Some Recent Advances in Muonium

V.W. Hughes

Gibbs Laboratory, Physics Department, Yale University,
New Haven, CT06520, USA

I. INTRODUCTION

Muonium (M) is the bound atomic state of a positive muon (μ^+) and of an electron (e^-) and hence it is a hydrogenic atom. Muonium was discovered[1] in 1960 through observation of its characteristic Larmor precession in a magnetic field. Since then research on the fundamental properties of M has been actively pursued[2,3], as has also the study of muonium collisions in gases, muonium chemistry and muonium in solids.[4]

The principal reason that muonium continues to be important to fundamental physics is that it is the simplest atom composed of two different leptons. The muon retains a central role as one of the elementary particles in the modern standard theory, but we still have no understanding as to "why the muon weighs" and in all respects behaves simply as a heavy electron. Muonium is an ideal system for determining the properties of the muon, for testing modern quantum electrodynamics, and for searching for effects of weak, strong, or unknown interactions in the electron-muon bound state. Basically muonium is a much simpler atom than hydrogen because the proton is a hadron and, unlike a lepton, has a structure that is determined by the strong interactions. Thus muonium provides a cleaner system to study than hydrogen for testing QED and the electroweak interaction.

II. GROUND STATE HYPERFINE STRUCTURE AND ZEEMAN EFFECT

After the discovery of muonium, measurements of its energy levels could be undertaken by microwave magnetic resonance spectroscopy utilizing the facts that the incident μ^+ are polarized so that polarized muonium is formed and that the decay positrons have an asymmetric angular distribution with respect to the muon spin direction.[5] The Breit-Rabi energy level diagram for the ground state of muonium is shown in Fig. 1. With the aim of determining the hyperfine structure interval $\Delta\nu$ and the muon magnetic moment μ_μ, transitions at both weak and strong magnetic fields have been measured as indicated. Starting in 1962 a series of increasingly accurate measurements were undertaken[2,3] by both the Yale-Heidelberg and Chicago groups. The latest experiment at the Los Alamos Meson Physics Facility (LAMPF) was a strong field measurement.[6] A schematic

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diagram of the experimental arrangement is shown in Fig. 2 and a photograph of the precision solenoid electromagnet in Fig. 3. Typical resonance curves are shown in Fig. 4.

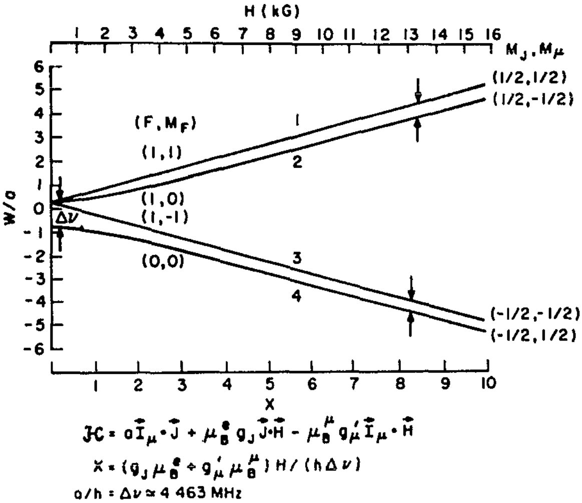


Fig. 1: Breit-Rabi energy level diagram for the ground state of muonium.

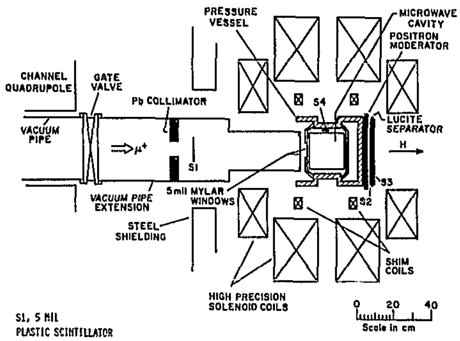


Fig. 2: Experiment at LAMPF in which the latest precision measurement of the hyperfine structure interval $\Delta\nu$ in muonium was made.

