

REACTION $\pi^-p \rightarrow \eta'n$ IN THE 15-40 GeV/c MOMENTUM RANGE

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ABSTRACT

Measurements were made of the cross-section of reactions $\pi^-p \rightarrow \eta'(958)n$, $\eta' \rightarrow 2\gamma$ at momenta of 15, 20, 25, 30, and 40 GeV/c. The experiment was carried out on the IHEP 70 GeV accelerator using the 648-channel hodoscope spectrometer NICE for γ -ray detection. A total of 6000 η' mesons were recorded. A sharp drop is seen in the differential cross-section for $t \rightarrow 0$. The dependences of the differential cross-sections for the reactions $\pi^-p \rightarrow \eta'n$ and $\pi^-p \rightarrow \eta n$ on t are identical. On the basis of the ratio of cross-sections for these reactions at $t = 0$, i.e. $R(\eta'/n)_{t=0} = 0.55 \pm 0.06$, the singlet-octet mixing angle for pseudo-scalar mesons was determined to be $\beta = -(18.2 \pm 1.4)^\circ$.

(Submitted to Physics Letters B)

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In the present paper, measurements are reported of the production cross-sections of η' mesons in collisions between π^- mesons and protons



for five momenta of the π^- mesons in the 15-40 GeV/c range. Some preliminary results have been published elsewhere [1]. The investigation of reaction (1) at high energies is of considerable interest, in particular from the point of view of SU_3 symmetry. A debate has gone on during quite a few years as to whether the η' meson is indeed the unitary pseudoscalar singlet, or whether this should be rather identified with the E meson, the η' meson having spin 2 [2]. Recently this question was solved experimentally: a spin parity of 1^+ has actually been ascribed to the E meson [3], and the η' meson has been shown to have spin parity 0^- [4], and hence presumably to belong to the nonet of pseudoscalar mesons, as partner of the η meson. A comparison of the cross-sections for reaction (1) and for the similar reaction with η production allows, in fact, the mixing of "pure" states in this nonet to be determined.

The experimental study of reaction (1) is made difficult by the very small size of its cross-section times branching ratio in two γ -rays. This reaction has already been investigated at momenta of up to 50 GeV/c [5-7], but at a statistical level of only $\sim 50 \eta' \rightarrow 2\gamma$ decays. In ref. 1 this number was increased by one order of magnitude. In the experiment described below we recorded 6000 η' mesons. This made it possible to widen the range of the determination of differential cross-sections to $|t| \approx 1.8 \text{ GeV}^2/c^2$, and also to study the region of small momentum transfers, where, in contradiction with the data of paper [8], a marked drop in the cross-section is seen for $t \rightarrow 0$.

The experiments were performed on the IHEP 70 GeV accelerator during several runs of the NICE set-up in 1974-75. A detailed description of the apparatus, measurement procedure, and data processing is given in a previous paper [9]. The measurements were made at momenta of 15, 20, 25, 30, and 40 GeV/c. In each of these experiments the distance (L) between the liquid hydrogen target and the

γ -spectrometer (table 1) was varied, which made it possible to check whether the definition of the geometric corrections was correct: during the transition to large L the acceptance of the spectrometer decreased by 2-3 times in a number of cases, but after the introduction of the corrections, the values of the cross-sections were identical for all L.

In order to determine the differential cross-sections of reaction (1), events were selected with two γ -rays in the final state, satisfying the condition $\cos \theta^* < 0.6$, where θ^* is the angle of decay in the centre-of-mass system. In the invariant mass spectra plotted for these events, a narrow peak is noticeable (fig. 1), corresponding to the production of the η' (958) mesons in reaction (1). The source of the background is provided by the comparatively intense processes $\pi^- p \rightarrow \omega n$ (with $\omega \rightarrow \pi^0 \gamma$), $\pi^- p \rightarrow \pi^0 \pi^0 n$, and also $\pi^- p \rightarrow f n$, $f \rightarrow \pi^0 \pi^0$. In a small fraction of cases they imitate reaction (1); that is, mainly when one or two γ -rays have an energy below the effective threshold of the spectrometer and are not recorded by the set-up. The level of this background in the region of the η' peak does not exceed 5% (fig. 1). It increases sharply for $\cos \theta^* \rightarrow 1$. The mass spectrum outside the peak corresponds well with the background calculated on the basis of the data concerning the above-mentioned reactions, obtained on the NICE installation in parallel with the experiment described here.

