EXPERIMENTS ON ELECTROMAGNETIC INTERACTION OF LINEARLY POLARIZED PHOTONS WITH NUCLEONS AND NUCLEI

V.G. Gorbenko, L.Ya. Kolesnikov
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: gorbenko@jlab.org

Experiments on electromagnetic interaction of nucleons and nuclei with linearly polarized photon beams produced by coherent bremsstrahlung of high energy electrons from diamond single crystal targets are reviewed. The details of experimental equipment, the methods of beam monitoring and photon polarization evaluation, as well as the methods for measuring cross section asymmetries are discussed. The experimental results for polarization parameters of pion photoproduction and photodisintegration reactions are presented and discussed along with theoretical analyses.

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From the beginning of the Kharkov Linac operation, the method of coherent bremsstrahlung of accelerated electron beams on a diamond crystal radiator has been one of the main methods used in high-energy physics experiments. In this electrodynamic process the coherent and linearly polarized high-energy photon beams can be produced. The facility for linearly polarized photon beam production on the beam line close to the main physical target was successfully developed in 1968. The facility included a set of goniometers with diamond crystals as targets, two adjustable collimators with bending magnets, a set of Wilson-type total-absorption quantameters. The goniometers were able to fix the horizontal and vertical angles of inclination of the crystal target relative to the beam direction with an accuracy of about 10 angular seconds, to provide the target rotation around the azimuthal axis or the beam momentum over the full angular range. A set of diamond plates with thicknesses ranging from 0.08 to 2 mm was cut closely to crystal planes and was used as targets. Two Ar-CO_2- or H_2-filled quantameters were used for absolute measurements of the total photon beam intensity.

As soon as the electron linear accelerator has a too low duty factor, the following two problems should be solved for a successful use of the beams in photopion production processes: (i) high-quality measurements of coherent photon spectra, starting from low energy up to the maximum photon energy, and (ii) obtaining appropriate photon polarization spectra. A further problem is the photon intensity monitoring for an operational integral intensity up to 10^{10} equivalent quanta per second. It appears too difficult to use the traditional methods of pair spectrometer or full absorption calorimeters for these purposes, because again the duty factor is too low and the total intensity is too high. The procedure of photon beam production has been described in [1].

The equipment employed for experiments on electromagnetic interaction of linearly polarized photons with nucleons and nuclei also included two high-resolution spectrometers and a set of physical cryogenic targets: liquid H^2, D^2, He^3 or He^4 and polarized proton targets. As a detector, plastic dE/dx scintillation-counter telescopes, high-pressure gas-filled Cherenkov counters or recoil proton polarimeters with wire chambers and carbon analyzer plates were used. The layout of the experimental equipment is presented in Fig. 1.

The key factor of the experimental procedure consisted in using the measurements of secondary particle yields for the determination of photon intensity and polarization values. As soon as the spectrometers were used for particle analysis and identification with fixed momentum and polar angle of the detected particles, the two-particle kinematics, typically investigated, was helpful to reconstruct the energy value of the initial photon. So, the secondary-particle intensity variation corresponded to the photon line intensity variation. In practice, to measure the polarization effects, the so-called "point effect" was used. Fig. 2 supplies an illustration of the secondary-particle yield (here, protons from the $\gamma p \to p\pi^0$ reaction) versus diamond crystal orientation angles for two directions of the photon polarization vector ($\perp$ perpendicular or $\|$ parallel) relative to the reaction plane.

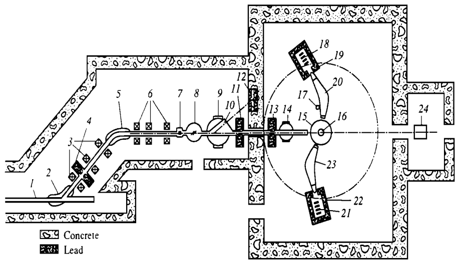

***Fig. 1.** Experimental layout: (1) electron beam line; (2) secondary emission monitor; (3) goniometer; (4) secondary electron spectrometer: (5), (7) photon collimators; (6) electron deflection secondary-emission monitor; (8) vacuum separating foil; (9) bending magnet; (10), (12) gas flow controls and He^3/He^4 pumping system; (11) bending magnet local protection; (13) polarized proton target chamber; (14) target cryostat; (15) NHF pumping and polarization variation system; (16), (19) magnetic spectrometers; (17), (20) counter telescopes; (18), (21) spectrometer shields; (22) Wilson-type quantameter*

