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$\bar{P} - P$ ANNIHILATIONS AT REST INTO TWO MESONS

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In the experiment carried out at the CERN P.S. with the Saclay 81 cm hydrogen bubble chamber to study the annihilations in hydrogen of antiprotons at rest, the absolute and relative rates have been measured for the following reactions:

$$\bar{p} + p \rightarrow \pi^+ + \pi^- \quad (1)$$

$$K^+ + K^- \quad (2)$$

$$K^o + \bar{K}^o \quad (3)$$

I. Reactions (1) and (2) are first considered

In a sample of 150'000 annihilations events, which on the scanning table looked approximately collinear, were selected for further measurement by I.E.P. and the geometry of the event and momenta of the tracks calculated using the GAP programme [1]. The distribution of angles between the two tracks is shown in Fig. 1. An estimation of the reconstruction errors leads us to the belief that those tracks with included angles equal or smaller than one degree may be considered as collinear.

To ensure a fair accuracy in the curvature determination of the tracks only those that had angles of dip (λ) smaller than 60 degrees were considered in the subsequent analysis. The final rates were corrected from the expected uniform distribution in sin λ. This uniformity was experimentally verified for $0^o \leqslant \lambda \leqslant 60^o$.

A certain background of events with neutral pions is nevertheless expected to escape the collinearity test. This background was estimated from the momentum distribution of all collinear events for which both tracks had lengths greater than 13 cm. The distribution is shown in Fig. 2, where the events group either at a momentum of 789 MeV/c (momentum of the kaon in reaction (2)) or at 928 MeV/c (momentum of the pion in reaction (1)). The dashed curve indicates the expected position of those annihilations into $\pi^+\pi^-\pi^o$ where the two charged mesons are collinear.

The fact that all the events except one are consistent - within their small experimental error - with production of two charged mesons with no neutral(s) associated particles, shows that the background is very small. By this test we have shown that the collinearity criterion is a good one to distinguish between two-body and multibody annihilations and in what follows we assume that collinearity implies a two-body annihilation.

To obtain the absolute value of the number of annihilations going into two charged mesons, we only considered events with dip angles λ smaller than 60^{o} in a fiducial region centered on the fairly narrow distribution of $\bar{p}$ stopping points. (Note that the tracks now do not have necessarily a length of 13 cm). The momentum distribution for these events is shown in Fig. 3. The dispersion of the points about the $(K\bar{K})$ and $(\pi\pi)$ momenta is wider than in Fig. 2 - this comes about because of the shorter average length of the tracks - but the general characteristics of the more accurate measurements in Fig. 2 are preserved. The results of Fig. 3 are:

Number of annihilations into $\pi^{+} + \pi^{-}$ per 10^{5} annihilations = 395 ± 38
Number of annihilations into $K^{+} + K^{-}$ per 10^{5} annihilations = 131 ± 18

As far as the ratio, "R", of reactions $\bar{p} + p \rightarrow \pi^{+} + \pi^{-}$ and $\bar{p} + p \rightarrow K^{+} + K^{-}$ is concerned, better statistical accuracy can be obtained - without thereby introducing a systematic error - by considering all those events in which at least one track is long enough (length >13 cm) to give an accurate value of the momentum while the other has to be long enough to establish the collinearity of the event without giving necessarily an accurate momentum measurement. The momentum spectrum of the well measured track is given in Fig. 4 and the result found is

$$R = \frac{p + \bar{p} \rightarrow \pi^{+} + \pi^{-}}{p + \bar{p} \rightarrow K^{+} + K^{-}} = 3.02 \pm 0.41.$$

These results are in good agreement with those obtained by Chadwick et al.[2)] in another series of photographs from the same run.

II. The annihilation $\bar{p} + p \rightarrow K^o + \bar{K}^o$

The observable modes of the reaction $\bar{p} + p \rightarrow K^o + \bar{K}^o$ are:

$$\bar{p} + p \rightarrow K_1^o + K_1^o \qquad (3a)$$
$$K_2^o + K_2^o \qquad (3b)$$
$$K_1^o + K_2^o \qquad (3c)$$

No attempt has been made so far in this experiment to identify K_2^o - events, so that we can only recognize reactions (3a) and (3c). In histograms 1 and 2, the momentum distributions of V^o's * appearing singly or in pairs, respectively, are given. No single example of $(V^o + V^o)$ - production has been observed while 54 single V^o - decays appear centered about P = 796 MeV/c - the characteristic momentum of K^o's produced in annihilations at rest. (The calculated mean value for the observed events is $P_{K^o} = (7\,94.5 \pm 1.6)$ MeV/c.

D'Espagnat[3)] and Schwartz[4)] have shown how reactions (3a) and (3c) can be utilized to determine the ratio of P-state to S-state capture absorption leading to the production of neutral kaons without pions.

