Photoproton cross section and angular distributions for ^{12}C in the giant dipole resonance region

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The energy spectra and angular distributions of photoprotons from the $^{12}C(\gamma, p)^{11}B$ reaction have been measured at seven angles simultaneously, using 30 MeV bremsstrahlung. The giant dipole resonance peaks at 22.5 MeV, and reaches an absolute cross section value of 13.1 ± 0.8 mb. The anisotropy parameter a_2 from the Legendre polynomial expansion of the angular distributions has an average value of about -0.55 but shows some structure especially around 25 MeV. On the other hand, the asymmetry coefficient a_1 is always positive and rises slowly with energy. Discussion of all coefficients leads to the conclusion that, although the photonuclear absorption mechanism in ^{12}C leading to photoproton emission is dominated by the $E1$ component, a nonnegligible $E2$ contribution (about 2%) might be present. A recent coupled-channel calculation by Birkholz satisfactorily describes our results.

[NUCLEAR REACTIONS $^{12}C(\gamma,p)$, $E=16.0-30.0$ MeV, $\theta=37-143°$; measured $\sigma(E, \theta)$; deduced $\sigma(E)$. Natural target.]

I. INTRODUCTION

During the past decade, the giant dipole resonance (GDR) for ^{12}C has formed the subject of an intensive study, both theoretically and experimentally.[1] In the photoneutron reaction channel, the shape and absolute magnitude of this giant resonance are now well established, especially since the advent of quasimonochromatic photon sources.[2-4] Since the early work by Penner and Leiss,[5] a number of significant photoproton experiments on carbon has been performed using either real photons[6-13] or a virtual γ-ray beam,[14,15] in the energy region of or just above the GDR. Apart from energy spectra of the ejected protons and (mostly relative) pseudo-ground-state cross sections, some authors[5,7,10,12,14,15] also measured angular distributions of the emitted photoparticles. The most complete investigation of the $^{12}C(\gamma,p)$-^{11}B reaction has been performed by Frederick and Sherick,[10] although these authors made no attempt to determine an absolute cross section scale. On the other hand, the giant dipole resonance in ^{12}C has also been studied by the proton radiative capture process[16,17] leading, however, to a discrepancy in the reported values of the absolute cross section. Finally, to complete the picture, the γ-ray spectra from the reactions $^{12}C(\gamma,n\gamma')$ and ^{12}C-$(\gamma,p\gamma')$ have been measured by Medicus *et al.*[18]; these authors conclude that, at a bremsstrahlung end point energy of 27 MeV, approximately 90% of the proton emission proceeds through the ground state of ^{11}B.

Since the original one-particle–one-hole calculations considerable progress has been made in the theoretical description of the structure[20-24] (i.e. energy location and strength) observed in the GDR of light nuclei. Recently, Birkholz[25,50] has calculated in an open-shell description the cross section and the angular distribution of photonucleons in the GDR of ^{12}C, employing a separation approximation for the solution of the continuum shell model. Although no complete agreement was reached, remarkable correspondence with the experimental data was observed. Likewise, within the framework of the eigenchannel theory of nuclear reactions, Mshelia, Barrett, and Greiner[26] extended the theory of collective correlations in nuclei to the nuclear continuum in order to investigate the ^{12}C giant resonance. Total, partial, and integrated photoreaction cross sections, as well as the A_2 coefficient of the Legendre polynomial expansion of the angular distribution were calculated, and qualitative agreement with the available experimental results was found.

It was the aim of the present experiment to measure the absolute magnitude of the cross section for the $^{12}C(\gamma,p)$ ^{11}B reaction, using a bremsstrahlung photon beam with an end point energy of 30 MeV, and to determine simultaneously the angular distribution for this photoreaction, in an attempt to remove the discrepancies[10,16,19] which exist in the values of the available angular distribution coefficients, especially in the energy region around 25 MeV. Finally, we want to verify the validity of the present-day theoretical results[25,50,26] by making a detailed comparison with our experimental data.

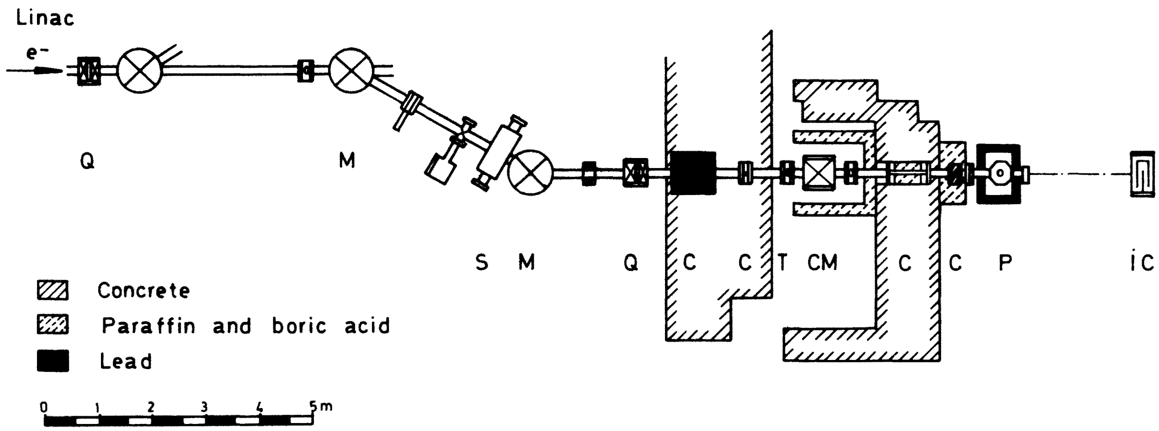

FIG. 1. General layout of the beam transport system and of the experimental arrangement. Q: quadrupole doublet; C: collimator; P: photoproton chamber; M: deflection magnet; T: Bremsstrahlung target; IC: ionization chamber; S: adjustable slit; CM: cleaning magnet.

