Photoneutron cross sections for ^{13}C

J. W. Jury,* B. L. Berman, D. D. Faul, P. Meyer, K. G. McNeill,† and J. G. Woodworth
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
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The photoneutron cross sections for ^{13}C have been measured from near threshold to over 40 MeV using monoenergetic photons from positron in-flight annihilation. Several sharp features below the giant resonance were distinguished. The results both for this "pygmy-resonance" region and for the giant resonance near 24 MeV differ markedly from previously reported measurements and provide a much better quantitative comparison with recent theoretical calculations of the photoneutron reaction in ^{13}C. Comparison of the measured total photoneutron cross section with recent data on the ground-state photoreaction and with average photoneutron energies provides evidence for the isospin splitting of the giant resonance for this nucleus.

[NUCLEAR REACTIONS: $^{13}C(\gamma,n)$, $E_\gamma=7.6-41.8$ MeV; measured 4π neutron yield for monoenergetic photons; $\sigma(E_\gamma,1n)$, $\sigma(E_\gamma,2n)$, integrated cross sections, isospin splitting of the giant resonance.]

I. INTRODUCTION

An interesting phenomenon has been observed in studies of the nuclear photoeffect in light nuclei having one or two nucleons outside closed ($4N$) shells. In several cases, such as ^{13}C, ^{17}O, and ^{18}O, the giant dipole resonance (GDR) is observed to be accompanied by a "pygmy" resonance at lower energy which in turn contains many narrow resonances suggestive of single-particle transitions. Another paper in this series[1] reports on the measurement of the photonuclear cross sections for ^{18}O, and a third paper[2] describes a measurement of the differential ground-state photoneutron cross section for ^{17}O. Other measurements reported over the last three years (Refs. 3–8) have employed a variety of techniques to study the photoreactions in ^{13}C and ^{13}N.

New theoretical studies on the photodisintegration of ^{13}C also have been reported recently (Refs. 9–12). These calculations, using bound-state and continuum shell-model and R-matrix theory, have predicted both total and partial photodisintegration cross sections. Comparison of these theoretical predictions of the structure in the pygmy and giant resonances in the photoneutron cross section of ^{13}C with older (γ,n) measurements (Refs. 13–16) is difficult because these older measurements were made with low resolution or spanned limited energy ranges. The recent experimental results by Koch and Thies[5] can be compared with the predictions of these calculations. However, agreement is generally poor and appears to be significantly worse than that resulting from the comparison of the partial cross sections (γ,n_0) and (γ,n_1) measured by Woodworth *et al.*[3] Also, the sum of these measured partial cross sections (corrected for angular-distribution effects) is nearly a factor of two larger in the region of the pygmy resonance than the result of Koch and Thies.[5] The measurement reported here was carried out in order to satisfy the clear need for an accurate, high-resolution measurement which extends from threshold to well beyond the giant resonance, and which can shed more light upon the phonomenon of isospin splitting of the GDR in light $(4N+1)$ nuclei.

A high-resolution measurement of the total photoneutron cross section for ^{13}C extending up to 40 MeV allows a comparison with the ground-state measurement of Woodworth *et al.*[4] In the region from threshold (4.95 MeV; see Table I) to 9.38 MeV, where neutron transitions to the ground state only of the ^{12}C daughter nucleus can occur, the two measurements should agree. Since the ground state of ^{13}C has isospin $T=\frac{1}{2}$, $E1$ photoexcitation leads to $T=\frac{1}{2}$ or $\frac{3}{2}$ states. In the absence of isospin mixing, neutron decay to the

TABLE I. Photonuclear thresholds for ^{13}C.[a]

Reaction	Threshold energy (MeV)
$^{13}C(\gamma,n)$	4.946
$^{13}C(\gamma,\alpha n)$	12.313
$^{13}C(\gamma,p)$	17.534
$^{13}C(\gamma,pn)$	20.903
$^{13}C(\gamma,2n)$	23.668
$^{13}C(\gamma,3n)$	36.792

[a] From Ref. 17.

$T=0$ ground state of ^{12}C can proceed only from $T=\frac{1}{2}$ states. Thus, at higher energies a comparison of the total photoneutron cross section with the ground-state data can help to determine the distribution of the $T=\frac{1}{2}$ and $T=\frac{3}{2}$ strength for this nucleus.

