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SEARCH FOR THE PROCESS $e^- + e^- \longrightarrow \mu^- + \mu^-$

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ABSTRACT

Speculating on the possible existence of a strong muon-electron coupling which has escaped observation because of a multiplicative muon conservation law, we have looked for the process $e^- + e^- \longrightarrow \mu^- + \mu^-$. We set an upper limit on the cross section of $.67 \times 10^{-32}$ cm^2 and conclude that such a coupling, if it exists, is no stronger than 610 times the normal vector coupling of weak interactions.

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The principle of muon conservation has served as the most concise explanation of the absence of a large number of processes involving leptons. As described in a paper by G. Feinberg and S. Weinberg,[1] the law of muon conservation may be formulated either in terms of additive quantum numbers such that the sum of muon number and electron number are separately conserved, or in terms of a multiplicative muon parity in which the product must be conserved in any interaction. At the present time, all experiments in weak interaction physics are consistent with either formulation.

An observation of the transition of muonium (μ^+, e^-) into antimuonium (μ^-, e^+) or the reaction $e^- + e^- \rightarrow \mu^- + \mu^-$ would permit one to choose the multiplicative law.[1,2] On the other hand, a null result in an experiment which was sufficiently sensitive would strongly favor the additive law. To quantify the word "sensitive," it is useful to introduce a phenomenological Hamiltonian describing a point interaction of strength G, such as

$$H = \frac{G}{\sqrt{2}} \left(\bar{\Psi}_\mu \gamma_\lambda (1 + \gamma_5) \Psi_e\right) \left(\bar{\Psi}_\mu \gamma_\lambda (1 + \gamma_5) \Psi_e\right) + \mathrm{H.C.} \qquad (1)$$

One would be tempted to give up the multiplicative law if the null result indicated $G \ll G_V = 10^{-5}/M_p^2$, the vector coupling constant.

Our present empirical knowledge on the limits of G is far removed from G_V. Recently, the first measurements on the muonium experiment were reported by Amato, Crane, Hughes, Rothberg, and Thompson.[3,4,5] They obtained a null result and were able to conclude $G < 5800\ G_V$.

This result is not pertinent to the question of the muon conservation law in the weak interactions. In fact, if an effect had been observed one would have had to conclude that there existed a strong leptonic force which had previously escaped detection. The present experiment addresses the same problem. We were motivated in part by the relevance of a force of this strength for the interpretation of current measurements of the electromagnetic structure of leptons.

We have searched for the reaction $e^- + e^- \longrightarrow \mu^- + \mu^-$ using a colliding beam technique. In 114 hours of beam-interacting counter-on-time, we find one event which passes our criteria for muons in the final state. However, the measured background (probably from cosmic rays) is 3.7 events and we conclude that we have not observed the process. Using Möller scattering to monitor the storage ring luminosity, we obtain an upper limit for the total cross section of 0.67×10^{-32} cm^2 (95% confidence). In terms of the Hamiltonian of Eq. (1), we have $G < 6.1 \times 10^{-3}/M_p^2$ or ($G < 610\ G_V$).

The experiment was carried out on the Princeton-Stanford electron storage rings at an energy E = 525 MeV in each beam. The operation of the storage rings has been described elsewhere.[6, 7, 8] The Stanford Mark III Linear Accelerator supplied 300 MeV electrons, which were stacked and raised to an energy of 525 MeV in a vacuum of 10^{-8} torr, with a mean storage time of 30 minutes. A typical counting cycle consisted of 20 minutes of data taking followed by a few minutes of electron injection. At the start of the data recording, the stored beam intensities were 50 to 100 mA.

A schematic of the detector is shown in Fig. 1. For projected polar angles greater than approximately 40°, there is sufficient lead and iron between the interaction region and counter 7 to reduce the (ctr 5 + ctr 7) coincidence efficiency for electrons coming from the storage ring to $< 1\%$. Muons coming from the reaction $e^- + e^- \longrightarrow \mu^- + \mu^-$ have sufficient range to pass through the shower chamber directly above ctr 5, but stop before reaching ctr 4. The spark chambers are triggered on the 8-fold coincidence of ctrs 5, 7, 9, 10, 11, 12, 13, 14, unless there is a veto signal provided by either a coincidence of any two of ctrs 1, 2, 3, 4, or a coincidence of ctrs 15 and 17. The veto system provided a factor of ~500 rejection against cosmic rays. For projected polar angles less than approximately

40^o, electrons from Möller scattering ($e^- + e^- \longrightarrow e^- + e^-$) can produce a spark chamber trigger. The electron events from this region are used for normalization in determining the cross section for the $e^- + e^- \longrightarrow \mu^- + \mu^-$ reaction.

