SEARCH FOR MUONIUM-ANTIMUONIUM CONVERSION*

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We have searched for the conversion of muonium to antimuonium, which would be allowed by a multiplicative muon number conservation law. The results are consistent with zero conversion rate, and set an upper limit to the magnitude of the weak-interaction coupling constant for the process of 5800 times the vector coupling constant of beta decay.

All present experimental evidence[1] is consistent with the existence of additive conservation laws of muonic and electronic lepton numbers, in which the sums $\sum L_\mu$ and $\sum L_e$ are separately conserved. However, this evidence is likewise consistent with a less restrictive, multiplicative law[2,3] in which only the sum $\sum(L_\mu + L_e)$ and the sign $(-1)^{\sum L_\mu}$ are conserved. The conversion of muonium ($M = \mu^+e^-$) to antimuonium ($\overline{M} = \mu^-e^+$) would be allowed by the multiplicative law, but forbidden by the additive law. This conversion process would also require the existence of neutral lepton currents in the weak-interaction Hamiltonian.

We report here an experimental search for the conversion of M to $\overline{M}$. Positive muons are stopped in argon gas and form muonium. If the conversion of M to $\overline{M}$ occurs, the $\overline{M}$ atom would with high probability collide with an Ar atom and form the argon muonic atom. Hence we look for the $2P$-$1S$ argon muonic x ray as the signature of the conversion.[4]

A four-fermion weak interaction of the universal $V-A$ form which can cause the conversion is[5]

$$H_W = (C/\sqrt{2})\overline{\Psi}_\mu \gamma_\lambda (1+\gamma_5)\Psi_e \overline{\Psi}_\mu \gamma^\lambda \times (1+\gamma_5)\Psi_e + \text{H.c.}, \quad (1)$$

in which the field operators and γ matrices have their usual meanings and C is the M-$\overline{M}$ coupling constant. The matrix element of H_W between M and $\overline{M}$ ground states is

$$\langle \overline{M} | H_W | M \rangle \equiv \tfrac{1}{2}\delta = 1.0\times 10^{-12} C/C_V \text{ eV}, \quad (2)$$

where C_V is the magnitude of the vector coupling constant of β decay. If M is formed at $t=0$, an $\overline{M}$ component of the system wave function $\Psi(t)$ develops with time due to the presence of H_W, and the probability in vacuum that the muon will decay from the M-$\overline{M}$ system as a μ^- rather than as a μ^+ is

$$P(\overline{M}) = \int_0^\infty \gamma e^{-\gamma t} |\langle \overline{M} | \Psi(t)\rangle|^2 dt$$
$$= \delta^2/2\hbar^2\gamma^2 = 2.5\times 10^{-5}(C/C_V)^2, \quad (3)$$

where γ is the free-muon decay rate of 4.5×10^5 sec^{-1}.

In a gas environment suitable for the formation of muonium,[6,7] the development of an $\overline{M}$ component is strongly retarded on account of collisional electric fields which remove the degeneracy between M and $\overline{M}$. In addition, an inelastic collision in which a μ^- is captured by a gas atom introduces another mode of breakup of the M-$\overline{M}$ system. For the case of argon gas, the collision leads to the formation of the argon muonic atom, with a high probability for the subsequent emission of the characteristic $2P$-$1S$ x ray of energy 643 keV.[8] Since the inelastic capture rate for a μ^- from an $\overline{M}$ atom in argon at suitable pressures is much greater than the muon decay rate,[9] this is the dominant mode of breakup of the M-$\overline{M}$ system from the $\overline{M}$ component. Figure 1 illustrates the sequence of physical processes.

