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PHOTOPRODUCTION AND NEUTRAL DECAY MODES OF THE η PARTICLE

by

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I am going to describe an experiment which is being done in Frascati by the following group:

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whose aim is to study some properties of production and decay of the η particle.

The η particle is one of the most recent and in many respects more unexpected objects among the pion resonances discovered in these years. The modes of decay of this particle, as well as the behaviour of the production cross-section, encourage the experiments and the theory to look deeper into the subject.

The quantum numbers of the η are now known to be 0^{-+} (spin 0; parity -1; G-parity +1).

Among the problems relevant to a better understanding of the η are the following:

a) The measurement of the production cross-section, σ_η, in strong channels and in photoproduction as a function of energy and angle.

b) The branching ratios among the different decay modes.

c) The width Γ_η , i.e. the mean-life.

The aim of this experiment is to contribute to points a) and b). I shall briefly present the situation on these points.

At present there is not a systematic set of measurements of the production cross-section σ_η at different energies in any reaction. The few known values of σ_η do not permit us to draw any conclusions and there is a puzzle in the behaviour of σ_η near threshold, in the reaction

$$K^- + p \rightarrow \Lambda + \eta .$$

In fact σ_η is rather high $(630 \pm 110)\mu b$ 20 MeV above threshold, and drops to less than 20 μb at 60 MeV above the threshold. This unexpected behaviour is more reminiscent of a composite system than of an elementary particle; however the importance of the forbidden decay $\eta \rightarrow \pi^+\pi^-\pi^0$ seems to indicate the opposite. Under these circumstances an exploration of the production cross-section in some other channel is rather important.

The fact that the quantum numbers of the η (spin, parity and charge-conjugation) are the same as for the pion suggests that one ought to measure σ_η around the region of the pion resonances, to see if σ_η also passes through a resonance. If σ_η has the same resonances, it would indicate that the isobar excited states can also decay through an η particle. Measurements of this kind are particularly important in view of so-called "higher symmetry" theories.

In regard to the branching ratios, the following is known:

a) The ratio of the charged modes ($\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$) to the total of the neutral modes ($\gamma+\gamma$, $3\pi^0$, $\pi^0+\gamma+\gamma$).

b) The ratio of the mode $\pi^+\pi^-\pi^0$ to the mode $\pi^+\pi^-\gamma$ both with an error of ~ 20%.

There is no direct measurement of the division between the various neutral decay modes.

A clear picture of the branching ratios would be useful in understanding this particle.

Calculations of the branching ratios have been done by many authors. Comparison between calculations and experimental values can in particular give information on the following points:

a) validity of higher symmetry models;

b) coupling constants among various particles ($\eta\rho\rho$, $\gamma\rho$, $\rho\pi\gamma$, etc.) which appear in the calculations.

The above points are the motivation for our research, namely:

- Measurement of the photoproduction cross-section of the η-particle in the process

$$\gamma + p \rightarrow \eta + p \qquad (1)$$

- Measurement of the relative importance of the γ+γ decay mode with respect to the other neutral decays.

The experimental arrangement is shown in fig. 1.

The γ-ray beam from the Frascati electron-synchrotron hits the 7 cm liquid hydrogen target H_2. The proton channel P detects the recoil proton from reaction (1) at an angle of $25.2° \pm 1.3°$ in the laboratory; the energy of the protons is measured by their range in the spark chamber (s.c.).

The counter set of the proton telescope can eliminate the relativistic particles and most part of the pions by means of the plexiglas Čerenkov counter C_{plx} in anticoincidence. To be sure that after this there is not important pion contamination, we also make a pulse-height analysis in two of the scintillation counters of the telescope, taking into account that, for a given range, protons have a specific ionization about twice as large with respect to pions. Elaborations of the data following these lines make us confident that there is practically no pion contamination in our measurements.

On the line-of-flight of the η there is a total absorption lead-glass Čerenkov counter C to detect γ rays in coincidence with the recoil protons; an anticoincidence counter 5 shielded by 6-7 gr/cm^2 wood is in front of C. The energy of the γ rays detected by C is measured by a pulse height analyser and recorded on the photograph of the spark chamber, by means of neon lamps. γ rays with energy < 200 MeV do not trigger the s.c. In this way protons from single pion photoproduction are avoided. The pulse height versus energy calibration of C was made with a monochromatic electron beam selected by the Frascati pair spectrometer.

With the geometrical arrangement and the absorbers chosen, we can detect the η produced in the reaction (1).

This can be done essentially by two different methods, briefly described in the following.

