# Photoproduction of $\pi$ mesons from $C^{12}$ in the photon-energy range from 250 to 1200 MeV

**N. V. Goncharov, A. I. Derebchinskiĭ, O. G. Konovalov, S. G. Tonapetyan, and V. M. Khvorostyan**

*Physico-technical Institute, Ukrainian Academy of Sciences*
(Submitted April 29, 1972)
Zh. Éksp. Teor. Fiz. **64**, 67-72 (January 1973)

Charged-pion energy spectra have been obtained in the interaction of photons with $E_\gamma^{max} = 250-1200$ MeV with $C^{12}$. Pions with kinetic energy $E_\pi = 30-120$ MeV were detected at an angle of 90° by a Freon bubble chamber. The cross sections $(d\sigma/d\Omega)_{90°}$ for $\pi^+$ and $\pi^-$ mesons and their sum were obtained as a function of photon energy by the photon difference method. The experimental values of the differential cross sections for photoproduction of $\pi$ mesons of all signs from the nucleons of the $C^{12}$ nucleus at energies $E_\gamma = 264$ MeV and $E_\gamma = 335$ MeV are found to agree with the theoretical values for these energies. The conclusion is drawn that photoproduction of pions in the $C^{12}$ nucleus occurs from all of the nucleons in the nucleus.

## 1. INTRODUCTION

Photoproduction of $\pi$ mesons from complex nuclei has been studied by many workers[1-12]. A number of the factors which distinguish this process from the photoproduction of mesons in a free nucleon are rather well understood. Among the main factors in this group are the momentum distribution of the nucleons in the nucleus, the Pauli principle, and the Coulomb field of the nucleus. One of the most difficult problems, which remains essentially unsolved up to the present time, is the question whether all of the nucleons of the nucleus take part in the $\pi$-meson photoproduction process. The problem in obtaining an answer to this question lies in taking into account reliably and quantitatively the interaction of the pions in the final state[3-12]. The difficulties in taking into account this interaction are due, first of all, to the absence of direct experimental proof of the validity of using the known elementary-particle coupling constants in intranuclear processes. Inclusion of the pion interaction in the final state is further complicated by the fact that a particle of another type can appear as the result of this interaction. An example of a process in which a $\pi$ meson is produced, and as the result of the final-state interaction a proton is emitted, is the photodisintegration of the deuteron[13,14]. Therefore the solution of the question whether pion photoproduction occurs in all of the nucleons requires an experiment in which all final reaction products are recorded simultaneously: $\pi$ mesons, nucleons, deuterons, tritons, and so forth.

Kihara[15] and Antuf'ev et al.[16] showed that in the interaction of photons with $C^{12}$ the yield of deuterons and tritons does not exceed several per cent of the proton yield. Charge invariance permits the yield of neutral particles (neutrons, $\pi^0$ mesons) to be included, which significantly facilitates the interpretation of the results. In this connection it is of interest to study the interaction of photons with $C^{12}$ with simultaneous detection of $\pi^+$ and $\pi^-$ mesons and protons over a wide $\gamma$-ray energy interval.

## 2. EXPERIMENTAL METHOD

The investigation was carried out in the photon beam of the 2-BeV linear electron accelerator of the Physico-technical Institute, Academy of Sciences, Ukrainian S.S.R. The shaping and intensity measurement of the photon beam have been described previously[17].

The experiment utilized $\gamma$ rays with maximum bremsstrahlung energies of 250, 293, 400, 600, 800, 1000, and 1200 MeV. A carbon target of thickness 2.12 g/cm² was placed in the photon beam at an angle of 45°. The secondary-particle detector was a Freon bubble chamber[17] which was placed at an angle of 90° to the photon-beam direction at a distance of 260 mm from the center of the target. The chamber recorded both $\pi^+$ and $\pi^-$ mesons with kinetic energies from 30 to 120 MeV. The energy of the $\pi$ mesons was determined from the range in the chamber liquid. Only stopped $\pi$ mesons were selected.

