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π^0 AND η SPECTRA FROM $p\bar{p}$ ANNIHILATIONS AT REST

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ABSTRACT

The low-energy part of the π^0 spectrum associated with $p\bar{p}$ annihilation at rest was measured in order to search for bound baryonium-like states. The upper limit for reaching such states via the emission of monochromatic π^0's was found to be 8% per annihilation in the mass region of 1650 MeV. The low-energy part of the η spectrum from $p\bar{p}$ annihilations at rest was also observed.

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The search for bound baryonium states has so far been done mainly by investigating the γ spectra associated with $p\bar{p}$ annihilation at rest [1-3]. Owing to the relative weakness of the electromagnetic vertex involved in reactions of the type $p\bar{p} \to \gamma X$ it seems probable that, for sufficiently deeply bound states X, reactions involving a π^0 instead of a γ ($p\bar{p} \to \pi^0 X$) have higher probability. Annihilations of this type have so far never been searched for experimentally.

Here we shall describe an experiment where the reaction $p\bar{p} \to \pi^0 X$ was studied in liquid hydrogen for a limited range of π^0 energy. Results are also presented for the low-energy part of the η spectrum.

The experimental set-up has been described earlier [3] and will therefore only be sketched briefly here. A $\bar{p}$ beam was stopped in a 25 cm long liquid-hydrogen target of 10 cm diameter. The beam diameter at the maximum of its stop distribution was about 7 cm. The target was viewed by two NaI γ detectors, a modular NaI system described by Blüm et al. [4], and a 10 in. × 12 in. NaI crystal described by Suffert et al. [5]. The target was surrounded by an annihilation multiplicity counter (charged particles and photons), which, however, was not used in the following evaluation owing to the limited statistics. The two γ detectors were placed opposite to each other such that two γ's could be measured in coincidence when the angle $\phi_{\gamma_1\gamma_2}$ between them was larger than 155°. The solid angle of the 10 in. × 12 in. detector was defined by a 10 cm thick lead collimator of 15 cm diameter. The acceptance of the modular system was limited by the requirement that the shower centre should not be located in the peripheral modules (cf. ref. 4). Assuming a point-like source, the fractional solid angle of the 10 in. × 12 in. crystal was $\Omega_1 = 0.69\%$ and that of the modular system was $\Omega_2 = 1.74\%$. Charged particles were vetoed by plastic scintillators in front of the detectors. The apparatus is shown schematically in fig. 1. Whenever one of the γ detectors gave a trigger both systems were read out. Cuts were only applied in the off-line analysis.

With the above-mentioned solid angles and assuming $N_\gamma = 3.93$ γ's per annihilation on the average [6], the probability for a single trigger is $N_\gamma(\Omega_1 + \Omega_2)$, and for the coincidences we expect in first approximation $N_\gamma(N_\gamma - 1)\Omega_1\Omega_2 = 1.38 \times 10^{-3}$ $\gamma\gamma$'s per annihilation. With a total of $N_{p\bar{p}} = 46 \times 10^6$ stopped $\bar{p}$'s this gives ∿ 63,500 $\gamma\gamma$ coincidences. This number is reduced by those events where a charged particle hits the same detector as one of the γ's. The total solid angle $\bar{\Omega}$ for the veto counters being about five times that of the γ-sensitive central region of the detector, and assuming 3.4 charged pions per annihilation, we roughly estimate a total of 40,000 $\gamma\gamma$ coincidences.

