Absolute $^{12}C(\gamma,p_0)^{11}B$ cross section in the giant dipole resonance region

E. Kerkhove, P. Berkvens, R. Van de Vyver, D. Declerck, D. Ryckbosch, P. Van Otten, H. Ferdinande, and E. Van Camp
Laboratorium voor Kernfysica, Rijksuniversiteit te Ghent, B-9000 Ghent, Belgium
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The absolute $^{12}C(\gamma,p_0)^{11}B$ cross section was measured in the energy region of the giant dipole resonance. The magnitude of our 90° differential cross section, which has an absolute uncertainty of about 12%, is in disagreement with the one obtained by detailed balance from a recent (p,γ_0) measurement, but is in reasonable correspondence with the combined data from the Argonne and Stanford groups.

I. INTRODUCTION

In a recent article, Collins *et al.*[1] reported on a new measurement of the $^{11}B(p,\gamma_0)^{12}C$ differential cross section at 90° in the giant dipole resonance (GDR) region. Their results strongly disagree with the previously available, combined data from the Stanford[2,3] and Argonne[4] groups. [One should note the fact that the $4\pi A_0$ values in the original paper of Allas *et al.*[4] contain an error in the cross section scale, but that the (p,γ_0) differential cross section at 90° is correctly shown. Indeed, converting the over-angles-integrated (p,γ_0) data to a (γ,p_0) cross section yields a peak value of 11.0 mb, while Hanna[3] quotes 13.4 mb. However, starting from the 90° cross section and taking into account the angular distribution coefficients, one directly arrives at this latter value. To this cross section an energy-independent scale-down factor has to be applied according to the suggestions of Calarco *et al.*[2]] On the other hand, our earlier results[5] for the $^{12}C(\gamma,p)^{11}B$ cross section, obtained at one bremsstrahlung end point energy (30 MeV), seemed to be in good agreement with the older data,[2–4] converted by detailed balance. Of course, a comparison between these (γ,p) and (γ,p_0) cross sections is only meaningful if the ground state branching in the $^{12}C(\gamma,p)$ reaction is close to 100%. This assumption of about negligible non-ground-state decay was based on measurements performed by Medicus *et al.*;[6] however, Collins *et al.*[1] also have doubts about this result, as the branching values of Medicus *et al.*[6] were partially based on the questioned data of Allas *et al.*[4] In an attempt to remove the present uncertainties, we have performed a careful absolute measurement of the $^{12}C(\gamma,p_0)^{11}B$ cross section and angular distributions, of which in this paper only the 90° differential cross section will be discussed.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

A. Experimental setup

Photoproton energy spectra from a 3.39 mg/cm^2 thick polystyrene target have been recorded at bremsstrahlung end point energies equal to 25, 27, and 29 MeV (with an allowed energy spread of ±0.3%). The bremsstrahlung photon beam was produced at the 70 MeV linear electron accelerator of Ghent State University, of which the beam deflection channel was calibrated in energy to an accuracy of ±0.3% using the floating wire technique. The general experimental arrangement, including this beam transport system and the layout of the detection apparatus, is extensively described in Ref. 5. The photon beam was hardened by a 19.5 cm thick graphite cylinder, placed about half-way between the Au bremsstrahlung converter target (thickness 90 mg/cm^2) and the reaction chamber. The photon beam spot size was determined by a specially-designed antiscattering collimator with a minimum aperture of 10 mm. Photoprotons were detected at seven angles simultaneously, varying between 37° and 143°, using uncooled Si(Li) solid state detectors with an active area of 200 mm^2 and a thickness of 3 mm. The angular resolution in this experiment amounted to ±3°, and is determined by the beam spot size, the dimensions of the detectors, and the collimation and shielding system that was placed in the detector channels. These detectors were energy calibrated using a mixed α source, containing ^{239}Pu, ^{241}Am, and ^{244}Cm, providing calibration lines at 5.15, 5.48, and 5.80 MeV. The accumulation and processing system for the proton signals was essentially the same as that described in a previous paper.[5]

To prevent particles other than photoprotons (especially α's) from being registered, measurements have also been performed wherein the Si(Li) detectors were shielded with thin Al foils. The thickness of these masks was varied between 25 and 100 μm, in order to determine the minimum

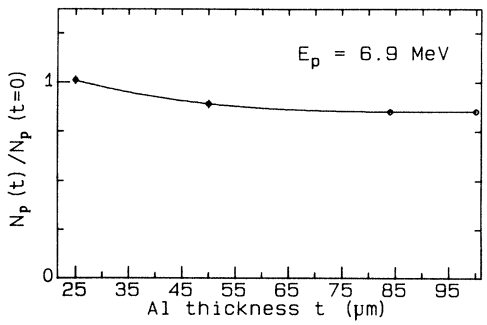

FIG. 1. The reduction of the number of counts N_p in the measured spectrum, as a function of the Al mask thickness t, at $E_p = 6.9$ MeV.

