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ЦЕНТРАЛЬНЫЙ НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ ИНСТИТУТ ИНФОРМАЦИИ И ТЕХНИКО-ЭКОНОМИЧЕСКИХ ИССЛЕДОВАНИЙ ПО АТОМНОЙ НАУКЕ И ТЕХНИКЕ

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DEUTERON PHOTODISINTEGRATION BY LINEARLY POLARIZED PHOTONS IN THE ENERGY RANGE $E_\gamma = 0.4 \div 0.8$ GEV

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ИССЛЕДОВАНИЕ РЕАКЦИИ ФОТОРАСЩЕПЛЕНИЯ ДЕЙТРОНА ЛИНЕЙНО-ПОЛЯРИЗОВАННЫМИ ФОТОНАМИ В ОБЛАСТИ ЭНЕРГИЙ E_γ= 0,4-0,8 ГэВ

Представлена экспериментальная методика и приведены результаты измерений асимметрии сечения Σ реакции $\gamma d \to pn$ линейно-поляризованными фотонами в области энергий E_γ = 0,4-0,8 ГэВ и углов протона в С.Ц.М. $\theta_p^* = 45^\circ$-95°. Экспериментальные исследования были проведены с помощью двухплечевой спектрометрической установки. Полученные результаты не согласуются как с расчетами в рамках феноменологических моделей, так и с предсказаниями парциально-волнового анализа, учитывающего вклад дибарионных резонансов. Проведен анализ данных по разности $\Delta\Sigma(\theta)=\Sigma(\theta)-\Sigma(\pi-\theta)$. Показано, что $\Delta\Sigma$ является более чувствительной к малым вкладам изоскалярных или изовекторных амплитуд.

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1. Introduction

The deuteron photodisintegration $\gamma d \to pn$ is one of the most fundamental processes in nuclear physics. The experimental and theoretical study of this reaction can give important information on the deuteron wave function at small internuclear distances and determine the contribution of different mechanisms such as meson exchange, isobar excitation etc. [1]. At the same time the detailed study of these problems would be helpful to define the role of pair correlations in photonuclear reactions at large transfer momenta, which will undoubtedly serve as a basis for the construction of theoretical models [2].

Intensive study of $\gamma d \to pn$ reaction in the past few years is related to the problem of the existence of dibaryon resonances. An indication to a possible existence of dibaryon resonances in the $\gamma d \to pn$ is firstly obtained from the recoil proton polarization (P) data [3]. The anomalous high polarization observed at the photon energy E_γ = 550 MeV was not explained by the existing models [4]. At the same time, the data on the differential cross section ($d\sigma/d\Omega$) and polarization (P) were described by the partial-wave analysis [5] taking into account the dibaryon resonances. However the results of further measurements of the beam asymmetry Σ [6,7,8] and target asymmetry T [9] did not confirm the predictions of the analysis [5], which showed the insufficiency of existed models of deuteron photodisintegration.

In this paper the experimental method is described and the measurements of the beam asymmetry Σ of the reaction $\gamma d \to pn$ for energies $E_\gamma = 400 \div 800$ MeV and angles $\theta_p^* = 45^\circ \div 95^\circ$ are reported. The present measurements, along with the data of Kharkov [6] ($E_\gamma = 400 \div 600$ MeV, $\theta_p^* = 75^\circ \div 125^\circ$) and Bonn [7] ($E_\gamma = 400 \div 800$ MeV; $\theta_p^* = 115^\circ, 135^\circ$) provided systematic data on the beam asymmetry Σ in the energy range $E_\gamma = 400 \div 800$ MeV at $\theta_p^* = 45^\circ \div 135^\circ$.

2. Experimental method and setup

The experiment was performed using the linearly polarized quasimonochromatic photon beam of the Yerevan synchrotron. The beam and experimental area are illustrated in fig.1. The beam was produced by the coherent bremsstrahlung on the internal monocrystalline diamond target (D). The photon beam was formed by a system of collimators (K_1, K_2) and sweeping magnets (SM1, SM2). The beam cross section at the liquid-deuterium target (LD_2) was about 10x10 mm^2. The photon beam was monitored by the Wilson quantometer (Q) and fast monitor (M), which is a telescope of scintillation counters used to detect charged particles from the converter (C_2).

