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G. Barbiellini, G. Bologna, G. Capon, J. De Wire, G. De Zorzi, G. Diambrini, F. L. Fabbri, G. P. Murtas and G. Sette : PHOTOPRODUCTION OF π^o BY POLARIZED GAMMA RAYS. -

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1. - INTRODUCTION. -

The photoproduction of π^o mesons has been extensively investigated both theoretically and experimentally in the past few years. A comprehensive reference index can be found in the report by Walker(1). In the present experiment the asymmetry of the cross sections from polarized photons, for π^o photoproduction on hydrogen ($\gamma p \rightarrow \pi^o p$), has been measured using the coherent bremsstrahlung beam from a diamond. This beam is a Frascati electron synchrotron facility(2). The asymmetry has been measured at a proton angle of 90^o in the center-of-mass system (CMS) for photon energies ranging from 230 to 380 MeV.

The experimental data have been collected in two periods, with slightly different experimental set-ups in each period (in the following we will refer to them as experiment 1 and experiment 2). Preliminary results have been presented previously(3, 4), but the evaluation of the polarization of the coherent gamma ray beam has now been improved(5), and in this paper we will give the old and the new data on the asymmetry, all evaluated with the new, more accurate polarization values.

Linearly polarized bremsstrahlung has previously been used to investigate π^o photoproduction by Drickey and Mozley(6). In their experiment polarized gamma rays were obtained by selecting a small cone of the bremsstrahlung beam from a thin radiator at the Stanford linear accelerator, Mark III.

II. - NOTATION AND THEORETICAL SUMMARY. -

The differential cross section for π^o photoproduction by linearly polarized photons is

$$(1) \qquad \frac{d\sigma}{d\Omega}(K,\theta^x,\varphi) = \left[\frac{d\sigma}{d\Omega}(K,\theta^x)\right]_{unpol} + \frac{q}{K} I(K,\theta^x)\, sen^2\theta^x \cos 2\varphi$$

where, in the center-of-mass system (CMS), K is the photon energy, q the pion momentum, θ^x the photon production angle and φ the angle between the photon polarization plane and the production plane. Here $(d\sigma/d\Omega)_{unpol}$ is the π^o photoproduction cross section for unpolarized photons. In terms of the usual Pauli amplitudes, $\mathcal{F}_i^{x}$ (7), the above functions are

$$(2) \qquad \frac{K}{q}\left[\frac{d\sigma}{d\Omega}(K,\theta^x)\right]_{unpol} = \left|\mathcal{F}_1\right|^2 + \left|\mathcal{F}_2\right|^2 - 2\cos\theta^x Re\,\mathcal{F}_1^x\mathcal{F}_2 + sen^2\theta^x I(K,\theta^x)$$

$$I(K,\theta^x) = \frac{1}{2}\left|\mathcal{F}_3\right|^2 + \frac{1}{2}\left|\mathcal{F}_4\right|^2 + \cos\theta^x Re\,\mathcal{F}_3^x\mathcal{F}_4 + Re\left\{\mathcal{F}_1^x\mathcal{F}_4 + \mathcal{F}_2^x\mathcal{F}_3\right\}$$

The $\mathcal{F}_i$ are, in general, complicated functions of $\cos\theta^x$ and of the photoproduction multipole amplitudes $E_{1\pm}$ and $M_{1\pm}$, but including only s-and p-waves, as seems reasonable in the region of the first pion-nucleon resonance, they are simplified considerably and are given by

$$\mathcal{F}_1 = E_{o+} + 3\cos\theta^*(E_{1+} + M_{1+})$$

$$\mathcal{F}_2 = 2M_{1+} + M_{1-}$$

$$\mathcal{F}_3 = 3(E_{1+} - M_{1+})$$

$$\mathcal{F}_4 = 0$$

This paper is concerned with the cross sections obtained using linearly polarized photons so let us concentrate on the information obtainable in such experiments.

For experimental purposes one writes equation (2) as

$$\frac{K}{q}\left[\frac{d\sigma}{d\Omega}(K,\theta^x)\right]_{unpol} = A + B\cos\theta^x + C\cos^2\theta^x + \dots.$$

where, neglecting d-and higher partial-waves,

$$A = |E_{o+}|^2 + \frac{5}{2}|M_{1+}|^2 + |M_{1-}|^2 + \frac{9}{2}|E_{1+}|^2 + \mathrm{Re}\left[M_{1+}^{x}(M_{1-} - 3E_{1+}) + 3M_{1-}^{x}E_{1+}\right]$$

$$B = 2\,\mathrm{Re}\left[E_{o+}^{x}(3E_{1+} + M_{1+} - M_{1-})\right]$$

$$C = \frac{9}{2}|E_{1+}|^2 - \frac{3}{2}|M_{1+}|^2 + 3\,\mathrm{Re}\left[M_{1+}^{x}(3E_{1+} - M_{1-}) - 3E_{1+}^{x}M_{1-}\right]$$

One has, also, that

$$I(K, \theta^{x}) = I_o + I_1 \cos\theta^{x} + \dots .$$

where in the s-and p-wave approximation

$$I_o = \frac{9}{2}|E_{1+}|^2 - \frac{3}{2}|M_{1+}|^2 - 3\,\mathrm{Re}\left[M_{1+}^{x}(M_{1-} + E_{1+}) - E_{1+}^{x}M_{1-}\right]$$

and the higher terms are all zero. The asymmetry is defined by

$$\Sigma(K, \theta^{x}) = \frac{d\sigma_{\perp}(K, \theta^{x}) - d\sigma_{\parallel}(K, \theta^{x})}{d\sigma_{\perp}(K, \theta^{x}) + d\sigma_{\parallel}(K, \theta^{x})}$$

where $d\sigma_{\perp,\parallel}(K, \theta^{*})$ are the π^{o} photoproduction cross sections for photons with polarization vectors, respectively, normal or parallel to the production plane. This expression for $\Sigma(K, \theta^{*})$ may be written

$$\Sigma(K, \theta^{x}) = -\frac{\mathrm{sen}^2\theta^{x}\, I(K, \theta^{x})}{\frac{K}{q}\left[\frac{d\sigma}{d\Omega}(K, \theta^{x})\right]_{unpol}}$$

One sees that, in fact, $I(K, \theta^{x})$ is independent of θ^{x} in the s-and p-wave approximation so that measurement of this quantity away from $\theta^{x} = 90^{o}$ gives a test of the approximation (an angular distribution of $I(K, \theta^{x})$ deviating from a straight line equal to $I(K, 90^{o})$ would indicate that higher partial waves are needed).

Another quantity of interest is the ratio I_o/C. In the s-and p-wave approximation this has the form

$$(3)\qquad \frac{I_o}{C} = \frac{\frac{9}{2}|E_{1+}|^2 - \frac{3}{2}|M_{1+}|^2 - 3\,\mathrm{Re}\left[M_{1+}^{x}(M_{1-} + E_{1+}) - E_{1+}^{x}M_{1-}\right]}{\frac{9}{2}|E_{1+}|^2 - \frac{3}{2}|M_{1+}|^2 + 3\,\mathrm{Re}\left[M_{1+}^{x}(3E_{1+} - M_{1-}) - 3E_{1+}^{x}M_{1-}\right]}$$

If $E_{1+} = 0$ then $I_o/C = 1$, so this quantity is sensitive to small values of E_{1+}/M_{1+}, a quantity of interest as a test of symmetry schemes. For example, in the non-relativistic quark model, Becchi and Morpurgo[8] show that the electric quadrupole amplitude to the P_{33} final state, $E^{(3)}_{1+}$, must be identically zero at the resonance position. Of course, at the first resonance there are also non-resonant contributions to E_{1+}, the isospin structure being

$$E^{\pi^o p}_{1+} = E^{(o)}_{1+} + \frac{1}{3} E^{(1)}_{1+} + \frac{2}{3} E^{(3)}_{1+}$$

in the usual notation. In fact, using the theoretical results of reference[7], $E^{(o)}_{1+} + \frac{1}{3} E^{(1)}_{1+}$ is fairly energy independent around the resonance position and has a magnitude (at 340 MeV photon lab energy)

$$\mathrm{Re}\left[E^{(0)}_{1+} + \frac{1}{3} E^{(1)}_{1+}\right] = 1{,}31\ 10^{-3}$$

$$\mathrm{Im}\left[E^{(0)}_{1+} + \frac{1}{3} E^{(1)}_{1+}\right] = 0{,}04\ 10^{-3}$$

Here the units are $\hbar = c = \mu = 1$. At the same energy one has

$$\mathrm{Re}\, M^{\pi^o p}_{1+} = 0{,}6\ 10^{-3} \qquad \mathrm{Im}\, M^{\pi^o p}_{1+} = 24{,}4\ 10^{-3}$$

$$\mathrm{Re}\, M^{\pi^o p}_{1-} = -5{,}53\ 10^{-3} \qquad \mathrm{Im}\, M^{\pi^o p}_{1-} = 0{,}55\ 10^{-3}$$

These values indicate that the interference terms in equation (3) are not negligible compared with $|M^{\pi^o p}_{1+}|^2$, and so I_o/C may differ significantly from unity without in any way invalidating the quark model.