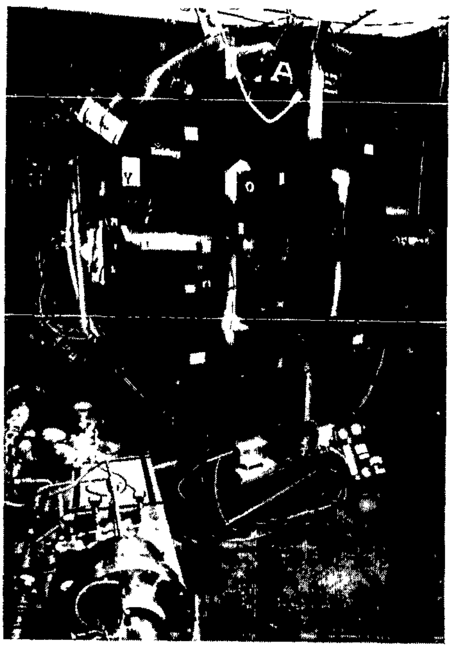


Fig. 3: Photograph of the large solenoid electromagnet. The outer diameter of the iron shield is 80 in.

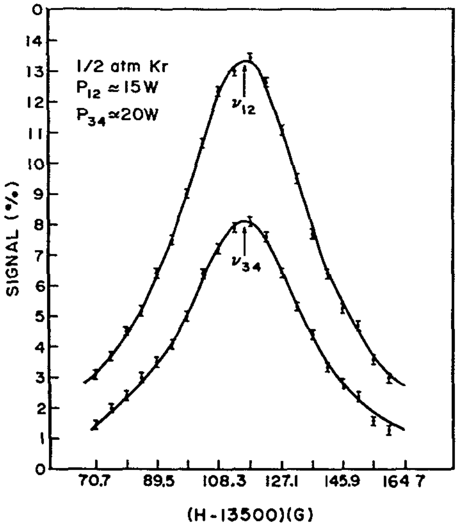


Fig. 4: Resonance lines fitted to the data from the experiment shown in Fig. 2. P_{12} and P_{34} are input powers to the microwave cavity.

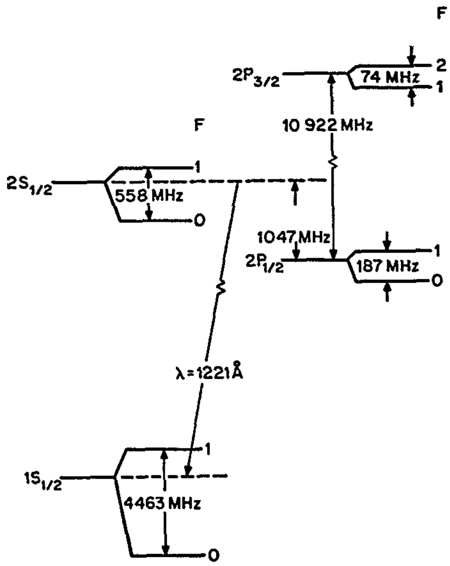


Fig. 5: Energy level diagram of the n=1 and n=2 states of muonium.

The experimental results for $\Delta\nu$ and μ_μ and the current theoretical value for $\Delta\nu$ are given in Table I. The radiative and recoil corrections to the leading Fermi value for $\Delta\nu$ have been computed to high order.[7] The principal error of 1.5 kHz or 0.34 ppm is due mostly to uncertainty in the value of the constant μ_μ/μ_p appearing in the Fermi term E_F. (The condensed matter value[8] of α is accurate to 0.09 ppm.) The error of 0.2 kHz is an estimate of numerical uncertainties in the calculated terms in ε_{QED}, and the 1.0 kHz error is an estimate of the size of uncalculated higher order radiative and recoil terms. A small hadronic vacuum polarization contribution of 0.22(4) kHz is included in the factor with 18.18 in the last term of δ'_μ. The experimental value for $\Delta\nu$ is known to 36 ppb, and the experimental and theoretical values agree well within the theoretical error of 0.4 ppm. This agreement constitutes one of the important, sensitive tests of quantum electrodynamics and of the behaviour of the muon as a heavy electron.

