New Search for the Spontaneous Conversion of Muonium to Antimuonium

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To search for spontaneous conversion of muonium to antimuonium with very low background, a new signature was implemented that required the coincident detection of the decay products of the antimuonium atom, the energetic e^- and the atomic e^+. No conversion events were seen, which sets an improved upper limit of 6.5×10^{-7} (90% C.L.) on the conversion probability. The corresponding limit on the coupling constant, using a $V-A$ form for the conversion Hamiltonian, is $G_{M\bar{M}}<0.16G_F$ (90% C.L.), where G_F is the Fermi coupling constant.

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There has been continuing interest in the possibility of conversion of muonium ($M\equiv\mu^+e^-$) to antimuonium ($\bar{M}\equiv\mu^-e^+$) from both the experimental[1,2] and theoretical sides.[3-7] As different neutrino flavors were unknown at the time, Pontecorvo suggested[8] in 1957 that $M\rightarrow\bar{M}$ might proceed through an intermediate state of two neutrinos in analogy to the K^0-$\bar{K}^0$ coupling via intermediate pions. The minimal standard model[9] forbids the $M\rightarrow\bar{M}$ coupling as it violates the separate, additive conservation of muon and electron number. Thus, searching for a mixing of M and $\bar{M}$ is a probe for physics beyond the standard model.

Traditionally, the results of searches for M to $\bar{M}$ conversion have been stated as upper limits on the coupling constant $G_{M\bar{M}}$, as it appears in the $V-A$ Hamiltonian density,[10]

$$\mathcal{H}_{M\bar{M}}=\frac{G_{M\bar{M}}}{\sqrt{2}}\bar{\mu}\gamma^{\lambda}(1-\gamma_5)e\bar{\mu}\gamma_{\lambda}(1-\gamma_5)e+\text{H.c.}\qquad(1)$$

This form is motivated by an analogy to the effective Hamiltonian densities for observed weak processes.

In the absence of external electromagnetic fields, the ground-state hyperfine levels of M and $\bar{M}$ are degenerate in energy. The nonvanishing matrix elements of the Hamiltonian are diagonal in the angular momentum quantum numbers. For the ground state, one obtains[10]

$$\langle\bar{M}(F,m_F)|\mathcal{H}_{M\bar{M}}|M(F,m_F)\rangle=(1.07\times10^{-12}\,\text{eV})\frac{G_{M\bar{M}}}{G_F},\qquad(2)$$

where F and m_F are the total angular momentum and its z component, respectively. Given an initial state of pure M, the coupling $\mathcal{H}_{M\bar{M}}$ leads to the development with time of an $\bar{M}$ component in the wave function of the system. The probability of decay from the $\bar{M}$ state is given by[10] $P_{\bar{M}}=(2.57\times10^{-5})(G_{M\bar{M}}/G_F)^2$.

Since the incident μ^+ beam used for M formation is fully polarized in the backward direction and the electron that is captured is unpolarized, M is formed equally in the $m_F=0$ (unpolarized) and in the $m_F=-1$ (polarized) substates, where the quantization axis has been chosen to lie along the beam axis. Magnetic fields shift the energy levels of M and $\bar{M}$ oppositely since the magnetic moments of the component leptons of $\bar{M}$ are reversed in sign from those of M. This removal of the degeneracy in energy of M and $\bar{M}$ causes a reduction of the conversion probability between polarized levels by a factor of 2 at 26 mG and between unpolarized levels by a factor of 2 at 1.6 kG. In general, diagonalization of the $n=1$ hyperfine states of the coupled $M\leftrightarrow\bar{M}$ system[11] yields magnetic-field-dependent eigenstates and eigenenergies with admixtures of M and $\bar{M}$ in each of the eight new states. Since the different interactions of M and $\bar{M}$ with atoms of a host medium remove their degeneracy in matter,[12] a sensitive search for the $M\rightarrow\bar{M}$ conversion requires that M be produced in vacuum.

Signatures used in previous searches for $M\rightarrow\bar{M}$ relied on radiations induced by μ^- interaction with the material of the detection medium. The most sensitive of these was recently completed by a group at TRIUMF with the result[1] of $P_{\bar{M}}<2.1\times10^{-6}$ and $G_{M\bar{M}}<0.29G_F$ at 90% confidence. The experiment described here is the first to seek the detection of *both* charged products of the $\bar{M}$ atom breakup; namely, the energetic e^- and the atomic e^+.