A stopped $\pi^+$-meson track was identified from the characteristic $\pi^+ \to \mu^+ \to e^+$ decay, and a $\pi^-$-meson track was established from the stars due to disintegration of the nuclei of the chamber liquid after capture of the stopped $\pi^-$ meson[18]. Only those $\pi^+$ and $\pi^-$ tracks were selected whose angle of scattering by the nuclei of the entrance window and the chamber liquid did not exceed 10°. The chamber operated in the moderate-superheating mode[17]. This permitted reliable separation of both $\pi^+$ and $\pi^-$ mesons and protons in the background of electron and positron tracks which formed the principal background in the chamber. It should be noted that the simultaneous detection of the charged particles avoided a number of experimental errors which are unavoidable in methods using separate detection.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

In analysis of the experimental results we took into account corrections for $\pi$-meson decay in flight before stopping in the chamber and for nuclear interaction of $\pi$ mesons with the nuclei of the entrance window and the chamber liquid. The cross sections from Barashenkov et al.[19] and Hughes[20] were used in calculation of the corrections for nuclear absorption of pions. The values of these corrections for the different pion energies are given below:

| $E_\pi$, MeV: | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|
| Decay in flight, %: | 5 | 5.2 | 5.4 | 5.7 | 5.9 | 6.2 | 6.4 | 6.7 | 6.9 | 7.2 |
| Absorption, %: | 6.7 | 9.0 | 11.4 | 14.2 | 17.8 | 22 | 26.8 | 32 | 38.6 | 45.5 |

The differential cross section per equivalent quantum for a given pion energy $E_\pi$ and a given $E_\gamma$ was calculated from the following formula:

$$\frac{d^2\sigma}{d\Omega\, dE_\pi Q} = \frac{N_\pi}{\eta N_n \Delta\Omega\, \Delta E_\pi Q},$$

where $\eta$ is the pion detection efficiency, $N_\pi$ is the number of events per Q equivalent quanta, $N_n$ is the number of target nuclei per cm$^2$, $\Delta\Omega$ is the solid angle subtended by the chamber, and $\Delta E_\pi$ is the $\pi$-meson energy-bin width.

The main results of the experiment are presented in Fig. 1, where the bremsstrahlung energy is taken as a parameter. The experimental points were approximated by polynomials of fourth and fifth degrees by the method of least squares. Only the statistical errors are shown. To determine the absolute experimental errors it is necessary to take into account in addition an error of 10–15% due mainly to errors in measurement of the photon-beam intensity and of the cross sections for interaction of pions with the nuclei of the entrance window and chamber medium, which are constant for all energies of photons and detected pions.

In Fig. 2 we have shown for the $C^{12}$ nucleus the experimental differential cross sections for photoproduction of $\pi^+$ and $\pi^-$ mesons and their sum, as a function of photon energy. The curves have been drawn freehand through the experimental points. The differential cross-section values were obtained by integration of the experimental $\pi$-meson spectra over $E_\pi$ and use of the photon difference method. As can be seen from Fig. 2, two peaks appear in the energy dependence. The first peak can be assigned to formation of the $\Delta_{3,3}$ isobar in bound

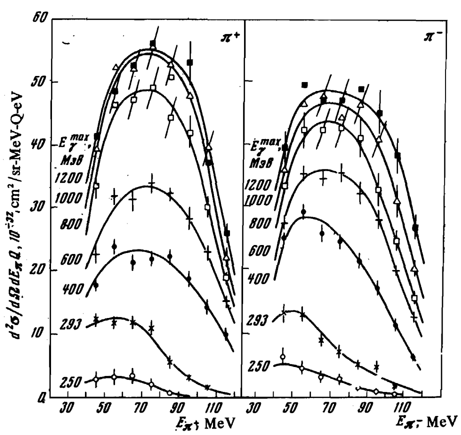


FIG. 1. Energy spectra of charged pions in interaction of photons of various energies with the $C^{12}$ nucleus ($\theta_{lab} = 90° \pm 7°$). The errors are statistical.