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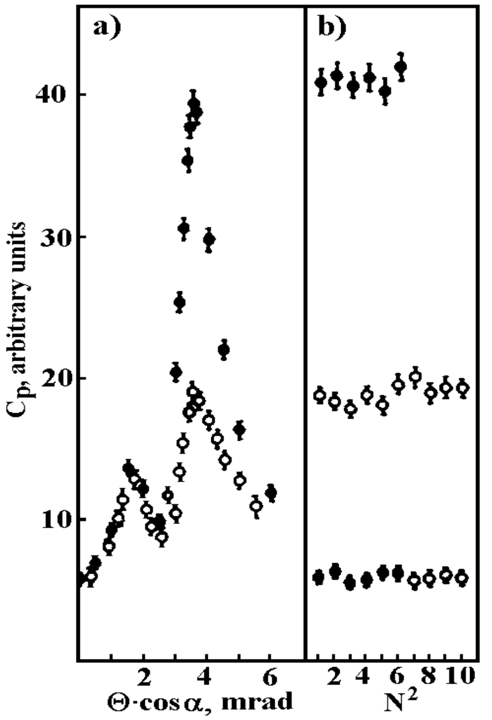

Fig. 2. *The proton counts ($\gamma p \rightarrow p\pi^0$ reaction product) versus crystal orientation angles. $\theta \sin\alpha$ = 75 mrad , solid points - $\theta = 90^o$, empty points - $\phi = 0^o$. a) Orientation curve. b) The statistics sampling for orientations corresponding to both the photon spectrum with a maximum at the energy selected and the coherence effect absence (at maxima and minima of orientation curves)*

The characteristic points of this function ($C^H_\perp$, $C^H_\parallel$ and C^H_o) were the subject of additional high-statistics measurements. In [2, 3], it has been indicated that there exists a certain relationship between the particle yields ($C^H_\perp$, $C^H_\parallel$ and C^H_o) and the effective photon polarization:

$$p_\gamma^{ef} = k_p k_x \frac{C_\perp^H + C_\parallel^H - 2C_o^H}{C_\perp^H + C_\parallel^H},$$

where k_p is the coefficient that is associated with the angular divergence and the multiple scattering of electrons in the crystal as well as with the appropriate energy resolution of the detecting device, $k_x=2(1-x)/[1+(1-x)^2]$, while $x=E_\gamma/E_o$ denotes the relative photon energy in the principal coherent maximum. Moreover, the non-coherent background yield that is due to either non-coherent photons or protons yields does not lead to variation in the measured asymmetry value because of the appropriate change in the p_γ^{ef} value. The k_p is the coefficient close to 1 and can be correctly calculated with an appropriate simulation procedure. Sometimes [5], for calibration purposes, special measurements of coherent electron bremsstrahlung spectrum were done by using the *NaJ*(*Tl*) total absorption detector. Generally, these measurements had no high statistics, because they could be done in a special accelerator regime with "cold" thermo-gun operation and a mean photon intensity of ~1 photon/second. The illustration is presented in Fig. 3.

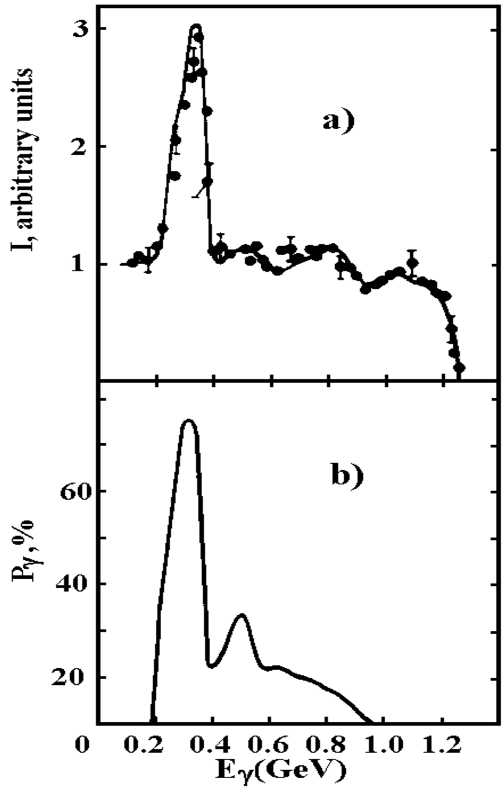

Fig. 3*. a) Coherent electron bremsstrahlung spectrum for 1200 MeV in a diamond single crystal, 300 μm thick. The solid curve shows the result of the spectrum fit with the parameters $dE\gamma/E\gamma$ = 8%, $\theta \sin\alpha$ = 75 mrad, $\theta \cos\alpha$ = 3.5 mrad; θ and α are the polar and azimuth angles of crystal orientation. b) Photon polarization spectrum with selected parameters*

An additional problem consisted in the monitoring procedure of counting rate measurements. Fortunately, for the above-mentioned "point effect", the total photon beam dose measured by the total-absorption quantameters is weakly dependent on the rotation angle of the crystal, and only a small correction (especially at minima and maxima of the coherent curve) should be done.