The values for the integrated cross-sections σ obtained for reaction (1) are listed in table 2. The table also gives the measured ratios for reaction (1) and for the reaction



which was investigated simultaneously in the same experimental conditions [9]. The values of σ are also shown in fig. 2, together with results from previous experiments [1,5-8].

The energy dependence of the cross-section, according to the data of table 2, is well described by the power-law function $\sim s^{-n}$:

$$\sigma = (830 \pm 160)(s/s_0)^{-1.48 \pm 0.12} \times 10^{-33} \text{ cm}^2 \quad (3)$$

(fig. 2), where s is the square of the energy in the centre-of-mass system. Here and below, $s_0 = 10 \text{ GeV}^2$. The dependence (3) is similar to that obtained for reaction (2), where $n = 1.53 \pm 0.03$ [9].

The results for the differential cross-sections $d\sigma/dt$ are shown in table 3 and in fig. 3. In order to improve the statistics, we have combined the data obtained at momenta of 20, 25, and 30 GeV/c, including a weighting for the relative differential cross-sections $d\sigma/\sigma dt$ (which are weakly dependent on the momentum), and have normalized them to the value of σ at $p = 25 \text{ GeV/c}$. The largest number of events (2200 η' mesons) was obtained at $p = 40 \text{ GeV/c}$, where the t -dependence of the differential cross-section has been studied up to $|t| \approx 1.8 (\text{GeV/c})^2$. At $|t| \approx 1 (\text{GeV/c})^2$ there is apparently a change of slope which is similar to that previously observed in reaction (2) [9].

For $t \rightarrow 0$ a sharp drop in the cross-sections is observed, as in reaction (2), which points to the dominating contribution of the processes with spin flip in the interval of momenta studied. The t -dependence of the differential cross-section is well described by the phenomenological formula [9,11]:

$$\frac{d\sigma}{dt} = \left. \frac{d\sigma}{dt} \right|_{t=0} \times (1 - gct) e^{ct} \quad (4)$$

with the parameters found by the least squares method shown in table 4. Here $g = \sigma_-/\sigma_+$ is the ratio of the cross-sections of reaction (1), integrated over t , with and without spin flip. The interval of t over which the fit is performed is $0 < |t| < 0.6 (\text{GeV/c})^2$. At $p = 15 \text{ GeV/c}$, where the statistical accuracy is comparatively small, $c = 10.8 \pm 2.5 (\text{GeV/c})^{-2}$, and the parameter g was determined with a large correlated error of $\sim 100\%$.

Within the limits of measurement errors, the values c and g are identical for reactions (1) and (2) (see table 4). The dependence of the cross-sections

on s and t are again found to be identical for both processes (table 2 and fig. 4) according to our data, and reaction (1) is simply a scaled-down version of reaction (2). These results are in contradiction with the experimental data provided by the Charged and Neutral Particle Spectrometer at the Argonne laboratory [8], where the ratio of the differential cross-sections of the reactions $\pi^- p \rightarrow \eta' n$ and $\pi^- p \rightarrow \eta n$, taking into account all decay modes, was found to be equal to 1 at $t = 0$ (fig. 4), whereas in the present experiment this ratio is

$$R(\eta'/\eta)_{t=0} = 0.55 \pm 0.06, \quad (5)$$

and $R(\eta'/\eta)$ does not depend on t.

In the general case the η' and η mesons can be expressed as combinations of "pure" states belonging to the unitary singlet (η_0) and octet (η_8) of the pseudo-scalar mesons:

$$|\eta\rangle = D_1(\cos \beta_1 |\eta_8\rangle - \sin \beta_1 |\eta_0\rangle), \quad (6)$$

$$|\eta'\rangle = D_2(\sin \beta_2 |\eta_8\rangle + \cos \beta_2 |\eta_0\rangle).$$

At high energies, where the difference in the phase spaces of reactions (1) and (2) is insignificant, the value of (5) is linked with the mixing angles by the relation

$$R(\eta'/\eta)_{t=0} = \left[\frac{D_2 \sin(\beta_2 + \beta_0)}{D_1 \cos(\beta_1 + \beta_0)} \right]^2 \quad (7)$$

with $\text{tg } \beta_0 = \sqrt{2}$ (see [12,13]; also [14] and references quoted therein). If there is a full overlap between the octet and singlet orbital wave functions, i.e.