The photon energy spectrum was measured and controlled by a 9-channel pair spectrometer (PS-9), consisting of an analyzing magnet (PSM), 6 telescopes of scintillation counters to detect e^+e^- pairs and a set of converters (C_1) with $10^{-4} \div 10^{-5}$

rad. length thickness. Different (3x3) combinations of coincidences between e^+ and e^- telescopes allowed to measure the photon spectrum simultaneously for 9 values of the photon energy in the range $\Delta E_\gamma = \pm 0.15 \bar{E}_\gamma$, where $\bar{E}_\gamma$ is the value of the pair spectrometer mean energy. The energy resolution of the pair spectrometer $(\sigma(E_\gamma)/E_\gamma)$ was ±1.2%. The PS-9 spectrometer, realized on-line with the measuring-computing system on the basis of CAMAC apparatus and an Э-60 computer [10], operated in the regime of mounting of the analyzing magnet current, statistics storage and control of photon energy spectrum stability. A typical γ-spectrum, measured by PS-9 as well as the calculated polarization curve [11] is shown in fig.2.

During the experiment the electron energy was adjusted so that the ratio $E_\gamma^{peak}/E_e = 0.2 \div 0.3$, where E_γ^{peak} is the energy of the coherent maximum of the quasimonochromatic bremsstrahlung spectrum (fig.2). This gave (50÷70%) of polarization of photons P_γ used in any setting of the experimental setup.

The experiment used a universal liquid cryogenic target (LCT) [12] for the H_2 and D_2 liquefaction. The irradiated appendix of the target was a 50x100 mm cylinder with an axis along the beam made of 50μm thick stainless steel. The outer vacuum shell of the target with 100μm thick lavsan windows provided a constructive-free kinematic region of angles.

The LCT exploitation conditions provided a stable density of liquid H_2 and D_2 in the target with an accuracy ±0.2%.

To detect the products of $\gamma d \to pn$ a two-arm spectrometer has been used (see fig.1). Protons were detected by a magnetic spectrometer (MS) [13] which contains a lense doublet (L_1, L_2), a bending magnet (BM) and a telescope of scintillator counters $S_1 \div S_5$. The choice of the new optical configuration of the doublet and optimization of the telescope counters' sizes leads to an increase in the angular acceptance of MS from 10^{-3} sr to 3.5×10^{-3} sr.

The momentum resolution of the spectrometer defined by TOF was ±3%. π^+ mesons were separated from protons on the 9 m flight path between the counters S_1 and S_4 with the time resolution about ±1 nsec. To decrease the multiple scattering and absorption effects, polyethylene bags with helium gas were placed along the trajectory of particles in the MS.

Nuetrons were detected in the 12-module time-of-flight spectrometer (NS) [14] which is a (4x3) counter matrix, each module being a plastic scintillator with a size 230x230x300 mm viewed by a photomultiplier ФЭУ-30. To subtract the background of charged particles and γ-quanta of the target, a lead converter of 2 rad. length thickness and a hodoscope composed of four thin scintillation anticoincidence counters (A1 ÷ A4) were mounted in front of NS. The time-of-flight analysis of neutrons was performed on the 3.3 m flight path between target and NS, using start pulses from S_1 counter of the proton arm.

The thresholds of neutron modules were calibrated by means of cosmic μ-mesons and were equal to $\sim$ 10 MeV (equivalent electron energy). The corresponding calculated efficiency [15] was about 25% in the energy region 150 ÷ 400 MeV. The time-of-flight calibration, the definition of time resolution and rescattering effects were performed using $\gamma p \to p\pi^{\circ}$ and $\gamma p \to \pi^+ n$ reaction on the liquid hydrogen target. Protons and π^+-mesons were detected by the magnetic spectrometer, while neutrons and γ-quanta from the π°-meson decay by a neutron spectrometer.

The peak observed in the time-of-flight spectrum (fig.3)

corresponding to γ-quanta from $\gamma p \to \pi^{\circ} p$ defined the position of particles with $\beta = 1$ on the time scale, and provided an absolute graduation of the time-of-flight.

Detection of neutrons from the $\gamma p \to \pi^+ n$ allowed to determine the time resolution of NS (±2 nsec) and the probability of rescatterings of the "mixing" and "multifiring" types [16] - about 5 ÷ 25% depending on neutron energy.

An additional detector (R) was used to define the contribution of accidentals between magnetic and neutron spectrometers. It was a shower counter in coincidence with the telescope of monitor counters and detected secondary electrons from the converter C_2. The pulses from R were used as start signals for the TOF analysis of accidentals between R and NS. The number of accidentals N_1 between MS and NS was defined by the number of accidentals N_2 between R and NS:

$$N_1 = N_2 \cdot N_{MS}/N_R$$

where N_{MS}/N_R is the counting ratio of the magnetic spectrometer and detector R. As is shown in [17], this method of measuring the contribution of accidentals is insensitive to the time structure of the beam and is more correct as compared to the traditional method of delayed coincidences.

3. Data acquisition

The beam asymmetry was defined by the $\gamma d \to pn$ yields for the photon polarization vector perpendicular and parallel to the reaction plane.