1. The step method

The energy E_0 of the electron synchrotron and the absorbers in the proton telescope are chosen in such a way that protons due to process (1) can reach at most the centre of the spark chamber (an appropriate wedge-shaped shim was inserted). When one plots the number of the protons as a function of their energy, a step appears due to process (1). The background processes (mostly multipion photoproduction) do not give rise to any step.

Along the line of flight of the η the process $\gamma + p \to \eta + p$ when $\eta \to \gamma + \gamma$ produces a γ-ray spectrum which is almost monochromatic, centred around ≈ 560 MeV; instead the decay $\eta \to 3\pi^0$ (and $\eta \to \pi^0 + \gamma + \gamma$) produces γ-rays which have a smooth spectrum ending at about 500 MeV. If one chooses only those protons which are in coincidence with γ rays of energy greater than 400 MeV, one obtains a step in the proton distribution predominantly due to η's which decay only via the $\gamma + \gamma$ mode. For γ-ray energies less than 400 MeV, the step is due to those η's which decay via three-body modes.

The multipion photoproduction gives rise to a spectrum similar to the one due to the process $\eta \to 3\pi^0$. (See fig. 4a)

2. The γ method

This method has already been used in a preliminary experiment by us[2)]. A relatively small energy band of protons is chosen, and we look at the spectrum of the γ rays which are in coincidence.

The experimental results of the step method are shown in figs. 2 and 3. Fig. 2a gives the proton distribution (corrected for nuclear absorption) for the γ-ray energy greater than 400 MeV, essentially the $\gamma + \gamma$ mode.

The multipion background was studied experimentally under kinematical conditions, in which the η could not be observed. All these background corrections (e.g. solid line fig. 2a) are extrapolated to the η region from a single function. Independent phase-space calculations of multipion production give very similar results.

The difference between the experimental results and the solid line of fig. 2a gives, in fig. 2b, the step distribution of the protons, as one expects from reaction (1). One sees that the mass of the η appears to be 550 + 6 MeV, in good agreement with the known mass, 548 ± 1 MeV [3)]. This makes us confident that we are really observing the η. The expected shape for the step was determined experimentally from the single photoproduction of π^0 mesons with the same equipment.

Figs. 2c and 2d show a multipion background measurement. Figs. 3a, 3b, 3c, and 3d are similar to fig. 2, but the energy of the γ ray in the Čerenkov C was between 240 and 400 MeV, corresponding to three-body decays of the η. In this case the determination of the η contribution is more uncertain than before due to the increased percentage of multipion processes.

Some of the spectra we obtained with the γ method are shown in fig. 4. Fig. 4a shows a spectrum taken where the η cannot contribute due to kinematical requirements. Figs. 4b, 4c, 4d, corresponding to different production energies show spectra where the η is present. In these cases, it is not possible to obtain a good fit with a line like the full line of fig. 4a (multipion production only); one must add a Gaussian centred at 560 MeV, having a width arising from the experimental resolution. In the upper part of each figure the multipion background has been subtracted. As we can see, the distributions appear to have the shape expected from the process $\eta \to \gamma + \gamma$ plus a contribution from the process $\eta \to 3\pi^0$.

It is important to note that a contribution to the three body neutral decays of the mode $\pi^0 + \gamma + \gamma$ is not excluded from our experiment and is not forbidden by selection rules. The decay $\pi^0 + \gamma + \gamma$ is a process of the same order, α^2, as the $\gamma + \gamma$ mode, but it should be depressed by phase space and the strength of the $\pi\rho\omega$ interaction. An estimate may be indirectly deduced from a paper of Gell-Mann, Sharp, and Wa er10). However, we have not found any theoretical consideration of this decay mode. The average efficiency of our apparatus for detecting the $\pi^0 + \gamma + \gamma$ and the $\pi^0 + \pi^0 + \pi^0$ decay mode is approximately the same. To get a quantitative evaluation of the different decay modes of the η, we have obtained the "best fit" values of a and b for the distributions of figs. 4b, 4c, 4d with curves of the type

$$a(\varphi_1 + b\varphi_2)$$

where φ_1 and φ_2 are the distributions expected from the decay modes $\eta \to 3\pi^0$ and $\eta \to \gamma + \gamma$, respectively. The curves obtained are shown in the upper part of figs. 4b, 4c, 4d, and it can be seen that they fit rather well. We wish to point out that these three curves are indpendent measurements of the branching ratio.

