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1. - INTRODUCTION. -

In the last years a big experimental effort has been undertaken in order to investigate the reaction

$$\gamma + n \longrightarrow p + \pi^- \tag{1}$$

and the inverse one with the main purpose of testing the $|\Delta I| \leq 1$ rule and the T-invariance of the electromagnetic interaction of hadrons.

The need for new data was in part due to some discrepancies in the results obtained with different or, sometimes, with similar techniques and has been supported by the parallel encouraging work of many theoreticians.

As it is well known; testing the $|\Delta I| \leq 1$ rule is, in principle, quite simple in the framework of the model due to Sanda and Shaw(1), which

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foresees a dip in the distribution of the quantity $\Delta = (k/q)[\sigma(\gamma n \to p\pi^-) - \sigma(\gamma p \to n\pi^+)]$ vs. E_γ if an isotensor contribution is present in the photoproduction amplitude.

Furthermore, the comparison of the differential cross-sections of reaction (1) with those of the inverse one, via detailed balance, in the first resonance region could be a sensitive test of T-invariance$^{(2)}$.

Many results on reaction (1) have been recently obtained both by direct measurements (with bubble chambers$^{(3,4)}$ and counters$^{(5)}$) and, indirectly, by measuring with electronic techniques the π^-/π^+ ratio on deuteron$^{(6,7)}$.

The direct measurements give the cross-section of the reaction

$$\gamma + D \to p + p + \pi^- . \tag{2}$$

To obtain the cross-section of the process (1), several effects (off-mass shell neutron, Fermi motion, Pauli principle, final state interaction), due to the use of deuteron as a target, should be taken into account.

From a theoretical point of view, the most suitable procedure is the Chew-Low extrapolation to the neutron pole$^{(8)}$; unfortunately this procedure, to give reliable results, requires very high statistics and careful measurements expecially at low momenta of the slower proton, which, for values less than about 100 MeV/c, cannot be directly measured even with bubble chambers.

Two alternative methods used to extract the photoproduction cross-section on neutron from direct measurements on deuteron are the impulse approximation with closure$^{(9)}$ and the so-called nucleon spectator model$^{(10)}$.

Both these methods have intrinsic limits$^{(11)}$; the main difference between them is that the closure takes into account, although in a model-dependent way, the effects of the Pauli principle and, implicitly, the p-p final state interactions.

The indirect measurements of the cross-section of reaction (1) are based on the assumption that

$$\frac{d\sigma/d\Omega\,(\gamma n \to p\pi^-)}{d\sigma/d\Omega\,(\gamma p \to n\pi^+)} = \frac{d\sigma/d\Omega\,(\gamma D \to pp\pi^-)}{d\sigma/d\Omega\,(\gamma D \to nn\pi^+)} \tag{3}$$

so that, in principle, the ratio of the yields of π^- and π^+ on deuteron multiplied by the cross-section of the reaction

$$\gamma + p \to n + \pi^+ \tag{4}$$

should give the cross-section of reaction (1).

As matter of fact, the equality (3) is not completely correct (see, for istance, the discussion in reference (11)); moreover the cross-section of reaction (1) obtained by this method is affected by the uncertainties in the extensively measured π^+ cross-section, with differences among the various authors up to 7 % in the total cross-section at the peak of the first resonance(12).

In conclusion, the measurement of the π^- photoproduction cross-section on neutron is in any case affected by uncertainties, depending on the adopted method, which impose some caution in using it in the important tests of the $|\Delta I| \leq 1$ rule and of the T-invariance of the electromagnetic interaction of hadrons.

In our previous paper(3) we presented the dip test of Sanda and Shaw, carried out using data on reaction (1), obtained (via the spectator model without the model-dependent corrections for Pauli principle and final state interactions) from the results of reaction (2), studied with a deuterium bubble chamber exposed to a hardened bremsstrahlung beam with $E_{max} = 1$ GeV. By comparing with the π^+ data, taken from a available compilation(13), we conclude that there was space for an isotensor contribution up to 20 % at most, in the framework of the Sanda and Shaw model. We want to note here that: a) due to the general uncertainty in the evaluation of the model-dependent corrections the π^- cross-section was, as we explicitly stressed in our paper, not corrected for all the deuteron effects ; b) the results of the test depends on the set of the π^+ data used.