The view of the spark chambers shown in Fig. 1 and the one orthogonal to it were photographed. In addition, for each event the following information was recorded on the film:

1. The phase of the rf cavity at the time the trigger counters fired.
2. The time delay, T_D, between the anode signals of ctrs 5 and 14, and the pulse heights (A_1 and A_2) of the dynode signal from each of these phototubes.

Since the circulating electron beam was bunched to a length of $\simeq 2.0$ meters, and the circumference of the orbit was $\simeq 12$ meters we were able to improve the cosmic ray rejection by a factor of 4 by measuring the phase of the rf. An additional rejection factor of 6 was obtained by measuring the time delay (T.O.F.) between the production of scintillation light in ctrs 5 and 14. Since the scintillators were large (21" × 25"), to obtain adequate resolution, it was necessary to correct for the propagation of light through the scintillator. The T.O.F. (in nanoseconds) was calculated from[9]

$$\text{T.O.F.} = 0.179\, T_D + 0.149(d_1 - d_2) + 13.5/A_1 - 12.7/A_2 - 5.8 \qquad (2)$$

where d_1, (d_2) is the distance (in inches) between the point at which the scintillation light was produced and the photocathode of ctrs 5.^{14}

80,000 photographs were obtained in 148 hours of picture taking. For 28 of these hours, 640 photographs were obtained without electron beams in the storage rings to provide a measurement of the cosmic ray background. The film was scanned for events which produced collinear tracks in the upper and lower chambers. 7000 such pictures were found. In the analysis, the events were separated into "muon" and "electron" events, depending on whether or not they passed through the Pb absorber between ctrs 7 and 9. These two classes of events were analyzed separately but in an identical manner.

First, a set of general criteria were imposed to insure that the events fell inside a fiducial volume in which the detector had uniform sensitivity.

a. The longitudinal (along beam line) and transverse displacement of the source of the event was required to be less than 2.5 inches from the center of the interaction region.

b. The projected polar angle (θ_0) was limited to $37.5 \leq \theta_0 \leq 110^\circ$.

c. The projected azimuthal angle (ϕ_0) was limited to $62.5^\circ \leq \phi_0 \leq 117.5^\circ$.

The remaining events were first sorted on y, their transverse displacement. In Fig. 2a, one sees the strong peak of "electrons," events coming from the center of the interaction region. The corresponding muon region histogram (Fig. 2b) shows no such peak. Events satisfying $-0.2'' \leq Y \leq +0.6''$ were then sorted on phase (see Figs. 2c and 2d). Those events which satisfied the criteria $10 \leq \text{phase} \leq 14$ were further sorted on T.O.F. (see histograms 2e and 2f). Five "muon" events remained in the T.O.F. range of -1.6 to + 1.3 nanosec.

Each of these 5 events were examined by us personally. On the basis of qualitative characteristics of the events (e.g., showering in the Pb-plate spark chambers), we were able to identify 4 of them as electrons. The single remaining event has a T.O.F. value of 1.2 which is just on the edge of the cut for cosmic rays.

A measurement of the background was made by varying one of the above criteria at a time and determining the number of "muon region" events which satisfied the modified criteria. In detail, we found

a. If the y criteria were $0.7'' \leq y \leq 1.5''$, that is, outside the colliding-beam source region, there remained 5 events.

b. If the phase were restricted to $15 \leq \text{phase} \leq 19$, there remained 3 events.

c. If the T.O.F. range were changed to 3.4 to 6.3 nanoseconds, there remained 3 events.