Their argument can be simply understood from the following table which summarizes the results of applying the usual conservation laws to the initial and final states of reactions (3). Only S- and P-states are considered.

---

* By V^o we denote the decay $K_1^o \rightarrow \pi^+ + \pi^-$

Table I

Allowed and forbidden modes in $\bar{p} + p \rightarrow K^o + \bar{K}^o$ if only S and P-states are considered

Initial State				Final State							
				$K_1^o K_1^o$ or $K_2^o K_2^o$				$K_1^o K_2^o$ or $K_2^o K_1^o$			
Symbol	ℓ	$P = (-1)^{\ell+1}$	$C=(-1)^{\ell+s}$	ℓ	$P = (-1)^{\ell}$	$C = +1$		ℓ	$P = (-1)^{\ell}$	$C = -1$	
$1\ S_o$	0	−	+	0	+	+	xx	0	+	−	xx
$3\ S_1$	0	−	−	1	−	+	x	1	−	−	
$1\ P_1$	1	+	−	1	−	+	xx	1	−	−	xx
$3\ P_o$	1	+	+	0	+	+		0	+	−	x
$3\ P_1$	1	+	+	1	−	+	xx	1	−	−	xx
$3\ P_2$	1	+	+	2	+	+		2	+	−	x

x = means forbidden by C (charge conjugation)

xx = means forbidden by P (Parity)

A blank case means that the state is allowed

From the table we see that the reactions (3a) and (3b) are allowed from the $3\ P_o$ and $3\ P_2$ states, while reaction (3c) can only come from the $3\ S_1$ state, i.e. if S-state absorption is effective in the production of pairs of neutral kaon and neutral antikaon pairs one should never observe two K_1^o - decays.

From the large discrepancy between the number of single V^o's and double V^o's, it is evident that the results imply a predominance of S-state capture. We now try to find what limits can be given to a possible P-state contribution to reactions (3). Following Snow[5)], we suppose that the relative number of reactions

(3a) and (3c) are given by the statistical weights of the initial states which can contribute to them. If we call η the contribution from the P-state and $(1 - \eta)$ that from the S-state, the weights of reactions (3a) and (3c) are, respectively:

$$\frac{3}{4}\left(\frac{1}{9} + \frac{5}{9}\right) \frac{1}{2}\eta = \frac{1}{4}\eta$$

$$\text{and} \quad \frac{3}{4}(1 - \eta)$$

where we have further weighted the different states by the factor $(2J + 1)$ and where we have included a factor of 1/2 in reaction (3a) to take into account the fact that for C = +1 the final state is a superposition of (3a) and (3b) with a (3a : 3b) branching ratio equal to 1 [6].

The probability of observing a V^0 - decay when one K_1^0 is produced being $\frac{2}{3}(1 - \varepsilon)$ (where $\frac{2}{3}$ is the branching ratio $\frac{K_1^0 \to \pi^+ + \pi^-}{(K_1^0 \to \pi^+ + \pi^-)+(K_1^0 \quad \pi^0\pi^0)}$ and $(1 - \varepsilon)$ is the probability of observing the V^0-decay in the fiducial volume of the chamber), we have:

Probability of observing 2 V^0's (they can only come from reaction 3a)

$$= \left(\frac{2}{3}\right)^2 (1 - \varepsilon)^2 \times \frac{1}{4}\eta$$

Probability of observing 1 V^0(it can come either from 3a or 3c)

$$= \frac{2}{3}(1 - \varepsilon)\frac{1}{3}(1 + 2\varepsilon) \cdot 2 \cdot \frac{1}{4}\eta + \frac{2}{3}(1 - \varepsilon)\frac{3}{4}(1 - \eta)$$

Probability of observing 0 V^0 (reactions 3a, 3b and 3c can contribute)

$$= \frac{1}{4} \cdot \frac{1}{9} \cdot \eta (1 + 2\varepsilon)^2 + \frac{1}{4}\eta + \frac{1}{3}(1 + 2\varepsilon) \cdot \frac{3}{4}(1 - \eta)$$

The average value of the correcting factor ε in this experiment was $\varepsilon = 0.195$. The expected ratio, R, of 2 V^0 to 1 V^0 events is given in terms of η (the P-state contribution) by

$$R = \frac{0.072\,\eta}{0.402 - 0.278\,\eta}$$

In Table II the ratio R is given for different values of η together with the probability P(0) that our experimental result of no 2 V^o event observed be compatible with the expected number (normalized to the 54 single V^o events in the sample).

Table II

Summary of results on P/S relative annihilation rates

η	$R = \frac{0.072\,\eta}{0.402 - 0.278\,\eta}$	Expected No of $2V^o$-events when 54 single V^o's have been seen x	P(0)
.05	0.0036 : 0.389	0.5	.63
.10	0.0072 : 0.375	1.04	.35
.15	0.0108 : 0.365	1.61	.20
.20	0.0144 : 0.347	2.24	.10

x : Expected number of double V^o-events when 54 single V^o's have been seen.

