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PHOTOPRODUCTION OF NEUTRAL PIONS AND POLARIZATION OF THE RECOIL PROTONS

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The knowledge of the cross section and of the polarization of the recoil proton in the photoproduction of the neutral pions may bring a fundamental contribution to the study of the resonances of the pion nucleon system.

Using these results and the corresponding ones for the charged pions, it should be possible to calculate the amplitudes and the phases of each state contributing to the interactions, provided the experiments gave very precise results at every energy. This is not by far the situation, and too little information is available at present, so we shall use the less satisfactory, inductive procedure of assuming some states to be present and compare the resulting predictions with the observed results. We limit our analysis to the 500-1000 MeV region of the γ rays.

Following these lines, we assume that, beyond the well-known 3,3 resonance (resonance A), the behaviour of the cross section and polarization at 500-1000 MeV. of the γ rays may be explained by two new states only. These are labelled by B (second resonance) and C (third resonance) and have maxima around 700 MeV and 1100 MeV respectively as already known.

A general discussion of the indications coming from previous experimental results when similar restricted hypotheses are introduced has been made by Peierls [1], who took into consideration the photoproduction and the pion scattering processes in order to get some conclusion on the amplitudes and the phases.

The aim of the present paper is not as general, and is experimental in character. More precisely our program is :

Sect. 1.—To report some results on the photoproduction of the neutral pions (by G. Cortellessa and A. Reale).

Sect. 2.—To report an experiment on the polarization of the recoil proton, which has been carried out by counter techniques (by R. Querzoli, G. Salvini and A. Silverman).

Sect. 3.—To report a similar experiment with bubble chamber techniques (by L. Bertanza, P. Franzini, I. Mannelli, V. Peterson, G. Silvestrini).

Sect. 4.—To discuss the results particularly from section 2, in respect to the assignment and evaluation of the states A, B, C.

SECT. 1 — PRELIMINARY RESULTS OF A MEASUREMENT OF THE DIFFERENTIAL CROSS SECTION FOR SINGLE π^0 MESON PHOTOPRODUCTION IN HYDROGEN.

(By *G. Cortellessa* and *A. Reale* of the Istituto Superiore di Sanità.)

The differential cross section for single π^0 meson photoproduction in hydrogen between the threshold and 1200 MeV has been extensively measured during the last eight years.

In particular the second " resonance " has been studied, from 500 to 900 MeV incident photon laboratory energy, by many experimenters, with some discrepancies among the data. These differences are more pronounced for the backward and forward c.m.s. angles for the meson.

The aim of the authors [2] (G. Cortellessa, A. Reale) in the present experiment has been to try to establish whether the discrepancies at the second resonance are due to lack of angular and energy resolution in the previous measurements.

The detection of single π^0 meson photoproduction is performed in this experiment through a coincidence between the recoil proton from the reaction and one of the gamma rays coming from the decay of the π^0 meson. A telescope built with five scintillation counters with absorbers between the counters, defines a proton event.

The counters have a thickness of 5 millimeters, and an area of 15×15 cm^2 except the first one that has an area of 10×10 cm^2. The telescope subtends a laboratory angle of $\pm 1^\circ$ at 58° from the beam. Electronically the five counters are connected as a four-fold coincidence among the first four counters anti-coincided by the last counter : $1+2+3+4-5$.

The gamma-ray telescope is made of a Čerenkov counter with a lead glass radiator. A scintillation counter, connected in anti-coincidence, in front of the Čerenkov counter eliminates the charged particles contribution.

The energy resolution of the system is of ± 30 MeV of the laboratory energy of the incoming gamma ray. This energy resolution has been obtained, in spite of the angular aperture of the telescope, by shaping properly the copper absorbers between counter 1 and 2 and counter 4 and 5.

The experimental results are summarized in Fig. 1 and correspond to a 56° c.m.s. angle for the π^0 meson.

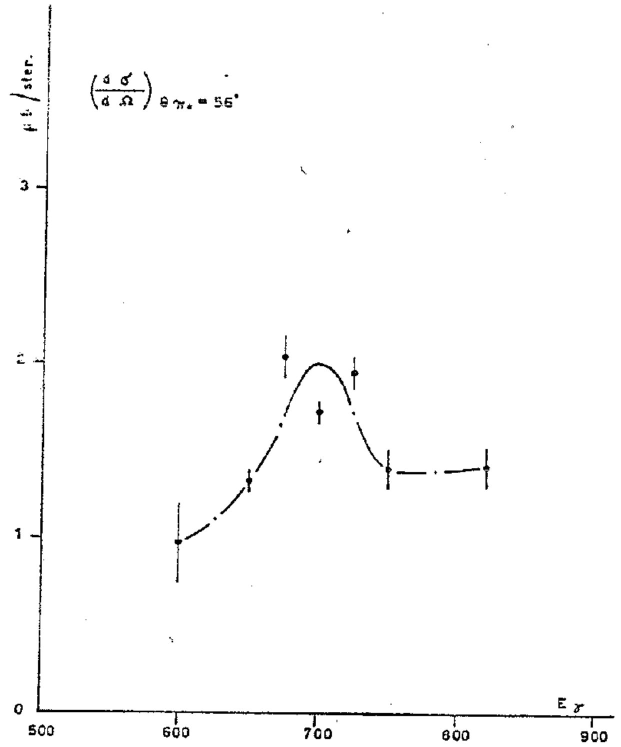


Fig. 1. Photoproduction cross section around the second resonance.

