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POLARIZATION OF PROTONS FROM THE REACTION $\gamma + n \to \pi^- + p$ IN THE PHOTON ENERGY INTERVAL 550–900 MeV

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A telescope of spark chambers and scintillation counters is used to measure the polarization of photoprotons from the C^{12} nucleus at γ-quantum energies E_γ^{max} = 650–1000 MeV, The experimental data are used to calculate the polarization of the protons from the $\gamma + n \to \pi^- + p$ reaction for photon energies between 550 and 900 MeV, under the assumption that the major mechanism of photoproduction of the protons in a nucleus in the kinematic region of pion photoproduction is the photoproduction of pions on quasi-free nucleons of the nucleus. The energy variation of the polarization of $\gamma + n \to \pi^- + p$ protons has a structure and reverses skgn at a proton energy 735 MeV. Between the P_{33} and D_{13} resonances, the polarization energy variation agrees satisfactorily with the theoretical variation, in which contribution of the P_{11} resonance is taken into account.

INTRODUCTION

An investigation of the polarization of protons in the process of single photoproduction of pions is of great importance for the study of resonant states of the πN system. This is confirmed by the intensive investigations of the polarization of the protons from the reaction $\gamma + p \to \pi^0 + p$[1-7] that have been carried out to date. These investigations were carried out not only because the polarization of the recoil protons made it possible to determine the parity and type of the absorbed γ quantum in the resonances P_{33}(1236), D_{13}(1518), and F_{15}(1683) observed in the process of photoproduction of single mesons. They were also carried out in order to obtain in the polarization experiments a confirmation of the existence of the resonances S_{11} and P_{11},[6] which were revealed by an analysis of the results of experiments on πp scattering. No such polarization measurements were made for the protons from the reaction $\gamma + n \to \pi^- + p$, owing to the lack of a pure neutron target.

Prior to the 15th International Conference on High Energy Physics (Kiev), where the preliminary results of the present investigation were reported, there was only the study of Kenemuth and Stein[8] on the measurement of the polarization of the protons from the reaction $\gamma + n \to \pi^- + p$ at 90° in the c.m.s. at E_γ = 715 MeV. The target used in that investigation consisted of the neutrons of liquid deuterium. The difficulties connected with the accompanying reaction $\gamma + p \to \pi^0 + p$ were resolved by a coincidence experiment. The good agreement between the proton polarization measured for the reaction $\gamma + p \to \pi^0 + p$ on liquid-deuterium and liquid-hydrogen targets has eliminated the problem of the momentum distribution of the nucleons in the deuterium, and has made measurements of the polarization of the protons from t the reaction $\gamma + n \to \pi^- + p$ reliable.

The proton-polarization analysis performed by Kenemuth and Stein[8] has shown that the negative value of the polarization cannot be attributed to interference of the amplitudes of only the P_{33}(1236) and D_{13}(1518) resonances in the photoproduction of single pions. The agreement of the sign of the polarization of the protons from the reaction $\gamma + n \to \pi^- + p$ with the sign of the polarization of the protons in the reaction $\gamma + p \to \pi^0 + p$ is obviously connected with the contribution of the resonances S_{11} and P_{11}.

We present here the results of an experimental determination of the polarization of the protons in this reaction using carbon as the neutron target.

EXPERIMENTAL PROCEDURE

The experiment was performed with the bremsstrahlung beam of the Khar'kov 2-GeV linear accelerator.

Figure 1 shows the experimental setup.

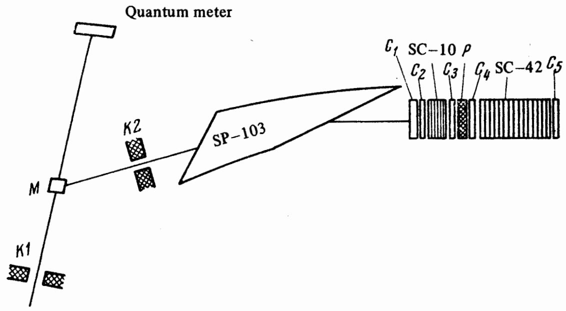

FIG. 1. Experimental setup.