Improvement by a factor of about 10 in the sensitivity of the comparison of theory and experiment for $\Delta\nu$ appears possible at this time.[9] With the use of a chopped muon beam now available at Los Alamos, line narrowing techniques can be employed.[10] Use of a higher magnetic field value will improve the accuracy in determining μ_μ/μ_p. Finally, the intensity and quality of the muon beam has been improved since the last measurement. Considering all these factors, a measurement of $\Delta\nu$ to about 5 ppb and of μ_μ/μ_p to 30 ppb appears possible.

Theoretical computation to about 0.1 kHz or 20 ppb appears realistic. We might remark that weak interaction contributions to $\Delta\nu$ are predicted[11] at the level of 16 ppb.

Table I. Theoretical value of muonium $\Delta\nu$ and comparison with experiment.

$$\Delta\nu_{th} = \left[\tfrac{16}{3}\alpha^2 c R_\infty (\mu_\mu/\mu_B^e)\right]\left[m_\mu/(m_e+m_\mu)\right]^3\left[1+\epsilon_{\rm QED}\right]$$

$$\Delta\nu_{th} = E_F(1+\epsilon_{\rm QED})$$

$$\epsilon_{\rm QED} = \tfrac{3}{2}\alpha^2 + a_e + \epsilon_1 + \epsilon_2 + \epsilon_3 - \delta'_\mu$$

$$a_e = (g_e-2)/2;\ \epsilon_1 = \alpha^2(\ln 2 - 5/2)$$

$$\epsilon_2 = -\tfrac{8\alpha^3}{3\pi}\ln\alpha\left(\ln\alpha - \ln 4 + \tfrac{281}{480}\right);\ \epsilon_3 = \tfrac{\alpha^3}{\pi}\,(15.38\pm0.29)$$

$$\delta'_\mu = \Big\{\tfrac{3\alpha}{\pi}\tfrac{m_R}{m_\mu - m_e}\ln m_\mu/m_e + \alpha^2\tfrac{m_R}{m_\mu+m_e}\left[2\ln\alpha + 8\ln 2 - 3\tfrac{11}{18}\right]$$

$$+(\alpha/\pi)^2 m_e/m_\mu \times \left[2\ln^2(m_\mu/m_e) - \tfrac{13}{12}\ln(m_\mu/m_e) - 18.18(63)\right]\Big\}\tfrac{1}{1+a_\mu}$$

where $m_R = m_e m_\mu/(m_e+m_\mu)$

$R_\infty = 1.097\ 373\ 152\ 1\ (11) \times 10^5 \mathrm{cm}^{-1}$ (0.001 ppm)

$c = 2.997\ 924\ 580 \times 10^{10}$ cm/sec

$\alpha^{-1} = 137.035\ 981\ (12)$ (0.09 ppm)

$a_e = 1\ 159\ 652\ 193\ (4) \times 10^{-12}$ (3.4 ppb)

$\mu_\mu/\mu_B^e = (\mu_\mu/\mu_p)(\mu_p/\mu_B^e);\ \mu_p/\mu_B^e = 1.521\ 032\ 209\ (16)$ (0.01 ppm)

$m_\mu/m_e = 206.768\ 259\ (62)$ (0.3 ppm)

$\mu_\mu/\mu_p = 3.183\ 345\ 47\ (95)$ (0.3 ppm)

[$\mu_\mu/\mu_p = 3.183\,346\,1\,(11)$ (0.36 ppm)] from muonium Zeeman effect

$a_\mu = (g_\mu - 2)/2 = 0.001\ 165\ 923\ 0(84)$ (7.2 ppm)

$E_F = 4\ 459\ 033.4\ (1.5)$ kHz

$\Delta\nu_{th} = 4\ 463\ 303.6(1.5)(0.2)(1.0)$ kHz (0.4 ppm)

$\Delta\nu_{exp} = 4\ 463\ 302.88(0.16)$ kHz (0.036 ppm)

$\Delta\nu_{th} - \Delta\nu_{exp} = (+0.7 \pm 1.8)$ kHz

Determination of α : $\alpha^{-1} = 137.035\ 988\ (20)$ (0.15 ppm), μ^+e^-

137.035 994 (5) (0.038 ppm), $g_e - 2$

137.035 981 (12) (0.09 ppm), condensed matter

III. LAMB SHIFT IN MUONIUM

With the development of a muonium beam in vacuum,[12] measurement of the Lamb shift in muonium became possible. The energy level diagram of the n=1 and n=2 states of muonium are shown in Fig. 5. Two measurements[13,14] have determined the Lamb shift $\mathcal{S}_L$ by observing the $2^2S_{1/2}$ to $2^2P_{1/2}$ transition in a radiofrequency spectroscopy experiment. Table II gives the current theoretical value of $\mathcal{S}_L$ and the two experimental values. The theoretical value for the muonium Lamb shift differs from that in hydrogen by the absence of a proton structure term and by the relatively greater importance of recoil terms. The experimental values agree with the theoretical value within the limited experimental accuracy of about 1%.

