Search for Spontaneous Conversion of Muonium to Antimuonium

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The results of an experimental search with a new method for the spontaneous conversion of muonium to antimuonium are reported. The upper limit for $G_{\mathrm{M\overline{M}}}$, the coupling constant characterizing the strength of the interaction leading to the conversion, is measured to be $G_{\mathrm{M\overline{M}}} < 7.5G_{\mathrm{F}}$ (90% confidence level), where G_{F} is the Fermi coupling constant. This result is about a factor of 3 lower than the previous limit and begins to probe predictions of the left-right-symmetric theory with a doubly charged Higgs triplet.

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The possibility of the spontaneous conversion of a muonium atom (μ^+e^- or M) to its antiatom, antimuonium (μ^-e^+ or $\overline{\mathrm{M}}$), was first suggested by Pontecorvo in 1957,[1] in analogy with the $(K^0,\bar K^0)$ system. More recently, there have been a number of theoretical discussions of this process. A multiplicative law of muon-number conservation, which would allow $\mathrm{M}\rightarrow\overline{\mathrm{M}}$ conversion, has been proposed.[2,3] Halprin[4] noted the close relationship of $\mathrm{M}\rightarrow\overline{\mathrm{M}}$ conversion to neutrinoless double-β decay and the possible occurrence of this conversion due to a massive Majorana neutrino or to a doubly charged Higgs triplet. These two processes would be allowed by a left-right-symmetric theory of the electroweak interaction.[5]

A four-fermion Hamiltonian of the $V-A$ type is usually chosen to represent $\mathrm{M}\rightarrow\overline{\mathrm{M}}$ conversion:

$$H_{\mathrm{M\overline{M}}}=(G_{\mathrm{M\overline{M}}}/\sqrt{2})\bar\psi_\mu\gamma_\lambda(1+\gamma_5)\psi_e\bar\psi_\mu\gamma^\lambda(1+\gamma_5)\psi_e+\mathrm{H.c.},\qquad(1)$$

in which $G_{\mathrm{M\overline{M}}}$ is a coupling constant characterizing the strength of the interaction. The left-right-symmetric theory with a doubly charged Higgs particle allows $G_{\mathrm{M\overline{M}}}$ as large as $10G_{\mathrm{F}}$, where G_{F} is the Fermi coupling constant.

Beginning in 1968 several experiments[6] have established upper limits for $G_{\mathrm{M\overline{M}}}$ with the best presently quoted limit being $G_{\mathrm{M\overline{M}}}\le 20G_{\mathrm{F}}$ [95% confidence level (C.L.)]. We present here the results[7] of a new experiment searching for $\mathrm{M}\rightarrow\overline{\mathrm{M}}$ conversion, which would detect the muonic x rays following the atomic capture of the μ^- in $\overline{\mathrm{M}}$.

In the absence of external electromagnetic fields, M and $\overline{\mathrm{M}}$ have the same ground-state energy levels as determined from a Hamiltonian H_0 including the electromagnetic interaction. The postulated weak interaction $H_{\mathrm{M\overline{M}}}$ of Eq. (1) will have diagonal matrix elements coupling M and $\overline{\mathrm{M}}$[8]:

$$\langle\overline{\mathrm{M}}(F,m_{\mathrm{F}})\,|\,H_{\mathrm{M\overline{M}}}\,|\,\mathrm{M}(F,m_{\mathrm{F}})\rangle \equiv \tfrac{1}{2}\delta=1.0\times10^{-12}G_{\mathrm{M\overline{M}}}/G_{\mathrm{F}}\,\mathrm{eV},\qquad(2)$$

in which F,m_{F} are quantum numbers for total angular momentum and its z component, respectively. The eigenstates of the $(\mathrm{M},\overline{\mathrm{M}})$ system with the total Hamiltonian $H_0+H_{\mathrm{M\overline{M}}}$ will then be $(|\mathrm{M}\rangle\pm|\overline{\mathrm{M}}\rangle)/\sqrt{2}$.

