Angular and Energy Distributions of Photoprotons From Be^9 and C^{12}

I. V. CHUVILO AND V. G. SHEVCHENKO

The P. N. Lebedev Physical Institute, Academy of Sciences, U.S.S.R.

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Results of measurements of the angular and energy distributions of protons produced in the photodisintegration of Be^9 and C^{12} are presented. The gamma-ray source was a 265-Mev electron synchrotron. The protons were recorded on photographic plates. Analysis of the results leads to the conclusion that in the 60 – 80 Mev range the gamma rays interact mainly with separate structures produced within the nuclei.

WE HAVE INVESTIGATED the angular and energy distributions of photoprotons produced in C^{12} by bremsstrahlung with $E_{\gamma_{max}} = 64$ and 84 Mev and in Be^9 by bremsstrahlung with $E_{\gamma_{max}} = 68$ and 84 Mev. The electron synchrotron of the Physical Institute of the Academy of Sciences, U.S.S.R., provided gamma rays with a maximum energy of 265 Mev.

Fig. 1 is a diagram of the experimental arrangement. The proton beam passad through a collimator of 0.5 × 3 cm aperture. The target inside the vacuum chamber formed a 30° angle with the direction of the gamma-ray beam. The thickness of the graphite target was 113 mg/cm² and that of the beryllium target 58 mg/cm²; the impurity content did not exceed 0.3%. Paraffin and lead shielding eliminated neutron and gamma-ray backgrounds on the plates. The electron background was removed from the gamma-ray beam by a magnetic field of about 3000 oersteds. The radiation doses were determined by an ionization chamber monitor which was calibrated absolutely by an ionization chamber in the manner described by Lax.[1]

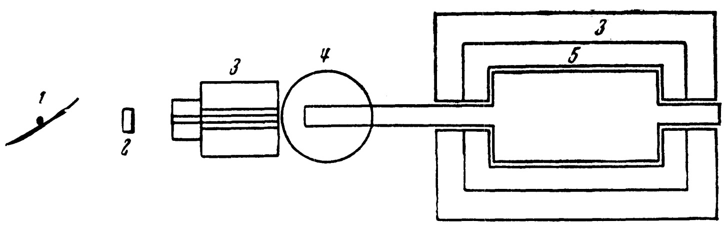

FIG. 1. Diagram of the experiment *1* – synchrotron; *2* – monitor; *3* – lead shield and collimator; *4* – magnet; *5* – graphite shield; *6* – camera.

The protons were registered on NIKFI (Cine-Photographic Research Institute) plates bearing 500 μ Ia-2 type emulsions placed in the camera at angles of 30, 45, 60, 75, 90, 120, and 150° with respect to the gamma-ray beam. The relative solid angles were calibrated with 3% accuracy by means of an alpha-ray source. The shift of the beam direction with respect to the target center was controlled by comparing the results on two plates at 90° which were placed symmetrically with respect to the target center. In addition, when the beam was focused on x-ray film its displacement from the target center did not exceed 0.2 – 0.3 mm. A correction was introduced for the shifting of the beam.

In scanning the plates we selected tracks proceeding from the irradiated portion of the target, beginning at the surface of the emulsion and corresponding to proton energies ⩾ 4 Mev. The energies of these protons were determined by using the range-energy curves for S-2 and Ia-2 emulsions, which practically coincide. The initial proton energy on leaving the target was determined from the absorber thickness with a correction for the target thickness. For the purpose of separating the various proton energy groups we used copper absorbers with thicknesses of 460, 560, 1000 and 1400 mg/cm². A correction was introduced for multiple proton scattering in the absorber.

