Photodisintegration of C^{12} with 345-MeV bremsstrahlung

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Energy spectra of charged pions and protons have been measured at angles of 30, 60, 90, 120, and 150° in the laboratory system for a bremsstrahlung maximum energy of 345 MeV. Charged pions with kinetic energies from 10 to 100 MeV and protons with energies from 30 to 160 MeV emitted from C^{12} nuclei were detected by the emulsion technique. The differential cross sections for photoproduction of protons agree with calculations according to the cascade model. For pions the agreement is poorer.

INTRODUCTION

The processes of charged pion production and ejection of protons and other heavy particles from nuclei by photons are qualitatively rather well explained at the present time in the impulse approximation with inclusion of the final-state interaction according to the optical model.[1] Theoretical papers have been published on the quantitative calculation of the particle yields from nuclei with various model assumptions.[2-5] The cascade model of nuclear reactions[6,7] has been very attractive for the description of the interaction of high-energy particles with nuclei. For the purpose of further refinement of the cascade-evaporative model it is of interest to study not so much the integrated, average characteristics as the differential cross sections. Particular interest is presented by the low-energy component of the particles produced.[6]

Photoproduction of charged pions from C^{12} with bremsstrahlung of maximum energy $E_0 < 345$ MeV has been studied by a number of authors.[8-10] Yields of pions with fixed kinetic energies T_π have been measured, mainly at large angles. The most complete measurements of the cross section for production of π^+ mesons with kinetic energies from 32 to 150 MeV for bremsstrahlung maximum energies from 265 to 1200 MeV were carried out[11,12] only at an angle $\theta = 90°$. The low-energy part of the pion spectra and the pion production cross sections at small angles have been particularly little studied. In addition, in the low-energy part of the pion spectrum there is a discrepancy in the experimental results obtained by different authors.[8,11,12] The yields of photoprotons from C^{12} for bremsstrahlung maximum energies from the production threshold to the double-pion production threshold have been studied mainly at small angles.[13-16] The earlier studies were not carried out with sufficient accuracy.[17]

Study of the yields of photoprotons and photopions from C^{12} presents interest because, on the one hand, carbon is still a rather simple nucleus with a rather high probability of secondary interactions and, on the other hand, the role of multiple collisions is still unimportant, which substantially simplifies the calculations. In the present work we have measured the cross sections for photoproduction of charged pions with kinetic energies from 10 to 100 MeV and the cross sections for production of photoprotons with kinetic energies from 30 to 160 MeV from the C^{12} nucleus at angles of 30, 60, 90, 120, and 150° in the laboratory system for a bremsstrahlung maximum energy $E_0 = 345$ MeV.

EXPERIMENTAL METHOD

The work was carried out in the 2-GeV electron linear accelerator of our Institute, with a bremsstrahlung maximum energy $E_0 = 345$ MeV. A carbon target of thickness 0.3 g/cm^2 was placed at an angle of 54° to the photon beam. Protons and π^+ and π^- mesons were detected simultaneously by means of emulsion chambers assembled from layers of type Ya-2 emulsion of thickness 400 μ. The background measured without a target was less than 0.5%. The systematic errors do not exceed ±5%. The experimental technique has been described in more detail in a previous article.[18]

The cross section for photoproduction of charged pions and protons in a nucleus is determined by the expression

$$\frac{d^2\sigma}{d\Omega\, dT}\frac{1}{Q}=\frac{N(E_0, T, \theta)}{\eta t \Delta\Omega\, \Delta T Q \xi}$$

where η is the detection efficiency for particles of a given type, N is the number of these particles detected for Q equivalent quanta, t is the number of target nuclei per cm^2, $\Delta\Omega$ is the solid angle of the detecting system, T is the kinetic energy and ΔT the width of the energy interval of the detected particles, E_0 is the maximum energy of the bremsstrahlung, ξ is the correction factor for decay in flight and nuclear absorption of the detected particles in emulsion, and θ is the emission angle of the particle in the laboratory system.

EXPERIMENTAL RESULTS AND DISCUSSION

The differential cross sections for photoproduction of charged pions per equivalent quantum are shown in Fig. 1 as functions of the pion kinetic energy for a bremsstrahlung maximum energy $E_0 = 345$ MeV. Only the statistical errors are shown. It is evident from the figure that the maxima of the π^+ and π^- energy spectra shift toward lower pion kinetic energies with increasing detection angle. For all angles the location of the maximum in the π^- photoproduction cross section is shifted relative to that for π^+ mesons, also toward lower energies. A similar pattern was observed by us also for the Ca^{40} nucleus.[19] This is apparently due to the interaction of charged pions with the Coulomb field of the nucleus, which accelerates the emitted π^+ mesons and slows down the π^- mesons.