If M is formed at time $t=0$, then, in vacuum and in the absence of an external electromagnetic field, a component of $\overline{\mathrm{M}}$ will develop with time so that the state wave function will be $\psi(t)=a(t)\,|\mathrm{M}\rangle+b(t)\,|\overline{\mathrm{M}}$, where $a(0)=1$ and $b(0)=0$. First-order perturbation theory for degenerate states gives

$$b(t)\simeq(\delta/2i\hbar)t.\qquad(3)$$

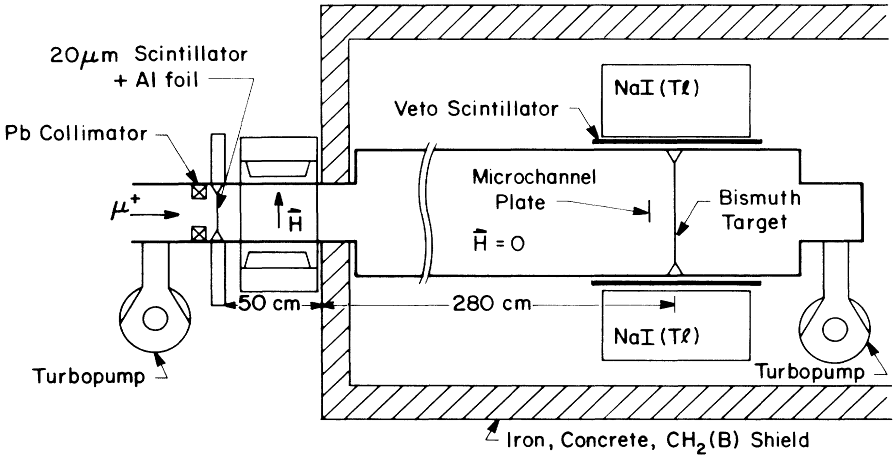

FIG. 1. Schematic diagram of the experimental apparatus.

In the presence of an external magnetic field H, a Zeeman-energy term must be added to H_0. The degeneracy of M and $\overline{\mathrm{M}}$ states with the same (F,m_F) values is now removed and so the development with time of the $|\overline{\mathrm{M}}\rangle$ component in ψ is reduced.[8] A magnetic field of 25 mG reduces $|b(t)|^2$ by one half for the $1S$ M states with $(F,m_F)=(1,\pm 1)$ compared to its value for $H=0$ but does not appreciably reduce $|b(t)|^2$ for the states with $m_F=0$.

The experiment was performed in the stopped-muon channel at the Los Alamos Meson Physics Facility. A schematic diagram of the apparatus is shown in Fig. 1. A separated μ^+ beam[9] with momentum $p_\mu = 10$ MeV/c and intensity 3×10^5 μ^+/s (average) was incident on a 20-μm plastic scintillator followed by a 0.75-μm Al foil where the M was formed with kinetic energies between 1 and 20 keV. After traversing a region with a 1.5-kG transverse magnetic field to sweep out free μ^+, the M beam traveled in vacuum a distance of 280 cm, of which 206 cm was shielded to ≤ 30 mG. The neutral beam was stopped on a 1-μm-thick Bi target that was evaporated onto a 50-μm aluminized Mylar backing; for one half of the data the Bi was coated with 7.5 nm of MgO. Upon the muonium's striking the Bi target, a muonic atom, μ^-Bi, was formed with a probability proportional to $|b(t)|^2$. The resulting cascade of muonic-atom characteristic x rays was taken as the signal of an $\mathrm{M}\rightarrow\overline{\mathrm{M}}$ conversion. In addition, a count from a detector indicating that M (or $\overline{\mathrm{M}}$) struck the Bi target was required. We calculate that <0.1% of the M or $\overline{\mathrm{M}}$ stop in the MgO.

In the M detector, secondary electrons emitted from the Bi were focused and accelerated onto a microchannel plate detector (μCP). The x rays from μ^-Bi were detected with the NaI(Tl) Crystal Box detector,[10] modified to extend its energy threshold to below 2 MeV. The $\overline{\mathrm{M}}$-event signature was defined as the coincidence of a μ^-Bi $L\alpha$ x ray ($E_{L\alpha}=2.55$ MeV), a μ^-Bi $K\alpha$ x ray ($E_{K\alpha}=6.05$ MeV), and a count in the μCP. The thin scintillator was used for beam tuning and monitoring.