This new search[13] for the M to $\bar{M}$ conversion was performed at the Los Alamos Clinton P. Anderson Meson

Physics Facility (LAMPF). The apparatus (Fig. 1) included a section in which thermal muonium was formed in a SiO_2 powder target and a detector which consisted of a multiwire proportional chamber (MWPC) spectrometer to detect high-energy e^+ or e^- from μ^+ or μ^- and a second spectrometer for the coincident detection of a low-energy atomic e^- or e^+ from M or $\overline{M}$.

A well collimated 20-MeV/c subsurface μ^+ beam[14] from the Stopped Muon Channel (SMC) with a momentum bite of $\Delta p/p \approx 10\%$ and a duty factor of 6.4% was used. The incoming muons were counted and moderated in a 150-μm plastic scintillator and then stopped in a fine SiO_2 powder target of 9 mg/cm^2 thickness[15] where they formed M that diffused into the vacuum region downstream of the target at thermal velocities. The detector could observe either M or $\overline{M}$ decays from the vacuum.

After passing through a 100-μm Al vacuum window, the decay positrons or electrons, whose energies range up to 52.83 MeV, were observed in an array of four MWPCs placed on an axis at a right angle to the beam line. A wide-gap C-yoke dipole magnet with a central field of 522 G was placed between the second and third MWPCs to deflect decay e^+ and e^- in opposite directions. Two layers of plastic scintillator behind MWPC4 provided the timing signal on a candidate track and a cylindrical NaI(Tl) crystal measured the energy of a particle in the spectrometer.

The atomic e^- or atomic e^+, remaining in the vacuum with a mean kinetic energy of 13.5 eV after a M or $\overline{M}$ atom decay, was electrostatically collected, focused, and accelerated to 5.7 keV with a system of eleven electrodes arranged in three stages. Either e^- or e^+ at this energy were then charge and momentum selected in an iron-free bending magnet with a central field of about 15 G and transported and focused with a solenoidal field of 11 G onto a 75-mm-diam chevron pair microchannel plate detector (MCP). Additional coils allowed control over all components of the magnetic field in the target region to counteract effects of the C-magnet fringe field on the e^+ and e^- trajectories, and axial coils (S1, S2, and S3) enhanced the transport efficiency of the system.

The production of thermal muonium in our apparatus was studied by the established technique,[16,17] which involved use of a low-intensity μ^+ rate, observation of the decay e^+ track with the MWPC system, and measurement of the time of flight between a pulse in the muon beam counter and a decay e^+ track in the spectrometer. The formation fraction observed was $(5.02 \pm 0.06)\%$ M per stopped μ^+, with $(56 \pm 2)\%$ of the incident μ^+ stopping in the powder. Hence, an overall fraction of $(2.8 \pm 0.1)\%$ of the incoming μ^+ captured an electron from the powder to form M that diffused into the vacuum region downstream of the target at thermal velocities. In the vacuum region, M was found to move from the powder surface with a mean velocity of 0.7 cm/μs, corresponding to a temperature of 300 K.

The first observation of thermal M in vacuum by the coincident detection of its decay e^+ and the atomic e^- served to verify the experimental method and to calibrate the acceptances of the apparatus. When detecting thermal M in vacuum in this way, the polarities of the C magnet, the bending magnet, the solenoid, the steering coils, and the potentials in the electrostatic optics were set appropriately. The time-of-flight (TOF) spectrum taken with M decays started by an event in the MWPC spectrometer and stopped by a count in the MCP is shown in Fig. 2. This spectrum required that the decay origin of the M atom lie in the vacuum downstream of

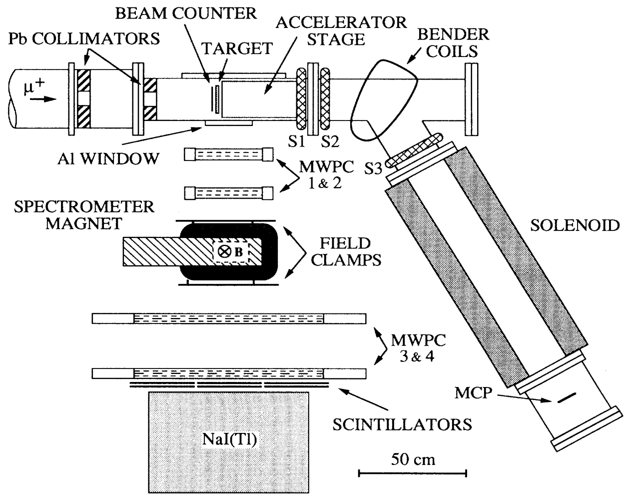

FIG. 1. Schematic view of the apparatus. Beam counter and target were mounted at 50° with respect to the incident muon beam.

