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C. Bacci, R. Baldini-Celio, G. Capon, C. Mencuccini, G. P. Murtas, G. Penso, A. Reale, G. Salvini, and B. Stella: MULTIHADRONIC CROSS SECTIONS FROM e^+e^- ANNIHILATION AT C. M. ENERGIES BETWEEN 1.4 AND 2.4 GeV. -

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C. Bacci[(x)], R. Baldini-Celio, G. Capon, C. Mencuccini, G. P. Murtas, G. Penso[(x)], A. Reale, G. Salvini[(x)], B. Stella[(x)]: MULTIHADRONIC CROSS SECTIONS FROM e^+e^- ANNIHILATION AT C. M. ENERGIES BETWEEN 1.4 AND 2.4 GeV.

ABSTRACT. -

Multihadronic production has been observed at the Adone e^+e^- storage ring, in the c. m. energy range 1.4 ÷ 2.4 GeV. The cross sections for the reactions $e^+ + e^- \rightarrow 2\pi^\pm + n\pi^0$ $(1 \leq n \leq 4)$ and $e^+ + e^- \rightarrow (4\pi^\pm + n\pi^0; 6\pi^\pm)$ $(0 \leq n \leq 2)$ have been measured, assuming that the produced particles are only pions with a pure phase space momentum distribution.

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In an experiment performed at the Adone electron-positron storage ring we have studied the reactions:

(1) $$e^+ + e^- \rightarrow \text{multihadronic production}$$

at center of mass energies 2E between 2 x 0.7 and 2 x 1.2 GeV.

We summarize our results as follows:

- Multiple hadronic events are produced at our energies. These events have three or more hadrons in the final state, and neutral pions are present in a large percentage of the cases.
- The cross sections for these processes are relatively large, and are in the region of values covered by the "pointlike" cross section for muon pair production (see Fig. 2).
- Reaction $e^+ + e^- \rightarrow \pi^+ + \pi^- + \pi^0$ has a cross section of the order of 2×10^{-33} cm^2 at c. m. energies averaged over 1.85 ÷ 2.1 GeV.

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In what follows we give the experimental details, and consider possible theoretical interpretations. Our experimental apparatus (Fig. 1) is similar to the one described in a previous paper[1]. It mainly consists of four blocks (A, B, D, S) of scintillation counters, lead converters and spark chambers, above and below the target area, and covers about 0.25 x x 4π solid angle. It may detect charged particles with efficiency, close to one and γ-rays with an energy dependent efficiency which is typically 80% for an energy $E_\gamma \gtrsim 250$ MeV[2]. A pion (kaon) must have at least 95 MeV (145 MeV) kinetic energy in order to trigger the electronics, and at least 55 MeV (95 MeV) to give a recognizable track in the spark chambers.