The bremsstrahlung beam of the accelerator was incident on the target after first being collimated with lead collimators K_1 and K_2, of 8 and 12 mm diameter, and after removal of the charged component with the aid of a clearing magnet. The diameter of the photon beam on the target did not exceed 15 mm. The intensity of the beam was determined with the aid of a Wilson quantum meter and amounted to $(2-3) \times 10^9$ eq.qu./sec. The recoil protons resulting from the interaction of the photons with the target nucleons were analyzed with a magnetic spectrometer[9] mounted at an angle of 41°. The angle subtended by the spectrometer was determined by the collimator K_2 and amount to ±2°. The proton registration was with a telescope of spark chambers and scintillation counters.[10] The telescope contained two spark chambers SC-10 and SC-42, and scintillation counters C_1, C_2, C_3, C_4, and C_5. The case of the stopping of a proton in the chamber SC-42 was registered by the coincidence of the pulses of C_1, C_2 and C_4 and by the anticoincidence of C_5. The protons were identified by the specific ionization losses in the counter C_3, by the ranges in the chamber SC-42, and by their momenta in the magnetic spectrometer. P in the figure represents a copper moderator.

Figure 2 shows the proton spectrum of the pulses of counter C_3 for a spectrometer momentum 653 ±22 MeV/c.

The spark chamber SC-10[11] with 10 electrodes of aluminum foil 0.15 mm thick was intended to separate the direction of the entrance of the proton into the chamber SC-42. The proton polarization analyzer was a spark chamber[12] having 42 graphite electrodes measuring 350 × 350 × 7 mm. Two mutually-perpendicular projections of the tracks were photographed with the aid of the optical system of the telescope on one frame of 35-mm photographic film.

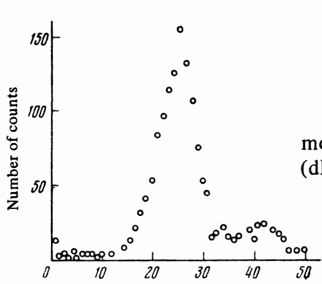

FIG. 2. Spectrum of protons with momentum 653 ± 22 MeV/c in the (dE/dx) counter.

SELECTION OF EVENTS AND DETERMINATION OF THE MAGNITUDE OF THE POLARIZATION

The experiment yielded approximately 300,000 photographs, from which cases of elastic scattering of protons by carbon nuclei were selected. The accuracy with which the scattering angle was measured was determined by the distortions of the track direction introduced by the optical system of the telescope, by the dimensions of the spark image, by their scatter relative to the main direction of the track, and also by the uncertainty connected with the multiple scattering in the graphite electrodes of the spark chamber. Allowance for the distortions introduced by the optical system was effected by photographing the track of the proton against a background of rectangular grids placed between the lenses of the optical system and the telescope.

The error in the determination of the centers of the sparks, which depended on the dimensions of the sparks, was ±0.25 mm. This was used to determine the error in the measurement of the angles:

$$\langle \Delta\varphi^2 \rangle^{1/2} \leqslant 2.6^\circ, \quad \langle \Delta\theta^2 \rangle^{1/2} \leqslant 0.8^\circ.$$

The scatter of the sparks relative to the principal direction of the track did not exceed 0.3 mm. The associated errors with respect to the azimuthal and spatial scattering angles were respectively

$$\langle \Delta\varphi^2 \rangle^{1/2} \leqslant 0.6^\circ, \quad \langle \Delta\theta^2 \rangle^{1/2} \leqslant 0.2^\circ.$$

Multiple scattering in the graphite electrodes produced an error in the determination of the spatial angle that depended on the energy of the proton and ranged from 0.5 to 1.6° for energies 250 and 80 MeV, respectively. The summary rms errors in the determination of the azimuthal and spatial angles did not exceed 3 and 1.8°, repsectively.