A time-of-flight analysis of neutrons was performed to distinguish the considered reaction from the many-particle background and accidentals. In fig.4 the time-of-flight spectrum of neutrons is shown for the E_γ = 500 MeV, $\theta_p^* = 45^\circ$ kinematics. As is seen from figures the time-of-flight spectra have characteristic peaks of ultrarelativistic particles from background processes and quasimonochromatic neutrons from the reaction considered.

The contribution of accidentals was defined by time-of-flight measurements between R and NS and was further subtracted after normalization to the N_{MS}/N_R ratio.

The background of many-particle processes due to the high-energy part of the bremsstrahlung was subtracted using the polynomial fit. The whole background contribution did not exceed 10%. The quality of the background subtraction is illustrated in fig.5, where the distribution of neutrons among NS columns is shown along with the results of Monte-Carlo calculations that are in a good agreement with experimental data. The background contribution from the appendix and other constructives of target was determined in empty target measurements and did not exceed 1%.

The beam asymmetry Σ was calculated from

$$\Sigma = \frac{N_\perp - N_\parallel}{P_\parallel N_\perp + P_\perp N_\parallel}$$

where $N_\perp$ and $N_\parallel$ are the numbers of events normalized to the number of γ-quanta for perpendicular and parallel orientations of the photon polarization. $P_\perp$ and $P_\parallel$ are the corresponding effective polarizations.

The differential cross section $d\sigma/d\Omega$ was calculated from

$$\frac{d\sigma}{d\Omega} = \frac{N_\perp P_\parallel + N_\parallel P_\perp}{P_\perp + P_\parallel} \cdot \frac{1}{N_d N_\gamma^\varepsilon \varepsilon}$$

where N_d is the number of deuterons per cm^2, N_γ^ε is the effective number of photons, ε is the efficiency of the experimental apparatus. N_γ^ε, ε as well as the energy and angular resolutions of the apparatus $\sigma(E_\gamma)$ and $\sigma(\theta_p^*)$ were Monte-Carlo simulated.

4. Results and discussion

Results on the beam asymmetry Σ and differential cross section $d\sigma/d\Omega$ of $\gamma d \to pn$ obtained in this work are plotted in table 1. Errors in Σ include statistical error in the definition of $N_\perp$ and $N_\parallel$ and about 10% error in photon polarizations ($P_\perp$ and $P_\parallel$). Errors in $d\sigma/d\Omega$ are statistical only. The possible systematic errors in $d\sigma/d\Omega$ estimated using the data on $\gamma p \to pn$ and Monte-Carlo calculations are within 10 - 15%.

The values of $d\sigma/d\Omega$ for most kinematic points for $E_\gamma > 500$ MeV are measured for the first time. A satisfactory agreement (see fig.6) with available experimental data is observed [18,19,20,21].

The data obtained for Σ together with data from refs. [6,7,22,23] are shown in figs.7 and 8 versus E_γ and θ_p^*. The curves in figs. 7 and 8 correspond to the results of theoretical calculations of Ogawa et al. [24], Huneke [25] and Laget [26] and also to the predictions of partial-wave analysis of Ikeda et al. [5], based on the calculations of Ogawa et al. [24] and taking into account the contribution of dibaryon resonances $1(3^-)$ (2.26), $0(1^+)$ (2.36) and $0(3^+)$ (2.35). As is seen from figs.7 and 8, the experimental data are inconsistent with theoretical curves.

The possible explanation for this fact can be the simplified description of $\gamma d \to pn$ reaction by a few simple diagrams. As is shown in [1,26], the final state interaction effects, such as rescatterings which are not considered may be essential and can lead to a bad agreement of experimental data with theoretical models. At the same time, the correct description of the process not involving dibaryon resonances discussed in ref.[1], is not obvious. As is indicated in ref.[27], the anomalous effects observed in the $N-N$ processes which in total are not explained in the framework of known diagrams of meson exchange, isobar excitation etc. and are attributed to dibaryon resonances apparently should be noticed in the $\gamma d \to pn$ reaction dynamics as well. Nevertheless, as is seen from figs. 7 and 8, involving the dibaryon resonances in [5] does not improve the quality of description of experimental data on the beam asymmetry Σ. Besides the noted remarks on calculations of Ogawa et al.[24], one should mention here both the existing ambiguity in the choice of dibaryon resonances and the quality of analysis, based only on the data on differential cross sections $d\sigma/d\Omega$ and recoil proton polarization P.