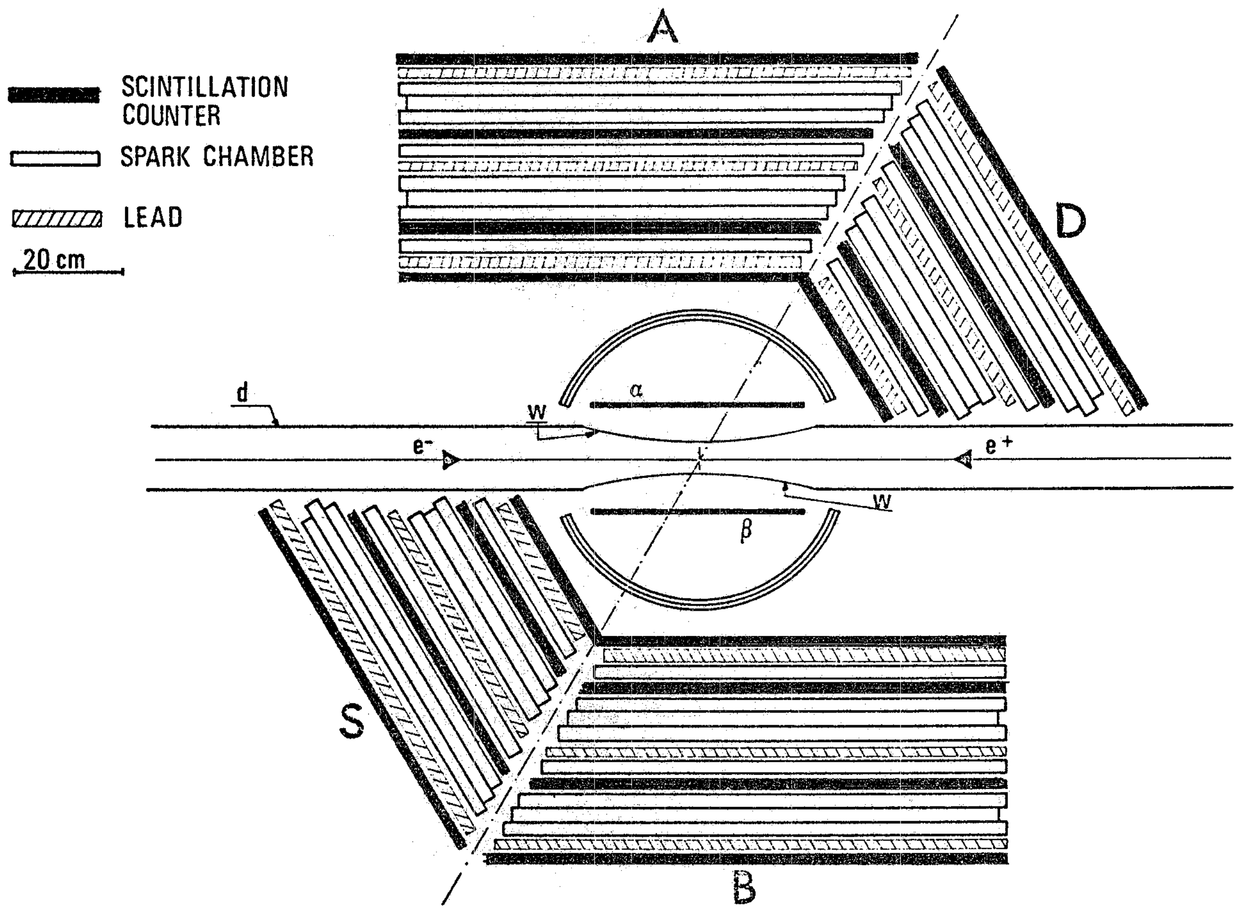

FIG. 1 - Experimental apparatus: front view from Adone center - d: doughnut; w: 0. 15 mm stainless steel window.

During the experiment we have placed close to the doughnut two cylindrical spark chambers. These are very thin (~ 0. 6 g/cm^2) and are convenient to improve the localization of the e^+e^- annihilation point and the identification of the charge of the particles. The apparatus was triggered whenever at least three tracks or showers had been detected in three of the four blocks ABDS, and counter α or β gave a signal (Fig. 1); i. e. one of the particles had to be charged.

Using this trigger we have obtained 146 multiple events; they have been distributed in categories c (see Table I) according to the number of showers and tracks observed and to the c. m. energy. The luminosity has been measured by using as a monitor the scattering $e^+ + e^- \longrightarrow e^+ + e^-$ at small momentum transfer[3]. The values of the luminosity are consistent with our contemporary results on the less frequent reaction $e^+ + e^- \longrightarrow \longrightarrow \gamma + \gamma$[1].

We assume in the following that the multiple events we discuss here are of hadronic nature, with the particles directly produced being pions or kaons. In fact, the number of nuclear interactions of the charged particles in the absorbers is in agreement with what may be expected in case the charged particles are pions.

The relative abundance of multiple hadronic events makes improbable at our energies any origin different from the well known[4] one photon annihilation diagram. The number of events from virtual γ-γ interaction[5] (that is reaction $e^+ + e^- \longrightarrow e^+ + e^- +$ hadrons) having the necessary configuration to be observed in our spark chambers, should be definitely lower than our results. More specifically, we assume also that the more relevant processes which contribute to our events are the following:

(2) $e^+ + e^- \longrightarrow \pi^+ + \pi^- + n\pi^o$, with $1 \leq n \leq 4$

(3a) $e^+ + e^- \longrightarrow \pi^+ + \pi^- + \pi^+ + \pi^- + n\pi^o$, with $0 \leq n \leq 2$

(3b) $e^+ + e^- \longrightarrow 3\pi^+ + 3\pi^-$.

This corresponds to the assumption that disregarding processes with more than six pions or with kaons does not affect appreciably our final results on the total cross section.

The cross sections at a given energy for the different processes (2), (3) may be in principle obtained by a system of relations of the type

(4) $$N_c = L_t \; \Sigma_i \; \sigma_i \; \varepsilon_{ic}$$

where N_c is the total number of the events belonging to the category c of Table I. By L_t we indicate the total luminosity for each energy. The eight cross sections σ_i are those related to the processes listed in (2), (3). ε_{ic} is the detection efficiency for events of category c coming from reaction i. The efficiencies we have used have been evaluated under the hypothesis of pure invariant phase space momentum distribution. The evaluation has been made by the Montecarlo method taking into account the details of our experimental apparatus, the length of the interaction region, the probabilities for detection of the γ-rays and for nuclear interaction of the charged particles.

We have looked for the best solution to the relations (4) under the condition that all the σ_i should be positive or zero. Because of the poor sta

TABLE I

Distribution of our events according to the number of tracks and showers at various energies.

			c. m. Energy 2E (GeV)						
Category c	Number of tracks	Number of showers	1. 4	1. 5	1. 85	1. 9	1. 94	2. 1	2. 4
1	1	2	1	2	4	4	0	21	8
2	1	3	0	1	0	0	0	0	1
3	2	1	1	2	1	4	5	19	7
4	2	2	1	0	1	1	2	8	3
5	2	3	0	0	1	0	1	4	0
6	3	0	2	5	1	4	3	9	2
7	3	1	1	0	0	2	0	5	0
8	3	2	0	0	0	0	0	3	1
9	4	0	1	0	0	0	0	4	0
Luminosity $(L_t \times 10^{-34})\ cm^{-2}$			0. 76	2. 96	2. 28	6. 2	4. 1	24. 8	4. 6

tistics each cross section thus estimated has a very large error; however it is possible to give a more reliable value for the sum of the cross sections:

$\sigma_{2\pm}$ = sum of the cross sections for processes (2)

$\sigma_{4\pm}$ = sum of the cross sections for processes (3)

$\sigma_T = \sigma_{2\pm} + \sigma_{4\pm}$ = total cross sections for processes (1)

This division is convenient, due to the fact that the events with at least 3 charged tracks detected (categories 6, 7, 8, 9 of Table I) contribute only to $\sigma_{4\pm}$.