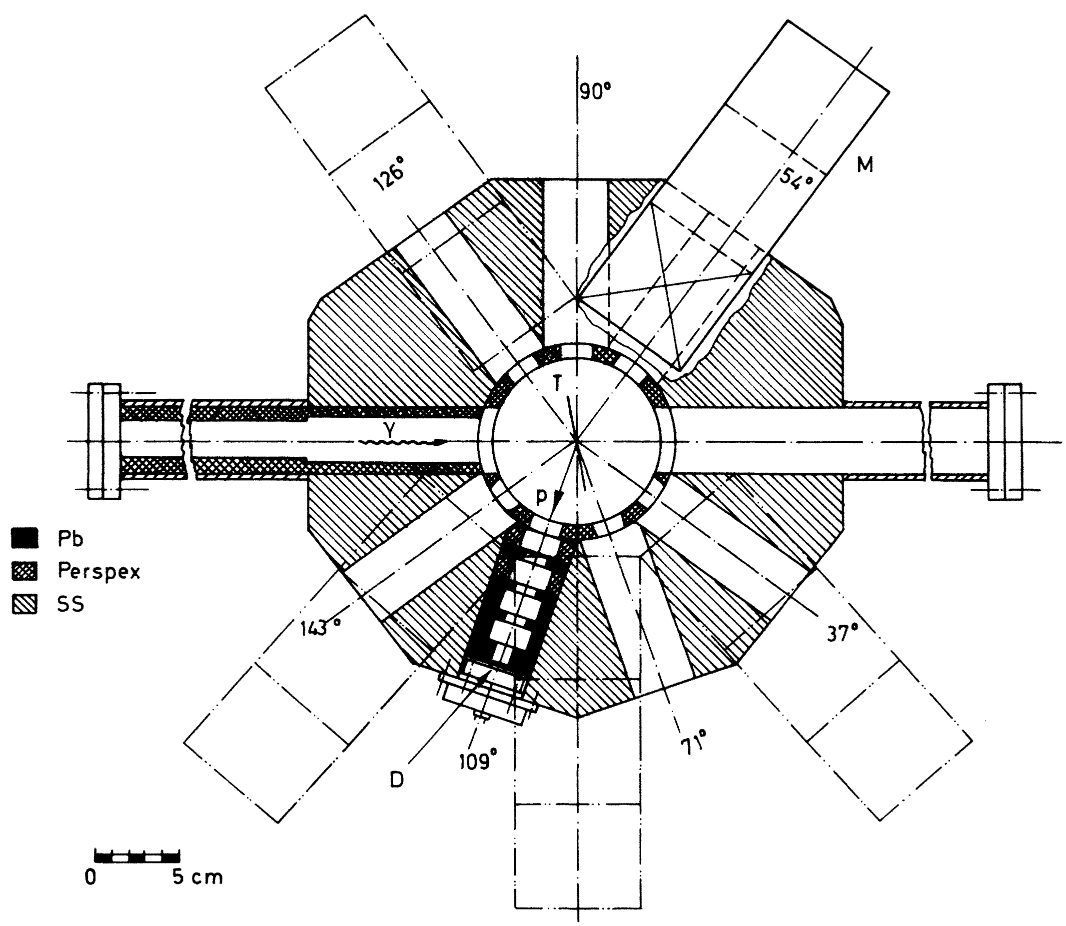

FIG. 2. Schematic drawing of the photoproton detection chamber. T: target; D: detector; M: magnet.

II. EXPERIMENTAL PROCEDURE

As a photon source we used the bremsstrahlung beam, produced at the 40 MeV linear electron accelerator of Ghent State University. The general experimental arrangement, including the beam transport system and the position of the detection apparatus, is shown in Fig. 1. This bremsstrahlung facility was nearly identical to the one used in our photoneutron research.[28] In addition the photon beam was now hardened by a 19.5 cm graphite cylinder, located directly in front of the antiscattering collimator. Consequently, the Schiff[27] thin-target integrated-over-angles (IOA) bremsstrahlung spectral shape was corrected for this attenuation, using the numerical tables of Hubbell.[53] The photons then impinged upon the photoproton target placed at the center of the reaction chamber. As target material we used a 6 cm × 10 cm polystyrene foil, with a thickness of 3.33 mg/cm^2. Photoproton spectra were simultaneously recorded at seven different angles: 37°, 54°, 71°, 90°, 109°, 126°, and 143°. A schematic sketch of the reaction chamber is shown in Fig. 2, where the detectors were located at a distance of 15.0 cm from the target center.

For suppressing the electron and γ background we adapted the philosophy as outlined by Baglin and Thompson[29] and by Keller *et al.*[30] Permanent magnets with a magnetic induction of about 1500 G, extended over 10 cm, were placed over the detector channels and over the entrance window of the reaction chamber. Additionally, the detector channels were lined with a baffle system (lead and Perspex) to prevent secondary scattered electrons from hitting the detector disks. The entrance channel was also equipped with several Perspex collimators, while the chamber inner walls were lined with a 1 cm thick Perspex ring. The entire detection system was externally heavily shielded with a least 25 cm of lead at the side of the incoming photon beam, while at all other sides 20 cm of lead was installed. Around this setup, cadmium plates and paraffin blocks were piled to minimize the effect of neutron background.

As proton detectors we used uncooled Si(Li) solid state detectors with an active area of 200 mm^2 and a thickness of 3 mm. Their intrinsic resolution was better than 30 keV for the 5.484 MeV α particles from ^{241}Am. Copper masks were mounted over the front periphery of the detectors to avoid edge effects; consequently the effective front area of the detectors was reduced to 113 mm^2. For the accumulation and processing of the proton signals we used conventional electronics. The signals from all detectors were individually preamplified in low noise, charge sensitive preamplifiers and subsequently semi-gaussian shaped in the main amplifiers, having integration and differentiation time constants of 0.3 μs. The outputs from the seven amplifiers were connected to an 8-input multiplexer-router unit which operated in combination with a single 512-channel analog-to-digital converter (ADC), interfaced to a DEC PDP-15/20 computer. To rule out the possibility of losing true proton pulses, the γ-beam intensity was kept sufficiently low, and a maximum count rate of 2 pulses per 100 bursts was accepted during this experiment. In addition, the ADC was triggered by a 10 μs gate, spanning the linac pulse. At regular intervals, checks were made of the stability of the electronic detection system as a whole; deviations of 0.5 channel a day and of 1 channel a week were typical.

The resolution of this spectrometer was to a large extent determined by the target thickness, i.e., by the energy loss of the photoprotons in the target, and by the angular resolution which amounted to ±2°. The correction for this energy loss will be discussed later. As the target was placed at 80° (measured clockwise) with respect to the photon beam, the experimental resolution varied with the angle. However, we estimate this resolution to be of the order of 100 keV, except at 71° and 90° where it is appreciably worse. For the energy calibration we used an α source, containing ^{239}Pu, ^{241}Am, and ^{244}Cm, so that we had three main calibration lines at 5.15, 5.48, and 5.80 MeV.

For the purpose of determining absolute differential cross sections the solid angles, subtended by the different detectors, have been calculated by a Monte Carlo method of which the computation procedure has been described in detail elsewhere.[31] All solid angles were identical within 1%, and corresponded to the point source value of 5.02×10^{-3} sr, with a net absolute deviation of $\pm 0.02 \times 10^{-3}$ sr.

III. TREATMENT OF DATA AND ANALYSIS

A. Background determination

In the detectors, pulses formed by particles that do not originate from the (γ,p) reaction are also registered. These pulses are due to γ radiation and secondary electrons, created in the shielding material, in the entrance and exit windows, in the chamber material, in the target itself, and in the collimators in front of the detectors. This background must be measured and has to be subtracted from the raw spectra. The most realistic way to estimate this background is to keep the original experimental situation undisturbed but at the same time, to eliminate the photoprotons. This was realized by putting thin aluminum plates (with a thickness of 1 or 2 mm) in front of the detectors.[32] The background spectra showed no structure and followed the shape of an exponential decay; for these reasons in the energy region between 1 and about 4 MeV we smoothed these data by adjusting a least squares straight line to the logarithms of the data points. Exponential extrapolation of this smoothed curve yielded new background values in the region of very low counting statistics, i.e., above 4 MeV equivalent proton energy, to remove the statistical fluctuations. However, when comparing at a specific angle the spectra taken without and with the aluminum absorbers (the so-called "raw" and background spectra), normalized to the same γ-ray dose, it appeared that in the region of low energies where no true proton counts could be expected, there was still a small amount of background left. Therefore, we decided to normalize both spectra with each other by choosing an energy interval (normally between 0.5 and 2.5 MeV equivalent proton energy) where the spectra had an identical shape, and by determining a normalization factor derived from the area under the spectral curves in that energy region. This normalization factor turned out to have a value of about 1.1–1.2. Straightforward subtraction then resulted in the net spectra. In Fig. 3 the photoproton spectrum taken at an angle of 90° and at 30 MeV bremsstrahlung end point energy is plotted. Here the target was placed at an angle of 135° with respect to the forward photon beam (such measurement was performed to obtain better energy resolution for the 71° and 90° data).

