Ground-state photoneutron reactions in ^{14}C

P. C-K. Kuo and K. G. McNeill
Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7

N. K. Sherman, S. Landsberger,* and W. F. Davidson
Division of Physics, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6

J. W. Jury and J. R. C. Lafontaine†
Department of Physics, Trent University, Peterborough, Ontario, Canada K9J 7B8
(Received 27 August 1984)

Photoneutron time-of-flight spectra from the $^{14}C(\gamma,n_0)^{13}C$ reaction were measured as functions of laboratory angle over the excitation energy region from 10 to 28 MeV. Angular distribution coefficients and differential cross sections were extracted as functions of excitation energy between 10 and 23 MeV. The angle-integrated ground-state cross section indicates that ground state transitions dominate the $T_<$ giant dipole resonance region below 13 MeV, but only contribute about 50% of the strength in the neutron channel in the rest of the giant dipole resonance region. The results support a mechanism of dominant $E1$ absorption in the energy region from 13 to 23 MeV where an average value of $a_2=-0.5$ indicates $p_{1/2}\rightarrow d_{3/2}$ single-particle neutron transitions. Angular distribution information suggests that much of a prominent resonance at 11.3 MeV (with an integrated cross section of about 1.03 MeV mb) is due to an $M1$ transition from the ground state of ^{14}C. If this is the case, there is little fragmentation of the $M1$ strength in ^{12}C brought about by the presence of valence neutrons. When combined with the observation of the lack of a pygmy $E1$ resonance below the giant dipole resonance region, these results suggest that a model of ^{14}C as a ^{12}C "core" with two valence, weakly coupled, neutrons is inappropriate. Below an excitation energy of about 19 MeV, there is reasonably good quantitative and qualitative agreement between the present data and the results of a recent shell model calculation.

I. INTRODUCTION

In the last few years, a series of photonuclear measurements has been aimed at studying the nuclear photoeffect in those light nuclei with one or two valence nucleons (or holes) associated with a nuclear "core." Examples are ^{13}C (Refs. 1), ^{15}N (Refs. 2 and 3), ^{17}O (Ref. 4), ^{18}O (Refs. 5), and ^{26}Mg (Refs. 6). To some extent the results of these experiments suggest that a weak coupling model can be used with standard shell model calculations to describe the observed photoabsorption cross sections in these nuclei.

There is relatively little experimental information reported on ^{14}C, which might be considered as a ^{12}C core plus two valence neutrons. The presently available data include electron-scattering work,[7–9] elastic neutron scattering from ^{13}C (Ref. 10), polarized-neutron capture into ^{13}C (Refs. 11 and 12), and a very recent $^{14}C(\gamma,n_{tot})$ measurement.[13] Limited availability of separated-isotope ^{14}C in the quantities necessary for photonuclear measurements (typically quantities of several moles) and the natural radioactivity of the sample are the primary reasons that the photoabsorption cross sections of ^{14}C have not been measured for all the major deexcitation channels.

Several shell model calculations have attempted to describe the $A=14$ system.[14–17] The calculated shape of the total photoabsorption cross section from a recent particle-hole shell model calculation by Assafiri and Morrison[17] was found to be in reasonable agreement with the $^{14}C(\gamma,n_{tot})$ cross section of Pywell *et al.*[13] This agreement indicates that the (as yet unreported) photoproton cross section does not contribute in a major way to the total absorption cross section, except possibly in the region from 25 to 27 MeV.

Since ^{14}C (with ground-state isospin $T=1$) is a light non-self-conjugate nucleus, one should be able to observe the isospin splitting of the giant dipole resonance (GDR). Based on the evidence presented in Refs. 1–6, part of the $T_<$ component could be expected to form a pygmy resonance at an energy below the GDR. It is in this region that transitions through single-particle states might be observed as identifiable resonances.

The ground state of ^{14}C is $J^\pi=0^+$, $T=1$. Electric dipole ($E1$) excitation will populate $J^\pi=1^-$, $T=1$ (the "T lower" or $T_<$) and $J^\pi=1^-$, $T=2$ (the "T upper" or $T_>$) states in the GDR of ^{14}C. Because $T_>$ states may not decay to the $J^\pi=\frac{1}{2}^-$, $T=\frac{1}{2}$ ground state of ^{13}C (the transition is forbidden by isospin selection rules), all neutron transitions to the ground state of ^{13}C must come from the excited $T_<$ states in ^{14}C.

From the recent $^{14}C(\gamma,n_{tot})$ measurement,[13] the only significant structures observed below an excitation energy of 14 MeV were a shoulder near 13 MeV and a well defined peak at about 11.3 MeV. However, this peak might be composed of transitions to a 1^+ state (i.e., not part of the $E1$ GDR) since it has been seen in a 180° electron-scattering measurement[9] [in which the magnetic dipole ($M1$) mode is preferentially excited[8]]. This finding has raised some interesting questions.