For the $\gamma d \to pn$ reaction the generalized Pauli principle connects helicity amplitudes with a definite value of isospin for proton production angles θ_p^* symmetric to $\pi/2$. Therefore, it will be attractive to analyze the experimental data on the difference of observables for θ_p^* symmetric to $\pi/2$. As is shown in Appendix A, the expression

$$A(\theta_p^*) = \frac{d\sigma}{d\Omega}(\theta_p^*)\Sigma(\theta_p^*) - \frac{d\sigma}{d\Omega}(\pi-\theta_p^*)\Sigma(\pi-\theta_p^*)$$

includes only interference terms such as $F_i^S F_j^V$. Thus

$A(\theta_p^*)$ may be more sensitive to small contributions of isoscalar or isovector amplitudes. Due to the absence of systematic data on differential cross sections $d\sigma/d\Omega$ we have analyzed the differences $\Delta\Sigma(\theta_p^*) = \Sigma(\theta_p^*) - \Sigma(\pi-\theta_p^*)$ taking into account the fact that such terms as $F^S F^S$ and $F^V F^V$ are suppressed for the factor $\left(\frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta)\right)/\left(\frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi-\theta)\right)$. In fig.9 the energy dependence $\Delta\Sigma(\theta_p^*)$ is shown for $\theta_p^* = 45^\circ$ and 65°. As is seen, a structure with a minimum near $E_\gamma = 500$ MeV which is lacking in the energy dependence Σ is observed. Taking into account that the isovector amplitudes dominate in π-meson photoproduction on nucleons near the I and II πN-resonances, the possible structure may be due to a small contribution of isocsalar amplitudes and, in particular, isoscalar dibaryons. The structure obtained qualitatively agrees with one of the solutions of the Ikeda analysis considering the isoscalar dibaryon contribution, while calculations without such contributions do not predict a minimum.

Thus the present state in the $\gamma d \to pn$ study does not define the role of different mechanisms in the process and answer adequately the question on the existence of dibaryon resonances. At the same time it is evident that the further progress in the investigations should be based on the accumulation of systematic data on various polarization observables (like the program of $pp \to pp$ investigation) to perform correct partial-wave analysis, and also on the improvement of theoretical concepts on the process mechanism.

Appendix A

The differential cross section $d\sigma/d\Omega$, the cross-section asymmetry Σ of the $\gamma d \rightarrow pn$ reaction are defined by means of the helicity amplitudes as [28]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{m}{8\pi E}\right)^2 \frac{P}{3\omega} \sum_{\delta=\pm 1} \sum_{i=1}^{6} |F_{i\delta}|^2 \qquad (A.1)$$

$$\Sigma(\theta) = \frac{-2Re[F_{1+}F_{3-}^* + F_{1-}F_{3+}^* - F_{2+}F_{2-}^* - F_{4+}F_{6-}^* - F_{4-}F_{6+}^* + F_{5+}F_{5-}^*]}{\sum_{\delta} \sum_{i} |F_{i\delta}|^2} \qquad (A.2)$$

where m is the nucelon mass; E, P and ω are the energy, nucleon momentum and photon energy in c.m.s., respectively.

Representing the helicity amplitudes $F_{i\delta}$ as a sum of isoscalar and isovector amplitudes $F_{i\delta} = F_{i\delta}^S + F_{i\delta}^V$ and using isotopic relations for helicity amplitudes [28]

$$F_{i\pm}^I(\pi-\theta) = (-1)^{I+i} F_{i\pm}^I(\theta) \quad \text{if} \quad i = 1,2,3$$

$$F_{i\pm}^I(\pi-\theta) = (-1)^{I+i+1} F_{i\pm}^I(\theta) \quad \text{if} \quad i = 4,5,6$$

where I is the photon isospin, for the value

$$A(\theta) = \frac{d\sigma}{d\Omega}(\theta)\,\Sigma(\theta) - \frac{d\sigma}{d\Omega}(\pi-\theta)\,\Sigma(\pi-\theta) \qquad (A.3)$$

we obtain the expression

$$A(\theta) = -\left(\frac{m}{8\pi E}\right)^2 \frac{P}{3\omega} 4Re\,[F_{1+}^V F_{3-}^{S*} + F_{1+}^S F_{3-}^{V*} + F_{1-}^V F_{3+}^{S*}$$
$$+ F_{1-}^S F_{3+}^{V*} - F_{2+}^V F_{2-}^{S*} - F_{2+}^S F_{2-}^{V*} - F_{4+}^V F_{6-}^{S*} - F_{4+}^S F_{6-}^{V*} \qquad (A.4)$$
$$- F_{4-}^V F_{6+}^{S*} - F_{4-}^S F_{6}^{V*} + F_{5+}^V F_{5-}^{S*} + F_{5+}^S F_{5-}^{V*}\,]$$