II. EXPERIMENTAL PROCEDURE

A detailed description of the experimental procedure used in the present experiment is given in Ref. 18; additional information can be found in reports of earlier work done at Livermore.[19-22] Only the main features of the experimental procedures are presented here. The 120-MeV electron beam from the Lawrence Livermore Laboratory Electron-Positron Linear Accelerator was incident upon a tungsten-rhenium converter target from which resulting positrons were collected, focused, and energy selected with a momentum resolution of $\leq 1\%$. The positron beam was directed upon a 0.76-mm thick beryllium annihilation target, where both annihilation photons and bremsstrahlung radiation were produced. A sweeping magnet then removed the remaining positrons from the photon beam and deflected them into a shielded 5-m deep beam dump. The photon energy resolution varied from less than 150 keV at the lowest energies to about 450 keV at the highest.

The photon beam passed through a calibrated transmission ion chamber (which served as the photon flux monitor) and was incident upon the photonuclear sample which was positioned at the center of the 4π neutron detector. This detector consisted of a 0.61-m cube of paraffin containing 48 high-pressure BF_3 tubes arranged in four concentric rings of twelve tubes each. Because of neutron moderation in the paraffin, the ratio of neutron counts recorded for the outer ring to those for the inner ring (the ring ratio) gives a measure of the average neutron energy (and hence the detector efficiency) for each data point.

The ^{13}C sample consisted of a 25.4-mm diameter cylinder of pressed elemental carbon powder, enriched to 95.9% of the ^{13}C isotope, and was packaged in a thin-walled Lucite container. The data-collection procedure involved the sequential measurement of photoneutrons from samples of ^{13}C, ^{17}O, ^{18}O, and an empty sample container. At every second energy, a measurement was made with the annihilation target removed and the ^{13}C sample in place to record backgrounds. In order to subtract the yield of photoneutrons produced by the positron bremsstrahlung, the measurements were repeated using electron instead of positron beams (see Ref. 18). A multiplicity analysis of these data enabled the $(\gamma,1n)$ and $(\gamma,2n)$ cross sections to be extracted simultaneously and independently.

III. DATA ANALYSIS AND UNCERTAINTIES

Details of the data-reduction procedure to extract $(\gamma,1n)$ and $(\gamma,2n)$ cross sections from the raw neutron-event data are thoroughly described in Ref. 18. A brief summary of the various steps in the analysis is presented here along with the estimated uncertainty introduced at each phase.

Initially, the recorded neutron events were corrected for pileup of counts in the detector. Because the counting rates were always kept low ($<1\%$), the uncertainty in this correction was negligible.

Following this, neutron and ion-chamber backgrounds (1% and 10% respectively) were subtracted for both the positron and electron measurements. Because these backgrounds were measured with very high precision, uncertainty in this procedure also was negligible.

Since the energy distribution of the annihilation-plus-bremsstrahlung radiation differs from purely bremsstrahlung photons, a measured correction was applied to the ion-chamber response to normalize electron and positron data. The uncertainty in this correction was never greater than 4%.

Normalized electron-run data were subtracted from the positron-run data. Uncertainties in this subtraction are negligible except perhaps at the very highest energies measured.

Measured sample-blank backgrounds were then subtracted from the ^{13}C-plus-sample-holder data. The maximum contribution from the Lucite sample holder was about 40% but was typically much less. The estimated uncertainty resulting from this subtraction does not exceed 2%.

After a correction for neutron multiplicity in each ring (which introduced negligible uncertainty), the data were corrected for the efficiency of the neutron detector using ring-ratio information discussed above. The uncertainty introduced by this procedure varied from an estimated 2% at low neutron energies to about 10% at the highest energies.

Finally, the data were converted to cross sections by applying the measured ion-chamber response per photon and the known number of ^{13}C nuclei in the beam. The uncertainty in the photon-flux calibration is about 6% below 30 MeV and slightly larger at higher energies.

IV. RESULTS AND DISCUSSION

The photoneutron cross sections measured in this experiment are shown in Fig. 1: Part (a)