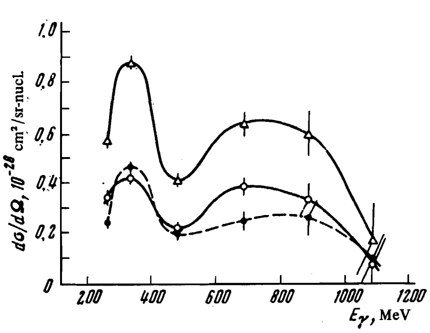


FIG. 2. Differential cross sections for photoproduction of mesons from $C^{12}$ nuclei ($\theta_{lab} = 90°$) as a function of photon energy: ●–$(d\sigma/d\Omega)_{\pi^-}$, ○–$(d\sigma/d\Omega)_{\pi^+}$, △–$(d\sigma/d\Omega)_{\pi^+} + (d\sigma/d\Omega)_{\pi^-}$. The errors are statistical.

nucleons of the $C^{12}$ nucleus[7]. The second peak is apparently due to multiple production of pions from the nucleons of the $C^{12}$ nucleus.

Protons were also recorded in the experiment simultaneously with $\pi^+$ and $\pi^-$ mesons. The mechanism of proton production has been studied previously by the authors[21] and it has been shown that the main contribution to the proton yield at an angle $\theta_{lab} = 90°$ in the $(\gamma, p)$ reaction in $C^{12}$ is from the mechanism of $\pi$-meson absorption in the nucleus. If we take into account that the yield of the $(\gamma, d)$ and $(\gamma, t)$ reactions in $C^{12}$ amounts to only a few per cent of the proton yield[15,16], we can assume that protons recorded by the Freon bubble chamber simultaneously with $\pi$ mesons are the result of absorption in the $C^{12}$ nucleus of pions which have been produced and which did not leave the nucleus.

Absorption of $\pi^0$ mesons from coherent photoproduction in the nucleus cannot give an appreciable contribution to the proton yield, since in this case the $\pi^0$ mesons are absorbed only in traversing the target material.

Several workers have shown[18,22,23] that absorption of pions in nuclei occurs mainly by two-nucleon clusters. For the same intensity of photoproduction of $\pi^+$, $\pi^-$, and $\pi^0$ mesons, charge conservation permits us to establish that one absorbed pion corresponds to one proton in the final state. Therefore the number of pions produced in the nucleus can be represented as the sum of the pions and protons which leave the nucleus. The cross sections for photoproduction of single $\pi^+$, $\pi^-$, and $\pi^0$ mesons from free nucleons are not actually the same. At energies $E_\gamma^{max}$ = 250, 293, and 400 MeV, the ratios between the intensities of the pion-photoproduction channels in free nucleons and the correction coefficient

$$K = \frac{I_{\pi^+} + I_{\pi^-}}{I_{\pi^+} + I_{\pi^-} + 2I_{\pi^0}},$$

which takes into account the correction for the $\pi^0$-meson channel, are given in Table I. The absorption of $\pi^+$ mesons by an np pair gives two protons in the final state, and absorption of a $\pi^-$ meson gives two neutrons. Thus, if only protons are detected in the experiment, and if the cross sections for production of $\pi^+$ and $\pi^-$ mesons are not identical (see Table I) and the absorption of pions in the nucleus occurs 60–70% by an np pair and 30–40% by nn and pp pairs,[23] then each proton detected for $E_\gamma^{max}$ = 250, 293, and 400 MeV will correspond to 1.053, 1.04, and 1.038 absorbed pions, respectively.

These coefficients were taken into account in calculation of the experimental differential cross section for photoproduction of $\pi$ mesons from $C^{12}$ on the basis of the detected protons. Here it was assumed that the interaction of the protons in the final state, which distorts the energy spectrum of the protons, does not lead to an appreciable change in the number of protons, and that the scattering of protons into other angles is compensated by protons scattered into the solid angle of the apparatus. The coefficient for cascade increase of the scattered