The first experiments to measure the polarized photon asymmetry Σ, were performed for two-particle reactions of single pion photoproduction on liquid hydrogen and deuterium targets: $\gamma p \rightarrow \Delta^{++}\pi^-$ [1], $\gamma p \rightarrow p\pi^0$ [4,5], $\gamma p \rightarrow n\pi^+$ and $\gamma d \rightarrow nn\pi^+$ [6,7], $\gamma n \rightarrow p\pi^-$ [8], $\gamma d \rightarrow d\pi^0$ [9]. Owing to a high duty factor of the electron linear accelerator, only one charged particle could be detected, but the registration of both the angle and the momentum in the l.s. allowed one to reconstruct both the c.m.s. kinematics and the initial photon energy. The detailed experimental data can be found in the mentioned above references and in the review [10].

The new experimental results combined with the world experimental data for the reactions of single pion photoproduction on nucleons were used in several multipole analyses in the first resonance energy region [11-14]. As a result, the energy behavior of isotopic components of lowest multipole amplitudes was reconstructed and analyzed in comparison with the predictions of dispersion theory and other models. However, from the viewpoint of the model-independent procedure of obtaining the full amplitude of photoproduction reactions, the additional polarization experiments should be done, including the measurements on polarized nucleons targets and circular polarized photon beams, as formulated in the program of complete experiments [15].

As a result of developing the experimental facility of the Kharkov 2 GeV Linac during early 80's, some experiments were made to investigate pion photoproduction on nucleons and the processes of light nuclei photodisintegration, using linearly polarized photon beams from coherent bremsstrahlung of electrons on diamond radiators. Earlier, the pion photoproduction processes were investigated in single polarization experiments by measuring separately the polarized photon asymmetry Σ, the polarized target asymmetry T, or the recoil proton polarization P_y. With the development of a polarized proton target with polarization vector directions normal or collinear to the pion production reaction plane, the possibilities of double polarization experiments opened up.

The experiments of the type were performed in 1981 by using a linearly polarized photon beam and a polarized proton target for positive pion production in the 280-420 MeV energy range [16], and later, in 1983, for neutral pion production in the energy range from 280 to 450 MeV [17] in order to get an additional information for determining the isotopic amplitudes and to perform the channel phase analysis of both reactions.

The special feature of these double polarization experiments is that they do not provide the measurements of really double polarization variables [15], but give us a possibility to measure the P-parameter without complicated measurements of recoil proton polarization and provide us with the method of measuring the single Σ, T, P polarization parameters in a single experimental procedure.

The measurements of Σ, T, P parameters in a double polarization experiment of beam-target type are based on the dependence of the differential cross section upon photon and proton polarizations [18]:

$$d\sigma\,(n,\phi\,,\theta^*_\pi) = d\sigma\,(\theta^*_\pi)\{1 - \Sigma\,(\theta^*_\pi)p_\gamma \cos 2\phi\; + \\ + T(\theta^*_\pi)p_y - P(\theta^*_\pi)p_\gamma\, p_y \cos 2\phi\,\},$$

where $d\sigma(\theta^*_\pi)$ is the photoproduction cross section for non-polarized particles; ϕ is the angle between the photon polarization vector and the reaction plane; p_γ and p_y are the beam photon and target proton polarizations, correspondingly.

Using a polarized proton target made of complex substance as a target material, and taking into account the contribution from intranuclear nucleons, we can write the total yield of the reaction, where only proton is registered as a reaction product:

$$C^\uparrow_\perp = C^N_o(1+\Sigma^N\tilde{p}_\gamma) + C^H_o(1+\Sigma p_\gamma + Tp_y + Pp_\gamma p_y),$$

$$C^\uparrow_\parallel = C^N_o(1-\Sigma^N\tilde{p}_\gamma) + C^H_o(1-\Sigma p_\gamma + Tp_y - Pp_\gamma p_y),$$

$$C^\downarrow_\perp = C^N_o(1+\Sigma^N\tilde{p}_\gamma) + C^H_o(1+\Sigma p_\gamma - Tp_y - Pp_\gamma p_y),$$

$$C^\downarrow_\parallel = C^N_o(1-\Sigma^N\tilde{p}_\gamma) + C^H_o(1-\Sigma p_\gamma - Tp_y + Pp_\gamma p_y),$$

where C^N_o and C^H_o are the photon and proton spin direction-averaged yields from complex nuclei and free polarized protons, respectively; Σ and Σ^N are the polarized photon cross section asymmetries of pion photoproduction on free protons and on complex nuclei of the polarized proton target; p_γ and $\tilde{p}_\gamma$ are, respectively, the photon polarizations averaged over the photon spectrum with due regard for the apparatus energy acceptance and the nucleon Fermi-motion. Here it is assumed that for intra-nuclear yields there are no terms containing T and P parameters.