The results on reaction (1) of the ABHHM collaboration(4), obtained meanwhile with the same technique but using different extraction procedures of the γn cross-section from the γ-d data (closure approximation and Chew-Low extrapolation in the limits of the available statistics), gave higher cross-section values in the first resonance region, in better agreement with the assumption of no isotensor contribution. A comparative analysis of the two works, however, indicated that the difference in the conclusions reached depended more on some intrinsic difference in the rough experimental data and slightly on the different method used to extract the cross-section on neutron.

The obvious interest for resolving this disagreement, the possibility of an a-priori unknown systematic experimental error, the importance of all the theoretical problems involved, convinced us of the need of carrying out a check measurement of the cross-section of reaction (1), using the same technique and a hardened bremsstrahlung gamma spectrum with $E_{\gamma max} = 450$ MeV to avoid the possible contamination due to multiple photoproduction reactions. The results of this latter experiment are presented in the following.

2. - EXPERIMENTAL METHOD AND RESULTS. -

The beam was hardened with two polythene radiation lengths and its intensity adjusted to get an average number of about 8 e^+e^- pairs per picture in the fiducial volume.

The photon spectrum was determined by measuring about 20000 e^+e^- pairs and using the theoretical total cross-section for pairs production. The spectrum was smoothed, between 150 and 400 MeV by polinomial fit.

The photon flux was determined in two ways :

a) by counting the e^+e^- pairs every 30-th picture ;
b) by means of a lead shower counter, normalizing and cross-checking the two procedures. The sistematic uncertainty in the total photon flux was estimated of the order of 6 %.

The 260000 pictures taken, were scanned for events with two and three visible prongs ; half of the pictures were scanned twice with an overall scanning efficiency of about 100 % for the two scanning ; for the remaining half of the pictures the scanning efficiency was 95 %.

The events, measured by standard digitized projectors, were geometrically and kinematically processed using the THRESH and GRIND program chain. 6414 events in the fiducial volume were fitted ; 6241 of them were assigned to reaction (2) fitted with 3 constraints. For the two prong events the usual assumption for the unseen proton was made ($p_x = p_y = (0 \pm 30)$ MeV/c ; $p_z = (0 \pm 41)$ MeV/c). Only events fitted with $\chi^2 \leq 10$ were used to obtain the cross-section.

Other events, 6 % of the total, failed, for various reasons, the geometrical or kinematical reconstruction or were unmeasurable ; these events were taken into account by a global correction on the yield of reaction (2). This yield was corrected also for the χ^2 cut and for the loss of events with the production plane parallel to the optical axes of the cameras. This latter correction was determined from the azimuthal anisotropy of the events.

Finally, the yield was corrected for the loss of events with two invisible protons (one prong events) in the following way. The distribution of the momenta of the slower proton in the three prong events showed a sensible deviation from the Fermi momentum distribution, calculated from the Gartenhaus deuteron wave function, for momenta $\lesssim 120$ MeV/c (see Fig.1). For this reason, the events with both the protons having momentum lower than 120 MeV/c were eliminated from the yield and an energy-dependent correction (Table I) was calculated by means of a MONTECARLO program.

The total cross-section of reaction (2) is reported in Table II and is shown in Fig. 2 together with that of our previous work (open squares)

