PHYSICAL REVIEW C VOLUME 47, NUMBER 3 MARCH 1993

Behavior of the Be and C total photonuclear cross section in the nucleon resonance region

M. Anghinolfi,(1) V. Lucherini,(2) P. Rossi,(3) N. Bianchi,(2) P. Corvisiero,(1) A. Deppman,(2) E. De Sanctis,(2) A. Ebolese,(2) A. Fantoni,(2) G. Gervino,(4) H. A. Gimm,(5) P. Levi Sandri,(2) L. Mazzaschi,(1) V. Mokeev,(1) V. Muccifora,(2) E. Polli,(2) A. R. Reolon,(2) G. Ricco,(1) M. Ripani,(1) M. Sanzone,(1) M. Taiuti,(1) G. M. Urciuoli,(3) and A. Zucchiatti(1)

(1)*Istituto Nazionale di Fisica Nucleare— Sezione di Genova e Dipartimento di Fisica dell'Università, I-16146 Genova, Italy*

(2)*Istituto Nazionale di Fisica Nucleare—Laboratori Nazionali di Frascati, P.O. 13 I-00044 Frascati, Italy*

(3)*Istituto Nazionale di Fisica Nucleare—Sezione Sanità, Viale Regina Elena 299, I-00185 Roma, Italy*

(4)*Istituto Nazionale di Fisica Nucleare—Sezione di Torino e Dipartimento di Fisica dell'Università, I-10125, Torino, Italy*

(5)*Max-Planck-Institute for Chemistry, D-6500, Mainz, Germany*

(Received 25 November 1992)

We present the total photonuclear cross section for Be and C measured between 200 and 1100 MeV, with the aim of clarifying the existence of a resonant behavior in the region above the Δ. We used a tagged photon beam and the transmission technique. The results show no evidence of baryon resonances that are clearly seen at ≈ 700 and ≈ 1000 MeV in photon absorption on the proton and the deuteron.

PACS number(s): 25.20.−x

The absorption of photons by nuclei has been investigated in many laboratories over a wide range of mass numbers and photon energies. From already existing data we may conclude that (i) in the Δ region, the shape and the strength of the total photoabsorption cross sections per nucleon, σ_n / A, are essentially the same for different nuclei [1,2], indicating an incoherent or volume-like absorption; (ii) above 2 GeV, the shadowing effect is well established, showing the relevance of the hadronic fluctuations of the photon [3]. In the region between about 500 MeV and about 2 GeV, the data on proton [4] and deuteron [5] show that the photon is able to excite nucleon resonances of mass higher than the Δ and with different quantum numbers [3]. For the heavier nuclei, there are only two data sets, both measured at Yerevan by detecting reaction products. The first set [6] was collected between 250 and 2700 MeV with an energy resolution ≥ 100 MeV, which could lead to smoothing of the higher resonance peaks. The second set [7] was obtained for photon energies ≤ 850 MeV and, in spite of a better energy resolution (≤ 40 MeV), was not able to draw a definitive conclusion. It is therefore not yet clear how these higher energy nucleon excited states couple to the photon and propagate inside the nucleus.

In this paper we present the results of the measurement of the total photonuclear absorption on Be and C, carried on at Frascati with the aim of investigating the possible presence of resonant behavior in the cross section for the region above the Δ. We used the Jet Target tagged photon beam [8], the transmission technique, and a BGO crystal photon spectrometer.

The photon beam was produced by the bremsstrahlung on an internal target of the electrons circulating in the ADONE storage ring (the maximum electron energy available was 1200 MeV). The radiator was a clustered, molecular argon beam [9] of $\leq 10^{-10}$ radiation length thickness in order not to degrade the circulating beam quality, and lifetime [10]. The recoil electrons were momentum analyzed by the next ADONE dipole and detected by a tagging hodoscope, which provided a constant photon energy resolution over the whole tagging range.

A schematic view of the experimental apparatus is shown in Fig. 1. Three magnets M1, M2, and M3 swept the charged particles off the photon beam, which was defined in size by the two collimators C1 and C2. The signals of the ADONE electron orbit monitors M8 and M9 were used to actively stabilize the electron orbit in