Most of these coincident γ's are, however, uncorrelated, i.e. not originating from the same particle, e.g. π^0 or η. Therefore their invariant mass

$$m_{\gamma_1\gamma_2} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\left(1 - \cos\,\phi_{\gamma_1\gamma_2}\right)} \qquad (1)$$

is usually not the π^0 mass or η mass, but covers a continuous spectrum. When reconstructing the invariant $\gamma\gamma$ mass from the data it was assumed that $\phi_{\gamma_1\gamma_2}$ was 180°. The error introduced by the finite angular acceptance of the system of

$$155^\circ \leq \phi_{\gamma_1\gamma_2} \leq 180^\circ$$

is only of the order of ±2.5% in the mass, hence much less than the energy resolution of the coincidence system (∿ 15%). The spectrum of the invariant $\gamma\gamma$ mass is shown in fig. 2. It contains 27,500 events, thus 31% lower than expected from the above estimate. The reduction is compatible with an energy cut at 25 MeV in the single γ energies, which was introduced in order to reduce low-energy neutron-induced and bremsstrahlung background. This cut affects mostly the uncorrelated background. As expected, the spectrum is essentially continuous. The π^0 peak at 135 MeV is quite prominent and contains 1000 ± 55 events. A second peak at ∿ 550 MeV, originating from η's which decay into two γ's, contains 272 ± 48 events.

The kinematics for π^0 decay in flight lead to a probability for the emission angle $\phi_{\gamma_1\gamma_2}$ of the form [7]:

$$W(\phi_{\gamma_1\gamma_2}) = \frac{1-\beta^2}{2\beta}\,\frac{\cos(\phi_{\gamma_1\gamma_2}/2)}{\sin^2(\phi_{\gamma_1\gamma_2}/2)}\,\frac{\Theta\left[\beta^2 - \cos^2(\phi_{\gamma_1\gamma_2}/2)\right]}{\sqrt{\beta^2 - \cos^2(\phi_{\gamma_1\gamma_2}/2)}}\ , \qquad (2)$$

where β is the velocity of the π^0 and Θ is a step function defining the minimum angle

$$\cos^2\left(\frac{\phi^{\min}_{\gamma_1\gamma_2}}{2}\right) = \beta^2 \ .$$

From these formulae we deduce that the minimum angle is also the most probable one, and that 180° is quite improbable for fast π^0's. Hence our set-up is expected to provide only reduced efficiency for energies higher than $E_{\pi^0} \geq 138$ MeV and $E_\eta \geq 562$ MeV. Figure 3 shows the efficiency of our apparatus as calculated for π^0 and η detection. It exhibits a short plateau, then drops down owing to the acceptance limitations, and finally is cut off owing to the energy cuts in the single γ energies.

When evaluating the $\gamma\gamma$ coincidences further, the greatest problem is obviously the very large uncorrelated background underneath the π^0 or η mass peaks in the invariant mass spectrum. In order to reduce this background the γ spectra in each detector were considered separately and approximated by smooth functions $F(E_\gamma)$. For each point in the E_{γ_1}-E_{γ_2} plane the background is then given by $F_1(E_{\gamma_1})F_2(E_{\gamma_2})$. The quality of this background approximation is demonstrated by the solid line in fig. 2. Obviously the correlated events in the π^0 or η peak are barely affected by this procedure, although the single γ spectra also contain correlated γ's.

In order to reconstruct the π^0 or η energy spectra, appropriate cuts were applied to the invariant mass $m_{\gamma_1\gamma_2}$ and the energies of the two γ's were added to give $E_{\pi^0,\eta} = E_{\gamma_1} + E_{\gamma_2}$. The spectra are shown in figs. 4a and 5a for the π^0 and η mass cuts, respectively. These spectra still contain uncorrelated background. By subtracting it, using again the functions F_1 and F_2 for the single γ-spectra, the "pure" π^0 and η energy spectra shown in figs. 4b and 5b are obtained.

The π^0 spectrum exhibits a peak at $E_{\pi^0} = 138$ MeV and a tail towards higher energies. The peak at 138 MeV is due to reactions of slow π^-'s from $p\bar{p}$ annihilations, which stop in the target and undergo charge exchange ($\pi^- p \rightarrow \pi^0 n$), whereas the tail is due to primary π^0's from annihilation.