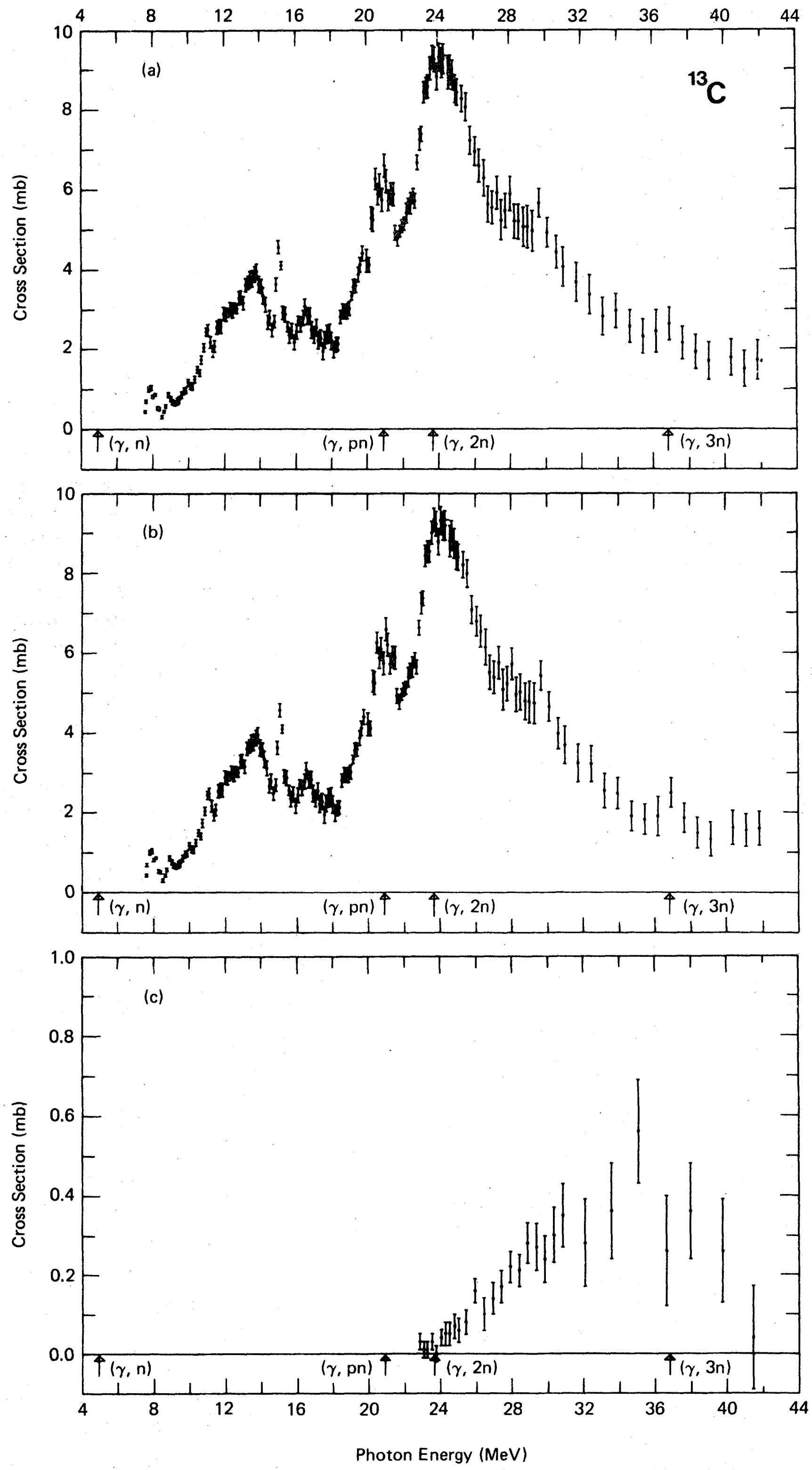

FIG. 1. Photoneutron cross sections for ^{13}C. Part (a) shows the total photoneutron cross section $\sigma[(\gamma,n)+(\gamma,pn)+(\gamma,\alpha n)+(\gamma,2n)]$, part (b) shows the single photoneutron cross section $\sigma[(\gamma,n)+(\gamma,pn)+(\gamma,\alpha n)]$, and part (c) shows $\sigma(\gamma,2n)$. The plotted error bars reflect the statistical uncertainties only.

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The integrated photoneutron cross sections and their moments are given in Table II. In the data from the present experiment, there is a relatively large uncertainty in the $(\gamma,1n)$ cross section at energies above about 30 MeV. However, this does not contribute very heavily to the uncertainty for the integrated cross sections. Moreover, the systematic uncertainty in the $(\gamma,2n)$ cross section of this experiment is considerably less than in the $(\gamma,1n)$ cross section (because of the near absence of backgrounds, including that caused by positron bremsstrahlung, in the doubles data), but, of course, the statistical uncertainties are larger. The overall uncertainty to be attached to the values given in Table II should not exceed 10%. Thus, the fraction of the Thomas-Reiche-Kuhn (TRK) sum rule exhausted by the photoneutron channels up to 41.8 MeV is $65\pm6\%$.

The discussion of the interesting features of the cross section can be divided into the consideration of three energy regions, as follows.

