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THE LOS ALAMOS CRYSTAL BOX EXPERIMENT: A SEARCH FOR $\mu \to e\gamma$, $\mu \to e\gamma\gamma$, AND $\mu \to eee$

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ABSTRACT

A search has been performed for the decays $\mu \to eee$, $\mu \to e\gamma$, and $\mu \to e\gamma\gamma$ with a sensitivity in the branching ratios at the level of 10^{-10}. The experiment used a surface muon beam at LAMPF with an average intensity of 300 kHz. A total of $> 10^{11}$ muon decays was examined for the present result. The detector for the experiment is the Crystal Box, which consists of a cylindrical drift chamber surrounded by 396 NaI(Tl) crystals. A layer of scintillation counters in front of the crystals provided timing for electrons and a veto for photons. The energy resolution for electrons and photons is ~6% (FWHM). The position resolution of the drift chamber is 350 μm leading to a vertex cut with a rejection of 10^3 for $\mu \to eee$. The timing resolution is ~400 ps from the scintillators and ~1 ns from the crystals. From these values, the eee and $e\gamma\gamma$ limits are expected to be background free.

INTRODUCTION

The decay modes $\mu \to e\gamma$, $\mu \to e\gamma\gamma$, and $\mu \to eee$ violate lepton-family conservation. Experimentally no such violations have been observed, and the standard model does not predict lepton-number violation. However, there are intuitive reasons to expect lepton-number violation. Lepton- and baryon-number conservation seem very artificial compared to other conservation laws; they do not relate to space-time symmetries as do energy and momentum conservation, nor are they associated with a massless gauge boson, as is electric charge. It would be peculiar if these quantities were absolutely conserved with no underlying reason. Several recent theoretical extensions can lead to lepton-family violation. These include massive neutrinos, an expanded Higgs sector, super-symmetric theories, and many others. In general, none of these theories does well in predicting an absolute decay rate. However, they usually do predict the ratios of decays such as $\mu \to e\gamma$, $\mu \to 3e$, $\mu^- Z \to e^- Z$, $\mu \to e\gamma\gamma$. The theories differ considerably as to which decay mode dominates; it is impossible to predict in which decay mode lepton number violation will first be seen. Consequently it is important for experiments to consider all channels. The current limits for the various lepton-number-violating decays are:

$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} < 1.7 \times 10^{-10} \qquad \text{(Ref. 1)}$$

$$\frac{\Gamma(\mu \to eee)}{\Gamma(\mu \to e\nu\bar{\nu})} < 1.6 \times 10^{-10} \qquad \text{(Ref. 2)}$$

$$\frac{\Gamma(\mu \to e\gamma\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} < 8.4 \times 10^{-9} \qquad \text{(Ref. 3)}$$

$$\frac{\Gamma(\mu^- Z \to e^- Z)}{\Gamma(\mu^- Z \to \nu Z-1)} < 2 \times 10^{-11} \qquad \text{(Ref. 4)}$$

The Crystal Box is shown in Fig. 1. It is a general purpose charged particle and photon detector of large solid angle, and is currently in place at the Stopped Muon Channel of the Los Alamos Meson Physics Facility (LAMPF). A large (7.4-cm effective radius), thin (52 mg/cm^2) polystyrene target stops positive muons. A thin target minimizes multiple scattering, bremsstrahlung, and other secondary processes; consequently a surface muon beam is ideal. Surrounding the target is a 728-wire, eight-plane, large-stereo-angle drift chamber, which allows one to determine in three dimensions, the tracks of charged particles. The single-plane resolution is about 350 μm FWHM. The drift chamber is surrounded by a 36-section segmented plastic scintillator hodoscope, which is used to provide charged particle identification, good timing, and a fast on-line charged particle position. Energy information is provided by a large-solid-angle 396-element segmented NaI(Tl) array. Three hundred sixty 6.35 × 6.35 × 30.5-cm crystals are arranged in four quadrants, each with nine rows of ten crystals. Thirty-six 6.35 × 6.35 × 63.5-cm crystals are arranged in four groups of nine, one in each corner between two quadrants. The detector has an energy resolution of approximately 6% FWHM at 50 MeV for both electrons and photons, and a timing resolution of about 400 ps FWHM for electrons and 1 ns for photons. The knowledge of the origin and the original