The behavior of the M detector was determined experimentally. The number of secondary electrons per incident proton, Γ, was measured for 2- to 50-keV protons incident on different materials in an auxiliary measurement at Oak Ridge National Laboratory.[11] For Bi with a 4-nm coating of MgO, Γ was greater than 5 in the relevant energy range. Studies of the actual detector with α particles incident suggested that the detection efficiency for M would be about 45%. The secondary-electron transit times should vary by about 50 ns, according to Monte Carlo simulations.

Figure 2 shows T, the difference between the signal time in the μCP and the time of detection of the μ^+ decay positron in the NaI(Tl), with M incident and the apparatus triggered on the presence of a single positron (1-e trigger). The events with $T<45$ ns were primarily

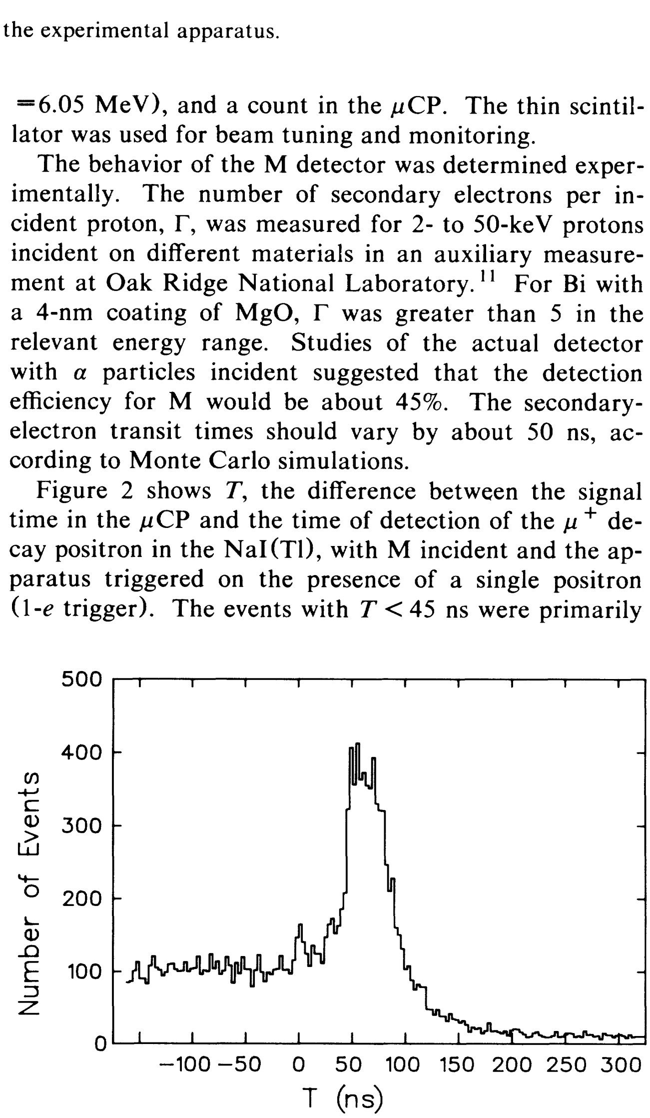

FIG. 2. Histogram of the time difference, $T=T_{\mu\mathrm{CP}}-T_{\mathrm{NaI}}$, for data with incident M and a 1-e trigger. $T_{\mu\mathrm{CP}}$ and T_{NaI} are the signal times in the μCP and the NaI(Tl), respectively.

due to the μCP detecting a M stop in the Bi target and the NaI(Tl) detecting the positron from the muon decay. The time distribution of these events yields a muon lifetime of 1.95 ± 1.56 μs. The measured positron energy spectrum for these events is a Michel spectrum from $\mu^+ \rightarrow e^+ \nu\bar{\nu}$ plus a small amount of low-energy background. A lifetime of 2.218 ± 0.020 μs was measured for events from the same data set but with -8 $\mu\mathrm{s} < T < 0$. The peak at 45 ns $< T <$ 105 ns is due to the above processes plus prompt processes such as events in which the μCP detected secondary electrons produced by μ^+-decay positrons in the Bi target.