Therefore from the measurement of I_o/C one cannot directly infer if $E^{(3)}_{1+}$ is equal or different from zero. The correct procedure should be to rely on a set of multipoles given by the theorists and then to compare the theoretical values of I_o/C (obtained with and without the position $E^{(3)}_{1+} = 0$) with the experimental value.

Another use of the quantity I_o is as a means of gaining information about the multipole M_{1-}. If the s-and p-wave approximation is valid and if one takes the E_{1+} and M_{1+} multipoles as given by theory, then the measurement of I_o in π^o photoproduction from protons can be combined with the recent measurement of the asymmetry of π^- photoproduction from neutrons, by Nishikawa et al.[9] to obtain an estimate of the multipoles $M^{(o)}_{1-}$ and $M^{(1)}_{1-}$. The isospin combinations are

(4)
$$M_{1-}^{\pi^o p} = M_{1-}^{(0)} + \frac{1}{3} M_{1-}^{(1)} + \frac{2}{3} M_{1-}^{(3)}$$

$$M_{1-}^{\pi^- p} = \sqrt{2} \left[M_{1-}^{(0)} - \frac{1}{3} M_{1-}^{(1)} + \frac{1}{3} M_{1-}^{(3)} \right]$$

where $M_{1-}^{(0)}$ and $M_{1-}^{(1)}$ are the isospin 1/2 multipoles for the P_{11} pion-nucleon final state which contains the Roper resonance. The study of the $M_{1-}^{(0,1)}$ multipoles is important because their size bears on the question of the existence of a $\{\overline{10}\}$ SU_3 multiplet, as emphasized recently by Donnachie(10). The point is that $\gamma + p$ is a U-spin doublet (U = 1/2) and $\gamma + n$ has U = 1. Since P_{11} in a $\{\overline{10}\}$ has U = 1, photoproduction of P_{11} from protons is forbidden and photoproduction of P_{11} from neutrons is allowed by U-spin conservation.

This is one of the tests of the existence of a $\{\overline{10}\}$ proposed by Lipkin(11). Recent theoretical investigations(12) had indicated that P_{11} photoproduction was greatly enhanced if the target was a neutron, this favouring the existence of $\{\overline{10}\}$. However the Japanese experiment(9) seems to indicate that P_{11} is not strongly produced in the reaction $\gamma + n \rightarrow \pi^- + p$. The quark model in its usual form does not permit the formation of a $\{\overline{10}\}$ so it would be favoured by this interpretation of the experiments. Theoretical estimate of $M_{1-}^{(0,1)}$ using partial wave dispersion relations depend on an evaluation of the dispersion integral over the Roper resonance, which is higly inelastic, so the Watson theorem does not apply and this makes the evaluation very difficult.

The best theoretical description of π^o photoproduction available at present is based on partial wave (multipole) dispersion relations(13), in which one projects out the multipoles from the fixed momentum-transfer dispersion relations for the twelve (including the isospin multiplicity) CGLN invariant photoproduction amplitudes, and then attempts to solve the resulting set of coupled integral equations using pion-nucleon phase shifts as input via the Watson theorem. Within these limitations there are, in addition, the following sources of error introduced in obtaining a solution to the dispersion relations:

1) Errors in the partial wave Born terms due to errors in the coupling constant g.

2) Errors introduced via the Watson theorem from the πN scattering phase shifts which themselves have errors attached.

3) Errors from the estimation of the rescattering contributions to the multipole $M_{1-}^{(0,1)}$ due to the P_{11} resonance, and to the multipoles $E_{2-}^{(0,1)}$, $M_{2-}^{(0,1)}$ due to the D_{13} resonance. These resonances are outside the region of validity of the Watson theorem for these particular partial waves but near enough to the energies of interest to affect the multipoles.

4) Errors due to the unknown high-energy behaviour of the multipoles.

One may summarize the present theoretical situation by noting that pure theory (pure in the sense that no parameters chosen to fit photo production data are included) inadequately describes the experimental data. There are several problems which complicate the theoretical evaluation. The first is that (in π^0 photoproduction on protons) near threshold there is almost complete cancellation of what showed nominally be the dominant terms, namely the E_{0+} transitions to the s-wave final states. This leaves the cross-section to be determined by the p-waves and near threshold the M_{1-} transition is as important as the M_{1+}. The second problem is that there should be some contribution from vector meson exchange as indicated by the way in which Reggeized ω exchange can adequately explain high energy π^0 photoproduction(14), especially if some background B exchange is included(15). Including the vector mesons correctly is not easy because:

1) The vector meson nucleon coupling constants are not well--known(16).

2) To be completely correct one must include the effect of the vector meson exchange on the entire multipole via the dispersion relation, and not simply adding the Born term.

3) The vector effect of the vector-meson exchange may be already partially included in the final state interactions introduced via the pion--nucleon phase shifts(17).

These difficulties have been partially overcome by the introduction of several free parameters into the theory either correlated, as vector meson parameters(7) or independent and representing the unknown high energy behaviour(17, 18).

Finally there is another approach to the problem of calculating the π^0 photoproduction cross sections, the isobar model, originally due to Gourdin and Salin(19). The most recent refinement of this model by Walker(20) gives satisfactory results for all the photoproduction processes.

III. - THE POLARIZED γ - BEAM. -

The linearly polarized gamma ray beam used in the experiment is obtained from electron bremsstrahlung on a crystal diamond. The primary electrons are accelerated at 1000 MeV energy in the Frascati electronsynchrotron. The properties of the coherent bremsstrahlung beam will be described in a paper(5) that will be soon published. If the following paragraphs we will briefly recall the employing features of the beam.

The diamond is oriented in such a way that the electron momentum $\vec{p}_1$ lies in the plane of the axes $[110]$, $[001]$ at a small angle θ with respect to the $[110]$ axis(x). Then the γ ray energy spectrum presents a

(x) - (see next page).

dominant peak of intensity, which is in correspondence to the polarization P reaching its maximum value. The energy of the peak depends angle θ between $\vec{p}_1$ and the [110] axis. The position of the peak can be chosen in such a way to obtain the largest number of useful photons in the required energy range. The polarization is defined as

$$P(K) = \frac{N_n(K) - N_p(K)}{N_n(K) + N_p(K)} = \frac{I_n(K) - I_p(K)}{I_n(K) + I_p(K)}$$

K is the photon energy and $N_{n(p)}(K)$ is the number of photons per unit energy interval with electric vector normal (parallel) to the [110] - [001] plane; $I_{n(p)}(K) = K \cdot N_{n,p}(K)$ is the bremsstrahlung intensity.

The experimental data are collected by using two diamonds: the plane [110] - [001] is vertical for the first one, horizontal for the second one. In the first (second) case we have an excess of photons with polarization vector parallel (normal) to the reaction plane which is horizontal in our experiment. Then, if $C_\perp$ and $C_\parallel$ are respectively the π^0 photoproduction counting rates for the two situations, one obtains the ratio of the cross sections via the formula(21)

$$\frac{d\sigma_\perp}{d\sigma_\parallel} = \frac{|P|(R_c + 1) + (R_c - 1)}{|P|(R_c + 1) - (R_c - 1)} \qquad R_c = \frac{C_\perp}{C_\parallel}$$

During the experiment the beam energy spectrum has been measured with a pair spectrometer of energy resolution $\Delta K/K \pm 4\%$.

The rotations of the diamond crystals are remotely controlled and their values are read on two goniometers.

Figs. 1a, b, c, d, shows the measured spectra for the two diamonds corresponding to the θ values used in the experiment. The solid line represents the calculated spectrum. This is obtained from a computer program where the interferential and amorphous bremsstrahlung cross sections are calculated and then folded with the experimental conditions as electron scattering in the diamond, beam collimation and finite energy resolution of the pair spectrometer. The normalization factor and the continuous part of the spectrum are left as free parameters and their values are determined from the comparison with the measured spectrum by means of a least squares.

(x) - Calling α the angle between planes [110], [001] and $\vec{p}_1$, [110]; this means that in our nominal working conditions, α is 0°. The beam polarization is also dependt on α and has a relative maximum (keeping θ fixed) at α = 0°. We estimate that the misalignment error on is less than 1° to which corresponds a polarization variation with respect to the nominal value of about $\Delta P = 0.01$.