The energy of the scattered protons was determined from their range in the spark chamber SC-42. The accuracy with which the proton energy was measured was determined by the average energy losses in one graphite electrode, which did not exceed, for the chosen electrode thickness, 5 MeV in the entire interval of energies of the registered protons (135–300 MeV). The interval of the proton momenta subtended by the telescope was 7%.

The alignment of the focal line of the spectrometer with the second gap of the proton-polarization analyzer chamber made it possible to carry out energy calibration of the focal line.[10] This has made it possible to determine the energy of the proton entering the telescope from the coordinate on the focal line of the spectrometer.

The selection of the events connected with the scattering of the protons by the carbon was based on the following criteria:

1. The proton prior to scattering should pass through the spark chamber SC-10 and the first two gaps of the chamber SC-42.
2. The direction of the proton track after scattering should be determined by not less than 5 "punctured" gaps.
3. The proton track after scattering terminates inside the analyzer chamber.
4. The proton scattering angle in the spark chamber SC-42 lies in the interval 5–25°.

5. The event connected with the scattering of a proton by carbon is assumed to be elastic if the following relation is satisfied:

$$E_0 - (E + \Delta E) \leqslant 5 \text{ MeV}, \tag{1}$$

where E_0 is the kinetic energy of the proton entering the chamber SC-42 and is determined by the position of its track on the focal line, E is the summary energy lost by the proton entering the chamber on the path before and after scattering, and ΔE is the energy lost by the proton in elastic scattering through an angle θ and is determined by the kinematics of the elastic scattering.

To exclude the possible asymmetry due to the different efficiencies of spark production on the edges of the spark chamber, we selected only those proton tracks which passed within ±30 mm from the central line of the proton-polarization analyzer chamber.

For each case of elastic scattering of a proton by carbon, we determined the spatial and azimuthal angles and the energy of the scattered proton E_p.

The proton polarization was calculated with the aid of a computer by the maximum-likelihood method using the expression

$$W(P) \sim \prod_{i=1}^{N} [1 + PA(\theta_i, E_i) \cos \varphi_i], \tag{2}$$

where $A(\theta_i, E_i)$ is the analyzing ability of the carbon[13] in the scattering of a proton of energy E_i through an angle θ_i, φ_i is the azimuthal angle, and W(P) is the probability that the protons have a polarization P.

RESULTS OF EXPERIMENT

To verify the given experimental procedure, we measured the polarization of the protons from the reaction $\gamma + p \to \pi^0 + p$ at a γ-quantum energy 750 MeV. The bremsstrahlung beam was incident on a liquid-hydrogen target forming a cylinder of 50 mm diameter. The obtained value of the polarization $P = -0.43 \pm 0.12$ is in good agreement with the data of [2,14].

In the present investigation, the neutrons of the C^{12} nuclei were used as the target for the measurement of the polarization of the protons from the reaction $\gamma + n \to \pi^- + p$. To eliminate cases of registration of protons from double pion production, the minimum energy of the working interval of the γ-quantum energies differed from the maximum energy of the bremsstrahlung spectrum by not more than 120 MeV. The measurements were made an an angle of 41° in the lab system ($\theta = 90°$ c.m.s.) in the kinematic region of the photoproduction of pions by free nucleons.

It was shown in [15] that the polarization of the protons from the C^{12} nucleus outside the meson kinematic region is close to zero for photon energies 600–930 MeV. The measured yield of the protons in the meson kinematic region turned out to be larger by one order of magnitude than the yield of the protons from the non-meson kinematic region. All this has made it possible to conclude that the non-meson mechanism of the interaction between photons and nucleons of the nucleus does not make a noticeable contribution to the polarization of the protons in the region of the meson kinematics.

Antuf'ev et al.[16] have shown that the main mechanism of photoproduction of protons on light nuclei is photoproduction of mesons on the quasifree nucleons of the nucleus.