The efficiency of the M detector was determined by measurement of the fraction of $\mu^+ \rightarrow e^+ \nu\bar{\nu}$ events for which the μ^+ gave a μCP signal with $T < 45$ ns, after correction for the fraction of the muon lifetime observed. The efficiency of the M detector with the coated Bi target was measured to be 37% ± 1% over the course of the experiment. Events from μ^- atomic capture (including those from incident $\overline{\mathrm{M}}$) should have 45 ns $< T <$ 105 ns, since the capture is so rapid. The noise rate in the M counter was about 1 kHz, probably due to thermionic emission from the large-area Bi target. The M stopping rate was determined from the total number of $\mu^+ \rightarrow e^+ \nu\bar{\nu}$ events in the 1-e data.

The trigger requirement used to search for $\mathrm{M} \rightarrow \overline{\mathrm{M}}$ conversion was that there be two coincident photons ($\Delta t = \pm 30$ ns) in nonadjacent rows of crystals (2-γ trigger). For each event, the time and pulse area from each NaI(Tl) crystal and the time of the μCP pulse were recorded for subsequent off-line analysis. There were 6.5×10^6 2-γ triggers in 150 h of data taking. The background trigger rate was $\simeq 12$ s^{-1} (average) due primarily to correlated γ rays originating from n capture. Requiring the opening angle between the two photons to be greater than 30° reduced this background.

The detection efficiency for a μ^- atomic capture producing a $K\alpha$-$L\alpha$ coincidence was calculated with a Monte Carlo program to be 8.3% ± 0.2%. This includes the probability that the atomic cascade[12] produces these two γ rays ($\simeq 82\%$) and the geometrical acceptance including the opening angle cut (10.2% ± 0.1%). The detection efficiency was measured in 2-γ runs with an incident 16-MeV/c μ^- beam to be 7.7% ± 0.1%. The measured detection efficiency is somewhat smaller than the calculated efficiency because of crystal-to-crystal variations of trigger thresholds and the possible depletion of the $K\alpha$ yield by radiationless transition leading to nuclear excitation in Bi.[13] The measured detection efficiency was used in the analysis.

The measured spectra of μ^-Bi x rays from data with incident μ^- and M are shown in Figs. 3(a) and 3(b), respectively. The $K\alpha$ and $L\alpha$ μ^-Bi x rays are plainly visible in the μ^- data. The M data were required to satisfy 35 ns $< T <$ 115 ns; 1783 events satisfy the cuts. No peaks are apparent here. There are 95 events with 5.4 MeV $\le E_{K\alpha} \le$ 6.6 MeV and 2.3 MeV $\le E_{L\alpha} \le$ 2.9 MeV. Using observed number of events outside this energy window, we expect 80 ± 10 background events within the window. This implies that there are <33 $\overline{\mathrm{M}}$ events within the window and <48 $\overline{\mathrm{M}}$ events (90% C.L.) at all energies.