The presence of a maximum in the π^+ energy spectrum agrees with the results of Peterson, Gilbert, and White[8] and disagrees with the data of the Japanese group.[11] The cross section for π^+ production at 90° with kinetic energies greater than 50 MeV is in good

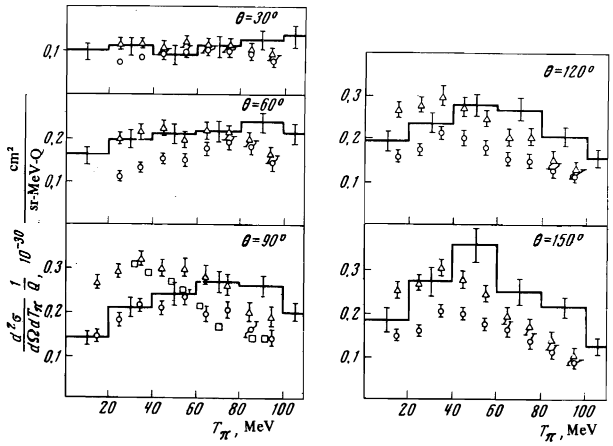

FIG. 1. Energy spectra of charged pions from C^{12} for bremsstrahlung maximum energy 345 MeV: Circles – π^+ mesons, triangles – π^- mesons, from the present work; squares – π^+ mesons from ref. 11. The stepped line shows the π^+ energy spectrum calculated with the cascade model

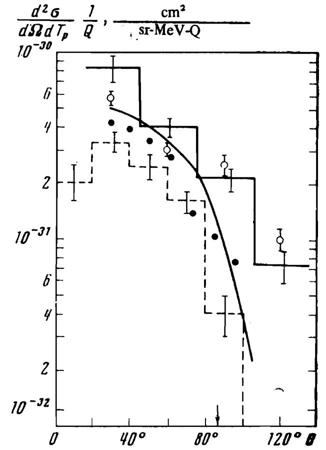

FIG. 2. Angular distributions of photoprotons with kinetic energies T_p = 155 MeV emitted from C^{12} for bremsstrahlung maximum energy E_0 = 345 MeV (hollow points); the solid points are data of Kim et al.[15] at T_p = 156 MeV, E_0 = 335 MeV. The designations of the curves are the same as in Fig. 3.

agreement with the experimental results of Kabe et al.[11] obtained also for a bremsstrahlung maximum energy of 345 MeV. For pion kinetic energies less than 50 MeV the production cross section drops, while in ref. 11 it rises. This discrepancy of the experimental results in the low-energy part of the pion spectrum may be due to the fact that Kabe et al.[11] used a rather thick carbon target.

We have compared the experimental results with calculations according to the cascade model. The calculations used the model of a nucleus with a constant density. The momentum distribution of the nucleon in the nucleus and the Pauli principle were taken into account. The Levinger[20] constant L was chosen[21] as 10. The method of calculation and the choice of parameters have been described in more detail elsewhere.[22] Since the cascade model is valid for γ-ray energies above the giant-resonance region, the bremsstrahlung spectrum, which extends from 0 to 345 MeV, was replaced in the calculations by a cut-off Schiff spectrum with γ-ray energies from 50 to 345 MeV.

The cross sections for photoproduction of positive pions at angles 30 ± 15, 60 ± 15, 90 ± 15, 120 ± 15, and 150 ± 15°, calculated according to the cascade model, are shown in Fig. 1 in the form of histograms. Only the statistical errors are shown. In all of the figures the absolute values of the experimental and calculated cross sections are shown. No normalization of the calculated

