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

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(Received 17 March 1969)

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 $e^- + e^- \to \mu^- + \mu^-$. We set an upper limit on the cross section of 0.67×10^{-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.

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 Feinberg and 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 $e^- + e^- \to \mu^- + \mu^-$ 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

$$H = 2^{-1/2} G [\bar{\Psi}_\mu \gamma_\lambda (1+\gamma_5) \Psi_e][\bar{\Psi}_\mu \gamma_\lambda (1+\gamma_5) \Psi_e] + \text{Hermitian conjugate.} \quad (1)$$

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 Hughes[3] and Amato, Crane, Hughes, Morgan, Rothberg, and Thompson.[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 $e^- + e^- \to \mu^- + \mu^-$ using a colliding-beam technique. In 114 h 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.[6-8] 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 min. A typical counting cycle consisted of 20 min of data taking followed by a few minutes of electron injection. At the start of the data recording, the stored-beam intensities were 50-100 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 (counter 5 + counter 7) coincidence efficiency for electrons coming from the storage ring to <1%. Muons coming from the reaction $e^- + e^- \to \mu^- + \mu^-$ have sufficient range to pass through the shower chamber directly above counter 5, but stop before reaching counter 4. The spark chambers are triggered on the eightfold coincidence of counters 5, 7, 9, 10, 11, 12, 13, 14 unless there is a veto signal provided by either a coincidence of any two of counters 1, 2, 3, 4, or a coincidence of counters 15 and 17. The veto system provided a factor of ~500 rejection against cosmic rays. For projected polar angles less than approximately 40°, electrons from Möller scattering ($e^- + e^- \to e^- + e^-$) can produce a spark-chamber trigger. The electron events from this region are used for normalization in determining the cross section for the reaction $e^- + e^- \to \mu^- + \mu^-$.

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 counters 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 ≃2.0 m and the circumference of the orbit was ≃12 m, 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 counters 5 and 14. Since the scintillators were large (21 in.×25 in.), 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

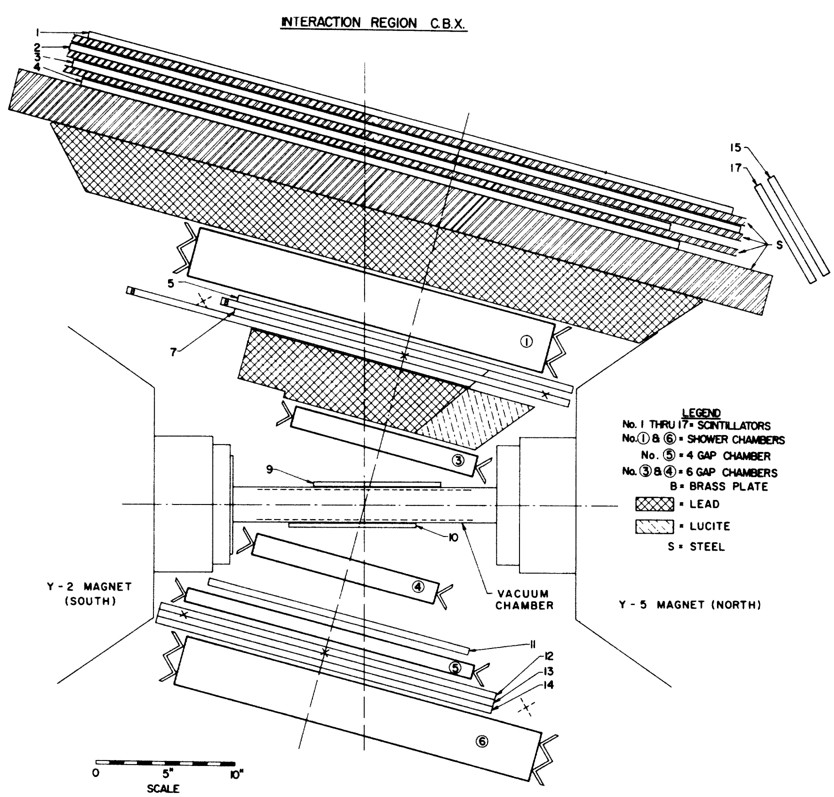

FIG. 1. Schematic of the spark-chamber detector.

the point at which the scintillation light was produced and the photocathode of counter 5 (14).

80 000 photographs were obtained in 148 h 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 counters 7 and 9. These two classes of events were analyzed separately but in an identical manner.

First, a set of general criteria was 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 in. from the center of the interaction region. (b) The projected polar angle (θ_0) was limited to $37.5° \leq \theta_0 \leq 110°$. (c) The projected azimuthal angle (Φ_0) was limited to $62.5° \leq \Phi_0 \leq 117.5°$.

The remaining events were first sorted on y, their transverse displacement. In Fig. 2(a) one sees the strong peak of "electrons," events coming from the center of the interaction region. The corresponding muon region histogram [Fig. 2(b)] shows no such peak. Events satisfying -0.2 in. $\leq y \leq +0.6$ in. were then sorted on phase [see Figs. 2(c) and 2(d)]. Those events which satisfied the criteria $10 \leq$ phase ≤ 14 were further sorted on T.O.F. [see histograms 2(e) and 2(f)]. Five "muon" events remained in the T.O.F. range of -1.6 to $+1.3$ nsec.