Each of the 11 events above were examined and found to be reasonable candidates for muons (aside from the one criterion which had been varied). The expected background in the muon region was taken to be 3.7 ± 1.1 events, the average of the three measurements.[10] More elaborate treatments of the background are possible, but we considered them unjustified because of the small total number of background events. Having found only one event under interacting beam conditions, we recognize that we have not observed the process and can obtain an upper limit. For 95% confidence we take this to be 3.7 events.[11]

The angular distribution of events from the "electron" region is displayed in Fig. 3 along with the expected distribution from Möller scattering. The theoretical histogram was normalized to the total number of electron events observed, $N_e = 505$. From N_e and the integral of the Möller cross section over the solid angle of the electron region of the detector, we obtain the time-integrated luminosity, L.

$$L = \frac{N_e}{\int_{\substack{\text{Electron}\\ \text{Detector}}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{Möller}} d\Omega} = 43 \times 10^{+32} \text{cm}^{-2} \tag{3}$$

L is the total number of events that would take place during the entire data taking period for a process with unit cross section. Assuming isotropy for the

$e^- + e^- \longrightarrow \mu^- + \mu^-$ process we obtain the total cross section from

$$\sigma_T(e^- + e^- \rightarrow \mu^- + \mu^-) = \frac{2\pi N_\mu}{L \int_{\substack{\text{Muon} \\ \text{Detector}}} d\Omega} = 0.18 \times 10^{-32} N_\mu \tag{4}$$

where N_μ is the number of muon events. Using our upper limit of 3.7 on N_μ, we find

$$\sigma_T(e^- + e^- \longrightarrow \mu^- + \mu^-) < 0.67 \times 10^{-32}\,\text{cm}^2 \tag{5}$$

From the interaction Hamiltonian of Eq. (1), we calculate the differential cross section,

$$\frac{d\sigma}{d\Omega} = \frac{G^2 (2E)^2}{2\pi^2} \tag{6}$$

and obtain the limit on G:

$$G < 6.1 \times \frac{10^{-3}}{M_p^2} \tag{7}$$

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10. Among the 640 events recorded during a 28 hour period in which there were no beams in the rings, we found no events satisfying our criteria for $e^- + e^- \rightarrow \mu^- + \mu^-$. This is not in disagreement with 3.7 events measured in 114 hours of interacting beam runs.
11. The equality of the 95% confidence upper limit, 3.7, and the average of the background, 3.7 ± 1.1 is accidental. The probability, $W(S_u)$, that the signal is less than S_u is

$$W(S_u) = \frac{4^{11}}{(11)!}\int_0^{S_u} dS \int_0^{\infty} dB \left[(S+B)e^{-(S+B)} B^{11} e^{-3B} \right]$$

where we have used the information:

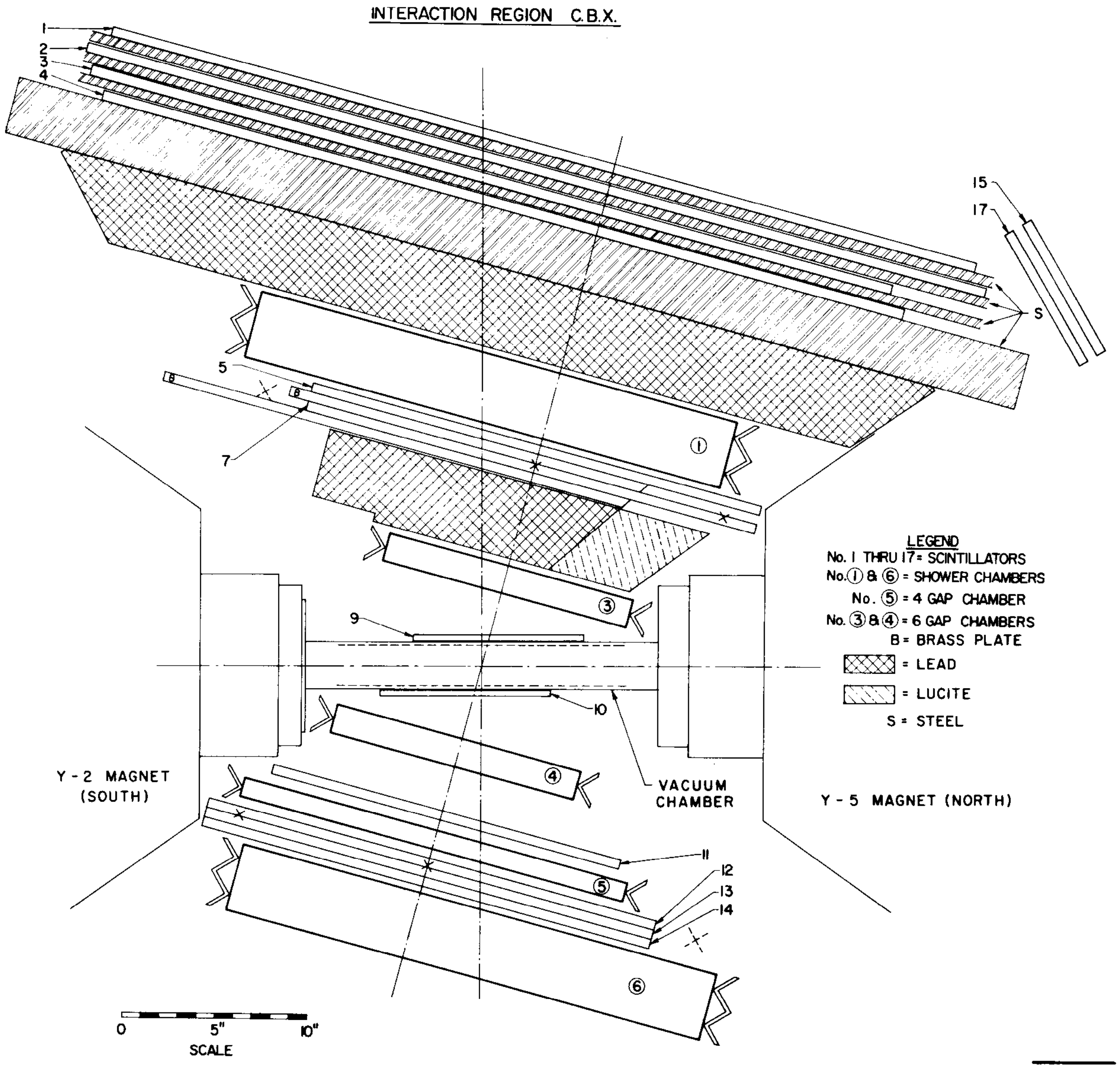
a) Three attempts to measure the background, B, resulted in 3, 5, and 3.

b) A single measurement of the signal plus background, (S + B), gave one event.

The upper limit is obtained by solving the equation $W(S_u) = 0.95$.