If we assume from theory that the $\pi^0 + \gamma + \gamma$ mode is negligible, then the above results lead us to believe we are observing, the $\eta \to 3\pi^0$ mode as well as the $\eta \to \gamma + \gamma$ mode. However, in Table I, we report the branching ratio in the form

$$R = \frac{(\gamma + \gamma)}{(3\pi^0) + (\pi^0 + \gamma + \gamma)} \qquad (2)$$

as obtained from our two methods. In the same Table I, the results of the cross-section are also reported.

One can see that the values of R are equal within the errors. In obtaining R, a correction was applied for the contribution of the decay $\pi^+ + \pi^- + \pi^0$ whose ratio to all the neutral modes is known4) as being 1 : 3.

We also can estimate $d\sigma/d\Omega$ and R by using the γ method on the events with protons which did not enter the spark chamber, but traversed all the counters (T_p = 248 ± 11 MeV). The results in this case are less certain, due to some possible larger systematic errors. These results are reported in parenthesis in Table I, and one cannot yet be sure that they indicate a change of the cross-section with the energy. Our final average result on the branching ratio

$$R = 0.8 \pm 0.25 \qquad (3)$$

does not disagree with the lower limit (0.9 ± 0.3) given by Chretien et al.5) for the ratio $(\gamma + \gamma)/(3\pi^0)$.

The branching ratio R found in our measurements when combined with the reported values 4) of $\frac{\text{all neutrals}}{(\pi^+\pi^-\pi^0)} = 3.0 \pm 0.5$ and $\frac{(\pi^+\pi^-\gamma)}{(\pi^+\pi^-\pi^0)} = 0.26 \pm 0.08$ enables one to list the following percentages for the various decay modes of η :

$(\pi^0\pi^0\pi^0) + (\pi^0\gamma\gamma)$: (40 ± 14)%
$(\gamma\gamma)$: (31 ± 11)%
$(\pi^+\pi^-\pi^0)$: (23 ± 4)%
$(\pi^+\pi^-\gamma)$: (6 ± 2)% .

The experimental values are compared with some theoretical prediction in Table II.

From our measurements we obtain that the ratio of π^0 photoproduction 6) to η photoproduction at the same centre-of-mass energy and angle is

$$\left(\frac{d\sigma}{d\Omega}\right)_{105^\circ,\pi^0} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{105^\circ,\eta} \simeq 8 \qquad (4)$$

The ratio of pion scattering 7) to pion production 8) of the η is also of the same order. For example:

$$\frac{\sigma(\pi^- + p \rightarrow \pi^- + p)\ 1015\ \text{MeV}}{\sigma(\pi^- + p \rightarrow n + \eta)\ 1015\ \text{MeV}} = \frac{18\ \text{mbarn}}{0.5 \times 3.2\ \text{mbarn}} \cong 11. \qquad (5)$$

As we see, the η is produced rather abundantly, and the equality of these ratios could indicate that the type of interaction which exists between the η and a nucleon is similar to that for a π and a nucleon. The above ratio, ~ 8, of photoproduction cross-sections is not inconsistent with a calculation by Fujii and Holloway 8) based on Unitary Symmetry Models.

TABLE I

Results of the Present Experiment (reaction $\gamma + p \rightarrow \eta + p$)

E_0 is the energy of the electrons in the synchrotron; $k \pm \Delta k$ is the lab. energy and energy interval of the photons hitting the proton; $T_p \pm \Delta T_p$ is the energy and energy interval for the proton; Θ^* is the c.m. angle of the η ; $(\frac{d\sigma}{d\Omega} \cdot \frac{\Gamma\gamma\gamma}{\Gamma_{total}})_{c.m.}$ is the differential cross-section for photoproduction of η's decaying in the $\gamma + \gamma$ mode; $d\sigma/d\Omega$ is the c.m. differential cross-section for η photoproduction [3.2 times the preceding values ; we obtain from the branching ratio measurements and other results that $(\Gamma\gamma\gamma/\Gamma_{total}) = \frac{1}{3.2}$] . $R = \frac{(\gamma+\gamma)}{(3\pi^0) + (\pi^0+\gamma+\gamma)}$ is the branching ratio. The numbers in parenthesis are less certain, see text. The errors include an estimate for our uncertainties in solid angle, efficiency, and background $^{1)}$.

