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Branching ratios for the $^{12}C(\gamma,p)$ reaction at an excitation energy of 28 MeV

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Photoparticle spectra from the $^{12}C(\gamma,p_i)$ and $^{12}C(\gamma,\alpha_0)$ reactions have been measured in an angular aperture (FWHM) of 60° centered around 90°, using 28 MeV quasimonochromatic photons from annihilation-in-flight of positrons. The branching ratio for the (γ,α_0) to (γ,p_0) transition amounts to $(2.9\pm1.2)\%$, while the (γ,p_i) branching to excited states in ^{11}B contributes $(24\pm2)\%$ to the observed (γ,p) cross section.

This paper reports on the branching ratios of the decay of the giant dipole resonance (GDR) in ^{12}C. More specifically, the photoproton decay to various excited states in ^{11}B was determined. This experiment can be seen as a natural sequel to our previous high-accuracy studies of the (γ,p_0) reaction on ^{12}C.[1,2] These studies served to settle the discrepancy between the existing (p,γ_0) experiments.[3,4] The purpose of this experiment was to obtain a direct measurement of the (γ,p_i) decay to excited states in ^{11}B, since for the magnitude of such transitions rather conflicting results have been obtained.[5,6] For a recent review of the experimental situation, see Ref. 7.

The physical interest of such an experiment lies in the fact that it yields, at low excitation energy, a comparison with the very recently determined branching ratios in the quasideuteron region.[8] At $E_\gamma=60$ MeV, a surprisingly strong branching to states with an excitation energy ≈ 7 MeV in ^{11}B was observed. Since such transitions are barely seen in the quasifree $(e,e'p)$ knockout reactions,[9] it indicates a different absorption mechanism for real photons, at least in the quasideuteron energy region. Experiments at lower energy, in the GDR, can indicate how far this strong transition to those excited states is specific for the quasideuteron region. Moreover, a comparison with the $(e,e'p)$ results can show how the branching to various states is modified when the reaction proceeds almost completely through a single collective doorway, the GDR, rather than via a quasifree knockout process. As such, it could give more information on the structure of the GDR than a study of the (γ,p_0) reaction only. A recent summary of the theoretical studies of the excitation and the decay of the dipole resonance in $1p$-shell nuclei in general, and ^{12}C in particular, was given by Goncharova *et al.*[10]

Quasimonochromatic annihilation photons with an energy of 28 MeV were produced by positrons (with a kinetic energy of 27.4 MeV) from the positron acceleration facility at the 90 MeV electron linac of Ghent State University. The general experimental arrangement has been extensively described in Ref. 11. In this experiment, a 0.5 mm thick Be foil was used as an annihilation target. Typical average positron currents are of the order of 4 nA, resulting in a photon flux of $\approx 10^4\ s^{-1}$ on the target.

The photonuclear target was a polystyrene foil $[(C_8H_8)_n]$ with a thickness of 8.04 mg/cm^2, positioned at an angle of 30° with respect to the forward γ-beam direction. At the target position, the photon beam had a radius of about 8 mm. Two uncooled, large area (1250 mm^2) Si(Li) detectors with a thickness of 2 mm were used to detect the emitted photoparticles. They were placed at a distance of only 25 mm from the center of the target, at an angle of 90° to the photon beam. Such a close geometry only enables us to measure an effective "perpendicular" cross section $\sigma_\perp$, given by

$$\sigma_\perp=\int_{\Delta\Omega}\frac{d\sigma}{d\Omega}d\Omega\ .$$

The effective solid angle was calculated with a Monte Carlo method,[12] and amounted to 1.328 msr. Photoparticles are detected in an angular aperture with a FWHM of 60° around 90°.

Apart from the quasimonochromatic annihilation photons, the positrons will also generate a continuous bremsstrahlung spectrum in the Be foil. The resulting contribution to the photoparticle spectrum was determined in separate runs with electrons of the same kinetic energy. Data were taken with a low-intensity electron beam (≈ 3 nA) irradiating the annihiltion target during almost the same time interval (≈ 50 h) as in the positron runs. Raw pulse height spectra for the e^+ and e^- runs are displayed in Fig. 1. The low-energy exponential background in the spectra, due to (Compton) electrons and indicated by the dashed lines in Fig. 1, was subtracted from the spectra of both e^+ and e^- runs. The electron-induced spectra were then normalized to the positron ones, on the basis of the total charge collected in the Faraday cup during both runs. In this way the bremsstrahlung-related part of the photoparticle spectrum can be removed, thus leaving the contribution from the quasimonochromatic annihilation photons only. As the ratio of the number of annihilation photons to the number of incoming positrons is not exactly known for the present experimental conditions, only relative cross sections could be derived.