A. The region below the giant resonance (7 to 19 MeV)

Here the cross section results entirely from (γ,n) reactions, since the thresholds for the (γ,pn) and $(\gamma,2n)$ reactions are at 20.9 and 23.7 MeV, respectively (see Table I). The resolution of this experiment was sufficient to distinguish several narrow peaks in this region which appear to be superimposed on the pygmy resonance. Most noticeable is a sharp feature at 15.1 MeV, which is the first $T=\frac{3}{2}$ ($J^\pi=\frac{3}{2}^-$) state in ^{13}C, (Ref. 23). The natural width is believed to be only 5 keV, whereas the data indicate a full width at half maximum (FWHM) of nearly 240 keV, thus yielding the effective experimental resolution at this energy. This state was observed only weakly in the ground-state differential cross section (at 98°) measured by Woodworth *et al.*[3] but it did appear in their measured cross section to the first excited state (at 4.43 MeV) in ^{12}C. Through isospin mixing of the dominant $T=\frac{3}{2}$ component with a finite $T=\frac{1}{2}$ component, this state can decay either to the ground state or to the first excited state of ^{12}C. It had been shown previously[24] that the branch which populates the first excited state is the larger. This is confirmed by

TABLE II. Integrated cross sections for ^{13}C.[a]

Reaction	$\sigma_{int}=\int\sigma\,dE$ (MeV mb)	$\sigma_{-1}=\int\sigma E^{-1}dE$ (mb)	$\sigma_{-2}=\int\sigma E^{-2}dE$ (mb MeV^{-1})
(γ,n)	121.3	5.58	0.301
$(\gamma,2n)$	4.7	0.14	0.004
(γ,n_{tot})	126.1[b]	5.72	0.306

[a] From threshold to $E_{\gamma\,max}=41.8$ MeV.
[b] TRK sum rule is $60NZ/A=193.8$ MeV mb.

the average neutron energy data of the present experiment, shown in Fig. 2. Here a sharp dip in the average energy of the emitted neutrons is observed at 15.1 MeV. This change in energy by about 4 MeV, from the nearby average of 8 MeV, suggests strongly that neutron decays from this state proceed mainly to the first excited state of ^{12}C. The measured amplitude of 5.4 ± 0.2 mb of this peak agrees well with the (higher resolution) 6.5 ± 0.8 mb result at Woodworth *et al.*[3] obtained by adding the ground- and first-excited-state cross sections. Area analysis of this peak yields a value for the ground-state γ-ray width $\Gamma_{\gamma_0}=19.7\pm2.0$ eV, in reasonable agreement with the value of 23.3 ± 2.7 eV from Ref. 23.

For energies below 9.38 MeV, the entire cross section should result in decay to the ground state of ^{12}C. Thus, a direct comparison with the recent (γ,n_0) measurement of Woodworth *et al.*[4] is possible, and this is shown in Fig. 3. The excellent agreement between the two results (except for resolution effects), one obtained using monoenergetic photons and a 4π detector and the other (Woodworth *et al.*[4]) employing bremsstrahlung and measuring photoneutron angular distributions,

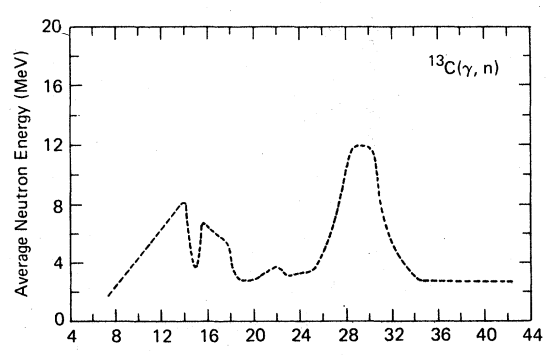

FIG. 2. Average neutron energy vs photon energy for ^{13}C, obtained directly for each data point by the ring-ratio technique (see text). In addition to the nuclear information contained in this plot, the efficiency of the neutron detector is determined for each data point.

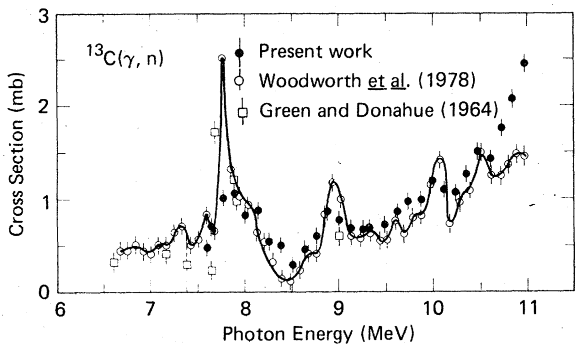

FIG. 3. Comparison of the present results for the $^{13}C(\gamma,n)$ cross section at low energies (solid circles) with those obtained from the ground-state angular-distribution experiment of Ref. 4 (open circles and line). Below 9.38 MeV (the threshold for photoneutron emission to the first excited state of ^{12}C), the two results should be identical (except for resolution effects). The data of Ref. 14 also are shown (as squares) at several discrete energies.

confirms the accuracy of these two independent measurements. The data of Green and Donahue[14] also are shown; they agree with both sets of results. It should be noted as well that the magnitudes of the ground-state and total photoneutron cross sections are essentially the same up to at least 10.5 MeV, thus demonstrating that the magnitude of the $^{13}C(\gamma,n_1)$ cross section is very small in this energy interval.