By using different combinations of photon polarization vector directions $\perp$ and $\parallel$, and of the initial proton polarization vectors $\uparrow$ and $\downarrow$, with parallel and anti-parallel directions of the target polarization and the vector ***n*** normal to the reaction plane, we can measure a set of four counting rates $C^\uparrow{}_\perp$, $C^\uparrow{}_\parallel$, $C^\downarrow{}_\perp$ and $C^\downarrow{}_\parallel$. It is easy to show that for the above-mentioned assumption additional measurements are needed only for Σ_P and Σ_N separation. Two different methods of intra-nuclei nucleons yield subtraction were used: the normalization procedure and Σ_P measurement with a liquid H_2 target [16], and the standard [19] Σ-measurements on polythene, carbon and He^3 targets with the corresponding normalization [17]. An additional small (2-10% for different energies) correction for pion pair production was used, that is the usual procedure when working with a linearly polarized beam from coherent bremsstrahlung.

As a result, sets of Σ, T, P polarization parameters for photon energies of 280, 300, 320, 340, 360, 380, 400 and 420 MeV and the c.m.s. pion angles ranging from 30 to 150° for $\gamma p\rightarrow p\pi^+$ [16], and at 280, 300, 320, 340, 360, 380, 400, 420 and 450 MeV and the c.m.s. pion angles in the 60-135° range for $\gamma p\rightarrow p\pi^o$ [17] were published. For illustration, Figs. 4 and 5 show the sets of angular distributions of Σ, T, P-parameters for $\gamma p\rightarrow p\pi^o$ and $\gamma p\rightarrow p\pi^+$ reactions in the photon energy range between 280 and 450 MeV. As far as the first πN resonance is concerned, the presented Σ, T, P data combined with other existing experimental data for these polarization parameters, and the differential cross sections for the this processes were used for the amplitude analysis.