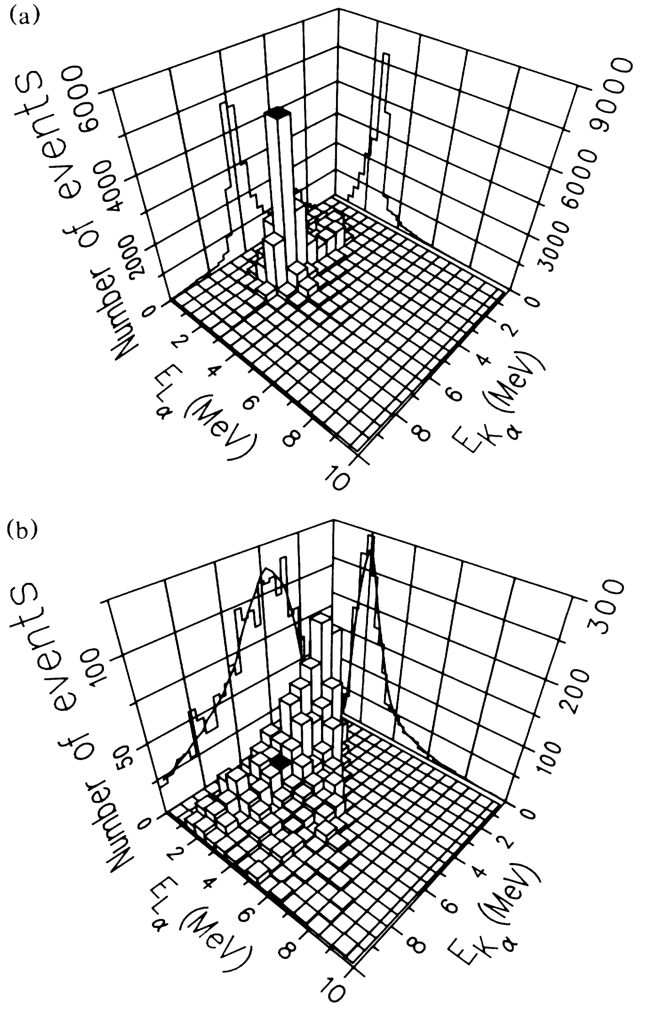

FIG. 3. Measured energy spectrum for the higher-energy photon, $E_{K\alpha}$, vs the lower-energy photon, $E_{L\alpha}$, with (a) incident μ^- and (b) incident M. The bin with the largest population in (a) is shaded in both distributions. The projections of the distributions are also shown. Note that the bins are smaller for the projections. The vertical scales on the left of the figures are for the two-dimensional plots and for the $E_{K\alpha}$ projections while the vertical scales on the right are for the $E_{L\alpha}$ projections. The smooth curves on the projections in (b) correspond to the maximum-likelihood fit with no $\overline{\mathrm{M}}$ signal.

The number of $\overline{\mathrm{M}}$ events was also estimated with a maximum-likelihood analysis.[14] We assume that the 2-γ data consist of some number of $\overline{\mathrm{M}}$ events and two types of background events: one from M (i.e., μ^+) decays in the Bi target (that are responsible for the peak in the T

distribution) and the other from decays in the regions upstream of the Bi target (that are randomly distributed in T). The background events include photons from neutron capture. The normalized two-dimensional probability distributions for the three sources of events are used to construct the likelihood function; the variables in these distributions are $E_{K\alpha}$ and $E_{L\alpha}$.

The $\overline{\mathrm{M}}$ probability distribution was generated by the Monte Carlo program and agrees with the distribution in Fig. 3(a). The background probability distributions were obtained from 2-γ data taken with an incident μ^+ beam, which predominantly come from decays in the Bi target, and from the first 750 events in each M data run without requiring the presence of a signal from the μCP, which have many events from upstream decays. Because there could be a small contamination of $\overline{\mathrm{M}}$-induced events in the M sample, a signal corresponding to $G_{\mathrm{M}\overline{\mathrm{M}}} = 20 G_{\mathrm{F}}$ was subtracted. The final result is insensitive to this subtraction.

The resulting likelihood function implies that there are <20 $\overline{\mathrm{M}}$ events (90% C.L.). This can be expressed as a limit for $G_{\mathrm{M}\overline{\mathrm{M}}}$ by use of Eqs. (2) and (3) once the M kinetic-energy spectrum and the effects of the nonzero magnetic field are included. The M kinetic-energy spectrum was measured in a separate time-of-flight experiment in which M was identified by a signal in a μCP and by the detection of the decay positron in a scintillator telescope. The magnetic field reduced the probability for $\mathrm{M} \rightarrow \overline{\mathrm{M}}$ by a factor of 0.69 ± 0.02, as calculated according to the formalism of Morgan.[15] The final result is $G_{\mathrm{M}\overline{\mathrm{M}}} < 7.5 G_{\mathrm{F}}$ (90% C.L.). This represents an improvement in the upper limit for $G_{\mathrm{M}\overline{\mathrm{M}}}$ by nearly a factor of 3.

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