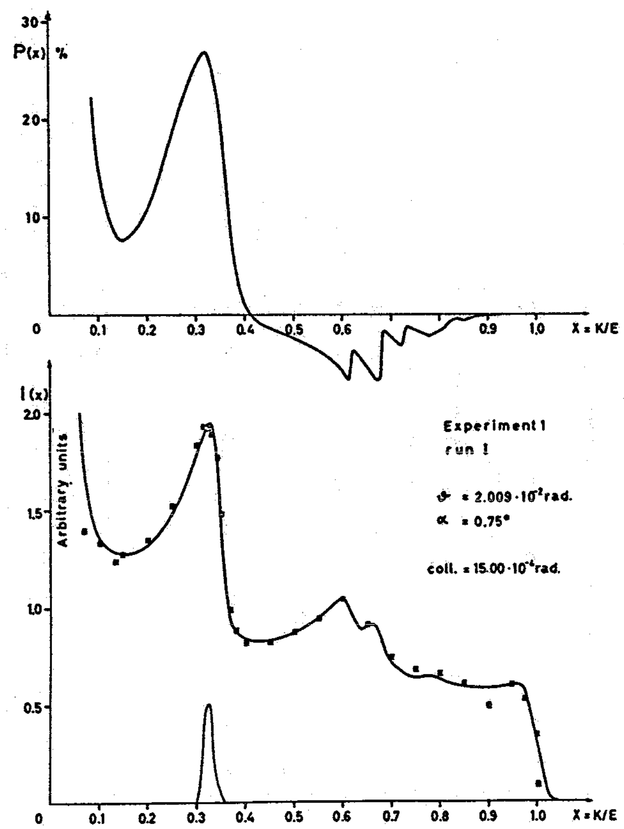

FIG. 1a

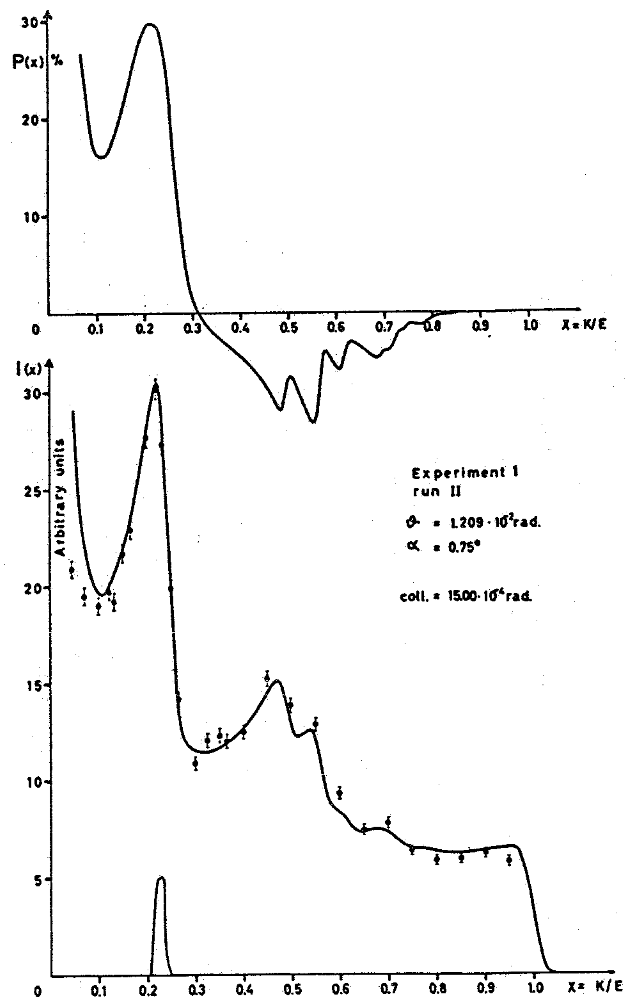

FIG. 1b

FIG. 1a, b, c, d - Beam polarization and intensity versus the fractional photon energy X=K/E for the different kinematical conditions. Full lines represent the calculated values. Experimental points refer to the measurements made with the electron pair spectrometer. The bell-shaped curves along the x axis represent the energy acceptance of the experimental apparatus for π^0 photoproduction.

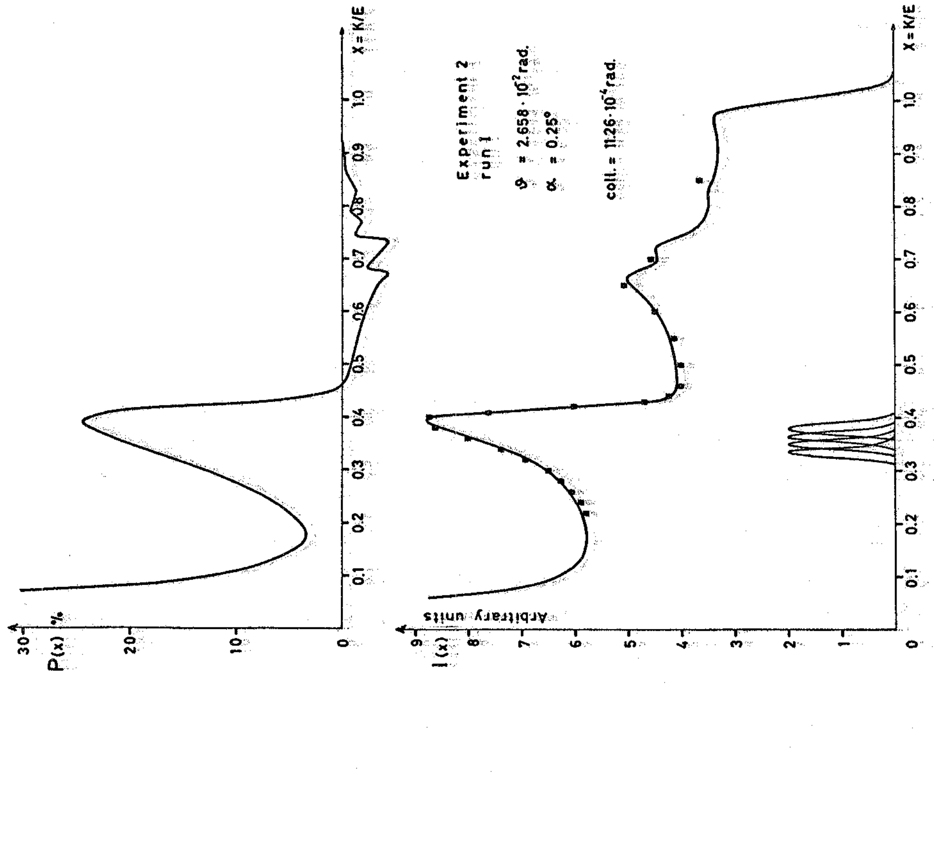
P(x) %
I(x)
Arbitrary units
X = K/E
Experiment 2
run I
ϑ = 2.658 · 10⁻² rad.
α = 0.25°
coll. = 11.26 · 10⁻⁴ rad.

FIG. 1c

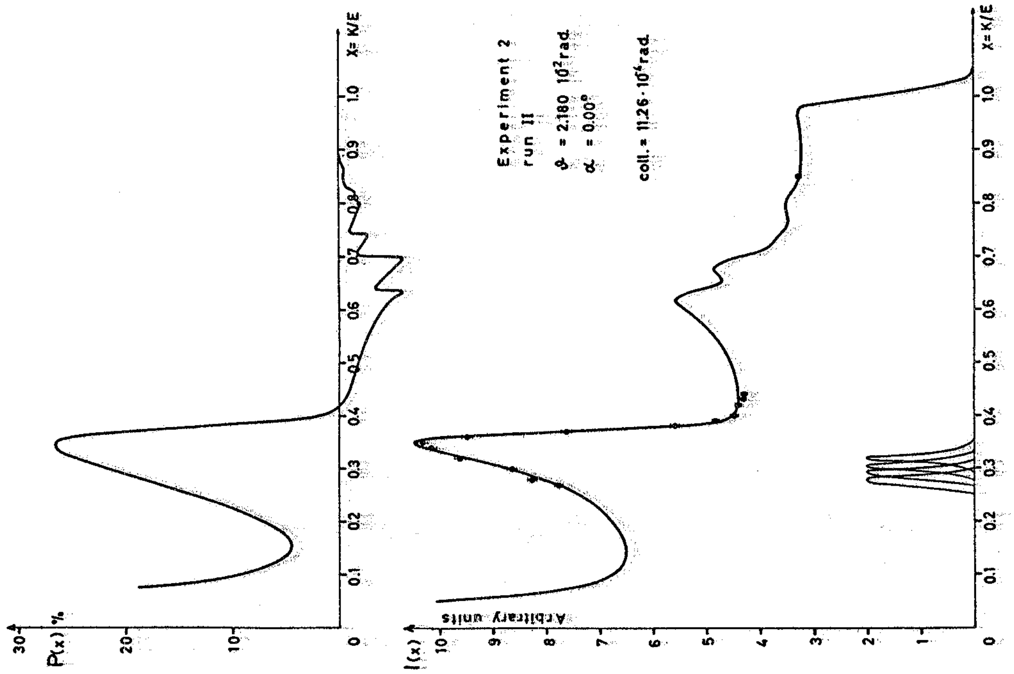
P(x) %
I(x)
Arbitrary units
X = K/E
Experiment 2
run II
ϑ = 2.180 10⁻² rad.
α = 0.00°
coll. = 11.26 · 10⁻⁴ rad.