Detailed calculations have been carried out[5,9,10] for the M-$\overline{M}$ conversion rate in argon gas. Scattering cross sections were evaluated using approximation procedures valid up to pressures of about 1 atm. The conversion probability for the breakup of the M-$\overline{M}$ system, which leads to the formation of the argon muonic atom and the subsequent decay or nuclear absorption of the μ^-, is approximately

$$P(\overline{M}) = \delta^2/[2\hbar^2(\gamma+\omega_I)(\gamma+\overline{\omega}_I)], \quad (4)$$

where ω_I and $\overline{\omega}_I$ are the total inelastic scattering cross sections for M and $\overline{M}$, respectively. Under the experimental conditions of 1 atm pressure and room temperature, $\omega_I \simeq 0$ and $\overline{\omega}_I = 1.2\times 10^{11}$

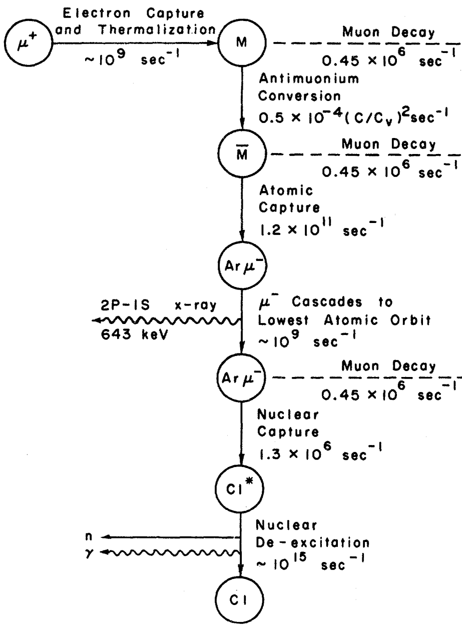

FIG. 1. Sequence of physical processes following a μ^+ stopping in argon gas, assuming a weak interaction coupling M to $\overline{M}$. The rates given are for an argon pressure of 1 atm at room temperature.

$\sec^{-1}$, and we obtain

$$P(\overline{M}) = 1.0\times10^{-10}(C/C_V)^2 \pm 20\%, \qquad (5)$$

in which the indicated uncertainty includes the effects of all approximations used.

A schematic diagram of the experimental apparatus is shown in Fig. 2. The signature of M-$\overline{M}$ conversion is the appearance of the $2P$-$1S$ argon muonic x ray following a stopped μ^+. We decided to reject potential x-ray events in which decay electrons (of either sign) were detected because for real M-$\overline{M}$ conversion events the branching ratio for μ^- decay (see Fig. 1) is only 26%, whereas for background γ-ray events there is a very high probability of seeing a fast e^+ from μ^+ decay. A muon stopping in the target is defined by a series of plastic scintillation counters in the muon beam of the Nevis synchrocyclotron. The target is purified argon gas at 1 atm, contained in a 6-in.-diam×12-in.-length cylinder of 0.003-in. thick stainless steel foil. The argon is continuously circulated over a heated titanium getter for purification since chemical impurities would decrease $P(\overline{M})$ by increasing the muonium inelastic scattering rate, chiefly through electron-spin-exchange collisions.[11,12] Decay electrons are detected by means of counters 2 and 5 which together surround the target on all sides. The total decay-electron detection efficiency is about 90%. A separate plastic counter on one side of the target is used in conjunction with a time-to-amplitude converter and a pulse-height analyzer to measure the time distribution of decay-positron counts following stopped positive muons. In this way the characteristic muonium spin-precession frequency[6] in the vertical magnetic field of 3.5 G is observed, confirming the formation of muonium.

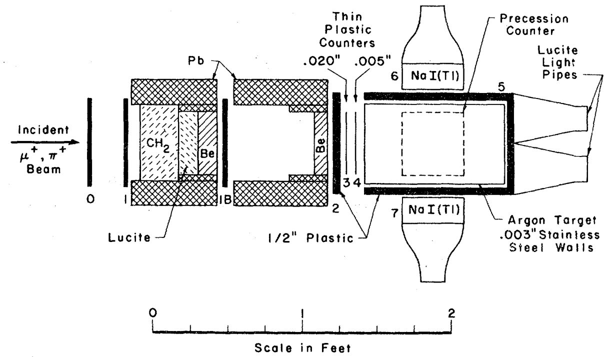

FIG. 2. Experimental arrangement. Gamma-ray shielding is not shown. The argon was continually circulated over a heated titanium getter to remove chemical impurities. Plastic scintillation counters defined a stopped muon $(01234\overline{5})$ and decay electrons $[\overline{0}(2+5)]$. The two NaI(Tl) crystals were each 5 in. in diameter by 2 in. thick.