E_0 MeV	$k \pm \Delta k$ MeV	$T_p \pm \Delta T_p$ MeV	Θ^*	$\frac{d\sigma}{d\Omega}\frac{\Gamma\gamma\gamma}{\Gamma tot}\ \frac{cm^2}{ster}$	$\frac{d\sigma}{d\Omega}\ \frac{cm^2}{ster}$	R	Method	Dosis eq.quanta
1000	978±22	278±18	106°±5°	$7.6 \pm 1.6 \times 10^{-32}$	$\sim 24 \times 10^{-32}$	0.78±0.34	γ-method	2.05×10^{14}
1000	978±22	278±18	106°±5°	$6.2 \pm 1.3 \times 10^{-32}$	$\sim 20 \times 10^{-32}$	0.83±0.31	step	3.5×10^{14}
1000	939±14	248±11	103°±5°	$(11.5 \pm 2.6 \times 10^{-32})$	$\sim(36 \times 10^{-32})$	(0.53±0.22)	γ-method	1.53×10^{14}
950	937±13	247±10	103°±5°	$(10 \pm 2.1 \times 10^{-32})$	$\sim(32 \times 10^{-32})$	(0.88±0.58)	γ-method	1.95×10^{14}

TABLE II

A Comparison of Experimental Values from our Results and Theoretical Prediction of Decay Ratios of the η

Decay ratio	Experimental value	Theoretical value	Authors	Basis of theoretical calculations
$\frac{\gamma\gamma}{\pi^+\pi^-\pi^0}$	1.3 ± 0.4	0.6 to 2.9	Barrett and Barton 9)	Unitary Symmetry Model 10,11) (The uncertainty is due to the uncertainty in the experimental value of the π^0.)
$\frac{3\pi^0}{\pi^+\pi^-\pi^0}$	$\leq 1.7 \pm 0.6$ *)	< 1.73 1.5 to 1.73	Feinberg and Pais 12) Wali 13) and Bég 14)	Similarity of the final states for K and η decays into 3π.
$\frac{\gamma\gamma}{\pi^+\pi^-\gamma}$	5.0 ± 1.6	≈ 4 8	Gell-Mann 10,15) Brown and Singer 16)	Unitary Symmetry Model " " "

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*) The equality holds if the $\pi^0\gamma\gamma$ decay is small with respect to the decay into $3\pi^0$.

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FIGURE CAPTIONS

Fig. 1 Experimental arrangement1): The wedge-shaped shim in the proton channel corrects for the angular dependence of the proton energy.

Fig. 2 Energy spectra of protons in coincidence with γ rays of energy > 400 MeV: (2a) is when the process $\gamma + p \rightarrow \eta + p$ is permitted kinematically; the full line is the expected contribution from multipion processes; (2b) shows the "η-events", namely the difference between the experimental points and the multipion background. The full line is the expected shape of the proton spectrum from the process $\gamma + p \rightarrow X^0 + p$ if X^0 has a mass of 550 MeV, that of the η. The dotted lines are for X^0, having a mass 530 and 570 MeV; (2c) and (2d) are the same as (2a) and (2b), except that the process $\gamma + p \rightarrow \eta + p$ is forbidden kinematically. This is a null check.

Fig. 3 Energy spectra of protons in coincidence with γ-rays of energy between 240 and 400 MeV: The step of fig. (3b) must be due to a three-body decay mode of the η (e.g. $\eta \rightarrow 3\pi^0$ and/or $\eta \rightarrow \pi^0 + \gamma + \gamma$). Figs. (3c) and (3d) are again a null check.

Fig. 4 Spectra obtained with the γ-ray method from the lead-glass Čerenkov detector and the multi-channel analyser: (4a) is a typical "non-η spectrum". In abscissae the energy in MeV of the γ ray detected in the Čerenkov C is given. The full line is the multipion contribution in this case obtained by a best fit to the experimental points. The upper part of the figure shows the difference between the experimental points and the multipion processes. Figures (4b), (4c) and (4d) are "η spectra" at different energies. The full lines in the lower part of each figure are the expected contributions from multipion processes. The upper part shows the difference between the experimental points and the full line. They are "best fitted" by a function of the form $a(\varphi_1 + b\varphi_2)$. See text.

