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Total Cross-Sections of $\pi^+\pi^-$ and $\pi^-\pi^0$ Photoproduction on Neutron in Deuterium Bubble Chamber up to 900 MeV.

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1. – Introduction.

We report here the preliminary results of an experimental investigation of the reactions $\gamma+d\to p+p+\pi^-+\pi^0$ and $\gamma+d\to p+n+\pi^++\pi^-$ carried out by means of a deuterium bubble chamber exposed to the 1 GeV bremsstrahlung beam of the Frascati electron-synchrotron.

Using the spectator nucleon model, the cross-sections for the reactions

(a) $$\gamma+n\to p+\pi^-+\pi^0\,,$$

(b) $$\gamma+n\to n+\pi^++\pi^-\,,$$

(c) $$\gamma+p\to p+\pi^++\pi^-\,,$$

were obtained.

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Up to now there have been no experimental data available for reactions (a) and (b), so that knowledge of the double photoproduction process at low energies is limited essentially to the main features of the reaction $\gamma+p\to p+\pi^++\pi^-$, leaving some unresolved ambiguities in the interpretation of the results.

In this paper the analysis procedure is described and the total cross-sections are given. More detailed features of the reactions considered will be reported when the full statistics of this experiment are available.

2. – Data reduction.

The data presented here are the result of the analysis of 250 000 pictures out of a total of 500 000 pictures obtained by exposing the CERN 30 HBC to a 1 GeV hardened bremsstrahlung beam. The incident photon flux and its spectrum were obtained by means of e^+e^--pair observation in the chamber, as described in a previous paper [1].

The film was scanned for two- and three-pronged events and the measurements were performed on standard digitized projectors. 9946 events were found in the fiducial volume and subdivided between the possible reactions as shown in Table I.

TABLE I. – *Number of events for the various reactions.* p_s and n_s indicate the spectator nucleon (lower-momentum nucleon).

Reaction	No. of events
(1) $\gamma+d\to p+\pi^-+\pi^0+p_s$	546
(2) $\to n+\pi^++\pi^-+p_s$	916
(3) $\to p+\pi^++\pi^-+n_s$	845
(4) $\to d+\pi^++\pi^-$	103
(5) $\to p+\pi^-+p_s$	7469
(6) ambiguous	67

The single-photoproduction reaction (5) as well as the coherent reaction (4) will be subject of separate papers. The contribution of three-pion ($\pi^+\pi^-\pi^0$ and $\pi^-\pi^0\pi^0$) photoproduction is assumed to be negligible. All the events were processed with the standard THRESH-GRIND program chain. It must be noted that the reactions under study, (1), (2) and (3), since they have a neutral particle in the final state, are kinematically determined but do not allow a fitting procedure (0-*C*), so that some care had to be taken in order to check the reliability of the measurements and calculations. The spectator nucleon was assumed to be the one with the lower momentum. With this criterion, the events were assigned to reactions (2) or (3), after being checked for the ionization of the positive track (π^+ or p). The results of a Monte Carlo calculation assured us that the probability of exchange of the role of the nucleons is completely negligible. Since the protons with the momentum lower than 80 MeV/c are not detected in the

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(1) S. DE SCHRYVER, L. FIORE, S. FOCARDI, G. GIALANELLA, V. ROSSI, B. STELLA and G. SUSINNO: Frascati Report LNF 68/21 (1968); G. GIALANELLA, A. PIAZZA, G. SUSINNO, L. FIORE and G. C. MANTOVANI: *Nuovo Cimento*, **63** A, 892 (1969).

chamber, in calculating the kinematics of the reactions (1) and (2), the unseen spectator protons are assumed to have zero momentum and this fact could induce some distortions in the kinematics. This does not happen for reaction (3).

