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

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The absolute differential cross sections for the reaction $^{12}C(\gamma, p_0)^{11}B$ were measured at seven angles in the energy region between 21 and 29 MeV. Using a standard Legendre polynomial expansion, the total integrated-over-angles absolute $^{12}C(\gamma, p_0)$ cross section was derived, as well as the angular distribution coefficients a_i $(i=1, \ldots, 4)$. Taking into account the statistical and systematic uncertainties, the present data confirm reasonably well the (p, γ_0) results of Allas *et al.*, both with regard to the absolute value and to the shape of the cross section, with the exception of the a_2 coefficient in the low energy region.

In a previous paper[1] we presented the results of an accurate measurement of the absolute 90° differential cross section for the $^{12}C(\gamma, p_0)$ reaction, in the energy region of the giant dipole resonance (GDR). During the same experiment photoproton energy spectra were recorded at seven different angles. The absolute integrated-over-angles cross section $\sigma(E)$ and the angular distribution coefficients could be derived from the well-known Legendre polynomial expansion

$$\frac{d\sigma}{d\Omega}(E,\theta)=\frac{\sigma(E)}{4\pi}\left[1+\sum_{i=1}^{n}a_i(E)P_i(\cos\theta)\right], \quad n=4 .$$

The general experimental arrangement was extensively described previously[2] while the details on the experimental procedure and data analysis can be found in Ref. 1. For the sake of clarity, however, a number of relevant items will be briefly discussed below.

Energy-analyzed electrons (with an allowed energy spread of ±0.3%) from a 90 MeV linear electron accelerator impinged upon a 90 mg/cm^2 Au bremsstrahlung converter target; the resulting photon beam was cleared from residual electrons by means of a cleaning magnet and was subsequently geometrically defined by a special antiscattering collimator (with a minimum aperture of 10 mm). Furthermore, the bremsstrahlung beam was hardened by a 19.5 cm thick graphite cylinder.

As a reaction target, a 3.39 mg/cm^2 thick polystyrene foil $(C_8H_8)_n$ was used, and the emitted photoprotons were detected at seven angles simultaneously (varying between 37° and 143°) using 3 mm thick uncooled Si(Li) detectors, with an active area of 200 mm^2; the angular resolution amounted to ±3°. The energy calibration of the detectors was performed by means of a mixed α source (containing ^{239}Pu, ^{241}Am, and ^{244}Cm). Photoproton energy spectra were recorded at three bremsstrahlung endpoint energies equal to 25, 27, and 29 MeV. Great care was taken to prevent particles other than photoprotons from being detected [especially those originating from the (γ, α) reaction, with a reaction threshold of 7.4 MeV]. For that purpose measurements were also performed wherein the detectors were shielded with 100 μm thick Al foils; this thickness was sufficient[1] to shift the energy of the α particles down to the background region (normally extending to about 5–6 MeV particle energy) of the spectra. For the monitoring of the absolute total photon intensity, a replica of the NBS-P2 ionization chamber was used. However, in order to determine the absolute cross section from the experimental data, the exact shape of the bremsstrahlung photon spectrum must be known. In Ref. 1 we have given extensive arguments proving that this shape is adequately described by the theoretical Schiff integrated-over-angles (IOA) expression.[3] Finally, as in the residual nucleus ^{11}B the first excited state is located at 2.12 MeV, the (γ, p_0) cross section can be deduced straightforwardly from the measured photoproton spectra, taken at the three mentioned bremsstrahlung end point energies, in the energy interval between 22.9 and 29 MeV.

The resulting integrated-over-angles cross section $\sigma(E)$ is shown in Fig. 1, while in Fig. 2 the angular distribution coefficients a_i $(i=1, \ldots, 4)$ are depicted. The error bars on the data points represent the statistical uncertainty only. As discussed in Ref. 1, the additional systematic error on $\sigma(E)$ could at most amount to about 12% in the energy in-