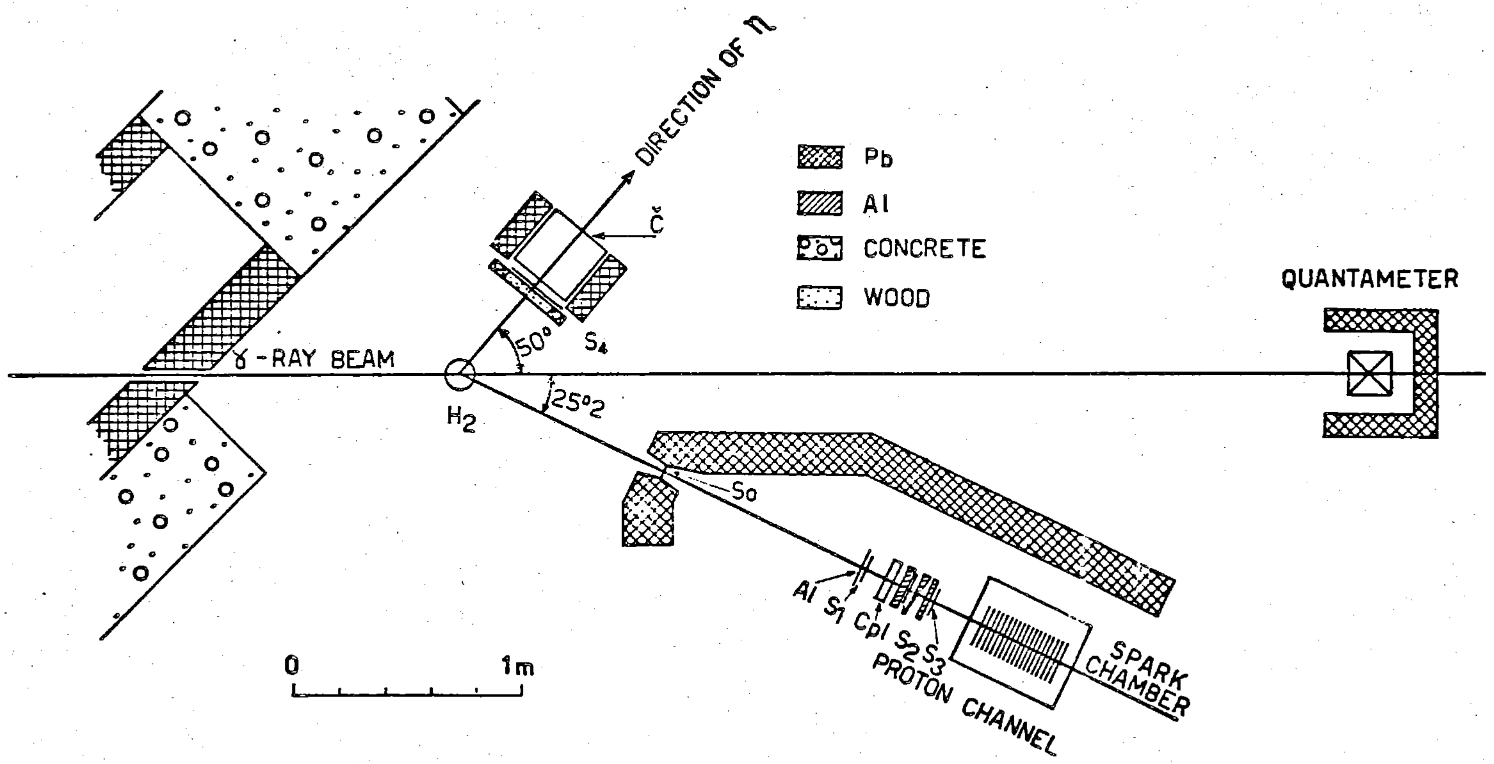


FIG 1 