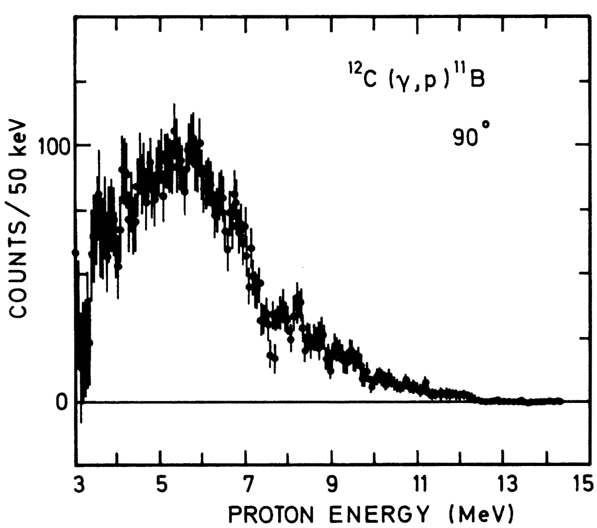

FIG. 3. Photoproton spectrum for the reaction ^{12}C-(γ,p)^{11}B at 90°, as a function of laboratory proton energy.

B. Analysis of the spectra

The energy scale of the net photoproton spectra, measured at the seven angles, was first redetermined by taking into account the energy loss of the protons in the polystyrene target. This correction was based upon the tables for energy loss of heavy charged particles, by Barkas and Berger.[33] Proton numbers were then regrouped in 50 keV bins, in accordance with the new energy scale. Subsequently, these proton spectra were converted to absolute differential cross sections by assuming that all transitions left the residual nucleus in the ground state; this assumption can be justified by the results of Medicus *et al.*[18] who claim that about 90% of the proton emission proceeds through the ground state of ^{11}B.

Figure 4 shows the differential cross sections for the seven angles, as a function of excitation energy (in the lab system); points are plotted every 150 keV. It should be noted that, although most cross sections are reproduced in the energy range between 19 and 30 MeV, the most forward angle (37°) only yields meaningful values in the interval between 21 and 30 MeV. The statistical accuracy in the top of the giant resonance is about 5% (one standard deviation); only these errors are shown. Additionally, we estimate the magnitude of the systematic error, due to inaccuracies in the knowledge of the photon spectrum, the target thickness, the angular resolution, the proton energy calibration, and the solid angles, to be of the order of 5% as well.

The angular distribution was expanded in Legendre polynomials using a computer program called LEGFIT:[34]

$$\frac{d\sigma}{d\Omega}(E_\gamma,\theta)=A_0(E_\gamma)\left[1+\sum_{i=1}^{4} a_i(E_\gamma)P_i(\cos\theta)\right].$$

The coefficients $a_i(E_\gamma)=A_i(E_\gamma)/A_0(E_\gamma)$ were transformed to the center-of-mass system, using the approximation proposed by Frederic and Sherick[10]; these values are used in the further presentation.

IV. RESULTS AND DISCUSSION

A. Differential cross sections

The absolute differential cross sections for the ^{12}C(γ,p) ^{11}B reaction, taken at the seven angles, as a function of lab energy are plotted in Fig. 4. The displayed cross sections were derived from the photoproton spectra measured with the target at 80° with respect to the forward photon beam, except the curves for 71° and 90° which were taken from the measurement with the sample at 135° with regard to the beam. From a careful analysis of the individual curves, we have made an attempt to determine the structure apparent in the cross

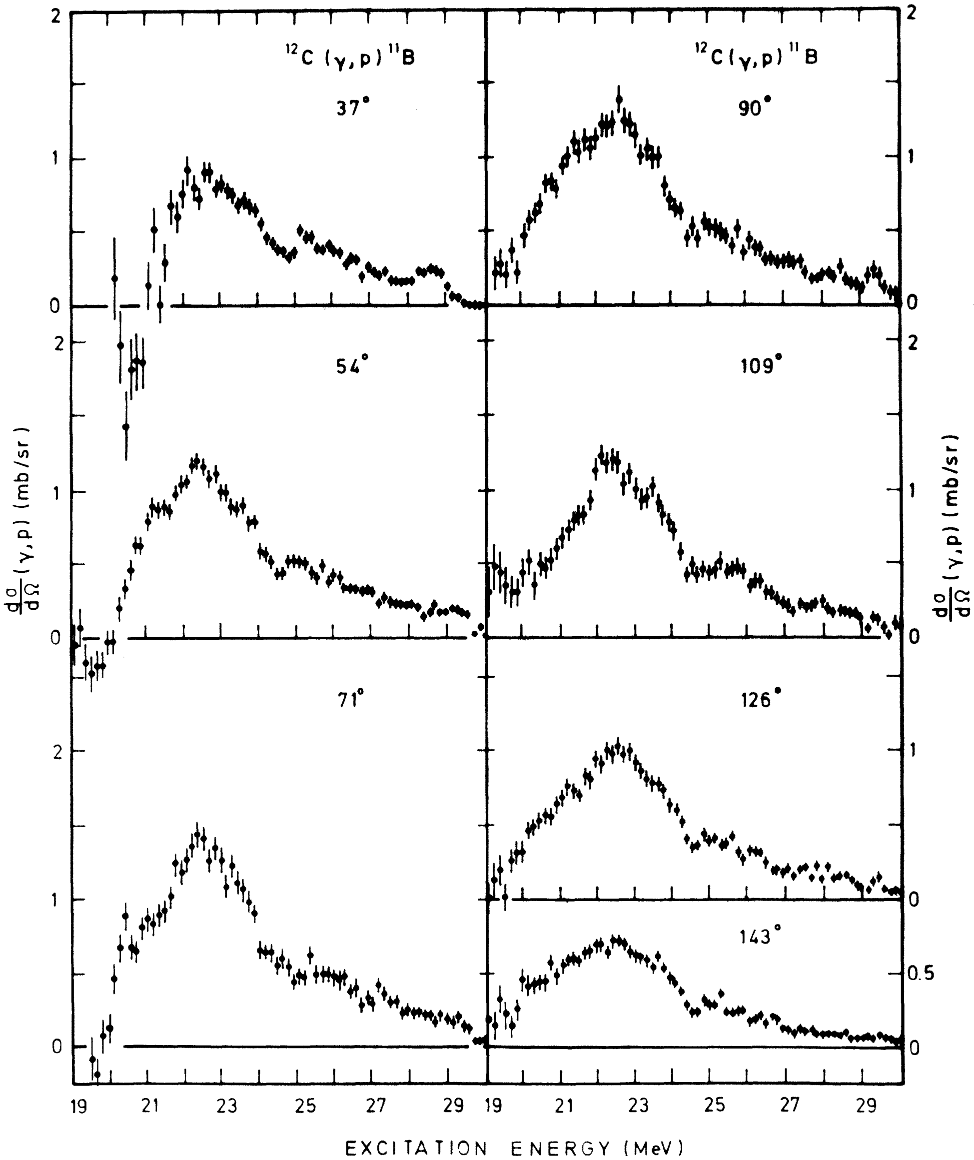

FIG. 4. $^{12}C(\gamma,p)^{11}B$ differential cross sections at seven angles in the laboratory system, derived from the proton spectra by assuming ground-state transitions only; values are plotted every 150 keV.