Gamma rays are detected by means of two 5-in.-diam×2-in.-thick NaI(Tl) crystals. Extensive neutron and γ-ray shielding (not shown in Fig. 2), consisting of steel, boron-loaded paraffin, and lead, is used to lower the ambient γ-ray counts. The signals from the two crystals as well as a set of logic pulses from the other counters are sent to two fast dual-beam oscilloscopes whose traces are photographed. The oscilloscopes are triggered whenever a stopped μ^+ is followed within 8 μsec by a γ ray in the proper energy range from either of the two crystals, provided the γ ray is not preceded by a decay electron. The energy scale is calibrated periodically by observing γ rays from Cs^{137} or Co^{60} radioactive sources. A direct measure of the energy resolution and overall detection efficiency for observation of the argon muonic x ray is obtained by taking data using the negative-muon beam. The energy resolution was 12% at 643 keV (a full width at half-maximum of 77 keV) and the x-ray detection efficiency was 1.5%, which corresponds to a fractional solid angle of about 8% and a photopeak efficiency of about 20%.

Events were collected with the positive-muon beam for a total of about 20 days running time. The total number of muon stoppings in the entire target was 5.2×10^7, and the film-drive dead time was about 5%. Because of low equivalent thickness of the gas (50 mg/cm^2) only about 9% of the total muon stoppings were in the argon, as estimated from the negative-beam data. The muonium-formation probability in argon is expected to be very close to 1, based on a comparison with proton charge-capture data[13,14]; this is consistent with the spin-precession results from this experiment and with past muonium experiments.[6] The total number of M formations in the argon is therefore about 4.2×10^6.

The photographic film was first scanned for the absence of decay electrons; if no electrons were present, the γ-ray pulse height and time of arrival relative to the muon stop were measured. A computer program was used to assemble pulse-height histograms after correcting for drifts in the gain by means of the γ-ray source data. The energy spectrum of γ rays which follow a stopped μ^+ and are not accompanied by a decay electron is shown in Fig. 3.

The great majority of these γ rays have a time distribution which fits the muon lifetime and are presumably correlated with decay positrons which escaped detection. The steep rise in the γ-ray spectrum at the low-energy end is therefore expected to be the effect of an annihilation photopeak centered at 511 keV. The spectrum of γ-ray energies in Fig. 3 was accordingly fitted by a background function (Gaussian photopeak centered at 511 keV plus a decreasing exponential) plus a Gaussian line shape centered at 643 keV to represent the argon muonic x ray. The widths of both Gaussian photopeaks were fixed from the negative-beam data. The free parameters were the exponential decay constant and the amplitudes of the exponential and of the two Gaussian photopeaks. The amplitude of the x-ray line shape was determined by a maximum-likelihood analysis and corresponded to a fitted number of events under the x-ray photopeak of -33 ± 64. Several different background functions were also tried, but the fitted x-ray amplitude was only weakly dependent on this choice.

The results were clearly consistent with zero conversion rate. An upper limit to the magnitude of the M-$\bar{M}$ coupling constant C is obtained by setting

