

NEUTRAL DECAYS OF THE η -MESONIHEP¹-IISN²-LAPP³ Collaboration

D. Alde^{4,5}, F. Binon², C. Bricman², S.V. Donskov¹, P. Duteil⁴,
 M. Gouanère³, A.V. Inyakin¹, D.B. Kakauridze¹, V.A. Kachanov¹,
 G.V. Khaustov¹, A.V. Kulik¹, J.P. Lagnaux², A.A. Lednev¹,
 V.A. Maisheev¹, Yu.M. Melnik¹, Yu.V. Mikhailov¹, Th. Mouthuy²,
 J.P. Peigneux³, A. Possoz⁴, Yu.D. Prokoshkin¹, Yu.V. Rodnov¹,
 S.A. Sadovsky¹, P.M. Shagin¹, D. Sillou³, A.V. Singovsky¹,
 J.P. Stroot² and V.P. Sugonyaev¹.

Joint Experiment of IHEP, Serpukhov, USSR

and

CERN, Geneva, Switzerland

ABSTRACT

The partial widths of η -meson decays $\eta \rightarrow 2\gamma$, $\eta \rightarrow 3\pi^0$ and $\eta \rightarrow \pi^0\gamma\gamma$ have been measured in a high accuracy experiment made at the IHEP accelerator with the hodoscope electromagnetic spectrometer GAMS-2000. An upper limit has been determined for the 3γ channel. The Dalitz plot of the η decay into $3\pi^0$ shows that the matrix element does not depend on the pion energy.

(Submitted to Zeitschrift für Physik C)

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1. Institute for High Energy Physics, Serpukhov, USSR.
 2. Institut Interuniversitaire des Sciences Nucléaires, Brussels, Belgium.
 3. Laboratoire d'Annecy de Physique des Particules, France.
 4. CERN, Geneva, Switzerland.
 5. Permanent address: Los Alamos National Laboratory, N.M. - U.S.A.

1. INTRODUCTION

In the present work are reported:

- a high precision measurement of the neutral decay channels of the η -meson, both into two gammas:

$$\eta \rightarrow 2\gamma \quad (1)$$

and in three neutral pions:

$$\eta \rightarrow 3\pi^0 \quad \begin{array}{l} \text{L} \\ \text{---} \end{array} \rightarrow 6\gamma \quad (2)$$

- a precise evaluation of the matrix element of the decay (2) through the Dalitz plot,
- the partial width of the rare radiative decay channel:

$$\eta \rightarrow \pi^0\gamma\gamma \quad (3)$$

- and an upper limit to the rate of the C-parity violating decay channel:

$$\eta \rightarrow 3\gamma \quad (4)$$

2. EXPERIMENTAL SET-UP

The data on decays (1)-(4) have been obtained with the hodoscope Cerenkov spectrometer GAMS-2000 in a 30 GeV/c negative pion beam at the IHEP 70 GeV accelerator [1]. Gammas from the decay of neutral mesons produced through charge-exchange reactions of the type:

$$\pi^-p \rightarrow M^0n \quad \begin{array}{l} \text{L} \\ \text{---} \end{array} \rightarrow k\gamma \quad (5)$$

including the reaction

$$\pi^-p \rightarrow \eta n \quad (6)$$

acting as a source of quasi-monoenergetic etas, were recorded in the spectrometer. All neutral decays with a multiplicity up to ten gammas were recorded simultaneously.

The experimental set-up and the method for data analysis have been described elsewhere [1-3]. A total of $6 \cdot 10^5$ η have been produced through reaction (6), improving the statistics of previous experiments by two orders of magnitude [4,5]. Systematic errors in the determination of partial width ratios are reduced to the one per-cent level.

3. DECAY $\eta \rightarrow 2\gamma$

The identification of $\eta \rightarrow 2\gamma$ events, because of their simple topology, does not present great difficulty in the chosen geometry [1,6]. Events that are reconstructed by the analysis program as two-photon events appear as a peak without background in the η mass region (fig. 1). After an overall mass calibration, the center of the peak is within 0.3% of the tabulated value of the η mass and its width is compatible with the instrumental resolution of the spectrometer. All measured quantities agree with the data previously obtained at the same energy, including the exponential dependance of $d\sigma/dt$ ($\pi p \rightarrow \eta n$) on t , the four-momentum transfer squared of reaction (6) [7].

