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A SEARCH FOR THE MUON-NUMBER VIOLATING DECAY $\mu \to e^+e^+e^-$

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ABSTRACT

A search has been performed for the muon-number-violating decay $\mu \to e^+e^+e^-$. No candidate event has been found, yielding an upper limit for the branching ratio of $B_{\mu 3e} < 1.3 \times 10^{-10}$ (90% C.L.). From part of the data taken with a trigger that enhanced $\mu^+ \to e^+e^+e^-\bar{\nu}_\mu \nu_e$ events, 11 such events were observed. They agree in number and spectra with expectations based on standard electroweak theory.

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Separate muon-, electron-, and tau-numbers are conserved in the minimal standard model[1] of electroweak interactions with massless neutrinos. However, in many extensions to the standard model[2] separate lepton numbers are not expected to be conserved quantities. The present experimental limits on neutrinoless rare muon decays such as $\mu^+ \rightarrow e^+e^+e^-$ that violate separate lepton-number conservation already provide strong constraints on many of the theories that go beyond the standard model. However, more sensitive experimental searches for these decays are needed to either discover separate lepton-number violation or to help eliminate some of these theories.

We report here an improved upper limit for the branching ratio

$$B_{\mu 3e} = \frac{\Gamma(\mu^+ \rightarrow e^+e^+e^-)}{\Gamma(\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu)}$$

from the first run with the Crystal Box detector (Fig. 1) in the Stopped Muon Channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). A separated, 26 MeV/c μ^+ beam was stopped in an elliptical, polystyrene target located at the center of the detector. The target was tilted by 45° with respect to the beam direction so that it presented a 6.7 cm radius projected circular cross section, 52 mg/cm^2 thick, to the beam. The muon stopping rate was typically 3×10^5 s^{-1} (average) with a duty factor of 6.8%. The polarization of decaying muons in polystyrene was measured to be (14.6 ± 1.4)%. The trajectories of charged particles emerging from the target and the energies and times of arrival of electrons, positrons, and photons were measured in the apparatus.

Decay positrons and electrons first traversed a cylindrical drift chamber[3] consisting of 8 concentric shells of wires at alternating angles of from 10° to 16° to the axis of the cylinder. The basic drift cell cross sectional area is 8 × 10 mm. The chamber has 728 drift cells. The position resolution of each wire is 140 μm (rms). The measured single track reconstruction efficiency is 95%. The chamber presents an average of 6.74×10^{-3} radiation lengths to a particle traversing it in a direction normal to the beam axis. There is no applied magnetic field.

Charged particles next traversed a scintillator hodoscope containing 36 counters. Each counter is 44.5 × 5.7 × 1.27 cm, with a photomultiplier coupled to each end by a light pipe. These counters define the fiducial volume for charged particles. Constant fraction discriminator[4] signals from the two ends of a scintillator are connected to a meantimer[5] for trigger coincidence decisions. The measured time resolution of each counter is 290 ps (FWHM). The regions upstream and downstream of the hodoscope are covered by 16 veto scintillation counters, each measuring 13.3 × 23.8 × 0.3 cm. These counters were used to help distinguish charged particles and photons.

The outermost part of the detector is an array of 360 NaI(Tl) face crystals, 6.35 × 6.35 cm cross section and 30.5 cm long, plus 36 corner crystals, 6.35 × 6.35 × 63.5 cm. These crystals are packaged in a single hermetically sealed container. Paper wrapping around each crystal provides optical isolation. Each face crystal is coupled to a single photomultiplier while the corner crystals have photomultipliers at both ends. The measured energy resolution function is approximately an asymmetric gaussian with a FWHM of 6.5% at 130 MeV. Each crystal has its own constant fraction discriminator with a threshold of 5 MeV. The timing resolution of the NaI(Tl) detectors is 1.1 ns (FWHM). The single particle acceptance in the fiducial area (which assures shower containment in the NaI(Tl)) is $\Omega/4\pi = 45\%$, including finite target-size effects.

The trigger requirements for a $\mu \to 3e$ candidate are:[6]

1. At least three hodoscope counter signals within 5 ns of each other.
2. At least three non-adjacent hodoscope counter signals within 10 ns.
3. A counter topology consistent with $\mu \to 3e$ decay.
4. Each hodoscope counter participating in the trigger having at least one discriminator from a NaI(Tl) crystal in the row behind that counter, or in an adjacent row, triggered within 15 ns.
5. For most of the data reported here, at least 80 MeV deposited in the entire NaI array. Approximately 10% of the data was taken without this last requirement to enhance the acceptance for $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ events.