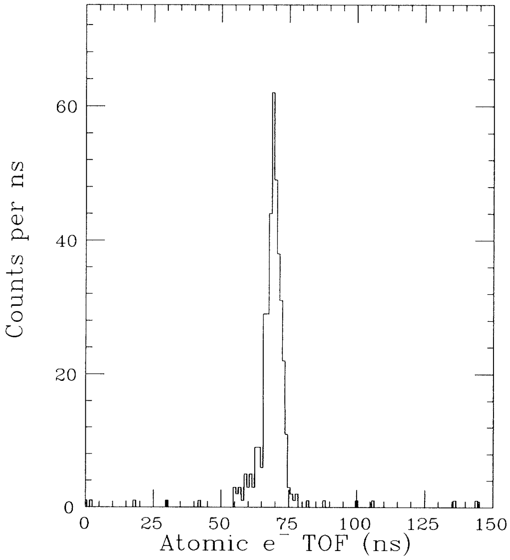

FIG. 2. Sample spectrum of the time of flight between decay e^+ and atomic e^- from M-atom decays in vacuum.

the target. The peak is therefore due to atomic e^- transported and detected after a M-atom decay. The transport acceptance and the MCP efficiency combined to allow detection of $(15.5 \pm 0.8)\%$ of the atomic electrons from thermal M decays in the vacuum. The acceptance of the high-energy spectrometer, including the solid angle, the detection efficiencies of the MWPCs and the plastic scintillators, and the efficiency of track reconstruction was $(2.50 \pm 0.02) \times 10^{-3}$.

To search for $\overline{M}$ decays, the electrostatic potentials and current directions in the high-energy and low-energy spectrometers were reversed in polarity and the full intensity of the incident μ^+ beam of $10^6\ \mathrm{s}^{-1}$ was used. To reduce the trigger rate and hence dead time for the data-acquisition system, the wires of all four planes detecting the position component perpendicular to the magnetic field were coarsely grouped to preselect e^- in the trigger by their curvature in the field. This preselection was 66% efficient in accepting e^- tracks and rejected 98.9% of the e^+ tracks. The remaining e^+ events were used as a monitor of M formation during the search for $\overline{M}$. To test the transport properties for low-energy e^+, the $\mathrm{SiO_2}$ target was replaced with a venetian-blind arrangement of W foils that moderated the β^+ from a $^{22}\mathrm{Na}$ source to energies of about 1 eV. The slow e^+ were detected by the MCP and were characterized by the same tuning behavior in each element of the system as the secondary e^- from e^+ impact on the foils.

We took approximately 270 h of data with a total of 9.8×10^{11} incident μ^+. To look for $\overline{M}$ decay candidates, it was required that a track in the MWPC spectrometer be successfully fitted, that its curvature indicate a negatively charged particle, that its fitted momentum lie above 22.5 MeV/c, that the track project back through the vacuum window, and that there be a count in the 75-ns window of the TOF spectrum determined from the M coincidence signal.

These events are displayed in a histogram of the decay position projected onto the axis perpendicular to the target plane (see Fig. 3). To find the most probable number of $\overline{M}$ events, a maximum-likelihood analysis of this distribution was carried out. A pure $\overline{M}$ signal was represented by a calculated reference distribution, while the characteristic distribution for the sum of all background processes was obtained from events that satisfy all $\overline{M}$ cuts except the TOF condition. The most probable number of $\overline{M}$ events was found to be zero, with a 90%-confidence-level upper limit of 2 counts. Thus, all events passing the cuts designed to emphasize a conversion signal were found to be most likely due to background. The total number of muonium atoms which could produce an observable conversion was determined from a maximum-likelihood analysis of the decay origin distribution along the axis perpendicular to the target plane. The result including an estimate for the total error is $(6.17 \pm 0.28) \times 10^6$, where the effect of the uncertainty on our final result is negligible.