$D_1 = D_2$, and the mixing angles are equal $\beta_1 = \beta_2 = \beta$, formula (7) is simplified as follows:

$$\text{tg } \beta = \frac{\sqrt{R} - \sqrt{2}}{1 + \sqrt{2R}}. \quad (8)$$

Using the measured value (5) for R, we obtain from (8) the mixing angle:

$$\beta = -(18.2 \pm 1.4)^\circ. \quad (9)$$

This does not include the error due to a 15% uncertainty in the $BR(\eta' \rightarrow 2\gamma)$, which increases the error in (9) to 2.3° . The value of the mixing angle, derived from the ratios \bar{R} of the integrated cross-sections (table 2), is $\beta = -(18.9 \pm 0.5)^\circ$. Using the quadratic mass formula for the mixing of the η' and η states, $|\beta| = 10^\circ$, which implies $R(\eta'/\eta) = 1$; whilst in the case of linear mixing, $|\beta| = 24^\circ$ and $R(\eta'/\eta) = 0.35$. A recent phenomenological analysis of the pseudoscalar nonet, based on chromodynamics [15], shows that the mixing angles β_1 and β_2 are slightly different from each other (-17° and -21° , respectively). Using (7) this implies $R(\eta'/\eta) = 0.53$, which agrees well with our result (5).

Finally we remark that assuming that the ratio of the integrated cross-sections $\bar{R}(\eta'/\eta)$ does not indeed depend appreciably on the incident pion momentum for $p \gtrsim 8$ GeV/c, then by using the values of \bar{R} obtained in the present paper and in ref. 8, the branching ratio for $\eta' \rightarrow 2\gamma$ decay, which had previously been measured with a considerable spread in the results [10], can be determined to be:

$$BR(\eta' \rightarrow 2\gamma) = 0.018 \pm 0.002 . \quad (10)$$

We take this opportunity to thank V.V. Anisovich and A.T. Filippov for discussions of the results. We are grateful to the Directorates of IHEP and CERN for their support in the joint NICE experiment. The staff of the Institut für Experimentelle Kernphysik, Karlsruhe, also expresses its thanks to the Bundesministerium für Forschung und Technologie for the financial support provided.

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Table 1

Data-taking conditions

Momentum ^{a)} (GeV/c)	Distance (m)	Number of recorded η' mesons in reaction (1)	
		Total	Used for determining the cross-sections
15.0 ^{b)}	3.5; 5	200	120
20.2	5; 7	550	320
25.0	3; 6; 9	1000	600
30.0	6; 9	650	370
40.0	3; 5; 10	4000	2200

a) Momentum spread $\Delta p/p = 0.5-1.5\%$.

b) To obtain a beam having a momentum of 15 GeV/c, the accelerator was tuned to an energy of $E_0 = 30$ GeV. In the remaining cases $E_0 = 70$ GeV.

Table 2

Integrated cross-sections for reaction (1)
and ratios with reaction (2)

Momentum p (GeV/c)	$\sigma(10^{-33} \text{ cm}^2)$	$\bar{R}[(\eta' \rightarrow 2\gamma)/(\eta \rightarrow 2\gamma)], \% \text{ a)}$	$\bar{R}(\eta'/\eta) \text{ b)}$
15.0	190 ± 20	3.10 ± 0.30	0.59 ± 0.06
20.2	105 ± 8	2.70 ± 0.16	0.51 ± 0.08
25.0	81 ± 6	2.75 ± 0.13	0.52 ± 0.03
30.0	62 ± 4	2.78 ± 0.16	0.53 ± 0.03
40.0	42 ± 3	2.74 ± 0.11	0.52 ± 0.02
Average:		$2.76 \pm 0.07 \%$	0.52 ± 0.02

a) Measured values of the ratios of the cross-sections integrated over t of reactions (1) and (2).

b) Ratio of the cross-sections of the reactions $\pi^- p \rightarrow \eta' n$ and $\pi^- p \rightarrow \eta n$ taking into account all decay modes: $BR(\eta \rightarrow 2\gamma) = 0.38 \pm 0.01$; $BR(\eta' \rightarrow 2\gamma) = 0.020 \pm 0.003$ [10]. The error due to the latter value has not been included in $\bar{R}(\eta'/\eta)$.