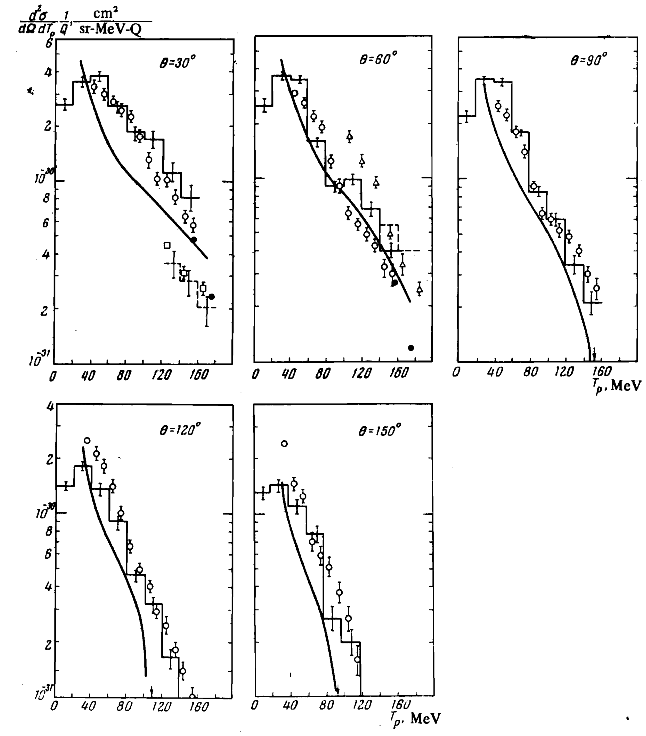

FIG. 3. Energy spectra of photoprotons from C^{12} for a bremsstrahlung maximum energy 345 MeV. Hollow circles – data of the present work, solid circles – data of Kim et al.[15], triangles – ref. 14, squares – ref. 13. The stepped line is a calculation according to the cascade model, and the smooth curve according to the quasideuteron model; the dashed lines show calculations by Gabriel and Alsmiller[7] according to the cascade model.

cross section was made. It is evident from the figure that the experimental results are in reasonable agreement with the cascade-model calculations. However, the location of the theoretical maximum in the cross section for production of charged pions is shifted relative to the experimental maximum, toward higher pion kinetic energies. This is particularly noticeable in comparison of the results obtained for small pion-emission angles.

With increasing angle of pion yield, an increase in the discrepancy between the theoretical and experimental results is noted in the high-energy part of the pion spectrum. A similar situation was also noted by Gabriel and Alsmiller.[7]

PROTON ENERGY SPECTRA

The differential cross sections for pion photoproduction are shown in Fig. 3 as a function of proton kinetic energy. It can be seen from the figure that our experimental results for protons with kinetic energies greater than 100 MeV, which were obtained at 30 and 60°, agree better with the results of Kim et al.[15] than with those of Levinthal and Silverman.[17] The cross sections for photoproduction of protons at angles 30 ± 15, 60 ± 15, 90 ± 15, 120 ± 15, and 150 ± 15, calculated according to the cascade model, are given in Fig. 3 in the form of a histogram. These cross sections were obtained simultaneously with the cross sections calculated for pion photoproduction.

Antuf'ev et al.[23-25] have shown that for bremsstrahlung maximum energies above 600 MeV the Levinger quasideuteron model cannot describe the features of proton photoproduction in nuclei at angles greater than 60°. However, for bremsstrahlung energies up to

250 MeV in the kinematic region where proton emission from the photomesonic mechanism is forbidden, the experimental results are in good agreement with calculations according to the quasideuteron model.[26] Therefore these calculations present independent interest as a check of the validity of the quasideuteron model over a wide range of angles at an intermediate value of bremsstrahlung maximum energy. For this reason we also made calculations with the same model parameters as used by Antuf'ev et al.[23-25] The proton yield from photodisintegration of quasideuterons, calculated analytically[27] from the Levinger quasideuteron model, is shown by the smooth curve in Fig. 3. The transparency of the C^{12} nucleus for protons was calculated according to the cascade model and was taken as 0.6 for all proton kinetic energies.

It is evident from Fig. 3 that the theoretical spectra calculated from the quasideuteron model agree with the experimental results only for angles of 60 and 90°. The proton yields for angles 30, 120, and 150° are significantly greater than those calculated according to the quasideuteron model. This is due to the fact that for an angle of 30° there is a large contribution of protons from the process

$$\gamma+p\to p+\pi^0,\quad \gamma+n\to p+\pi^-.$$

For angles 120 and 150° there is a significant contribution from absorption of π^+ mesons by quasideuterons during the passage of created pions through the nucleus:

$$\pi^+ + d\to p+p.$$

The cascade model describes the photoproton energy spectra at all angles.

Figure 2 shows the angular distribution of photoprotons with kinetic energy 155 MeV. The arrows in Figs. 2 and 3 show the limits of the kinematically allowed yield of protons from photodisintegration of a free deuteron for γ-ray energies of 345 MeV. Even the inclusion of the momentum distribution of the quasideuterons in the nucleus cannot explain the appreciable yield of photoprotons in the kinematically forbidden region. The yield of these protons can be explained by cascade processes in their production.

The cascade-model calculations by Gudima et al.[6] agree with our calculations with the quasideuteron model and disagree with our calculations with the cascade model. This may be due to the fact that Gudima et al. assumed the angular distribution of photopions to be isotropic, while an asymmetry is observed for $\theta > 90°$ at $E_0 > 260$ MeV.

The material presented above permits the following conclusions to be drawn:

1. For a bremsstrahlung maximum energy of 345 MeV the main contribution to the proton yield is from the quasideuteron mechanism. For angles of 30, 120, and 150° there is an appreciable contribution from the mesonic process.

2. Photoproduction of charged pions occurs in all nucleons of the nucleus with subsequent interaction with the residual nucleus.

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3