section. Resonances are observed at about 21.3, 22.4, 23.4, 25.2, 25.6, 26.1, 27.2, and 28.6 MeV, while there is some indication of structure at 20.8, 22.0, 22.8, 24.8, and 29.3 MeV. We estimate these energy values to be accurate within 100 keV. Most of these energies have been observed in the (γ,p) measurement by Frederick *et al.*,[10,11] except the weak structure at 22.8 MeV and the resonances at 25.6 and 28.6 MeV. These same authors suggest that the well-known resonance around 25.2 MeV is split into three peaks located at 24.85, 25.05, and 25.25 MeV. On the other hand, our experiment shows structure at 24.8 and 25.2 MeV, while an additional peak is observed at 25.6 MeV. Our experimental resolution was certainly insufficient to observe eventually the resonance at 25.05 MeV. However, this same peak did not show up either in a very recent measurement[13] of the 90° photoproton spectrum from carbon, performed with good energy resolution, while almost all other observed peaks can be identified with our quoted resonances. Moreover, Spamer[35] at Darmstadt has recently performed an inelastic electron scattering experiment of ^{12}C, with an incident energy between 54.6 and 57.1 MeV, while the scattered electrons were detected at angles of 141° and 165°. Within the error, most of the detected structure corresponds with our resonance energies, including the small peaks at 22.8 and 25.6 MeV, but the resonance at 28.6 MeV was not observed.

Finally, there seems to exist reasonable agreement between the structure observed in our photoproton experiment and the structure detected in a recent high-resolution photoneutron measurement[4] of ^{12}C.

B. Total cross section

The total cross section for the (γ,p) reaction, given by $4\pi A_0$ and shown in Fig. 5, reaches a maximum value of 13.1 ± 0.8 mb (systematic error included) at 22.5 MeV, and the full width at half maximum (FWHM) of the giant resonance equals 3.20 ±0.05 MeV. It is remarkable that the GDR as observed in the photoproton experiments shows a relatively sharp peak as compared with the results from photoneutron measurements. The second smaller maximum around 25.2 MeV has a σ_{max} equal to 5.6 ± 0.3 mb, while its FWHM is of the order of 2 MeV. Making a direct comparison of these absolute magnitudes with values obtained in previous (γ,p) measurements is not conclusive as most other experiments only give relative data. However, using the principle of detailed balance we can compare our values with the results from the (p,γ_0) experiment by Allas *et al.*[16] At an excitation energy of 22.6 MeV, the deduced (γ,p_0) cross section reaches a maximum of 13.4 mb.[36] A more recent improved measurement by the same group[36] yields a σ_{max} value of 12.2 ± 1.2 mb. These values are in good agreement with our results. Incidentally, we have also made a comparison between our differential (γ,p) cross section at 90° and the curve derived from the ^{11}B$(p,\gamma_0)^{12}$C yield at 90°, by detailed balancing; again the correspondence turns out to be remarkable at all energies.

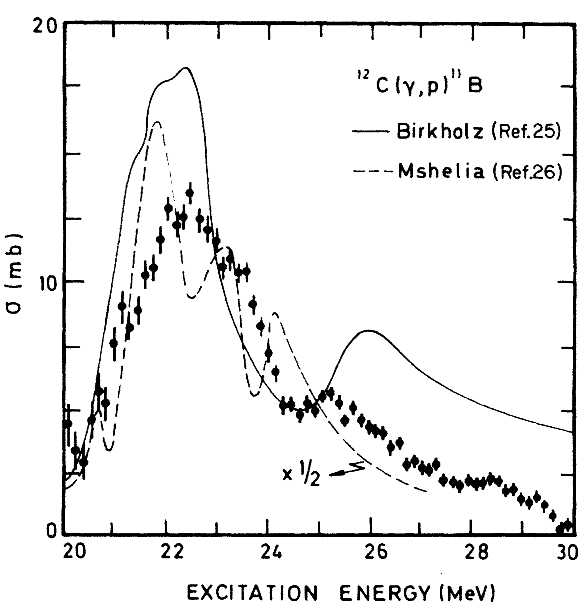

FIG. 5. The total photoproton cross section $(4\pi A_0)$ assuming ground-state transitions only. Also shown are the theoretical predictions by Mshelia *et al.* (Ref. 26) and by Birkholz (Ref. 25).

As far as the total cross section is concerned, there seems to exist some confusion in the absolute value of the (γ,p) cross section deduced from the total yield of the (p,γ_0) reaction. Dixon and Thompson[19] find a peak value of something like 11 mb, which seems to be derived directly from the total cross section $4\pi A_0$ for the (p,γ_0) reaction[16] and which is in direct contradiction with the value of 13.4 mb as quoted by Hanna.[36] We think that this discrepancy is due to the fact that the $4\pi A_0$ values in the original paper of Allas *et al.*[16] show an error in the cross section scale. Therefore, we have taken the (p,γ_0) yield at 90° as being correct and have converted this to an absolute total cross section, taking into account the value of their coefficients of the Legendre polynomial expansion. This procedure leads to numbers which conform to the values as quoted by Hanna.[36] If we scale this cross section down, taking into account the new σ_{max} value of 12.2 mb, an excellent agreement with our total (γ,p) cross section shape is observed. However, if this is the case and if our conversion procedure is correct, this means that the argument developed by Dixon and Thompson[19] on the effect of excited-state decay on the measured angular distributions and total cross section of the ^{12}C$(\gamma,p)^{11}$B reaction is overestimated (on the question of the effect on the angular distribution coefficients, we will explicitly come back later in this paper). Based on the fact that there exists a distinct difference between the (normalized) ^{12}C(γ,p) cross section as measured by Frederick and Sherick[10] and the cross section value as derived from the inverse reaction,[16] especially in the energy region between 24.2 and 25.5 MeV, these authors[19] propose the existence of photoproton cross sections for excited-state decay of ^{12}C to states in ^{11}B at 4.44 and 5.02 MeV. These cross sections should be located around 29 MeV, and around 30 MeV, respectively, and reach a maximum value of about 1.5 mb. On the contrary, the fact that our photoproton cross section around 25 MeV seems to be in good agreement with the one deduced from the (p,γ_0) reaction suggests that the effect of excited-state decay is certainly less pronounced than was originally believed, which indicates that less than 10% non-ground-state proton contamination occurs in the (γ,p) cross section derived from our data taken at a bremsstrahlung end point energy of 30 MeV. If not, it could also indicate that the eventual non-ground-state transitions are smeared out over several levels between 2.12 and 8.0 MeV in ^{11}B, as suggested by Medicus *et al.*,[18] which then would make the effect less explicitly visible.