The value of the efficiency for two-photon detection, $\epsilon_{2\gamma}$, has been determined by Monte-Carlo calculations with a bank of real showers collected in GAMS itself [1]. The events simulated by this method were analysed with the same programs, using the same cuts that were used for the analysis of the experimental data.

Systematic errors have been studied through the variation of a series of parameters like the energy threshold for gamma detection in GAMS, the total energy of gammas, the minimum $|t|$ value accepted, the geometry of the detector (useful lateral dimensions of GAMS, dimensions of its central hole). Fig. 2a shows the way $N_{2\gamma}$, the number of observed 2γ events, and $\epsilon_{2\gamma}$ depend on the energy threshold E_{thr} . One sees that although $N_{2\gamma}$ decreases by a factor 1.5 when E_{thr} is increased from 0.25 GeV

to 6 GeV, the effective number of events $N_{2\gamma}/\epsilon_{2\gamma}$ remains constant within the limits of statistical accuracy (0.3%) (Fig. 2b). This number is also shown not to depend on variations of the other above mentioned parameters. So, a decrease of the geometrical acceptance of the spectrometer by a factor two increases $N_{2\gamma}/\epsilon_{2\gamma}$ by only a fraction of a per-cent.

4. THE $\eta \rightarrow 3\pi^0$ CHANNEL AND ITS MATRIX ELEMENT

The study of the G-parity violating decay (2) is of great interest for QCD, the current theory of strong interactions (cf. literature in [3]). It presents more experimental difficulty than decay (1). An efficient detection of six gammas in GAMS together with the kinematical reconstruction of the decaying particles over a large combinatorial background (there are 15 possible pairings for six γ) is required. In the case of decay (2) the number of recorded events is more dependent on the instrumental parameters (E_{thr} , etc.) imposing stronger requirements to a precise determination of the efficiency $\epsilon_{3\pi^0}$.

Decay (2) events are identified amongst those events reconstructed as 6γ events from reaction (5). Only those which satisfy the kinematics of the reaction $\pi^-p \rightarrow 3\pi^0n$ with $\chi^2 < 10$ (95 % confidence level, 4-C fit, neutron and π^0 masses fixed) go to the next stage of analysis. The resulting $3\pi^0$ mass spectrum (Fig. 1b) shows a narrow peak, with practically no background, which comes from reaction (6) followed by the decay (2) of the η . The central value of this peak is in agreement with that of the 2γ spectrum (Fig. 1a). Its shape is in agreement with the instrumental resolution of the spectrometer ($\sigma_M/M = 0.8\%$). The event χ^2 distribution is standard. The t-distribution of $3\pi^0$ events is similar to that of the 2γ events.

Fifty thousand reconstructed $\eta \rightarrow 3\pi^0$ decays have been put in the Dalitz plot. These events also satisfy an additional fifth constraint that the mass of the three pions is fixed to that of the η . This was done to improve the energy resolution for the neutral pions in the rest system of the η . The Dalitz plot is uniformly populated if due account of the

efficiency is taken. It radically differs from the plot for $\eta \rightarrow \pi^+\pi^-\pi^0$, where the event density varies by an order of magnitude over the area of the plot (due to ρ -pole contribution) [8].

The square of the matrix element of decay (2) may be expressed as

$$|\mathcal{M}(\eta \rightarrow 3\pi^0)|^2 = C(1 + 2\alpha z) \quad (7)$$

up to second order terms in the pion energy E_{π^0} [9]. Formula (7) contains one free parameter α , apart from the normalisation C to the reaction cross-section and to the width of the decay $\Gamma(\eta \rightarrow 3\pi^0)$. z is the square of the relative distance to the center of the Dalitz plot

$$z = (r/r_{\max})^2 = \frac{6}{(m_\eta - 3m_{\pi^0})^2} \sum_{i=1}^3 \left(E_{\pi^0}^{(i)} - \frac{m_\eta}{3} \right)^2 \quad (8)$$

$r = r_{\max}$ at the points where one pion is at rest. The parameter α has been measured in an earlier work with a rather limited accuracy : $\alpha = -0.32 \pm 0.37$ [5].