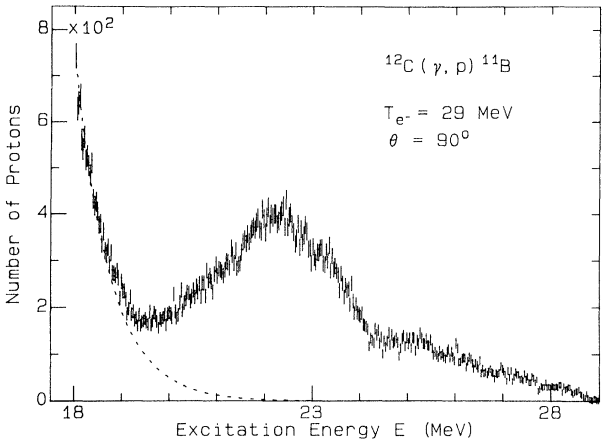

FIG. 2. A 90° photoproton spectrum taken at a bremsstrahlung end point energy of 29 MeV. The horizontal scale represents the excitation energy for ground state proton decay, i.e., $E \simeq E_p A(A-1)^{-1}+S_0$, where S_0 stands for the ground state photoproton separation energy. The dashed line shows the exponentially decreasing background.

thickness sufficient to shift the energy of the α particles down to the background region of the particle spectrum. The resulting reduction of the number of counts in the spectrum, which proved to be only slightly dependent on the proton energy E_p, seemed to reach a constant value at a foil thickness of about 100 μm (see Fig. 1). As those masks were placed directly in front of the detectors, the effect of multiple scattering on the photoproton energy distribution was negligible, but the energy loss suffered by the protons was properly taken into account. Consequently, all data and cross sections reported on in this paper are based on the photoproton spectra taken with a 100 μm Al shielding. To illustrate the quality of our data, a raw 90° photoproton spectrum, taken at an end point energy of 29 MeV, is shown in Fig. 2. The exponentially decreasing background, due to scattered γ radiation and secondary electrons, extends to an excitation energy of about 22–23 MeV, where it represents at most 1% of the actual number of counts. This is equally true for the spectra taken at end point energies of 25 and 27 MeV.

B. Analysis of the spectra

As the first and second excited states in the residual nucleus ^{11}B are located at 2.12 and 4.45 MeV, respectively, one can deduce from the measured spectra in a straightforward way the (γ,p_0) cross section between 22.9 and 29 MeV, and the (γ,p_1) cross section between 25 and 29 MeV. However, such a procedure requires the knowledge of the exact shape of the bremsstrahlung photon spectrum. Absolute knowledge of the number of photons per unit energy is not a prerequisite, as in our experiment the total photon intensity is normalized using a replica of the NBS-P2/4 ionization chamber. The overall shape of the bremsstrahlung spectrum was checked in a separate experiment, using the photoproton energy spectrum from the ^{2}H(γ,p) reaction at an end point energy of 35 MeV. From this spectrum the incident photon energy distribution was deduced using the best deuteron photodisintegration cross section, obtained in a recent accurate analysis and a fit of the experimental data.[7] The result is shown in Fig. 3. It is clear that the experimental spectral shape of the bremsstrahlung beam agrees extremely well with the calculated shape, using the Schiff integrated-over-angle (IOA) spectrum,[8] except maybe near the end point, where one should explicitly take into account the energy loss of the incident electrons suffered in the converter target. To account for this effect (together with the intrinsic uncertainty on the absolute knowledge of the electron energy, and with the energy spread of the electron beam) the Schiff IOA spectrum was calculated at an end point energy equal to 34.5 MeV.