Table 1

E_γ (MeV)	θ_p^{cm}	Σ	$\frac{d\sigma}{d\Omega}$ (μb/sr)
398 ± 21	45 ± 0.7	-0.02 ± 0.04	1.70 ± 0.08
396 ± 22	55 ± 0.8	0.04 ± 0.05	1.80 ± 0.08
395 ± 24	65 ± 0.9	0.28 ± 0.05	1.75 ± 0.08
447 ± 24	45 ± 0.8	0.06 ± 0.06	1.15 ± 0.05
446 ± 25	55 ± 0.8	0.01 ± 0.05	1.29 ± 0.06
446 ± 26	65 ± 0.9	0.08 ± 0.05	1.16 ± 0.05
497 ± 33	45 ± 2.5	-0.15 ± 0.05	0.95 ± 0.05
500 ± 26	55 ± 0.8	-0.10 ± 0.05	0.90 ± 0.04
496 ± 28	65 ± 0.9	-0.06 ± 0.06	0.93 ± 0.04
548 ± 27	45 ± 0.8	-0.18 ± 0.05	0.92 ± 0.04
546 ± 28	55 ± 0.9	-0.25 ± 0.05	0.88 ± 0.04
547 ± 30	65 ± 1.0	-0.02 ± 0.05	0.84 ± 0.04
598 ± 40	45 ± 2.5	-0.18 ± 0.05	0.60 ± 0.04
596 ± 42	55 ± 2.6	-0.28 ± 0.05	0.65 ± 0.04
600 ± 32	65 ± 1.0	-0.25 ± 0.05	0.55 ± 0.03
598 ± 34	75 ± 1.1	-0.20 ± 0.07	0.74 ± 0.04
597 ± 37	85 ± 1.2	-0.03 ± 0.06	0.67 ± 0.04
592 ± 39	94 ± 1.2	-0.15 ± 0.07	0.5 ± 0.03
696 ± 32	45 ± 0.8	-0.23 ± 0.05	0.38 ± 0.02
693 ± 34	55 ± 0.9	-0.32 ± 0.05	0.30 ± 0.02
693 ± 35	65 ± 1.0	-0.35 ± 0.06	0.33 ± 0.02
693 ± 38	75 ± 1.1	-0.15 ± 0.05	0.20 ± 0.01
696 ± 38	85 ± 1.1	-0.34 ± 0.08	0.25 ± 0.02
698 ± 41	95 ± 1.2	-0.18 ± 0.07	0.28 ± 0.02
796 ± 35	45 ± 0.9	-0.38 ± 0.07	0.15 ± 0.01
797 ± 38	55 ± 1.0	-0.42 ± 0.07	0.17 ± 0.01
794 ± 41	65 ± 1.2	-0.34 ± 0.07	0.13 ± 0.01
792 ± 44	75 ± 1.2	-0.24 ± 0.07	0.13 ± 0.01
796 ± 47	85 ± 1.2	-0.45 ± 0.08	0.13 ± 0.01
795 ± 52	95 ± 1.3	-0.23 ± 0.07	0.17 ± 0.01

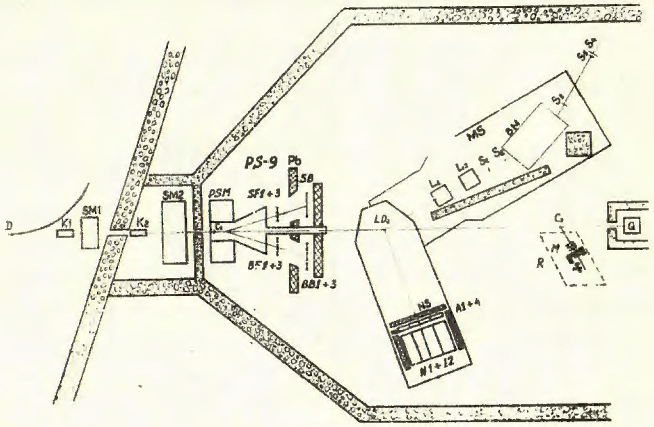


Fig.1. Experimental setup: D - diamond target, K - collimators, SM - sweeping magnets, PS-9 - pair spectrometer, Pb - lead shield, LD_2 - liquid deuterium (hydrogen) target, MS - magnetic spectrometer. NS - neutron time-of-flight spectrometer, C - converters, M - quick monitor, Sc - shower counter, Q - quantometer.