FIG. 1d

square method. The polarization P(K) associated with this so-calculate intensity spectrum is assumed to be true beam polarization and is also shown in Figs. 1. The error on the polarization values may be due either to the approximations still present in the calculation due to the statistical uncertainties in fitting the experimental spectrum. As a reasonable estimate from the least squares analysis, we have assumed $\Delta P=0.01$ as a standard error on the polarization. (For more details on the polarization calculation see (5)).

The beam experimental apparatus is shown in Fig. 2. Leaving the synchrotron doughnut, the γ -ray beam passes trough collimators C_1 C_2 C_3 C_4. Its angular aperture is defined by C_3 while C_1 has the function of eliminating the parasytic non polarized beam coming from the diamond holder and C_2, C_4 reduce the background in the electron pair spectrometer.

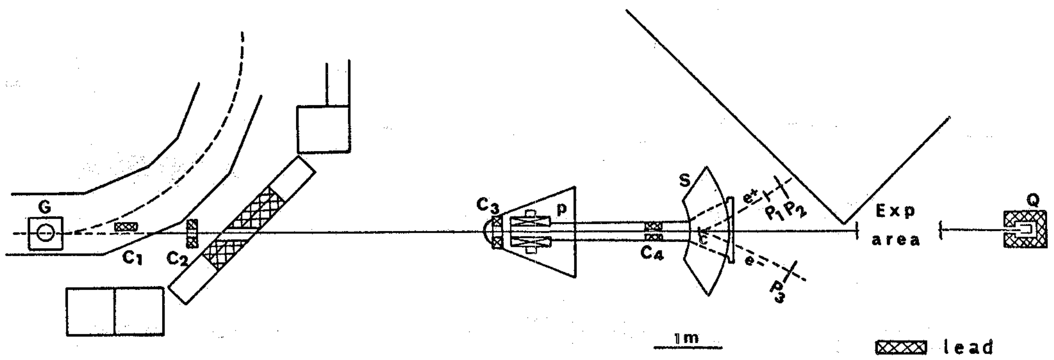

FIG. 2 - General layout of the polarized beam. G: goniometer holding the crystal diamond (installed inside the synchrotron vacuum chamber). C_1,C_2,C_3,C_4: lead collimators. P: broom magnet. S: electron pair spectrometer. P_1, P_2, P_3: electron pair counters. Q: Wilson type quantameter.

After the collimation, the beam enters in the liquid hydrogen target H. P is a broom magnet and Q is a Wilson type quantameter where the beam intensity is monitored.

IV. - EXPERIMENTAL APPARATUS. -

The π^0 photoproduction events are defined by a pulse coincidence between a proton range telescope and a lead glass Cerenkov counter that detects one of the γ 's from the π^0 decay. A plastic scintillator A, in front of the Cerenkov counter, vetoes the detection of charged particles.

The proton range telescope is an array of plastic scintillation counters and aluminum absorbers. In the first experiment, it only defines one energy channel. In the second one, three more counters and absorbers have been added (see Figs. 3a, b) in order to collect events simultaneously in four energy channels. The pulse height of the scintillation counter S_1 (S_2) in experiment 1 (2) is analyzed in a multichannel in order to control pion and electron contamination in the proton telescope. The central kinematic conditions for the two experiments are written below.

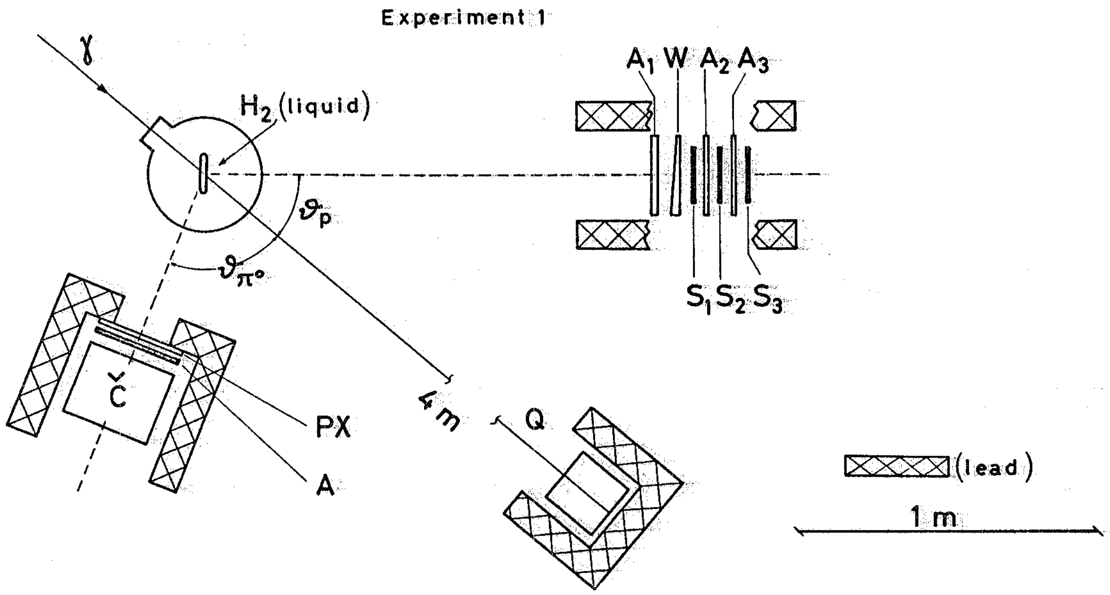

FIG. 3a

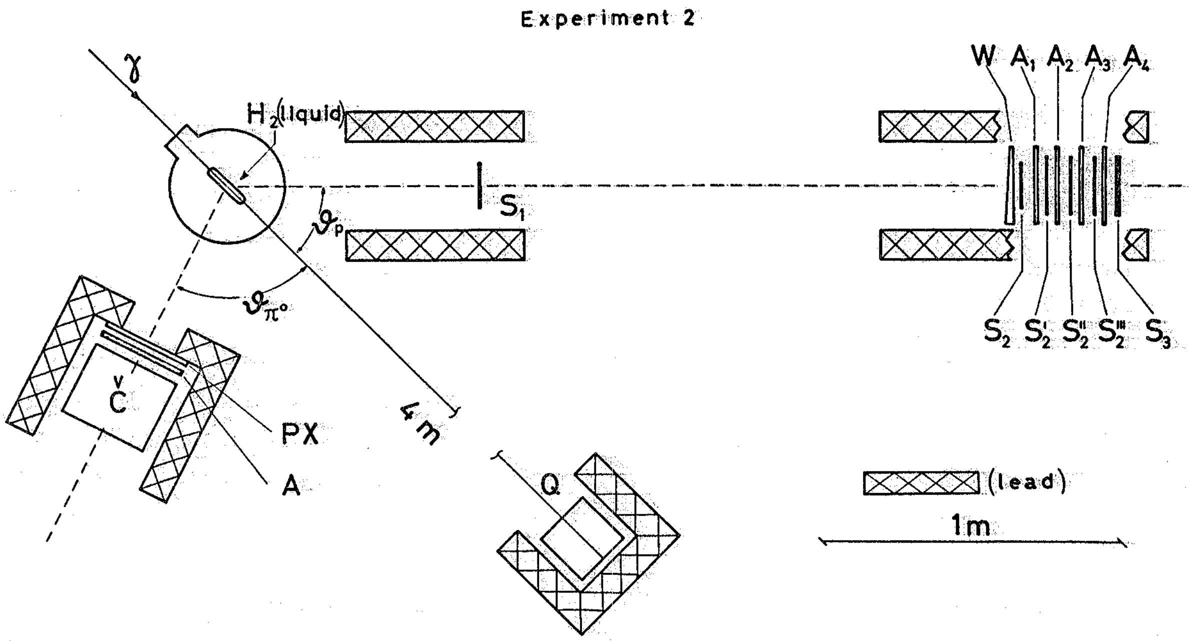

FIG. 3b

FIG. 3a, b - Set up for experiment 1 and 2. A_1, A_2, A_3, A_4, W: Aluminum absorbers. $S_1, S_2, S_2', S_2'', S_2'''$, S_3, A: plastic scintillation counters. Č: integral lead glass Cerenkov counter. Px: plexiglass layer (to stop slow electrons).