Recently, at LAMPF, the fine structure transition $2^2S_{1/2}$ to $2^3P_{3/2}$ in muonium has been studied.[15] Figure 6 indicates the experimental method. Muonium is formed in the metastable $2^2S_{1/2}$ state at an Al foil just downstream of a low gas pressure MWPC. After collimation, the M(2S) beam enters a microwave cavity operating at a frequency of about 10 GHz which drives the transition $2^2S_{1/2} \rightarrow 2^2P_{3/2}$. From the $2^2P_{3/2}$ state M decays to the ground 1S state with a mean life of 1.6 ns, and the Lyman-α 1221 A photon is detected by a UV photomultiplier tube, while the resulting M(1S) atom travels to a microchannel plate where it is detected. The signal due to the microwave field, defined as a delayed triple coincidence between a μ^+ count in the MWPC detector, a Lyman-α photon, and a microchannel plate count, is shown in Fig. 7 as a function of the microwave frequency, together with the predicted line centers. The analysis is in progress so no fitted line shape or result can yet be quoted. Further development of

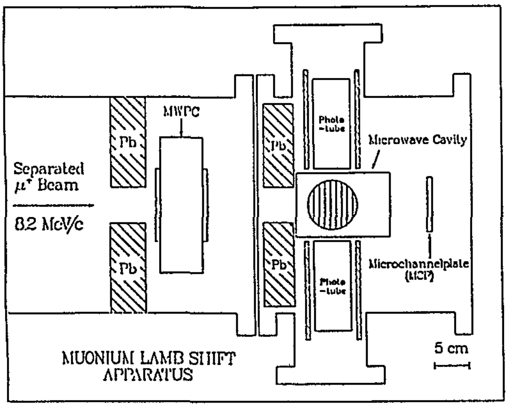


Fig 6: Diagram of the apparatus used in observation of the muonium fine structure transition $2^2S_{1/2} \rightarrow 2^2P_{3/2}$.

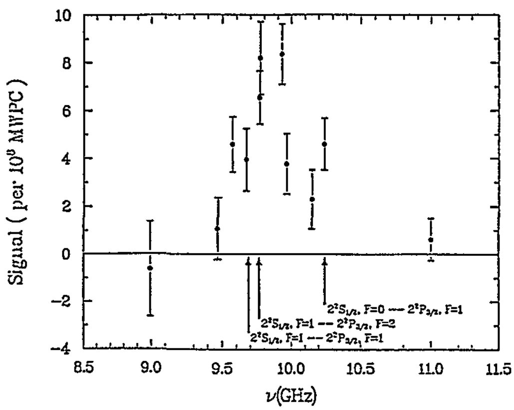


Fig. 7: Muonium $2S^2_{1/2} - 2P^2_{2/3}$ transition showing raw data. (No correction is made for variation of microwave power with frequency).

Table II. Muonium Lamb Shift Theoretical Value

CORRECTION	ORDER (mc^2)	VALUE (MHz)
Self energy	$\alpha(Z\alpha)^4[\ln(Z\alpha)^{-2},1,Z\alpha,...]$	1 085.812
Vacuum polarization	$\alpha(Z\alpha)^4[1,Z\alpha,...]$	-26.897
Fourth order	$\alpha^2(Z\alpha)^4$	0.101
Reduced mass	$\alpha(Z\alpha)^4 m/M_\mu[\ln(Z\alpha)^{-2},1]$	-14.626
Relativistic recoil	$(Z\alpha)^5 m/M_\mu[\ln(Z\alpha)^{-2},1]$	+3.188
Total		1 047.578(300)MHz

The estimated uncertainty in the theoretical value is due to uncalculated terms of higher order in m/M_μ and in $\alpha m/M_\mu$, that is the terms (m/M_μ)(reduced mass term) and α (reduced mass term). An estimate of the size of these terms is 0.3 MHz.