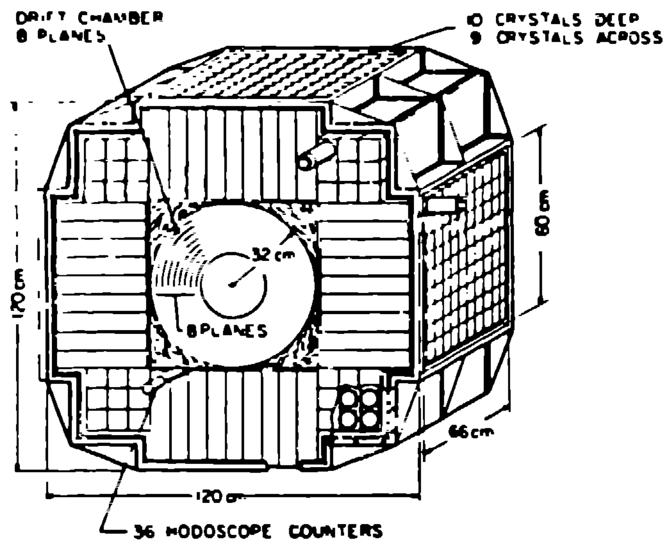

Fig. 1. The Crystal Box Detector

direction of a charged particle is limited by multiple scattering in the target, the target frame, and the inner drift-chamber foil. The position resolution of the origin on the target is on the order of 2 mm. The photon conversion point is determined to about 1.6 cm by the energy sharing in the different NaI crystals. The solid angle times efficiency is approximately 12% for 3e events, 40% for $e\gamma$ events, and 14% for $e\gamma\gamma$ events.

The limits on the sensitivity of an experiment looking for rare processes are determined by how well the backgrounds are suppressed. The sources of background are random coincidences between Michel electrons and bremsstrahlung photons, and the prompt processes $\mu \to eee\nu\bar{\nu}$, $\mu \to e\gamma\nu\bar{\nu}$, and $\mu \to e\gamma\gamma\nu\bar{\nu}$. Random coincidences dominate the background for the Crystal Box in all three decay modes. However, for the $e\gamma$ mode the prompt background contributes about 10%. Using the energy, time, and position resolutions one places the requirement on all decay modes that the particles be in time, that the total energy be equal to that of the muon, and that the vector sum of the momenta be zero. In addition, for 3e events, one can require that all tracks have a common origin on the target. The suppressions that one gains from these cuts are considerable. The dominant suppression of randoms in all cases is due to timing. For the $e\gamma$ case, energy cuts suppress the random background by a factor of ~100, and the prompt background by a factor of ~1000; a subsequent vector momentum cut reduces the randoms a further factor of ~200 and the prompts by a factor of two. For the 3e case, requiring all three electrons to originate from the same point on the target reduces randoms by a factor of ~3000; a vector momentum cut adds an additional factor of ~4000. Figure 2 summarizes the sensitivity of the experiment as a function of running time and beam intensity.