Does the 11.3 MeV peak observed in the neutron channel[13] arise from $M1$ transitions to a 1^+ state? The first indication of a 1^+ state near 11.3 MeV was reported by Kaschl *et al.*[18] in a ^{15}N(d,^{3}He) measurement. It has also been identified in a neutron scattering measurement of Lane *et al.*[10] If the resonance is indeed an $M1$ transition, then how much $M1$ strength does it have and is this $M1$ resonance fragmented due to the presence of two valence neutrons?

This paper reports on the measurement of the angular distributions of the ground-state photoneutrons in the energy region 10—28 MeV. This new information provides an indication of the multipolarity of the peak at 11.3 MeV and the absorption process leading to formation of $T_<$ states in the continuum.

Comparison of the present single channel (γ,n_0) results with the (γ,n_{tot}) measurement can lead to an understanding of the decay processes in the GDR region. Moreover, a single channel measurement permits the investigation of specific multiparticle-multihole (mp-mh) interference effects, such as the possibility of a second doorway state, as recently reported for ^{13}C.[19]

II. EXPERIMENTAL DETAILS

The measurement of the cross section and neutron angular distributions for the $^{14}C(\gamma,n_0)^{13}C$ reaction was carried out using the photoneutron time-of-flight angular distribution facility at the electron linear accelerator laboratory of the National Research Council of Canada. Because this facility has been described in some detail elsewhere,[3,20] only some of the features most relevant to this experiment will be described here.

Since the first excited state in ^{13}C is at 3.09 MeV, the highest 3.09-MeV-wide region of the tip of the neutron energy spectrum corresponds unambiguously to ground-state transitions. Consequently, photoneutron time-of-flight spectra were measured in 3 MeV intervals between 13.5 and 28.5 MeV.

The ^{14}C sample was in the form of calcium carbonate ($CaCO_3$) powder of activity 52.98 Ci. This is 11.9 g or 0.85 moles of ^{14}C. This sample was sealed in an aluminum cylindrical tube of length 102mm, diameter 44 mm, and wall thickness 1.2 mm. This thin wall caused negligible neutron or photon attenuation. Inactive calcium carbonate powder in an identical container was used to measure the background. Samples of D_2O and H_2O were used to monitor and measure the photon distribution. These samples were in cast acrylic plastic tubes of the same outer dimensions as the aluminum containers but machined to a wall thickness of 2 mm. In order to ensure that all the photoneutron samples received the same amount of photon flux, a computer-controlled sample changer was used to cycle the samples in and out of the photon beam with a period of typically 1—2 min.

For each of the samples used, eight neutron time-of-flight spectra were recorded simultaneously, using 10 m flight paths spread over an angular span from 48° to 139° in 13° steps. Each of the eight neutron detectors sent a "stop" signal to an independent time-to-digital converter (TDC) which was part of a standard CAMAC data acquisition system. Each TDC was started by a fast pulse generated by the photon beam striking a detector placed near the sample. The time calibration of the time-of-flight systems and the determination of the relative efficiencies of the neutron detectors were obtained as previously reported.[3,20]

III. DATA REDUCTION

The reduction of data from the series of photoneutron time-of-flight spectra to yield a total ground-state cross section and the anisotropy coefficients was accomplished by the following steps.

Initial corrections for dead time and natural and sample background were performed on the time-of-flight spectra before they were converted into neutron energy spectra in the center-of-mass frame. The neutron energy spectra were then corrected for detector efficiency and converted to the excitation energy scale.

Legendre polynomials up to second order were fitted to these energy spectra and the normalized angular distribution coefficients a_i $(i=0,1,2)$ were obtained using the following expression:

$$\text{Yield }(E_x)=\sum_{i=0}^{2}A_iP_i(\cos\theta)$$

and (1)

$$a_i=A_i/A_0 \ .$$

The coefficients a_i were extracted as functions of excitation energy using a weighted least-squares technique.[21]

The total angle-integrated cross section was obtained by dividing $4\pi A_0$ by the (measured) bremsstrahlung distribution scaled to the relative number of nuclei of ^{14}C and ^{2}H exposed to the photon beam. The scale of the cross section was determined relative to the deuterium cross section, calculated by Arenhövel *et al.*[22] for E_γ less than 10 MeV and by Partovi[23] for E_γ greater than 10 MeV.

IV. RESULTS AND DISCUSSION

The total angle-integrated cross section for the $^{14}C(\gamma,n_0)^{13}C$ reaction is shown in Fig. 1(a). Shown in Figs. 1(b) and 1(c) are, respectively, the normalized angular distribution coefficients a_1 and a_2, extracted from second-order Legendre polynomial fits.