It is possible to see that the three points at 675, 700, 725 MeV laboratory energy for the gamma ray are higher than the others. The first conclusion that we draw is that the peak of the differential cross section at 56° c.m.s. angle is at a laboratory energy of about 700 MeV and that the width of the resonance is of the order of 50 MeV.

A complete analysis of the width and position of the second peak in the total cross section will be possible when we shall have completed our measurements for other c.m.s. angles.

We think now that there is some evidence, also from these preliminary data, that the resonance is quite narrow and centered at the same energy as the resonance for single π^+ meson photoproduction.

We think that the experimental results are not in contrast with the previous determinations of the differential cross section for single π^0 meson photoproduction. The present measurement has been made with a resolution, both in gamma ray energy and π^0 meson c.m.s. angle, two or three times better than previous measurements. A confirmation of this steep variation of the differential cross section with the energy, together with the already-known steep variation with the angle in some regions of the angular distribution should be measured again with the highest practical resolution.

Cortellessa and Reale have very recently taken the data at 90° c.m. The peak is less pronounced than at 56° c.m., still somewhat higher than from other authors, with a half-width of about 100 MeV. Measurements at more angles are in progress, stimulated by the more recent theoretical views [3].

SECT. 2 — THE POLARIZATION OF THE PROTON FROM THE PROCESS $\gamma+p \rightarrow p+\pi^0$ IN THE REGION OF THE HIGHER RESONANCES.

(By *R. Querzoli*, *G. Salvini*, of the Frascati Laboratories, *A. Silverman* of Cornell University).

1. We report in the present paper an experiment by counter technique to measure the polarization of the recoil proton in the neutral photoproduction at 500-900 MeV of the γ ray.

Generally speaking the interest in the polarization of the recoil proton comes from the following arguments, which hold as long as the process may be described in the general frame of quantum mechanics, with a transition matrix which is a sum of the contributing multipole transitions, each with a total angular momentum, a given parity, and a definite isotopic spin value :

(*a*) there is polarization of the recoil proton only when at least two different states are present.

(*b*) The polarization may indicate the relative parity of the states: in particular the polarization is absent for the proton emitted at 90° in the center-of-mass system, if the two states are present with the same parity.

From (*a*), (*b*) one deduces that the measurements of the polarization at 90° in the center-of-mass may contribute to find out those γ ray energies where only one state can describe the pion-nucleon system, and may contribute to determine the relative parity of the interfering states. The interest of the polarization has been recently underlined by Sakurai [4] as a method to establish the parity of the second resonance.

We have measured the polarization of the protons at 90° c.m. in order to get an information which is very useful to establish which multipole transition can describe the photo-production phenomena in the region 500-1000 MeV of the incident γ rays.

The polarization of the protons has been measured until now up to a maximum of 700 MeV by Stein [5].