EXPERIMENTAL ARRANGEMENT

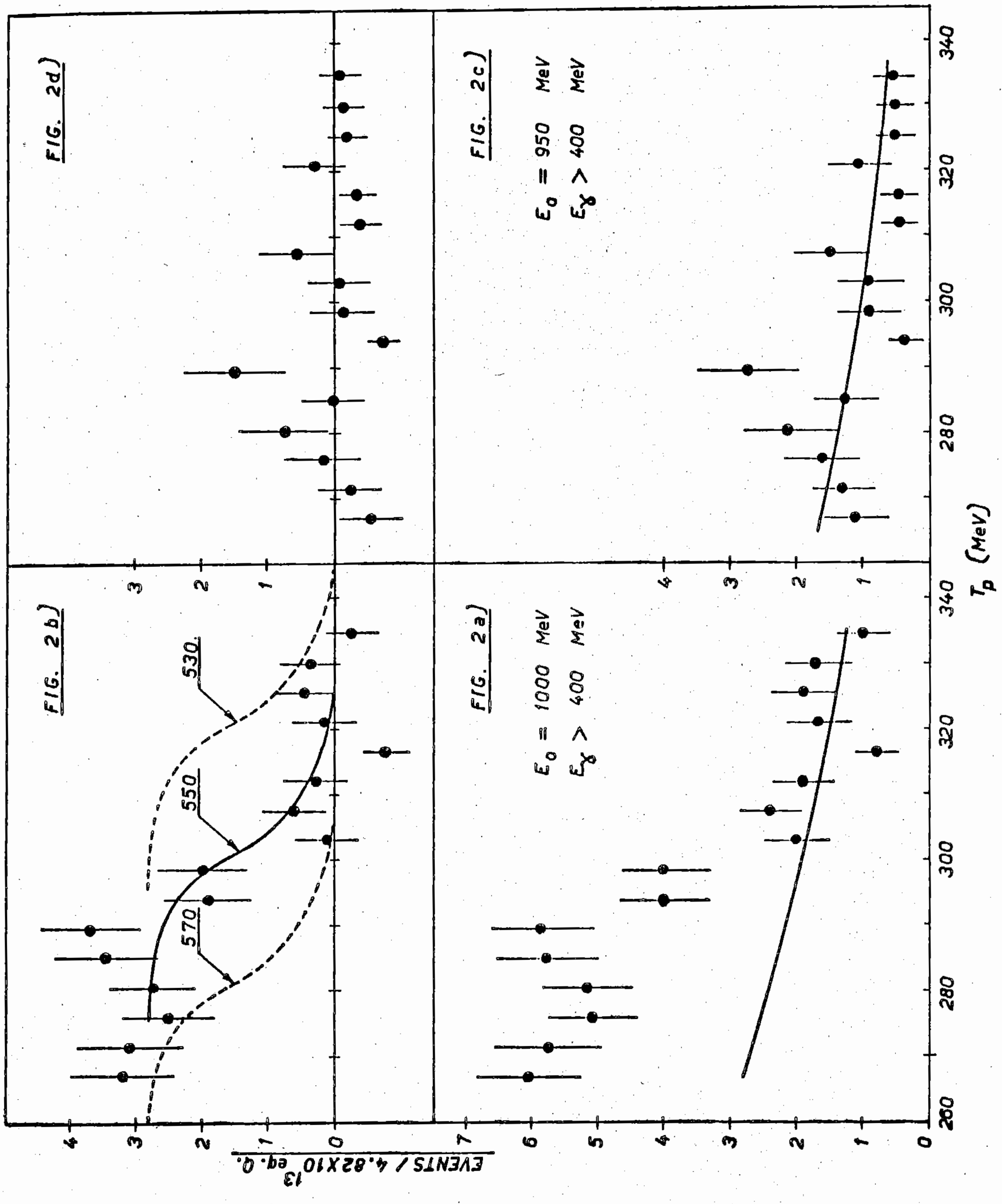