P(0): The probability of observing 0 double V^o-events when x are expected is given by the Poisson-law: $P(m) = \frac{e^{-x} x^m}{m}$

The conclusion is that although our results show no evidence for P-state production of $K^o + \bar{K}^o$, the statistics are such that there is a 10 o/o chance that the P-state contribution be as large as 20 o/o.

To obtain the absolute rate of the reaction

$$\bar{p} + p \longrightarrow K^o + \bar{K}^o \qquad (3)$$

a reduced fiducial volume was used: this to minimize the contamination of interactions in flight. The corrected number of single V^o's obtained was 54 and the corresponding number of antiprotons 144500. Assuming pure $3\,S_1$ - production, the rate (3) is : $(0.56 \pm 0.08) \times 10^{-3}$.

We have finally calculated the percentage of all annihilations leading to the production of $K\bar{K}$ - pairs associated with any number of pions. Two approximations are made in this estimation:

a) that no selection rules inhibit or enhance the different annihilation modes

and b) that $K^+K^- n\pi = \dfrac{(K^0\bar{K}^0 + \bar{K}^0K^+ + K^0K^-)n\pi}{3}$.

The result is:

$$R_K = \frac{\text{Number of } (K\bar{K}n\pi) \text{ annihilations}}{\text{All annihilations}} = (6.82 \pm 0.25)\ \text{o/o}.$$

The results of this experiment are summarized below:

Proportion of all annihilations going into $(K\bar{K}n\pi)$	$= (6.82 \pm 0.25) \cdot 10^{-2}$
Rate $\bar{p} + p \longrightarrow \pi^+ + \pi^-$	$= (3.95 \pm 0.38) \cdot 10^{-3}$
" $\bar{p} + p \longrightarrow K^+ + K^-$	$= (1.31 \pm 0.38) \cdot 10^{-3}$
" $\bar{p} + p \longrightarrow K^0 + \bar{K}^0$	$= (0.56 \pm 0.08) \cdot 10^{-3}$

References :

1) A. Kernan et al., CERN Internal Report

2) G.B. Chadwick, W.T. Davies, M. Derrick, J.H. Mulvey, D. Radojicic and C.A. Wilkinson (Oxford), M. Cresti, S. Limentani, A. Loria and R. Santangelo (Padova)

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$3\ S_1$	0	−	−	1	−	+	x	1	−	−	
$1\ P_1$	1	+	−	1	−	+	xx	1	−	−	xx
$3\ P_0$	1	+	+	0	+	+		0	+	−	x
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The probability of observing a V^o - decay when one K_1^o is produced being $\frac{2}{3}(1 - \varepsilon)$ (where $\frac{2}{3}$ is the branching ratio $\frac{K_1^o \to \pi^+ + \pi^-}{(K_1^o \to \pi^+ + \pi^-)+(K_1^o \quad \pi^o\pi^o)}$ and $(1 - \varepsilon)$ is the probability of observing the V^o-decay in the fiducial volume of the chamber), we have:

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$$= \frac{2}{3}(1 - \varepsilon)\frac{1}{3}(1 + 2\varepsilon) \cdot 2 \cdot \frac{1}{4}\eta + \frac{2}{3}(1 - \varepsilon)\frac{3}{4}(1 - \eta)$$

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$$= \frac{1}{4} \cdot \frac{1}{9} \cdot \eta\,(1 + 2\varepsilon)^2 + \frac{1}{4}\eta + \frac{1}{3}(1 + 2\varepsilon) \cdot \frac{3}{4}(1 - \eta)$$

The average value of the correcting factor ε in this experiment was $\varepsilon = 0.195$. The expected ratio, R, of 2 V^o to 1 V^o events is given in terms of η (the P-state contribution) by

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The results of this experiment are summarized below:

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Rate $\bar{p} + p \longrightarrow \pi^+ + \pi^- = (3.95 \pm 0.38) \cdot 10^{-3}$

" $\bar{p} + p \longrightarrow K^+ + K^- = (1.31 \pm 0.38) \cdot 10^{-3}$

" $\bar{p} + p \longrightarrow K^o + \bar{K}^o = (0.56 \pm 0.08) \cdot 10^{-3}$

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References :