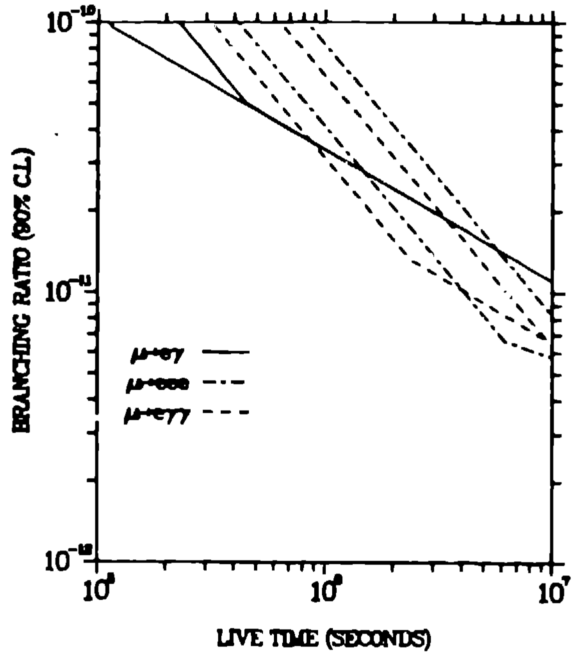

Fig. 2. Monte Carlo prediction of branching ratio sensitivity as a function of running time and muon stopping rate. For each mode the upper line corresponds to a rate of 250 kHz and the lower line to a rate of 500 kHz. The cusps represent the points where background is expected to enter.

In order to reduce the data stream to manageable proportions, the trigger of the experiment is quite sophisticated. The trigger defines an electron as a signal in a hodoscope scintillator with more than 5 MeV of energy in a crystal in one of the three rows of crystals directly behind the scintillator. A photon quadrant is defined by requiring energy in the NaI with no scintillator firing in front of it, or in the nearest scintillator in the adjacent two quadrants. The 3e trigger requires that there be signals in three non-adjacent plastic scintillators within about 10 ns, that the scintillators be in a geometric pattern kinematically consistent with a 3e decay, and that three scintillators fire within 5 ns of each other. The eγ trigger requires that there be an electron and photon quadrant opposite each other, and that each have a NaI energy greater than 35 MeV. The eγγ trigger requires at least two gamma quadrants one electron quadrant, and a total energy in all NaI of more than about 70 MeV. These trigger requirements generate a trigger rate of about 20 Hz with 7.7 MHz instantaneous of muons stopping in the target at a 7% duty factor (500 kHz average).

The apparatus is instrumented with analog-to-digital converters (ADC's) and time-to-digital converters (TDC's) on all of the plastic scintillators and NaI crystals. The drift-chamber wire signals are discriminated and used to stop individual TDC's. In addition, a second ADC with a different gate is used on the NaI crystals as a pileup rejector. The trigger starts all the TDC's, provides a gate for the ADC's, and provides a start signal for the readout of the event. For each event all the scintillator, ADC, and TDC data are recorded. Distributed processors are used to perform a sparse data scan for the drift-chamber TDC information and the NaI pulse height and timing information. Taking data in this fashion makes each event about 500 16-bit words long. At fixed intervals a number of scalers are read out; these provide information about the number of muons stopped, the duty factor, and dead time. A PDP-11 is used to acquire and tape the data. The option exists to reduce the taping rate by using the data acquisition computer to make cuts on the data before taping.

A small amount of data was collected this January. We acquired data at about 300 kHz of muons and 7.5% duty factor. Approximately 2×10^{11} muons were stopped. All the data were processed by a multistage filtering process. A first pass consisted of software timing cuts and geometrical cuts that could be applied without using the drift chamber reconstruction routines. This reduced the amount of data by a factor of ~10. A second pass used the drift chamber tracks to allow one to do more severe timing and geometrical cuts, and provided a further reduction of a factor of ~10. The effects of the major data reductions are shown in Table I. The data remaining after the first two passes consist of 10^3-10^4 events in each of the data streams. These are carefully investigated to look for a prompt signal and any candidates for lepton family violating decays. We expect to be able to put limits on the order of 10^{-10} for all decay modes with this set of data.

We have found several $\mu \rightarrow 3e\nu\bar{\nu}$ events. The acceptance of the detector for these events was greatly reduced for most of the run by requiring a total energy of 75 MeV in the NaI. In subsequent data acquisition this requirement will be relaxed and several hundred $\mu \rightarrow 3e\nu\bar{\nu}$ events should be seen. Figure 3 shows one of these events. Currently the $e\gamma\nu\bar{\nu}$ events are being studied. We are seeing a considerable enhancement in the time spectrum of such events; however, it is not yet known whether we will be able to make this sample background-free.