These cross sections are reported in Table II and shown in Fig. 2 and refer to four different c. m. energy regions 2E: 1. 4 ÷ 1. 5 GeV; 1. 85 ÷ ÷ 1. 94 GeV; 2. 1 GeV; 2. 4 GeV.

The cross sections are given with two kind of errors indicated. The lines (Fig. 2) are pure statistical errors. The rectangles indicate a reasonable estimate of the width of our possible systematic errors, as due to various sources: uncertainties on the evaluation of the nuclear interactions of the charged particles, and on the detection efficiency of the low energy photons; distinction between low energy γ-rays and tracks; actual sensitive area of the apparatus; uncertainties in the elaboration of relations (4); possiblé radiative corrections to the monitor, not yet calculated.

TABLE II

Cross sections for the processes $e^+ + e^- \to$ multiple production, as obtained under the following hypothesis (see text):

a) Multiple production follows a pure phase-space distribution.
b) Charged particles observed are pions.
c) The photons come from neutral pions.

The first error is the statistical one. In parenthesis we report a reasonable estimate of the systematic error.

Type of process	Cross section at different total c.m.energies 2E (10^{-33} cm^2)			
	2·(0.7 ÷ 0.75) (GeV)	2·(0.925 ÷ 0.97) (GeV)	2·(1.05) (GeV)	2·(1.2) (GeV)
$e^+ + e^- \to$ 2 charged pions + neutrals (reaction (2))	8 ± 8 (± 2)	6 ± 5 (±2)	8.5 ± 4 (±2)	27 ± 14 (±7)
$e^+ + e^- \to$ at least four charged pions plus any number of neutrals (reaction (3))	47 ± 16 (±12)	9.5 ± 3 (±2)	8.5 ± 3 (±2)	7 ± 5 (±2)
$e^+ + e^- \to$ any multiple process with at least 3 particles, two at least being charged (reactions (2) + (3))	55 ± 15 (±14)	15.5 ± 4 (± 4)	17 ± 4 (±4)	34 ± 12 (±9)

The data in Table I indicate the presence of a significant number of e. m. showers (191 showers and 298 tracks). Actually our best fits give the general indication that multiple reactions with neutral pions are relatively more abundant than those with only charged particles. As an average we have

$$\frac{\sigma(\text{4 or 6 charged pions + neutral pions})}{\sigma(\text{4 or 6 charged pions})} \approx 2$$

In Fig. 2 we report also the data from ref. (6). The energy behaviour of our $\sigma_{4\pm}$ data is in reasonable agreement with that of reference (6) and seems to reflect the behaviour of the $\pi^+ + \pi^- + \pi^+ + \pi^-$ channel reported by the same authors. According to Bramon and Greco[8] this effect could be due to the ϱ' production.

In this case the same authors predict a branching ratio $(\varrho' \to \pi^+ + \pi^- + \pi^+ + \pi^-)/(\varrho' \to \pi^+ + \pi^- + \pi^0 + \pi^0)$ of the order of unity. However this prevision does not seem to agree with our results on $\sigma_{2\pm}$, which indicate that the cross section for the process $e^+ + e^- \to \pi^+ + \pi^- + \pi^0 + \pi^0$ in the ϱ' region is lower than the corresponding cross section for the process $e^+ + e^- \to \pi^+ + \pi^- + \pi^+ + \pi^-$ reported in ref. (6, 7).

We note that ref. (6) and (7) quote some higher values for $\sigma_{4\pm}$ and σ_T in the energy region around 2 GeV. This difference can perhaps be explained considering the different kinematical regions explored and the different cuts in energy, due to the different triggers. In fact the assumption of a pure invariant phase space distribution of the pions, used both by us and the authors of ref. (6, 7) is only a rough approach.