The z -distribution of events obtained in the present experiment is given on Fig. 3a. It is in good agreement with the phase space of the decay. It is constant over the interval $0 < z \leq 0.7$; it decreases when z further increases as the corresponding circle starts to cross over the boundaries of the Dalitz plot.

This distribution divided by the phase space, i.e. the square of the matrix element, is shown on Fig 3b. To determine the slope parameter α , the distribution has been fitted with formula (7). The resulting value

$$\alpha = -0.022 \pm 0.023 \quad (9)$$

shows that the matrix element of the decay is constant with high accuracy. This is in agreement with theoretical calculations [10,11].

The number of decay (2) events has been determined from the number of events in the peak $N_{3\pi^0}$ (Fig.1b) taking the efficiency $\epsilon_{3\pi^0}$ into account. The influence of the same parameters which were used for the

analysis of decay (1) was also studied. The matrix element was taken constant for the determination of $\epsilon_{3\pi^0}$. The small deviation of α from zero (9) induces insignificant changes in efficiency (cf. § 7).

The dependence of $N_{3\pi^0}$ on the energy threshold is shown on Fig. 2c. It decreases by a factor four when E_{thr} goes from 0.25 GeV to 1.5 GeV. Nevertheless the effective number of events $N_{3\pi^0}/\epsilon_{3\pi^0}$ remains constant in the limits of statistical errors, changing by less than one per-cent (Fig. 2d). Variations of the other parameters do not change this number significantly. For example, a decrease of $N_{3\pi^0}$ by a factor two obtained by reducing the fiducial area of GAMS or by increasing its central hole does not entail more than a per-cent change in $N_{3\pi^0}/\epsilon_{3\pi^0}$. The ratio of the number of events for both η decay modes

$$R(3\pi^0/2\gamma) = \frac{N_{3\pi^0} \epsilon_{2\gamma}}{N_{2\gamma} \epsilon_{3\pi^0} BR^{\eta}(\pi^0 + 2\gamma)} \quad (10)$$

where $BR(\pi^0 + 2\gamma) = \Gamma(\pi^0 + 2\gamma)/\Gamma(\pi^0 + \text{all}) = 98.8 \%$, is even less sensitive to changes in event selection criteria. To determine the ratio (10) GAMS fiducial area has been limited to 40×24 cells (out of 48×32) in order to eliminate edge effects in the recording of gammas by the spectrometer. The resulting value is

$$R(3\pi^0/2\gamma) = 0.719 \pm 0.004 \quad (11)$$

The error is statistical only. To deduce from this number the ratio of decay probabilities $BR(\eta + 3\pi^0)/BR(\eta + 2\gamma)$ a series of small corrections and systematic effects have to be taken into account (cf. § 7).

5. DECAY $\eta + \pi^0\gamma\gamma$

The rare decay $\eta + \pi^0\gamma\gamma$ was first discovered through our previous work [1]. In the present experiment, events from reaction (5) with a gamma multiplicity of 4 have been analysed with a better program for the reconstruction of showers in GAMS [3]. This new analysis shows that the background coming from the intense channel $\eta + 3\pi^0$, which is observed at the left of the η peak in the mass spectrum of the $\pi^0\gamma\gamma$ system [1], is

largely due to errors in identifying strongly overlapping showers. The new program decreases this background significantly. The simulation with real showers [1] of decay (3) together with the background from decay (2) fully reproduces the results.

The background is also decreased by excluding events with one gamma either near the edges or near the central hole of GAMS for which the shower is not entirely absorbed in the spectrometer. As a result of such a cut, the background is decreased by a factor two at the cost of only a 20 % reduction of good events.

The final effective mass spectrum of the $\pi^0\gamma\gamma$ system is shown on Fig. 1c. In contrast with the previous result [1] the background around the η peak is small. The ratio of probabilities of decays (3) and (1) is

$$\frac{\Gamma(\eta \rightarrow \pi^0\gamma\gamma)}{\Gamma(\eta \rightarrow 2\gamma)} = (1.8 \pm 0.4)10^{-3} \quad (12)$$

in agreement with [1].

6. UPPER LIMIT TO THE RATE OF THE DECAY $\eta \rightarrow 3\gamma$

The effective mass spectrum of the system M^0 (5) with a visible gamma multiplicity of three shows a small peak in the region of the η mass in addition to the well known decay $\omega \rightarrow \pi^0\gamma + 3\gamma$ [1]. This peak is very sensitive to the threshold gamma energy in GAMS and it disappears when E_{thr} is larger than 1.5 GeV leaving the dominating ω peak only. Thus the decay channel $\eta \rightarrow 3\gamma$ is not seen in the spectrum.