TABLE 1

| $E_\gamma$, MeV | Relative intensity of pion photoproduction | | | K |
|---|---|---|---|---|
| | $I_{\pi^+}$ | $I_{\pi^-}$ | $2I_{\pi^0}$ | |
| 250 | 1 | 1,21 | 0,54 | 0.80 |
| 293 | 1 | 1,203 | 1,132 | 0,66 |
| 400 | 1 | 1.26 | 2.08 | 0,52 |

TABLE 2

| $E_\gamma$, MeV | $(d\sigma/d\Omega)_{90°}$, $10^{-28}$ cm$^2$/sr-nucl. | |
|---|---|---|
| | Theory | Experiment |
| 264 | 2.88 | 2.58±0.51 |
| 335 | 3,90 | 3.44±0.37 |

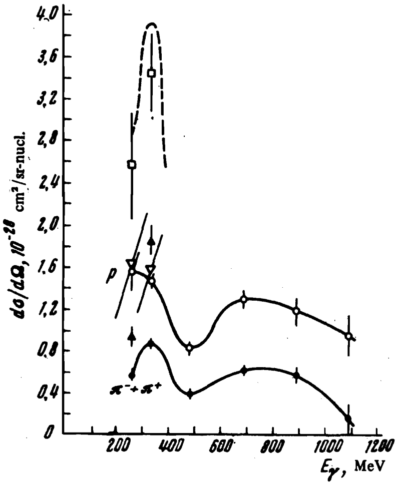


FIG. 3. Comparison of experimental and theoretical differential cross sections for photoproduction of pions from $C^{12}$ ($\theta_{lab} = 90°$). ●—Experimental values of $(d\sigma/d\Omega)_{\pi^+} + (d\sigma/d\Omega)_{\pi^-}$, ○—experimental values of $(d\sigma/d\Omega)_p$ from ref. 21. The errors are statistical. ▲—Experimental values of $(d\sigma/d\Omega)_\pi$ with inclusion of $\pi^0$ mesons, ▽—$(d\sigma/d\Omega)_\pi$ obtained from detected protons, □—sum of the cross sections denoted by ▲ and ▽. The errors are the total errors. The dashed curve is the cross section $(d\sigma/d\Omega)_\pi$ obtained theoretically.

protons, determined for $C^{12}$ from calculations carried out on the basis of the work of Metropolis et al.[24] and which is equal to 1.1, is consistent with these assumptions. In these estimates we used a transparency of 0.6 for the $C^{12}$ nucleus for protons of energy 80—235 MeV.

In Fig. 3 we have shown the sum of the experimental differential cross sections for photoproduction of $\pi^+$ and $\pi^-$ mesons and the differential cross section for the $(\gamma, p)$ reaction in $C^{12}$[19] as a function of photon energy. The dashed curve shows the calculated combined differential cross section for photoproduction of pions of all signs from the nucleons of the $C^{12}$ nucleus. Here we used the calculations made by Kabe et al.[7], who used the impulse approximation, took into account the Pauli principle, and assumed a Gaussian momentum distribution of the nucleons for the $C^{12}$ nucleus.

In the same figure we have given for photon energies $E_\gamma$ = 264 and 335 MeV the differential cross section for photoproduction of pions of all signs from nucleons of the $C^{12}$ nucleus, obtained by addition of the experimental cross sections for photoproduction of $\pi^+$ and $\pi^-$ mesons with inclusion of the $\pi^0$-meson contribution, the cross section for absorption of $\pi$ mesons in the $C^{12}$ nucleus, obtained from the detected protons, and the sum of these cross sections. In Table II we have given the theoretical and experimental values of the differential cross sections for photoproduction of $\pi$ mesons from the nucleons of the $C^{12}$ nucleus for these two photon energies.

Comparison of the cross sections shows that the theoretical and experimental differential cross sections are not greatly different. This permits us to conclude that photoproduction of pions in $C^{12}$ occurs in all of the nucleons.

The somewhat smaller value of the experimental differential cross section for photoproduction of $\pi$ mesons in the nucleons of $C^{12}$ in comparison with the calculated value is evidently due to the fact that the experimental value did not take into account the contribution of deuterons and tritons, whose yield from the nucleus can also be due to pion absorption.