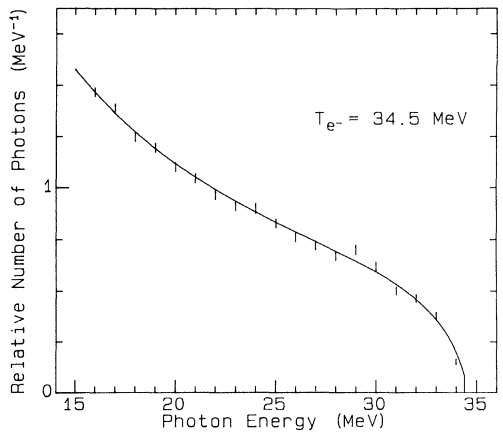

FIG. 3. The relative number of bremsstrahlung photons per unit energy; the experimental points are derived from a ^{2}H(γ,p) photoproton measurement at an end point energy of 35 MeV. The full line shows the calculated bremsstrahlung shape, at an end point energy of 34.5 MeV, using the Schiff IOA formula (Ref. 8).

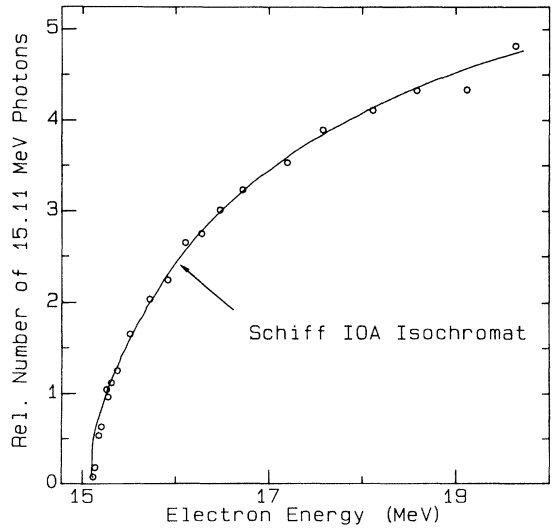

FIG. 4. Experimental isochromat for the scattering of bremsstrahlung photons from the 15.11 MeV level in ^{12}C, taken from Ref. 9. The circles represent the experimental data points for a 0.05 rl Pt target, while the solid line is the calculated Schiff IOA isochromat.

On the other hand, the accuracy of the theoretical Schiff spectrum near the end point was checked by the Melbourne group[9] in an experiment wherein isochromats from elastic scattering of bremsstrahlung photons from the ^{12}C 15.11 MeV level have been measured. The bremsstrahlung radiator consisted of a 0.05 radiation length (rl) Pt target; the result is shown in Fig. 4, wherein the solid line represents the computed Schiff IOA isochromat. The agreement between calculation and experiment is very good, except in the upper 100—200 keV region. As our bremsstrahlung converter (about 0.015 rl) is at least three times thinner than the one used in the Melbourne experiment, we feel confident that the upper 3 MeV of the experimental bremsstrahlung spectrum is also accurately described by the Schiff IOA formula. In fact this has been verified[10] by an independent study of the $^{12}C(\gamma,p)^{11}B$ reaction, the results of which were analyzed using the known cross section for this reaction that was derived by the method of detailed balance from the $^{11}B(p,\gamma_0)^{12}C$ reaction data, i.e., without the use of a bremsstrahlung photon spectrum. For this latter cross section the data of Allas *et al.*[4] were used, and the result for an incident electron energy of 23.5 MeV is shown in the lower part of Fig. 5. The points represent the experimentally determined number of photons per unit energy, while the full line shows the photon spectrum, calculated at a slightly lower end point energy (keeping in mind again the energy loss of the electrons in the Au radiator) with the use of the Schiff IOA formula. Over the entire energy range, the experimental photon spectral shape corresponds quite accurately to the theoretical spectrum. However, one could argue that this latter experiment cannot serve as conclusive evidence, as the questioned data of Allas *et al.*[4] have been used in the analysis. If, on the other hand, the results of Collins *et al.*[1] were taken (which imply an energy-dependent correction of the Argonne data), one arrives at the bremsstrahlung shape which is shown in the upper part of Fig. 5. Although the shape of the high-energy part of the spectrum still corresponds to a theoretical Schiff spectral shape (full curve), the experimental points clearly deviate from the curve at energies 1.5 MeV below the end point. As has been proven above, this is the energy region where there exists full agreement between the calculated shape of the Schiff spectrum and the experiment. This already suggests that the cross section data of Collins *et al.*,[1] apart from their absolute magnitude, do have the wrong energy dependence, which is one of the issues that we want to prove in this paper.