Apart from protons, only α particles are emitted from the target and observed in the detectors. The few counts visible above the (γ,p_0) peak in Fig. 1 are due to the (γ,α_0) reaction. From the net particle spectra (after sub-

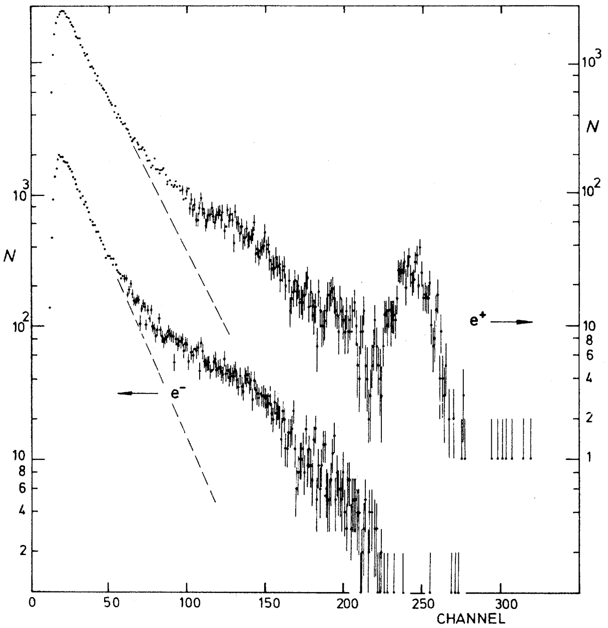

FIG. 1. Photoparticle pulse height spectra obtained in runs with 27.4 MeV positrons (right-hand scale) and electrons (left-hand scale).

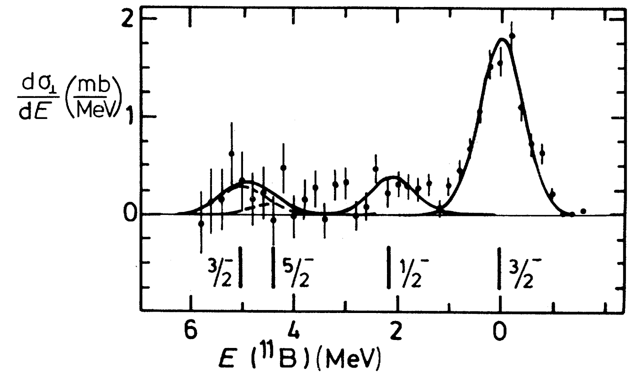

FIG. 2. The relative ^{12}C photoproton perpendicular cross section versus the excitation energy in the residual nucleus ^{11}B. The solid line is the result of a fit with a sum of Gauss curves corresponding to the population of various excited states, indicated below the spectrum.

traction of the bremsstrahlung contribution) one finds for the branching ratio

$$\frac{\sigma_\perp(\gamma,\alpha_0)}{\sigma_\perp(\gamma,p_0)}=(2.9\pm1.2)\% ,$$

where the quoted uncertainty is purely statistical. Such small branching already indicates that the influence of α_0 particles on the spectra will be extremely small. However, whereas the (γ,α_0) decay is isospin-forbidden, the (γ,α) reaction leading to the $T=1$ states in ^{8}Be at 16.63, 16.92, and 17.64 MeV is not. As such, the fact that roughly 90% of the (γ,α) reaction leads to these states[13] is not surprising. Since these states decay into two α's, one expects in the spectra a broad distribution of alphas extending from about 8.5 MeV downwards. This contribution to our spectra was calculated[1,13] with a Monte Carlo method and subtracted from the spectra to yield finally the net photoproton perpendicular cross section, given in Fig. 2.