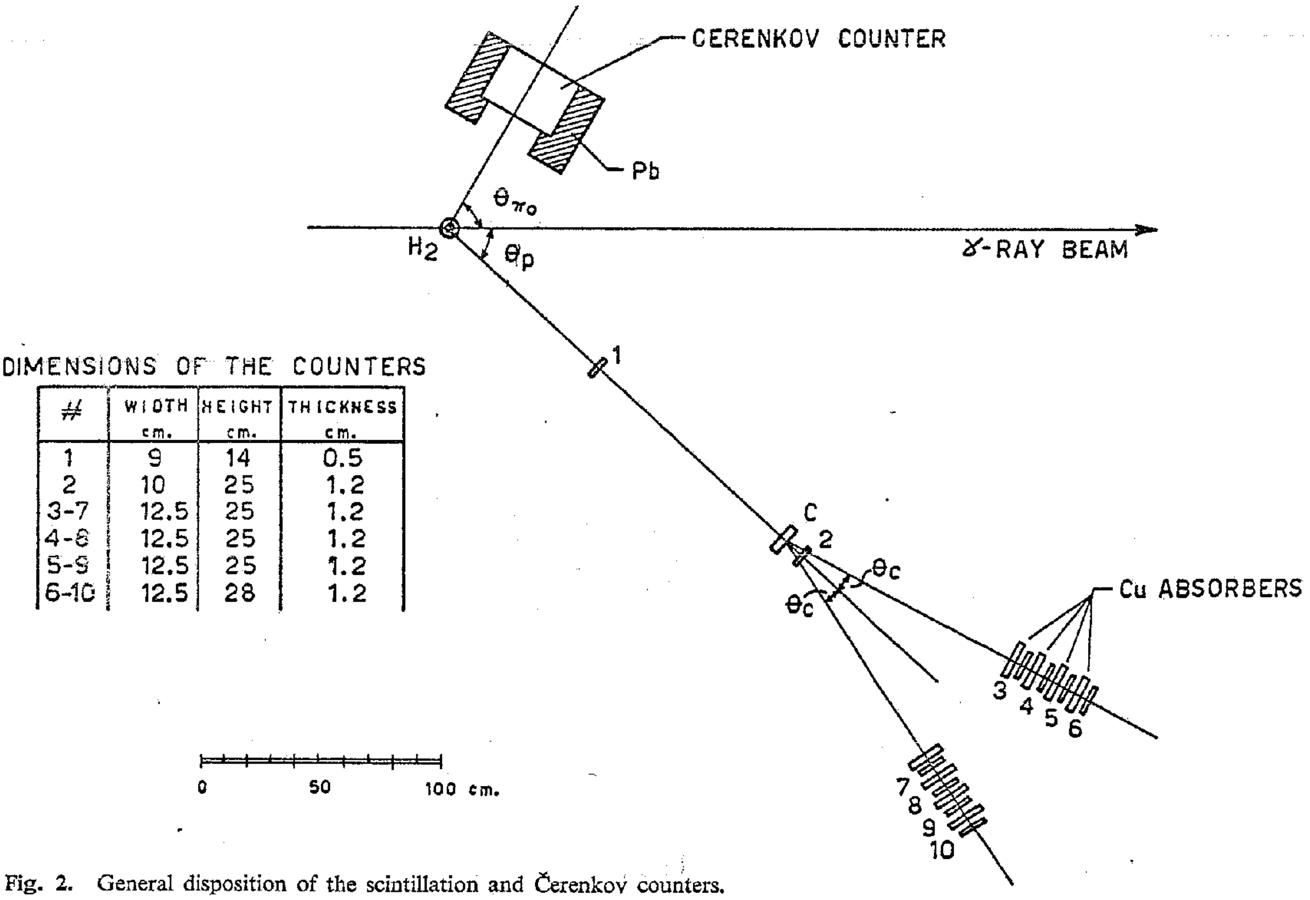
2. Experimental disposition

The aim of the present experiment is then the measurement of the polarization of the recoil protons from the reaction

$$\gamma + p \rightarrow p + \pi^0$$

To get the polarization we measure the left to right asymmetry in the scattering of protons from carbon at different angles between 14° and 16°.

The experimental disposition is given in Fig. 2. The counters 1, 2, ..., 10 are plastic scintillation



DIMENSIONS OF THE COUNTERS

#	WIDTH cm.	HEIGHT cm.	THICKNESS cm.
1	9	14	0.5
2	10	25	1.2
3-7	12.5	25	1.2
4-8	12.5	25	1.2
5-9	12.5	25	1.2
6-10	12.5	28	1.2

Fig. 2. General disposition of the scintillation and Čerenkov counters.

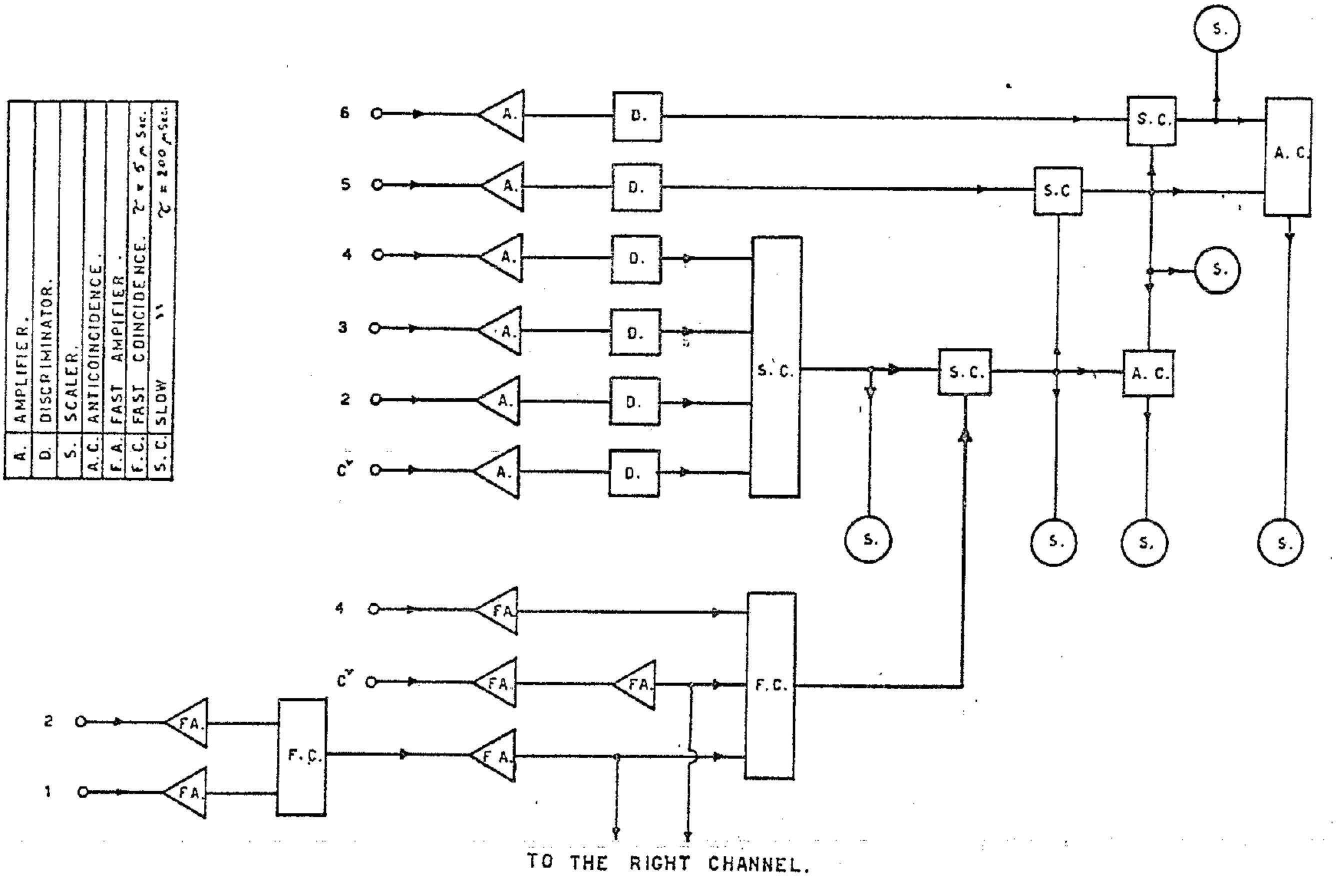


Fig. 3. Block diagram of the electronics for the left channel.

counters which detect the proton; the Čerenkov counter detects the π^0 meson through its decay rays. We indicate by C the carbon scatterer, whose thickness was changed according to the proton energy; Cu are the copper absorbers which define the range of the protons.