A total of 2.2×10^{11} muons were stopped in the target during the live time of the apparatus. This resulted in 1.74×10^6 $\mu \to 3e$ candidate event triggers. The data written on magnetic tape for each trigger includes timing and pulse height information from every scintillation counter and from each NaI(Tl) crystal having at least 0.1 MeV deposited energy, and timing information from each drift chamber cell whose discriminator fired.

The absolute gain of each NaI(Tl) crystal was calibrated using a Pu-α-Be source (4.43 MeV γ) and the reactions $\pi^- p \to n\pi^0$, $\pi^0 \to \gamma\gamma$ ($55 \leq E_\gamma \leq 83$ MeV) and $\pi^- p \to n\gamma$ ($E_\gamma = 129.4$ MeV). The pion data were taken with a liquid hydrogen target replacing the drift chamber. The stability of the gain of each NaI(Tl) channel was monitored every two hours using a Xe flash tube and fiber optics cables connected to each photomultiplier.

The signature for a $\mu^+ \to e^+e^+e^-$ event is that the three trajectories should emerge from a common vertex in the target in time coincidence, ΣE, the sum of the three energies deposited in the NaI(Tl) plus the ionization energy losses in other materials should equal the muon mass, and the vector sum of the three momenta ($|\Sigma\vec{p}|$) should be zero.

The main source of triggers was the random coincidence of positrons from three independent ordinary muon decays. These events tend not to satisfy any of the above constraints. Events due to $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$, a process which does not violate separate lepton number conservation, have $\Sigma E + |\Sigma\vec{p}| < M_\mu$ and ΣE generally much less than M_μ.

The first analysis pass required that three non-adjacent scintillator meantimes occur within a 1.5 ns interval, and that each of these scintillators have behind it a NaI(Tl) clump with at least 10 MeV within a 5 ns interval. A clump is defined as the crystal with the largest local pulse height plus the nearest 24 surrounding crystals. The output of the first pass was 1.3×10^5 events.

For the second pass, the drift chamber information was used to reconstruct tracks that intersect the struck scintillators. The reconstruction program required hits in at least 7 of the 8 drift chamber layers for each track. The analysis required three tracks that intersect the target plane with an angle of more than 3°, such that the rms sum of the distances between the three track intersection points on the target (the vertex) must be less than radius 6 cm. Finally, a cut

$\Sigma E + |\Sigma\vec{p}| < 120$ MeV, was imposed. A total of 3112 events survived these cuts.

The third analysis pass tightened the vertex cut after weighting each track-target intersection point according to the uncertainty in the measurement of that point. The 1.5 ns scintillator timing cut was reimposed after correcting each particle's time-of-flight for the path length from the vertex to the scintillator. This pass reduced the number of events to 83.

The final cuts required that $\Sigma E + |\Sigma\vec{p}| < 110$ MeV, $|\Sigma\vec{p}| < 12$ MeV, and that the three scintillator meantimes occur within a 1 ns interval. No events passed these cuts. The acceptance of the apparatus was calculated with a Monte Carlo program that accurately reproduces the response of the detectors to positrons, electrons, and photons. Electromagnetic showers are simulated with the shower code EGS.[7] The product of the acceptance and detector efficiency for $\mu \to 3e$ events, assuming a constant matrix element, is (8.5 ± 0.8%). We obtain an upper limit of

$$B_{\mu 3e} < 1.3 \times 10^{-10} \text{ (90\% C.L.)} \quad .$$

A group at SIN[8] has also recently reported a new upper limit

$$B_{\mu 3e} < 1.6 \times 10^{-10} \text{ (90\% C.L.)} \quad .$$

As a check of the performance of the apparatus and the normalization, the portion of the data taken without the total NaI energy requirement (2.55×10^{10} muons stopped) was analyzed for $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ events. Since these events tend to have a non-zero vector momentum sum, the $|\Sigma\vec{p}|$ cut was removed. Eleven events passed these cuts. The Monte Carlo program predicts 12 ± 2 events, using a matrix element based on standard electroweak theory.[9] The distributions of ΣE, $\Sigma E + |\Sigma\vec{p}|$, vertex, and timing for the data and the Monte Carlo events agree with each other. The agreement of these distributions and of the number of events, verifies the validity of the assumed detector resolutions efficiencies, calibrations, and the beam normalization. Figure 2a shows the distribution of

ΣE vs. $\Sigma|\vec{p}|$ for the detected $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ events and the contour containing 90% of $\mu^+ \to e^+e^+e^-$ events. Figure 2b shows the unnormalized distribution for $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ events from the Monte Carlo simulation.