It is shown in Devanathan's theoretical paper[17] that if the nuclei are described by the simple shell model and the amplitudes of the transition between the many-nucleon systems are expressed by a linear sum of the amplitudes of the transition of the individual nucleons, then the polarization of the secondary nucleons from the nuclei does not depend on the initial state, and is the same as the polarization observed in the case of free nucleons. Therefore the polarization of the protons from a nucleus in the meson region can be regarded as the summary polarization by individual nucleons of the nucleus and represented in the form

$$\bar{P}_{\text{nuc}} = \left[(A - Z) \left(\frac{d\sigma}{d\Omega} \right)_n P_n + Z \left(\frac{d\sigma}{d\Omega} \right)_p P_p \right] \times \left[(A - Z) \left(\frac{d\sigma}{d\Omega} \right)_n + Z \left(\frac{d\sigma}{d\Omega} \right)_p \right]^{-1}, \tag{3}$$

where $(d\sigma/d\Omega)_n$ and P_n are respectively the differential cross section and the polarization of the protons in the reaction $\gamma + n \to \pi^- + p$, $(d\sigma/d\Omega)_p$ and P_p are the analogous quantities for the reaction $\gamma + p \to \pi^0 + p$, and A and Z are respectively the mass number and charge of the nucleus.

The results of the measurements of the mean value of the polarization of the protons $\bar{P}_{\text{nuc}}$, obtained for the nucleus C^{12}, are given in Table I. Figure 3 shows the dependence of the average value of the proton polarization $\bar{P}_{\text{nuc}}$ on the photon energy $E_\gamma^{\max}$ for the angle 41° in the l.s. In the photon energy interval 650–850 MeV, the average polarization $\bar{P}_{\text{nuc}}$ is different from zero, and it is close to zero in the photon energy interval 850–1000 MeV.

Table I. Polarization of protons in the interaction of γ quanta with the nucleus ${}_6C^{12}$

$E_\gamma^{\max}$ Mev	p_{sp} Mev/c	Δp_{sp} Mev/c	Number of cases	$\bar{P}_{\text{nuc}}$	$\Delta\bar{P}_{\text{nuc}}$
650	525	$^{+32}_{-5}$	320	−0.32	±0.2
700	563	$^{+34}_{-6}$	315	−0.36	±0.19
750	600	$^{+36}_{-6}$	381	−0.47	±0.18
800	645	$^{+39}_{-6.5}$	463	−0.45	±0.13
850	668	$^{+40}_{-7}$	908	−0.05	±0.04
900	702	$^{+42}_{-7}$	263	0.02	±0.16
950	734	$^{+44}_{-7}$	290	0.01	±0.11
1000	764	$^{+46}_{-7.5}$	217	0.12	±0.15

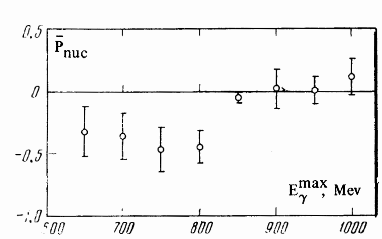

FIG. 3. Polarization of the protons from the nucleus C^{12} as a function of the maximum energy of the γ spectrum.

The values of the polarization P_n of the protons from the reaction $\gamma + n \rightarrow \pi^- + p$ were calculated from expression (3) using the value $\overline{P}_{nuc}$ from Table I, the values of P_p from [5], and $(d\sigma/d\Omega)_n$ and $(d\sigma/d\Omega)_p$ from [18]. In the calculation of the errors ΔP_n, we took into account those uncertainties with which the quantities used in (3) were measured, without taking into account the influence of the momentum distribution of the nucleons in the nucleus and the contribution of the protons from the non-meson region. The results of the calculations are given in Table II.

Table II. Polarization of protons from the reaction $\gamma + n \rightarrow \pi^- + p$, produced in the interaction of γ quanta with neutrons of $_6C^{12}$

E_γ^{max} Mev	E_γ^{eff} Mev	ΔE_γ Mev	P_n	ΔP_n	E_γ^{max} Mev	E_γ^{eff} Mev	ΔE_γ Mev	P_n	ΔP_n
650	550	±27	−0,248	±0,179	850	750	±36	0,220	±0.160
700	600	±28	−0,186	±0,123	900	800	±40	0.655	±0.372
750	650	±29	−0.416	±0.228	950	850	±45	0.637	±0.252
800	715	±32	−0.289	±0.104	1000	900	±49	0.484	±0.370

The good agreement between the value of the polarization of the protons from the reaction $\gamma + n \rightarrow \pi^- + p$, obtained on carbon at an energy $E_\gamma = 715$ MeV, with the result of [8], where deuterium was used as the target, is proof that the momentum distribution of the nucleons in the C^{12} nucleus does not introduce significant changes in the measured polarization.