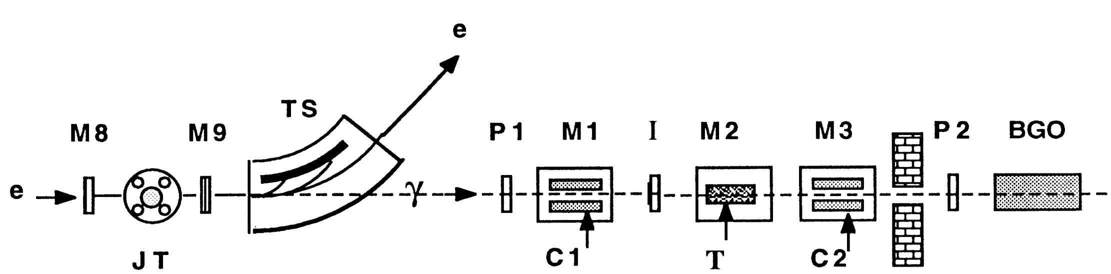

FIG. 1. Layout of the Jet Target photon beam (not to scale): JT, jet target; TS, tagging system; P1 and P2, movable photon beam profile chambers; M1, M2, and M3, sweeping magnets; C1 and C2, collimators; M8 and M9, electron orbit monitors; I, photon beam relative monitor; T, target; BGO, crystal photon spectrometer.

the Jet Target straight section to better than 0.1 mm. Two multiwire proportional chambers (P1 and P2) measured the position, dimension, and angular divergence of the photon beam. Two thin plastic scintillators (I), positioned on the photon beam, were used as a relative monitor detecting in coincidence the Compton and pair electrons produced by the photons on a thin gold converter: The stability of this simple detector was checked over several days and found to be about $\pm 0.1\%$ [11]. Finally, a cylindrical BGO crystal was used as a photon spectrometer. Its diameter and length were sufficient to contain more than 97% of the shower energy for a photon beam of 1 GeV energy and ≈ 2 cm diameter. This spectrometer provided a measurement of the bremsstrahlung spectrum from 80 MeV up to the maximum photon energy, with a linearity better than 1% [12]. The 200–1100 MeV energy range covered by this experiment was obtained with different settings of the energy of the machine, E_0, and using the fraction $(0.3-0.9)E_0$ of the bremsstrahlung spectrum.

To obtain the total photonuclear cross section on Be and C nuclei, we used the transmission method, which consists in measuring the total attenuation cross section and subtracting the atomic absorption cross section σ_a computable, for light nuclei, with high accuracy [13]. Photons crossed the absorption target (a 85.77 ± 0.01-cm-long, 99.9% pure Be cylinder or a 59.95 ± 0.06-cm-long nuclear reactor graphite containing $<0.15\times 10^{-3}$ impurities) situated inside a 1.2 T magnetic field and were detected, about 13 m downstream, by the BGO spectrometer. This layout assured a very good rejection of the forward components of the electromagnetic showers created in the absorber, as shown by a simulation of the experiment performed by using the GEANT code [14].

Since the nuclear signal is only 1%–2% of the total, particular care was taken to minimize both statistical and systematic errors which could destroy an eventual resonant behavior of the cross section. Two spectra were simultaneously recorded, with both target-in and target-out configurations, using fast analog to digital converters, specifically (1) the bremsstrahlung spectrum measured by the BGO spectrometer; and (2) the same spectrum in coincidence with four tagging channels, suitably selected in order to allow on-line energy calibration. Moreover, in order to correct possible phototube gain variations, the signals of three LEDs mounted in the BGO were also recorded.

The photon intensity on the BGO spectrometer was kept constant at a selected rate ($\approx 2\times 10^3$ photons/s) in all working conditions by tuning the thickness of the argon jet. This low photon rate allowed the minimization of pile-up and dead-time effects. To normalize the target-in and target-out photon spectra, we used the counts of the photon monitor I. Measurements were carried out at several electron beam energies and were divided into several runs for each electron injection. For each injection the same statistics with target-in and target-out spectra were accumulated. The data obtained with the various injections showed good consistency with each other and could be averaged.

The value of the nuclear cross section obtained on Be and C with this method strongly depended on (a) possible density inhomogeneities in the absorber, (b) the stability of the photon monitoring, (c) the stability of the detecting system, (d) the residual contamination of secondaries on the photon beam, and (e) the accurate knowledge of the atomic cross section. However, points (a) and (b) only produced a simple upward-downward shift of all experimental points, but do not affect the energy behavior. Points (c), (d), and (e) instead could also distort the energy behavior of the extracted photonuclear cross section and, therefore, their influence has been carefully investigated.

Point (c) has been discussed above. As for point (d), a Monte Carlo simulation of the experiment, employing the code GEANT, showed that the residual contamination of secondary particles on the BGO spectrometer was significant only at the low energy region ($\leq 0.4E_0$), producing there a small correction (always $\leq 15\%$) to the extracted σ_n. The reliability of this simulation was checked by comparing its predictions to the measured BGO response function to tagged photons with and without the absorbing target inserted on the photon beam.