Each of these five 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 four 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 that (a) if the y criteria were 0.7 in. $\leq y \leq 1.5$ in., that is, outside the colliding-beam source region, there remained five events; (b) if the phase were restricted to $15 \leq$ phase ≤ 19, there remained three events; (c) if the T.O.F. range were changed to 3.4 to 6.3 nsec, there remained three events.

Each of the 11 events above was examined and found to be a reasonable candidate for a muon (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 scat-

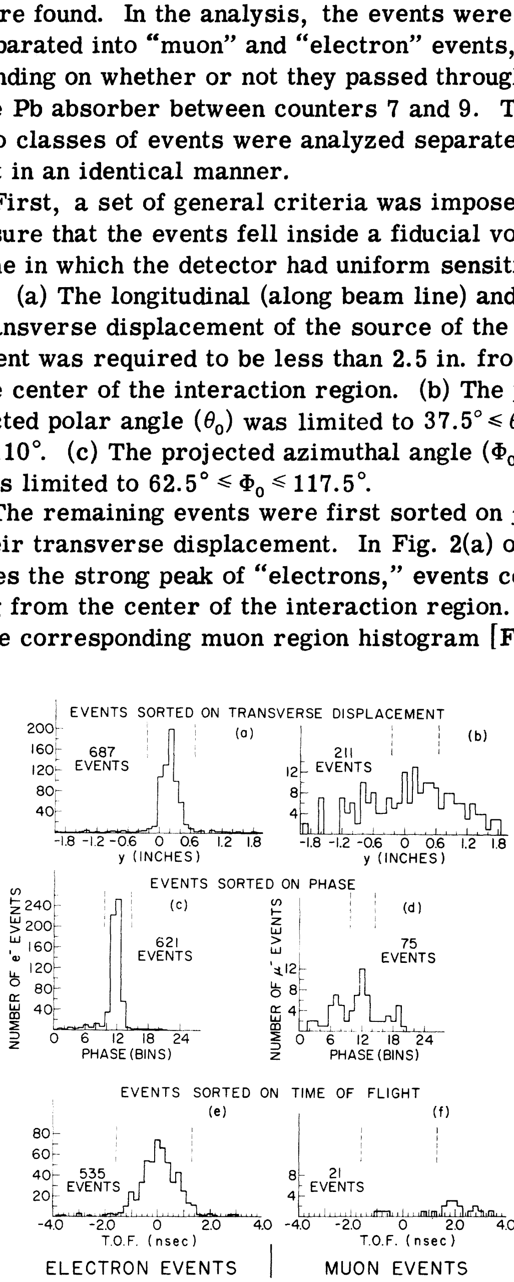

FIG. 2. Histograms of event selection in the data-analysis plots on the left are for events in the "electron region" of the detector; on the right, for the "muon region."

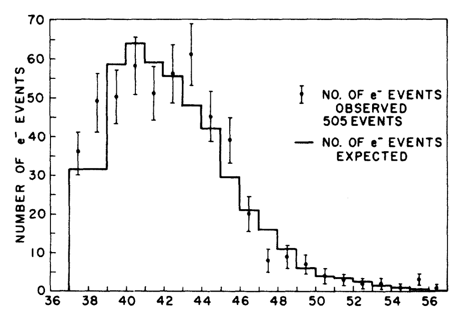

FIG. 3. Angular distribution of the electron events.

tering. 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:

$$L = \frac{N_e}{\int_{\substack{\text{electron}\\ \text{detector}}} (d\sigma/d\Omega)_{\text{Möller}}\, d\Omega} = 43 \times 10^{+32}\ \text{cm}^{-2}. \tag{3}$$

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

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

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

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

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

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

and obtain the limit on G,

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

We wish to thank C. Noyer and other members of the Stanford University High-Energy Physics Laboratory staff for their help in reactivating the storage rings and running the experiment, and A. Barna and D. Horelick of the Stanford Linear Accelerator Center Electronics Group for the design and construction of the electronic instrumentation for the time-of-flight measurements. We also want to acknowledge several enlightening conversations with Professor S. Brodsky and Professor S. Drell on the implications of the strong leptonic interaction for electrodynamic processes.

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*Work supported by U. S. Atomic Energy Commission under Contract No. AT(30-1)-2098.

†Work supported by U. S. Atomic Energy Commission under Contract No. AT(04-3)-515.

‡Work supported by Office of Naval Research, U. S. Navy under Contract No. NONR-1858(39).

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[10] Among the 640 events recorded during a 28-h period in which there were no beams in the rings we found no events satisfying our criteria for $e^- + e^- \to \mu^- + \mu^-$. This is not in disagreement with 3.7 events measured in 114 h 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

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

where we have used the following 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 $W(S_u) = 0.95$.