In many cases the events of single pion photoproduction (reaction (5)) were kinematically compatible with the reaction (1) (an additional π^0), and the difference in the calculated ionization of the tracks was not sufficient to distinguish between the two reactions. This notwithstanding, it was possible to decide the assignment for almost all the events on the basis of the χ^2 distribution obtained by measuring each event 6 times. 1803 out of 1954 ambiguous events were assigned to the reaction (5), 84 to the reaction (1) and the other 67 events were left ambiguous.

In order to obtain a qualitative check of the reliability of the measurements and kinematical calculations of the 0-*C* reactions we have made the following test. We have selected those events of the reaction (3) having the momentum of the spectator neutron, $p(n_s)$, lower than 80 MeV/c and we have calculated them again, imposing on $p(n_s)$ the condition $p_x = p_y = p_z = 0$, $\Delta p_x = \Delta p_y = 30$ MeV/c, $\Delta p_z = 41$ MeV/c (*i.e.* the standard value for an unseen spectator proton). In such a way a 3-*C* fit was possible.

Moreover, in the same sample, the visible proton was omitted (as if it was a neutron) and the events were calculated again with no constraints (0-*C*), thereby obtaining a sample of events completely comparable with those of the reaction (2).

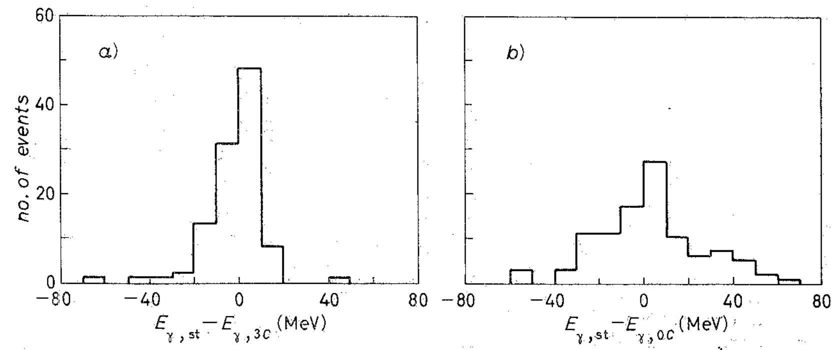

Fig. 1. – Difference between the incident photon energies for events $\gamma + d \to p + \pi^+ + \pi^- + n_s$ ($n_s < 80$ MeV/c) calculated (see text) in the standard way (0-*C*), and *a*) 3-*C* fit ($n_s = 0 \pm \Delta p$), and *b*) 0-*C* simulating reaction (2) ($n_s = 0$, proton unmeasured).

In Fig. 1 the difference between the incident photon energies calculated in the three mentioned ways (standard 0-*C*, 3-*C* fit, 0-*C* simulating reaction (2)) for the events of the reaction (3) is plotted. When one considers that these distributions are centered on the 0-value, that they are symmetric in shape and that their width is of the same order as our experimental resolution ((30÷40) MeV), one can conclude that it is quite reasonable to consider reliable our results, even if calculated without fitting.

We assume that the events with the spectator nucleon momentum lower than 250 MeV/c satisfy the impulse approximation. This assumption is supported by the comparison of the experimental momentum distribution of the spectator nucleon with the distribution in the deuterium nucleus, calculated using the Hulthén wave function. Consequently an upper limit of 250 MeV/c was placed on the spectator nucleon momen-

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([2]) D. H. WHITE, R. M. SCHECTMAN and B. M. CHASAN: *Phys. Rev.*, **120**, 614 (1960).

tum to deduce the cross-sections. A detailed discussion on the validity of the impulse approximation in the photoproduction processes will be reported elsewhere. The total cross-sections for the reactions (a), (b) and (c) are plotted *vs.* E^{*2}, that is the squared invariant mass of the $\pi\pi\mathcal{N}$ system.

From the measured spectrum, we calculated the actual photodistribution as a function of E^{*2} by means of a Monte Carlo computation which, taking into account the momentum distribution of the spectator ($\mathcal{N}_s$), simulates the reaction $\gamma+d\to\mathcal{N}_s+\mathcal{N}\pi\pi$. By so doing, even the correction for kinematical inaccessibility, as discussed in ref. (2), is automatically taken into account.