It follows from the data an upper limit to the partial width of the C-violating decay (4)

$$\frac{\Gamma(\eta \rightarrow 3\gamma)}{\Gamma(\eta \rightarrow 2\gamma)} < 1.2 \cdot 10^{-3} \quad (13)$$

at the 95 % confidence level.

7. THE PARTIAL WIDTHS OF THE NEUTRAL η DECAYS

The fake peak that is observed in the 3γ mass spectrum at the η position is due to the leakage of a small number of 2γ events into a class of events with a larger apparent multiplicity because the presence of noise in the counters and in the electronic chain which simulate extra low energy γ [12]. This effect has to be taken into account for the determination of the true number of 2γ events. The same effect is observed in the case of the $3\pi^0$ channel where 6 % of the 6γ events leak into the 7γ class: a fake peak is also seen in the 7γ mass spectrum at the η position in analogy with the 3γ spectrum.

The corresponding corrections for this effect largely cancel in the evaluation of the ratio of decay probabilities. The final correction to the ratio $R(3\gamma/2\gamma)$ is 1.6 % (cf. table I).

The main corrections to the ratio (11) are due to the absorption of gammas in the production target and in the scintillators behind it. They are given in table I. Although the probability of conversion of one gamma is only 3 % the total correction amounts to 13 %, being larger for decay (2) with four gammas more than in decay (1).

Another small (1 %) correction to the ratio (11) arises because a hardware processor cuts events with a radial moment less than 350 MeV [1]. This has been determined through simulation with real showers.

The total correction to the measured ratio (11) amounts to $(14.2 \pm 1.2)\%$ including systematic errors (table I). The ratio of partial widths of decays (2) and (1) is

$$\frac{\Gamma(\eta \rightarrow 3\pi^0)}{\Gamma(\eta \rightarrow 2\gamma)} = 0.822 \pm 0.009 \quad (14)$$

The previous result was 0.81 ± 0.05 [4].

The partial widths of the η neutral decay channels evaluated through the measured ratios (14) and (12) are gathered in Table II.

8. CONCLUSION

A high precision determination of the partial widths of the η neutral decay channels is presented. The comparison of the measured matrix element of the channel $\eta \rightarrow 3\pi^0$ with theoretical calculations might give an evaluation of pion final state interactions [11,15] and, perhaps, an estimate of the contribution of different mechanisms of G-parity violation in strong interactions to this decay.

The decay $\eta \rightarrow \pi^0\gamma\gamma$, first observed two years ago, is the least studied η neutral decay channel. The knowledge of its matrix element, which would require a substantial increase in statistics, would be of great interest. Its comparison with the predictions from different models like vector meson dominance, scalar meson dominance and others [1] could allow a definite choice to be made between them.

We would like to thank B.L. Ioffe for discussions of our results. We thank the IHEP and CERN directorates for their support of the GAMS program.

FIGURE CAPTIONS

Fig.1 Effective mass spectra of: a) 2γ , b) $3\pi^0$, c) $\pi^0\gamma\gamma$, produced in reaction (5). The arrow points to the tabulated value of the η mass.

Fig.2 a) Number of $\eta + 2\gamma$ events as a function of the threshold gamma energy. The curve indicates the behaviour of the efficiency $\epsilon_{2\gamma}$. b) Effective number of $\eta + 2\gamma$ decay events. c) and d) Idem for the decay $\eta + 3\pi^0$.

Fig.3 a) z -distribution of $\eta + 3\pi^0$ events on the Dalitz plot (8). The dashed line shows the phase space ($|\mathcal{M}|^2 = \text{constant}$). b) z -dependence of the square of the matrix element of the $\eta + 3\pi^0$ decay. The normalisation is $|\mathcal{M}|^2 = 1$ at $z = 0$. The straight line shows the fit (7) with $\alpha = -0.022$.