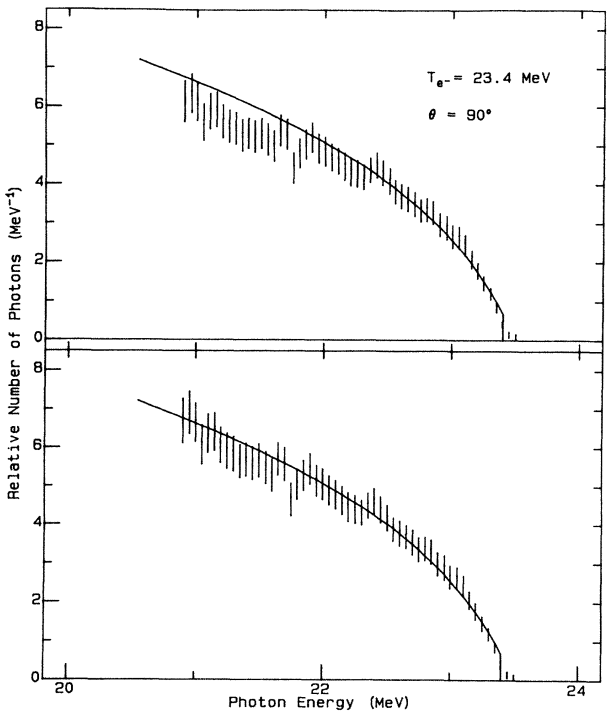

FIG. 5. The relative number of bremsstrahlung photons per unit energy; the data points are derived from a $^{12}C(\gamma,p)^{11}B$ photoproton measurement, at an electron energy of 23.5 MeV (Ref. 10), using the cross section for the inverse reaction from Allas *et al.* (Ref. 4) (lower part of the figure), or from Collins *et al.* (Ref. 1) (upper part of the figure). The solid line shows the calculated bremsstrahlung shape, at an end point energy of 23.4 MeV, using the Schiff formula (Ref. 8).

Consequently, in the determination of the ^{12}C photoproton cross sections, we are convinced that the shape of the bremsstrahlung spectrum is adequately described by the Schiff IOA expression. Nevertheless, as explained above, the end point was always slightly adjusted (with an amount of the order of 100 keV) to take into account the mean energy loss of the electrons in the radiator, the error in the absolute calibration of the beam channel, and the effect of the finite width of the energy-defining slits. This energy shift was determined by the requirement that, in the energy range where overlap occurs, the (γ,p_0) cross sections derived from measurements at different end point energies should show perfect agreement. Finally, due to their limited statistical accuracy, the top energy points in the photoproton spectrum were not taken into account in the treatment of our data.

Our analysis showed that the $^{12}C(\gamma,p_1)$ cross section turned out to be negligibly small. This is illustrated in Fig. 6, where the three 90° pseudo-ground-state cross sections are shown, obtained directly from the photoproton spectra (taken at 25, 27, and 29 MeV bremsstrahlung end

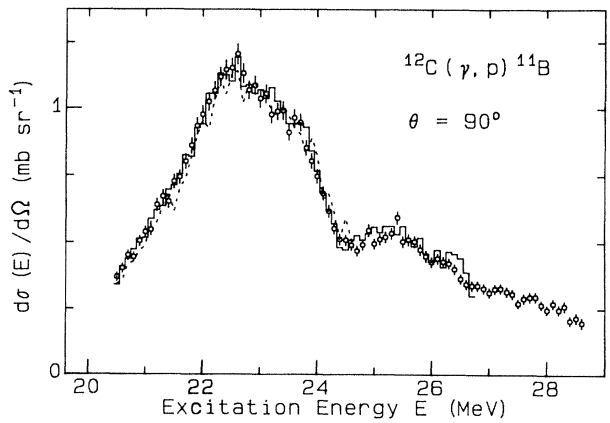

FIG. 6. Comparison of the pseudo-ground-state differential cross sections taken at end point energies of 25 MeV (dashed line), 27 MeV (histogram), and 29 MeV (data points).

point energy) under the assumption that only ground state decay occurs.