The data presented in this figure were obtained from four independent measurements of the reaction at bremsstrahlung end point energies 13.5—28.5 MeV in steps of 3 MeV. Because of the very low photon flux near the tip of the bremsstrahlung beam, the data lying in the energy region within 300 keV of each of the end points contained too few events to justify a Legendre fit and were discarded. This resulted in three 300-keV-wide gaps where no usable data are available. Legendre fits to higher orders

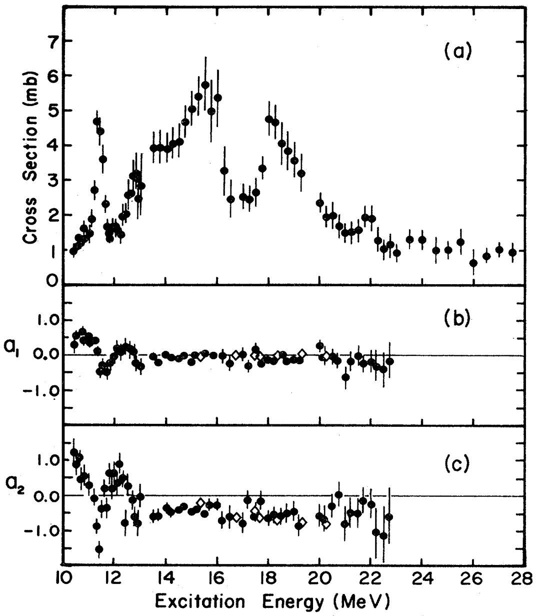

FIG. 1. Present results (full circles) for the ground-state photoneutron reactions in ^{14}C: (a) the total angle-integrated cross section; (b) and (c) the normalized angular distribution coefficients a_1 and a_2, respectively, as functions of energy. Also shown in (b) and (c) are comparisons with results from Ref. 12 (open diamonds). Good agreement is seen between the two sets of data.

(i.e., P_3 and P_4) were attempted but no decrease in the reduced χ^2 values of the fits was observed, and there was an increase in the error estimates for the a_1 and a_2 coefficients. This effect was attributed to the relatively large statistical uncertainties (of about 10%) on the measured data points. Insufficient statistics were accumulated for the last two end point energies (25.5 and 28.5 MeV) to justify the extraction of meaningful angular distribution coefficients. Hence, no a_1 and a_2 values are reported for energies above 22.2 MeV.

A. The ground-state cross section

Considerable structure is observed in the ground-state cross section [see Fig. 1(a)]. In particular, a sharp peak at 11.3 MeV is suggestive of a resonance of single-particle character. There is evidence of a shoulder near 13 MeV. Three broader peaks are seen at 15.5, 18.2, and 21.8 MeV.

The pronounced and narrow resonance centered at 11.3 MeV has been observed in the total photoneutron measurement[13] where an integrated strength of 1.1 ± 0.1 MeV mb was reported (after removal of the underlying $E1$ GDR tail). The present results show a value of 1.03 ± 0.06 MeV mb (with a similar background subtraction). This is excellent agreement. Both experiments measure the cross section for the same reaction at this excitation energy, since only the ground-state neutron channel is open for decay by particle emission. The observed agreement is encouraging in that these experiments employed entirely different techniques, one using quasimonochromatic photons produced by in-flight positron annihilation and a 4π neutron detector consisting of BF_3 tubes,[13] while the present measurement used kinematically-selected monochromatic segments of bremsstrahlung radiation with a multiangle neutron time-of-flight spectrometer.

As is discussed in the following, other measurements have detected an even parity state at this energy suggesting a possible $M1$ character for the absorption mechanism. Analysis of the anisotropy coefficients measured in this experiment supports this hypothesis (see the following).

The two peaks at 15.5 and 18.2 MeV seem to be distorted. This might be caused by interference of mp-mh states with the primary 1p-1h states in the GDR. Such effects have been noted previously for ^{16}O (Ref. 24) and, recently, for ^{13}C near an excitation energy of 20.6 MeV.[19] In the latter case it was apparent that interference with a 3p-2h secondary state caused a distortion in the shape of the primary 2p-1h state at this energy. There was also a corresponding effect on the a_2 coefficient causing the values to deviate towards zero. There is some indication that this effect is seen in the a_2 values measured in this experiment near 17.5 MeV.

The shoulder near 13 MeV is seen more clearly in the ^{14}C(γ,n$_{tot}$) measurement.[13] When compared to the total photoneutron cross section, the lower ground-state cross section suggests the possible presence of a single-particle state which can decay to the first $(\frac{1}{2}^+)$ or second $(\frac{3}{2}^-)$ excited state in ^{13}C as well as (in the present case) to the ground state; 1^- excited states in the ^{14}C GDR cannot decay to the $J=\frac{5}{2}^+$ (third) excited state in ^{13}C. This is consistent with the observation of Mordechai et al.[25] in a ^{12}C(t,p) measurement. They made a tentative $J=(1^-)$ assignment to a state at 12.96 MeV.

The present observed peak at 21.8 MeV is seen, but less clearly, in both the (γ,1n) and (γ,2n) data of Pywell et al.[13] This suggests that at 21.8 MeV there exist $J=1^-$ states of both isospin $T_>$ and $T_<$. There is no evidence in the ground state cross section measured in this work for the peak seen at 26 MeV in the total photoneutron cross section measured by Pywell et al.[13] (see Fig. 3).

The integrated cross section between 10.4 and 28.0 MeV (excluding the 11.3 MeV peak) was found to be 42 ± 0.3 MeV mb, exhausting $20\pm0.2\%$ of the classical Thomas-Reiche-Kuhn (TRK) dipole sum rule value of 206 MeV mb for ^{14}C. On the other hand, the total photoneutron cross section [including (γ,np) and (γ,2n) channels] of Ref. 13 exhausts about 60% of the TRK sum rule between 8 and 36 MeV.