Other peaks superimposed on the pygmy resonance are observed at 11.0, 13.8, 16.5, and 17.8 MeV. A dip at 11.74 MeV was seen by Measday *et al.*,[25] who measured the differential (p,γ_o) cross section to ^{13}N. They interpreted this dip as an interference effect (a $\frac{3}{2}^+$ level interfering with the predominant $\frac{3}{2}^+$ pygmy resonance). In the present results, no evidence of an interference minimum is found.

B. The giant-resonance region (19 to 30 MeV)

The data of Fig. 2 show a sudden drop of the average neutron energy at about 19 MeV to low values, which persist over the maximum of the giant resonance. This indicates that the GDR of ^{13}C decays predominantly by low-energy neutron emission, leaving the ^{12}C daughter nucleus in highly excited states. The absence in this energy region of any appreciable strength in the ground-state cross section of Woodworth *et al.*[3] suggests that the major part of the giant resonance is of a $T=\frac{3}{2}$ $(T_>)$ nature which decays by allowed neutron transitions to the (highly excited) $T=1$ states in ^{12}C. (The first such state is at 15.1 MeV.)

On either side of the central peak of the giant resonance (Fig. 1) are seen "shoulder" resonances, one at 20.8 MeV and one at about 30 MeV. Some evidence for the former peak is observed in the ground- and first-excited-state measurements of Woodworth *et al.*,[3] and their estimated total cross section is less than 4 mb, whereas here it is about 6.5 mb. This difference, together with the low average neutron energy over this peak, shows that there is substantial decay to highly excited states in ^{12}C, which might indicate the presence of some $T_>$ strength in this shoulder. The shoulder at 30 MeV yields a much higher value for the average neutron energy, showing that here, too, a significant portion of the decays are taking place to the ground or low-lying $(T=0)$ states in ^{12}C, and thus that appreciable $T=\frac{1}{2}$ strength still is present at this energy. Additional evidence supporting this interpretation of the data is the ground-plus-first-excited-state value of 2 mb here, which is approximately 40% of the value measured in this experiment.

C. The region above the giant resonance (30 to 42 MeV)

There is some evidence for a weak resonance at about 37 MeV superimposed on the high-energy tail of the GDR. A broad peak near this energy also is present in the $(\gamma,2n)$ data. The average neutron energy here is quite low, probably indicating $T=\frac{3}{2}$ strength which decays to $T=1$ states in ^{12}C. This might be the predicted $1s\to 1p$ nucleon excitation of the core, which has been calculated[12] to lie at about 33 MeV in ^{13}C and for which some evidence exists (at 36 MeV) in the results of Fultz *et al.*[26] for ^{12}C. If so, this would indicate that single-particle transitions from deep core states are little affected by the presence of an extra-core nucleon.

V. COMPARISON WITH OTHER MEASUREMENTS

It is of interest to compare the (γ,n_{tot}) cross section of the present measurement with the work of others. Figure 4 (a) shows this comparison with the recent bremsstrahlung yield work of Koch and Thies.[5] Although there is reasonable agreement with the energies of most of the major features of the cross section, the magnitude of their results is not borne out by the present data. Figure 4(b) compares the present results with the data (also obtained with bremsstrahlung) of McKenzie.[6] Here the agreement might be somewhat better for the magnitude, but is somewhat worse for the energy dependence of the cross section than for Ref. 5. Both these results, however, seem to be inadequate in the GDR itself; the data of Ref. 4, in fact, show a deep valley at about 25 MeV which is not observed in