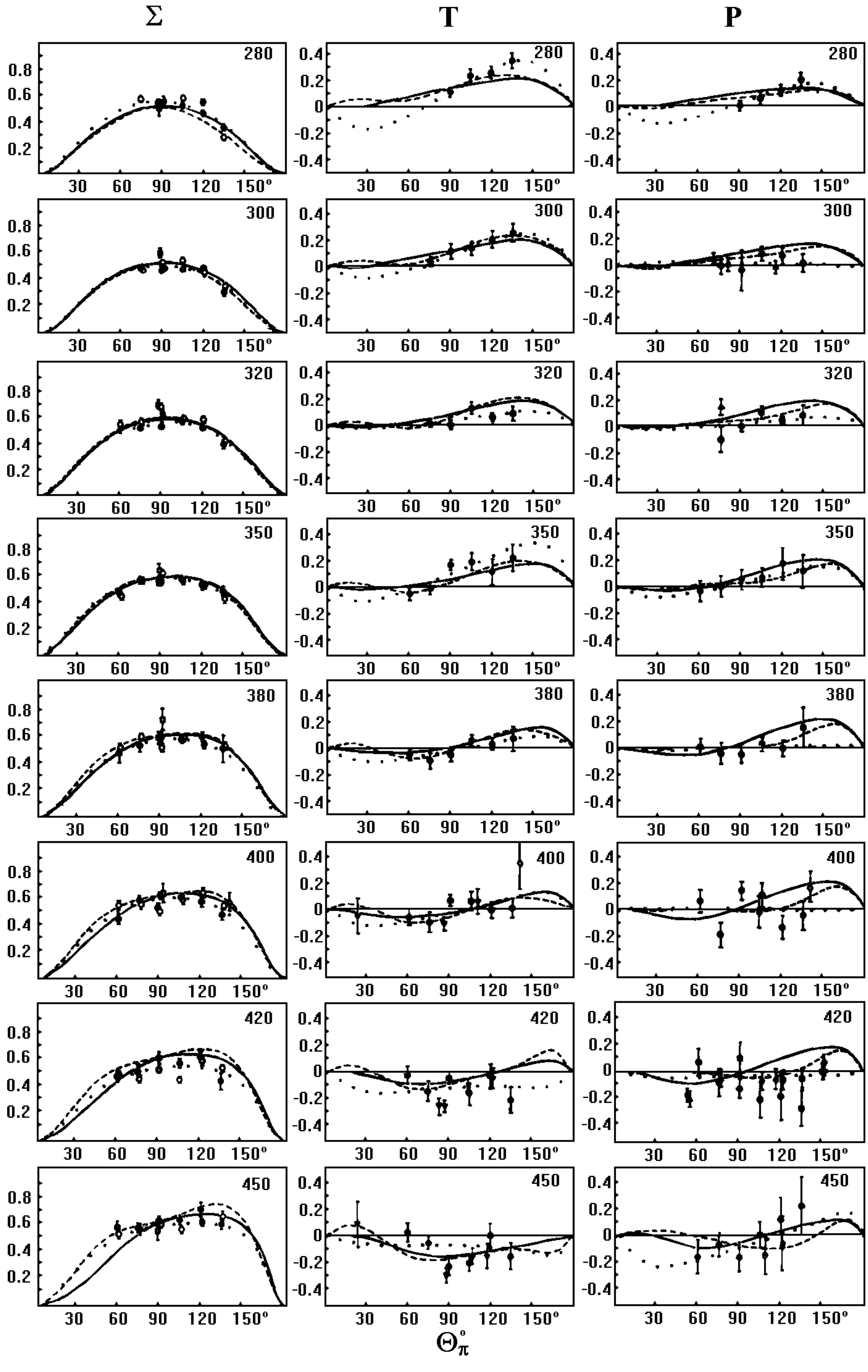

Fig. 4. *Angular distributions of Σ, T, P parameters for the $\gamma p \to p\pi^0$ reaction. Experimental results: closed circles – Kharkov data [17], open circles – ref. [17], the remainder is taken from the compilation [20]. Theoretical curves: dotted curve – home analysis, the rest – see [17]*