The present measurement shows no evidence of an $E1$ pygmy resonance. This is contrary to the observations in other light nuclei having two valence neutrons outside a core, such as ^{18}O (Ref. 5) and ^{26}Mg (Ref. 6).

B. Angular distributions

As already noted, an attempt was made to fit the present data to third-order Legendre polynomials, but for several energies the cross section extrapolated to 0° became negative and no improvement in the reduced χ^2 values was observed. It was concluded that within the statistical uncertainty of the data, there is no detectable amount of $E2$ absorption in the energy region presently studied.

The angular distribution coefficients can be expressed in terms of single-particle transition matrix elements and phase shifts. The angular distribution coefficients for ^{14}C in terms of the $E1$ and $M1$ matrix elements and phase shifts are presented in Table I. The channel spin representation has been used,[26] and $E2$ matrix elements have not been included.

From Table I, it is apparent that a detailed analysis of the angular distribution coefficients is impossible without information on the relative phase shifts involved, or measurements of photoneutron or photon polarization. However, the relations in Table I show how the Legendre coefficients depend on the $E1$ and $M1$ transition matrix elements, and a qualitative analysis of the variation of these coefficients with energy can indicate the nature of the matrix elements involved.

1. The a_1 values

The measured a_1 coefficients, which represent the amount of $E1$-$M1$ interference (assuming negligible $E2$ absorption here) in the photoabsorption matrix elements for the reaction, are seen in Fig. 1(b) to be zero over most of the energy region studied. However, a dramatic deviation from the zero value is observed in the region of the 11.3 MeV peak. This suggests the presence of $M1$ absorption strength interfering with the dominant $E1$ absorption process. An expanded plot of the data in this region is shown in Fig. 2. The variation of a_1 with energy in this region shows a transition from (large) positive values of about +0.4 to (large) negative values of −0.4, occurring with the zero-crossing point at 11.3 MeV, the energy center of the resonance. This behavior is characteristic of the interference of a narrow resonance ($M1$) with an underlying broader one ($E1$) where the relative phase between the two resonances is changing by π radians across the narrow resonance. Small nonzero a_1 values are also found in the energy regions of 16.5—18.0 MeV and 20.0—21.0 MeV, indicating small amounts of $M1$ strength, or possibly, strength due to other higher order multipolarities.

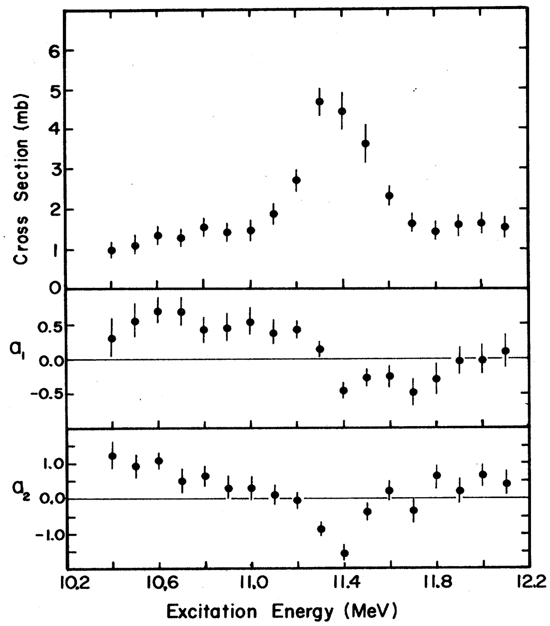

FIG. 2. An expanded scale plot of the data presented in Fig. 1. Near 11.3 MeV, the a_1 coefficient is seen to change sign suggesting $M1$-$E1$ interference for which the relative phase angle is changing rapidly over a narrow energy region.

TABLE I. Angular distribution coefficients for ^{14}C given in terms of the $E1$ and $M1$ single-particle matrix elements and relative phase shifts. The matrix elements are expressed in the form $E1(l,J,s)$ and $M1(l,J,s)$, where l is the orbital angular momentum of the emitted particle, J is the angular momentum of the intermediate excited states, and s is the channel spin. δ_i's are relative phase shifts.

$$A_0=3E1(011)^2+3E1(211)^2+3M1(110)^2+3M1(111)^2$$

$$A_1=-7.3E1(011)M1(111)\cos\delta_1 -5.2E1(211)M1(111)\cos\delta_2$$

$$A_2=-1.5E1(211)^2-3M1(110)^2+1.5M1(111)^2 +4.2E1(011)E1(211)\cos\delta_3$$

The indication that the 11.3 MeV peak is due to a $M1$ transition from the ground state of ^{14}C is consistent with the observations of Kaschl *et al.*,[18] the results of the 180° electron-scattering measurement of Crannell *et al.*,[9] and the neutron scattering work of Lane *et al.*[10] In the latter reference it was suggested that, between 11 and 12 MeV, there are broad $E1$ states underlying the narrow 1^+ state at 11.3 MeV. This is consistent with the present data which show an underlying background of about 1 mb in the $E1$ GDR tail between 10 and 12 MeV. The present experimental results give an integrated cross section of the 11.3 MeV peak of 1.03±0.06 MeV mb (after removing the GDR tail).

