SOVIET PHYSICS

JETP

A Translation of Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki

Vol. 36, No. 6, pp. 1033-1238 (Russian Original Vol. 63, No. 6, pp. 1955-2348) June 1973

PHOTODISINTEGRATION OF C^{12} AT γ-RAY ENERGIES FROM 250 TO 1200 MeV

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Submitted April 29, 1972

Zh. Eksp. Teor. Fiz. **63**, 1955–1960 (December, 1972)

Energy spectra are presented for protons arising in interaction with C^{12} nuclei of photons with energy E_γ^{max} = 250, 293, 400, 600, 800, 1000, and 1200 MeV. Protons with kinetic energies from 70 to 240 MeV were detected at an angle $\theta_{lab} = 90°$ by a Freon bubble chamber. The deviation of the spectra from those calculated with the quasideuteron model is established. A substantial difference is shown in the behavior of the differential cross sections $d\sigma/d\Omega$ for $\theta = 90°$ as a function of photon energy for disintegration of C^{12} nuclei and deuterons. Analysis of the experimental results permits the conclusion that the dominant mechanism corresponding to the proton yield at an angle $\theta_{lab} = 90°$ in the (γ, p) reaction in the C^{12} nucleus is the absorption of π mesons.

INTRODUCTION

THE (γ, p) reaction in C^{12} has been studied by many workers[1-5] above the π-meson photoproduction threshold. It has been shown[1-3] that at high photon energies the Levinger quasideuteron model cannot describe all the observed features of the photoproduction of protons in nuclei at large angles ($\theta > 60°$). It is well known that in the photodisintegration of the deuteron a substantial contribution is made by reabsorption of π mesons,[6] as a result of which a maximum in the region of the 3/3 isobar is observed in the photodisintegration cross section as a function of photon energy.

In this connection it is of interest to study the proton spectra over a wide range of photon energies at large proton angles ($\theta > 60°$), where proton yield from meson photoproduction in quasifree nucleons of the nucleus is kinematically forbidden. Integration of these spectra and use of the photon difference method permits the C^{12} photodisintegration differential cross section to be obtained as a function of the energy of monochromatic photons. Comparison of this function with the deuteron photodisintegration cross section as a function of photon energy can be useful in clarifying the proton production mechanism.

EXPERIMENTAL APPARATUS

The investigations were carried out in the photon beam of the 2-BeV linear electron accelerator at the Physico-technical Institute, Academy of Sciences, Ukrainian SSR. The shaping of the beam and clearing of charged components have been described previously[7]. The photon beam intensity was measured by means of a Wilson quantameter. The experiment was performed with γ rays of maximum energy 250, 293, 400, 600, 800, 1000, and 1200 MeV. A carbon target of thickness 2.12 g/cm^2 was placed in the photon beam at an angle of 45°.

The photons were detected by a Freon bubble chamber[7] 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 permitted detection of stopping protons with kinetic energies from 70 to 240 MeV in the range of angles 90 ± 7°. The proton energy was determined from the range in the chamber medium. The chamber operated without a magnetic field, and therefore only stopping protons were recorded. On interaction of high-energy photons with a nucleus, charged particle tracks (e^+, e^-, π^+, π^-, and p) appeared in the working region of the chamber. The chamber operated in the moderate-superheating mode with stabilization of a reference pressure, which permitted identification of proton tracks in a background of tracks from other particles[7-9]. In the selection we separated protons whose scattering angle in the nuclei of the entrance window and the working medium of the chamber did not exceed 10°. The experimental results were corrected for attenuation of the number of protons in their passage through the target, the entrance window (2.5 mm of stainless steel), and the working liquid of the chamber. In calculation of these corrections we used the cross sections obtained by Barashenkov et al.[10] and Hughes[11].

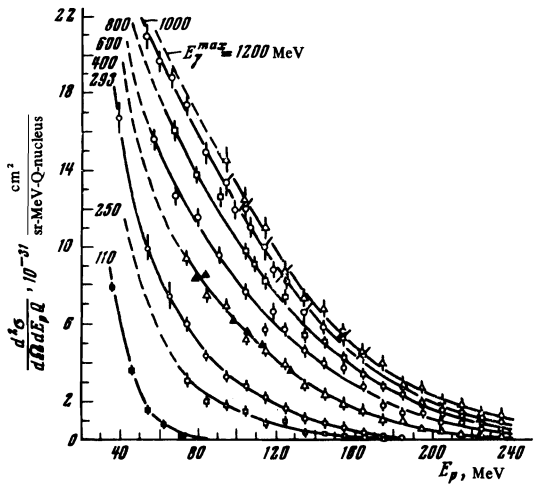

FIG. 1. Energy spectra of photoprotons from C^{12} at an angle θ_{lab} = 90° for bremsstrahlung photons with maximum energy from 110 to 1200 MeV. The errors are statistical. Hollow points—results of the present work, solid points—data from other sources: ■—ref. 12, ●—ref. 4, ▲—ref. 5.