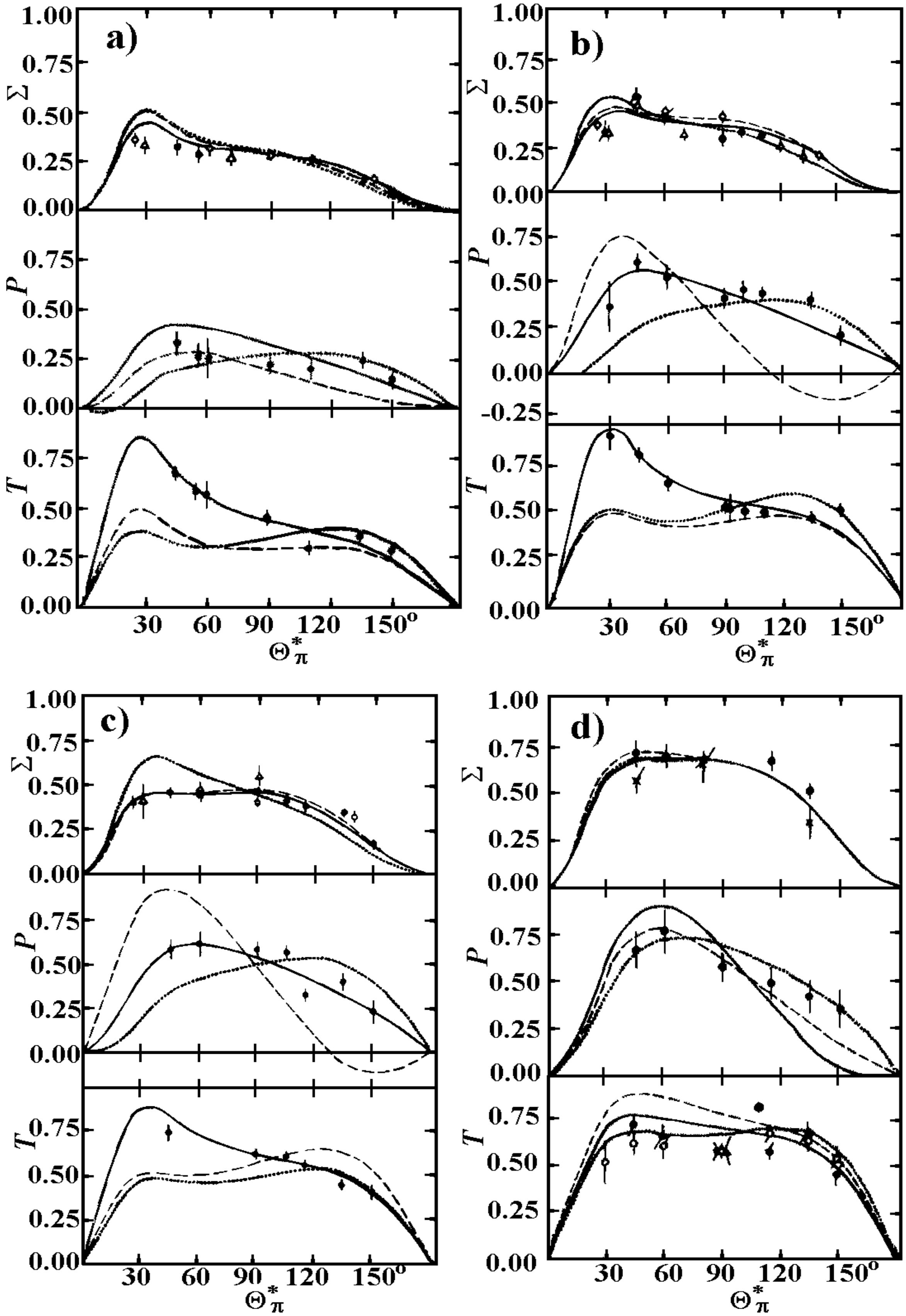

Fig. 5. *Angular distribution of the polarization observables Σ, T and P for the $\gamma p \rightarrow p\pi^+$ reaction at photon energies: a) 280 MeV; b) 300 MeV; c) 320 MeV; d) 340 MeV; e) 360 MeV; f) 380 MeV; g) 400 MeV; h) 420 MeV. The solid circles are Kharkov data [16]. The other points - as cited in [16]. Solid, dash-dotted and dotted curves correspond to three solutions of the present analysis with minimum R_{tot} values arranged in the increasing order*