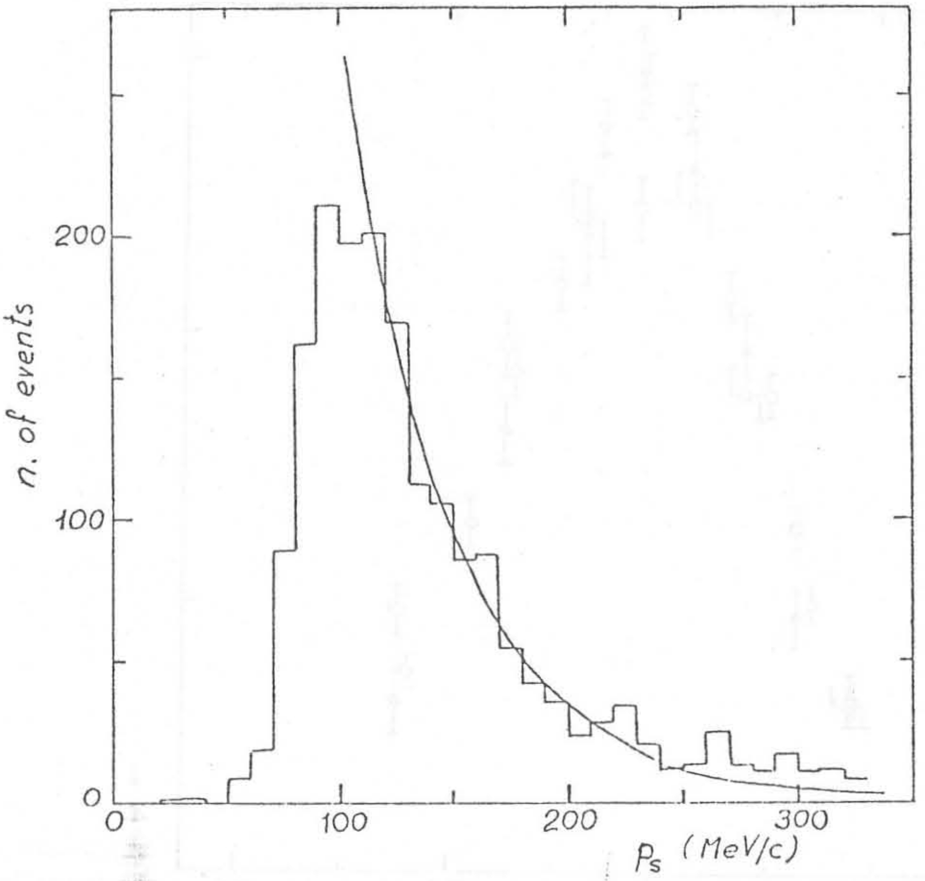

FIG. 1 - Distribution of the momentum of the slower proton of the three prongs events. The superimposed curve is the prediction of the spectator model.

E_γ(MeV)	$\beta(E_\gamma)$
200-225	1.125
225-250	1.09
250-275	1.08
275-300	1.06
300-325	1.05
325-350	1.05
350-400	1.04
400-500	1.02

TABLE I -

Correction coefficients for the calculation of the $\gamma D \rightarrow pp\pi^-$ total cross-section due to the cut of events with both protons with momenta < 120 MeV/c.

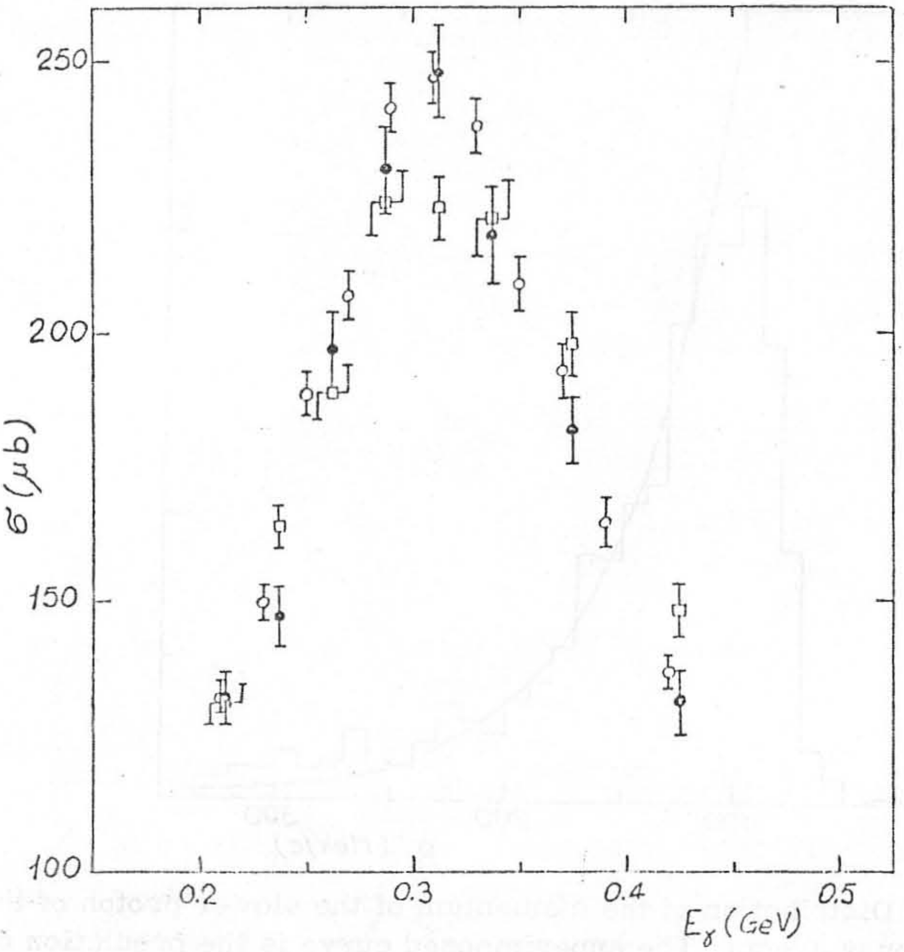

FIG. 2 - Total cross-sections for the reaction $\gamma + D \rightarrow p + p + \pi^-$: ● this experiment, □ ref. (3), o ref. (4).