First we analyse the peak at 138 MeV in order to obtain an estimate of the total number of primary π^0's. This peak contains 500 ± 10 events. The peak width at half maximum corresponds to 11.5%. From ref. 3 we know that the corresponding radiative capture ($p\pi^- \rightarrow n\gamma$) amounts to $Y_{n\gamma} = (3 \pm 1) \times 10^{-3}$ per annihilation for our set-up. Using the Panofsky ratio

$$R = \frac{\Gamma_{p\pi^- \rightarrow n\pi^0}}{\Gamma_{p\pi^- \rightarrow n\gamma}} = 1.546 \pm 0.009 \quad [8] ,$$

and taking into account the reduction due to charged particles as discussed above, we expect the number of π^0's from charge exchange to be

$$N_{\pi^- p \rightarrow n\pi^0} = N_{p\bar{p}} \, Y_{n\gamma} R \Omega_{\mathrm{coinc}} \, (1 - \bar{\Omega})^{N_{\pi^+} + N_{\pi^-} - 1} ,$$

where Ω_{coinc} is the average effective fractional solid angle for coincidences of correlated γ's, i.e. the cone defined by the condition $155^\circ < \phi_{\gamma_1\gamma_2} < 180^\circ$ and the solid angles of the two detectors. With $\Omega_{\mathrm{coinc}} = 0.66\%$ and $N_{\pi^+} = N_{\pi^-} = 1.7$ per annihilation, the expected number of π^0's from charge exchange is $N_{\pi^- p \rightarrow n\pi^0} =$ $= 1000 \pm 340$. This number is higher than the measured one, hence indicating that we have overestimated the detection efficiency, but it is a safe upper limit to be used for normalization, i.e. a redefinition of the effective number of stopped $\bar{p}$'s which becomes $N_{p\bar{p}}^{\mathrm{eff}} = (23 \pm 8) \times 10^6$. The number of primary π^0's from annihilation which we expect to observe is therefore $(1.6 \pm 0.5) \times 10^5$, when assuming 1.7 π^0's per annihilation on an average.

The number of primary π^0's from annihilation may also be obtained directly from the spectrum. To this end the remaining tail of the spectrum has to be explained by the spectral shape of π^0's from $p\bar{p}$ annihilations at rest. A Monte Carlo simulation using the same annihilation channels as used in ref. 6 was performed. This simulated spectrum normalized to one π^0 was folded with the assumed resolution of $7\%/\sqrt[4]{E_{\pi^0}[\mathrm{GeV}]}$ (which reproduces the peak at 138 MeV) and the efficiency as displayed in fig. 3. The number of π^0's was adjusted to the measured spectrum and corresponds to $(1.0 \pm 0.1) \times 10^5$, hence lower than, but not in disagreement with, the expectation as derived from the π^0 peak at 138 MeV. The solid line in fig. 4b represents the peak at 138 MeV and the simulated π^0 spectrum.

Obviously there is no structure left over which could be attributed to a sharp baryonium-like state. With an efficiency of 3.1% at 180 MeV (see fig. 3) the limit at 3σ confidence for baryonium formation at $E_{\pi^0} = 180$ MeV is 8% per annihilation when normalized to the fitted number of π^0's and assuming 1.7 π^0's per annihilation in average. This limit would not change when normalization had been carried out with respect to the expected number of π^0's.

The η spectrum, fig. 5a, may also be reduced by the uncorrelated background. The remainder is displayed in fig. 5b. This spectrum seems to contain only low-energetic η's. Comparison with a Monte Carlo simulated η spectrum is not possible since only very little is known about annihilation channels involving η's. Therefore a determination of the number of η's from the low-energy part of the spectrum is not possible. In the energy range of our acceptance (see fig. 2), i.e. for $m_\eta < E_\eta < 600$ MeV, there are 270 ± 50 $\gamma\gamma$ events or, using the branching ratio $R_{\eta \to \gamma\gamma} = 0.39$, a total of 700 ± 125 η's. The number of η's produced in this energy range is thus $N_\eta \geq 0.46\%$ per annihilation. If only annihilation into $\eta\pi\pi$ is assumed to contribute to our spectrum, this channel would have to have a yield of (18 ± 7)% per annihilation. In view of the upper limit for η production in low-energy $p\bar{p}$ annihilation of $\eta/\pi^0 \leq 0.11$ [9] or $N_\eta \leq 19\%$ (assuming 1.7 π^0's per annihilation) this indicates a fairly large amount of four-body or more complicated final states associated with η production in $p\bar{p}$ annihilation at rest.