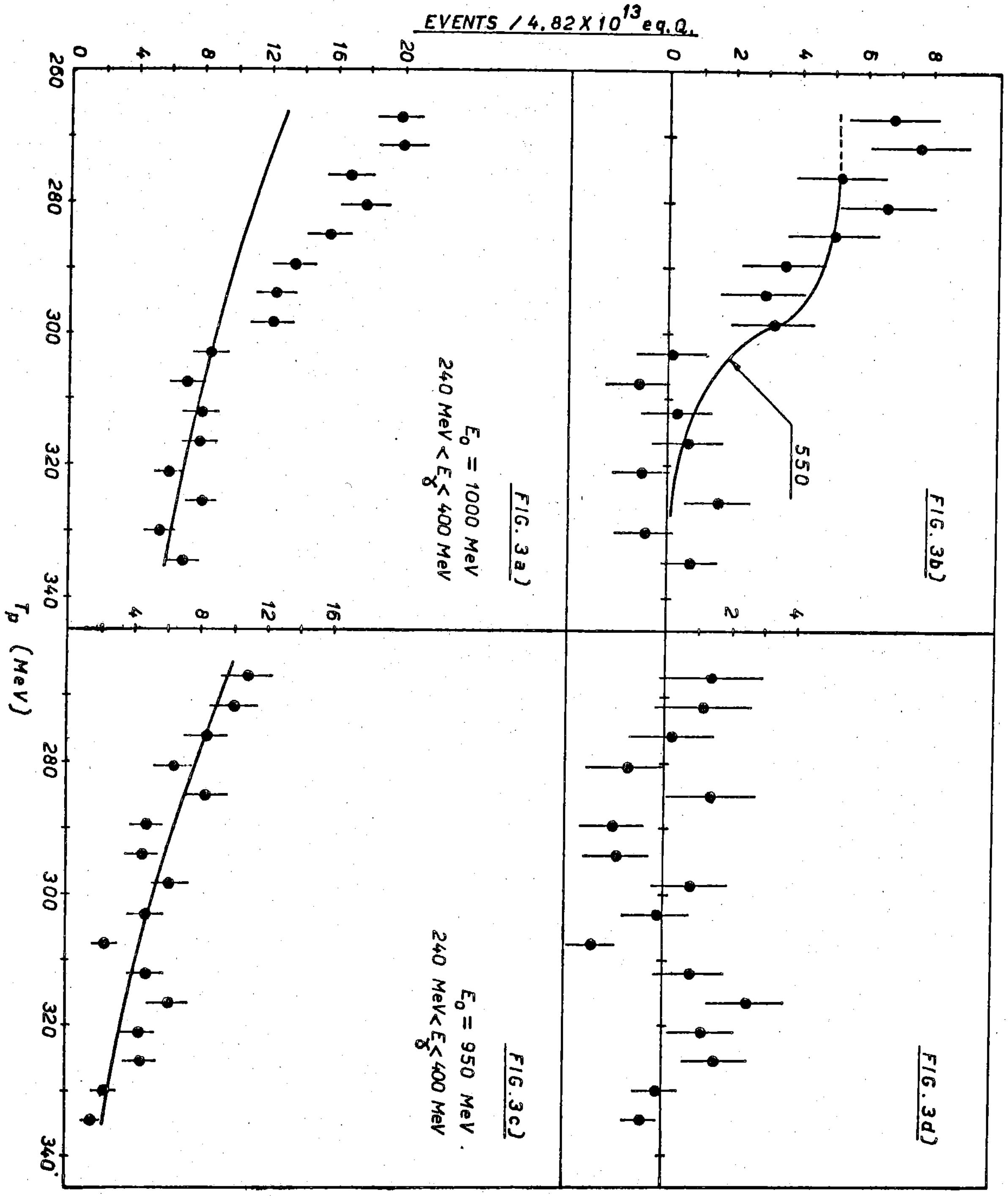