As for point (e), the atomic cross section contribution, we used data provided by Hubbel *et al.* [13]. However, as stated above, the aim of this measurement was to study the possible presence of the nucleon resonances in nuclei above the Δ. To this end we studied the effect of the uncertainties of σ_a in the photonuclear cross section determination investigating the energy dependence of the pair production, which is by far the main contribution to the atomic absorption ($\sim 80\%$). The pair production cross section is given by [15] $\sigma_p=(\sigma_{\rm BH}\text{-}\Delta S\text{-}\Delta_{\rm Coul})f_{\rm rad}$, where $\sigma_{\rm BH}$ is the unscreened plane wave approximation of Bethe and Heitler (which is exactly calculable), ΔS, $\Delta_{\rm Coul}$, and $f_{\rm rad}$ are the screening, Coulomb, and radiative corrections, respectively. We did not examine the effect of the approximations in $\Delta_{\rm Coul}$ and $f_{\rm rad}$, because in our energy range and for light nuclei they give small ($\sim 0.02\%$ and $<1\%$ of $\sigma_{\rm BH}$, respectively) and energy independent contributions. However, the screening corrections (which are 15–30 % of $\sigma_{\rm BH}$) were evaluated for Be using (1) two atomic form factors calculated with relativistic Hartree-Fock [16] and with correlated ground-state wave functions [17], and (2) two experimental form factors measured from $1.2\times 10^{-2}m_0c$ momentum transfer [18,19], and suitably extrapolated below this value. All these evaluations produced a smooth correction ($\approx 6\%$ at the maximum photon energy) on the nuclear cross section behavior which remains inside the experimental errors, as seen in Fig. 2. For carbon, we expect a behavior comparable to the one found for beryllium because the electron structure of beryllium metal [20] and graphite [21] are very similar.

In conclusion, both points (d) and (e) gave small, smooth corrections, which can affect the absolute value, but which are not able to simulate or destroy any resonant behavior of the photonuclear cross section. Thus, our measurements provide a reliable energy behavior of the nuclear photoabsorption cross section. The absolute normalization has been obtained by the overlap to the existing data in the Δ region. This normalizing value is

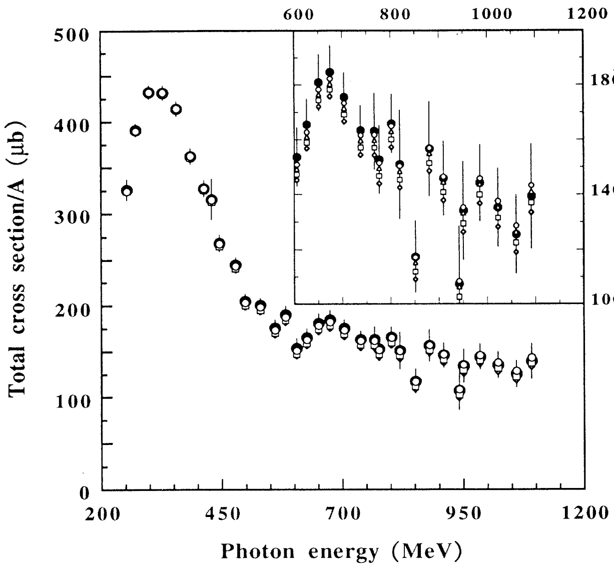

FIG. 2. Variation of the Be total nuclear absorption cross section for different atomic form factors: (●), Ref. [13]; (◇), Ref. [16]; (△), Ref. [17]; (□), Ref. [18]; (○), Ref. [19].

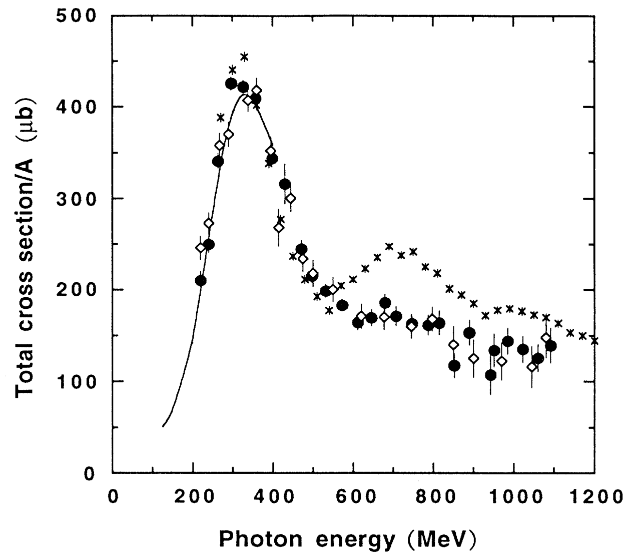

FIG. 3. The total nuclear absorption cross section per nucleon for Be (full circles) and C (open diamonds) together with the available data on ^{2}H [5] (crosses) and the universal behavior in the Δ region (solid line curve) derived from data on Be [1] and C [1,22].