On the other hand, using a suitable linear combination of spectra taken at the three different end points, one can construct a photoproton spectrum corresponding to an artificial semimonoenergetic photon spectrum[11] at $E_\gamma \simeq 27$ MeV, with a FWHM of about 2 MeV. In spite of the poor energy resolution, this result again indicated that the (γ,p_1) as well as the (γ,p_2) cross sections are small around 27 MeV excitation energy. From the above arguments, a realistic estimate of the branching to the ^{11}B ground state in this energy region amounts to $(90\pm4)\%$, in good agreement with the conclusions of Medicus *et al.*[6]

III. RESULTS AND DISCUSSION

A. Results and error discussion

As the prime intention of this paper was to make a detailed comparison with the results of Collins *et al.*,[1] the further discussion will be limited to the 90° differential photoproton cross section. In Fig. 7 this absolute $^{12}C(\gamma,p_0)$ cross section is shown in the energy region between 22.9 and 29 MeV. In the interval 20.5–22.9 MeV a pseudo-ground-state cross section is depicted, where a few percent (γ,p_1) contamination may be present. The error bars on the individual data points only represent the statistical uncertainties. However, the absolute accuracy of the cross section values is mainly determined by the systematic uncertainties that are inherent to the experiment. The individual contributions to this source of error are the following:

(a) The polystyrene target: Its mean thickness and its purity are accurately known, but its inhomogeneity is smaller than 2%.

(b) The angle between the target and the incident beam direction is determined to better than 0.5°, causing an uncertainty of 1% on the effective sample thickness.

(c) The angle between beam direction and detector (90°) and the angular resolution (±3°) cause a negligible effect.

(d) The solid angle subtended by the detector with respect to the target was calculated using a Monte Carlo procedure[12] with an error well below 1%.

(e) The calibration constant of the NBS-P2/4 ionization chamber, adjusted for the temperature and the pressure of the air in the chamber, is accurate to about 3%.

(f) The BIC-Mod 1000 ionization current integrator is responsible for a negligible error.

(g) The attenuation of the bremsstrahlung photon beam in the 19.5 cm thick graphite beam hardener was calculated using the numerical tables of Hubbell *et al.*,[13] leading to an uncertainty of the order of 1%.

(h) The bremsstrahlung photon spectral shape is adequately described by the Schiff IOA formula within 3% (see Sec. II B).

(i) The uncertainty on the knowledge of the end point energy and the energy spread are taken into account by the determination of an effective end point energy (see Sec. II B).

(j) Errors caused by the calibration of the proton energy scale (using an α source) are believed to be less than 0.5%, while the effects due to the limited proton energy resolution (mainly determined by the target thickness) are negligible, as the $^{12}C(\gamma,p_0)$ cross section does not show pronounced structure.

(k) Pileup effects in the electronic apparatus have been kept low by adjusting the incident photon beam intensity; nevertheless, a correction for eventual count losses has been applied, resulting in a maximum error of 0.5%.

(l) Finally, the subtraction of the exponential background,[11] which extends up to 22.5 MeV, may result in a maximum error of 5% at 21 MeV, but is negligible in the remainder of the energy region (22–29 MeV).

Consequently, we estimate the total systematic error which contributes to the (γ,p_0) cross section in the energy interval 22.9–29 MeV to be smaller than 12%.

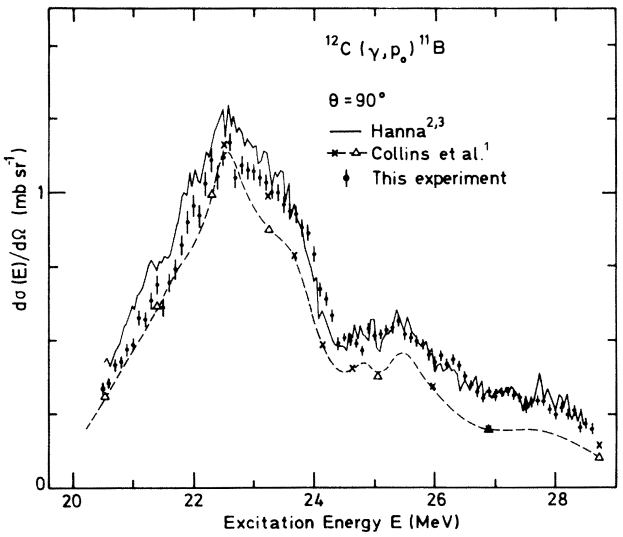

FIG. 7. The absolute 90° differential $^{12}C(\gamma,p_0)^{11}B$ cross section obtained in this experiment, as compared with the results of Collins *et al.* (Ref. 1) (dashed line) and of the Stanford and Argonne group (Refs. 2–4) (full line).