If we now add the photoproton and photoneutron cross sections in the region of the giant resonance, we can have a fairly good idea of the total photonuclear reaction cross section. Recent $^{12}C(\gamma,n_0)$ experiments[36,37] using a quasimonoenergetic photon beam and the $4\pi A_0$ value derived from a photoneutron angular distribution measurement[38] both at an excitation energy of 22.5 MeV, yield a cross section value of about 6.5 mb. Thus it seems that the sum of the photoproton and photoneutron cross section at 22.5 MeV, equals about 19.6 ± 0.8 mb. However, we should draw here attention to the fact that a very recent (γ,n) experiment performed at Giessen,[39] also using monochromatic photons, reaches a cross section value of about 8 mb at the same energy. Anyway, the summed value has to be compared with the results from the measurement of the total nuclear absorption of γ rays in carbon. At 22.5 MeV, Bezić *et al.*[40] find a value of 21 ± 0.6 mb, while Ahrens *et al.*[41] report 19 ± 0.7 mb. The agreement with the number mentioned

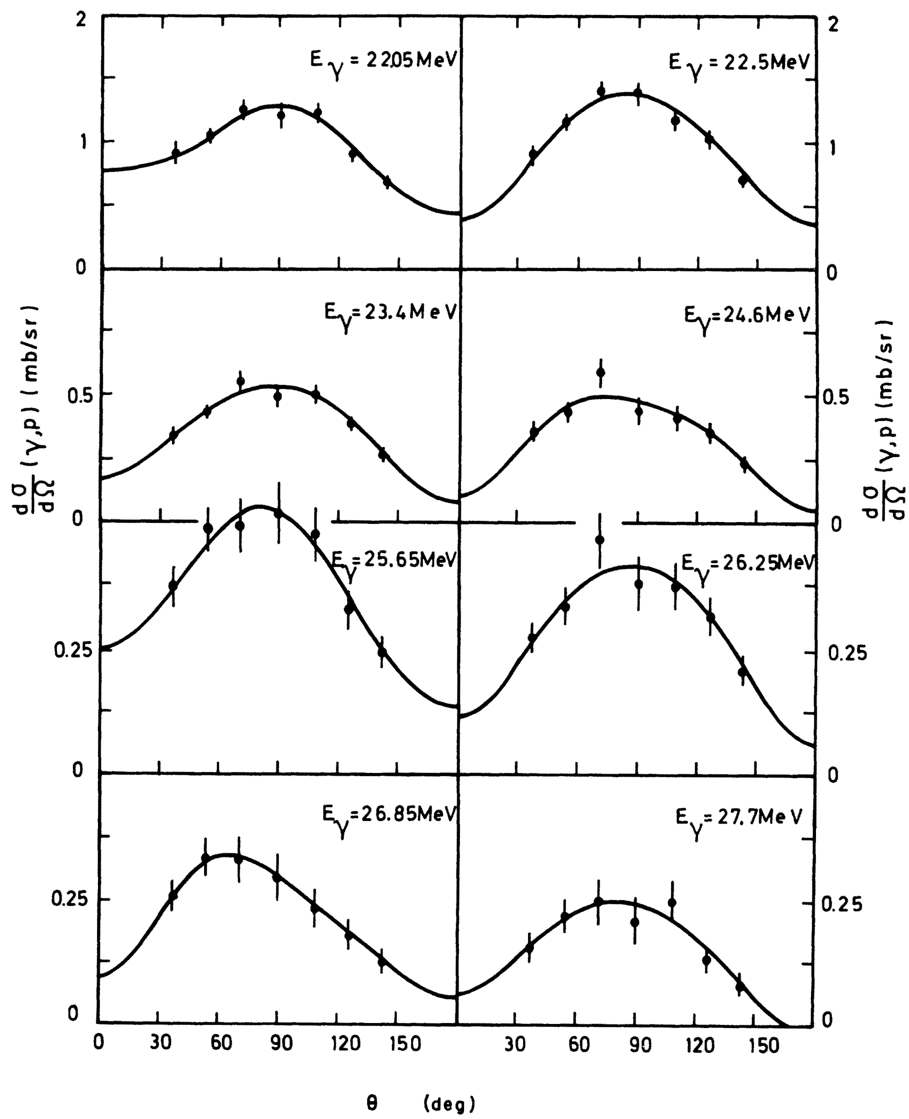

FIG. 6. Angular distribution fits at eight particular excitation energies, as a function of lab angle θ.

above is remarkable.

From a direct comparison of the partial photoproton and photoneutron cross sections, it is possible to determine the energy dependence of the isospin mixing in the GDR.[42] For a self-conjugate nucleus like ^{12}C, the ratio of the (γ,p) to (γ,n) cross section can be expressed as a function of the amplitudes of the isospin components, using the well-known Barker and Mann[43] relation. The Giessen[39] photoneutron cross section in combination with our photoproton data yields, in the assumption that only d-wave particles are emitted,[55] an isospin amplitude mixing ratio $\alpha(T=0)/\alpha(T=1)$, which reaches a maximum value of 0.08 ± 0.01 at 22.5 MeV, and which slowly drops towards -0.04 ± 0.01 in the energy region between 25 and 28 MeV. If we would take into account all possible systematic errors in the partial cross sections, our results would indicate a negligible isospin mixing, except in the region of the electric dipole resonance, where the $T=0$ component could reach a value of maximum 1% in intensity. These results are not inconsistent with previously reported conclusions by Wu *et al.*[42] and by Brassard and co-workers.[17] Moreover, it is in perfect agreement with the considerations made by Tanner.[56]

C. Angular distributions

To illustrate the behavior of the angular distributions we have plotted in Fig. 6 a number of differential cross sections as a function of the angle θ, at several different excitation energies between 22 and 28 MeV, which give an idea of the accuracy of the fitting of a sum of Legendre polynomials to our data as described in Sec. III. Also the slight forward peaking of the cross section is demonstrated. The coefficients $a_i(E_\gamma)$ $(i=1,4)$ which result from this fitting are presented in Fig. 7; values are plotted at 150 keV intervals in the energy range between 21 and 29 MeV.

The asymmetry parameter a_1 as presented in Fig. 7(a) is always positive and rises slowly from about zero at 21.6 MeV to a value of 0.4 at 28 MeV, with a slight indication of structural behavior. Our data seem to be in fair agreement with the results of Frederick *et al.*[10] and of Allas *et al.*[16] The a_1 values deduced from a recent photoneutron angular distribution experiment[44] show a similar behavior although they only rise to 0.1 between 23 and 25 MeV, while beyond this latter energy they show a tendency to drop off.

The other asymmetry parameter a_3 is shown in Fig. 7(c); over the entire energy range its value fluctuates around zero, although it becomes slightly positive above 25 MeV, while around 27 MeV it is definitely negative. This behavior is in agreement with the results obtained in the inverse (p,γ_0) reaction[16] and with the data obtained in photoneutron work,[38] while Federick *et al.*[10] undisputably found negative a_3 values in the analysis of their photoproton data (−0.3 at 29 MeV). On the