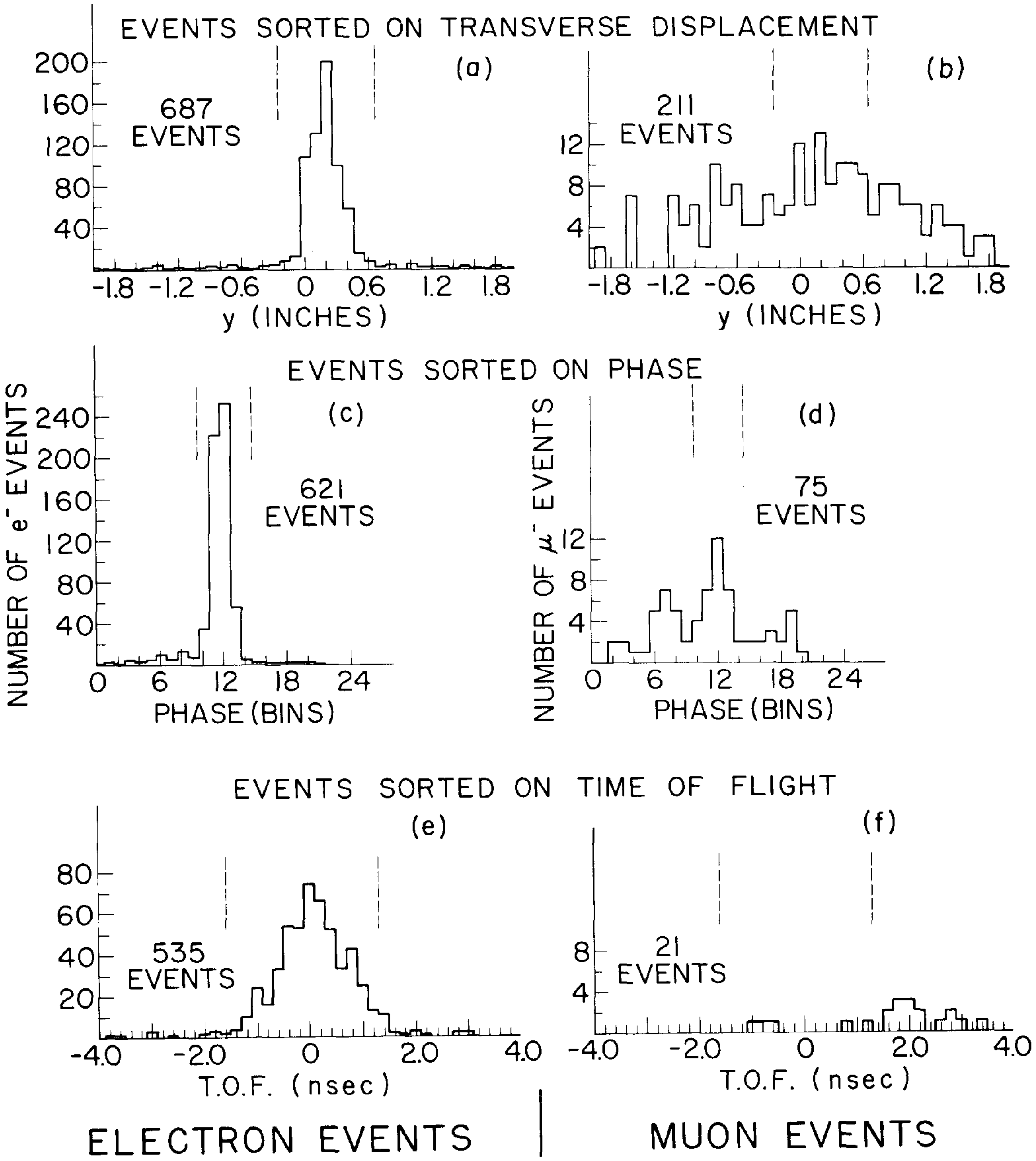
FIGURE CAPTIONS

1. Schematic of the spark chamber detector.
2. Histograms of event selection in the data analysis-plots on the left are for events in the "electron region" of the detector; on the right, for the "muon region."
3. Angular distribution of the electron events.


INTERACTION REGION C.B.X.
1
2
3
4
15
17
S
5
B
B
7
①
③
9
10
④
VACUUM CHAMBER
Y - 2 MAGNET (SOUTH)
Y - 5 MAGNET (NORTH)
11
12
13
14
⑤
⑥
LEGEND
No. 1 THRU 17 = SCINTILLATORS
No. ① & ⑥ = SHOWER CHAMBERS
No. ⑤ = 4 GAP CHAMBER
No. ③ & ④ = 6 GAP CHAMBERS
B = BRASS PLATE
▨ = LEAD
▨ = LUCITE
S = STEEL
0
5"
10"
SCALE