1) A. Kernan et al., CERN Internal Report

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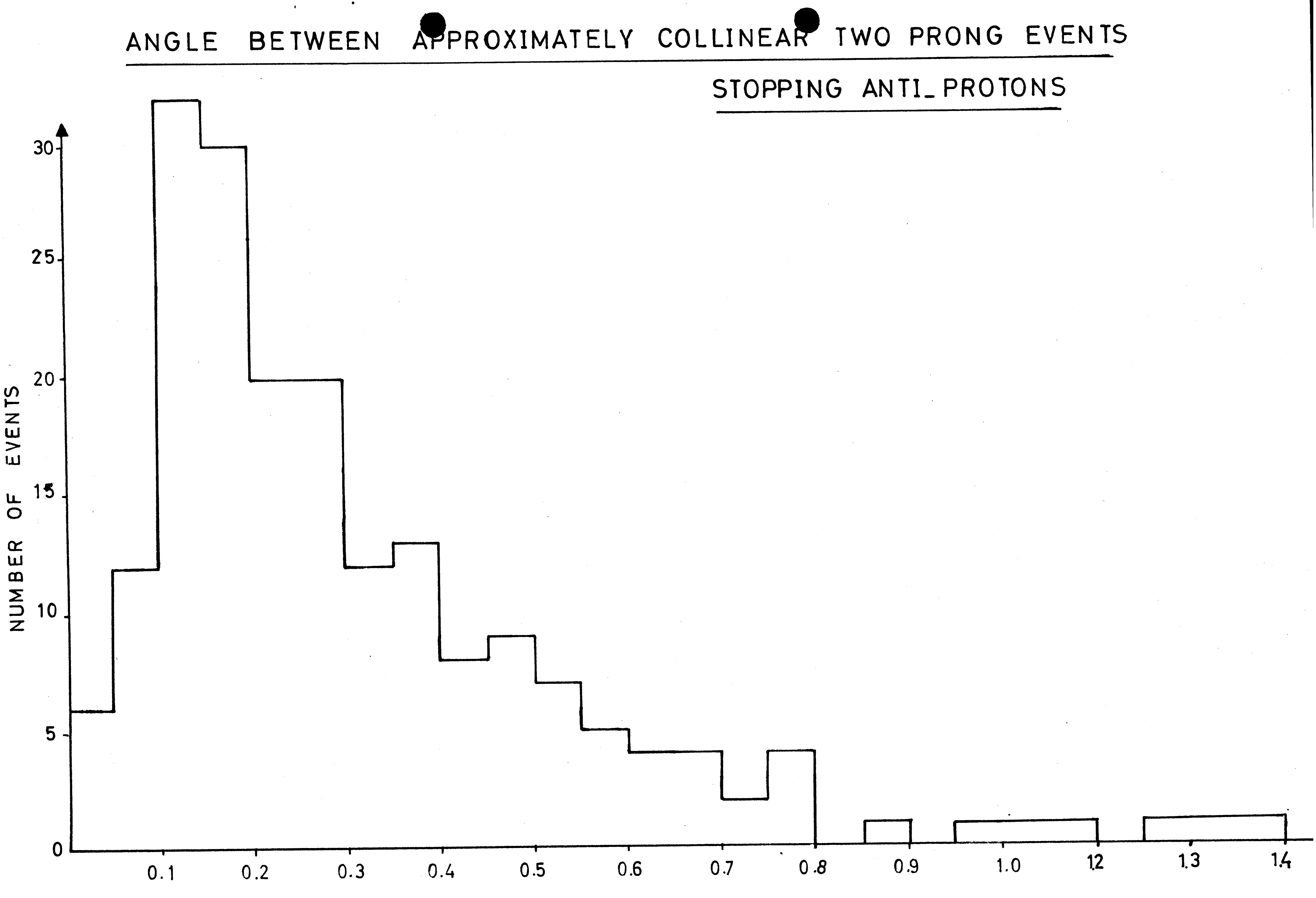

ANGLE BETWEEN APPROXIMATELY COLLINEAR TWO PRONG EVENTS
STOPPING ANTI_PROTONS
NUMBER OF EVENTS
0
5
10
15
20
25
30
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
12
1.3
1.4
ANGL BETWEEN TRACKS, DEGREES

FIG. 1

MOMENTUM DISTRIBUTION OF 2 - PRONG COLLINEAR EVENTS

STOPPING ANTI - PROTONS.