Decay of the GDR to the ground state ($\frac{3}{2}^-$) is clearly observed, while decay to the first excited state ($\frac{1}{2}^-$; 2.125 MeV) and third excited state ($\frac{3}{2}^-$; 5.020 MeV) in ^{11}B is much less pronounced. From proton knockout studies it is well known that these three states carry almost all of the $p_{3/2}$-hole strength. A sum of Gauss curves with a width of 1 MeV and position corresponding to the ground state and three lowest excited states was fitted to the data. No statistically significant decay to the $\frac{5}{2}^-$; 4.445 MeV state was observed. The deduced photoproton branching ratios are $(76\pm4)\%$ for the (γ,p_0), $(13\pm1.3)\%$ for the (γ,p_1), and $(11\pm1.2)\%$ for the (γ,p_{2+3}) decay cross section. This means that at 28 MeV excitation energy, the branching ratio of the (perpendicular) (γ,p) cross section for transitions leading to excited states in ^{11}B equals $(24\pm2)\%$.

In his recent review, Fuller (Ref. 7, Figs. 2.1 and 2.3) suggests $(49^{+11}_{-7})\%$ for this ratio in the angle-integrated cross sections. For the 90° differential cross section at the same excitation energy of 28 MeV, a value of $(50\pm10)\%$ was deduced in Ref. 6. On the other hand, Medicus *et al.*[5] claim only 10% for this ratio in the energy-integrated differential cross section at 112°. It is important, however, to keep in mind that all these figures originate from investigations where no direct observation of the decay to excited states was made, as in this work. Indeed, Fuller obtained the value of 49% from a comparison of the (γ,p_0) cross section to the difference between the total absorption cross section and the sum of the (γ,n), $(\gamma,3\alpha)$, and $(\gamma,{}^3\text{He})$ cross sections. Any discrepancy in any of these cross sections [the controversy about the (γ,p_0) cross section may serve as an example] may lead to large errors in his deduced branching ratios. The value given by Ishkhanov *et al.*[6] results from a comparison of the photoproton spectra obtained with

TABLE I. Branching ratios for the perpendicular cross section (this work) or the total cross section (theory) in the (γ,p_i) channel for ^{12}C at 28 MeV excitation energy compared to spectroscopic factor ratios in ^{12}C$(e,e'p)$.

Transition →state i	This work	Theory[a]	Theory[b]	$(e,e'p)$[c]
g.s.	0.76±0.4	0.44	0.47	0.79
2.125	0.13±0.013		0.23	0.12
4.445	0.11±0.012	0.56	0.13	
5.020			0.17	0.09

[a] Reference 14.
[b] Reference 15.
[c] Reference 9.

bremsstrahlung at slightly different end-point energies. In view of the dominance of the (γ,p_0) cross section, the systematic uncertainties inherent to such difference methods are bound to be large. Finally, the data of Ref. 5 are deduced from the deexcitation gamma spectrum after irradiation with a continuous bremsstrahlung beam and thus represent only differential cross sections integrated from threshold up to a certain end-point energy. Since our data are the first reported, obtained with quasimonochromatic photons and a direct observation of the decay to the ^{11}B states, we believe that the older data should be regarded with caution.

The fact that the $\frac{5}{2}^-$ state at 4.445 MeV is not significantly excited is consistent with the observations in the (γ,p) reaction at 60 MeV excitation energy.[8] Also in quasifree knockout $(e,e'p)$ reactions, this excitation corresponds to a weak transition.[9] In contrast to the situation with real photons of 60 MeV, however, where a strong transition is seen to states at an excitation energy of about 7 MeV in ^{11}B, no indications for such transitions are found in this experiment. Notwithstanding the fact that the systematic errors in our experiment increase in this energy region, due to the larger bremsstrahlung contribution to be subtracted, it is very difficult to see that a transition with the strength observed in Ref. 8 could be missed. As such, we conclude that this strong transition is specific to the quasideuteron energy region, and is indeed likely to carry information on the absorption mechanism pertinent to that region.

In Table I, we compare the branchings found in this work with the $(e,e'p)$ data from Ref. 9 and the available theoretical calculations.[14,15] Within the experimental errors, the branching ratios observed in the present reaction, which proceeds through the high-energy tail of the GDR, are equal to those found in the quasifree $(e,e'p)$ reaction. The structure of the GDR thus hardly seems to modify the transition strengths at this excitation energy. This is, however, in contrast to the situation expected from the theoretical work, where a stronger branching to the excited states is predicted. It is probably worthwhile to add here that in $(e,e'p)$ reactions proceeding through the $E1$ resonance, but at a much higher momentum transfer than probed with real photons, one finds a larger branching ratio for the $(e,e'p_1)$ channel[16] than obtained here. A comprehensive study of the proton decay branchings in the decay of the $E1$ resonance at different values for the momentum transfer could thus yield valuable information on the particle-hole structure of the GDR.

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