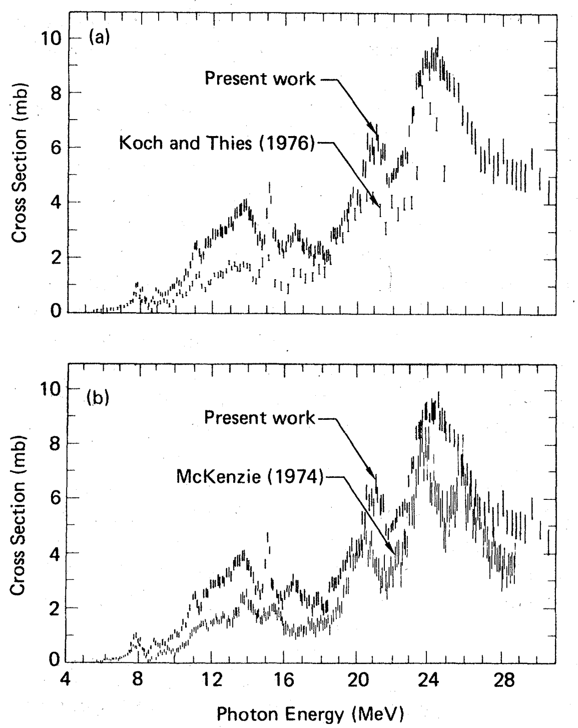

FIG. 4. Comparison of the present results for the $^{13}C(\gamma,n_{tot})$ cross section with those obtained from bremsstrahlung yield experiments. Part (a) shows the results of Ref. 5 and part (b) shows the results of Ref. 6.

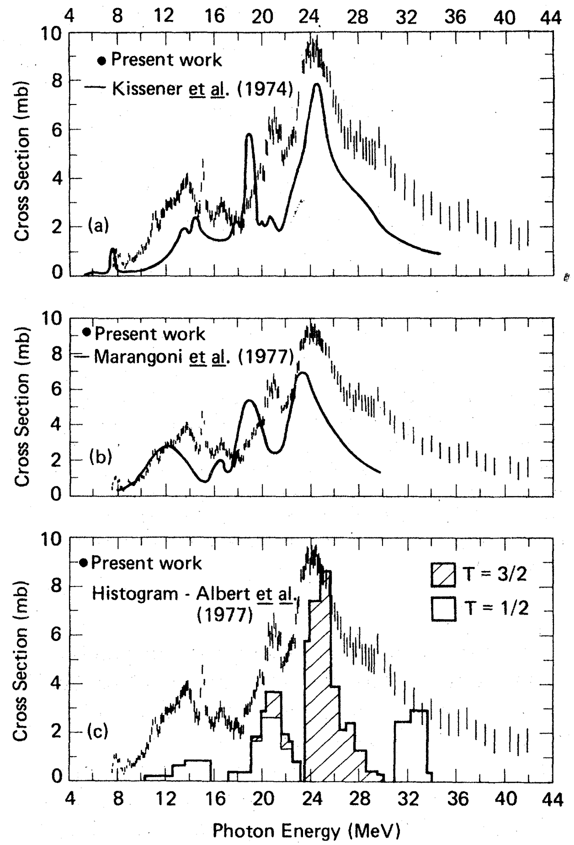

FIG. 5. Comparison of the $^{13}C(\gamma,n_{tot})$ cross section with theoretical predictions. Part (a) shows the prediction of Ref. 9, part (b) shows the prediction of Ref. 11, and part (c) shows that prediction of Ref. 12 which makes use of the Soper interaction.

the results of the present experiment.

Information on the structure of the electromagnetic strength for ^{13}C also can be obtained from the inelastic electron-scattering results of Bergstrom *et al.*[27] Their results, particularly for the case of low incident electron energy and forward angle (low momentum transfer), agree very well with the present results with regard to both magnitude and features.

VI. COMPARISON WITH THEORY

The present results are compared with recent theoretical calculations in Fig. 5. The agreement with the calculated cross section by Kissener *et al.*[9] [Fig. 5 (a)] is generally quite good (allowing for a reduction factor of 0.4 applied to the calculated values), suggesting that the various residual interactions and configuration spaces used by Kissener *et al.* are good approximations. Their calculation of isospin splitting, with concentrations of $T_<$ strength near 14 and 20 MeV and $T_>$ strength above 21 MeV, also seems to be in agreement with the present measurement. A comparison of their calculated integrated strengths for various regions of the photoneutron cross section is given in Table III. Good agreement is apparent at the lower energies, but this theoretical treatment overestimates the photoneutron strength in the giant-resonance region and above by about 60%.

Also presented in Table III are the theoretical results of Marangoni *et al.*[11] as well as corresponding measurements from other experiments. It should be noted that the theoretical calculations are presented here for the (γ,n) reaction, whereas the experimental measurements represent the sum $[(\gamma,n)+(\gamma,2n)+(\gamma,3n)+(\gamma,pn)+(\gamma,\alpha n)]$. However, the results of the present experiment show that the $(\gamma,2n)$ integrated cross section is small (3.9 MeV mb up to 38 MeV) and the $(\gamma,3n)$ integrated cross section is essentially zero up to 42 MeV. Also, Kissener *et al.* have stated that the (γ,pn) channel should not compete seriously with the single-nucleon channels, and it is reasonable to assume that the $(\gamma,\alpha n)$ integrated cross section does not contribute significantly to the $(\gamma,1n)$ cross section measured here. It should be noted that the value of 20 MeV mb for

TABLE III. Comparisons of integrated photoneutron cross sections for ^{13}C.