RESULTS AND DISCUSSION

Figure 1 shows the experimental proton spectra for photons with maximum energies from 250 to 1200 MeV. Only statistical errors are shown. In estimating the accuracy of the absolute measurements it is necessary to include an error of 10–15% due mainly to constant errors in measurement of the photon beam intensity and of the cross sections used in the corrections for interaction of the protons with the target nuclei, the entrance window, and the chamber working liquid. The experimental points were approximated by fourth and fifth degree polynomials by the method of least squares. The relative behavior of the proton spectra for E_γ^{max} = 600, 800, and 1000 MeV in the proton energy range 60–120 MeV was measured by us by means of a scintillation counter telescope and a magnetic spectrometer[2,3,12]. The proton spectrum for E_γ^{max} = 293 MeV in the energy range E_p = 30–70 MeV was taken from Ref. 4 and normalized at the point for E_p = 70 MeV. In the figure we have shown the proton spectrum for E_γ^{max} = 400 MeV obtained by Dougan and Stiefler[5]. The good agreement with our spectrum is evident. For a photon energy E_γ^{max} = 110 MeV the proton spectrum was taken from Whitehead et al.[13]

By comparison of the proton spectra at large angles (θ_{lab} = 90°), where the proton yield from meson photoproduction in quasifree nucleons of the nucleus is kinematically forbidden, with the spectra calculated from Levinger's quasideuteron model[14], we can deduce the mechanism of the (γ, p) reaction in the nucleus for a photon energy above the meson photoproduction threshold.

Calculations of the proton spectra for E_γ^{max} = 250, 293, 400, 600, and 800 MeV were carried out by computer on the basis of the quasideuteron model[14,15] according to the formula

$$\frac{d^2\sigma}{d\Omega\, dE_p Q} = L\frac{NZ}{A}\iiint \frac{f(E_0, k)}{k}\frac{d\sigma^*}{d\Omega} J \frac{dk^*}{dE_p^*} F(p_d)\, d^3p, \qquad (1)$$

where N, Z, and A are respectively the number of neutrons, protons, and mass number of the target-nucleus; $f(E_0, k)$ is the Schiff function; E_0 is the bremsstrahlung maximum energy; $d\sigma^*/d\Omega$ is the experimental cross section for photodisintegration of the deuteron in the center-of-mass system; J is the Jacobian of the transformation to the laboratory system, k is the photon energy determined by the kinematics of the reaction $\gamma + d \to p + n$ in a stationary deuteron. The momentum distribution of quasideuterons in the C^{12} nucleus was taken as

$$F(p_d) = F_s(p_d) + F_p(p_d),$$

where

$$F_s(p_d) = \frac{1}{\pi^{3/2}\alpha_s^3}\exp\left[-\frac{p_d^2}{\alpha_s^2}\right] \quad \text{for} \quad \alpha_s = 222\,\frac{\text{MeV}}{c},$$

$$F_p(p_d) = \frac{2}{3\pi^{3/2}\alpha_p^3}\frac{p_d^2}{\alpha_p^2}\exp\left[-\frac{p_d^2}{\alpha_p^2}\right] \quad \text{for} \quad \alpha_p = 137\,\frac{\text{MeV}}{c}.$$

The normalization coefficients L were obtained by matching the theoretical spectra with the experimental values for E_p = 90 MeV.

Figure 2 shows a comparison of the experimental and calculated proton spectra. It is evident that with increasing photon energy the coefficient L increases (L = 3, 4.4, 6.4, 7.7, and 9.1 for E_γ^{max} = 250, 293, 400, 600, and 800 MeV, respectively) and, in addition, the theoretical proton spectra differ significantly from the experimental spectra. This shows that the yield of photo photoprotons from the C^{12} nucleus cannot be explained by photodisintegration of quasideuterons of the nucleus.