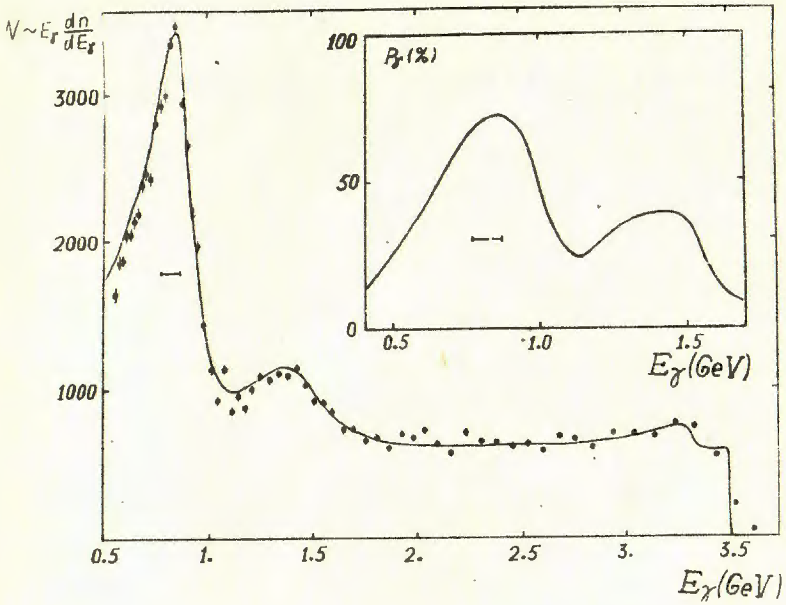


Fig.2. Photon spectrum and calculated polarization curve at E_γ^{peak} = 800 MeV. The line is the setup acceptance (FWHM).

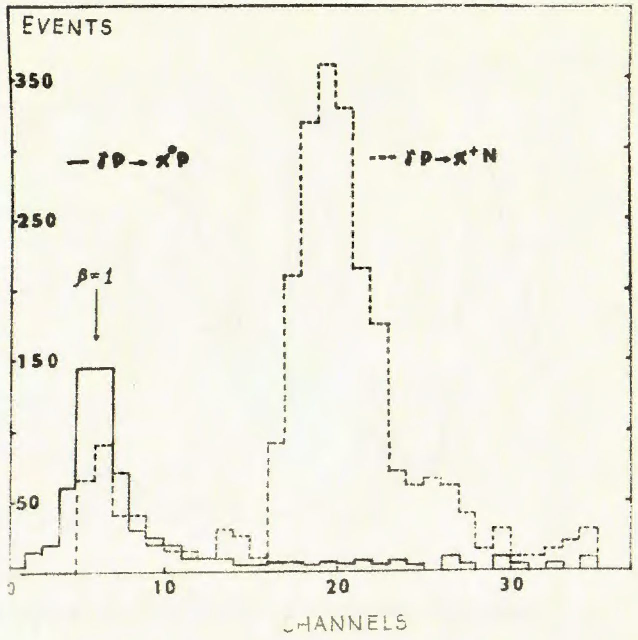
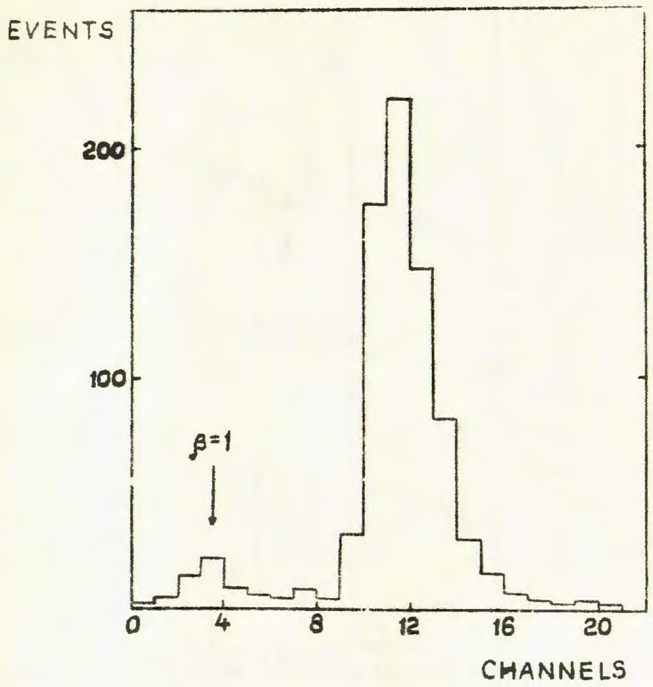


Fig.3. Time-of-flight spectrum of neutrons from $\gamma p \to \pi^+ n$ (dot line) and time-of-flight spectrum of γ-quanta from $\gamma p \to \pi^0 p$ reaction (dashed line). The channel width is $\sim$ 0.8 nsec.



ig.4. Time-of-flight spectrum of neutrons from $\gamma d \to pn$ at E_γ = 500 MeV and $\Theta_p^* = 45^0$ kinematics. The chan-nel width is 1.3 nsec.