We conclude that this measurement, although very sensitive to low-energetic π^0's and η's, could not acquire sufficient statistics to reveal narrow baryonium-like states. The upper limit for baryonium production through π^0 emission is 8% in the mass region of ∿ 1650 MeV. The number of η's produced per annihilation with kinetic energies below 50 MeV was found to be at least 0.46%.

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Figure captions

Fig. 1 : Experimental set-up. Cross-section perpendicular to the beam.

Fig. 2 : Spectrum of the invariant $\gamma\gamma$ mass. The solid line represents the background from uncorrelated γ's. The structure around 700 MeV is due to the decay of ω's into $\pi^0\gamma$. As expected and confirmed by Monte Carlo simulations, this decay mode leads to such a structure in the $\gamma\gamma$ mass spectrum.

Fig. 3 : Detection efficiency for π^0's and η's as a function of the total energy of the particle.

Fig. 4 : a) π^0 energy spectrum. The solid line represents the uncorrelated background. b) π^0 energy spectrum after subtraction of the uncorrelated background. The solid line represents the peak from π^0 charge exchange at rest and the Monte Carlo simulated π^0 spectrum.

Fig. 5 : a) η energy spectrum. The solid line represents the uncorrelated background. b) η energy spectrum after background subtraction.

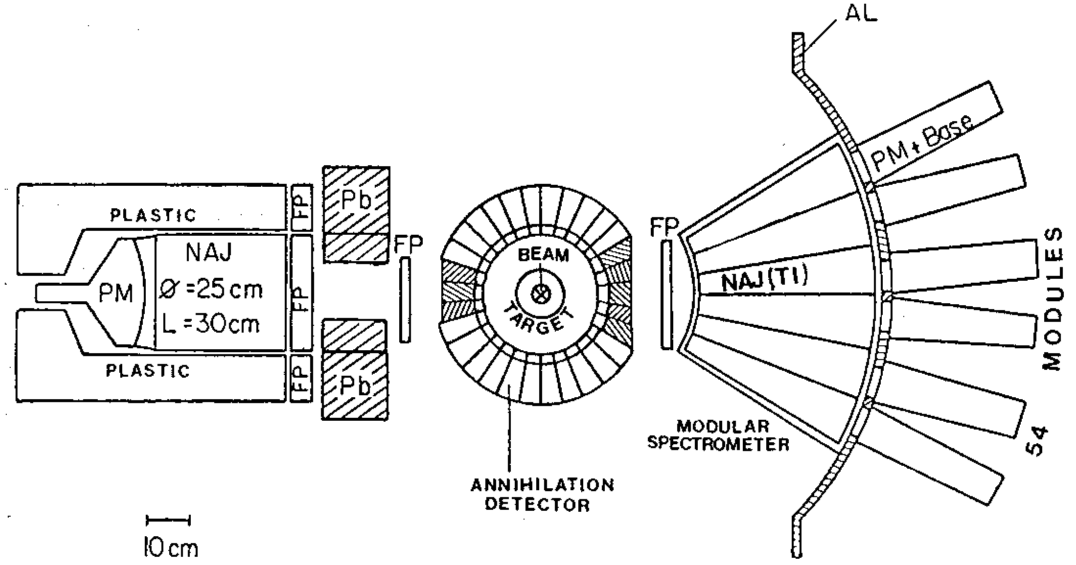
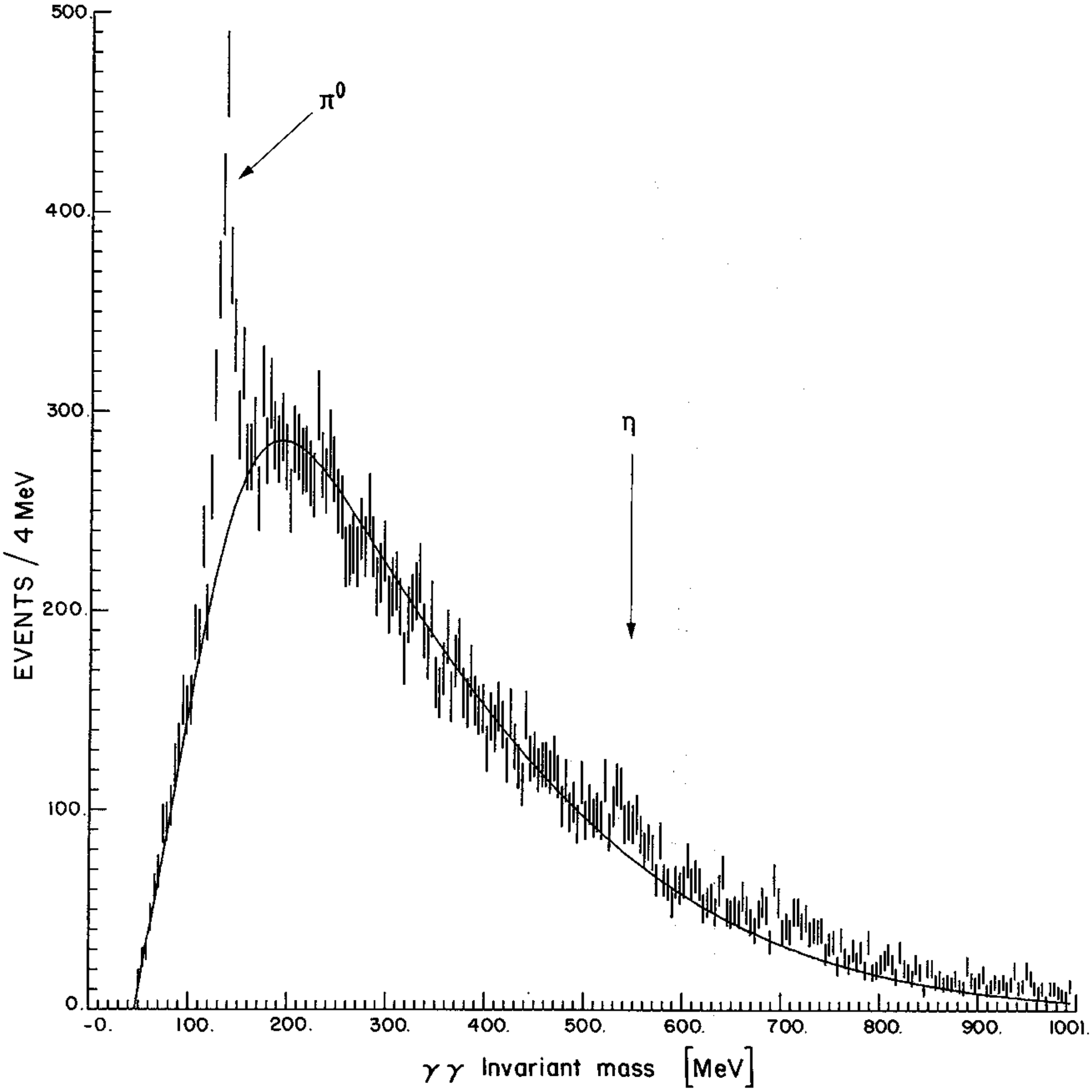

AL
PM + Base
PLASTIC
FP
Pb
NAJ
PM
Ø =25 cm
L =30cm
FP
PLASTIC
FP
Pb
FP
BEAM
TARGET
FP
NAJ(Tl)
MODULES
54
MODULAR
SPECTROMETER
ANNIHILATION
DETECTOR
10 cm