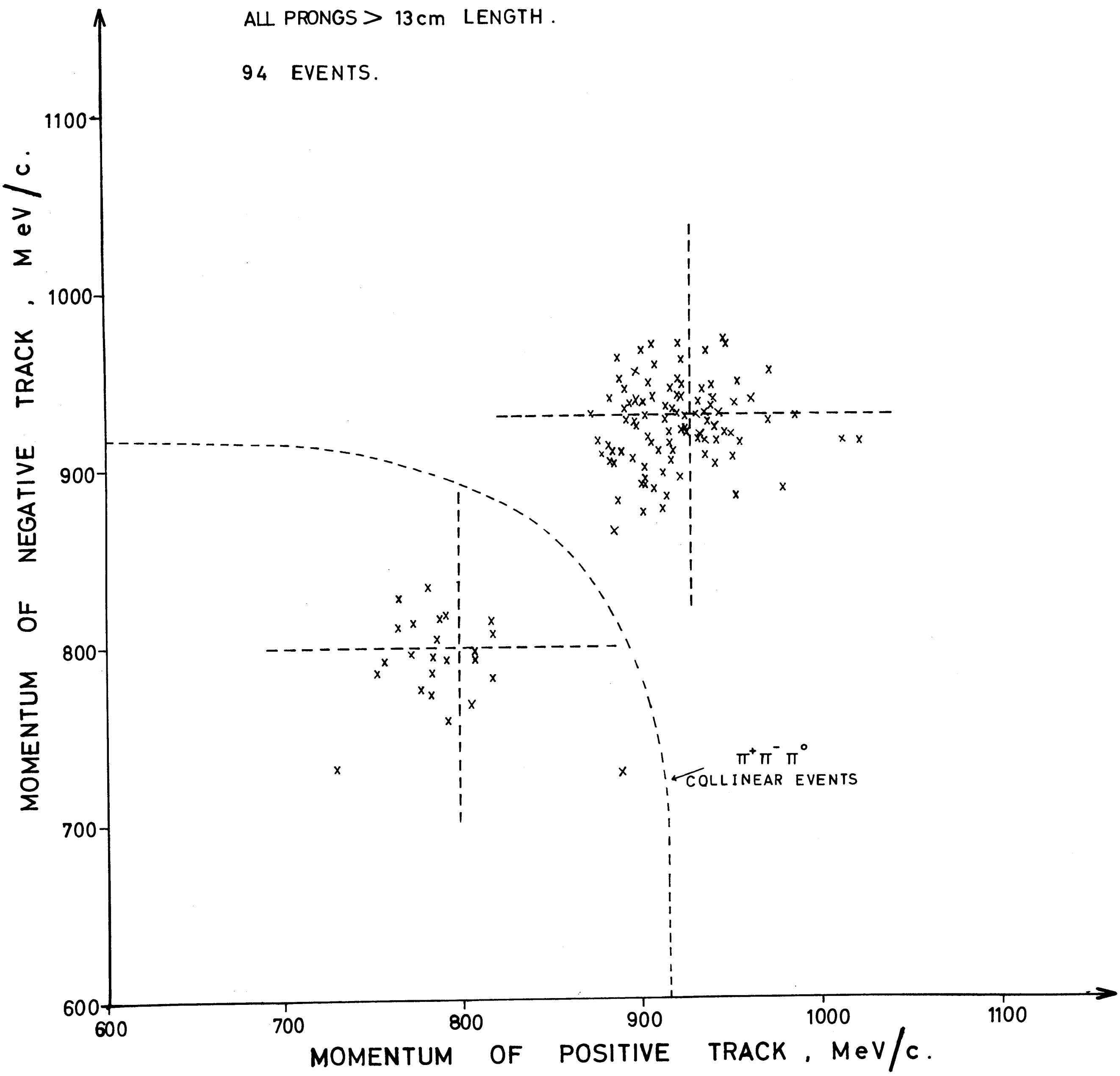


FIG. 2

SIS/R/4787

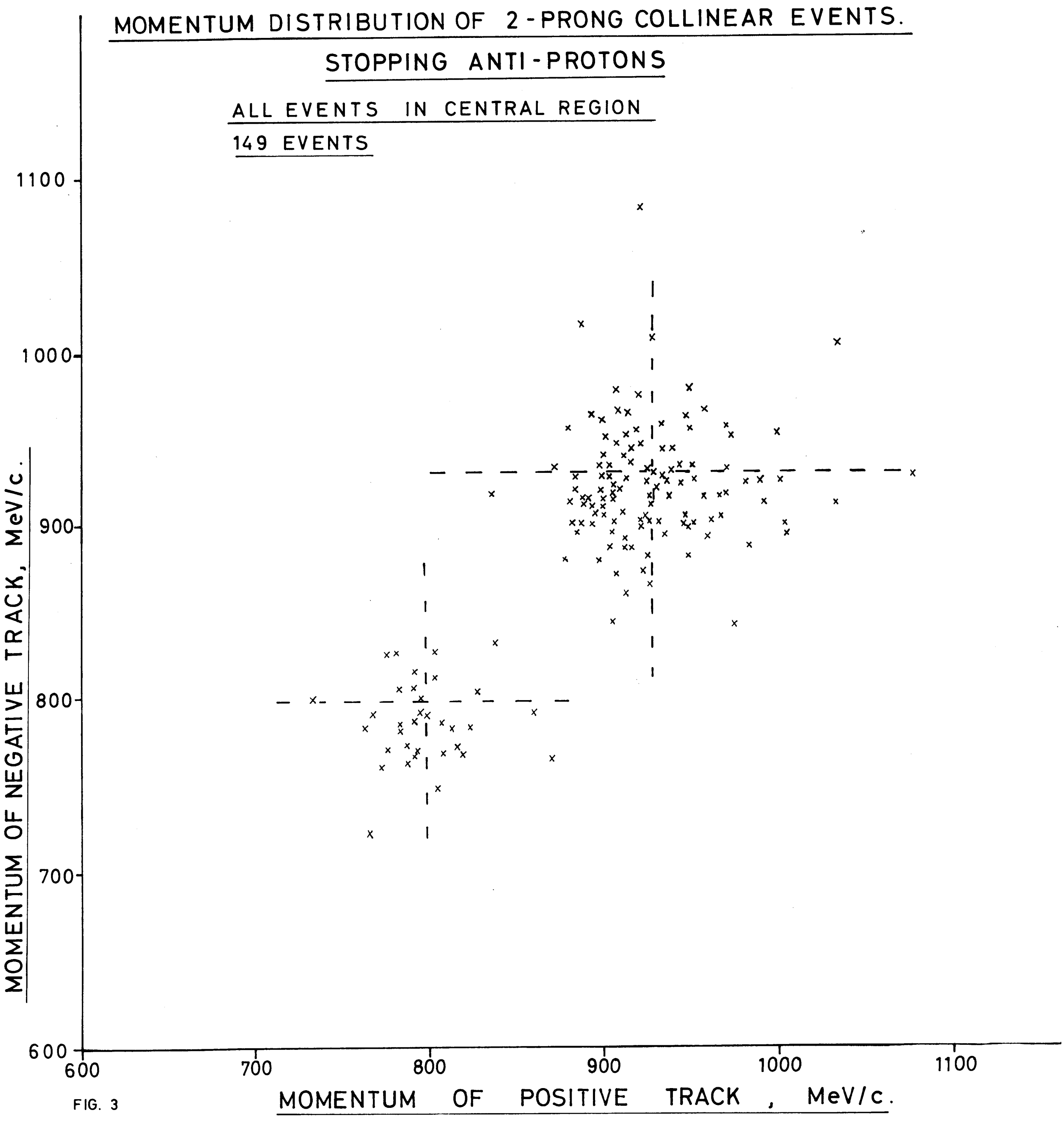


FIG. 3

SIS/R/4786

STOPPING ANTI-PROTONS

MOMENTUM SPECTRUM OF 2-PRONG COLLINEAR EVENTS

ALL PRONGS > 13cm LENGTH 281 EVENTS ; 400 PRONGS.