TABLE I

Summary of corrections to $R(3\pi^0/2\gamma)$ (in %)

Gamma absorption	
- in the H_2 target	7.5 ± 0.3
- in the counters behind the target	5.0 ± 0.6
Gamma conversion in air	0.4 ± 0.2
Loss of events due to wrong γ multiplicity assignment	1.6 ± 0.4
Radial moment cuts by the processor	-0.8 ± 0.2
Systematic error on $\epsilon_{3\pi^0}/\epsilon_{2\gamma}$	0.0 ± 0.5
Contribution of $\alpha \neq 0$	0.02 ± 0.02
Systematic errors evaluated through the variation of	
- GAMS dimensions	0.0 ± 0.5
- the dimensions of the central hole in GAMS	0.0 ± 0.2
- t cuts	0.0 ± 0.3
Total correction	14.2 ± 1.2

TABLE II

Partial widths of the neutral decays of η

Channel	$\Gamma_i/\Gamma(\eta \rightarrow \text{neutrals})$	$BR_i(\%)*)$	$\Gamma_i(\text{KeV})^{**)}$
$\eta \rightarrow 2\gamma$	0.549 ± 0.004	38.9 ± 0.4	470 ± 120
$\eta \rightarrow 3\pi^0$	0.450 ± 0.004	31.9 ± 0.4	380 ± 100
$\eta \rightarrow \pi^0\gamma\gamma$	0.0010 ± 0.0002	0.071 ± 0.017	0.85 ± 0.28
$\eta \rightarrow 3\gamma$	< 0.0007	< 0.05	< 0.6

*) $BR(\eta \rightarrow \text{neutrals}) = (70.9 \pm 0.7)\%$ [4].

***) $\Gamma(\eta \rightarrow \text{all}) = (1.2 \pm 0.3) \text{ MeV}$ [13,14].

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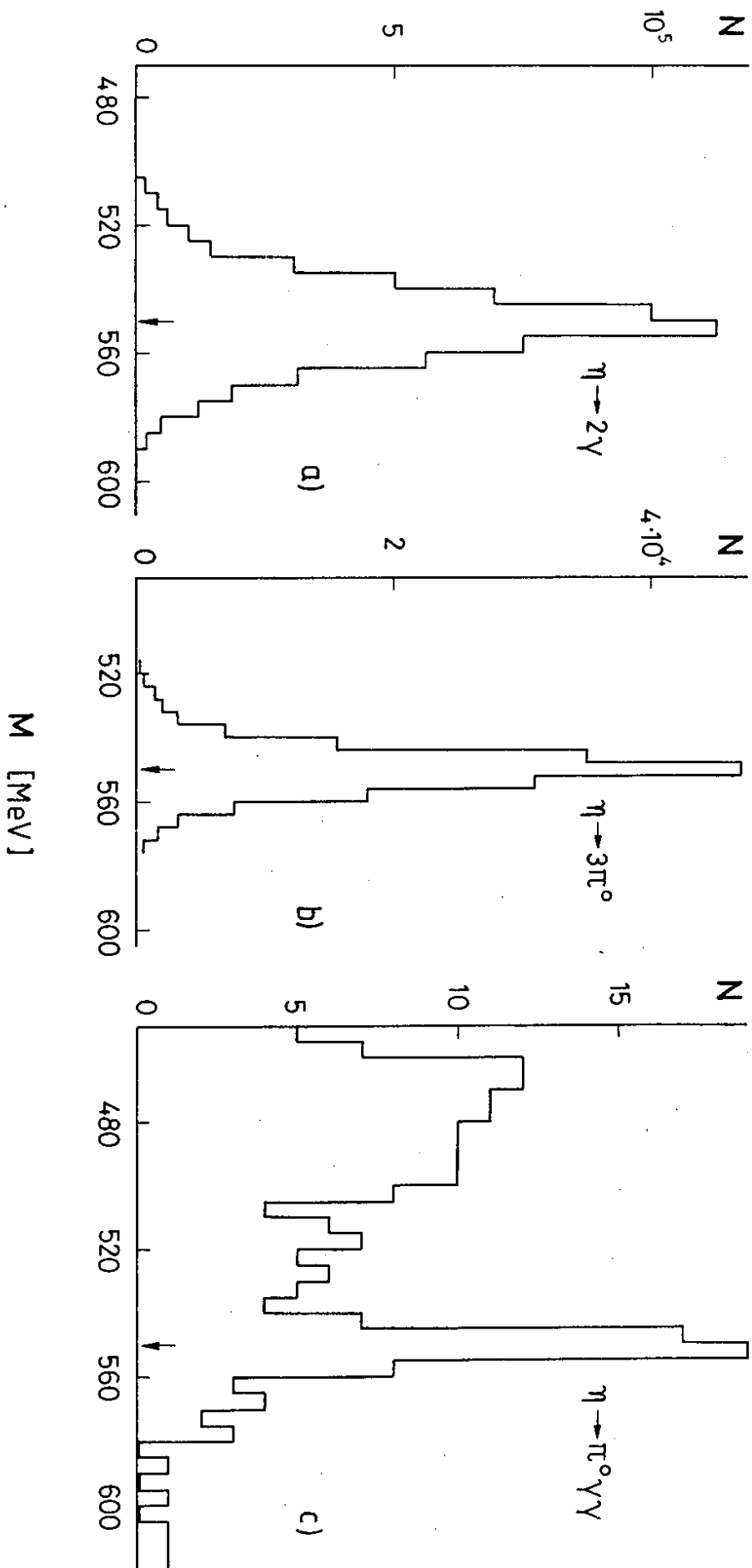