3. – Results.

The total cross-sections for the reactions (a), (b) and (c) as a function of E^{*2} are shown in Fig. 2, 3 and 4, and are reported in Table II. For ease of comparison with the cross-sections on free proton, the energy scale is also given in terms of equivalent incident photon energy (E_γ).

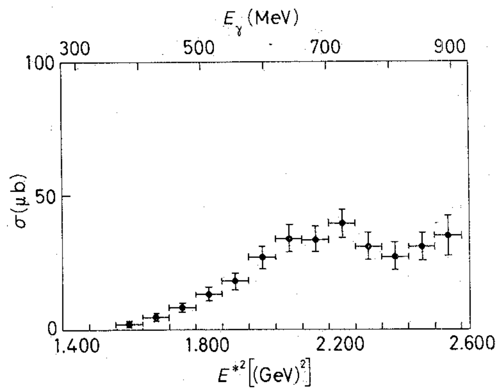

Fig. 2. – Total cross-section of the reaction $\gamma+n\to p+\pi^-+\pi^0$ *vs.* the squared invariant mass of the $\pi\pi\mathcal{N}$ system.

The quoted errors include the statistical error of the events and of the sample of e^+e^- pairs used to determine the photon spectrum. A possible systematic error (of the order of 5%) on the photon flux is not included.

All corrections (scanning efficiency, geometrical losses, $p_s < 250$ MeV/c cut, etc.), but those connected with the use of the deuterium as a target, are included.

The comparison between the cross-sections of reaction (c) in hydrogen and deuterium could enable one to estimate

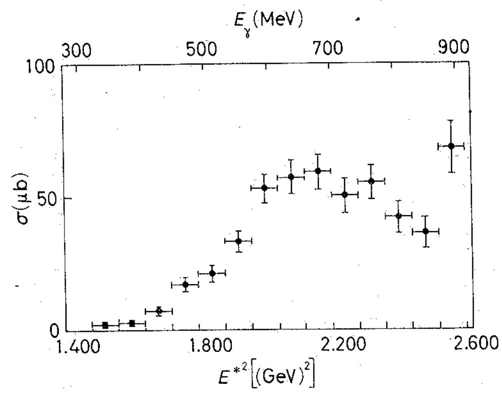

Fig. 3. – Total cross-section of the reaction $\gamma+n\to n+\pi^++\pi^-$ *vs.* the squared invariant mass of the $\pi\pi\mathcal{N}$ system.

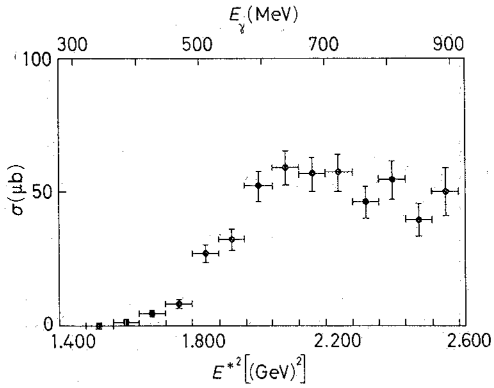

Fig. 4. – Total cross-section of the reaction $\gamma+p\to p+\pi^++\pi^-$ *vs.* the squared invariant mass of the $\pi\pi\mathcal{N}$ system.

TABLE II. – *Total cross-sections of the double-photoproduction reactions between the threshold and* 0.9 GeV.