Crannell *et al.*[9] reported an electromagnetic transition width (Γ_{γ_0}) of 6.8±1.4 eV for this 11.3 MeV peak, while Pywell *et al.*[13] gave a width of 12±2 eV for the same state. The present measurement yields a width of 11±2 eV, in agreement with the result of Ref. 13. The broader widths measured by using real photons are most likely due to the presence of both $E1$ and $M1$ absorption while the 180° electron-scattering work of Crannell *et al.*[9] measured the width due only to $M1$ transitions. Under this assumption the measured photon width (Γ_{γ_0}) can be compared in terms of effective integrated cross section strength over the 11.3 MeV peak as in Table II. Thus, the ratio of $M1$ strength to the total ($M1$ plus $E1$) cross section is

$$\frac{0.6\pm0.2}{1.65\pm0.12}=0.36\pm0.12\ ,$$

TABLE II. The measured photon width (T_{γ_0}) compared in terms of effective integrated cross section strength over the 11.3 MeV peak.

Experiment	Integrated cross section	(MeV mb)
180° electron scattering (Ref. 9)	($M1$)	0.6 ± 0.2
Present results	($E1+M1$)	1.65 ± 0.12[a]

[a]Peak area, 1.03 ± 0.06; underlying GDR tail, 0.62 ± 0.06.

indicating that more than one-third of the strength of this peak is due to $M1$ transitions. Furthermore, the ratio of the $M1$ to $E1$ cross sections is about 0.56 ± 0.18 at this energy.

To set this value into perspective, a comparison can be made with the $M1$ and $E1$ strengths reported recently by Snover *et al.*[27] for several states seen in the $^{15}N(\vec{p},\gamma_0)^{16}O$ reaction. This radiative-capture experiment has determined Γ_{γ_0} values for 1^+ states at 16.21 and 17.12 MeV in ^{16}O to be 3.7 and 6.72 eV, respectively. A nearby 1^- state at 17.27 MeV was observed to have a width of $\Gamma_{\gamma_0}=61$ eV. Therefore, near excitation energies of 17 MeV in ^{16}O, a ratio of $M1$ and $E1$ absorption strength of about 0.17 is found. This is considerably less than the present observation of an $M1/E1$ ratio of about 0.56 near 11.3 MeV in the ^{14}C nucleus.

Since the a_1 values are seen to be near zero in the energy region between 14 and 23 MeV, it is reasonable to conclude that little additional $M1$ strength is present. Thus, it appears that the $M1$ strength near 11.3 MeV is not fragmented. This is quite different from the observed[8] fragmentation of the $M1$ strength in other light, non-self-conjugate nuclei when one to two nucleons (or holes) are added to a "self-conjugate core" (such as ^{13}C, ^{22}Ne, and ^{26}Mg).

2. *The a_2 values*

In the energy region of 13 to 23 MeV, the a_2 coefficient shows an "average" value of about -0.5. This average value is in agreement with the special case of (i) no $M1$ strength, (ii) no $E2$ strength, and (iii) pure d-wave neutron emission after $E1$ absorption ($p_{1/2} \rightarrow d_{3/2}$ transitions in this case; see the expressions for A_0 and A_2 in Table I). However, the a_2 value is not constant at -0.5, indicating such simplifying assumptions are not generally applicable.

We conclude that the main structures observed in the ground state cross section, except a component of the peak at 11.3 MeV, comprise the $T_<$ component of the electric dipole GDR and that this cross section is composed largely of transitions resulting in d-wave neutron emission.

C. Comparison with $^{13}C(\vec{n},\gamma_0)$ results

Shown in Fig. 3 is a comparison of the present measurement with the results of Wright.[12] This neutron-capture work was performed using the polarized neutron beam at the Triangle Universities Nuclear Laboratory; the results have been converted for comparison with photonuclear cross sections by the application of the principle of detailed balance. Excellent agreement is found in the energy region of overlap.

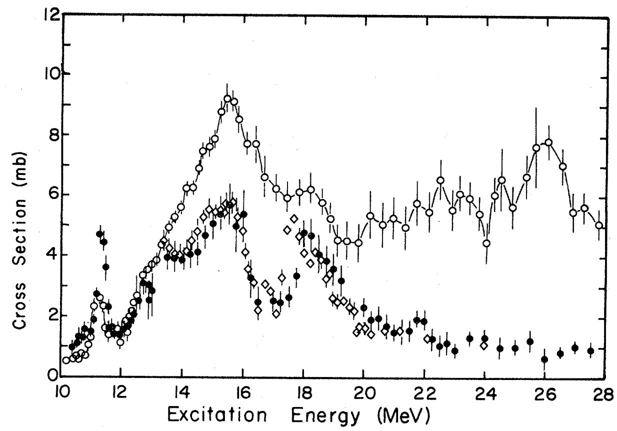

FIG. 3. A comparison of the present measurement (full circles) with the neutron capture work of Wright (Ref. 12) (open diamonds; converted by application of detailed balance). Excellent agreement is seen between the two sets of measurements in the region of overlap. Also shown is the total photoneutron measurement (open circles connected by a continuous line) of Pywell *et al.* (Ref. 13). Good agreement is found between the present measurement and that of Ref. 13 for excitation energies below 13 MeV.