Fig. 1

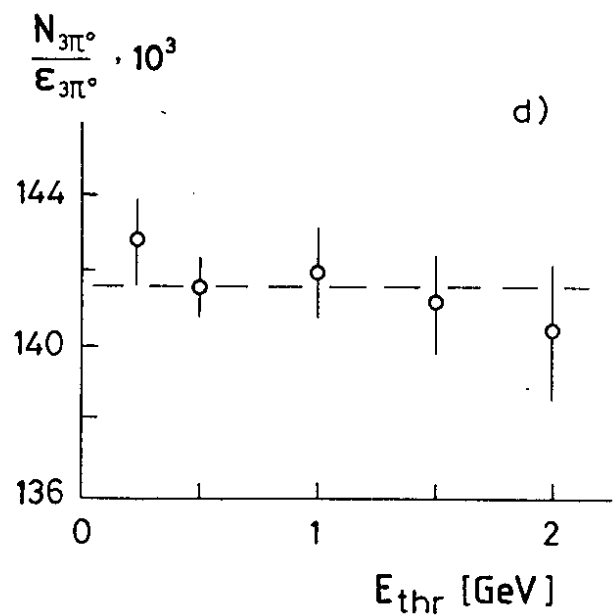
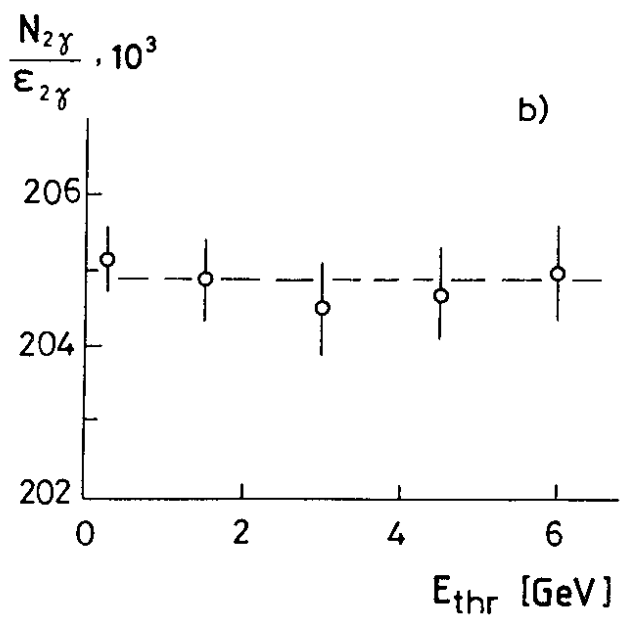