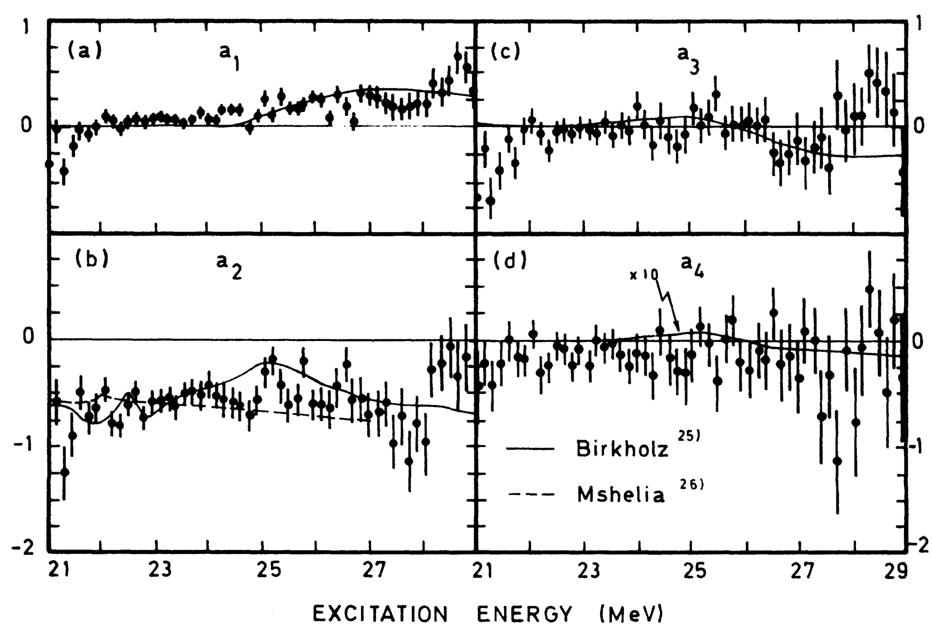

FIG. 7. Photoproton angular distribution coefficients deduced from the Legendre polynomial fit, as a function of center-of-mass excitation energy. The results from the theoretical calculations by Mshelia *et al.* (Ref. 26) (dashed line) and by Birkholz (Ref. 52) (solid line) are shown for comparison.

other hand, more recent photoneutron data from Jury *et al.*[44] definitely show a positive a_3 coefficient (+0.2 at 28 MeV). Thus it seems that there still remains some ambiguity as far as the sign and the exact magnitude of this parameter are concerned.

The coefficient a_1 originates from interference between either electric dipole ($E1$) and magnetic dipole ($M1$) photoexcitation, or from ($E1,E2$) interference, or from both, whereas a_3 cannot involve magnetic dipole transitions and stems purely from ($E1,E2$) interference. Although both $M1$ and $E2$ giant resonances can be expected, a strong argument for neglecting $M1$ radiation can be found in the results of the calculations by Vinh-Mau and Brown,[4,5] who computed the highly excited states of ^{12}C in a bound-state shell model. The $M1$ transition strength was placed in the 1^+ level at 16.1 MeV. This $(1p_{3/2})^{-1}(1p_{1/2})$ configuration contained almost 100% of the total $M1$ strength. Thus it seems justified to presume that very little $M1$ electromagnetic excitation is present above 20 MeV. Thus we can conclude that only in the neighborhood of 27 MeV is there a strong indication of the occurrence of some $E2$ strength, in agreement with the expectations which place the $E2$ resonance at a higher energy than the $E1$ resonance peak.

The anisotropy parameter a_2, determined by the $E1$, $E2$, and $M1$ components in the photonuclear absorption and depicted in Fig. 7(b) as a function of excitation energy, is always negative but shows an appreciable amount of structure, especially in the energy region between 25 and 27 MeV. Throughout the giant resonance peak, a_2 has an average value of about −0.55, but increases suddenly to a maximum value of −0.20 at 25.2 MeV, beyond which energy a few more fluctuations are observed (−0.25 at 26.6 MeV); finally it drops gradually off. There exists a very good correspondence with the results from the inverse ground-state reaction[16] except at higher energy (> 27 MeV), where this gradual fall of the magnitude is not observed. However, this agreement, especially at the energies where structure is observed (the minimum of −0.7 at 24.7 MeV), is in marked contrast with the discrepancy established between the a_2 values deduced from the (p,γ_0) reaction by Allas *et al.*[16] and those derived from the (γ,p) reaction by Frederick and Sherick[10] in the energy region between 24 and 25 MeV. Dixon and Thompson[19] claimed that this difference could be explained by a contribution in this energy region from non-ground-state protons with a positive a_2 value. The present observations again weaken their argument. Consequently, the postulated cross section, if any, for decay to the $\frac{5}{2}^-$ state at 4.44 MeV in ^{11}B seems to play a minor role in the comparison of our data with the (p,γ_0) results. However, we should add that the phenomenon discussed by Dixon and Thompson[19] is based upon the comparison with (γ,p) measurements[10] taken at a bremsstrahlung end point energy of 32.1 MeV, while ours are performed with 30 MeV bremsstrahlung. This could well have an observable effect on the a_2 values.

Photoneutron angular distribution measurements[44] yield an A_2/A_0 value which is also negative over the energy interval between 21 and 28 MeV, although its magnitude is somewhat smaller than that observed in the photoproton data. Its general trend is similar to the (γ,p) results, but a pronounced maximum, almost attaining zero, is detected at 22.25 MeV.

Although the quadrupole interaction parameter a_4 shows large statistical errors and fluctuates appreciably, as can be seen from Fig. 7(d), its average magnitude is not inconsistent with zero. This behavior is identical to that observed in previous experiments[10,16]. Our data, however, give an indication that measurements with very high statistical accuracy could yield a net a_4 value, smaller than about −0.20, throughout the energy range covered by our data. This would point to the existence of a small $E2$ component in the γ absorption mechanism throughout the GDR.

The angular distribution coefficients can now be interpreted in terms of the channel spin formalism.[46] Carr and Baglin[47] and Maute and co-workers[48] tabulated these coefficients A_l/A_0 for photonuclear reactions as a function of the transition amplitudes for the different processes involved. They denoted these transition amplitudes by $EN(L,S)$ and $MN(L,S)$, where EN and MN represent the multipolarity of the absorbed radiation and L stands for the orbital angular momentum of the ejected proton, while S signifies the channel spin (vector sum of the spins of the decay products). In the following discussion we assumed that only $E1$, $M1$, and $E2$ photon absorption has to be taken into account.

As the giant resonance is dominated by electric dipole absorption, one can write [47,48] in very good approximation

$$\frac{A_2}{A_0} \simeq \frac{-1.5E1^2(2,1)+1.5E1^2(2,2)}{3.0E1^2(0,1)+3.0E1^2(2,1)+3.0E1^2(2,2)}\,.$$

Figure 7(b) indicates that over the entire energy range, the mean value of A_2/A_0 equals about −0.5; consequently, the above relation can only be fulfilled if $E1(2,1)$ represents the dominant term. This means that the photoproton reaction is characterized by $E1$ photon absorption followed by d-wave proton emission, with channel spin equal to one. This is of course in agreement with the conclusions drawn from other experimental results,[10,16,18,38] and from theoretical considerations on the basis of the standard $1p$-$1h$ model.[45,49] In these latter calculations where the ^{12}C ground state is taken as a pure jj-coupling shell-model state with a closed $p_{3/2}$ shell, the giant resonance is essentially described by the $(p_{3/2})^{-1}d_{5/2}$ configuration.