We were counting at the same time four kinds of coincidences:

$(\check{C}\text{er}, 1, 2, 3, 4, -5) = L_I$; $(\check{C}\text{er}, 1, 2, 3, 4, 5, -6) = L_{II}$;

$(\check{C}\text{er}, 1, 2, 7, 8, -9) = R_I$; $(\check{C}\text{er}, 1, 2, 7, 8, 9, -10) = R_{II}$

It is therefore possible to measure two different energy intervals of the protons, corresponding to two different energy intervals of the γ's.

Discrimination of the protons against the pions is guaranteed by the required coincidence with the Čerenkov counter as well as by pulse height discrimination in counters 2, 3, 7.

The block diagram of our electronics is given in Fig. 3.

All the measurements reported in this paper have been taken on the protons emitted at an angle of 42° in the laboratory system which corresponds to an angle close to 90° in the center-of-mass system for all our energies (see Table I).

The choice of the dimensions and the distances of the counters as well as the angle of scattering from the carbon is made on the basis of the measured elastic cross sections and analyzing power of protons in carbon. We define the analyzing power P_c in the usual way, as the asymmetry:

$$\varepsilon = \frac{\text{Left}-\text{Right}}{\text{Left}+\text{Right}} \tag{1}$$

for an incident beam of polarization + 1.

Table I. Experimental parameters and results.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
E_γ	E_m	ΔE_γ	θ_{pcm}	T	C(g/cm^2)	θ_c	#1	Left	Right	Left	Right	$R/L_{\rm unc}$	$-\varepsilon_{\rm unc}$	$-\varepsilon$
560	650	70	90.7±5.2	129−155	3.7	16.5°	yes	230	365	7.6±0.50	11.4±0.8	1.5±0.14	0.20±0.07	0.25±0.09
700	830	95	91.4±5.2	180−216	8.08	14°	no	194	398	16.9±1.4	32.4±2.5	1.92±0.22	0.33±0.07	0.42±0.10
							yes	124	251	19.0±1.7	38.4±2.4	2.02±0.22		
750	870	110	91.7±5.2	195−238	8.08	14°	no	161	284	18.8±1.5	29.4±2.1	1.69±0.19	0.26±0.09	0.30±0.12
800	930	118	92.2±5.2	214−258	8.08	14°	yes	216	392	10.7±1.1	20.0±1.0	1.87±0.21	.30±0.09	0.37±0.13
850	990	130	92.5±5.2	236−276	8.08	14°	no	139	234	7.6±0.8	12.9±1.0	1.7±0.22	.26±0.10	0.32±0.14

Table II. Experimental parameters and results

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
475	650	75	90.7±5.2	93−129	3.7	16.5°	yes	1368	1424	42.5±1.8	43.9±1.6	1.03±0.06	0±0.03	
610	830	84	90.9±5.2	144−180	8.08	14°	no	527	749	40.1±4.4	62.7±3	1.56±0.19	0.25±0.07	0.42±0.18
							yes	194	325	26.1±3.3	47.9±3.2	1.84±0.28		
650	870	90	91.1±5.2	162−195	8.08	14°	no	284	476	28.8±2.1	47.5±2.6	1.65±0.15	0.25±0.07	0.41±0.17
700	930	92	91.4±5.2	180−214	8.08	14°	yes	355	666	18.1±1.4	35.2±1.4	1.95±0.17	0.32±0.08	0.50±0.19
750	990	110	91.7±5.2	192−236	8.08	14°	no	478	754	26.0±1.5	40.0±1.7	1.52±0.11	0.21±0.05	0.31±0.1

Entries same as for Table I.

Columns meaning: **1**: Mean energy of the γ's; **2**: energy of the synchrotron; **3**: energy width; **4**: proton c.m. angle; **5**: kinetic energy of the proton; **6**: Carbon thickness; **7**: Carbon scattering angle; **8**: counter 1 present or not; **9-10**: total number of protons in the left (right) telescope (not yet corrected for accidentals and background); **11-12**: frequency of the left (right) telescope; **13**: ratio right to left; **14**: asymmetry $\varepsilon_{\rm unc}$; **15**: the same corrected for inelastic scattering. All energies are in MeV.

The choice of the scattering angle and of the dimensions of the hydrogen target and of the counters has to take into account the following features of the proton-carbon interactions [6] :

The elastic cross section is a steep function of the angle (increasing for smaller angles);

There is a definite maximum of the analyzing power at rather low values of the elastic cross section.

The Rutherford scattering has to be taken into account in the choice of the scattering angle.

The analyzing power of the carbon decreases with cos ϕ, ϕ being the angle between the photoproduction plane and the plane of scattering in the carbon.

The vertical dimensions of the counters are larger than the horizontal dimensions, but with the general conditions that cos $\phi \leq 0.8$.