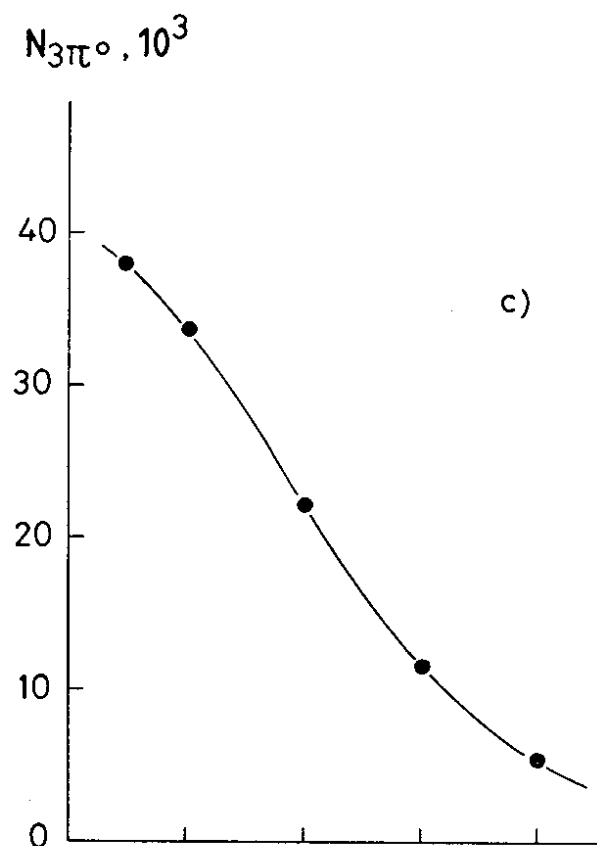
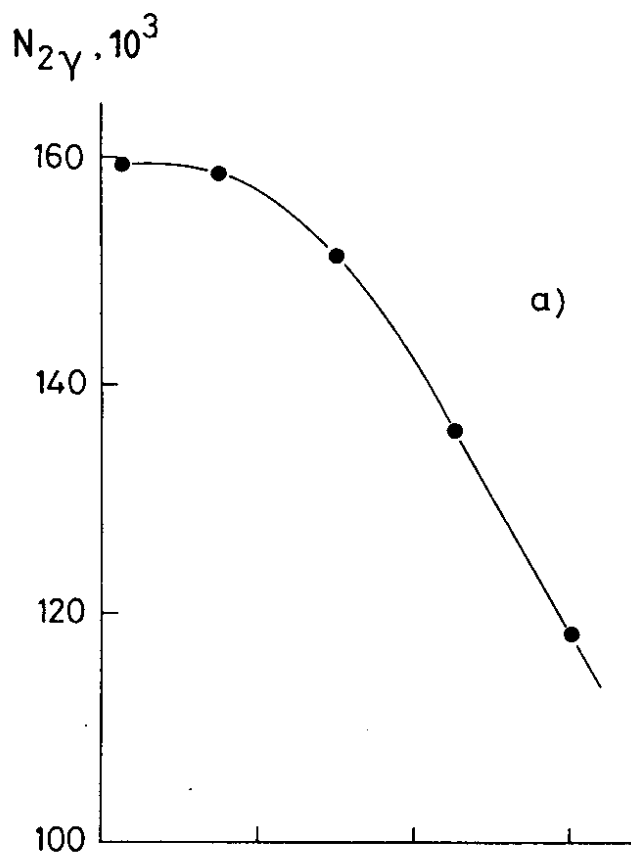