Experiment 1. -

Run	K_o(MeV)	θ_p	T_p(MeV)	θ_{π^o}	$\Delta\Omega_p$(Sr)	ε_{π^o}
I	325	40.5°	61	73°	0.0064	0.25
II	230	35.6°	28.5	74°	0.0064	0.13

ε_{π^o} is the mean geometrical Cerenkov efficiency for detecting a π^o decay. The hydrogen target used in this experiment is a disk shaped cell 2.2 cm thick having its axis parallel to the proton direction.

Experiment 2. -

Run	K_o(MeV)	θ_p	T_p(MeV)	θ_{π^o}	$\Delta\Omega_p$(Sr)	ε_{π^o}
I	335	41°	61	72°	0.0036	0.13
	350	"	67	"	"	0.14
	365	"	72	"	"	0.155
	380	"	78	"	"	0.165
II	275	40°	41.5	73°	"	0.15
	290	"	46.5	"	"	0.17
	305	"	52.5	"	"	0.18
	320	"	58	"	"	0.20

In Fig. 4 is shown the electronic block diagram for experiment 2 (for experiment 1 the same logic has been used, but in a simplified version because of the absence of counters S_2', S_2'', S_2'''). Moreover, in experiment 2, discrimination between protons and pions has also been achieved by using their different time of flight, because of the increased distance between counters S_1 and S_2.

The resolution power of the apparatus with respect to the initial photon energy k has been calculated for all kinematical conditions by a MonteCarlo method. In Fig. 1 the calculated resolution functions are shown: the typical total width at half height is 20-30 MeV. Properly shaped absorbers have been used to obtain the form of the resolution function as square as possible.

The presence of steeply falling peaks in the beam spectrum allows to energy calibrate our apparatus. By changing the crystal angle θ, it is possible to shift the coherent photon peak along the k axis. Then the π^o photoproduction counting rate versus θ will have a relative maximum whenever a beam peak overimposes itself on the k-resolution curve of the experimental apparatus. The fit of the experimental data with the calculated previsions, obtained from the known photon energy spectra shape, gives the central energy value k_o and the width of the resolution function.

ELECTRONICS BLOCK DIAGRAM (Experiment 2)

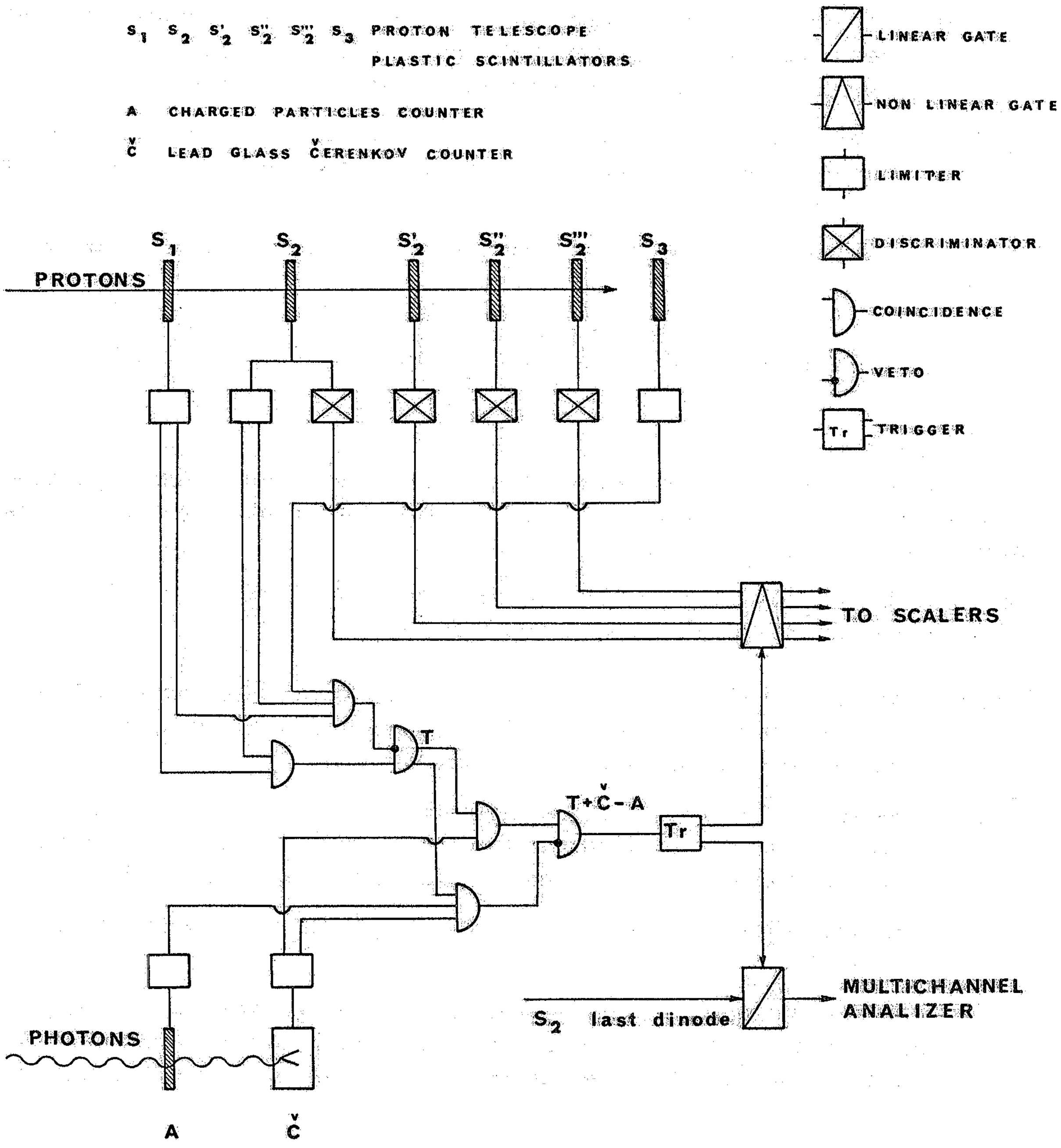

FIG. 4 - Electronics block diagram (for experiment 2)

The experimentally measured quantity is:

$$Y^{\perp,\parallel}_{exp}(\theta) = \frac{C_{\perp,\parallel}(\theta)}{N_e(\theta)}$$

where

$C_{\perp,\parallel}$ (θ) are the π^o photoproduction events per unit beam dose detected when the diamond is set at the angle θ and with the polarization respectively normal or parallel to the reaction plane.

$N_e(\theta)$ is the number of the electron pairs, counted with the pair spectrometer per unit beam dose produced by 850 MeV photons when the diamond is set at the angle θ[x].

The calculated value Y_C (θ) to be compared to the experimental one is given by:

(5) $$Y_c^{\perp,\parallel}(\theta) = N \frac{\int \eta(k - k_o)\; n(\theta, k) \frac{d\sigma}{d\Omega}(k) \left[1 \pm \Sigma(k) P(\theta, k)\right] dk}{\left[N_e(\theta)\right]_c}$$

Where N is a normalization factor; η $(k-k_o)$ is the experimental apparatus resolution function evaluated with the MonteCarlo method and k_o is the nominal central energy value.

$n(\theta, k)$ is the calculated beam energy spectrum at the crystal angle θ. $P(\theta, k)$ is the corresponding beam polarization.

$\frac{d\sigma(k)}{d\Omega}$ is the π^o photoproduction differential cross section at 90^o in the center mass system. The values used in the integral are the experimental data taken from ref. (1).

$\Sigma(k)$ is the π^o photoproduction asymmetry previously defined. For our purposes, an accurate knowledge of Σ (k) is not necessary; we have used the theoretical values given by Rollnik[18].

$\left[N_e(\theta)\right]_c$ is the calculated value of the yield $N_e(\theta)$ of the electron pairs (see (5)).

The experimental points with the corresponding calculated previsions are shown in Fig. 5a, b, c, d. The calculated curves have been optimized with the minimum χ^2 method respect to the following parameters:

(x) - For practical reasons (see also (5)), it is more convenient to normalize the π^o counting rates to the number of electron pairs rather than to the absolute beam dose.