FIG. 2d)
FIG. 2b)
530
550
570
FIG. 2c)
E_o = 950 MeV
E_γ > 400 MeV
FIG. 2a)
E_o = 1000 MeV
E_γ > 400 MeV
EVENTS / 4.82X10^{13} eq. Q.
T_p (MeV)
260
280
300
320
340
0
1
2
3
4
5
6
7


EVENTS / 4.82 X 10^{13} eq.Q.
FIG. 3a)
E_0 = 1000 MeV
240 MeV < E_γ < 400 MeV
FIG. 3b)
550
FIG. 3c)
E_0 = 950 MeV.
240 MeV < E_γ < 400 MeV
FIG. 3d)
T_p (MeV)
260
280
300
320
340
0
4
8
12
16
20
2
6

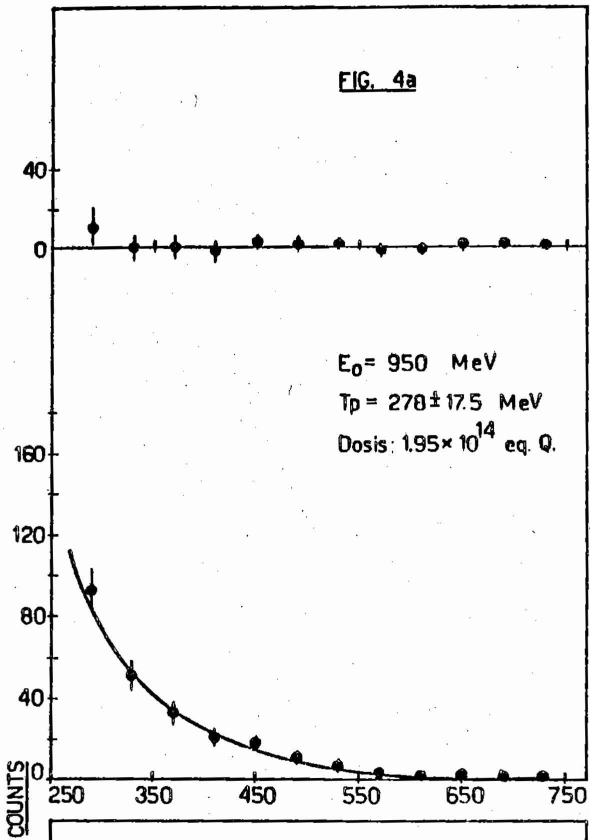


FIG. 4a

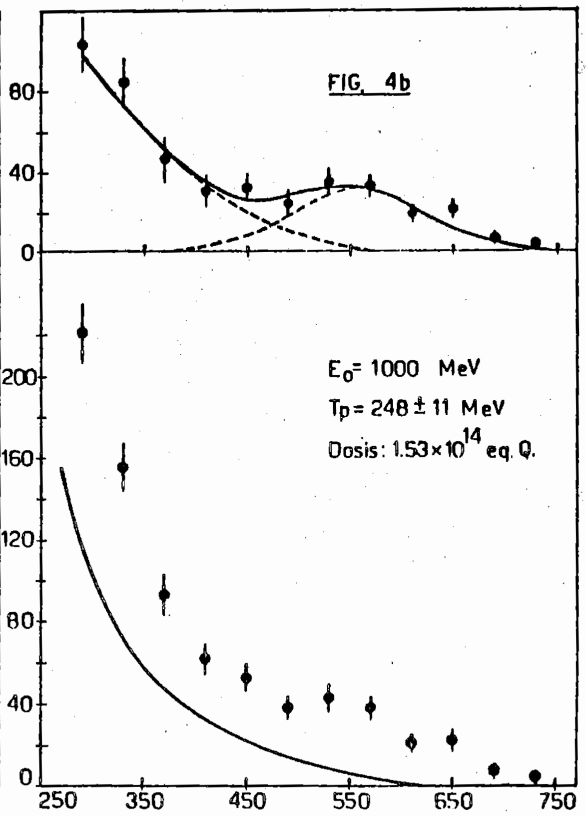


FIG. 4b

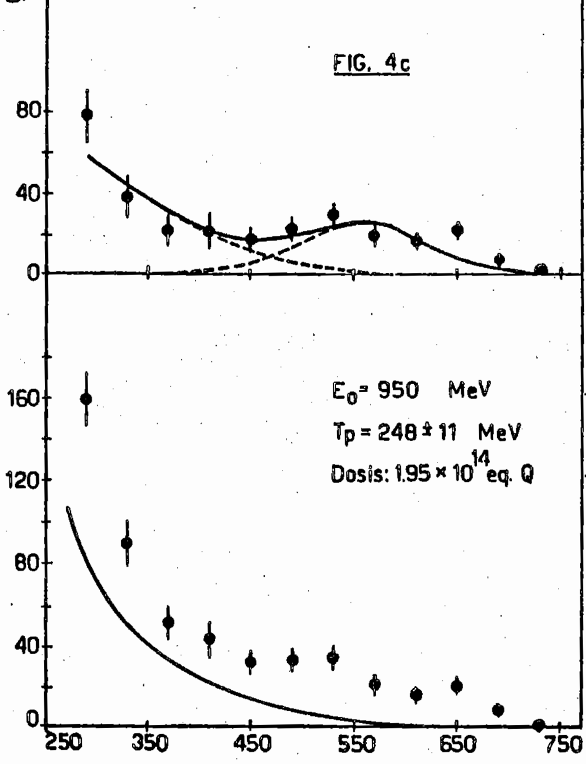


FIG. 4c

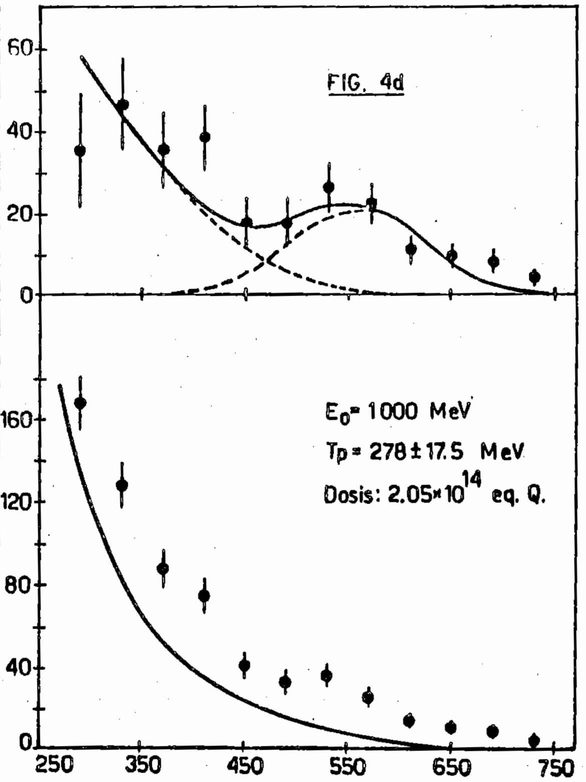


FIG. 4d