E^{*2} ((GeV)^2)	E_γ (MeV)	$\sigma(\gamma n, p\pi^-\pi^0)$ (μb)	$\sigma(\gamma n, n\pi^+\pi^-)$ (μb)	$\sigma(\gamma p, p\pi^+\pi^-)$ (μb)
1.480 ÷ 1.560	340		2.09 ± 0.66	0.20 ± 0.20
1.560 ÷ 1.640	382	2.02 ± 0.71	2.27 ± 0.76	1.23 ± 0.55
1.640 ÷ 1.720	425	4.06 ± 1.12	6.79 ± 1.45	4.53 ± 1.17
1.720 ÷ 1.800	468	8.39 ± 1.75	16.97 ± 2.45	8.31 ± 1.70
1.800 ÷ 1.880	510	13.37 ± 2.44	21.40 ± 3.06	26.84 ± 3.35
1.880 ÷ 1.960	553	18.59 ± 3.10	32.72 ± 4.09	32.25 ± 4.00
1.960 ÷ 2.040	595	27.19 ± 4.01	52.71 ± 5.58	52.24 ± 5.48
2.040 ÷ 2.120	638	33.80 ± 5.04	57.08 ± 6.55	58.76 ± 6.61
2.120 ÷ 2.200	681	33.59 ± 5.12	59.37 ± 6.81	56.48 ± 6.61
2.200 ÷ 2.280	723	39.37 ± 5.68	50.03 ± 6.41	56.86 ± 6.80
2.280 ÷ 2.360	766	33.11 ± 5.05	54.84 ± 6.70	45.84 ± 6.13
2.360 ÷ 2.440	808	27.65 ± 4.97	42.40 ± 6.12	54.41 ± 6.97
2.440 ÷ 2.520	851	30.91 ± 5.55	36.18 ± 5.95	39.50 ± 6.24
2.520 ÷ 2.600	894	34.97 ± 7.46	67.90 ± 10.24	49.87 ± 8.82

the corrections due to the deuterium effect. A nearly constant difference of the cross-section values with respect to that measured in hydrogen can be observed. However in the limit of the present statistics, we do not try to interpret this effect.

As far as reactions (b) and (c) are concerned, the total cross-sections are equal within their errors, while for reactions (a) and (b) we observe a difference in the threshold behaviour as well as in the values of cross-sections. The experimental data on the double-photoproduction processes available up to now concern the reactions $\gamma+p\to p+\pi^++\pi^-$ and $\gamma+p\to n+\pi^++\pi^0$, for which the ratio $\sigma(p\pi^+\pi^-)/\sigma(n\pi^+\pi^0)\simeq 1$ was found [3]. This result contradicts the isobar excitation model [1,4], which assumes a $T=\frac{1}{2}$ intermediate state decaying into $\Delta+\pi$. This isobar model provides a value of 2.5 for the above ratio.

Apart from any consideration on the validity of this model for the reactions on neutrons, which will be analysed as soon as improved statistics are available, our experimental ratio $\sigma(n\pi^+\pi^-)/\sigma(p\pi^-\pi^0)$ is consistent with the isobar model.

4. – Conclusions.

We have reported the first direct measurement of the total cross-section for the reactions $\gamma+n\to p+\pi^-+\pi^0$ and $\gamma+n\to n+\pi^++\pi^-$. The different behaviour of the cross-sections as a function of the photon energy does not contradict the hypothesis

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(3) M. BLOCH and M. SANDS: *Phys. Rev.*, **108**, 1101 (1967); **113**, 305 (1959); R. M. FRIEDMAN and K. M. CROWE: *Phys. Rev.*, **105**, 1369 (1957); A. KUSUMEGI, Y. KOBAYASHI, Y. MURATA, H. SASAKI, K. TAKAMATSU and A. MASAIKE: *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies*, vol. **2** (Hamburg, 1965), p. 253; S. COSTA, S. FERRONI, V. G. GRACCO, E. SILVA and C. SCHAERF: *Nuovo Cimento*, **45 A**, 696 (1966).

(4) CAMBRIDGE BUBBLE CHAMBER GROUP: *Phys. Rev.*, **163**, 1510 (1967).

of the formation of an intermediate isobar state with $T = \frac{1}{2}$, which was wuggested to interpret the data of double charged-pion photoproduction processes.

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