Fig. 1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400.
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EVENTS / 4 MeV
-0.
100.
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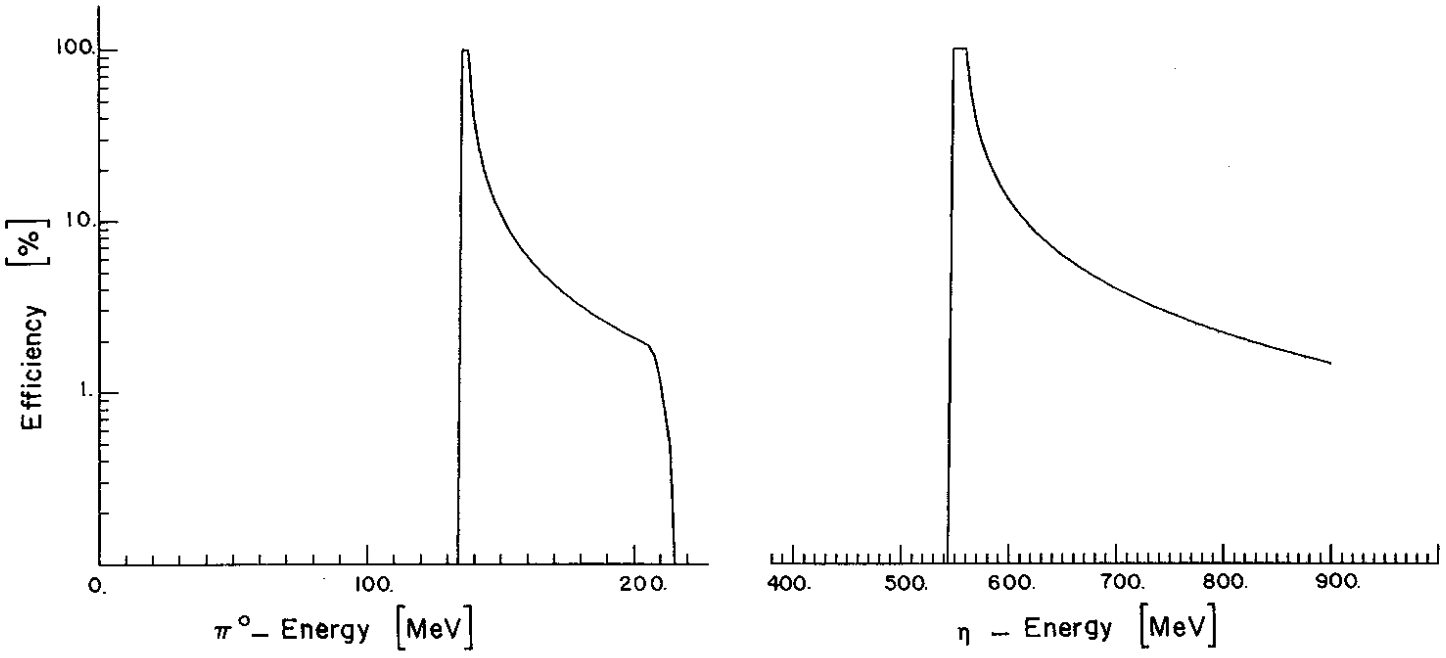
600.
700.
800.
900.
1001.
$\gamma\gamma$ Invariant mass [MeV]
π^0
η

