at 21.7 MeV by Firk is considerably enhanced over a weak transition which appears in our work at that energy. The enhancement of the photoneutron peak is probably due to a transition from the 23.6-MeV state in C^{12} to the 2-MeV state in C^{11}. While a transition corresponding to a state at 23.7 MeV is reported by Firk, this transition is less prominent in the photoneutron energy distribution than in the cross section measured here. Although it is difficult to assess the background of neutrons in the energy distribution, if a reasonable choice is made for the background and the excess of photoneutrons in the 21.7-MeV peak is placed in the 23.6-MeV region, the two curves will be quite similar.

In the $C^{12}(\gamma,p)B^{11}$ photoproton energy distributions of Dodge and Barber[5] peaks are reported as levels at 22.5, 23.3, and 23.85 MeV in C^{12}. As in the photoneutron experiment, excited-state transitions to the 2.14-MeV level in B^{11} should be possible. However, no evidence for an excited-state transition from the reported 23.85 MeV is seen, although many more low-energy protons are seen than would be expected if the total cross section for photoabsorption followed the photoneutron cross section. This excess of low-energy photoprotons may represent excited-state transitions from giant resonance states in C^{12}, although other possibilities exist. While three peaks appear in the photoproton energy distribution, as well as in the photoneutron cross section, the energy is displaced by about 300 keV. Thus, the minimum at 22.5 MeV in the photoneutron cross section coincides with a maximum in the photoproton cross section. Although a shift in energy scales of this magnitude is difficult to envision, especially since comparisons of peak energies in O^{16} agree, differences in energy scales are still common occurrences in experiments at these energies. Thus, possible differences between (γ,n) and (γ,p) reactions in carbon should still be considered to be an unresolved experimental question.

This experiment shows that the difference between (p,γ_0) and all direct methods of studying the photonuclear cross section of C^{12} is real. Microscopic reversibility relates the $B^{11}(p,\gamma_0)C^{12}$ cross section to the partial cross section for $C^{12}(\gamma,p)B^{11}$, with B^{11} in its ground state. Thus, the partial cross section studied by the inverse reaction seems to be too specialized to give all structure of the carbon nucleus which can be excited by photons.

The Argonne group[17] and Tanner[18] have recently proposed, on the basis of the angular distributions of the (p,γ_0) reactions, that the giant resonance is a single broad state modulated by residual interactions in carbon and split into individual peaks in other nuclei such as O^{16}, Si^{28}, and S^{32}. On this basis the particle-hole model is dismissed, since it predicts differing photoproton angular distributions for the differing resonances. While it is clear that many nuclei have more structure than predicted by the particle-hole model, so that the model is certainly incomplete, until photonucleon angular distributions for all resonances observed in photoexcitation in the giant resonance have been measured, the particle-hole model should not be dismissed.

Theoretical predictions of the energies and transition probabilities for the 1^- $T=1$ states of the giant resonance in C^{12} have been made using the particle-hole model of the nucleus. Vinh Mau and Brown[8] give results using *j-j* coupling of nucleons in a spherical potential, while Nash[9] has assumed $SU(3)$ coupling for the nucleons. Nilsson, Sawicki, and Glendenning[19] have made calculations assuming carbon to be an oblate spheroid. The predicted energies and strengths for the dipole transitions for these calculations are given in Table II, together with the experimental energy values.

In *j-j* coupling the giant resonance would be one level near 22.2 MeV while experimentally the giant resonance has considerable structure. In a spheroidal nucleus $E1$ transitions to states corresponding to rotational bands with intrinsic quantum number $K=0$ and $K=1$ are possible. Thus many more transitions are involved in these cases. In particular, three strong transitions at 22.2, 23.0, and 23.7 MeV are predicted in this model.[19] These correspond quite closely to the observed energies in the giant resonance, however, until the spins and parities of these levels are known such identification of experimentally observed levels with theoretical levels should be considered as suggestive only. The $SU(3)$ coupling model[9] gives only one $K=1$ state in the giant resonance with two $K=0$ states at higher energy. Although this level scheme does not fit the experimental levels perhaps a refinement of the calculations will move the energies closer together and preserve the triplet nature of the giant resonance.

The structure above the giant resonance near 25.5 MeV found in this work has been seen in all high-resolution work extending to this energy. In the present work the structure is resolved into two peaks at 25.35 MeV and 26.0 MeV. Dodge and Barber report fine structure at 8.9- and 9.7-MeV proton energy corresponding to 25.7 and 26.5 MeV in C^{12}. The calculations of Nilsson *et al.* have two strong $E1$ transitions at 24.7 and 26.3 MeV in reasonable agreement with our results.

One feature of all calculations made to date is the strong $E1$ absorption in the 30–50-MeV region corresponding to a $1s_{1/2}$ to $1p_{1/2}$ transition in the *j-j* coupling model. Reay[14] has reported a weak transition in the (p,γ_0) reaction at 34.5 MeV but since many channels are possible at this relatively high energy the total strength could be much stronger than found in that

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[17] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, R. E. Segel, P. P. Singh, and Z. Vager, Phys. Rev. Letters **13**, 628 (1964).

[18] N. W. Tanner, Nucl. Phys. **63**, 383 (1965).

[19] S. G. Nilsson, J. Sawicki, and N. K. Glendenning, Nucl. Phys. **33**, 239 (1961).

TABLE II. Comparison of the results of this work with the predictions of the particle-hole model. By "strength" is meant the square of the dipole operator matrix element with no energy factors. In the last column M^2 is the matrix element squared as described in Ref. 19.

Present work	Vinh Mau and Brown[a]		%		Nash[b]	%		Nilsson *et al.*[c]	
E (MeV)	$J\pi$, T	E (MeV)	strength	K	E (MeV)	strength	K	E (MeV)	M^2
19.80	1^-, 1	18.7	6.5				1	19.74	0.08
20.10									
20.35									
20.60									
20.90							0	20.85	0.08
21.30									
21.65									
22.10	1^{-1}, 1	22.2	75	1	22	33	1	22.21	3.66
22.75							1	22.97	1.08
23.60	1^{-1}, 1	23.9	0.5				0	23.74	1.08
25.35							1	24.7	1.04
26.00							0	26.31	1.26
27.55				0	28	27			
29.50							1	29.5	1.04
32.70	1^{-1}, 1	34.3	18				0	31.91	3.52
36.40				0	38	40			

[a] Reference 8.
[b] Reference 9.
[c] Reference 19.

work. In the (γ,n) cross section a small reproducible increase in cross section is found near 32.7 MeV, but no prominent structure appears. Although this energy is above the (γ,pn) threshold by about 5 MeV the (γ,n) cross section still has reasonable magnitude and should be representative of the total absorption in this region. Thus no evidence for a sharply defined $1s_{1/2}-1p_{1/2}$ transition is found.

V. SUMMARY

The giant resonance is split into at least three partially resolved states separated by about 800 keV. Thus the differences between the evidence given by $B^{11}(p,\gamma_0)C^{12}$ and direct methods for studying states reached in C^{12} by photon transitions are real.

A comparison of neutron energy spectra with cross-section measurements shows that excited-state transitions are quite strong. Thus, extreme caution must be taken to identify neutron groups with states in the excited nucleus.

No evidence for large dipole oscillator strength near 35 MeV was found.

In marked contrast to O^{16} no structure was found in the $C^{12}(\gamma,n)C^{11}$ cross section above 40 MeV.

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