Energy interval (MeV)	Present results (MeV mb)	Kissener *et al.* [a] (MeV mb)	Marangoni *et al.* [b] (MeV mb)	Other experiments (MeV mb)
5–10	2.4	1		2 [c]
10–14	10.6	10		14 [c]
5–17	21.8	22		20, [d] 22 [e]
17–38	97.7	158		95 [e]
5–42	126.1		157	

[a] Reference 9.
[b] Reference 11.
[c] Fukuda, Ref. 15.
[d] Bergstrom *et al.*, Ref. 27.
[e] Cook, Ref. 13.

the photoabsorption cross section integrated from 5 to 17 MeV which was derived from the electron-scattering data of Ref. 27 can be ascribed entirely to the (γ,n) reaction, since the (γ,p) threshold lies above this energy (at 17.5 MeV). Finally, the value of 157 MeV mb attributed to Marangoni *et al.* has been deduced by multiplying their value of 267 MeV mb for the total dipole sum by the ratio of their truncated value for the (γ,n) channel (71 MeV mb) to that for the sum of the (γ,n) and (γ,p) (71 + 50 MeV mb) channels.

In Fig. 5(b) the present results for $\sigma(\gamma,n_{tot})$ are compared with the recent two-particle–one-hole continuum shell-model calculation of Marangoni *et al.*[10,11] Here the theoretical results provide a better description of the location and strength of the pygmy resonance than does the Kissener work. Perhaps this better agreement arises because Marangoni *et al.* have analyzed their theoretical partial cross sections for the (γ,n) reaction to deduce that the pygmy and 20.5-MeV resonances decay by neutron emission to the ground and first excited states of ^{12}C with the ground-state transition being the stronger of the two. This is in disagreement with the calculation of Kissener *et al.*, but is observed in the work of Woodworth *et al.*[3] However, unlike those of Kissener *et al.*, the predictions of Marangoni *et al.* for the positions of the peak of the giant resonance and the peak at 20.5 MeV are low by about 1 MeV. There is no theoretical prediction for the second peak in the giant resonance observed in the experiment of McKenzie[6] at about 26 MeV (and not observed here).

It also is instructive to compare the present results with the recent theoretical predictions of the photonuclear cross sections by Albert *et al.*,[12] who performed a two-particle–one-hole shell-model calculation with $E1$ and $M2$ absorption, Their predictions which use a zero-range Soper mixture are shown in Fig. 5(c) in the form of a histogram. This calculation is in substantially better agreement with the data from the present experiment than is their other calculation, which uses the Tabakin interaction. Also, their assignments of $T=\frac{3}{2}$ strength are in reasonable agreement with the results of the discussion in Sec. IV above. The calculated peak above 30 MeV results from the $(1s_{1/2})^{-1}$ configuration and their prediction that this strength lies near 32.5 MeV is in reasonable agreement with the interpretation, presented above, that the weak structure at 36 MeV in the experimental results might reflect excitation from deep-lying $1s_{1/2}$ states in the nuclear core.

The first moment of the integrated cross section can be decomposed into its isospin components, defined as

$$\sigma_{-1}(T)=\int\sigma(T)E^{-1}dE\ .$$

O'Connell[28] has shown that an isospin sum rule can be written as

$$\sigma_{-1}(\tfrac{1}{2})-\tfrac{1}{2}\sigma_{-1}(\tfrac{3}{2})=\frac{\pi^2e^2}{3\hbar c}\left(N\langle R_n^{\,2}\rangle-Z\langle R_p^{\,2}\rangle\right),$$

where $\langle R_n^2\rangle$ and $\langle R_p^2\rangle$ are the mean-square neutron and proton distribution radii, respectively. Assuming that $R_n=R_p$ and using the electron-

TABLE IV. Isospin sum-rule comparisons for ^{13}C.