Table 3

Differential cross-sections for reaction (1)

Δt (GeV/c) ²	\bar{E} (GeV/c) ²	$d\sigma/dt [10^{-33} \text{ cm}^2/(\text{GeV}/c)^2]$ and $R(\eta'/\eta)$ a)					
		p = 15 GeV/c		25 GeV/c b)		40 GeV/c	
		$d\sigma/dt$	$R(\eta'/\eta)$	$d\sigma/dt$	$R(\eta'/\eta)$	$d\sigma/dt$	$R(\eta'/\eta)$
0-0.02	0.01	-	-	-	-	109 ± 13	0.55 ± 0.07
0.02-0.04	0.03	-	-	-	-	150 ± 13	0.64 ± 0.06
0-0.04	0.02	420 ± 120	0.55 ± 0.04	210 ± 16	0.55 ± 0.04	-	-
0.04-0.08	0.06	800 ± 170	0.62 ± 0.05	293 ± 19	0.62 ± 0.05	164 ± 9	0.60 ± 0.05
0.08-0.12	0.10	800 ± 170	0.58 ± 0.05	276 ± 19	0.58 ± 0.05	172 ± 9	0.62 ± 0.05
0.12-0.16	0.14	610 ± 150	0.56 ± 0.04	259 ± 18	0.56 ± 0.04	143 ± 8	0.56 ± 0.04
0.16-0.20	0.18	380 ± 120	0.55 ± 0.04	227 ± 16	0.55 ± 0.04	105 ± 7	0.49 ± 0.04
0.2-0.3	0.25	320 ± 80	0.54 ± 0.04	156 ± 11	0.54 ± 0.04	67 ± 4	0.43 ± 0.04
0.3-0.4	0.35	210 ± 60	0.43 ± 0.05	77 ± 8	0.43 ± 0.05	34 ± 3	0.41 ± 0.04
0.4-0.5	0.45	-	0.36 ± 0.07	32 ± 6	0.36 ± 0.07	16 ± 2	0.37 ± 0.05
0.5-0.6	0.55	-	0.43 ± 0.09	20 ± 4	0.43 ± 0.09	9.6 ± 1.7	0.49 ± 0.08
0.6-0.7	0.65	-	0.47 ± 0.10	11.3 ± 2.4	0.47 ± 0.10	3.4 ± 0.8	0.36 ± 0.10
0.7-0.8	0.75	-	0.44 ± 0.14	5.0 ± 1.6	0.44 ± 0.14	1.3 ± 0.4	0.26 ± 0.10
0.8-1.0	0.9	-	-	-	-	0.6 ± 0.3	0.42 ± 0.21
1.0-1.4	1.2	-	-	-	-	0.30 ± 0.15	0.67 ± 0.34
1.4-1.8	1.6	-	-	-	-	0.13 ± 0.06	0.62 ± 0.31

a) Ratio of the differential cross-sections of reactions (1) and (2) (see reference in table 2).

b) Averaged cross-sections: the values of $d\sigma/dt$ at 20, 25, and 30 GeV/c were summed and normalized to the cross-section σ at 25 GeV/c.