We have actually observed discrepancies between our experimental data and

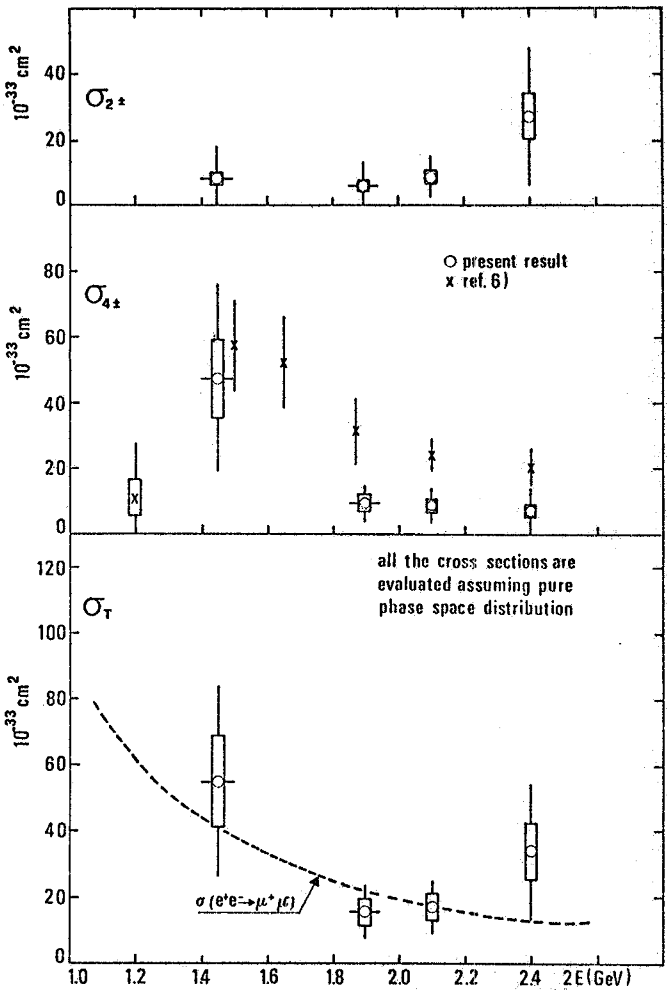

FIG. 2 - Results on σ_T (total cross section for reactions (1)), $\sigma_{4\pm}$ (reactions (3)), $\sigma_{2\pm}$ (reaction (2)) as a function of 2E, total energy in the c. m. system. The rectangles indicate a reasonable estimate of the width of our possible systematic errors. The bars represent the statistical errors. All these values are obtained under the assumption of a pure invariant phase space distribution: The limitations of this model are discussed in the text. The dashed line indicate the total cross section for the process $e^+ + e^- \longrightarrow \mu^+ + \mu^-$.

the predictions of the phase space model. For instance in the cases when the reaction $e^+ + e^- \longrightarrow \pi^+ + \pi^- + \pi^0$ is excluded by momentum conservation, events with two tracks and one shower detected (category 3) seem to be more coplanar than expected.

We are now trying alternatively, to interpret our results by assuming that processes (1) go through some particular channel, like for instance, $e^+ + e^- \to \omega + \pi^0$; $\pi^+ + \pi^- + \eta$. For instance at 2E = 2. 4 GeV the multiplicity of our events (see Table I) can be well explained with only the single process $e^+ + e^- \longrightarrow \pi^+ + \pi^- + \eta$, when assuming for the η the known decays with their branching ratios(9) and disregarding the dynamical correlations. In this case the value of σ_T for $e^+ + e^- \longrightarrow \pi^+ + \pi^- + \eta$ turns out to be $(40 \pm \pm 10) \times 10^{-33}$ cm^2.

Furthermore we have also investigated, in the energy range 1. 85 $\leq$ 2E $\leq$ 2. 1 GeV, by means of a detailed kinematical analysis, the events of categories 3 and 4 of Table I in order to separate the process:

(5) $$e^+ + e^- \longrightarrow \pi^+ + \pi^- + \pi^0$$

(6) $$e^+ + e^- \longrightarrow K^+ + K^- + \pi^0.$$

In category 3 we find that only 10 events, out of a total of 29, could be due to reaction (5); from this we obtain

$$\sigma(e^+ + e^- \longrightarrow \pi^+ + \pi^- + \pi^0) \leq (5 \pm 2) \times 10^{-33}\ \mathrm{cm}^2$$

In category 4 there is only one event which can be interpreted as due to process $e^+ + e^- \rightarrow \pi^+ + \pi^- + \pi^0$. This corresponds to a cross section of $(2 \pm 2) \times 10^{-33}$ cm^2, in agreement with the previous value.

From a similar analysis in the same energy region, one gets a limiting value: $\sigma(e^+ + e^- \rightarrow K^+ + K^- + \pi^0) \leq 6 \times 10^{-33}$ cm^2 with 90% confidence level.

A comparison of our results with the theoretical predictions is not easy, for there is not a unique theory of reactions (1) at our energies. The theoretical models presented until now may be divided into two types: a first group is based on vector dominance, either with the well known (ϱ, ω, φ) vector mesons, which are supposed to be present at high energies with the slowly decreasing tail of their propagator(10), or with a new meson (the ϱ')(11). These models do not exclude cross section values in the range of $(10 \div 30) \times 10^{-33}$ cm^2 at our energies, which could agree with our results.

The second group of models, like the jet model(12) and the statistical model(13), is connected to the general problematic of deep inelastic electron scattering. These models predict a value $\sigma(e^+ + e^- \rightarrow \text{hadrons}) \simeq \sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)$. In the simplest quark model case(14) we should have $\sigma(e^+ + e^- \rightarrow \text{hadrons}) \simeq 2/3\ \sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)$. In Fig. 2 we have reported the total cross section for the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

It is quite possible, of course, that the contributions from more than one model, which are not alternative choices, must be added together, also taking into account their interferences.