E_γ(MeV)	σ (μb)
200-225	131.3 ± 5.2
225-250	147.1 ± 5.9
250-275	197.9 ± 7.3
275-300	229.6 ± 8.3
300-325	247.8 ± 9.0
325-350	217.5 ± 8.9
350-400	181.7 ± 6.4
400-450	131.0 ± 6.3

TABLE II - Total cross-section of the reaction $\gamma D \rightarrow pp\pi^-$

and that of ABHHM collaboration(4) (open circles).

The results of our two independent measurements are in good agreement; the difference between them can be ascribed to statistical fluctuations both in the yield of events and in photon spectrum.

The rise in the peak point seems to improve the agreement with the results of ABHHM collaboration; however, our results remain still lower in the region of the resonance peak.

To calculate the cross-section on neutron we adopted the nucleon spectator model using the same procedure extensively described in our previous paper(3).

The sample of events satisfying the spectator model was selected operating a cut on θ_s^*, the emission angle of spectator proton (the proton with lower momentum in the laboratory system) in the γ-D C. M. S. and on p_s, the momentum of the spectator proton in the L. S.

In order to obtain a good agreement between the momentum and angular distribution of the spectator proton in the L. S. and the same distributions calculated with a MONTECARLO program according to the spectator model, only events with $\theta_s^* \lesssim 90^o$ and $p_s \lesssim 250$ MeV/c were considered.

The program generates events of the two steps reaction:

$$\gamma + D \rightarrow p_s + Q$$
$$\qquad\qquad\quad \llcorner\!\rightarrow p + \pi^- .$$

The photon is extracted from the experimental spectrum and the spectator proton (p_s) is generated according to the Gartenhaus deuteron wave function and with an angular distribution

$$\frac{dN_s}{d\Omega} \propto 1 + \beta_s \cos \theta$$

in the L. S. in order to take into account the Fermi motion in the flux factor.

The decay $Q \rightarrow p + \pi^-$ is generated according to the phase-space distribution; when p has a momentum lower than that of p_s, the two protons are interchanged so as to reproduce the choice made for real events.

Each simulated event is weighted, according to its value of E^{*2} (total c. m. squared energy of the $p\pi^-$ system), by the measured value of the cross-section $\sigma_{\gamma n}(E^{*2})$. The program provides the correction coefficients for the experimental data due to: 1) wrong choice of the "spectator proton"; 2) loss of one prong events; 3) cuts on θ_s^* and p_s. Moreover, not weighting the simulated events with the experimen tal cross-section, the program provides also $N_\gamma(E^{*2})dE^{*2}$, i.e. the effective photon spectrum as a function of E^{*2}.

We used this spectrum to determine the cross-section on neutron which is parametrized in terms of E^{*2}, or, equivalently, in terms of E'_γ, the effective photon energy, i.e. the energy necessary to get on a free neutron a total c.m. energy E^* ($E'_\gamma = (E^{*2} - M_n^2)/2M_n$; M_n is the neutron mass).

Because the results of the Montecarlo calculations are not very sensitive to the weighting function $\sigma_{\gamma n}(E^{*2})$, we initially used our previously measured cross-section.

Table III gives the correction coefficients for the sample of selected events as function of E^{*2}. The cut of events with both protons with momentum lower than 120 MeV/c gives the main contribution to the corrections.

E^{*2}(GeV^2)	$\beta(E^{*2})$
1.26-1.34	1.16
1.34-1.38	1.13
1.38-1.42	1.09
1.42-1.46	1.09
1.46-1.50	1.08
1.50-1.54	1.06
1.54-1.62	1.06
1.62-1.70	1.04

TABLE III -

Correction coefficients for the calculation of the $\gamma n \rightarrow p\pi^-$ cross-section due to the following cuts : a) cut of events with both protons with momenta $<$ 120 MeV/c, b) p_s cut, c) θ_s^* cut.

The total cross-section for reaction (1), obtained with the procedure outlined above, is reported in Table IV and shown in Fig. 3 as a function both of E^{*2} and E'_γ. The results of the present work (black dots) are in good statistical agreement with those of our previous measurements (open squares).