Table 4

Best fit of small $|t|$ differential cross-sections for reaction (1)
and ratios with reaction (2) at $t = 0$

Momentum p (GeV/c)	$\pi^- p \rightarrow \eta' n, \eta' \rightarrow 2\gamma$			$\pi^- p \rightarrow \eta n, \eta \rightarrow 2\gamma$			R(η'/η) _{t=0} ^{a)}
	c (GeV/c) ⁻²	g	$\frac{d\sigma}{dt}_{t=0}$ [$10^{-33} \frac{\text{cm}^2}{(\text{GeV}/c)^2}$]	c (GeV/c) ⁻²	g	$\frac{d\sigma}{dt}_{t=0}$ [$10^{-30} \frac{\text{cm}^2}{(\text{GeV}/c)^2}$]	
25.0	9.4 ± 0.5	4.5 ± 1.2	140 ± 22	8.4 ± 0.1	3.7 ± 0.2	5.30 ± 0.20	0.50 ± 0.08
40.0	10.3 ± 0.5	3.5 ± 0.7	93 ± 11	9.2 ± 0.1	3.7 ± 0.2	3.00 ± 0.13	0.59 ± 0.07

a) See reference in table 2.

Figure captions

- Fig. 1 : Spectrum of invariant masses of pairs of γ -rays in the reaction $\pi^- p \rightarrow M^0 n, M^0 \rightarrow 2\gamma$ (1C-fit, with neutron as recoil, $\chi^2 < 2.5$). The arrow indicates the value of the η' mass [10]. a) $p = 30$ GeV/c, $L = 6$ m; b) $p = 40$ GeV/c, $L = 3$ m. The widths of the peaks coincide with the calculated resolution of the spectrometer.
- Fig. 2 : Dependence of the cross-section of reaction (1) on momentum p .
Notation: \bullet = data from the present experiment; $-$, \times , \square and \circ are data from refs. 1, 5-7; \otimes are data from ref. 8, recalculated for the decay mode $\eta' \rightarrow 2\gamma$. The straight line is the best fit power-law function (3) drawn through our points.
- Fig. 3 : The differential cross-sections of reaction (1) at $p = 15, 25,$ and 40 GeV/c. The points represent the data of the present experiment; the curves represent the dependences (4), calculated with the parameters given in table 4.
- Fig. 4 : Ratios of the differential cross-sections of reactions $\pi^- p \rightarrow \eta' n$ and $\eta^- p \rightarrow \eta n$ for various t . Notation $\circ = 25$ GeV/c and $\bullet = 40$ GeV/c, data from present experiment. The dashed line has been drawn through the data of ref. 8.