Experimental Value

$\mathcal{S}_{expt}$ = 1054 ± 22 MHz LAMPF

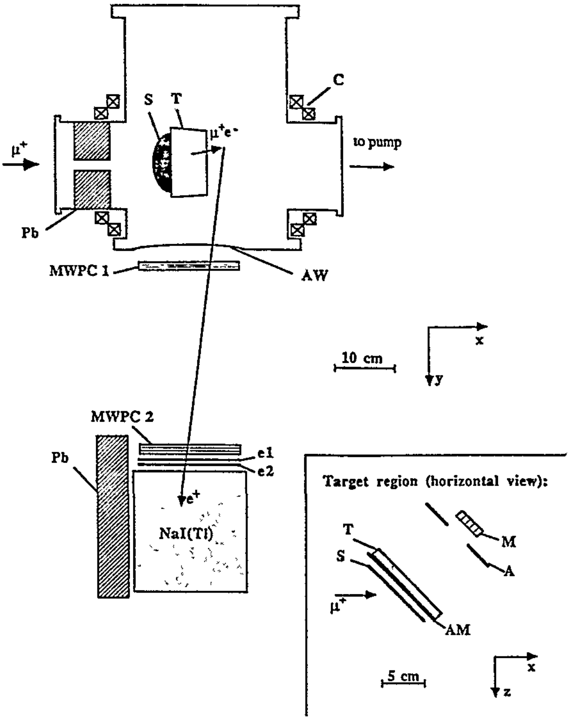
1070^{+12}_{-15} MHz TRIUMPF

this experiment involving the suppression of Doppler effect by the choice of cavity mode relative to the M velocity direction, the use of M(2S) production from the foil at about 30° to the incident μ^+ direction to reduce the background associated with energetic μ^+, and photon detectors with improved efficiency should make possible a precision of about 0.1% in the determination of $\mathcal{S}_L$. This experiment is severely limited by signal rate which at present amounts to about 10 counts/hr, and additional future progress would require higher M(2S) beam intensities.

IV. GROUND STATE $\Delta\nu$ AND THE 1S–2S TRANSITION WITH THERMAL MUONIUM

At SIN, the Heidelberg-Yale group established that thermal muonium emitted from SiO_2 powder is polarized.[16] Figure 8 shows the experimental arrangement and Figure 9 shows the characteristic muonium precession, not only from the region of the powder but also from the free-space region beyond the powder occupied by thermal muonium.

Using a microwave cavity in the free magnetic field region downstream of the SiO_2 target, the hfs transition $\Delta\nu$ = 4 463 MHz in n=1 state muonium was observed.[17] Because of the Doppler effect it does not appear that this type of observation can lead to a high precision determination of $\Delta\nu$, competitive with the existing value.



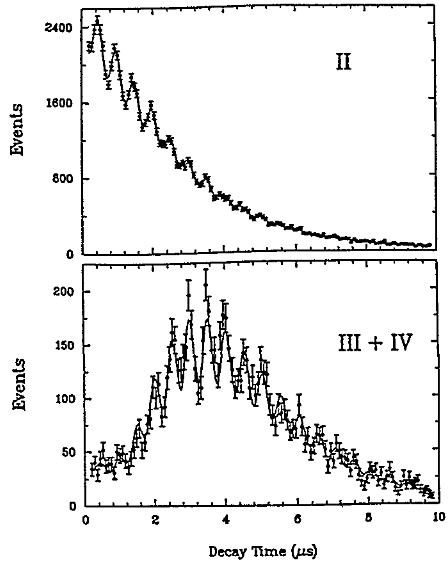


Fig. 8: Schematic of the experimental apparatus showing the μ^+ scintillator (S), SiO_2 target (T), magnetic field coils (C), Al window (AW), and e^+ scintillators (e_1 and e_2). The aperture electrode, the microchannel plate, and one pair of field coils have been omitted in order to simplify the picture. The inset shows a horizontal view of the target region with the μ^+ scintillator (S), aluminized mylar foil (AM), SiO_2 target (T), aperture electrode (A), and microchannel plate (M).