Data were taken simultaneously with different trigger requirements to search for $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+\gamma\gamma$. The results will be presented at a later time. A longer data run will begin shortly.

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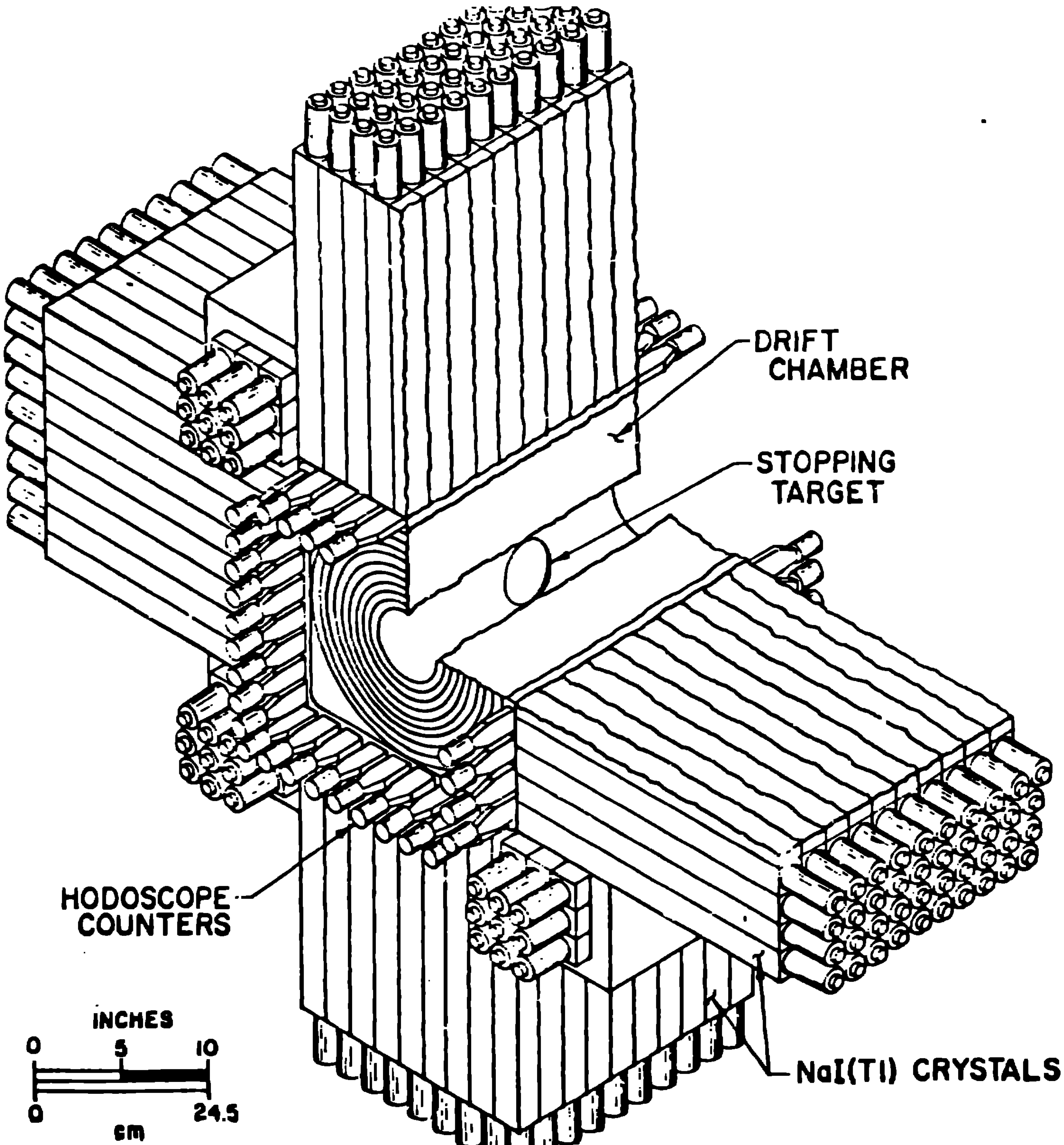
FIGURE CAPTIONS

1. A schematic diagram of the Crystal Box detector.

2a. The vector sum of the momenta for the two positrons and the electron ($|\Sigma\vec{p}|$) vs. the sum of their energies (ΣE) for data events. The sloping line represents the condition $\Sigma E + |\Sigma\vec{p}| = M_\mu$. The area enclosed near $\Sigma E = 100$ MeV, $|\Sigma\vec{p}| = 0$ contains 90% of Monte Carlo $\mu^+ \to e^+e^+e^-$ events.