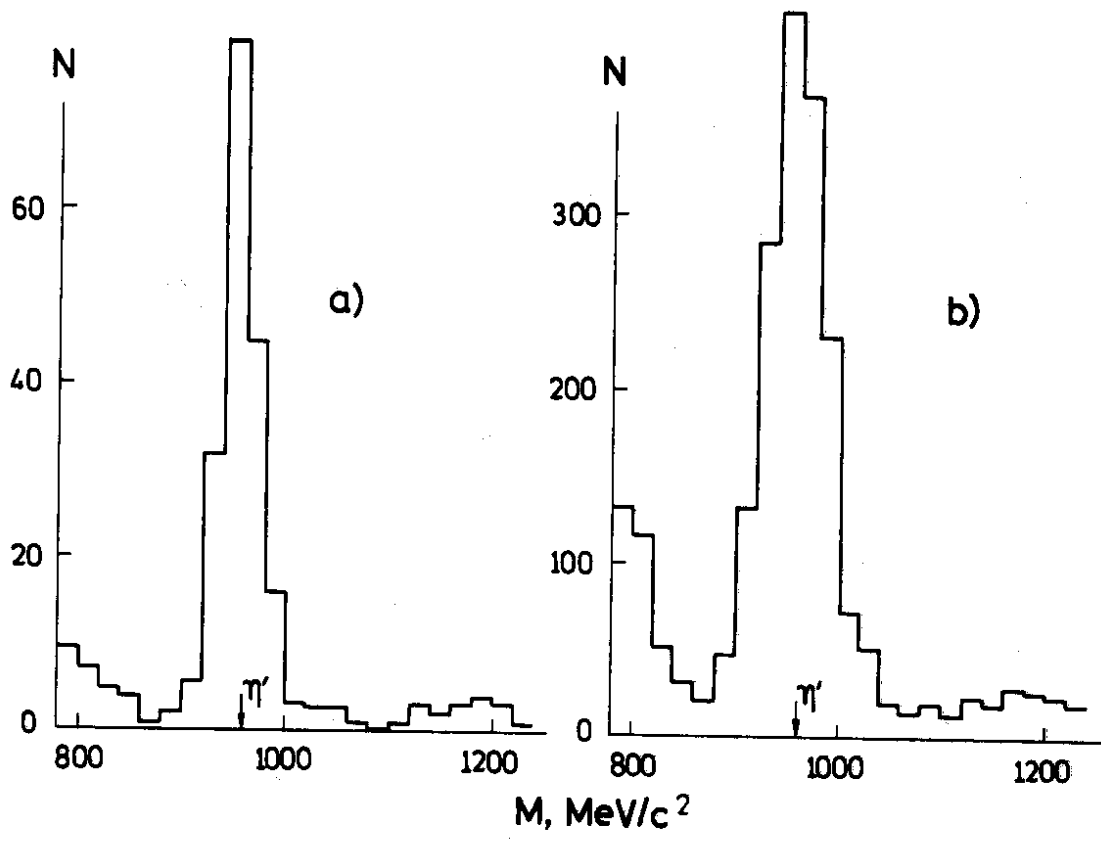


Fig. 1