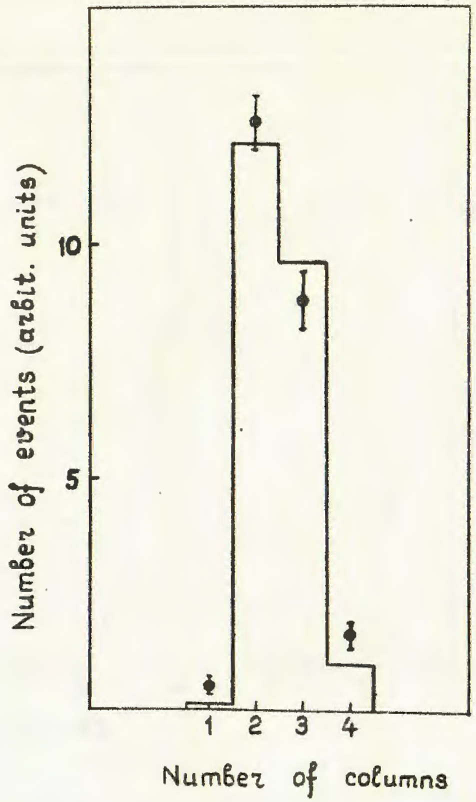


Fig.5. Distribution of neutrons from $\gamma d \to pn$ among columns of NS. Points - experiment, histogram - results of Monte-Carlo calculations.

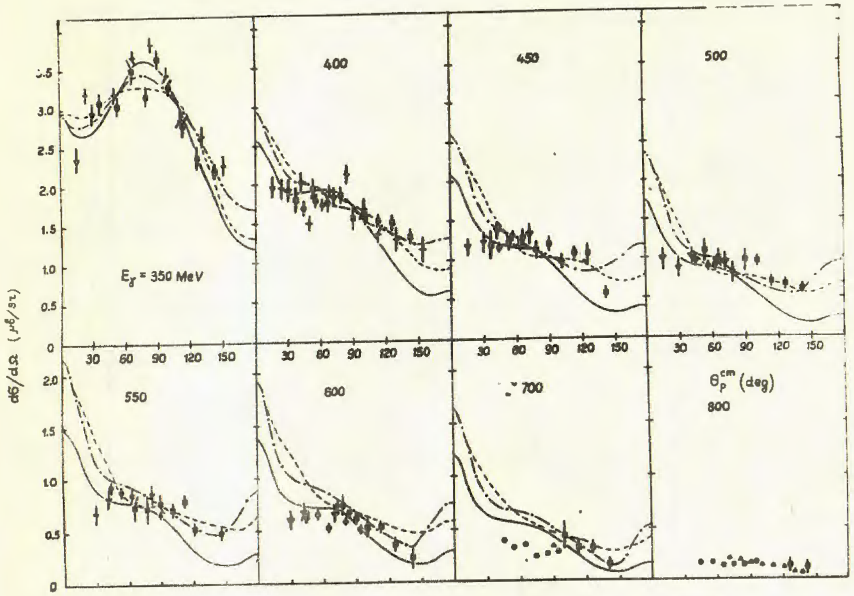


Fig.6. Angular dependence of differential cross section $d\sigma/d\Omega$ for $\gamma d \to pn$. Points: ▲ - Stanford [18], ■ - Lund [19], ▽ - Tokyo [20], ⊥ - Bonn [21], ● - present experiment. Curves - results of calculations: solid - ref.[24], dot and dot-and-dash - ref.[5].