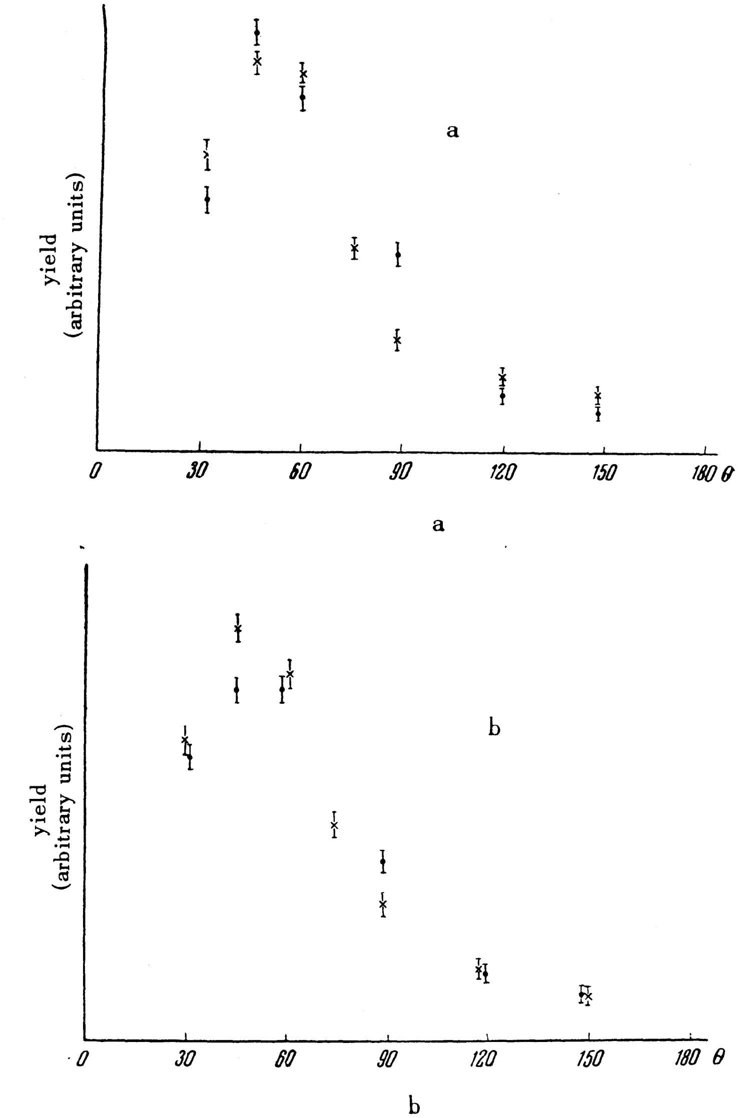

FIG. 2. Angular distributions of the photoprotons. *a*) Be^9: dots – $E_p > 20$ Mev, $E_{\gamma\,max} = 68$ Mev; crosses – $E_p > 32$ Mev, $E_{\gamma\,max} = 84$ Mev; *b*) C^{12}: dots – $E_p > 18$ Mev, $E_{\gamma\,max} = 64$ Mev; crosses – $E_p > 26$ Mev, $E_{\gamma\,max} = 84$ Mev.

The proton background was measured in the absence of the target. This was found to be 10 – 15% of the effect under investigation on plates forming angles of 30° and 150° with the beam and 3 – 4% on the other plates. The background consisted principally of 7-Mev protons.

Fig. 2 shows the angular distributions of the photoprotons. The marked asymmetry with respect to the 90° direction and the forward peaking from both beryllium and carbon can be explained most naturally by assuming that gamma rays of the given energies interact mainly with separate structures produced within the nuclei. This hypothesis is supported by the good agreement between the angular distribution of photoprotons from Be^9 (assuming a two-nucleon interaction mechanism) and from deuterons obtained with 60 and 80-Mev gamma rays.[2]

The above hypothesis is also supported by an analysis of the photoproton energy distribution for Be^9 (Fig. 3). The energy dependences of the cross sections for photodisintegration of the deuteron and Be^9 are in good agreement for protons of the same energies. The energy spectra are marked by characteristic bending at points which agree qualitatively as a function of the angle of proton flight with the corresponding points in the photoproton spectra of the deuteron.