In Table I, II, are reported the values of the elastic scattering angles θ_c we have chosen at different proton energies.

The hydrogen target is similar to the type already in use at Cornell University: the hydrogen container is a cylindrical vessel with a vertical axis. The diameter is 7.4 cm., and it is 8.7 cm. high. The wall is a foil of stainless steel plus mylar, with a total thickness per wall of 22 mg/cm^2. The vessel is contained in a cylindrical stainless steel vacuum chamber.

In Fig. 4 we can give as an example the kinematical situation of our measurements. The rectangles are determined by the thickness of the copper absorbers we have chosen and by the dimensions of the counters.

The proton flux on the carbon scatterer may differ from point to point: to correct this, we have measured the differential flux of the protons at each energy, as a function of the angle of emission.

The Čerenkov counter is made with a lead glass cylinder 18 cm thick and with a diameter of 35 cm. Light is collected by three photomultipliers in parallel, type 6364, which are in direct contact with the glass.

Counter 1 has been added in order to avoid the possibility that a neutron coming from a charged pion photoproduction may arrive at the carbon, produce a proton in a quasi-elastic collision, and be detected as a scattered proton in our coincidences.

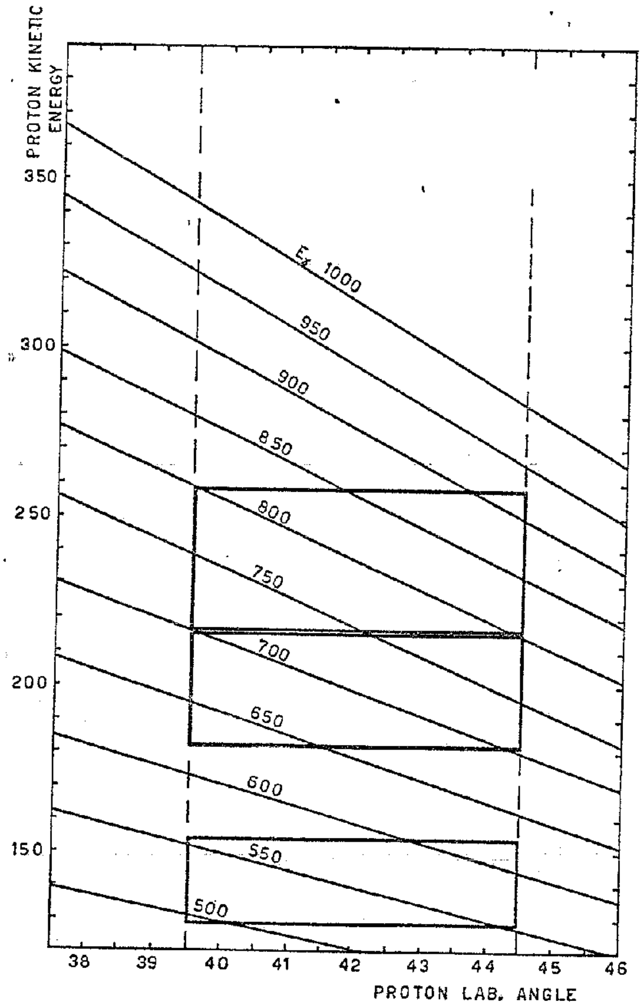


Fig. 4 Proton kinematics in the process $\gamma+p\rightarrow p+\pi^0$ and positions of the observed " points " at 560,700,800 Mev.

The discussion of the results have confirmed to us that the presence of counter number 1 was not strictly necessary.

We have therefore included in our results some measurements which were taken without counter 1 in position.

3. Measurements and controls

The measurements for each γ ray energy were taken in the following order. First, one of the two telescopes (for instance that at the right) is aligned with the hydrogen target and with counter number 1, and the thresholds of the discriminators of counters 4, 5, 6 are fixed to a level corresponding to an energy loss of at least 3 MeV in the scintillator. Second, on the basis of a photographic analysis of the height of the pulses, the levels of the discriminators of counters 1, 2, 3 are fixed, so that they certainly count the protons and only a very small per cent of the pions. The further discrimination against the pions is made by the Čerenkov counter.

Third, the threshold of the Čerenkov counter is fixed to a value that makes the counting rate quite independent of its voltage.

Similar preliminary measurements are made on the telescope at the left, and by alternatively aligning the right and the left telescope we verify that the counting rate is the same within statistics (usually within 4%).

After these controls have been made the two telescopes are finally set at the chosen scattering angle and the measurements start. Measurements with and without liquid hydrogen in the target, and with delays on the Čerenkov counter, on the counters 1 and 2, on the counters 4 and 8 are taken in order to measure accidentals. Every three to four hours each telescope is aligned to check that the counting rates are equal.

One of the main difficulties in our measurements is due to the fast dependence of the proton-carbon elastic cross section on the angle: as a consequence any local difference in efficiency of our large counters may give rise to an apparent asymmetry. To be safe from this effect some further controls were made:

(a) Measurements have been taken of the protons scattered from the carbon at different angles between 0° and 16°, to the left and to the right, at energies for which the proton flux arriving to the carbon was rather uniform.

(b) Measurements have been made with the carbon substituted by an equivalent amount of lead, and placing the telescopes at angles of four to six degrees. Considering the large contribution of Rutherford scattering and the lower analysing power of the lead, we should expect equal counting for the two telescopes. The good results of these control measurements strongly contribute to increase our confidence in our results.