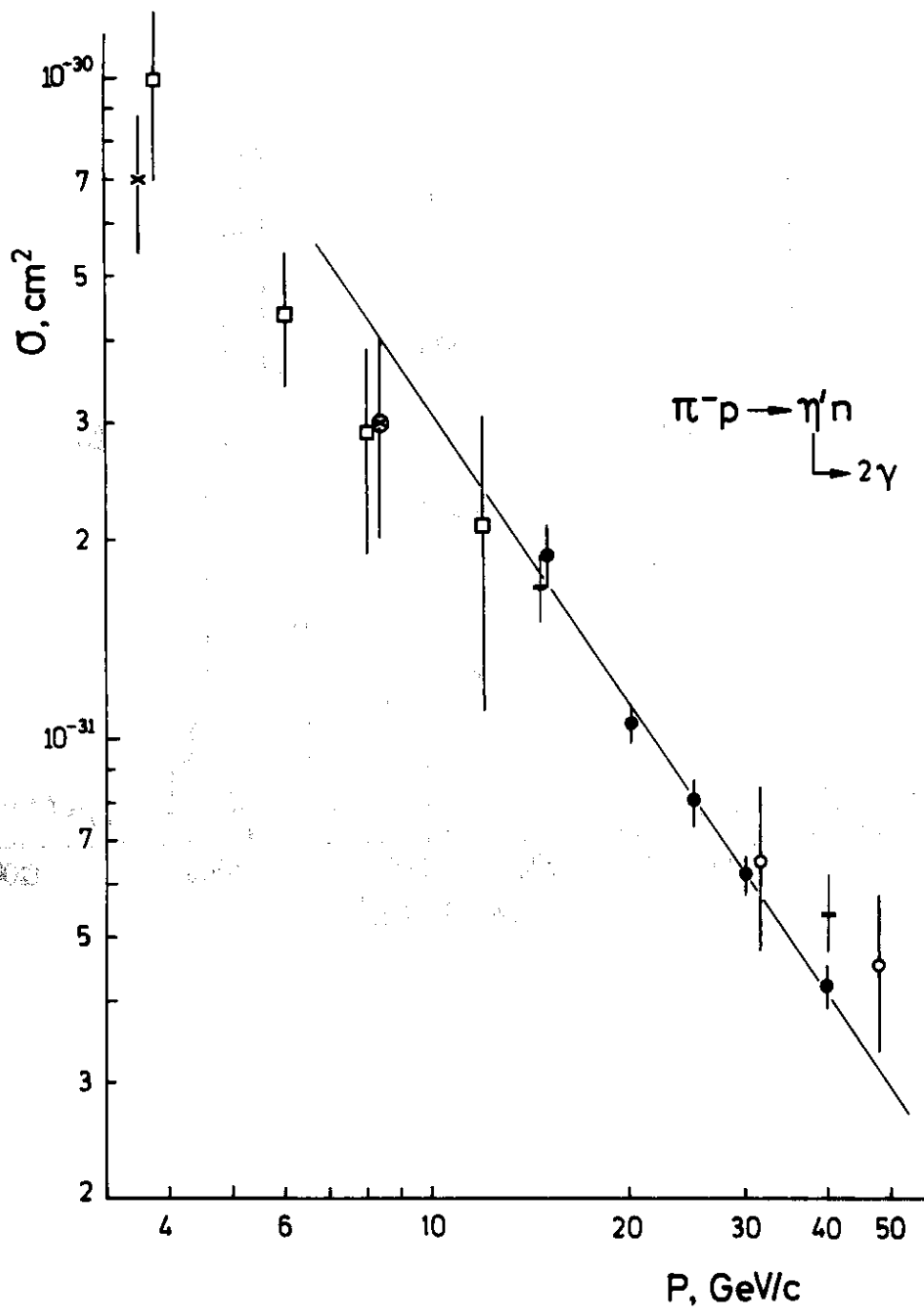


Fig. 2

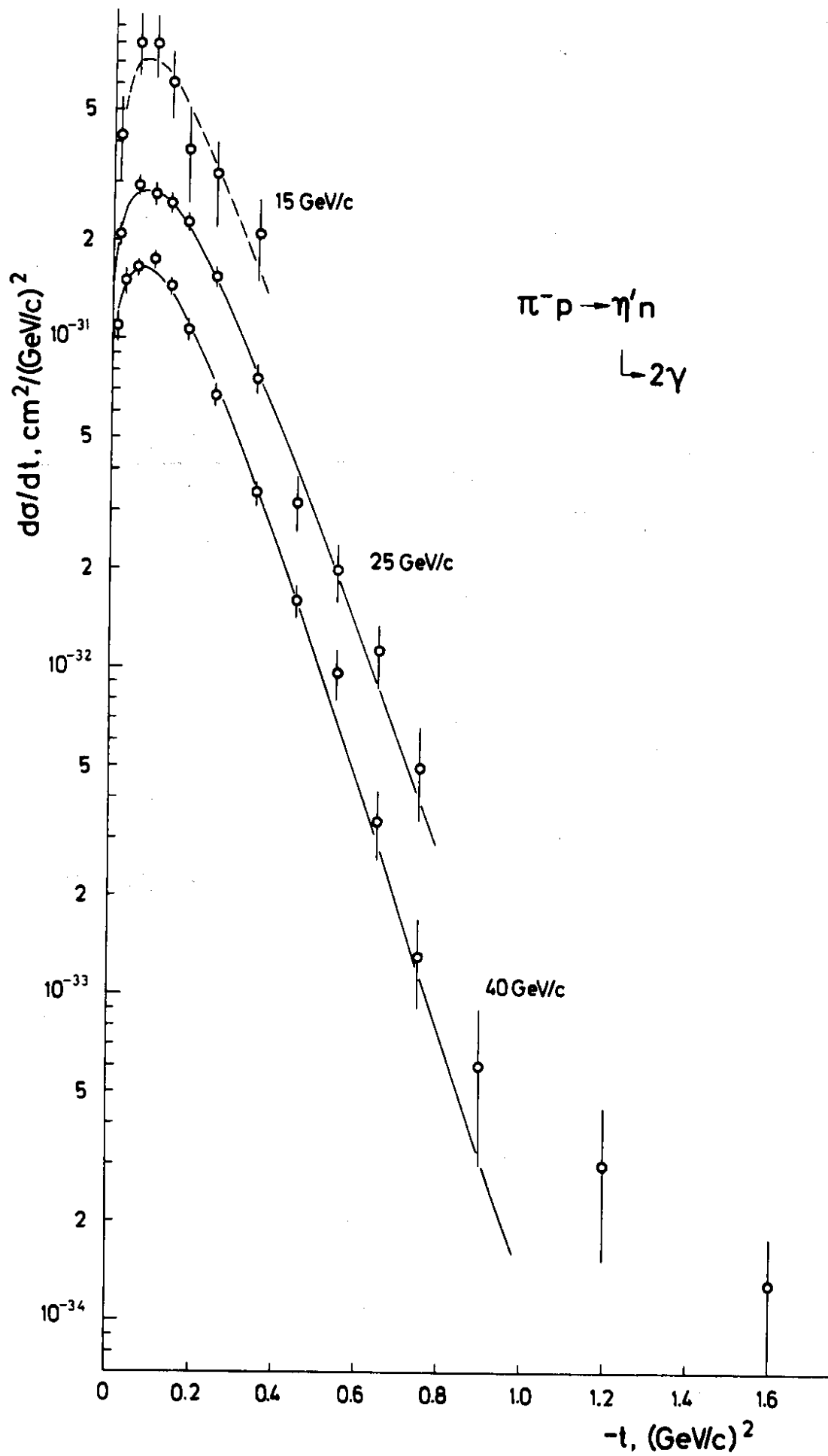