3. - CONCLUSIONS. -

A comparison with the total cross-section of reference (4), obtained with bubble chamber experiment using the closure approximation, and those of references (6) and (7), obtained measuring the π^-/π^+ ratio on deuterium, shows that our results are sistematically smaller in the region of the rise and peak of the resonance.

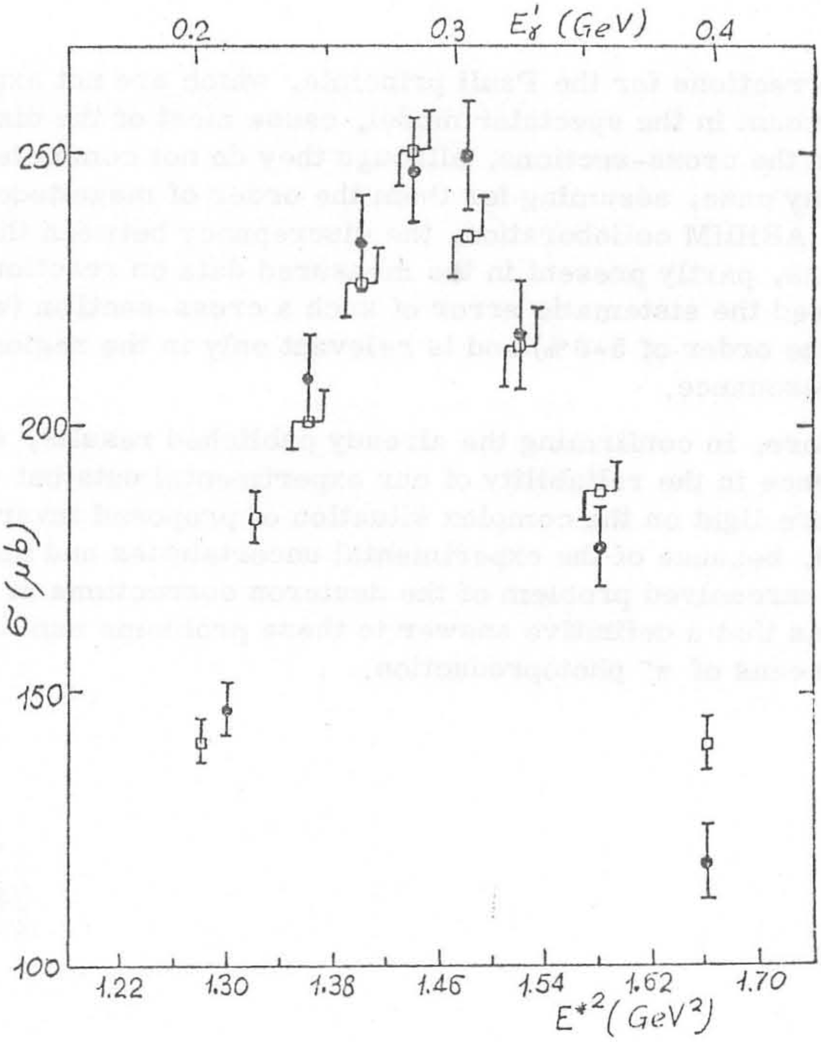

FIG. 3 - Total cross-sections for the reaction $\gamma + n \rightarrow p + \pi^-$:
● this experiment, ◻ ref. (3).

E^{*2}(GeV^2)	σ (μb)
1.26-1.34	147.0 ± 4.6
1.34-1.38	209.2 ± 8.4
1.38-1.42	233.7 ± 9.2
1.42-1.46	247.0 ± 9.9
1.46-1.50	249.9 ± 10.6
1.50-1.54	217.3 ± 10.4
1.54-1.62	177.4 ± 7.2
1.62-1.70	119.2 ± 6.8

<u>TABLE IV -</u>

Total cross-section of the reaction $\gamma n \rightarrow p \pi^-$.

The corrections for the Pauli principle, which are not explicitly taken into account in the spectator model, cause most of the disagreement between the cross-sections, although they do not completely explain it. In any case, assuming for them the order of magnitude evaluated by the ABHHM collaboration, the discrepancy between the γn cross-sections, partly present in the measured data on reaction (2), does not exceed the sistematic error of such a cross-section (which is typically of the order of 5-6 %) and is relevant only in the region of the peak of the resonance.

Therefore, in confirming the already published results, we get more confidence in the reliability of our experimental data but we cannot throw more light on the complex situation of proposed invariance tests. In fact, because of the experimental uncertainties and more because of the unresolved problem of the deuteron corrections at low energies, it seems that a definitive answer to these problems can hardly be reached by means of π^- photoproduction.

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