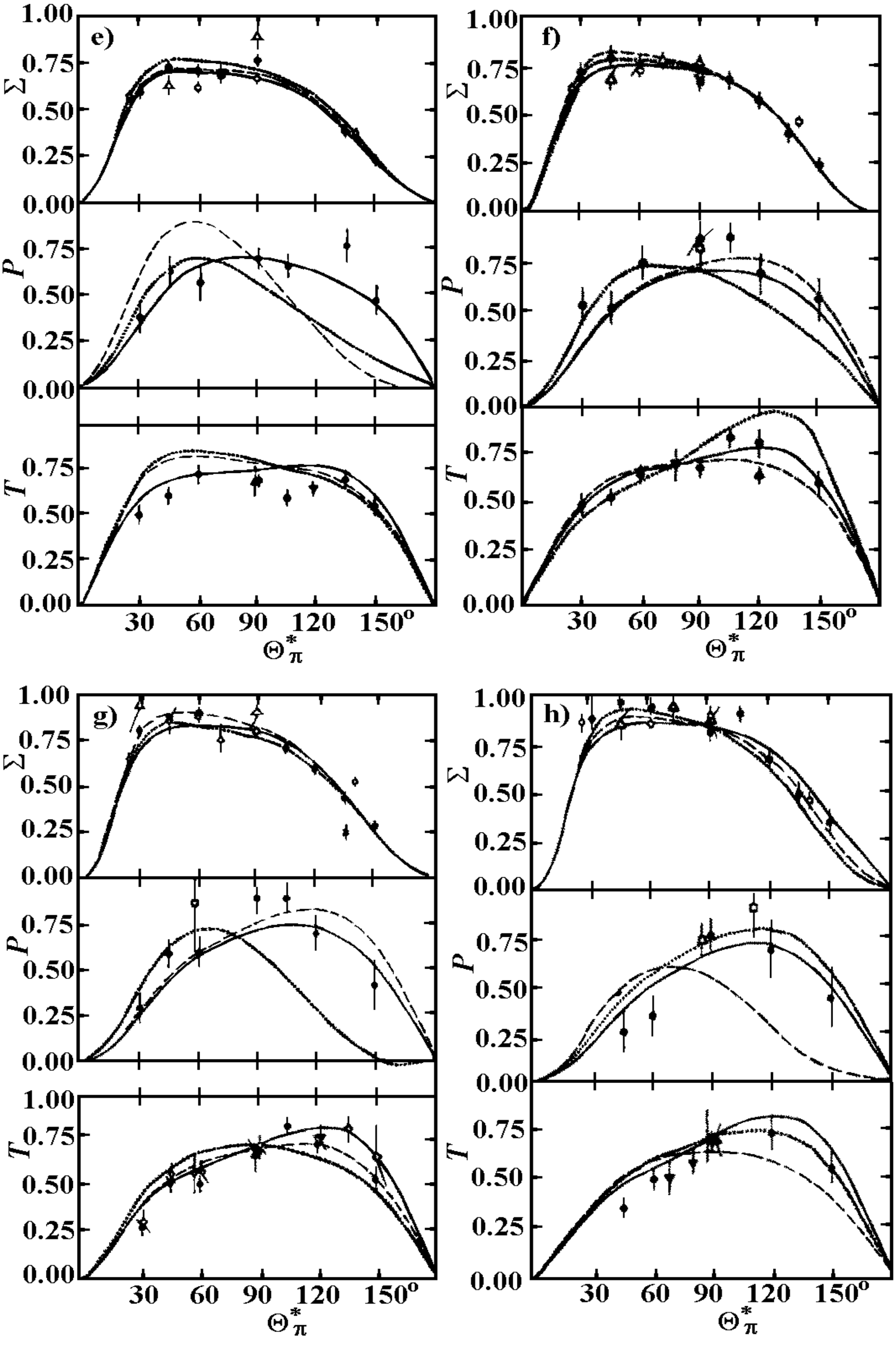

Fig. 5 (continued). *Angular distribution of the polarization observables Σ, T and P for the* $\gamma p \rightarrow p\pi^{+}$ *reaction at photon energies: a) 280 MeV; b) 300 MeV; c) 320 MeV; d) 340 MeV; e) 360 MeV; f) 380 MeV; g) 400 MeV; h) 420 MeV*

In the next time period, i.e., in early 80's, an additional development of the experimental equipment was made. Particularly, a new goniometer providing the oriented crystal rotation around the electron beam momentum (P_o-rotation) was designed and used in experiments [21], a new proton polarized target was used in the reaction plane [22], and a new multi-appendix cryogenic system with deuterium, He^3 and He^4 targets was designed. So, new, really double polarization experiments were started. First of all, the observables O_x and O_z were measured [23,24] in the $\gamma p \rightarrow p\pi^0$ reaction as a result of double polarized experiment, with the use of linearly polarized photons with the azimuth direction ϕ=45° of vector polarization to the reaction plane and by measuring the P_x and P_z components of the recoil proton polarization vector. The second type of the double polarized experiment was realized through the use of the polarized proton target with the polarization vector in the reaction plane, and the linearly polarized photons with the vector azimuth direction ϕ=45° to the reaction plane. In this case, the polarization parameters G and H [15] were measured for the $\gamma p \rightarrow n\pi^+$ reaction [25] at a certain set of c.m.s polar angles of emitted pions in the first πN-resonance energy region. The experimental results were compared with the predictions of an energy-independent phenomenological analysis. Those experiments have demonstrated the experimental possibilities of measuring the double polarization (beam-target and beam-recoil) observables in the pion photoproduction on nucleons under conditions of the electron linear accelerator with a low duty cycle. Systematic measurements of both the O_x, O_z and G, H parameters are scheduled to be done in future.

As a result, new experimental data were included in a number of phenomenological multipole analyses, and new information about the radiation decay amplitudes was obtained, that provided an additional knowledge of the quark interaction and the hybrid quark-gluon states in nucleons. The review of those analyses was published in [26].

The second direction of experiments was connected with the interaction of linearly polarized photons with the deuteron and the isotopes of helium. It was supposed that the investigation of these processes would provide the information about dibaryon resonances and the quark structure of the nucleus. Here we may mention the experiments measuring the cross-section Σ asymmetry in the deuteron disintegration by polarized photons for θ_p in the c.m.s. in the angular range 75-150° and in the photon energy range 80-600 MeV [27]; the experiments to determine the deuteron disintegration cross-sections by using photons polarized parallel and perpendicular to the reaction plane at θ_p=90° in the c.m.s. in the photon energy range 30...100 MeV [28]; and the experiments measuring the differential cross-sections for photodisintegration of the deuteron by polarized photons in the energy range 250...500 MeV at c.m.s. proton angles of 90°, 105°, 120° and 135° [29, 30]. The experimental results for the energy distributions of cross-section Σ asymmetry are presented in Fig. 6.