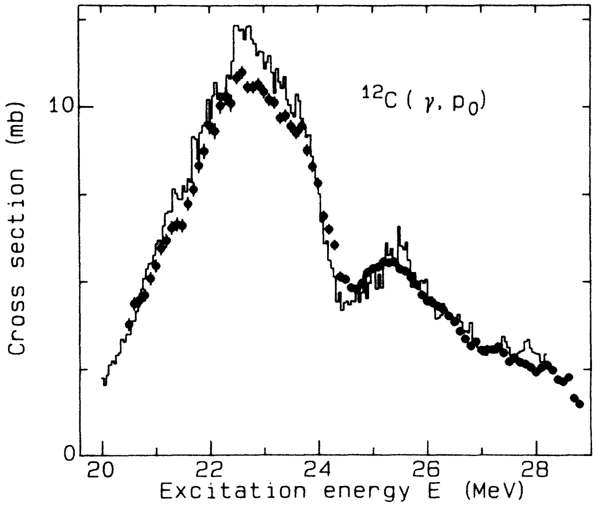

FIG. 1. The absolute total $^{12}C(\gamma, p_0)^{11}B$ cross section obtained in this experiment; the histogram represents the results of the Stanford and Argonne group (Refs. 5–7). The error bars represent the statistical uncertainty only.

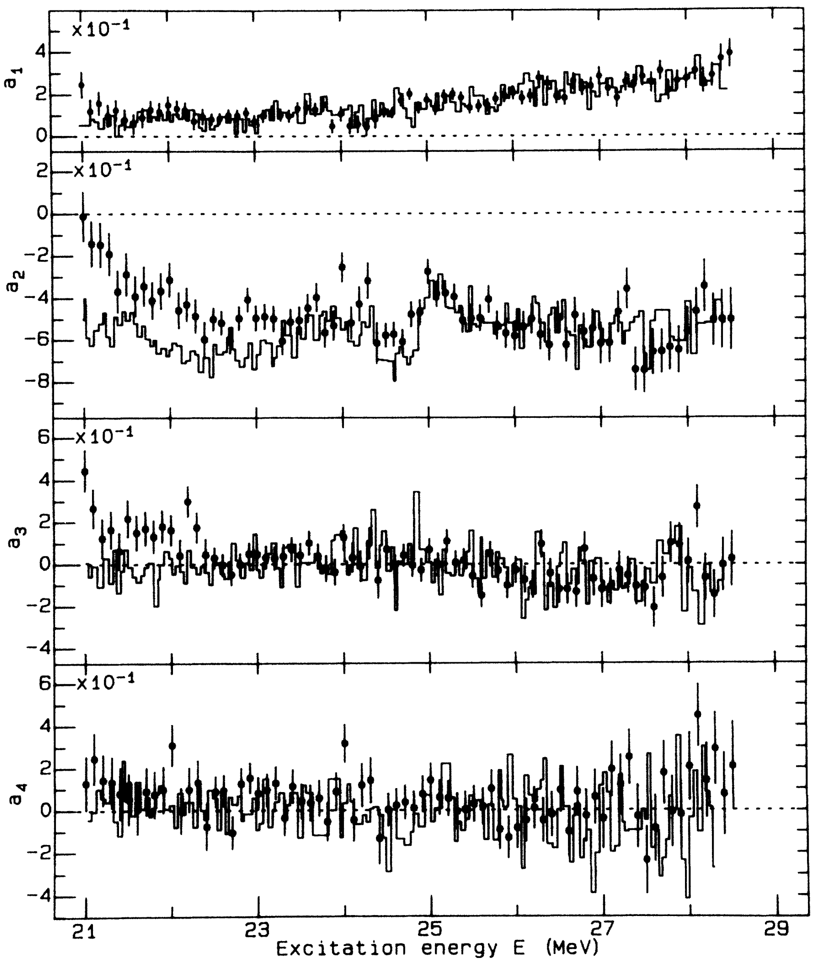

FIG. 2. The photoproton angular distribution coefficients deduced from a Legendre polynomial fit, as a function of the excitation energy. The solid line again shows the results of the Stanford and Argonne group (Refs. 5–7). The error bars represent the statistical uncertainty only.