As explained earlier, the a_4 coefficient which only arises from $E2$ absorption, shows a tendency to be slightly negative in the energy range between 21 and 29 MeV [Fig. 7(d)]. We therefore assume that A_4 is dominated by the transition amplitude $E2(3,1)$, which indicates the emission of f-wave protons. Besides, this assumption is confirmed by a theoretical calculation by Birkholz,[50] who ascribes the electric quadrupole strength in ^{12}C as primarily due to the promotion of a nucleon from the $1p$ shell to the $f_{7/2}$ continuum state. Consequently, the asymmetry parameter A_3/A_0 can be written as

$$\frac{A_3}{A_0} \simeq \frac{2\{-2.19\,\mathrm{Re}[E1^*(2,1)E2(3,1)]\}}{3.0E1^2(2,1)} .$$

Experimentally [Fig. 7(c)] this coefficient is everywhere near zero, except around 27 MeV, where it has an average value of about −0.20. This magnitude can be used to determine a lower limit of the ratio of the $E2$ to $E1$ intensity.[51] From the above relation, we derive

$$\frac{A_3}{A_0} \simeq -1.46\,\frac{E2(3,1)\cos\delta}{E1(2,1)} ,$$

wherein δ signifies the difference between d and f-wave phase shifts. By setting $\cos\delta = 1$, we obtain a lower limit for the ratio of $E2(3,1)/E1(2,1)$:

$$0.20 \leq \left|1.46\,\frac{E2(3,1)}{E1(2,1)}\right| .$$

This results in

$$\left|\frac{E2(3,1)}{E1(2,1)}\right|^2 \geq 0.02$$

so that, at an excitation energy of about 27 MeV, we estimate the ratio of the $E2$ channel spin 1 intensity to the $E1$ channel spin 1 intensity to be of the order of 2%. This is in extremely good agreement with the theoretical predictions by Birkholz.[50] Very recent polarized proton capture experiments[54] on ^{11}B estimate the lower limit of the ratio of the quadrupole to the dipole cross section to be 5% at an excitation energy of 27 MeV.

As a check on this estimation we can now try to make a prediction of the A_1/A_0 asymmetry coefficient. We hereby neglect all transition amplitudes, except $E1(2,1)$ and $E2(3,1)$, so that we can write

$$\frac{A_1}{A_0} \simeq \frac{4.9\,\mathrm{Re}[E1^*(2,1)E2(3,1)]}{3.0E1^2(2,1)}$$

or

$$\frac{A_1}{A_0} \simeq 3.26\,\frac{E2(3,1)}{E1(2,1)}\cos\delta .$$

Using the values obtained in the A_3/A_0 discussion, we find

$$\frac{A_1}{A_0} \simeq 0.45 .$$

This estimation is not inconsistent with the observed value of about 0.3 ± 0.1 at 27 MeV. Furthermore, using the same picture, the gradual fall of this coefficient at lower excitation energies is quite understandable as the effect of the $E2$ amplitude weakens as the excitation energy decreases.

We can thus conclude that the photoproton process can be described primarily by $E1$ photon absorption followed by channel spin 1, d-wave proton emission, but that also a small amount (~2%) of $E2(3,1)$ absorption, peaked around 27 MeV, seems to be necessary in order to explain the experimental data. Although we cannot make an estimation of the absolute magnitude of the other possible transition amplitudes, their effect seems to be of less importance in the discussed region.

D. Comparison with theory

Although a lot of computational effort[20-26] has been devoted to the description of the giant dipole resonance in ^{12}C, we will limit ourselves to a comparison of our experimental data with recent theoretical results.

Mshelia and co-workers[26] investigated the giant dipole photonuclear cross section of ^{12}C using a formulation based on the collective correlation model, whereby the continuum particle states were properly treated within the framework of the eigenchannel method. It was the aim of these authors to explain, apart form the gross features of the GDR, the occurrence of the so-called intermediate structure interpreted as due to the interaction of the GDR with other collective degrees of freedom. Using the angular momentum coupling scheme B, as explained in their paper[26] (i.e., coupling of the hole to the phonon to give the angular momentum $\bar{I}$ of the residual nucleus; this is then coupled with the particle yielding the total angular momentum of the compound nucleus), the ^{12}C$(\gamma,p)^{11}$B cross section was calculated. This result is shown in Fig. 5; it is clear that the absolute magnitude of the theoretical cross section is more than a factor of 2 larger than the experimental one. Although a pronounced splitting of the strength in the GDR is produced, the vibrational satellite lies about 1 MeV lower than the experimentally observed peak at 25.2 MeV. The calculated coefficient A_2/A_0 of the photoproton angular distribution is presented in Fig. 7(b). Apart from a slight bump at 22 MeV, no structure is produced. Although this theoretical coefficient has about the right magnitude, its general behavior does not fit the experimental points.

A different theoretical approach for the description of the characteristics of the GDR was successfully attempted by Birkholz.[25] Using a separation approximation scheme for treating a relatively large number of coupled channels in the continuum shell model, Birkholz investigated how the structure of the photonuclear cross section of ^{12}C is affected by the inclusion of more complex configurations. Instead of assuming a closed $1p_{3/2}$ shell for the ^{12}C ground state and pure one-hole configurations for the states of the residual nucleus ^{11}B, the simple particle-hole concept was generalized such that these states were derived from shell-model diagonalizations within the partially filled $1p_{3/2}$ and $1p_{1/2}$ shells. Thereby all intermediate coupling shell-model states of the residual mass-11 nucleus below 10 MeV excitation energy were taken into account. The obtained total photoproton cross section is shown in Fig. 5. Although the absolute magnitude is still some 30% too high, the calculated photoproton results agree on the location of the GDR and on its total width. A sizable part of the total dipole transition strength seems to be shifted towards higher energies, and a clearly defined resonance appears at about 26 MeV; this is to be compared with the experimentally observed complex structure in the 25–25.5 MeV region.

In Fig. 7 we plotted the theoretically predicted Legendre coefficients A_i/A_0 for $^{12}C(\gamma,p_0)$, obtained in an open-shell calculation including $E1$ and $E2$ transitions by the same author.[52] The general behavior (sign and magnitude) of the experimental data is rather nicely reproduced, especially the maximum around 25 MeV in the a_2 parameter. However, the experimentally determined A_1/A_0 coefficient shows possibly some more structure than indicated by the theoretical curve. Encouraged by the fair agreement between theory and experiment for the GDR, Birkholz[50] also performed a continuum shell-model calculation of the electric quadrupole strength in ^{12}C. In this procedure the coupling of the high-lying $E2$ exciation mode with low-energy excitations (within the $1p$ shell) was neglected, and the giant quadrupole states were constructed by exciting a nucleon from the $1p$ shell to p and f continuum states. This model predicts the appearance of isoscalar $E2$ strength around 27 MeV, dominated by the $f_{7/2}$ channel. This prediction is in surprisingly good agreement with our conclusions, reached in the preceding section. Moreover, this same calculation yields for the ratio of the $E2$ to $E1$ strength a value of about 2%, which again corresponds nicely with our estimate. Finally, the fact that the a_1 and a_3 coefficients, which arise essentially from $E1$-$E2$ interference, find an adequate description in this model confirms the assumption that a non-negligible amount of $E2$ absorption appears in the ^{12}C giant resonance.

V. CONCLUSION

We have measured the photoproton cross section and angular distributions for ^{12}C in the energy range between 21 and 29 MeV using a bremsstrahlung photon beam produced by 30 MeV electrons from our linac. Although the present data suffer from limited statistical accuracy and from restricted energy resolution, it was possible to determine the absolute magnitude of and the structure in the cross section with reasonable precision. The giant dipole resonance peaks at 22.5 MeV, where it reaches a cross section value of 13.1 ± 0.8 mb. This result is in good agreement with the data from the inverse (p,γ_0) reaction while, combined with accurate photoneutron[37-39] results taken from the literature, it corresponds satisfactorily to the results from total absorption experiments.[40,41]

The observed angular distributions indicate a slight forward peaking and agree much better with those determined in the (p,γ_0) process than was the case in earlier experiments.[10] The anisotropy coefficient a_2 in the Legendre polynomial expansion of the angular distributions shows some structure and can reasonably well be described by a recent coupled-channel calculation by Birkholz.[25] Discussion of all coefficients A_i/A_0 leads to the conclusion that the photonuclear absorption mechanism of ^{12}C leading to photoproton emission, is dominated by the $E1$ component, but that also a non-negligible quadrupole contribution (of the order of 2%) is present, in contrast to the results obtained in the study of the photoneutron channel.[38] However, further experiments with high statistical accuracy are required to confirm the latter observation.