4. Results

Our results are reported in Tables I, II. Table I refers to the high energy channels R_I and L_I, and Table II reports the results from the low energy channels R_{II} and L_{II}. E_γ is the average energy of the photons producing the protons; E_m is the maximum energy of the γ ray spectrum; ΔE_γ is the energy interval of the photons which contains 75% of the counted protons. θ_{pcm} is the average angle of the emitted protons in the center of mass.

T is the energy interval of the protons; C is the thickness of the scattering carbon; θ_c is the average scattering angle of the protons in carbon. Column 8 specifies if counter one is in position or not. Columns 9 and 10 give the total number of protons scattered to the left and to the right, not yet corrected for accidentals and background. Columns 11 and 12 give the intensity of the protons scattered to the right and to the left respectively, per 10^{13} equivalent quanta, corrected for accidentals and background. In column 13 the ratio is given between the right and the left intensity, and in column 14 the asymmetry is given, defined as:

$$\varepsilon_{\text{unc}} = \left[\frac{L-R}{L+R}\right]_{\text{unc}}$$

The results of columns 11, 12, 13, 14 are already corrected for empty hydrogen target and for accidentals, but they have not been corrected yet for the contribution of the inelastic collisions. This contribution is calculated in 5. When the contribution of the inelastic events is subtracted, we finally obtain the correct value ε of the asymmetry. This value is given in column 15.

During the measurements the average intensity of our collimated γ ray beam was of the order of 2.5×10^{11} equivalent quanta per minute.

5. Analysis of the data—corrections

In order to get the value of the polarization P from the measured left to right asymmetry, one must introduce a number of corrections. We give a list of those we took into consideration. The correction *(e)* is the most important of the group.

- *(a)* Empty target corrections and accidentals.
- *(b)* Unwanted detection of processes other than the single neutral pion photoproduction.
- *(c)* Interactions of the recoil protons in the copper absorbers.
- *(d)* Different proton flux at different points in the carbon, that is, in different points in counter number 2.
- *(e)* Inelastic collisions of the protons on carbon. The protons emitted in the photoproduction process which initially have an energy higher than the energy defined in the two channels of our telescopes, may undergo in the carbon an inelastic collision which reduces their energy, and may therefore enter one of the two proton channels. The left to right asymmetry of the protons in these inelastic collisions is definitely smaller than in the elastic ones : as a consequence the inelastic processes, if not subtracted, have a tendency to reduce the total analyzing power of the carbon.

The method we used to estimate the corrections, when we decided we had to take them into account, is fully explained elsewhere.[7)]

In Tables I, II, column 15, the values of ε, the asymmetry corrected for the spurious effects we mentioned above, is given for each channel. In Table III and in Fig. 5 we added together the asymmetries resulting from the first as well as from the second channel.

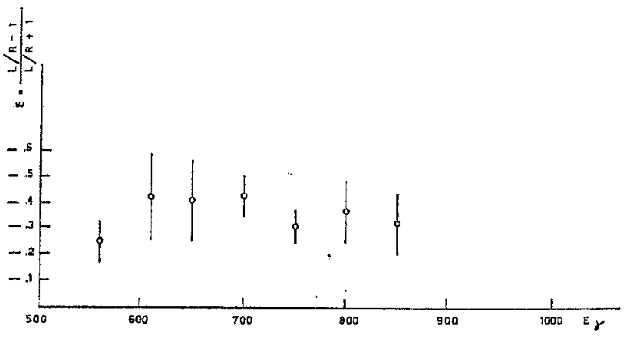


Fig. 5. The asymmetry ε versus the energy of the photons.

6. The computation of the polarization p from the corrected asymmetry. The Monte Carlo method.

Let's call $P_c(\alpha)$ the analysing power of the carbon at the angle α, that is the asymmetry $\varepsilon = \frac{L-R}{L+R}$ for an incident proton beam of polarization$+1$. Let us call P the polarization of the recoil protons we are measuring. As well known, the relation holds :

$$\varepsilon = P_c(\alpha)P \tag{2}$$

Relation (2) is exactly valid at a definite angle α. In an extended telescope a range of angles α is involved and the value of P_c is an average obtained from a proper integration on all possible angles α. To get the average analyzing power of our telescope we made a proper integration on all possible angles α subtended by our telescopes. The integration has been performed by the Monte Carlo method using the Finac electronic computer of the Istituto Nazionale del Calcolo.

7. The sign and the value of the polarization

We have found a Right/Left ratio larger than one in all our measurements, and we made our measurements at the right of the γ ray beam (see Fig. 2). The intensity of the protons scattered from the carbon is therefore lower at the telescope which is closer to the γ ray beam. By knowing the analyzing power of the carbon, we can say that most of our protons emitted from the hydrogen target have the spin down. If we define the sign of the polarization by the vector (**n**) as we show in formula (3), then the sign of our polarization is negative.

In Table III we give the results on the polarization : The energy of the γ ray beam is given in column (1); the asymmetry ε as resulting from the Monte Carlo method when the incident protons have polarization $P = -1$ is given in column (2); the same for $P = 0$ in column (3); column (4) reports the experimental value we found for the asymmetry (which is negative according to our definition), and finally we give in column (5) the value we found for the polarization of the recoil protons.