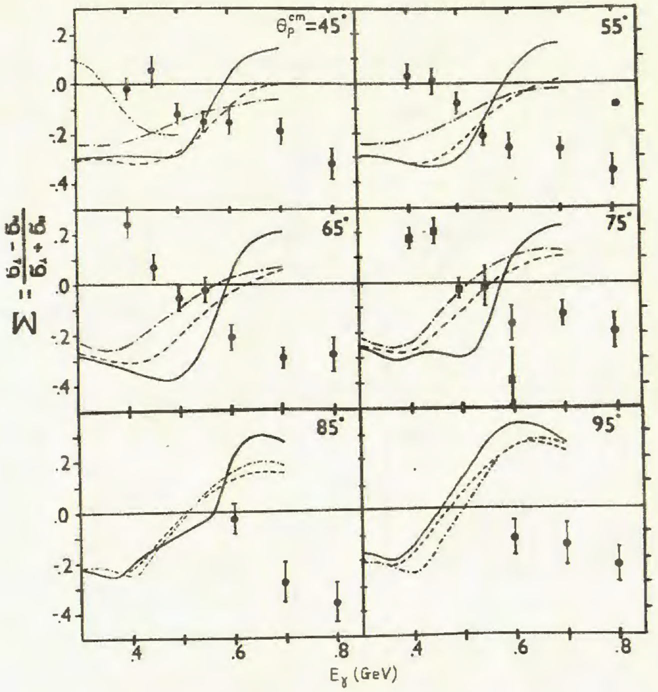


Fig.7. Energy dependence of the cross-section asymmetry Σ of $\gamma d \rightarrow pn$ for the proton angles $\theta_p^* = 45^\circ, 55^\circ, 65^\circ, 75^\circ, 85^\circ, 95^\circ$. Points: o - Frascati [22], × - Bonn-79 [23], ■ - Kharkov [6], ▲ - Bonn-82 7 , ● - present work. Curves - results of calculations: double-dot-and-dash - Laget [26], dot-and-dash - Ogawa et al. [24], pointed - Huneke [25], dot and solid - Ikeda et al. [5] involving the contribution of dibaryon resonances $1(3^-)$, $0(1^+)$ and $1(3^-)$, $0(3^+)$, respectively.

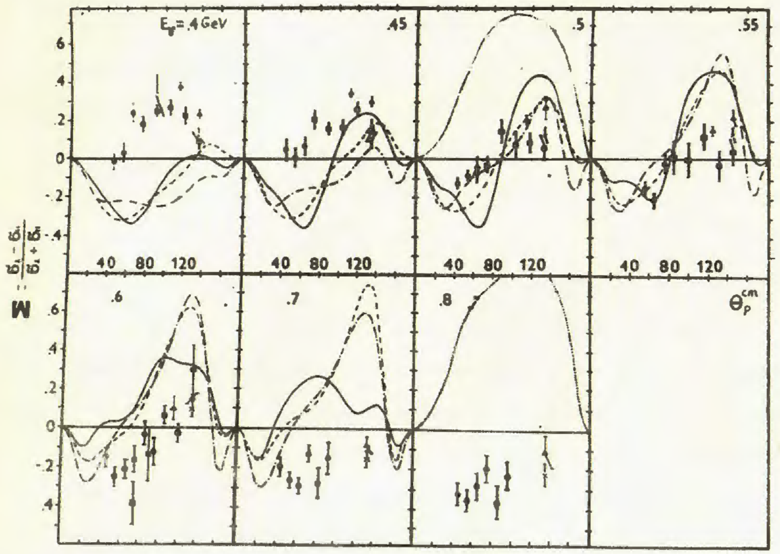


Fig.8. Angular dependence of the beam asymmetry Σ of $\gamma d \rightarrow pn$ at the photon energy in laboratory system $E_\gamma = 0.4 \div 0.8$ GeV. Points and curves are the same as in

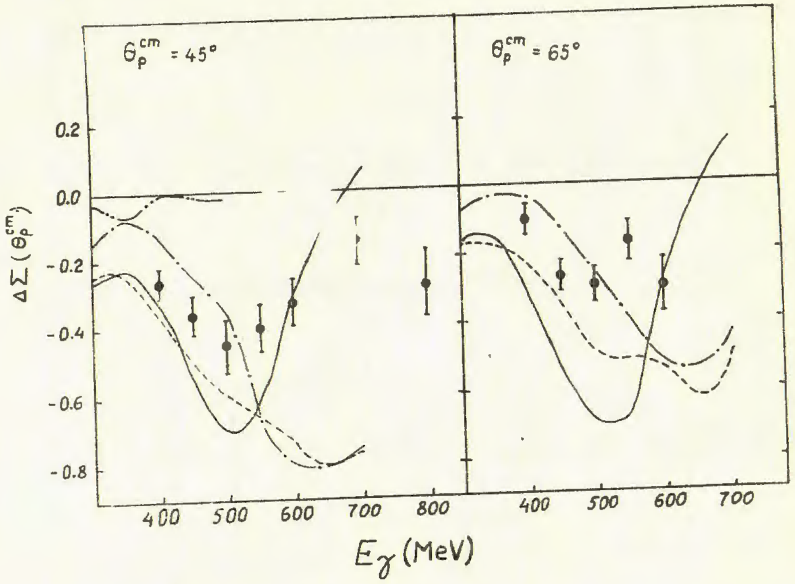


Fig.9. Energy dependence of $\Delta\Sigma(\theta_p^*)$ for $\theta_p^* = 45^\circ$ and 65°. Curves are the same as in fig.7.

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ИССЛЕДОВАНИЕ РЕАКЦИИ ФОТОРАСЩЕПЛЕНИЯ ДЕЙТРОНА ЛИНЕЙНО-ПОЛЯРИЗОВАННЫМИ ФОТОНАМИ В ОБЛАСТИ ЭНЕРГИЙ E_γ =0,4-0,8 ГэВ,

(на английском языке, перевод Л.Н.Багдасаряна)

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