59.1 ± 1.2 mb MeV/nucleon, which is the mean value of the integral between 220 and 385 MeV of the photoabsorption cross section provided by the previous experiments on Be [1] and C [1,22].

In Fig. 3 we show the photoabsorption cross section values per nucleon we obtained for Be and C with the above described procedure, together with the data available in the literature for deuteron [5] and the universal behavior in the Δ region (solid line curve) derived from data on Be [1] and C [1,22]. The error bars include only the statistical uncertainties. Our data were averaged over ≤ 30 MeV photon energy.

From these data it is evident that our photoabsorption cross sections per nucleon for Be and C (1) agree among each other within the experimental errors in the whole explored energy region; (2) at energies below 500 MeV, reproduce, within the statistical errors, the Δ(1232) resonance shape obtained by other laboratories; (3) do not show evidence of the baryon resonances seen in the photon absorption on the proton and the deuteron at energies of ≈ 0.7 and ≈ 1 GeV, which correspond mainly to the $D_{13}(1520)$ and $F_{15}(1680)$ resonances. Moreover, it is worth noting that the present results agree, within the systematic errors, with the values for the total photoabsorption cross section on ^{238}U, which we recently obtained with the photofission technique [23].

There are a number of possible reasons for the absence of resonant behavior in the cross sections above the Δ, such as broadening due to Fermi motion, Pauli blocking, or even a possible change of the photon coupling. However, a confirmation of these experimental results on light nuclei, using a method of measurement which gives also the absolute values of the cross section, is needed before a quantitative comparison with theory can be done.

It is a pleasure to thank Dr. C. Natoli for helpful discussions on the atomic cross section evaluation.

[1] J. Ahrens *et al.*, Phys. Lett. **146B**, 303 (1984); J. Ahrens, Nucl. Phys. **A466**, 229c (1985), and references therein.

[2] R. Bergère, in *Proceedings of the Second Workshop on Perspectives in Nuclear Physics at Internal Energies,* Trieste, 1985, edited by S. Boffi, C. Ciofi degli Atti, and M. M. Giannini (World Scientific, Singapore, 1985), p. 153.

[3] T. H. Bauer, R. D. Spital, and D. R. Yennie, Rev. Mod. Phys. **50**, 261 (1978), and references therein.

[4] T. A. Armstrong *et al.*, Phys. Rev. D **5**, 1640 (1972).

[5] T. A. Armstrong *et al.*, Nucl. Phys. **B41**, 445 (1972).

[6] E. A. Arakelyan *et al.*, Yad. Fiz. **38**, 980 (1983) [Sov. J. Nucl. Phys. **38**, 589 (1983)].

[7] A. K. Ananikyan *et al.*, Yad. Fiz. **49**, 1253 (1989) [Sov. J. Nucl. Phys. **49**, 780 (1989)]; *ibid.* **52**, 1387 (1989) [**52**, 878 (1989)].

[8] N. Bianchi *et al.*, Nucl. Instrum. Methods **A311**, 173 (1992).

[9] M. Taiuti *et al.*, Nucl. Instrum. Methods **A297**, 354 (1990).

[10] V. Muccifora *et al.*, Nucl. Instrum. Methods **A295**, 65 (1990).

[11] M. Anghinolfi *et al.*, INFN Internal Report INFN/BE-90/10.

[12] M. Anghinolfi *et al.*, Nucl. Instrum. Methods **A317**, 173 (1992).

[13] J. H. Hubbell, H. A. Gimm, and I. Overbo, J. Phys. Chem. Ref. Data **9**, 1023 (1980).

[14] R. Brun *et al.*, *GEANT 3,* CERN, Data Handling Division DD/EE/84-1, 1987.

[15] H. A. Gimm and J. H. Hubbel, NBS technical note, 968,

1978.

[16] J. H. Hubbel and I. Overbo, J. Phys. Chem. Ref. Data **8**, 69 (1979).

[17] R. T. Brown, Phys. Rev. A **2**, 614 (1970).

[18] F. K. Larsen and N. K. Hansen, Acta Cryst. **B40**, 169 (1984).

[19] N. K. Hansen *et al.*, Acta Cryst. **A43**, 1763 (1987).

[20] M. Y. Chou, P. K. Lam, and M. L. Cohen, Phys. Rev. B **28**, 4179 (1983).

[21] R. Chen, P. Trucano, and R. F. Stewart, Acta Cryst. **A33**, 823 (1977).

[22] P. Carlos, in *Proceedings of the International School of Intermediate Energy Nuclear Physics,* Verona, 1985, edited by R. Bergère, S. Costa, and C. Schaerf (World Scientific, Singapore, 1985), p. 1.

[23] N. Bianchi *et al.*, Phys. Lett. B **299**, 219 (1993).