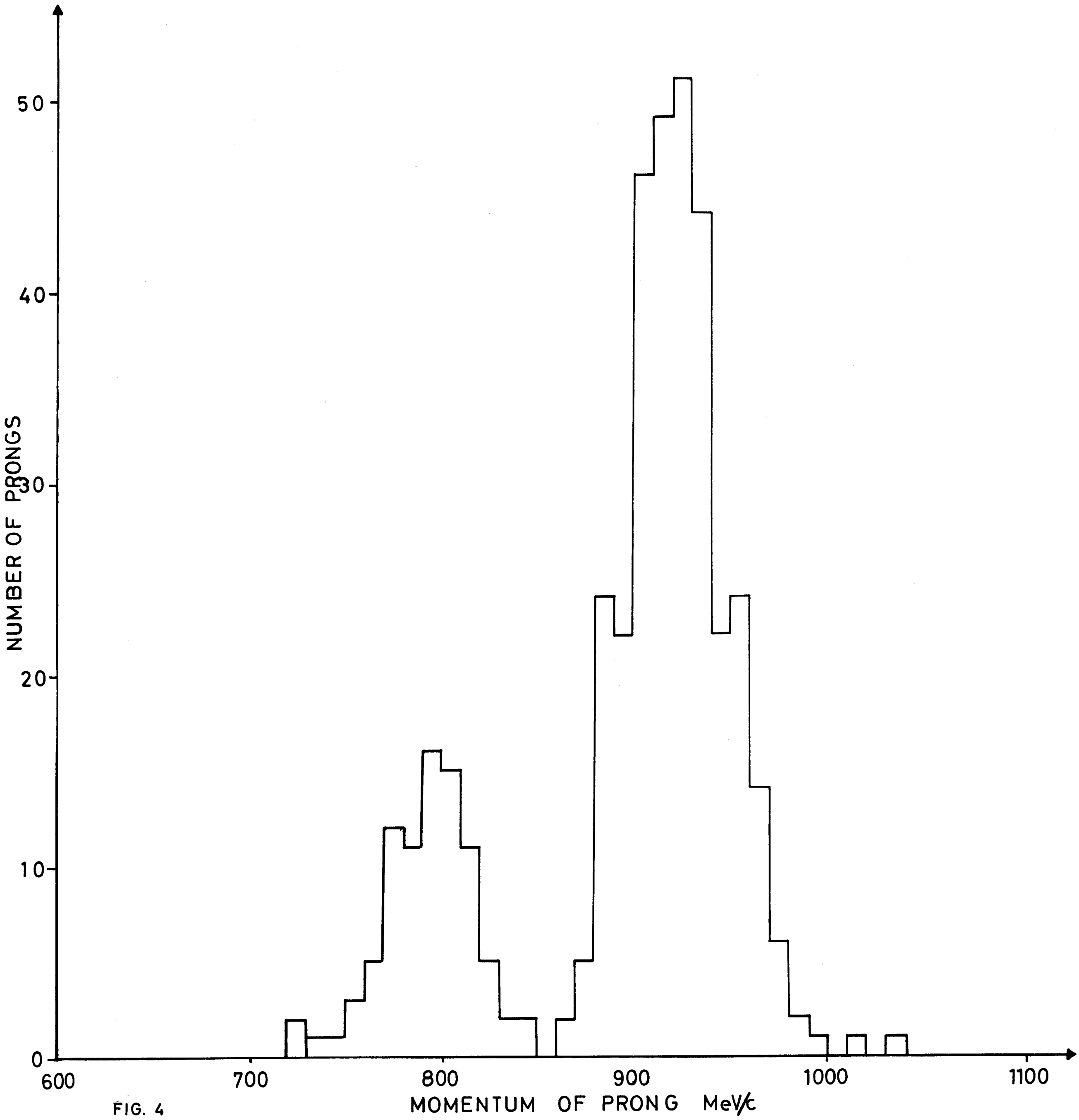
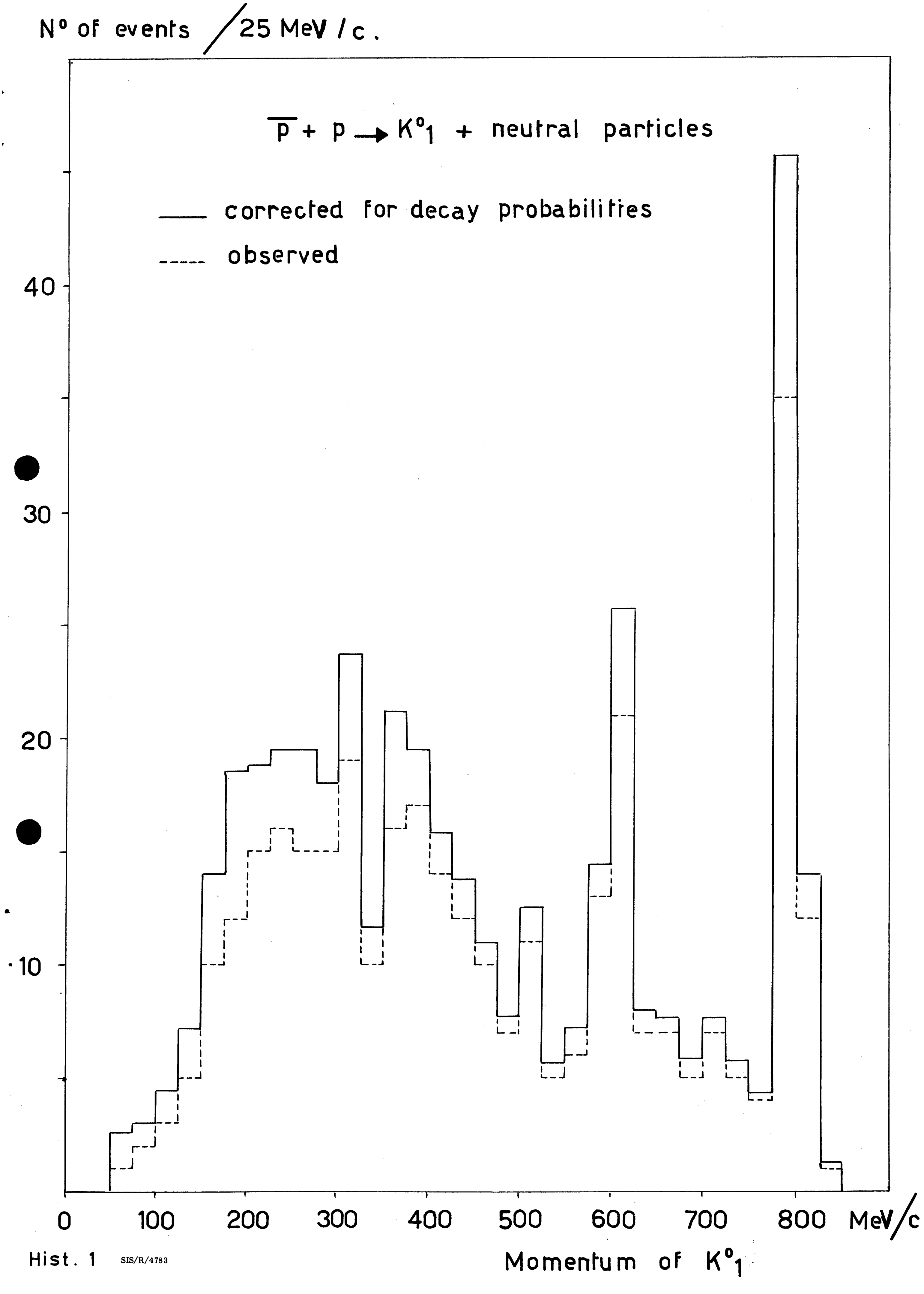