Table III. The asymmetry to be expected according to the Monte Carlo method for $P = -1$ and for $P = 0$, the experimental value of ε (col. 4) and the corresponding value of the polarization of the recoil proton (col. 5)

1	2	3	4	5
E(MeV)	ε_c ($P = -1$)	ε_c ($P = 0$)	ε	P
560	0.64	0.01	-0.25 ± 0.09	-0.4 ± 0.14
610			-0.42 ± 0.18	-0.63 ± 0.23
650	0.69	0	-0.41 ± 0.17	-0.6 ± 0.25
700			-0.43 ± 0.09	-0.57 ± 0.12
750	0.82	0	-0.31 ± 0.07	-0.38 ± 0.09
800			-0.37 ± 0.13	-0.5 ± 0.17
850	0.68	-0.04	-0.32 ± 0.14	-0.5 ± 0.22

The value of the polarization P as a function of the γ ray energy is also given in Fig. 6.

We remark that our results at 700 MeV and 550 MeV are in agreement with the results of Stein.

SECT. 3 — A BUBBLE CHAMBER EXPERIMENT TO MEASURE THE POLARIZATION OF THE RECOIL PROTON IN THE PHOTOPRODUCTION OF π^0 MESONS.

(By *L. Bertanza, P. Franzini, I. Mannelli, G. V. Silvestrini* of the University of Pisa and *V. Z. Peterson*, California Institute of Technology).

An experiment is in progress at the Frascati electron-synchrotron to measure the polarization of the recoil proton in photoproduction using a propane-ethane bubble chamber and magnetic selection. The use of a visual method makes it possible to observe each scatter, which reduces the chances for systematic errors due to uneven illumination of the scatterer and the finite size of both the target and the scatterer. In addition an examination of the complete angular distribution of single scattering events enables one to evaluate, within the data of this experiment, the contribution of inelastic scatters to the sample selected for the measurement of the polarization.

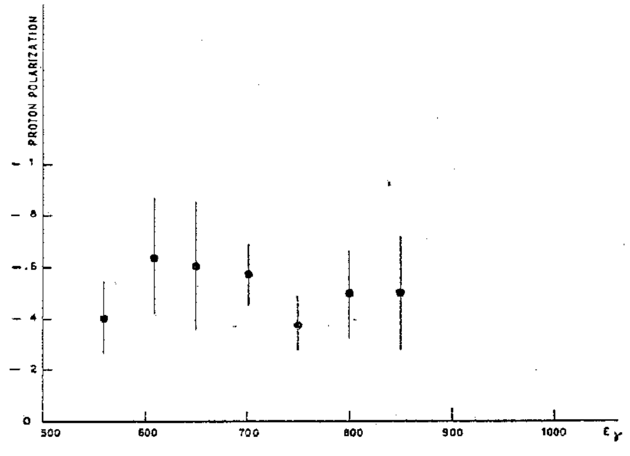


Fig. 6. The polarization P of the recoil proton at 90° c.m.

A strong focusing magnet selects protons at angle of 43°±4° (k = 700 MeV) or 51.4°±4° (k = 900 MeV) from a liquid hydrogen target and focuses them upon the window of the bubble chamber. The magnetic field is greater for wider angle protons entering the magnet; this tends to eliminate the spread in the incident photon energy due to the finite size of the target.

An advantage of the magnetic selection is that only protons in the momentum-angle interval of interest fall upon the scatterer; thus higher energy protons which could produce inelastic and elastic "background" scatters are excluded.

A counter telescope selects only protons which will enter the thin window of the bubble chamber, and the coincidence triggers the flash for the chamber. The bubble chamber (volume, approx. 1.5 liters) is expanded 4 times/sec (every 5th synchrotron pulse) in synchronism with the accelerator. With normal beam intensity 10^{11} Q/min there are 12 photographs/minute for k = 700 MeV and about 6 for k = 900 MeV. The bubble chamber contains approximately equal parts by weight of ethane gas disolved in propane, and operates at room temperature with tap-water cooling.

We have not used a Čerenkov counter to detect the π^0 in coincidence with the proton because of the reduction in counting rate this would entail. The range curves show that our proton telescope selects protons (2.2 minimum or above) with less than 5% charged pion or electron contamination. In addition we can be sure we have a proton by the chamber photographs. Hence we have accepted a 20% background, and subtract its effect statistically.

We report here initial results for one point, for which the mean photon energy k is 725 MeV and the center of mass angle β is 87°.

The 725 MeV Point

At the lab. angle of 43° the resulting proton has a kinetic energy of 190 MeV.

Range measurements were made by inserting copper absorbers between counters $C-2$ and $C-3$, to determine the actual mean proton energy and energy spread from the full aperture, and from the two half apertures 39°-43° (" I ") and 43°-47° (" O ") separately.

It was found that the illumination of the full aperture was not uniform; with weighting factor considered, the experiment accepts a mean photon energy of 725 MeV with a photon energy spread of about ±100 MeV.

For this point we have analysed about 23,000 single view photos containing 15,200 incident protons. Each proton has an average useful path length in the chamber of 12 cm. In this sample we see 474 single scatters without visible recoil or associated prong, 153 $p-p$ scatters in which the recoil prong is visible, and 102 stars (mostly 2-prong). The 474 single scatters include events up to 90° projected angle of scatter, and the known angular distribution of elastic and inelastic scattering in this proton energy range makes it clear that essentially all events beyond 30° are inelastic scatters from carbon. A few of the events at small angles are $p-p$ scatters in which we cannot see the recoil proton (less than two millimeters projected range). In Table IV the comparison between predicted yields and that observed by us is shown.

Table IV. Predicted and observed number of scatters as a function of scattering angle.