Wilson[6] showed that photodisintegration of the deuteron occurs not only as the result of dipole electric absorption of γ rays, but also as the result of absorption of π mesons at the moment of their production. It is well known that the principal mechanism of absorption of stopped π mesons in matter[9,16] and also of fast mesons in interaction with nuclei[17] is also the absorption of π mesons by an np pair. In photoproduction of π mesons from the nucleons of the deuterium nucleus, part of the mesons are absorbed at the moment of production and the remaining mesons leave the deuteron. By equating the photoproduction and absorption of pions in deuterium and C^{12} and taking into account the existence of two mechanisms of pion absorption, we can suggest that in photoproduction of π mesons from quasideuterons of the C^{12} nucleus there will occur an additional absorption of π mesons at the time of their passage (drift) through the nucleus, as a result of which in the (γ, p) reaction in the C^{12} nucleus an additional proton yield is possible which is proportional to the number of π mesons of all signs produced in the nucleus. The deuteron photodisintegration cross section drops sharply in the region of multiple photoproduction of π mesons, and therefore we can expect that in this photon energy region the energy dependence of the photodisintegration cross sections of the deuteron and the C^{12} nucleus will differ most strongly.

In order to verify this suggestion, the proton energy spectra were integrated over E_p, and the photon-difference method was used to obtain the differential photoproduction cross section for protons in C^{12} as a function of photon energy. This dependence is shown in Fig. 3—curves 1 and 2. In the same figure we have shown also

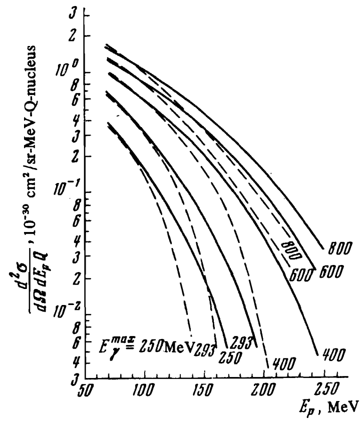

FIG. 2

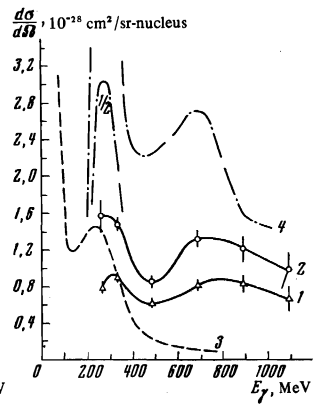

FIG. 3

FIG. 2. Comparison of experimental proton energy spectra for E_γ^{max} = 250, 293, 400 600, and 800 MeV with spectra calculated from Eq. (1), where L is taken respectively as 3, 4.4, 6.4, 7.7, and 9.1; solid curves—experiment, dashed curves—quasideuteron model.

FIG. 3. Differential cross section for photodisintegration of C^{12} at $\theta_{lab} = 90°$ as a function of E_γ: Δ—results of the present work when integration over E_p is carried out in the region E_p = 70—240 MeV, O—integration over E_p in the region E_p = 30—240 MeV (curves 1 and 2 have been drawn through the experimental points). The errors are statistical. Curve 3—differential cross section for photodisintegration of the deuteron, increased by 30 times; curve 4—the sum of the differential cross sections for photoproduction of 1, 2, and 3 π mesons of all signs in nucleons of C^{12}.

the dependence of the differential cross section for deuteron photodisintegration as a function of photon energy[18,19], increased by a factor of 30, i.e., in the Levinger formula for obtaining the (γ, p) reaction cross section in C^{12} the parameter L was chosen as 10 (curve 3); also shown in Fig. 3 is the sum of the differential cross sections for photoproduction of 1, 2, and 3 π mesons of all signs from the nucleons of the C^{12} nucleus (curve 4).

In obtaining curves 1 and 2 it was assumed that the interaction of the protons in the final state, which partially distorts the proton energy spectrum, does not lead to a significant change in their number, and that the scattering of protons into other angles is compensated by protons scattered into the solid angle of the apparatus. The cascade increase coefficient for scattered protons, found for C^{12} from calculations based on the work of Metropolis et al.[20] and which turned out to be 1.35, is consistent with these assumptions. In these estimates we used a transparency of the C^{12} nucleus for 80—235-MeV protons of 0.6.

Curves 1 and 2 in Fig. 3 have appreciable peaks in the vicinity of the first and second (πN) resonances and differ significantly from curve 3. This qualitatively confirms our suggestions that in photodisintegration of the C^{12} nucleus an important contribution is made by absorption of π mesons produced in the C^{12} nucleons and not absorbed at the moment of production.

Thus, from the results presented we can conclude that, beginning with the π-meson photoproduction threshold, the dominant mechanism of photodisintegration of C^{12} at $\theta_{lab} = 90°$ is π-meson absorption occurring both at the moment of pion production in a nucleon of the nucleus and in the course of passage of the mesons through the nucleus.

In conclusion the authors express their gratitude to V. L. Agranovich, N. G. Afanas'ev, I. I. Miroshnichenko, and P. V. Sorokin for making the experimental apparatus available for performance of additional measurements, and to G. L. Bochek for assistance in making the calculations.

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