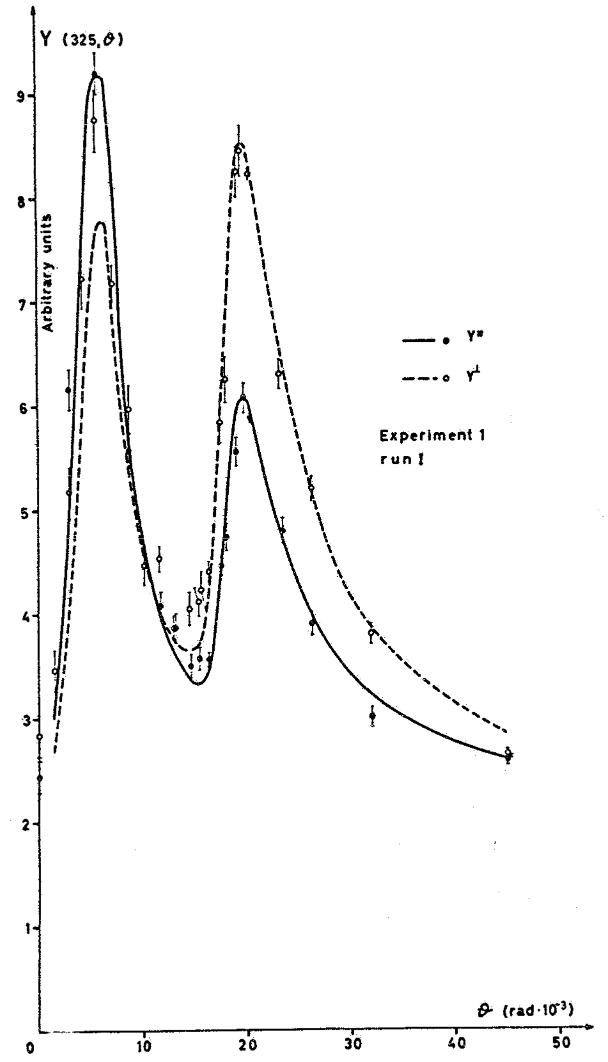
Y (325, ϑ)
Arbitrary units
Y∥
Y⊥
Experiment 1
run I
ϑ (rad·10⁻³)
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9

FIG. 5a

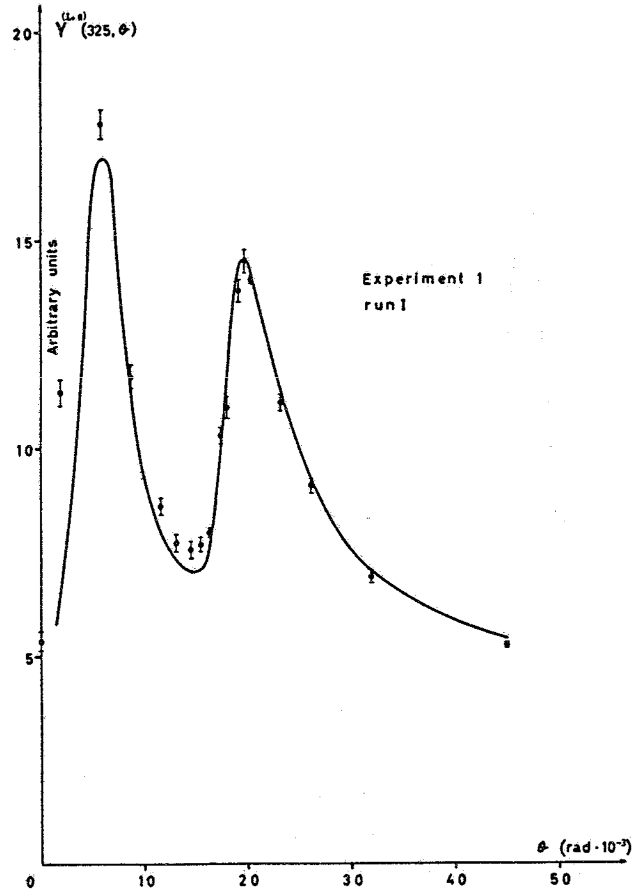
Y (325, ϑ)
Arbitrary units
Experiment 1
run I
ϑ (rad·10⁻³)
0
10
20
30
40
50
5
10
15
20

FIG. 5b

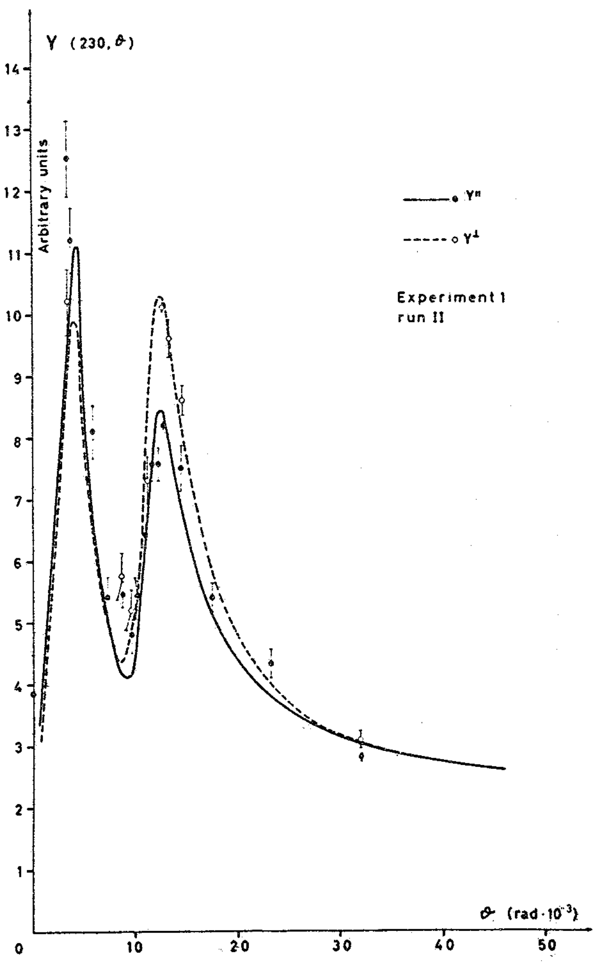

FIG. 5c

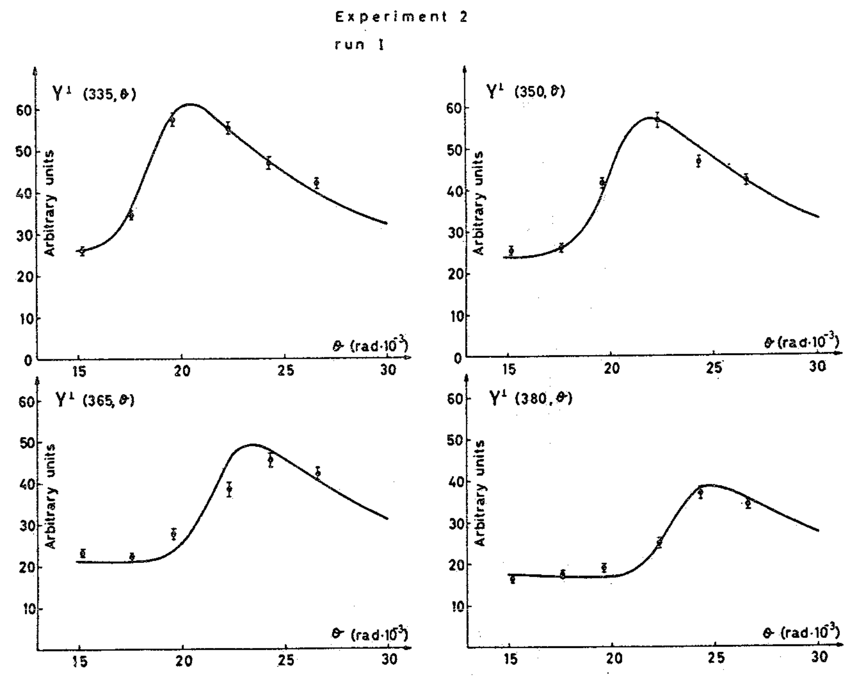

FIG. 5d

FIG. 5a, b, c, d - Yield of photoproduction events versus the crystal angle θ for the different kinematical conditions. The continuous and dashed curves represent, in arbitrary units, $Y^{\perp}(\theta)$, $Y^{\parallel}(\theta)$ and their sum calculated according equation (5).

1) α (assumed to be constant for all the spectra with the same θ);

2) the percentage of the continuous (noncoherent) part in the beam spectrum;

3) the central value k_o of the energy resolution function and the normalization factor N.

The position of the last peak of the yield $Y(\theta)$ is very sensitive to the k_o value. The comparison between experimental points and calculated prevision allows an evaluation of k_o with an error of $\pm$ 5 MeV.