Figure 4 shows the energy dependence of the polarization of protons from the reaction $\gamma + n \rightarrow \pi^- + p$ on the photon energy for the angle $\theta_\pi = 90°$ in the c.m.s., obtained in the present investigation. This dependence shows that the polarization of the protons in the photoproduction of π^- mesons in the photon energy region between the P_{33} and D_{13} resonances has a negative sign. In the region between the D_{13} and S_{15} resonances, the sign of the polarization is positive. At $E_\gamma = 735$ MeV, the polarization reverses sign.

The same figure shows the values of the proton polarization obtained with liquid-deuterium targets in [8] and in [19], which was reported at the 15th International Conference in Kiev. A comparison of the results of the present work with the results of [8,19] shows good agreement in the compared energy interval.

Figure 4 shows simultaneously a comparison of the experimental data with theoretical calculations of [20-22], performed for the photon energy interval between the P_{33} and D_{13} resonances.

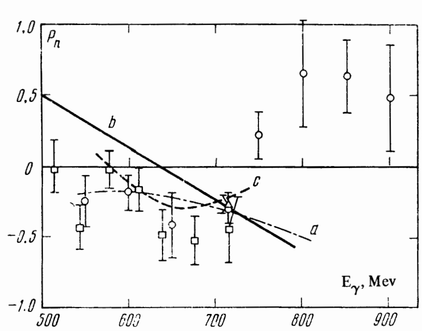

FIG. 4. Energy dependence of the polarization of the protons in the reaction $\gamma + n \rightarrow \pi^- + p$. Curve b–calculations taken from [20], a–from [21], c–from [22], □–data of [19], Δ–data of [8], O–present data.

Curve a was calculated[20] with allowance for the contributions made to the polarization by the states D_{13}, P_{11}, and S_{11}. Curve b was obtained[21] with allowance for the contributions of the states D_{13} and S_{11}, but without allowance for the P_{11} resonance. Curve c takes into account[22] the contribution of the D_{13} and P_{11} resonant states without the state S_{11}.

The general behavior of the experimental points agrees better with the predictions of [22], where account is taken of the contribution of the P_{11} resonance but not of the contribution of the S_{11} state.

Figure 5 shows a comparison of the theoretical predictions of the angular distributions of the polarization [20,21] with the available experimental points for the reaction $\gamma + n \rightarrow \pi^- + p$ at γ-quantum energies 600 and 700 MeV. Whereas at $E_\gamma = 700$ MeV it is difficult to give preference to any of these two models, owing to the poor statistics, at $E_\gamma = 600$ MeV it is clearly seen that only allowance for the P_{11} state can explain the negative sign of the polarization at E = 600 MeV.

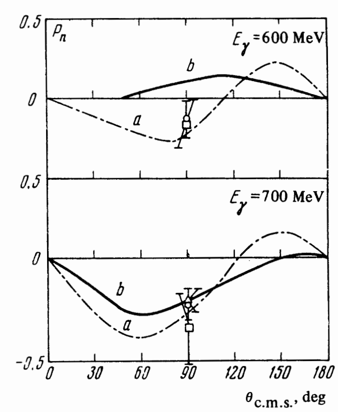

FIG. 5. Angular dependence of the polarization at γ-quantum energies 600 and 700 MeV. The notation is the same as in Fig. 4.

Unfortunately, the theoretical calculations were not continued into the region between the D_{13} and F_{15} resonances where, in accordance with our results, the polarization of the protons reverses sign. Such theoretical investigations would make it possible to determine which states of the πN system make the main contribution to the polarization in the region between the D_{13} and F_{15} resonances.

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