Fig. 2


100.
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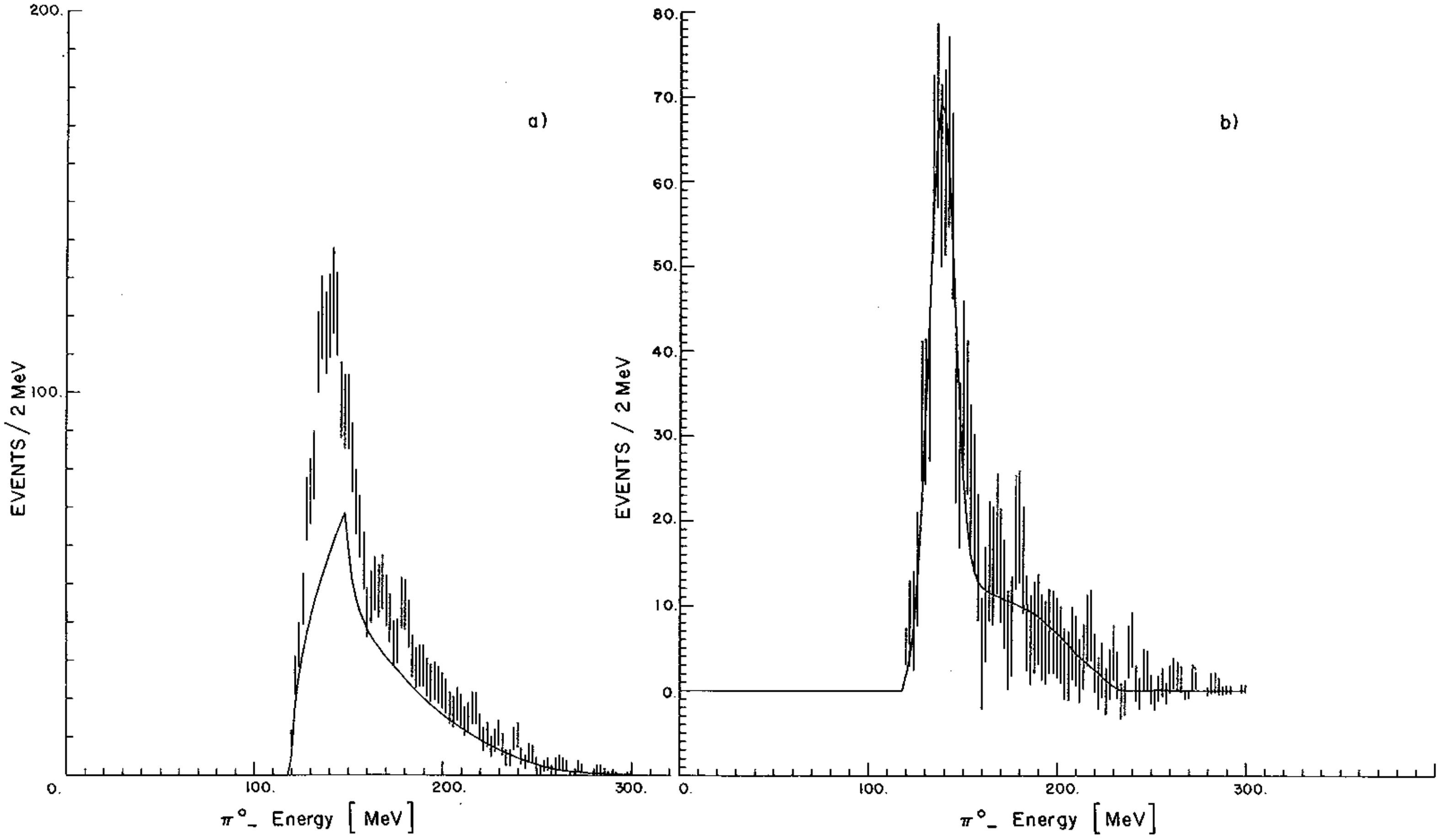
η – Energy [MeV]