The authors express their gratitude to A. P. Klyucharev and P. I. Vatset for their interest in this work, and also to M. T. Dorofeev, V. N. Skusinets, and O. G. Kovalenko for assistance in performing the experiment.


1. R. M. Littauer and D. Walker, Phys. Rev. **86**, 838 (1952).
2. V. M. Popova, N. G. Semashko, and F. Ya. Yagudina, Zh. Eksp. Teor. Fiz. **36**, 1357 (1959) [Sov. Phys.-JETP **9**, 965 (1959)].
3. A. S. Belousov, B. Govorkov, and V. I. Gol'danskiĭ, Zh. Eksp. Teor. Fiz. **36**, 244 (1959) [Sov. Phys.-JETP **9**, 164 (1959)].
4. W. S. C. Williams, K. M. Crowe, and R. M. Friedman, Phys. Rev. **105**, 1840 (1957).
5. T. R. Palfrey, B. M. K. Nefkens, L. Mortara, and F. J. Loeffler, Phys. Rev. **122**, 1323 (1961).
6. W. Imhof, E. A. Knapp, H. Easterday, and V. Perez-Mendez, Phys. Rev. **108**, 1040 (1957).
7. S. Kabe, S. Kato, T. Kifune, Y. Kimura, and T. Nishikawa, J. Phys. Soc. Japan **19**, 1800 (1964).
8. G. F. Chew and G. C. Wick, Phys. Rev. **85**, 636 (1952).
9. K. A. Brueckner, R. Serber, and K. M. Watson, Phys. Rev. **84**, 258 (1951).
10. M. Lax and H. Feshbach, Phys. Rev. **81**, 189 (1951).
11. S. T. Butler, Phys. Rev. **87**, 1117 (1952).
12. R. R. Wilson, Phys. Rev. **104**, 218 (1956).
13. J. C. Keck and A. V. Tollestrup, Phys. Rev. **101**, 360 (1956).
14. R. Ching and C. Schaerf, Phys. Rev. **141**, 1320 (1966).
15. M. Kihara, J. Phys. Soc. Japan **20**, 1313 (1965).
16. Yu. P. Antuf'ev, V. L. Agranovich, and V. B. Ganenko, et al., Yad. Fiz. **13**, 473 (1971) [Sov. J. Nucl. Phys. **13**, 265 (1971)].
17. N. V. Goncharov, A. I. Derebchinskiĭ, O. G. Konovalov, S. G. Tonapetyan, and V. M. Khvorostyan, Prib. Tekh. Eksp., 3, 106 (1970).
18. N. V. Goncharov, A. I. Derebchinskiĭ, O. G. Konovalov, S. G. Tonapetyan, and V. M. Khvorostyan, Yad. Fiz. **14**, 922 (1971) [Sov. J. Nucl. Phys. **14**, 516 (1972)].
19. V. S. Barashenkov, K. K. Gudina, and V. D. Toneev, JINR Preprint R-2-4068, 1968.
20. D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, BNL-325, 1958. Russ. transl., IIL, 1959.
21. N. V. Goncharov, S. G. Tonapetyan, O. G. Konovalov, A. I. Derebchinskiĭ, and V. M. Khvorostyan, Materialy IV Mizhdunar. konf. po fizike vysokikh energiĭ i struktura yadra (Proceedings, IV Intern. Conf. on High-Energy Physics and Nuclear Structure), Dubna, 1971, D1-5988, p. 138.
22. J. Favier, T. Bressani, G. Charpak, L. Massonnet, W. E. Meyerhof, and C. Zupancic, Nucl. Phys. **A169**, 540 (1971).
23. V. S. Demidov, V. S. Verebryusov, V. G. Kirillov-Ugryumov, A. K. Ponosov, and F. N. Sergeev, Zh. Eksp. Teor. Fiz. **46**, 1220 (1964) [Sov. Phys.-JETP **19**, 826 (1964)].
24. N. Metropolis, R. Bevins, M. Storm, J. M. Miller, G. Friedlander, and A. Turkevich, Phys. Rev. **110**, 204 (1958).


Translated by C. S. Robinson
5