The angular distribution coefficients a_1 and a_2 obtained from third-order Legendre fits by Wright[12] are also in good agreement with the present results [see Figs. 1(b) and (c)] which were obtained from second-order Legendre fits.

The a_3 values of Wright[12] in the excitation energy region between 15.4 and 20.3 MeV are zero within the quoted uncertainties, with the exception of 17.7 MeV where a_3 has a value of $+0.135 \pm 0.046$, indicating the possible presence of $E2$ strength.

D. Comparison with the $^{14}C(\gamma,n_{tot})$ cross section

Also shown in Fig. 3 is a comparison between the present ground-state and the total photoneutron[13] cross sections. It is seen that the two measurements are in excellent agreement up to 13 MeV (taking into account resolution effects on the 11.3 MeV peak). This indicates that in the region from 11.3 to 13.0 MeV, 100% of all transitions proceed to the ground state of ^{13}C, even though non-ground-state transitions are kinematically possible. The dominant reaction mechanism here seems to be the excitation of the single-particle transitions involving the $p_{1/2}$ neutrons.

As already discussed, the integrated area under the 11.3 MeV peak (after removing the $E1$ GDR tail) of the present work is 1.03 ± 0.06 MeV mb, again in excellent agreement with the results of Pywell *et al.*[13] of 1.1 ± 0.1 MeV mb. The difference in magnitude of the 11.3 MeV peak is attributed to the different energy resolution at that energy. The resolution of Ref. 13 at 11.3 MeV is 350 keV, while the present energy resolution at the same energy is about 150 keV. Between 13 and 18 MeV it is seen that only about one-half of the total photoneutron cross section results in transitions to the ground state. The dip in the average (singles) neutron energy observed by Pywell *et al.*[13] supports this.

A valley is seen in the ground-state cross section, but not in the total photoneutron cross section, between 16 and 18 MeV. In this energy region, transitions to the first two (bound) excited states near 3.5 MeV in ^{13}C are possible and could account for this difference. Also, the $(\gamma,2n)$ channel has opened up at 13.12 MeV, but the measured $(\gamma,2n)$ cross section of Ref. 13 shows no appreciable strength up to about 19 MeV.

In the energy region of 18 to 27 MeV, it is again seen that transitions to excited states are preferred. A peak at 26 MeV was observed in the total photoneutron cross section but not seen in the present ground-state data. This supports the interpretation of Pywell *et al.*[13] that the peak at 26 MeV is a $T_>$ state, since neutron emission to the ground state of ^{13}C from $T_>$ excited states in ^{14}C is forbidden by isospin conservation. However, because the ground-state cross section is not zero (about 1 mb) in this region, some $T_<$ strength is still present at this energy.

E. Comparison with theory

A comparison of the present ground-state measurement with the total photon absorption shell model calculation of Kissener *et al.*[15] is shown in Fig. 4. The scale of the calculated cross section has been reduced by a factor of 2 to facilitate comparison with the experiment. It can be seen that the gross structure of the ground-state cross section is reproduced but not the positions of the peaks. The

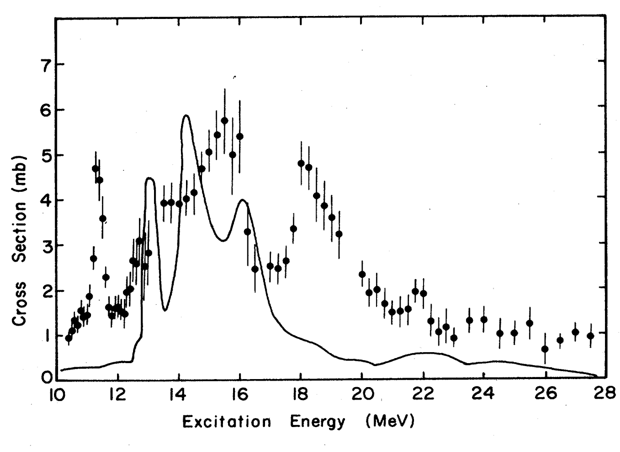

FIG. 4. The present ground-state results (full circles) are compared with the bound-state shell model calculation (solid line) of Kissener *et al.* (Ref. 15) for the ground-state cross section. The scale of the calculated cross section has been reduced by a factor of 2 to facilitate comparison with the present measurement. The calculation reproduces the gross structure of the cross section but not the positions of the peaks.