A comparison of the photoproton production cross

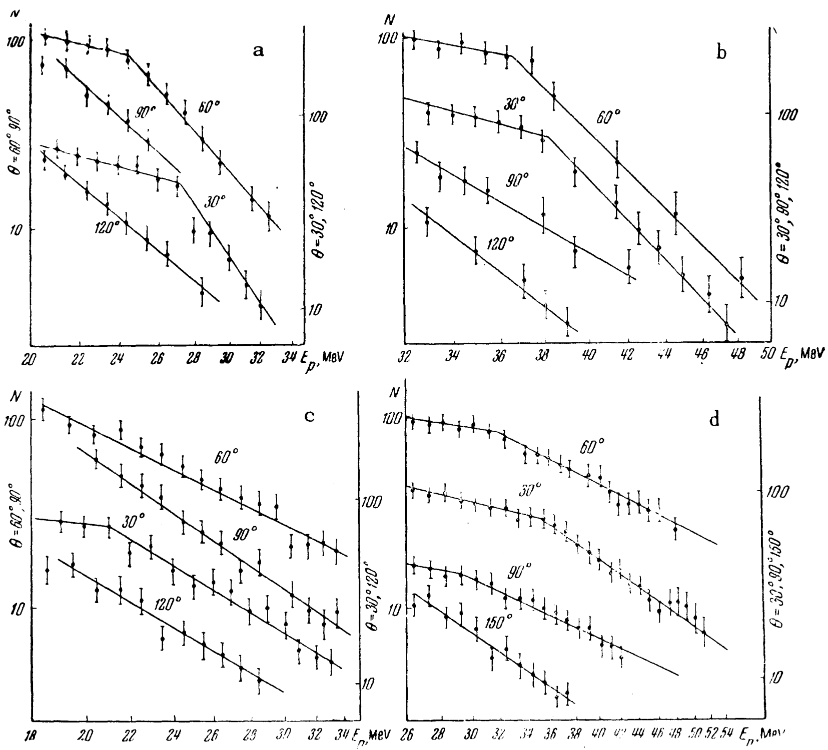

FIG. 3. Energy distribution of photoprotons (yield given in relative units): a – Be^9, $E_{\gamma max}$ = 68 Mev; b – Be^9, $E_{\gamma max}$ = 84 Mev; c – C^{12}, $E_{\gamma max}$ = 64 Mev; d – C^{12}, $E_{\gamma max}$ = 84 Mev.

sections of Be^9 and the deuteron gives $\sigma_{Be} = (0.8 \pm 0.2) A\sigma_d$ for $E_{\gamma max}$ = 84 Mev and E_p = 32 – 38 Mev and $\sigma_{Be} = (1.0 \pm 0.2) A\sigma_d$ for $E_{\gamma max}$ = 68 Mev and E_p = 20 – 26 Mev, where σ_{Be} is the cross section per effective quantum for Be^9 and σ_d is the cross section per effective quantum for the deuteron. Unfortunately the comparison could only be made by utilizing a rough theoretical estimate[3] of the absolute cross-section for the quasideuteron interaction ($\sigma_A = 1.6 A\sigma_d$) neglecting the secondary processes, which can be important for gamma rays in the given energy range. It is noteworthy that the ratio of the deuteron and Be^9 photoproduction cross sections is constant within the limits of experimental error for the different proton energy groups when $E_{\gamma max}$ = 68 and 84 Mev. These results are thus also not inconsistent with the hypothesis that the quasideuteron interaction is predominant.