Work is in progress to increase the statistics and to make a more detailed kinematical analysis of our events. A new experimental apparatus specifically designed to observe these new hadronic processes is under construction.

We wish to thank our technician, V. Bidoli, for this continuous assistance during the experiment and Mr. G. Di Stefano and coworkers for their helpful assistance. We thank also the Adone staff for the smooth operation of the machine.

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FIG. 3, 4, 5, 6 and 7

Some multihadronic events from our spark chambers.
At the bottom is a front view of our apparatus (see Fig. 1).
At the top is the side view reverted by our mirrors.

Fig. 3	cathegory 6	(3 tracks)
Fig. 4	cathegory 6	(3 tracks)
Fig. 5	cathegory 6	(3 tracks)
Fig. 6	cathegory 9	(4 tracks)
Fig. 7	cathegory 4	(2 tracks and 2 showers).

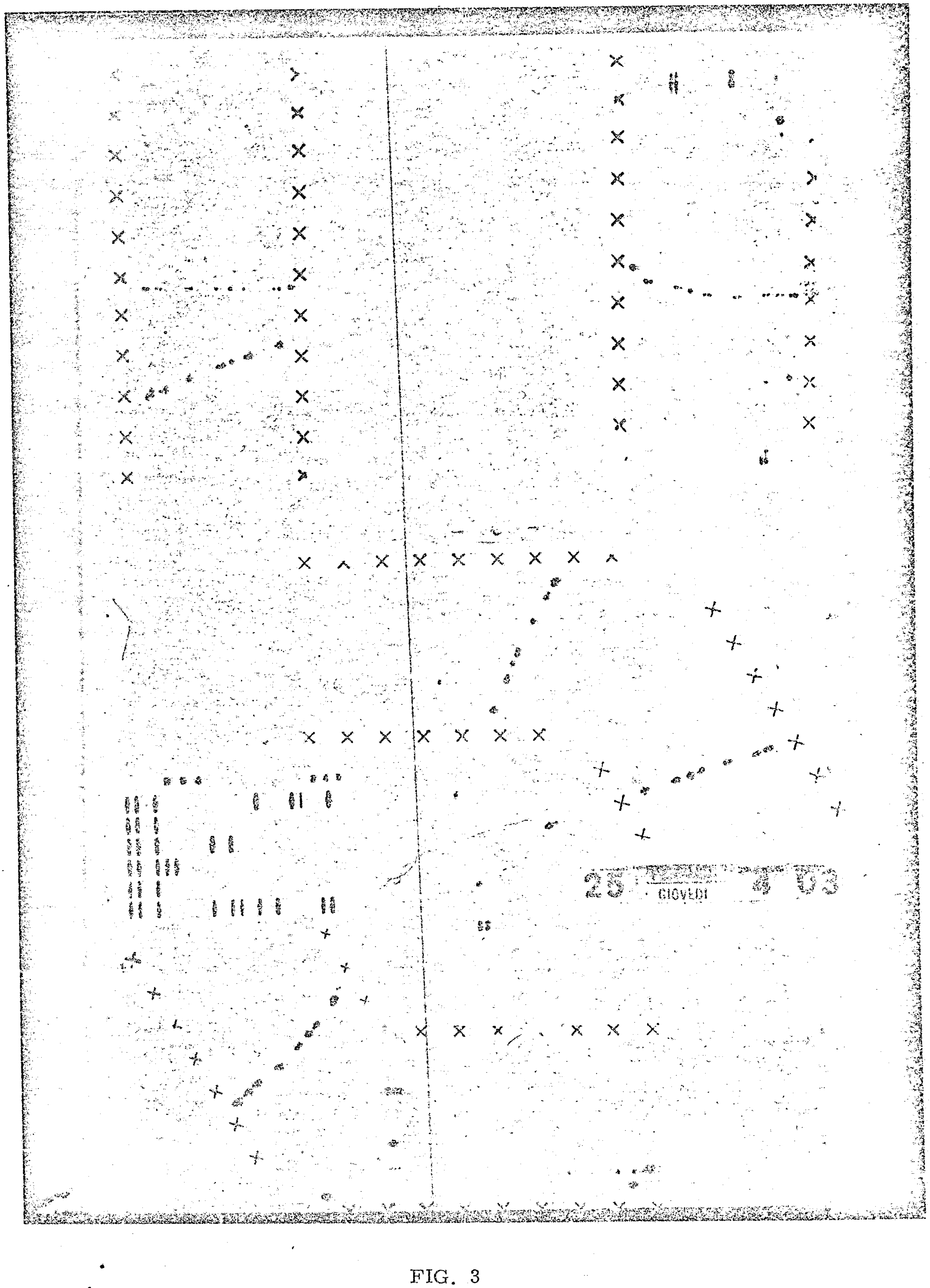

FIG. 3

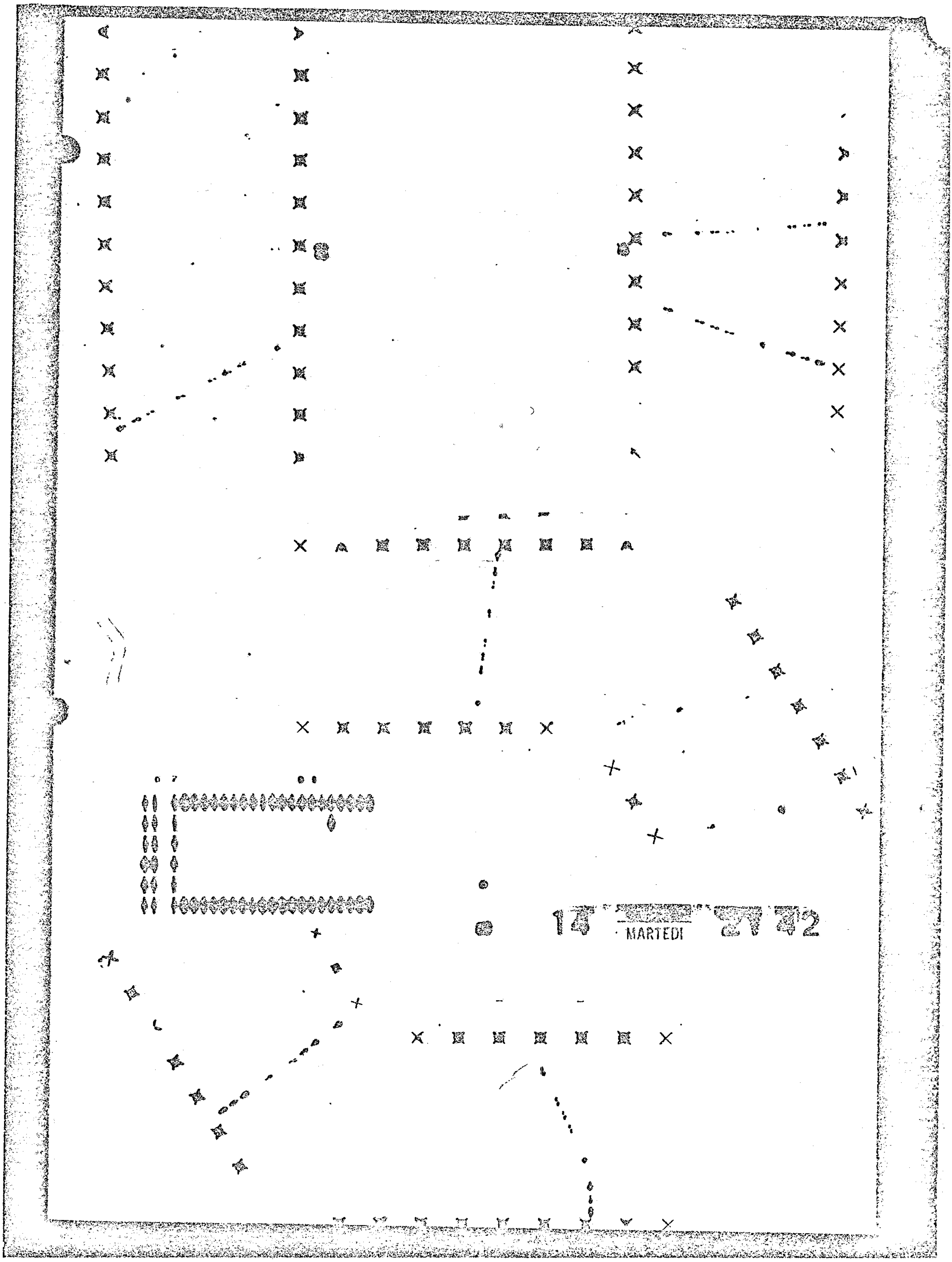

FIG. 4

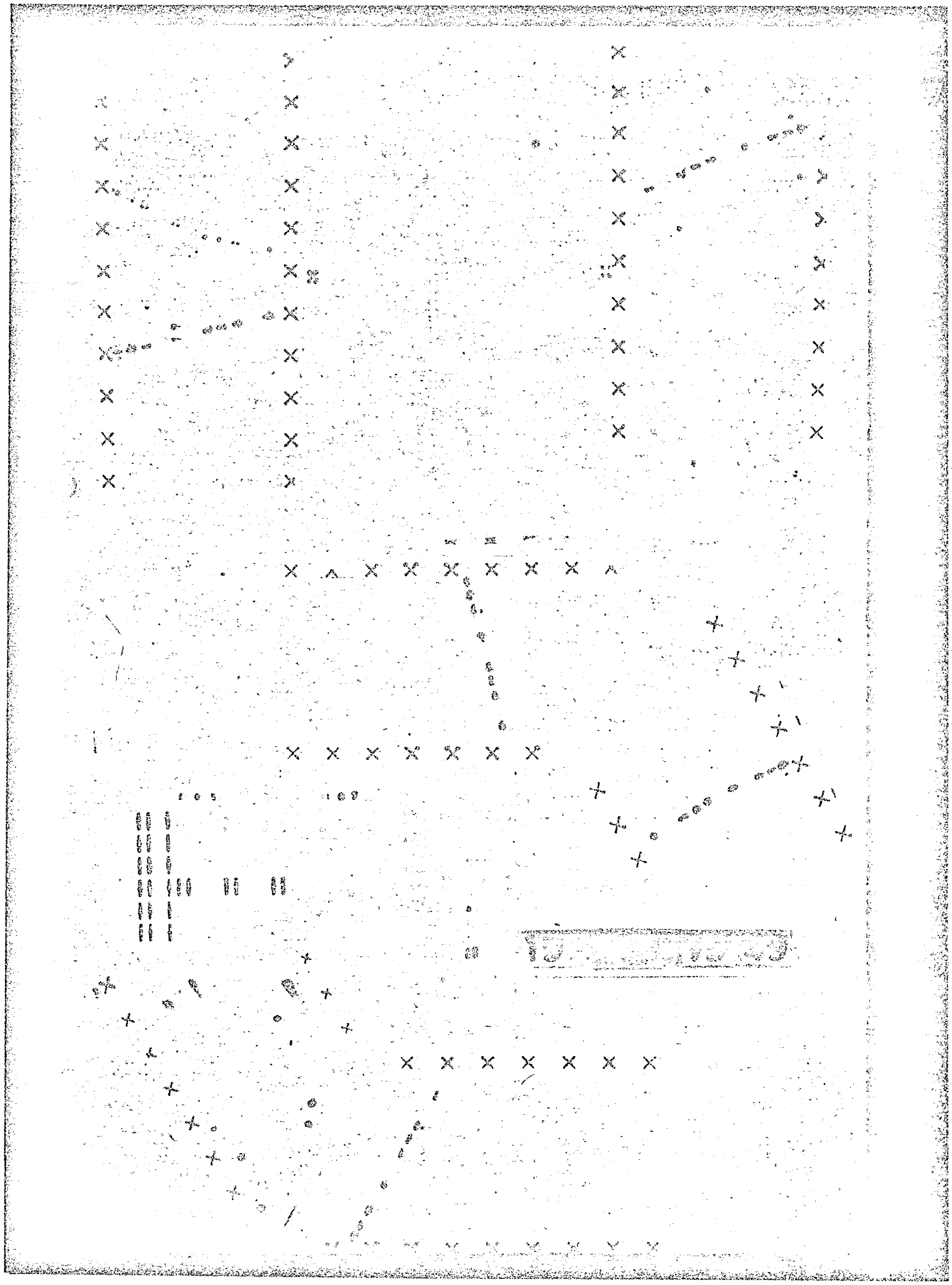

FIG. 5

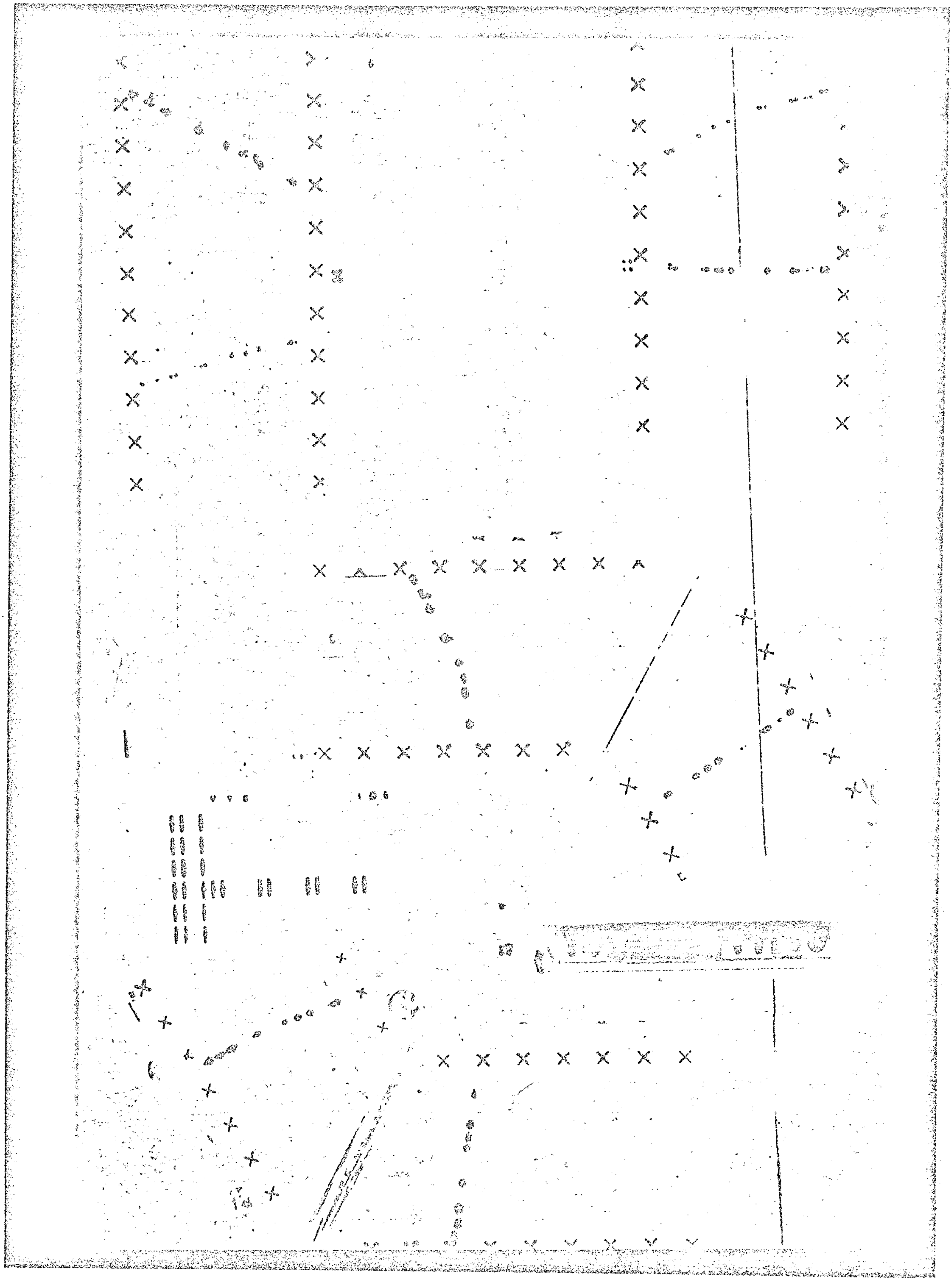

FIG. 6

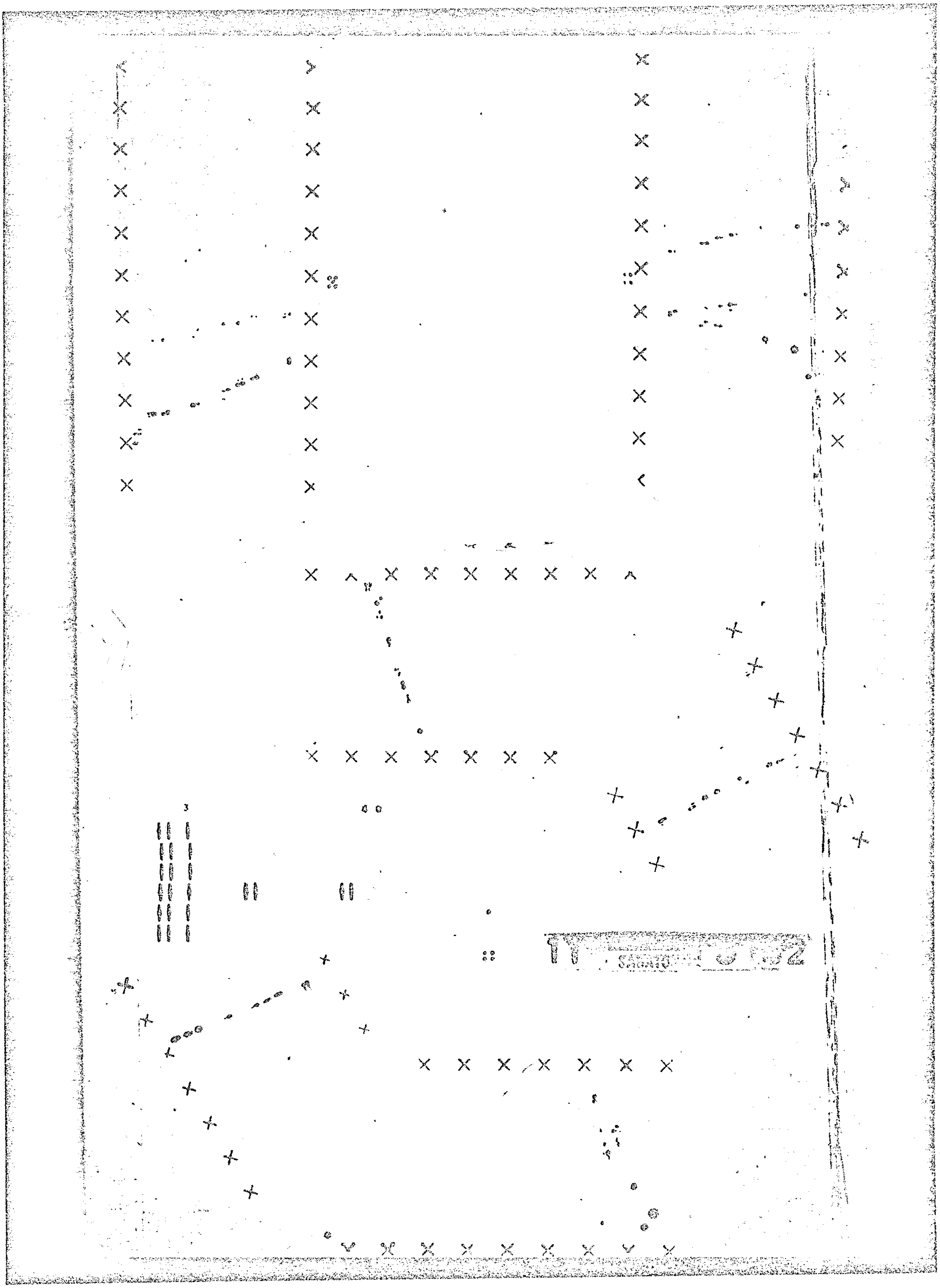

FIG. 7