Fig. 2

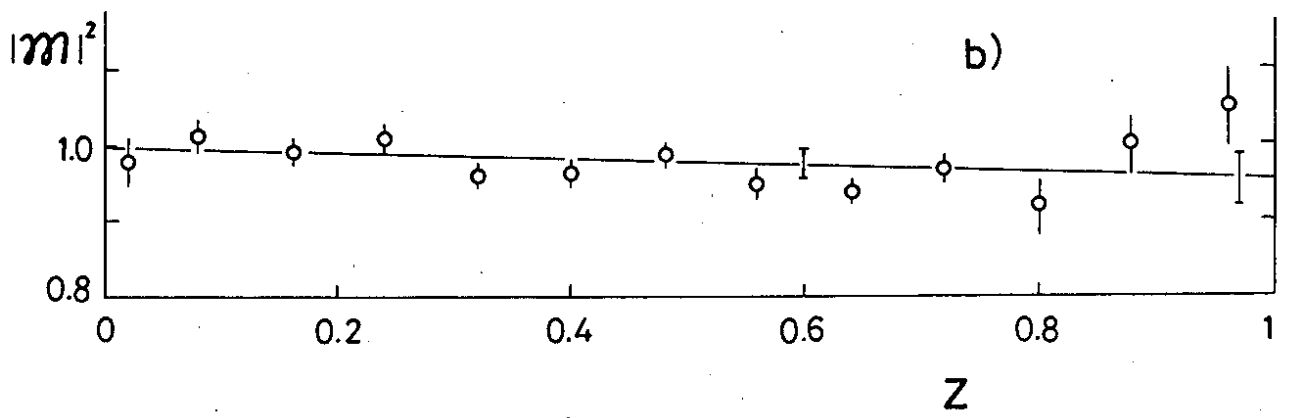
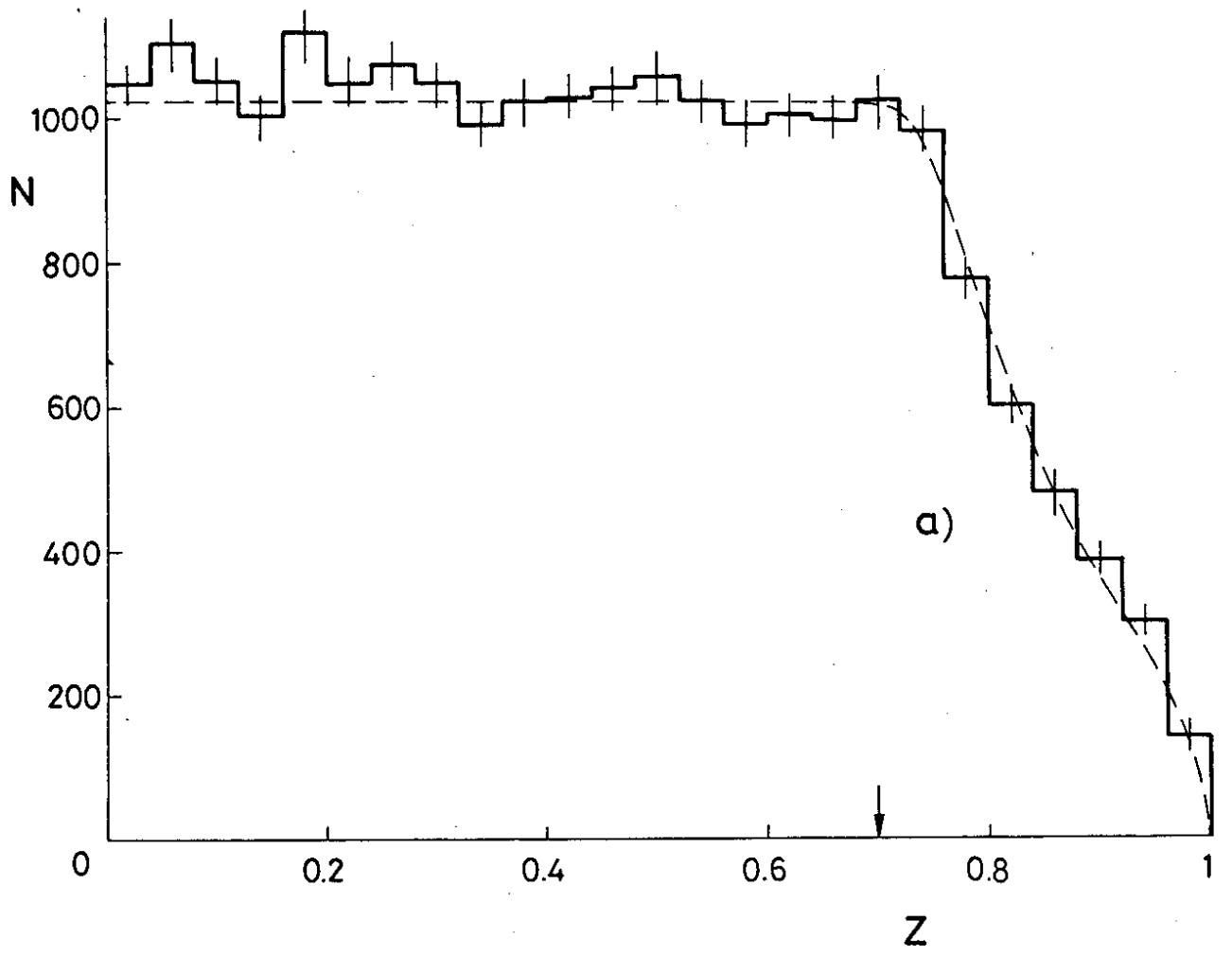


Fig. 3