Let us turn now to the results obtained for carbon. The angular distribution and cross section for the photoproduction of 18 – 28 Mev protons in C^{12} by gamma rays with $E_{\gamma max}$ = 64 Mev are in poor agree ment with the results obtained for the deuteron. It follows that although the reaction in the case of C^{12} also involves principally structures formed within the nucleus, either there is a two-nucleon absorption mechanism with a high (γ, np)-reaction threshold leading to the ejection of individual protons or the reaction involves more complex structures within the C^{12} nucleus. Such structures could be quasi alpha particles. The latter possibility is favored by the extremely large cross section of carbon decay into three alpha particles, which indicates a relatively large probability for the formation of quasi alpha particles within the C^{12} nucleus. The photodisintegration of C^{12} by gamma rays with $E_{\gamma max}$ = 84 Mev presents a different picture. A comparison of the experimental findings on the energy spectra and angular distributions of 26 – 36 Mev proton groups with corresponding data for the deuteron shows satisfactory agreement with the quasi-deuteron mechanism. The cross sections for C^{12} photoproton production and for deuteron photodisintegration give $\sigma_C = (1.1 \pm 0.2) A\sigma_d$, where σ_C is the carbon cross section per effective quantum. This relationship is similar to that obtained for the photodisintegration of Be^9. It is also of interest that the energy spectrum for C^{12} with $E_{\gamma max}$ = 84 Mev shows a maximum proton energy of 55 Mev, which gives a reaction energy of 28 Mev, thus agreeing with the energy of the

(γ, np) reaction in C^{12}. This indicates a small cross section for the (γ, p) reaction in carbon at the given energy. When C^{12} is irradiated with bremsstrahlung of $E_{\gamma_{max}} = 64$ Mev the maximum proton energy corresponds to the energy threshold of the (γ, p) reaction; thus indicating that the latter reaction makes a considerable contribution to the total photoproton yield at the given excitation energy. Similar conclusions cannot be drawn for Be^9 because in this instance the thresholds of the (γ, p) and (γ, np) reactions practically coincide.

We converted the angular distributions to the center-of-mass system on the assumption that the principal contribution is made by the reactions C^{12} (γ, p) B^{11} and Be^9 (γ, p) Li^8 when ejection of a proton transfers recoil energy to the residual nucleus. These results can be approximated by curves of the form

$$a + b \sin^2 \theta (1 + \gamma \cos \theta)^2.$$

In this analysis the relative amount of quadrupole absorption was found to be unsually large, amounting to 60 – 80% of the dipole contribution. This fact produces doubt as to the correctness of the scheme chosen to describe the interaction between quanta and the nuclei under consideration. A recalculation must be based on the above hypothesis that in the given energy range gamma rays interact with nuclei mainly through structures formed within the nucleus.

The extensive experimental results which are now available for light nuclei can be interpreted on the basis of theoretical concepts regarding the existence of structural units within the nuclei, *i.e.*, that a nucleon in a nucleus interacts not with all the other nucleons of the nucleus but only with those which are in definite states of motion with respect to the given nucleon (see Ref. 4, for example).

Our experimental data on photoprotons from Be^9 and C^{12} are in agreement with this hypothesis.

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Correlations in $\pi \to \mu \to e$-Decay

A. O. VAISENBERG AND V. A. SMIRNITSKII
Academy of Sciences, U.S.S.R.

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120 positrons from $\pi \to \mu \to e$ decays in emulsion were analysed by energy and by the angle between μ-meson and positron tracks. The observed distributions are in qualitative agreement with the two-component neutrino theory. If λ is the theoretical asymmetry parameter and α the fraction of the μ-mesons not depolarized by the emulsion, the measurements give the result $\alpha\lambda = 0.5 \pm 0.25$.

THIS PAPER DESCRIBES measurements of the positron energy and of the angle between μ-meson and positron tracks in $\pi^+ \to \mu^+ \to e^+$ decays in photographic emulsion. The problem arose from the observation by Lee and Yang[1] that a departure from parity conservation could lead to a correlation between the directions of μ-meson and electron. Landau[2] suggested that the interactions such as $\pi \to \mu \to e$ decay in which parity is not conserved are still invariant under "combined inversion," the combination of space-reflection with charge conjugation. He also showed that if the neutrino is polarized