2b. The distribution of Monte Carlo $\mu^+ \to e^+e^+e^-\nu_e\bar{\nu}_\mu$ events. The number of Monte Carlo events is not normalized to the number of data events.


DRIFT CHAMBER
STOPPING TARGET
HODOSCOPE COUNTERS
NaI(Tl) CRYSTALS
INCHES
0
5
10
0
24.5
cm

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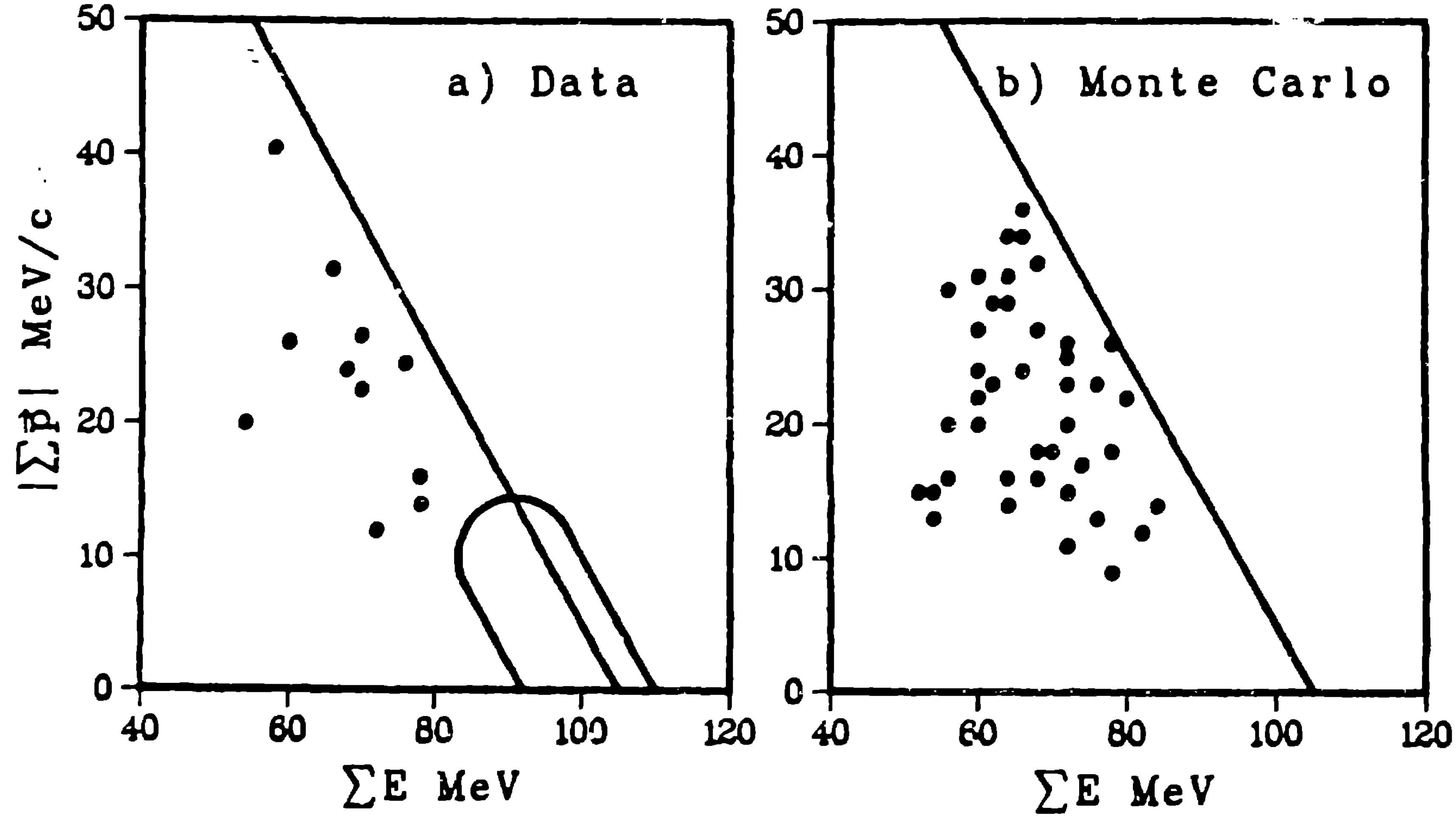

Fig. 2