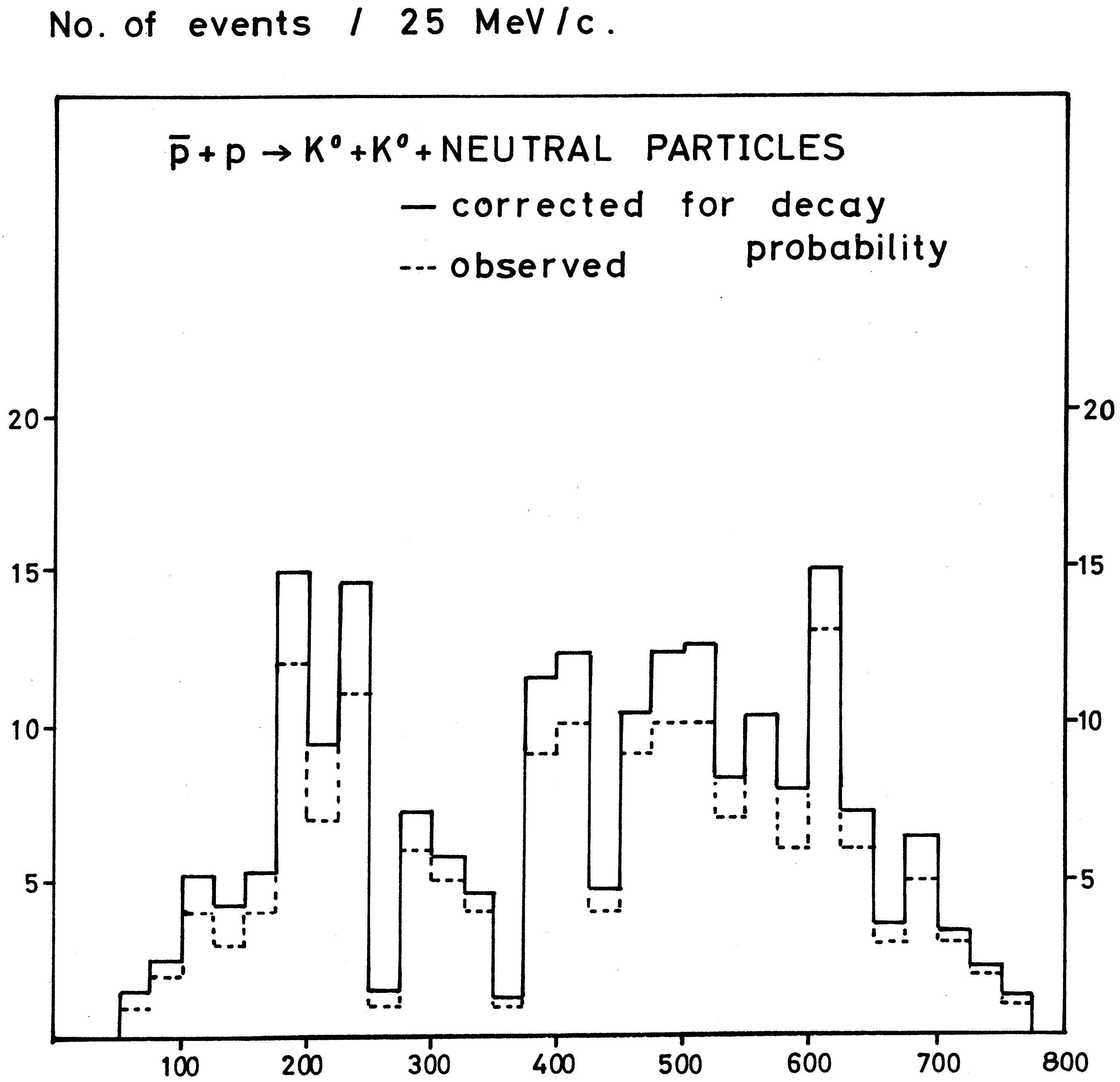
FIG. 4

/R/4785



Hist. 1 SIS/R/4783

MOMENTUM OF K^0_1



Hist. 2

SIS/R/4782