Projected angle	Predicted				Observed
	Elastic	Inelastic	p-p	Total	
6°-12°	95	19	14	128	165
12°-20°	40	60	2	102	118
20°-30°	11	59	0	64	63
30°-40°	2	32	0	34	40
40°-60°	1	39	0	40	39

The $p-p$ events are the ones with non-visible recoils; the predicted total of 16 events agrees with the missing number in an angular distribution plot of the 153 visible events.

The inelastic events in Table IV do not include stars; the inelastic prediction includes only excitation energy 10-50 MeV; however, this is not very important since the shape of the angular distribution is practically constant over the energy range.

It is necessary to make substantial corrections to the 283 scatters (173 Left, 110 R) in the 6°-20° interval in order to obtain the polarization. A small asymmetry applies to the $p-p$ scattering, and to a few of the inelastic scatters; the result is that we subtract 9L and 7R $p-p$ scatters, and 42L and 37R inelastic scatters. The 20% background (which we have measured to be symmetric) is then subtracted from the remaining 188 elastic events, yielding carbon elastic scatters of L/R = 103/47 = 2.29±0.43. This results in a preliminary value of the polarization:

$$P = 0.83 \pm 0.28 \text{ (in the direction } \mathbf{k}\times\mathbf{P}_{\text{proton}}\text{)}.$$

SECT. 4 — DISCUSSION OF THE RESULTS

The more interesting feature of our results (the following considerations mainly rest on the results of section 2), is that the polarization remains rather high from 550 to 850 MeV, as if at each energy two or more interfering states, with a resulting polarization of negative sign, were present.. In particular no clear minimum of the polarization appears around 700 MeV.

We must therefore look for those states which can describe the already known results of the differential cross sections, and which can produce a polarization of negative sign and rather constant in our range of energies.

(a) Assignment of the levels.

In the hypothesis that the three states A, B, C and only those are present, the expression of the polarization at 90° becomes (we follow the notations and the results explicitly given by Peierls) of the type:

$$P(\theta) = \frac{1}{d\sigma/d\Omega}\left\{-4AB\sin(\delta_A-\delta_B) - 2\sqrt{3}BC\sin(\delta_B-\delta_C)\right\}(\sin\theta)\mathbf{n}$$

$$\mathbf{n} \equiv \frac{(\mathbf{k}\times\mathbf{q})}{|\mathbf{k}\times\mathbf{q}|};\ \mathbf{k},\mathbf{q} = \text{photon and pion momenta.} \qquad (3)$$

The interference term AC is not present, for it goes with $\cos\theta$ and is zero at 90°.

In the simplest hypothesis that the polarization is due to the term AB below 700 MeV (the maximum of the second resonance) and to the term BC at energies beyond the second resonance, we are brought to conclude that B has opposite parity to both A and C. We can therefore construct Table V:

Table V. Quantum number assignments for the states A, B, and C. J is the total angular momentum of the state indicated in column 1; T is the isotopic spin; l is the multipole order. These quantities have been evaluated [1] from the pion photoproduction cross sections. Column 5 gives the parity of the states, as indicated by our measurements of the polarization; column 6 gives the multipole transition we consider responsible for the resonance.

(1) state	(2) J	(3) T	(4) l	(5) parity	(6)
A	$^3/_2$	$^3/_2$	1	+	$M_1\,^3/_2$
B	$^3/_2$	$^1/_2$	1	−	$E_1\,^3/_2$
C	$^5/_2$	$^1/_2$	2	+	$E_2\,^5/_2$

The conclusion that B is an $E_1 D^{3/2}$ state agrees with the experimental results of Stein, and also with the recent theoretical considerations of Pellegrini and Stoppini.

Furthermore, Maloy from the California Institute recently concluded that the interference of a possible $E_1(^1/_2)$ state with the $M_1(^3/_2, ^1/_2)$ state which had been proposed by Wilson cannot give the rather high polarization we found.

(b) Amplitudes of the levels at different energies.

It is reasonable to assume [1] that the amplitude of C is negligible below 700 MeV. In fact there is no evidence of any appreciable amount of the term $\cos^4\theta$ in the angular distributions below 800 MeV; this implies that at least at 700 MeV $C^2 \ll A^2+B^2$.

In this case the high polarization we observe at 700 MeV must be due to the interference AB: that is, the amplitude A of the first resonance extends beyond 700 MeV. When the energy increases the contribution of the AB interference decreases, but at the same time the interference BC comes out, and this can explain our experimental result that the polarization remains rather constant up to 850 MeV. Our statistical uncertainties do not allow us to establish if there is a real minimum around 750 MeV.

Taking as a working hypothesis these assignments for A, B, C and assuming for these states the amplitudes we have now suggested, we tried to calculate the corresponding polarization, and we found results in agreement with our experimental values.

While we believe the qualitative indications that we derived from our results, we did not consider it fruitful to try to get precise quantitative results, because of the present large statistical errors in the measurements of the polarization and of the cross section. It may be interesting also to examine the function $P(\theta)$ at other angles than $\theta = 90°$ of the recoil proton.

In conclusion, our results agree with the hypothesis that:

(1) The three states A, B, C corresponding to the first, second, third resonance are sufficient to explain the single π^0 photoproduction in the range of energies 500-900 MeV.

(2) The three states A, B, C have multipole order M, total angular momentum J, parity and isotopic spin as assigned in Table V.

(3) The resonance A extends its amplitude rather beyond 700 MeV (for instance up to 800 MeV).

(4) The resonance C has an amplitude of the same order as B, and starts to be important from 750 MeV up.

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