B. Discussion of results

In Fig. 7 our $^{12}C(\gamma,p_0)$ cross section results are compared to the (p,γ_0) data from Stanford and Argonne[2–4] and of Collins *et al.*,[1] converted by detailed balance. It is obvious that the agreement between our data and those of the Stanford and Argonne groups is remarkable in the energy region between 23.5 and 29 MeV, where the discrepancy, according to Collins *et al.*, is the most pronounced.

Since Collins *et al.*[1] prefer to use the older Argonne results[4] as a "reference," we will proceed in the same manner. In Fig. 8 the ratio of the various 90° differential (γ,p_0) cross sections to the data of Allas *et al.*[4] is plotted. The data points are deduced from our experimental result (averaged over 0.5 MeV), while the dashed line represents the ratio proposed by Collins *et al.*[1] The full line is the suggested normalization factor (equal to 0.9) between the Stanford[2,3] and the Argonne[4] data. The histogram depicts the ratio based on the relative measurement of Snover

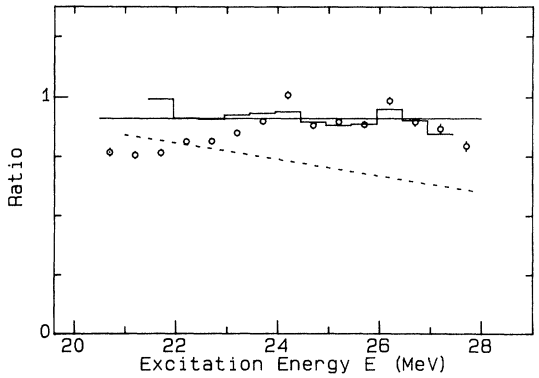

FIG. 8. The ratio of the various 90° differential (γ,p_0) cross sections to the data of Allas *et al.* (Ref. 4): Our result, data points; Hanna (Refs. 2 and 3), full line; Collins *et al.* (Ref. 1), dashed line; and Snover *et al.* (Ref. 14), histogram.

et al.,[14] normalized to the cross section of Hanna[2,3] around 22.4 MeV. In the latter case what is important, however, is not the value of the ratio, but the fact that it remains fairly constant over the entire energy region, confirming the energy dependence of the Argonne data. The ratio obtained with our data agrees neither with the suggested constant value[2,3] of 0.9, nor with the correction factor of Collins *et al.*[1] However, the disagreement with the Stanford result[2,3] is only significant at lower energies ($E<23$ MeV), while the correspondence at higher energies is remarkable, as can be seen from Fig. 7. On the other hand, in the rising edge of the giant dipole resonance, our cross section values seem to be in fair agreement with the data of Collins *et al.*,[1] although in the lower energy region our results have to be interpreted with some caution, as discussed above. However, the magnitude at the peak of our cross section amounts to 1.17 ± 0.12 mb/sr, which is in extremely good agreement with the value of 1.16 ± 0.12 mb/sr as quoted by Collins *et al.*;[1] moreover, the Stanford value[2,3] of 1.31 ± 0.13 mb/sr is also compatible with the above results.

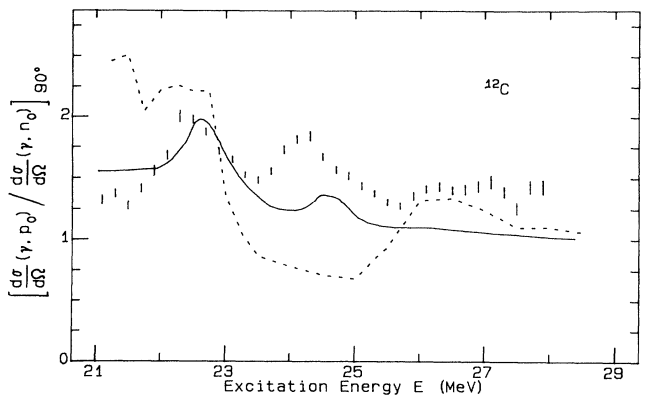

FIG. 9. The ratio of the differential $^{12}C(\gamma,p_0)$ to the $^{12}C(\gamma,n_0)$ cross section (Ref. 15) at 90°: This work, data points; Collins *et al.* (Ref. 1), full line. The result of the theoretical calculation by Birkholz (Ref. 16) is shown as the dashed line.