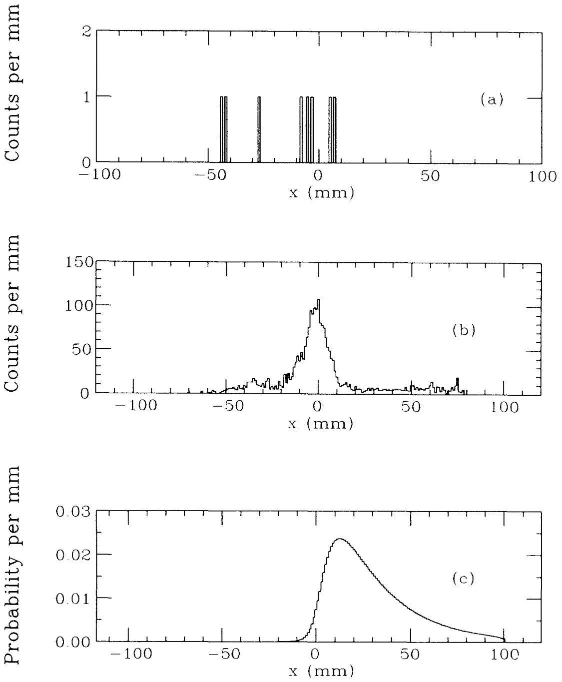

FIG. 3. Decay position distributions projected onto the target normal of (a) all $\overline{M}$ candidates, (b) sample of measured knock-on e^- background, and (c) calculated pure $\overline{M}$ signal. Positive values of x correspond to the downstream side of the target.

Since the magnetic field in the muonium cloud was about 10 G, a conversion would have been suppressed by a factor of 2. The resulting upper limit on the probability for the M to $\overline{M}$ conversion per atom is $P_{\overline{M}} < 6.5 \times 10^{-7}$ (90% C.L.). This gives an upper limit of

$$G_{M\overline{M}} < 0.16 G_F \quad (90\%\ \text{C.L.}) \tag{3}$$

on the effective coupling constant of Eq. (1).

Background events are due to accidental coincidences of random counts in the MCP ($10^3\ \mathrm{s}^{-1}$ instantaneous) with knock-on electrons produced by decay e^+ in the MWPC spectrometer material before the C magnet (about 2×10^{-5} observed knock-on e^- above 22.5 MeV/c per e^+ reconstructed as originating in the vacuum region). We estimate this background at about 10^{-13} event per incident μ^+. The suppression of background on the MCP correlated to the incident beam is achieved by the TOF cut; further, 89% of the knock-on e^- are rejected by the momentum cut, while maintaining an acceptance of 87% for decay e^-.

The $M \rightarrow \overline{M}$ conversion is one of many processes which are strictly forbidden in the present standard model of particle physics. Speculative theories based on many different specific models[18] which violate the standard model can allow for these rare decays, but general criteria for comparing the sensitivity of different rare-decay searches are not known. The M to $\overline{M}$ conversion as well as the muon decay mode $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ both violate additive conservation of muon and electron number, but they are allowed by the multiplicative conservation laws for muon and electron parity,[10] according to which the quantities $\prod(-1)^{L_\mu}$ and $\prod(-1)^{L_e}$ are conserved. However, other rare muon decay processes, such as $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$, violate both the additive and multiplicative conservation laws. Hence, $M \rightarrow \overline{M}$ conversion and the forbidden mode of μ^+ decay are of particular interest to test the applicability of a multiplicative rather than an additive law. A search for the decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ in an experiment[19] at LAMPF established the limit $R < 0.1$ (90% C.L.) relative to the normal decay mode, thus favoring the additive law. Our experiment establishes a limit for $M \rightarrow \overline{M}$ and hence also supports the additive law.

A particularly interesting model which would allow $M \rightarrow \overline{M}$ conversion at the present level of experimental sensitivity is the left-right symmetric model of Mohapatra and Senjanović[20] with an additional Higgs-boson triplet that violates lepton number conservation in its couplings. The doubly charged member of this triplet Δ^{++} mediates the M to $\overline{M}$ conversion at the tree level.[7] Within this model, the forbidden decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ is also allowed as a first-order weak interaction through the singly charged Higgs boson Δ^+. However, a direct comparison of $M \rightarrow \overline{M}$ conversion and the forbidden μ^+ decay cannot be made because the masses of the Δ^{++} and the Δ^+ are not known.

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