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[1]E. G. Fuller, H. M. Gerstenberg, H. Vander Molen, and T. C. Dunn, *Photonuclear Reaction Data* (NBS Special Publication No. 380, March, 1973).

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

[3]S. C. Fultz, J. T. Caldwell, B. L. Berman, R. L. Bramblett, and R. R. Harvey, Phys. Rev. 143, 790 (1966).

[4]B. L. Berman, R. A. Alvarez, D. D. Paul, F. H. Lewis, Jr., P. Meyer, and T. W. Phillips, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973*, edited by B. L. Berman (Lawrence Livermore Laboratory, Univ. of California, 1973), Vol. 2, p. 1073.

[5]S. Penner and J. E. Leiss, Phys. Rev. 114, 1101 (1959).

[6]E. Finckh, P. Kosiek, K. H. Lindenberger, K. Maier, U. Meyer-Berkhout, M. Schechter, and J. Zimmerer, Z. Phys. 174, 337 (1963).

[7]H. D. Warren and A. P. Batson, Nucl. Phys. 48, 361 (1963).

[8]G. G. Taran and A. N. Gorbunov, Zh. Eksp. Teor. Fiz. 46, 149 (1964) [Sov. Phys.–JETP 19, 1010 (1964)].

[9]Y. M. Shin and W. E. Stephens, Phys. Rev. 136, 660 (1964).

[10]D. E. Frederick and A. D. Sherick, Phys. Rev. 176, 1177 (1968).

[11]D. E. Frederick, Nucl. Phys. A119, 347 (1968).

[12]G. G. Taran, Yad. Fiz. 10, 211 (1969) [Sov. J. Nucl. Phys. 10, 119 (1970)].

[13]K. Wienhard, K. Bangert, R. Stock, and H. Wolf, Z. Phys. 270, 93 (1974).

[14]V. J. Vanhuyse, Nucl. Phys. 26, 233 (1961).

[15]W. R. Dodge and W. C. Barber, Phys. Rev. 127, 1746 (1962).

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

[17]C. Brassard, H. D. Shay, J. P. Coffin, W. Scholz, and D. A. Bromley, Phys. Rev. C 6, 53 (1972).

[18]H. A. Medicus, E. M. Bowey, D. B. Gayther, B. H. Patrick, and E. J. Winhold, Nucl. Phys. A156, 257 (1970).

[19]J. M. Dixon and M. N. Thompson, Aust. J. Phys. 27, 301 (1974).

[20]D. Drechsel, J. B. Seaborn, and W. Greiner, Phys. Rev. 162, 983 (1967).

[21]M. Kamimura, K. Ikeda, and A. Arima, Nucl. Phys. A95, 129 (1967).

[22]M. Marangoni and A. M. Saruis, Phys. Lett. 24B, 218 (1967).

[23]M. Marangoni and A. M. Saruis, Nucl. Phys. A132, 649 (1969).

[24]G. Baur and K. Alder, Helv. Phys. Acta 44, 49 (1971).

[25]J. Birkholz, Phys. Lett. 34B, 1 (1971); Nucl. Phys. A189, 385 (1972); F. Beck and J. Birkholz, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973* (see Ref. 4), Vol. 1, p. 159.

[26]E. D. Mshelia, R. F. Barrett, and W. Greiner, Phys. Rev. Lett. 28, 847 (1972); E. D. Mshelia and R. F. Barrett, Nucl. Phys. A205, 581 (1973); Z. Phys. 261, 313 (1973).

[27]L. I. Schiff, Phys. Rev. 83, 252 (1951).

[28]R. E. Van de Vyver, H. Ferdinande, G. Knuyt, R. Carchon, and J. Devos, Nucl. Phys. A198, 144 (1972).

[29]J. E. E. Baglin and M. N. Thompson, Nucl. Instrum. Methods 71, 71 (1969).

[30]N. K. Keller, J. K. P. Lee, and D. B. McConnell, Can. J. Phys. 47, 611 (1969).

[31]R. Carchon, E. Van Camp, G. Knuyt, R. Van de Vyver, J. Devos, and H. Ferdinande, Nucl. Instrum. Methods 128, 195 (1975).

[32]D. Brajnik, D. Jamnik, G. Kernel, U. Miklavžič, and J. Šnajder, Nucl. Instrum. Methods 103, 189 (1972).

[33]W. H. Barkas and M. J. Berger, NASA Report No. NASA SP-3013, 1964 (unpublished).

[34]P. R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, New York, 1969), p. 155.

[35]E. Spamer (private communication).

[36]S. S. Hanna, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973* (see Ref. 4), Vol. 1, p. 417.

[37]B. L. Berman, At. Data Nucl. Data Tables 15, 319 (1975).

[38]J. W. Jury, J. S. Hewitt, and K. G. McNeill, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Asilomar, 1973* (see Ref. 4), Vol. 1, p. 157.

[39]U. Kneissl (private communication).

[40]N. Bezić, D. Brajnik, D. Jamnik, and G. Kernel, Nucl. Phys. A128, 426 (1969).

[41]J. Ahrens, H. Borchert, H. B. Eppler, H. Gimm, H. Gundrum, P. Riehn, G. Sita Ram, A. Zieger, M. Kröning, and B. Ziegler, in *Proceedings of the International Conference on Nuclear Structure Studies Using Electron Scattering and Photoreaction, Sendai, Japan, 1972*, edited by K. Shoda and H. Ui (Tohoku Univ., Sendai, Japan, 1972), p. 213.

[42]C. P. Wu, F. W. K. Firk, and T. W. Phillips, Phys. Rev. Lett. 20, 1182 (1968).

[43]F. C. Barker and A. K. Mann, Phil. Mag. 2, 5 (1957).

[44]J. W. Jury (private communication).

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

[46]S. Devons and L. J. B. Goldfarb, Handbuch der Physik 42, 362 (1957).

[47]R. W. Carr and J. E. E. Baglin, Nucl. Data Tables A10, 143 (1971).

[48]R. E. Maute, D. P. D'Amato, and S. L. Blatt, At. Data Nucl. Data Tables 13, 499 (1974).

[49]V. Gillet and N. Vinh-Mau, Nucl. Phys. 54, 321 (1964).

[50]J. Birkholz, Phys. Rev. C 11, 1861 (1975).

[51]J. D. Irish, R. G. Johnson, B. L. Berman, B. J. Thomas, K. G. McNeill, and J. W. Jury, Can. J. Phys. 53, 802 (1975).

[52]J. Birkholz (private communication).

[53]J. H. Hubbell, NBS Report No. NSRDS-NBS 29, 1969 (unpublished).

[54]S. S. Hanna (private communication).

[55]G. S. Mani, M. A. Melkanoff, and I. Iori, Commissariat à l'Energie Atomique, Reports Nos. CEA-R-2379 and CEA-R-2380, 1963 (unpublished).

[56]N. W. Tanner, in Proceedings of the Seminar on Electromagnetic Interactions of Nuclei at Low and Medium Energies, Moscow, 11–13 December, 1972, edited by L. Lazareva (unpublished), p. 261.