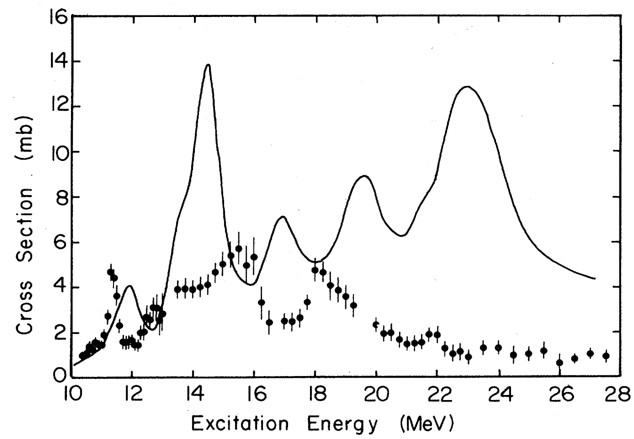

FIG. 5. Fair agreement is found between the present measured $T_<$ strength (full circles) and the predicted (solid line) cross section of Assafiri and Morrison (Ref. 17). In general, the calculated strength is greater than the measurement.

calculation was performed in the framework of the bound-state shell model combined with R-matrix theory.

The predicted distribution of the $T_<$ strength from a recent particle-hole shell model calculation by Assafiri and Morrison[17] is shown in Fig. 5 together with the present data. This calculation ("set No. 3") was carried out under a dipole approximation using the residual nucleon-nucleon interaction of Cooper and Eisenberg[28] with a well depth of 50 MeV.

Fair agreement is seen between the prediction of the $T_<$ cross section and the present measurement. The magnitude of the calculated strength is seen to be higher than the measured values in some energy regions. This is expected since, although the ground state transitions are exclusively $T_<$, they do not necessarily exhaust all the $T_<$ strength in the GDR region. Transitions to $T_<$ excited states in ^{13}C are not measured in this experiment. However, the comparison with the total photoneutron cross section data[13] also shows the calculation to be too high in regions below 21 MeV. Little analysis of the theoretical predictions can be carried out for the energy region above 21 MeV until the photoproton cross section is available [the threshold for the ^{14}C(γ,p) channel is 20.8 MeV].

Jäger *et al.*[14] have predicted the locations of the strongest $T=1$ dipole states in ^{14}C to be at 15.2, 18.2, and 21.8 MeV. This is in excellent agreement with the present $(T=1)$ ground-state cross section which displays peaks at 15.5, 18.2, and 21.8 MeV. These authors also predicted small amounts of $T=2$ strength near 21.8 MeV. This is in agreement with the observation that a resonance at 21.8 MeV is seen in both the present $(T=1)$ measurement and the $(\gamma,2n)$ (mostly $T=2$) cross section.[13]

V. SUMMARY

The present data suggest that nearly 100% of the photoneutron transitions proceed to the ground state of ^{13}C below about 13 MeV. Above this energy, only about one-half of the $T_<$ GDR strength is in the ground-state neutron channel. There is no evidence of an $E1$ pygmy resonance below the GDR region. In other light nuclei, addition of a neutron to a closed (sub)shell, as in ^{13}C and ^{17}O, and the subtraction of a proton in the case of ^{15}N, appears to be the cause of pygmy $E1$ resonances lying at energies below the GDR. Similarly, the addition of two neutrons in the case of ^{18}O is accomplished by the appearance of a pygmy resonance. Yet in the case of ^{14}C there does not appear to be a distinct $E1$ pygmy resonance.

The only significant structure seen below the GDR is a sharp peak at 11.3 MeV. The present experiment shows that this is a dipole state exhibiting an a_2 coefficient differing distinctly from the local average, and that there is even-odd multipole interference in this energy region and not elsewhere, as shown by the finite value of a_1. Furthermore, there is no evidence for $E2$ excitation in the energy range from 15 to 20 MeV since the a_3 coefficient reported in Ref. 12 remains zero. There are strong indications of $E1$-$M1$ interference at 11.3 MeV. It is likely that a major contributing amplitude is $M1$, with the other strength being of an $E1$ character. Our results cannot rule out the possibility that the local change in a_2 is due to $E1$ strength involving a different neutron angular momentum than the rest of the $E1$ cross section, interfering with a weak $M1$ transition. However, inelastic electron scattering and neutron scattering experiments also see $M1$ strength which dominates at 11.3 MeV. The simplest interpretation is that the 11.3 MeV peak has a large component of $M1$ strength, possibly as much as 36% of the total photoabsorption cross section. However, we cannot rule out the possibility that we are observing a weak $M1$ transition through its interference with a strong $E1$ transition.

It is useful to recall that strong $M1$ transitions occur to states in ^{12}C at 15.11 MeV, in ^{13}C at 15.1 MeV, and in ^{16}O at 13.7, 16.2, and 17.1 MeV. Indeed, strong compact $M1$ transitions appear systematically in the light nuclei. These systematics encourage us to assign spin and parity of 1^+ to the 11.3 MeV state of ^{14}C we see in the (γ,n_0) cross section.

ACKNOWLEDGMENTS

We gratefully acknowledge the expert assistance of Mr. Alex Nowak and the staff of the electron linear accelerator laboratory of the National Research Council of Canada during the data-acquisition phase of the experiment. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada.

*Present address: Nuclear Reactor, McMaster University, Hamilton, Ontario, Canada L8S 4K1.

†Present address: Department of Physics, Queen's University, Kingston, Ontario, Canada K7L 3N6.