Fig. 3

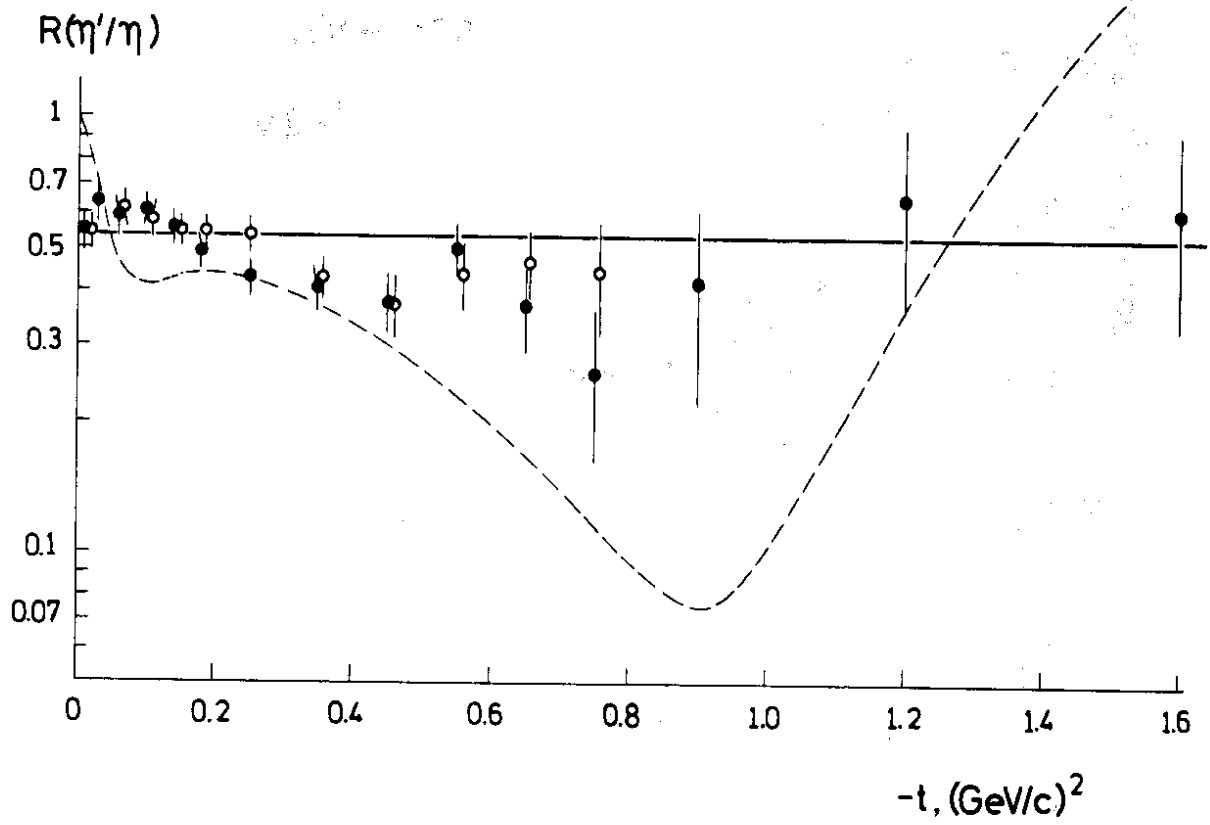


Fig. 4