The agreement between the calculated curves and the experimental points is rather satisfactory. The deviations still existing can be attributed to:

a) Errors in the crystal angle θ measurement;

b) contamination arising from the proton Compton effect. The number of events resulting from the Compton effect is on the average small (1-2%). However the percentage of these events increases for some values of the crystal angle θ because of the different photon energy regions contributing to π^o photoproduction and Compton effect at the same proton kinematics;

c) the approximations introduced in the photon energy spectrum calculation start to fail at high values of the crystal angle θ. At these angles the calculated previsions overestimate the photon intensity and consequently $Y_c(\theta)$.

EXPERIMENTAL RESULTS. -

The experimental values for the asymmetry are presented in the following table.

TABLE I

K_o	N	$\bar{P}$	R_c	$\Sigma(90^o)$	Exp.
325	60.000	0.262	1.371 $\pm$ 0.011	0.596 $\pm$ 0.028 (x)	1
230	20.000	0.290	1.258 $\pm$ 0.017	0.435 $\pm$ 0.041	
275	16.800	0.185	1.196 $\pm$ 0.018	0.485 $\pm$ 0.049	2
290	31.800	0.210	1.284 $\pm$ 0.014	0.592 $\pm$ 0.039	
305	29.300	0.233	1.276 $\pm$ 0.014	0.521 $\pm$ 0.034	
320	34.300	0.252	1.408 $\pm$ 0.015	0.672 $\pm$ 0.034	
335	17.300	0.183	1.251 $\pm$ 0.019	0.609 $\pm$ 0.053	
350	15.300	0.204	1.297 $\pm$ 0.020	0.634 $\pm$ 0.050	
365	10.300	0.223	1.322 $\pm$ 0.025	0.603 $\pm$ 0.052	
380	11.200	0.236	1.319 $\pm$ 0.024	0.583 $\pm$ 0.047	

(x) - The errors on the asymmetry have been calculated according equation (6). Only for Σ(230 MeV), which has a large background correction, we have included a systematic error equal to 20% of the calculated correction.

N is the total number of π^o photoproduction events.

$\overline{P}$ is the polarization value obtained averaging P(k) over the product of the k-resolving power multiplied by the beam spectrum and by the differential π^o production cross section. The values of $\overline{P}$ are slightly different from the values of $P(k_o)$ corresponding to the center of the resolution curve.

The following concurrent reactions have to be considered:

a) Proton Compton effect. The contamination introduced by the proton Compton effect is small because the cross section for this process is nearly 1% of the π^o corresponding cross section. We have not made corrections for this effect.

b) Double π^o photoproduction. The production of polarized photons with coherent bremsstrahlung requires that the maximum energy of the spectrum stays beyond the energy value of the useful polarized photons. Photons from the high energy part of the spectrum (where the polarization is nearly zero) produce double π^o photoproduction events which are seen by our apparatus. This background independent from the polarization has the effect of reducing the experimental ratio R_c and consequently introduces an underestimation of the asymmetry. Since precise experimental information on double π^o photoproduction cross section is lacking, we have measured the contamination of this process in our experiment. This has been done only for the experimental situation corresponding to the photon energy k_o = 325 MeV. This contamination is measured as the difference of the yields in our apparatus, per constant flux of 325 MeV photons, by setting the tip of an amorphous bremsstrahlung spectrum at 1000 MeV and 500 MeV respectively. In the second situation, all the photons are below our kinematical threshold for two π^o production. By taking into account the difference between the amorphous and the coherent bremsstrahlung spectrum the measured double π^o contamination turns out to be 1.6% of the good events.(after correction for nuclear absorption).

For the other kinematical conditions the double π^o contamination has been estimated from the previous one (measured at k_o = 325 MeV) by correcting it for the following effects:

a) differences in the yields of photons contributing to single and double π^o photoproduction;

b) variation of the Cerenkov geometrical efficiency for single and double π^o production;

c) variation of the single π^o photoproduction cross section.

The energy behaviour of the total $2\pi^o$ cross section has been assumed to be equal to the experimental one of $\pi^+\pi^-$ photoproduction multiplied by a scale factor equal to 0.4. The angular distribution of the two π^o's has been calculated according to phase space. The double π^o contamination calculated in this manner varies from 2% up to 6%, this last value being reached for the measurement at k_o = 230 MeV. All the values of R_c and Σ reported in table I have already been corrected for the $2\pi^o$ background.

The error on the asymmetry has been calculated from the formula

(6) $$\frac{\Delta\Sigma}{\Sigma} = \sqrt{\frac{1}{N}\frac{1}{(\Sigma\,\overline{P})^2} + \left(\frac{\Delta\overline{P}}{\overline{P}}\right)^2}$$

The total number of events N and consequently the measurement time have been chosen in order to have almost the same contributions to $\Delta\Sigma/\Sigma$ from the two terms appearing in the square root in the formula (6). As previously mentioned, for the error on the polarization, we assumed $\Delta\overline{P} = 0.01$.

Other sources of systematic errors like liquid hydrogen density variation, stability of beam monitor, have not been considered.

We stress that because the asymmetry measurement is a relative one, any counting loss due to counters inefficiency or proton nuclear absorption do not affect the measured asymmetry value.

However, nuclear absorption can stop in our telescope energetic protons produced by non polarized photons. We have calculated the correction to make on the asymmetry values because of this effect taking into account the whole flux, through our telescope, of photoproduced protons. The correction turns out to be less than 3% except for the point measured at k_o = 230 MeV which is largely contamined by protons coming from the resonance region (in this case this correction amounts to 15%).

The final values of the asymmetry are also shown in Fig. 6. The previous asymmetry measurements made by Drickey and Mozley[(6)(x)] are presented in the same figure.

(x) - Of the four asymmetry values measured by the Stanford group, those at 285 and 435 MeV have been measured at a proton angle $\theta=90^o$ in the center mass system. Those at 235 and 335 MeV have been done at $\theta^* = 60^o$ and 120^o respectively. The corresponding values for the asymmetry at 90^o have been obtained from the relationship

$$\Sigma'(\theta^x) = \Sigma(90^o)\ \mathrm{sen}^2\theta^x \left[d\sigma(90^o)/d\sigma(\theta^x)\right]_{unpol}$$

which is derived from (1) assuming that the coefficient $I(k, \theta^x)$ does not depend on θ^x.

The ratio $\left[d\sigma(90^o)/d\sigma(\theta^x)\right]_{unpol}$

has been taken from the data of the Bonn group[(22)].

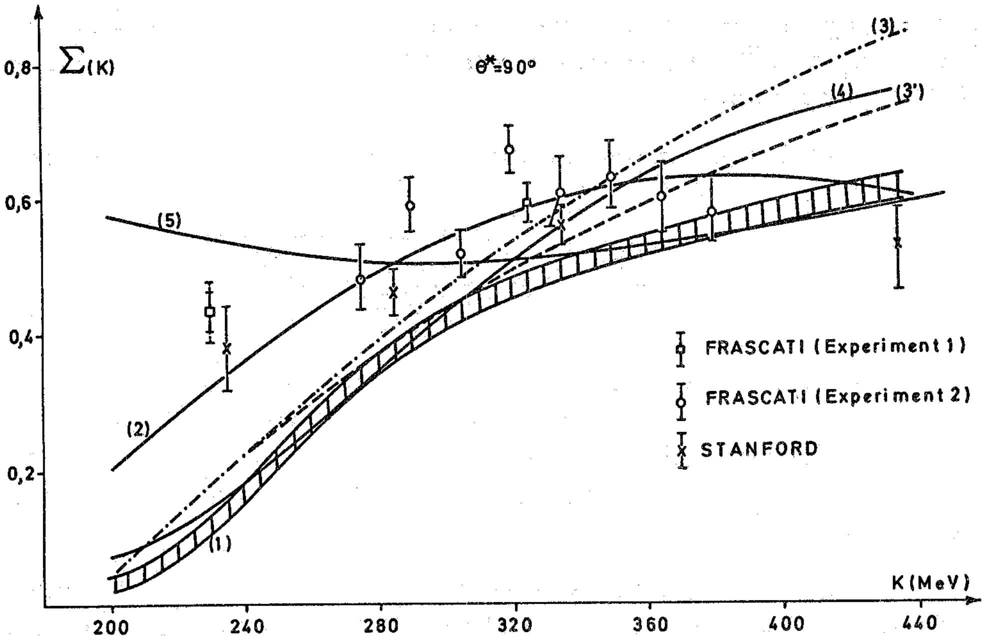

FIG. 6 - Asymmetry for π^{o} photoproduction at θ^{x}=90^{o}. The Stanford points are taken from reference (6). Theoretical curves 1, 2, 3 and 3', 4, 5 are taken respectively from references (7), (18), (17), (13), (20).