It is expected that we will stop 10^{12} muons this summer and that limits on the order of 10^{-11} will be placed on all three decay modes.

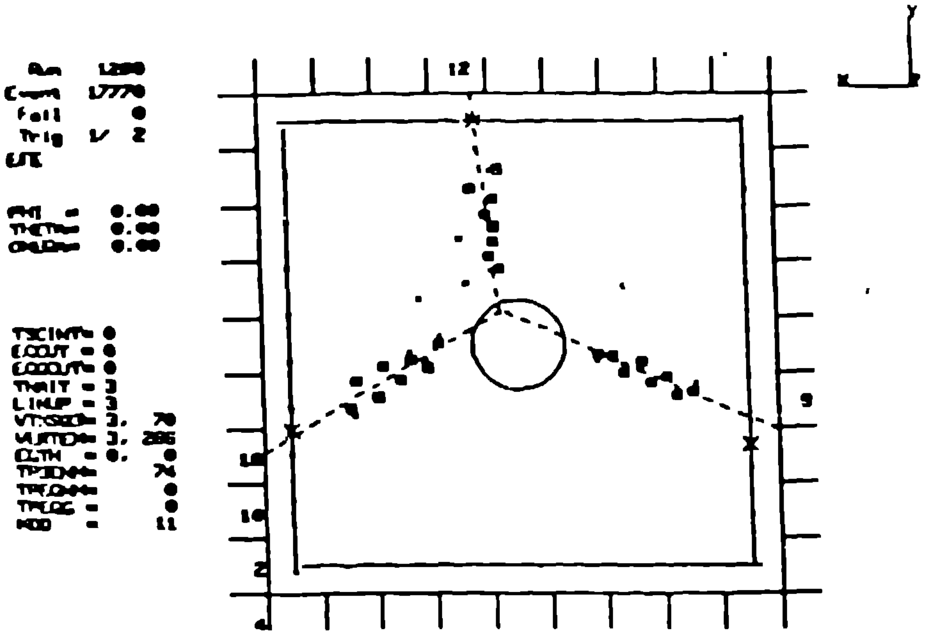

Fig. 3. A $3e\nu\bar{\nu}$ event (looking along the beam axis). The numbers represent the energy (MeV) deposited in a row of NaI crystals. The x's are hodoscope scintillators that fired; and the dashed lines are the drift chamber reconstructed tracks. The large squares are shown on the wires used in the reconstruction. The small squares are other wires that fired. The offset of wires from the reconstructed track is due to the drift chamber wire stereo angles.

TABLE I

DATA REDUCTION

μ stops:	2.2×10^{11}
3e Events:	**# Events Surviving**
Triggers	17.4×10^5
Δ_t < 1.5ns	3.4×10^5
E/track > 10 MeV (in NaI)	1.5×10^5
Each track has $t_{NaI} - t_{scint}$ < 5ns	1.3×10^5
3 drift chamber tracks reconstruct to vertex	52500
Vertex cut	9800
Energy + missing momentum <120 MeV	3383
eγ Events:	
Triggers	12.9×10^5
$t_{gamma} - t_{electron}$ <4ns	7.9×10^5
No energy in scintillator ADC's in gamma quadrant	4.8×10^5
E_e > 10 MeV, E_γ > 10 MeV, $E_{e\gamma}$ > 30 MeV, Δ_t < 3.5 ns	1.4×10^5
Electron track reconstructs to target	1×10^5
eγ angle >140°	56000
$E_{e\gamma}$ + missing momentum <120 MeV	41000
eγγ:	
Triggers	4.3×10^5
Scintillator ADC's in gamma quadrants have no energy	1.9×10^5
E_e, E_γ >10 MeV, Δ t < 4.5ns	26470
Drift Chamber track that reconstructs to target	15325
$E_{e\gamma\gamma}$ + missing momentum <120 MeV	10384

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