Fig. 3


200.
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EVENTS / 2 MeV
a)
100.
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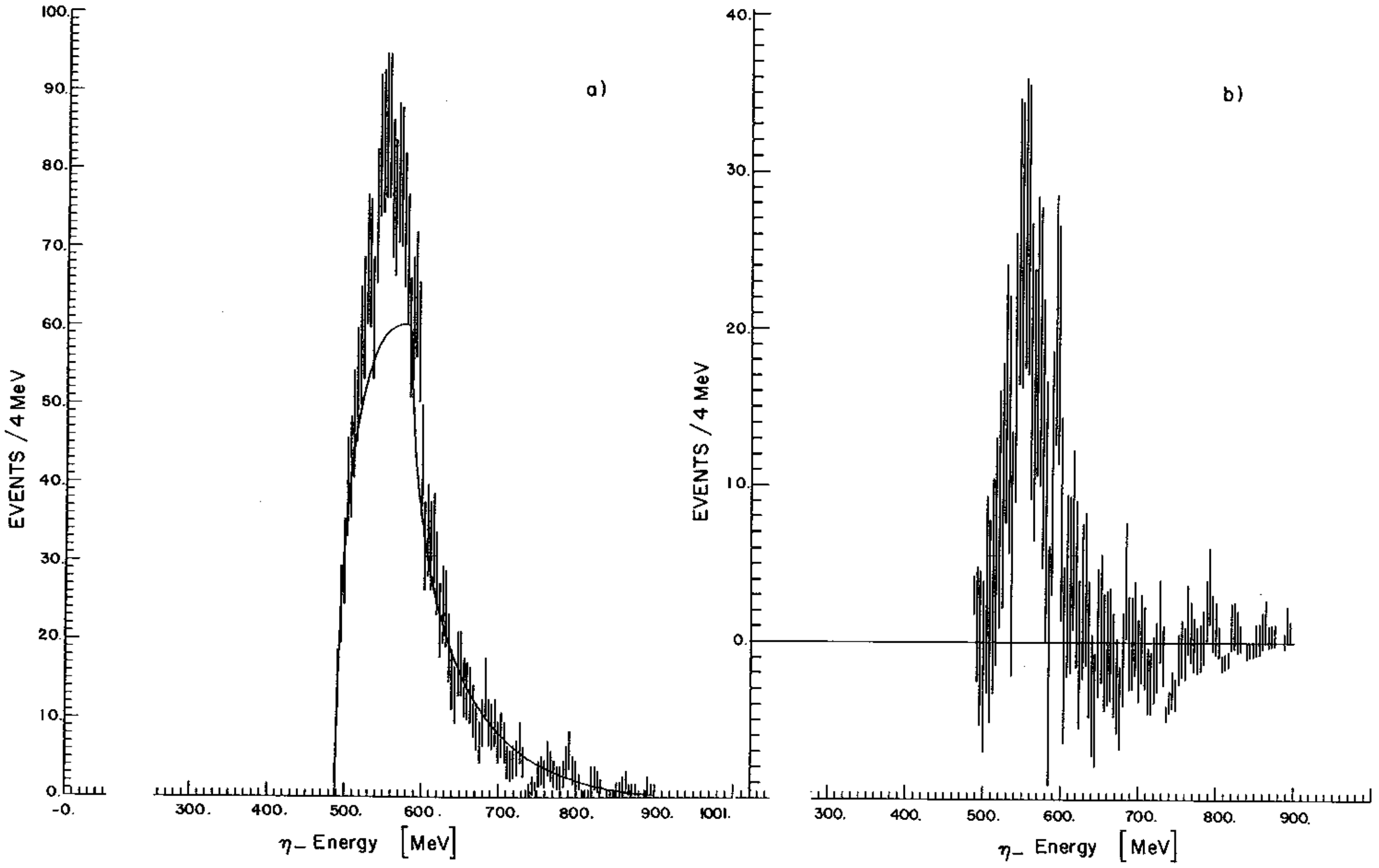
π°_ Energy [MeV]
80.
70.
60.
50.
40.
30.
20.
10.
0.
EVENTS / 2 MeV
b)
0.
100.
200.
300.
π°_ Energy [MeV]

Fig. 4


a)
EVENTS / 4 MeV
100.
90.
80.
70.
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40.
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10.
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300.
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500.
600.
700.
800.
900.
1001.
η– Energy [MeV]
b)
EVENTS / 4 MeV
40.
30.
20.
10.
0.
300.
400.
500.
600.
700.
800.
900.
η– Energy [MeV]

Fig. 5