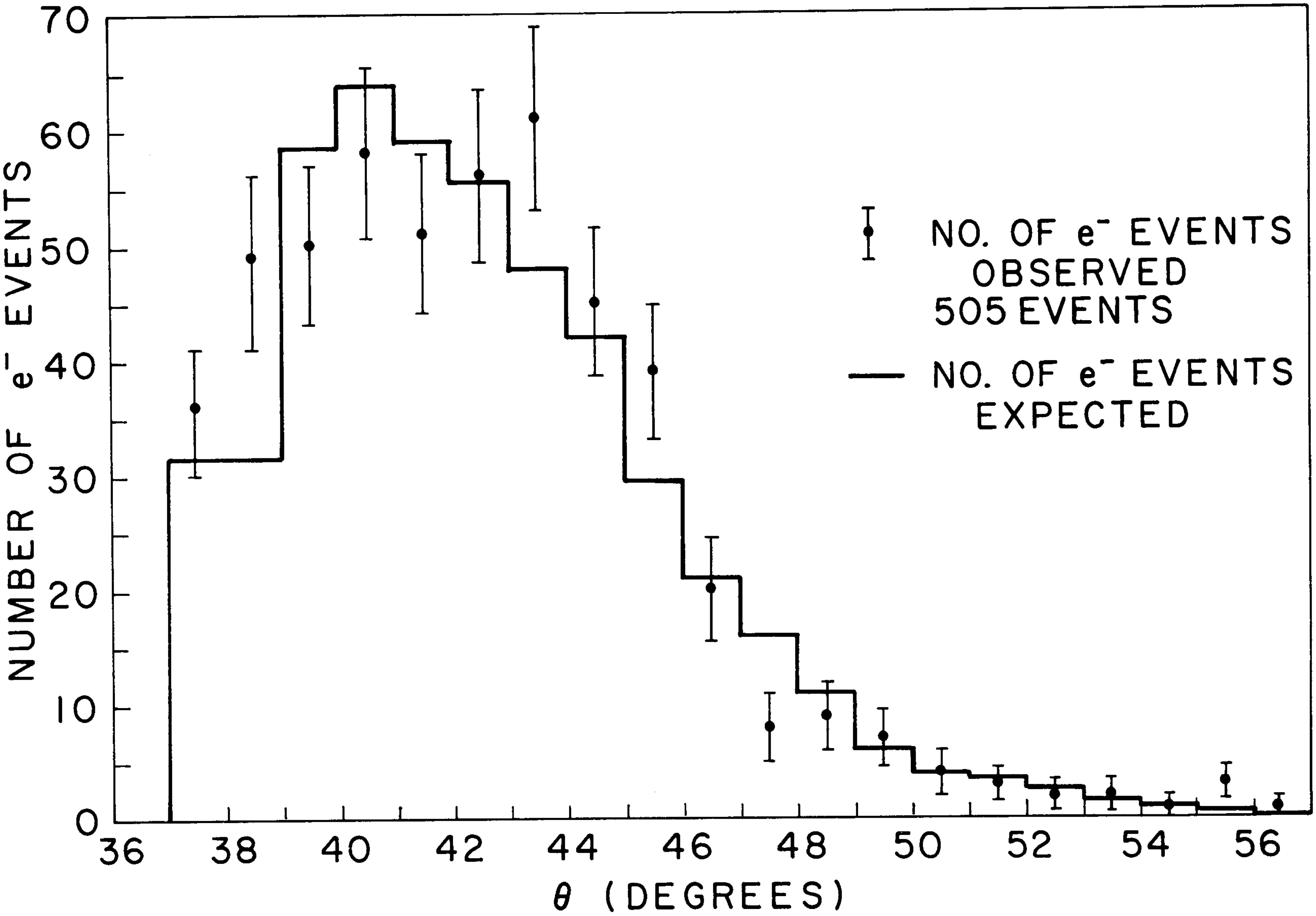
1258A1

Fig. 1


EVENTS SORTED ON TRANSVERSE DISPLACEMENT
(a)
687 EVENTS
200
160
120
80
40
-1.8 -1.2 -0.6 0 0.6 1.2 1.8
y (INCHES)
(b)
211 EVENTS
12
8
4
-1.8 -1.2 -0.6 0 0.6 1.2 1.8
y (INCHES)
EVENTS SORTED ON PHASE
NUMBER OF e⁻ EVENTS
240
200
160
120
80
40
(c)
621 EVENTS
0 6 12 18 24
PHASE (BINS)
NUMBER OF μ⁻ EVENTS
(d)
75 EVENTS
12
8
4
0 6 12 18 24
PHASE (BINS)
EVENTS SORTED ON TIME OF FLIGHT
(e)
80
60
40
20
535 EVENTS
-4.0 -2.0 0 2.0 4.0
T.O.F. (nsec)
(f)
8
4
21 EVENTS
-4.0 -2.0 0 2.0 4.0
T.O.F. (nsec)
ELECTRON EVENTS
MUON EVENTS

1258A2

Fig. 2



70
60
50
40
30
20
10
0
36
38
40
42
44
46
48
50
52
54
56
NUMBER OF e⁻ EVENTS
θ (DEGREES)
NO. OF e⁻ EVENTS OBSERVED 505 EVENTS
NO. OF e⁻ EVENTS EXPECTED

1258A3

Fig. 3