$$P(\bar{M})\leq N_X/(N_M\epsilon). \qquad (6)$$

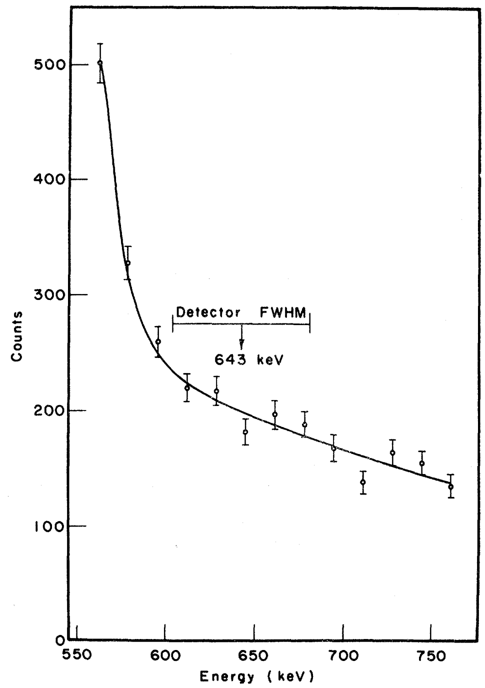

FIG. 3. Energy spectrum of γ rays following a stopped μ^+ and unaccompanied by a decay electron. The data from both NaI(Tl) counters have been summed. The fitted function is a Gaussian photopeak centered at 511 keV plus a decreasing exponential. The detector full width at half-maximum at the argon muonic x-ray energy is indicated. The fitted error in the amplitude of a Gaussian photopeak centered at 643 keV with the indicated width is 13 counts in the peak channel.

In this expression $P(\bar{M})$ is the probability of conversion given in Eq. (5). N_X is the maximum number of detected argon muonic x rays, obtained from the fitting program (128, or 2 standard deviations above zero). N_M is the number of muonium formations in the argon (4.2×10^6). The overall x-ray detection efficiency ϵ was obtained from the negative-beam data and gave a value of 1.1×10^{-2} after correcting for finite gate time (92%) and the branching ratio for real events without electrons (74%). It is important to note that the product $N_M\epsilon$ is known to much greater accuracy than N_M or ϵ individually. This is because each of those factors involves the ratio of muon stops in argon to total muon stops, which is known only approximately; however, this quantity cancels out of the product $N_M\epsilon$.

Equation (6) then gives an upper limit of 5300 for C/C_V, with a limit of error of 10% due to the uncertainty in $P(\bar{M})$. We therefore obtain a 95%

confidence level upper limit of

$$C \leq 5800 C_V = 8.1 \times 10^{-46} \text{ erg cm}^3. \tag{7}$$

This represents the first quantitative information on the M-$\bar{M}$ coupling constant.[13] This experiment can be modified for greater sensitivity, particularly when more intense muon beams become available.

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FOUR-PION DECAY OF THE f^0 MESON*

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The reaction $\pi^- p \to f^0 n \to 2\pi^+ 2\pi^- n$ has been observed at 5 Gev/c with $\sigma = 11.5 \pm 4$ μb ($1.20 < m_{4\pi} < 1.32$, $|t| < 0.2$ GeV^2).

The f^0 meson was first observed by Selove et al.[1] and by Viellet et al.[2] in the reaction $\pi^- p \to \pi^+\pi^- n$. The existence of the f^0 has been confirmed in many experiments and its quantum numbers, $J^P = 2^+$, $I^G = 0^+$, appear firmly established.[3] Evidence for decay modes other than $f^0 \to 2\pi$ is less clear. In particular only upper limits appear to have been given for the decay mode $f^0 \to 4\pi$.[4]

We report here the observation of a peak in the 4π mass spectrum from the reaction

$$\pi^- p \to \pi^+\pi^+\pi^-\pi^- n. \tag{1}$$

The position of the peak, the highly peripheral mode of its production, and its decay distributions all suggest that the peak is due to the decay $f^0 \to 4\pi$.

The study is based on a 4.0-event/μb sample of four-prong interactions produced in the 72-in. hydrogen bubble chamber by a 5-GeV/c π^- beam at the Lawrence Radiation Laboratory. In this sample 4144 events are consistent with Reaction (1) by kinematics and ionization.

Figure 1 shows the 4π mass spectrum for all 4144 events and for 336 events with small momentum transfers to the nucleon ($|t| < 0.2$ GeV^2). In the sample with small momentum transfers a peak is seen near the lower end of the spectrum. Our best estimates for the mass and width are

$$m_{4\pi} = 1.27 \pm 0.01 \text{ GeV}, \quad \Gamma = 0.09 \pm 0.03 \text{ GeV}.$$

Inspection of the spectra suggests that additional peaks at higher masses may also exist, but the present data are inadequate to warrant definite conclusions. This uncertainty makes it difficult, however, to obtain a reliable estimate of the background level near the 1.27-GeV peak. We assume tentatively that the background is low and return to this question later.

Figure 2 shows various decay distributions for 78 events with $1.18 < m_{4\pi} < 1.36$ and $|t| < 0.2$