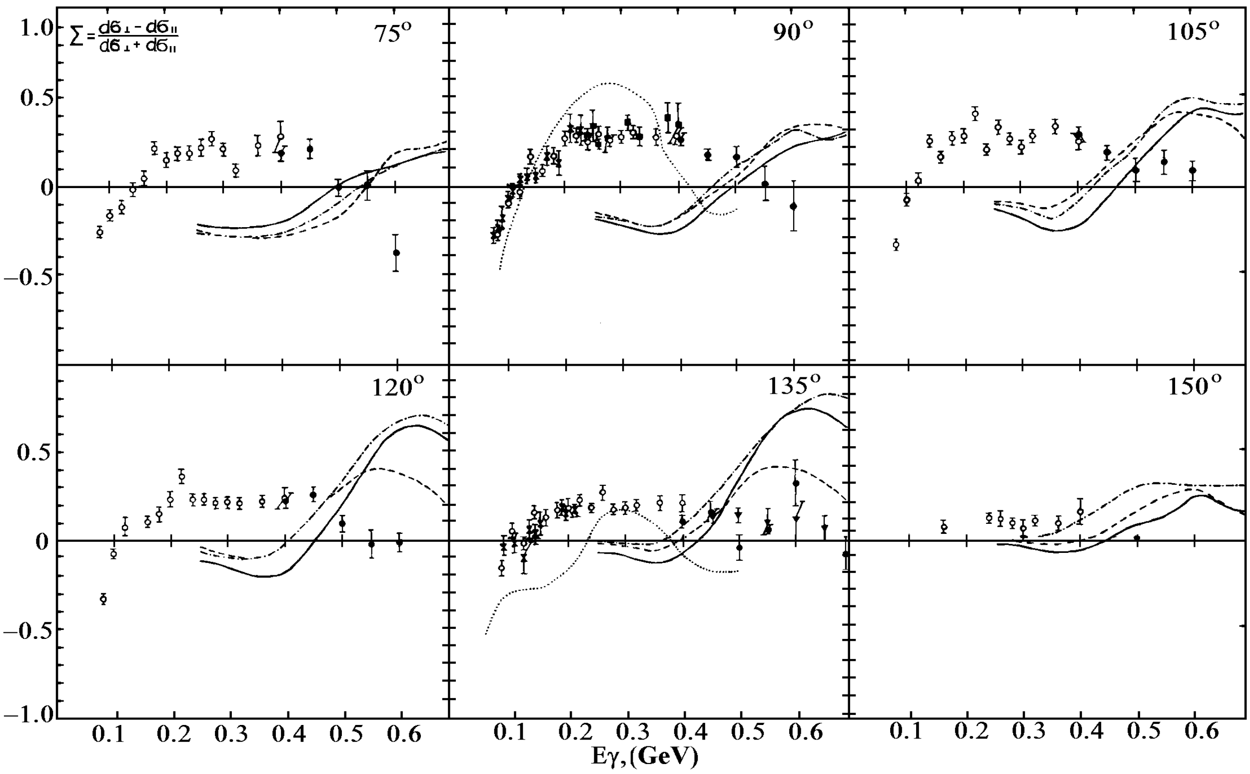

Fig. 6. *Energy distributions of the cross section Σ asymmetry $\gamma d \rightarrow \pi^o d$. Open and closed circles - Kharkov data from [27], the rest data and curves– other world laboratory data, as cited in [27]*

For the deuteron disintegration reaction, a double polarization experiment was performed with measurements of polarization observables Σ, P_y, T_I at initial photon energies between 200 and 600 MeV [31, 32]. The common conclusion from these sets of experiments can be formulated as follows: the direct indication of the presence of dibaryon resonances in the measured polarization values has not been observed, but it has been demonstrated that the inclusion of dibaryon resonances in the theoretical models substantially improves their agreement with experimental data.

The experience gained from the deuteron disintegration experiments conducted at the Kharkov Linac was put into the Proposal [33] of the experiment on deuteron disintegration by linear polarized photons as a part of the experimental program of Hall B of Thomas Jefferson National Accelerator Facility, Newport News, USA. This Proposal was postponed for the reason of insufficient funding and manpower.

The experiments on the measurement of Σ asymmetry and recoil proton polarization in the $\gamma He^3 \to pd$ reaction with linearly polarized photons [34-36] have provided information on the role of meson exchange currents, the structure of a three-nucleon system, the final-state interaction and other effects in small-nucleon nuclei. As a result, the Σ asymmetry for a proton c.m.s. angle of 110° in the energy range from 100 to 250 MeV and the Σ asymmetry for proton emission angles in the range between 45° and 140° at γ-ray energy of 200 MeV were measured [34]. The proton and the deuteron were registered by two magnetic spectrometers in coincidence. Experimental data are compared with wave function predictions for different types of the He^3 nucleus potential. As the first test of a double polarization experiment, the Σ, P_y, T_I polarization parameters were measured for the $\gamma He^3 \to pd$ reaction at 200 MeV photon energy and at 45° c.m. proton angle [35]. The Σ asymmetry for the inclusive processes $\gamma He^{3,4} \to px$, $\gamma He^3 \to \pi^{\pm} x$ and $\gamma He^4 \to \pi^- x$ has been measured for a particle emission angle of 90° in the l.s. at photon energies of 60, 140 and 350 MeV for the (γ,p) reaction and at 300 MeV for the (γ,π) reaction [36]. The asymmetry value turns out to be close to that for the elementary processes $\gamma d \to pn$ and $\gamma N \to N\pi$. Later, the Σ asymmetry of the inclusive reaction of charged pion photoproduction was measured as a function of the atomic number for the nuclei Li^6, Li^7, Be^9, C^{12}, Al^{27} and W^{184} at the 90º l.s pion angle and 350 MeV photon energy [37]. It has been shown that the Σ asymmetry decreases from 0.57 at A=1 to 0.26 at $A \cong$ 20 and is constant for higher A values.

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