Reference	$[\sigma_{-1}(\frac{1}{2})-0.5\sigma_{-1}(\frac{3}{2})]$ (mb)
Present (γ,n) work plus (γ,p) work of Cook, Ref. 13	1.2 ± 0.2 [a]
Albert *et al.*, Ref. 12	
Soper interaction	1.12
Tabakin interaction	0.86
Marangoni *et al.*, Ref. 11	1.78

[a] See text.

scattering value[29] of 2.36 fm for the charge radius R_p, the right-hand side of this equation can be evaluated[28] to give 1.34 mb. Table IV presents experimental values for $\sigma_{-1}(\frac{1}{2}) - \frac{1}{2}\sigma_{-1}(\frac{3}{2})$ obtained by adding to the (γ,n) results of the present experiment the (γ,p) data of Cook,[13] assuming as an approximation pure $T=\frac{1}{2}$ strength below 21.7 ± 0.5 MeV and pure $T=\frac{3}{2}$ strength above this energy (21.7 MeV is the location of the deep minimum in the measured cross section). Also shown in Table IV are the results of the sum-rule calculations of Maragoni *et al.*[11] and Albert *et al.*[12] The measured value again favors the calculation of Albert *et al.* which uses the Soper interaction over that which uses the Tabakin interaction.

VII. COMPARISON WITH THE ^{12}C CROSS SECTION

Finally, it is of interest to compare the (γ,n_{tot}) cross section for ^{13}C with the results for ^{12}C of Fultz *et al.*[26]; this is seen in Fig. 6. The difference between these two cross sections must come about from the presence of the extra neutron added to the ^{12}C nucleus. The main features of the difference are most noticeable below the giant resonance, where the pygmy resonance and the peak at 20.5 MeV are evident. However, the main strength of the giant resonances appears to lie at about the same energy ($E_\gamma \approx 24$ MeV). In addition, the weak peaks at about 30 and 36 MeV have their counterparts at nearly the same energies in ^{12}C, perhaps indicating the common influence of deep-lying shell configurations on the photoabsorption process.

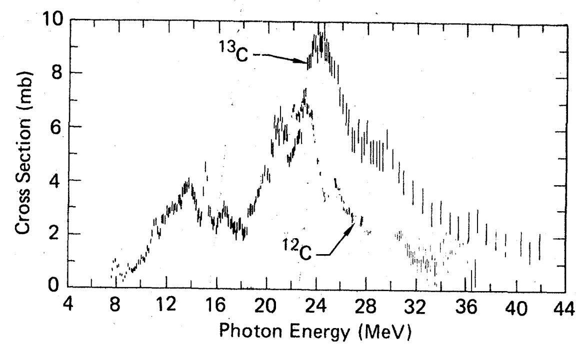

FIG. 6. Comparison of the ^{13}C(γ,n_{tot}) cross section with the ^{12}C(γ,n_{tot}) cross section of Ref. 26.

The effect of the extra neutron, manifested perhaps as core polarization, is well treated by a theory (Kissener *et al.*) using a ^{13}C ground state with a 73% $P^1_{1/2}$ and 26% $P^{-2}_{3/2}\,P^3_{1/2}$ configuration which predicts, correctly, large $P_{3/2} \to d_{5/2}$ transition amplitudes up to 30 MeV. Valence neutron excitations of the form $P_{1/2} \to d_{3/2}$ are found at lower energies and appear to make up a substantial part of the pygmy resonance.

A shoulder at about 30 MeV is characterized by a substantial peak in the average energy of the emitted photoneutrons, and hence probably represents $T_<$ strength. If so, this would be the first time that $T_<$ strength has been found above the GDR.

Finally, some evidence is seen for a possible transition from a deep-lying $s_{1/2}$ core state at about 36 MeV, which might be the same effect as seen in the ^{12}C$(p,\gamma)^{13}$N reaction at 33 MeV and the ^{12}C$(\gamma,n)^{11}$C reaction at 35 MeV. If so, this might be a core-excitation effect relatively unaffected by the presence of an additional nucleon.

VIII. CONCLUSIONS

The photoneutron cross sections for ^{13}C obtained in this experiment have improved upon the existing measurements to a point where quantitative comparison with the results of theoretical calculations can be made with confidence. The agreement with features of the work of Kissener *et al.*,[9] Marangoni *et al.*,[10,11] and Albert *et al.*[12] generally is quite good, confirming the isospin splitting of the ^{13}C cross section with the $T_<$ component lying mainly below about 22 MeV and the $T_>$ component concentrated in the main giant resonance above this energy. The present data do not support the conclusion of Kissener *et al.* that the pygmy resonance decays mainly to the first excited state (2^+, 4.43 MeV) in ^{12}C, but rather support the description by Marangoni *et al.* that the pygmy resonance decays mostly to the ground state. The 15.1-MeV state, on the other hand, decays mainly to the first excited state, and its strength has been determined to be in satisfactory agreement with previous results.

A preliminary report of this work appeared as Ref 30. The data in this paper supersede the preliminary data presented in Lawrence Livermore Laboratory Report No. UCRL-78482, 1976 (unpublished).

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*Permanent address: Department of Physics, Trent University, Peterborough, Ontario, Canada K9J 7B8.
†Permanent address: Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7.

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