terval from 22.9 to 29 MeV. Most probably, this uncertainty will increase towards lower energies due to the background subtraction procedure. Moreover, as the background contribution is relatively more important at forward angles, the associated uncertainty will be angle dependent, resulting in an additional error on the angular distribution coefficients as well. Although realistic quantitative estimates of this uncertainty cannot be given, it is believed to be relatively important at photoproton energies up to 5–6 MeV (i.e., 21–22 MeV excitation energy), decreasing to an almost negligible effect at higher energy. Finally, above 22.9 MeV excitation energy, the shown $\sigma(E)$ result represents a pure (γ,p_0) cross section, while at lower energies a contribution from the (γ,p_1) reaction is included. This latter contribution, however, should have only a limited significance because of the following considerations. (a) The intensity of the bremsstrahlung photon beam is rather small in the upper 2 MeV end point energy region (23–25 MeV) wherefrom the "contaminating" (γ,p_1) protons originate; in our analysis these particles are wrongly placed 2.12 MeV too low in the pseudoground state cross section, while on the other hand, the (γ,p_0) protons are created by photons from the 21–22.9 MeV energy interval, i.e., with a much larger relative intensity. (b) The (γ,p_1) cross section itself is most probably much smaller than the (γ,p_0) cross section, at least below 23 MeV excitation energy; from an experiment with monochromatic photons,[4] performed at our laboratory, a branching ratio $\sigma(\gamma,p_1)/\sigma(\gamma,p_0) \leq 0.17$ was obtained at 28 MeV, and this ratio is bound to decrease towards lower excitation energies [the (γ,p_1) reaction threshold being 2.12 MeV higher than the (γ,p_0) threshold].

The only absolute angular distribution data for the $^{12}C(\gamma,p_0)^{11}B$ reaction, available up till now, are those deduced from a (p,γ_0) measurement of Allas *et al.*[5] The angular distribution results from Carchon *et al.*[2] are not useful as reference data, as no attempt was made to make a separation between ground state and nonground state photoprotons (still, it is worth noting that the reported angular distribution coefficients agree quite well with the data of Allas *et al.*, again suggesting small nonground state contributions at excitation energies below 28 MeV). For comparison, the results of Allas *et al.*[5] are also shown in Figs. 1 and 2 as solid lines. The curve in Fig. 1 was obtained from the 90° $^{11}B(p,\gamma_0)^{12}C$ differential cross section (Fig. 6 in Ref. 5), normalized to the results of Calarco *et al.*[6] and combined with the angular distribution coefficients of Ref. 5, to yield an integrated-over-angles cross section, which was then converted by detailed balance. (Note that this

TABLE I. Total ^{12}C(γ, p$_0$) cross section values at $E \simeq 22.5$ MeV.

Reference	$\sigma(E)$ (mb)	$\Delta\sigma(E)$ (mb)	Remarks
Allas *et al.* (Ref. 5)	12.2	1.2	Interpreted according to Hanna (Ref. 7)
Carchon *et al.* (Ref. 2)	13.1	0.8	(γ, p$_0$+p$_1$)
Collins *et al.* (Ref. 8)	10.9	1.1	Deduced from the 90° differential cross section
This work	11.0	1.1	Contains a small amount of (γ, p$_1$) below 22.9 MeV

result does not agree with the values one would obtain directly from the total cross section in Ref. 5—their Fig. 13—but our procedure is stated to be correct by one of the authors.[7]) The agreement between our data points and the curve is very satisfying, both in shape and in absolute magnitude (with some reserve in the leading edge and in the peak of the cross section), taking into account the systematic error of about 10%, inherent to both measurements. This is also illustrated in Table I, where the ^{12}C(γ, p$_0$) cross section maxima (situated at an energy of about 22.5 MeV) obtained in various recent experiments are compared with our results and those of Allas *et al.* Note that the value quoted in Ref. 2 is somewhat higher than the others, probably because of the inclusion of nonground state decay. The value of Collins *et al.*[8] was derived from their 90° differential (p, γ_0) cross section, combined with the angular distribution coefficients of Allas *et al.*,[5] and converted by detailed balance. As far as the energy-integrated (γ, p$_0$) cross section is concerned, we refer the reader to the discussion presented in Ref. 1.

Figure 2 shows the angular distribution coefficients of Ref. 5 (again presented as full lines) for comparison with our results. The two sets of data agree reasonably well at energies above about 23 MeV, confirming their reliability. The observed deviations in the low energy region, especially in the a_2 and a_3 angular distribution coefficients, seem to have some real significance, as only part of them can be explained by angle-dependent inaccuracies in our background subtraction (see higher) and, to a lesser extent, by contributions from the (γ, p$_1$) reaction.

Concluding, it seems that there exists now a fair correspondence between the results from the (γ, p$_0$) and the (p, γ_0) measurements for the determination of the ^{12}C ground state photoproton cross section, certainly in the energy region between 23 and 28 MeV, settling a longstanding discrepancy between the results from both types of experiments.

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