[1]J. W. Jury, B. L. Berman, D. D. Faul, P. Meyer, K. G. McNeill, and J. G. Woodworth, Phys. Rev. C **19**, 1684 (1979); D. Zubanov, R. A. Sutton, M. N. Thompson, and J. W. Jury, *ibid.* **27**, 1957 (1983).

[2]J. W. Jury, B. L. Berman, J. G. Woodworth, M. N. Thompson, R. E. Pywell, and K. G. McNeill, Phys. Rev. C **26**, 777 (1982).

[3]J. D. Watson, J. W. Jury, P.C-K. Kuo, N. K. Sherman, W. F. Davidson, and K. G. McNeill, Phys. Rev. C **27**, 506 (1983); J. D. Watson, thesis, Trent University, 1983.

[4]J. W. Jury, B. L. Berman, D. D. Faul, P. Meyer, and J. G. Woodworth, Phys. Rev. C **21**, 503 (1980).

[5]B. L. Berman, D. D. Faul, R. A. Alvarez, and P. Meyer, Phys. Rev. Lett. **36**, 1441 (1976); J. G. Woodworth, K. G. McNeill, J. W. Jury, R. A. Alvarez, B. L. Berman, D. D. Faul, and P. Meyer, Phys. Rev. C **19**, 1667 (1979).

[6]S. C. Fultz, R. A. Alvarez, B. L. Berman, M. A. Kelly, D. R. Lahser, T. W. Phillips, and J. McElhinney, Phys. Rev. C **4**, 149 (1971); K. Bangert, U. E. P. Berg, G. Junghans, K. Wienhard, and H. Wolf, Nucl. Phys. **A261**, 149 (1976).

[7]F. J. Kline, H. Crannell, J. T. O'Brien, J. McCarthy, and R. R. Whitney, Nucl. Phys. **A209**, 381 (1973); F. J. Kline, H. Crannell, J. M. Finn, P. L. Hallowell, J. T. O'Brien, and C. W. Werntz, Nuovo Cimento **23A**, 137 (1974).

[8]L. W. Fagg, Rev. Mod. Phys. **47**, 683 (1975).

[9]H. Crannell, J. M. Finn, P. Hallowell, J. T. O'Brien, N. Ensslin, L. W. Fagg, E. C. Jones, Jr., and W. L. Bendel, Nucl. Phys. **A278**, 253 (1977).

[10]R. O. Lane, H. D. Knox, P. Hoffmann-Pinther, R. M. White, and G. F. Auchampaugh, Phys. Rev. C **23**, 1883 (1981).

[11]M. J. Jensen, D. R. Tilley, S. A. Wender, N. R. Roberson, and H. R. Weller, Bull. Am. Phys. Soc. **25**, 603 (1980); M. J. Jensen, Ph.D. thesis, North Carolina State University, 1981.

[12]M. C. Wright, Ph.D. thesis, Duke University, 1983.

[13]R. E. Pywell, B. L. Berman, J. G. Woodworth, J. W. Jury, K. G. McNeill, and M. N. Thompson, Physics in Canada **40**, 68 (1984); and private communication.

[14]H. U. Jäger, H. R. Kissener, and R. A. Eramzhyan, Nucl. Phys. **A171**, 584 (1971).

[15]H. R. Kissener, R. A. Eramzhyan, and H. U. Jager, Nucl. Phys. **A207**, 78 (1973).

[16]H. R. Kissener and R. A. Eramzhyan, Nucl. Phys. **A326**, 289 (1979).

[17]Y. I. Assafiri and I. Morrison, Nucl. Phys. **A427**, 460 (1984).

[18]G. Kaschl, G. Mairle, H. Mackh, D. Hartwig, and U. Schwinn, Nucl. Phys. **A178**, 275 (1971).

[19]J. G. Woodworth, R. A. August, N. R. Roberson, D. R. Tilley, H. R. Weller, and J. W. Jury, Phys. Rev. C **29**, 1186 (1984).

[20]J. W. Jury, C. K. Ross, and N. K. Sherman, Nucl. Phys. **A337**, 523 (1980).

[21]P. R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 1969), pp. 148—160.

[22]H. Arenhövel, W. Fabian, and H. G. Miller, Phys. Rev. Lett. **52B**, 303 (1974).

[23]F. Partovi, Ann. Phys. (N.Y.) **27**, 29 (1964).

[24]J. R. Calarco, S. W. Wissink, M. Sasao, K. Wienhard, and S. S. Hanna, Phys. Rev. Lett. **39**, 925 (1977).

[25]S. Mordechai, H. T. Fortune, G. E. Moore, M. E. Cobern, R. V. Kollarits, and R. Middleton, Nucl. Phys. **A301**, 463 (1978).

[26]R. W. Carr and J. E. E. Baglin, Nucl. Data Tables **10**, 143 (1971).

[27]K. A. Snover, E. G. Adelberger, P. G. Ikossi, and B. A. Brown, Phys. Rev. C **27**, 1837 (1983).

[28]B. S. Cooper and J. M. Eisenberg, Nucl. Phys. **A114**, 184 (1968).