The theoretical curves shown in Fig. 6 refer to the following calculations:

Curve (1) - (Berends et al.[(7)]): The theoretical previsions are made on the basis of the dispersion relations (The shadow area reflects the uncertainty due to the approximations introduced in the calculations). The ω exchange in the t channel is not considered. There are no free parameters in the theory.

Curve (2) - (Rollnik et al.[(18)]): This calculation is also based on the dispersion theory. The ω (and also the ρ) exchange is introduced as a pole in the t channel. Three parameters have been introduced and their values have been fixed by the authors from the fit of the angular distributions.

Curve (3) and (3'). - (Schwela[(17)]): The calculation has been made by using dispersion relations. The ω contribution is not taken account, but its relevance on the theory is discussed in this paper together with the uncertainty on the proper way to evaluate the ω exchange.

Curve (4) - (Schmidt[(13)]): This curve is also calculated from dispersion-relation theory.

Curve (5) - (Walker[(20)]): This calculation is based in a phenomenological model where the electric Born term is considered together with the resonances known from the pion nucleon scattering phase shifts analysis.

A correction for the non resonant part is introduced as a parameter with the restriction of a smooth energy behaviour.

From Fig. 6 one sees that the curve in better agreement with the experimental results is curve (2) calculated by Rollnik et al. [18]. We recall that this is the only curve that takes explicitly into account vector meson exchange. In fact the authors introduced ω exchange and ρ exchange (this last one, however, should be less important) with the following coupling constants[18]:

$$\frac{g^2_{\omega\pi\gamma}}{4\pi} = 0,15 \qquad \frac{g^2_{\rho\pi\gamma}}{4\pi} = 0,02$$

which were taken from the quark model; and with:

$$\frac{g^2_{\omega NN1}}{4\pi} = 2,83 \qquad \frac{g^2_{\rho NN1}}{4\pi} = 0,86$$

$$\frac{g^2_{\omega NN2}}{4\pi} = 0,03 \qquad \frac{g^2_{\rho NN2}}{4\pi} = 9,66$$

which were derived from nucleon-nucleon scattering.

The marked difference in Fig. 6 between curve (2) and the other ones in the low energy region could then be due to ω exchange, whose importance would be so confirmed by the asymmetry measurements. However it is hard to understand what amount of this difference is due to ω exchange and what to the different methods employed in applying the dispersion relations to photoproduction: in fact, no author has published both the predictions (with or without ω -exchange) of its theory on the asymmetry.

In order to get information on the multipole $E^{(3)}_{1+}$ at the resonance we computed[x] the values of the asymmetry using the multipoles of Berends et al. [7] (that are the only ones available in numerical tables).

We found that the asymmetry is not very sensitive to the value of the leading multipole $M^{(3)}_{1+}$ while it is greatly influenced by $E^{(3)}_{1+}$. Our results are in much better agreement with $E^{(3)}_{1+}$ equal to zero than with $E^{(3)}_{1+}$ equal to the BDW estimate.

(x) - We must thank here M. Nigro, P. Spillantini and V. Valente who lent us a general program for calculating all photoproduction cross sections, asymmetries and polarizations.

However, in the mean time, we noticed that the BDW multipoles are not in good agreement with the recent measurements of the Bonn group[22] on the cross sections. These last ones seem to require:

1) a position of the 33 resonance (at k = 349 MeV according BDW) shifted towards lower energies (this does not affect the asymmetry significantly);

2) a value of $M_{1+}^{(3)}$ a few percent higher;

3) $E_{1+}^{(3)}$ different from zero.

In order to bring the BDW previsions in better agreement with both the asymmetry and cross sections measurements in addition to points 1) and 2) a value of $E_{1+}^{(3)}$ intermediate between zero and the BDW estimate would be required.

The $M_{1-}^{(0)}$ and $M_{1-}^{(1)}$ multipoles which concern the P_{11} resonance could be tentatively obtained from the relations: (s and p wave approximation)

$$-\frac{k}{q}\frac{d\sigma}{d\Omega}(90^o)\cdot\sum(90^o)\Big|_{p\pi^o,\,p\pi^-} = 3\,\mathrm{Re}\,(E_{1+}-M_{1+})^{x}\left(\frac{3}{2}E_{1+}+\frac{1}{2}M_{1+}+M_{1-}\right)\Big|_{p\pi^o,\,p\pi^-}$$

putting in the first member the experimental results on reaction $\gamma p \to p\pi^o$ and $\gamma n \to p\pi^-$, and in the second member the BDW multipoles leaving only Re $M_{1-}^{(0)}$ and Re $M_{1-}^{(1)}$ to be determined. However, this analysis is not free of ambiguities for the following two reasons:

1) the BDW multipoles are not in good agreement with the Bonn results on $d\sigma/d\Omega$ as previously mentioned;

2) there is a big cancellation when performing the sum $M_{1-}^{(0)}$ + + 1/3 $M_{1-}^{(1)}$ because of the isospin decomposition (4), in the π^o case. This fact makes it very hard to detect P_{11} effect in π^o photoproduction.

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Thanks are also due to Mr. Di Stefano and coworkers for their skilled technical work. Finally, we would like to mention that the synchrotron staff collaborated very much with us providing a smooth machine operation.

At the moment of printing we have received a preprint from the Orsay group[23] reporting measurements of the angular distributions for π^o photoproduction at the first pion nucleon resonance.

Their results seem to confirm the behaviour of the cross sections measured by the Bonn group but are slightly smaller (up to 5 – 7% at $\theta^* = 90^o$).

This leaves substantially unaffected our conclusions drawn by the simultaneous analysis of angular distributions and asymmetry measurements.

REFERENCES. -

(1) - J. T. Beale, S. D. Eckund and R. L. Walker, Report CTSL-42, CALT 68/108 (1968).
(2) - G. Barbiellini, G. Bologna, G. Diambrini and G. P. Murtas, Phys. Rev. Letters 8, 112 (1962).
(3) - G. Barbiellini, G. Bologna, J. De Wire, G. Diambrini, G. P. Murtas and G. Sette, Proceedings XII Conference on High Energy Phys., Dubna, (1964) pag. 838.
(4) - G. Barbiellini, G. Capon, G. De Zorzi, F. L. Fabbri and G. P. Murtas, contribution to the Heidelberg International Conference on Elementa ry Particles.
(5) - G. Barbiellini, G. Bologna, G. Diambrini and G. P. Murtas, (In prepa ration); for a general survey on the subject see also:
G. Diambrini-Palazzi, Revs. Modern Phys. 40, 611 (1968).
(6) - D. J. Drichey and R. F. Mozley, Phys. Rev. 136B, 543 (1964).
(7) - F. A. Berends, A. Donnachie and D. L. Weaver, Nuclear Phys. B5, 1, 54, 103 (1967) (cited as BDW).
(8) - C. Becchi and G. Morpurgo, Phys. Letters 17, 352 (1965).
(9) - T. Nishikawa et al., Phys. Rev. Letters 21, 1288 (1968).
(10) - A. Donnachie, Phys. Letters 24B, 420 (1967).
(11) - H. J. Lipkin, Phys. Letters 12, 154 (1964).
(12) - W. Schmidt, Proceedings of the Dubna Conference, (1967).
(13) - Most recent works on dispersion relations for pion photoproduction beyond the cited one by Berends et al., are D. Schwela, H. Rollnik, A. Weizel and W. Korth, Z. Physik 202, 452 (1967);
W. Schmidt, SLAC-PUB-415 (1968).
(14) - H. P. Locher and H. Rollnik, Phys. Letters 22, 696 (1966).
(15) - J. P. Ader, M. Capdeville and Ph. Salin, CERN Preprint TH-803 (1967).
(16) - D. L. Weaver, Phys. Letters 26B, 451 (1968).
(17) - D. Schwela, Thesis, Bonn University.
(18) - H. Rollnik, Proceedings of the Heidelberg International Conference on Elementary Particles, (1967), pag. 400.
H. Rollnik, D. Schwela and R. Werzley, Contribution to the Heidel- berg International Conference on Elementary Particles (1967).
(19) - H. Gourdin and P. Salin, Nuovo Cimento 27, 193 (1963).
(20) - R. L. Walker, Caltech Report, CALT-158/68 (1968).
(21) - J. De Wire, Frascati Report, LNF-61/39 (1961).
(22) - G. Fischer et al., University of Bonn, Report 1-044 (1968).
(23) - R. Morand, E. F. Erickson, J. P. Pahin and M. G. Grossiaux, Orsay Preprint, LAL 1201.