One of the arguments presented by Collins *et al.*[1] to support their preference for their data over those of Hanna[2,3] is the comparison between the experimental and theoretical values for the quantity $[\sigma(\gamma,p_0)/\sigma(\gamma,n_0)]_{90°}$. This ratio, based on our (γ,p_0) cross section and on the data of Collins, respectively, and the (γ,n_0) cross section of Wu *et al.*,[15] is shown in Fig. 9. It is quite obvious that the theoretical result[16] agrees with neither of the experimental values. Although the curve derived from the result of Collins seems to approach the theoretical estimate[16] reasonably well in the high energy region (up to 35 MeV), one should keep in mind that such extrapolation is based on a limited set of data points. Furthermore, we believe that a discussion of the extracted $E2$ cross section, as presented in Ref. 1, also cannot provide a reasonable means of distinguishing between the various experimental results: There seem to be too many uncertainties left, and the sum rule fraction obtained in the (γ,p_0) channel remains inexplicably high, whatever result is used.

Data on the dipole sum, however, are much better known and may eventually serve as a good reference. In the excitation energy region covered by this work (20.5—28.8 MeV), the integrated cross section for the (γ,p_0), (γ,n_{tot}), and (γ,tot) reactions are equal to 49 ± 1 MeV mb (this result), 42 ± 1 MeV mb (Ref. 17), and 103 ± 2 MeV mb (Ref. 18), respectively. The (γ,p_0) result was derived using the measured angular distributions, also determined in the present experiment (and which will be reported on in a forthcoming paper); our angular distribution coefficients are in good agreement with the data of Allas *et al.*[4] Besides the above-mentioned reaction channels, the total absorption cross section $\sigma(\gamma,tot)$ can include contributions from the (γ,α) and $(\gamma,p_{i\neq0})$ reactions. From older measurements[19] of the (γ,α) reaction, its integrated cross section in the energy interval 20.5—28.8 MeV can be estimated to lie between 1 and 2 MeV mb. Later experiments[20,21] indicated, however, that these older results are about 50% too high. Consequently, a reasonable estimate of the (γ,α) contribution seems to be at most 1 MeV mb. The $(\gamma,p_{i\neq0})$ reaction cross sections may amount to 10—15 % of the (γ,p_0) value (see above), and contribute therefore about 5—8 MeV mb. The sum of all partial cross sections leads to an estimated value of 97—100 MeV mb, remarkably close to the Mainz (γ,tot) result.[18] If, however, one were to rely on the (γ,p_0) data of Collins *et al.*,[1] and using our angular distribution coefficients, one would obtain for the integrated cross section a value of 41 MeV mb, leading to an integrated total cross section of 88—91 MeV mb.

Recently, the absolute magnitude of the integrated total photonuclear cross sections, as measured by the Mainz group,[18] has been questioned[22] for ^{16}O. However, as far as the ^{12}C case is concerned, the absolute cross section scale of the Mainz results has been confirmed in a very recent experiment[23] of nuclear photon scattering by ^{12}C, from which the absolute total photonuclear absorption cross section could be determined around 23.5 MeV. Moreover, the sum of the partial cross sections (integrated up to 30 MeV) is also in satisfactory agreement[24] with the data of Ahrens *et al.*[18] This shows that the above comparison with the integrated cross section is appropriate.

IV. CONCLUSIONS

In conclusion, in the present experiment we have determined the absolute $^{12}C(\gamma,p_0)^{11}B$ cross section in the GDR region, with an uncertainty of about 10%. Our 90° differential cross section is in good agreement with the older results,[2–4] especially in the energy region between 23.5 and 29 MeV, although there exists a slight but definite deviation at lower energies. Anyhow, we cannot confirm the data of Collins *et al.*,[1] and therefore the proposed 30—40% reduction of the Argonne cross section[4] in the interval 24—29 MeV seems to be unrealistic.

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