Fig. 9: Observed numbers of positrons as a function of time with an applied magnetic field of 1.4G. The upper histogram corresponds to decays from Region II, which includes the target and the immediate downstream region, and the lower histogram to decays from Regions III and IV, which is the free-space region downstream of the target.

Using the high intensity pulsed muon beam from the Rutherford Laboratory 1 GeV proton synchrotron, the Heidelberg group[18] has initiated a new experiment to measure the 1S-2S transition in muonium by two-photon laser spectroscopy with the objective of determining this interval to about 1 part in 10^9.

V. MUONIUM → ANTIMUONIUM CONVERSION

The muon and the electron may be considered to belong to two different generations of leptons, which thus far appear to remain separate because of the independent conservation laws of muon number and of electron number. Any connection between the muon and the electron, such as a process which would violate muon number conservation, would be an important clue to the relationship between the two generations.[19] Speculative modern theories which seek a more unified theory of particles and their interactions predict muon number violating processes.[20] As yet no such rare decay process has been observed,[21] and with our present knowledge theory has little useful predictive power.

The conversion of muonium (μ^+e^-) to its antiatom antimuonium (μ^-e^+) would be an example of a muon number violating process,[2] and like neutrinoless double beta decay would involve ΔL_e=2. The M-$\bar{M}$ system also bears some relation to the K°-$\overline{K^\circ}$ system, since the neutral atoms M and $\bar{M}$ are degenerate in the absence of an interaction which couples them. In Table III a four-Fermion Hamiltonian term coupling M and $\bar{M}$ is postulated, and the probability that M formed at time t=0 will decay from the $\bar{M}$ mode is given. Present experimental limits[22,23] for the coupling constant G are indicated and are larger than the Fermi constant G_F.

Two new experiments are in progress to search for the M→$\bar{M}$ transition using thermal muonium from SiO_2. At TRIUMF[24] the signal in the experiment would be an induced radioactivity due to a μ^- nucleus capture. At LAMPF[23,25], the signal would be a coincident high energy e^-($\gtrsim$30 MeV) and a low energy e^+(~10 eV). Figure 10 shows a schematic diagram of the apparatus and Figure 11 is a photograph of the apparatus. A successful checkout of this experiment took place in the summer of 1988 and with the data-taking planned a sensitivity $G_{M\bar{M}} \sim 10^{-2}\ G_F$ might be achieved.

Table III. Muonium-antimuonium conversion including present experimental limits.

$\mu^+e^- \rightarrow \mu^-e^+$

Muon number, L_μ, +1(-1) for $\mu^-(\mu^+), \nu_\mu(\bar{\nu}_\mu)$, 0 for other particles.

Violates additive conservation law for muon number, ΣL_μ = constant.

Allowed by multiplicative conservation law, $(-1)^{\Sigma L_\mu}$ = constant.

$$\mathcal{H}_{M\rightarrow\bar{M}} = \frac{G_{M\bar{M}}}{\sqrt{2}}\ \bar{\psi}_\mu \gamma_\lambda (1+\gamma_5)\ \psi_e \bar{\psi}_\mu \gamma^\lambda (1+\gamma_5)\ \psi_e + \text{H.C.}$$

$$P(\bar{M}) = \int_0^\infty \gamma\, e^{-\gamma t} \left|\langle \bar{M} | \psi(t) \rangle\right|^2 dt = 2.5 \times 10^{-5} \left(\frac{G_{M\bar{M}}}{G_F}\right)^2$$

Probability of decay of M from $\bar{M}$ state reduced by collisions in a gas by factor of (number of collisions during muon lifetime)$^{-1}$.

$G_{M\bar{M}} < 5800\ G_F$ (M→$\bar{M}$ in gas; Nevis: 1968)

$G_{M\bar{M}} < 600\ G_F$ ($e^-e^- \rightarrow \mu^-\mu^-$; HEPL; 1969)

$G_{M\bar{M}} < 20\ G_F$ (M→$\bar{M}$ in powers; TRIUMF; 1982,1986)

$G_{M\bar{M}} < 7.5\ G_F$ (M with keV kinetic energies in vacuum; LAMPF; 1987).

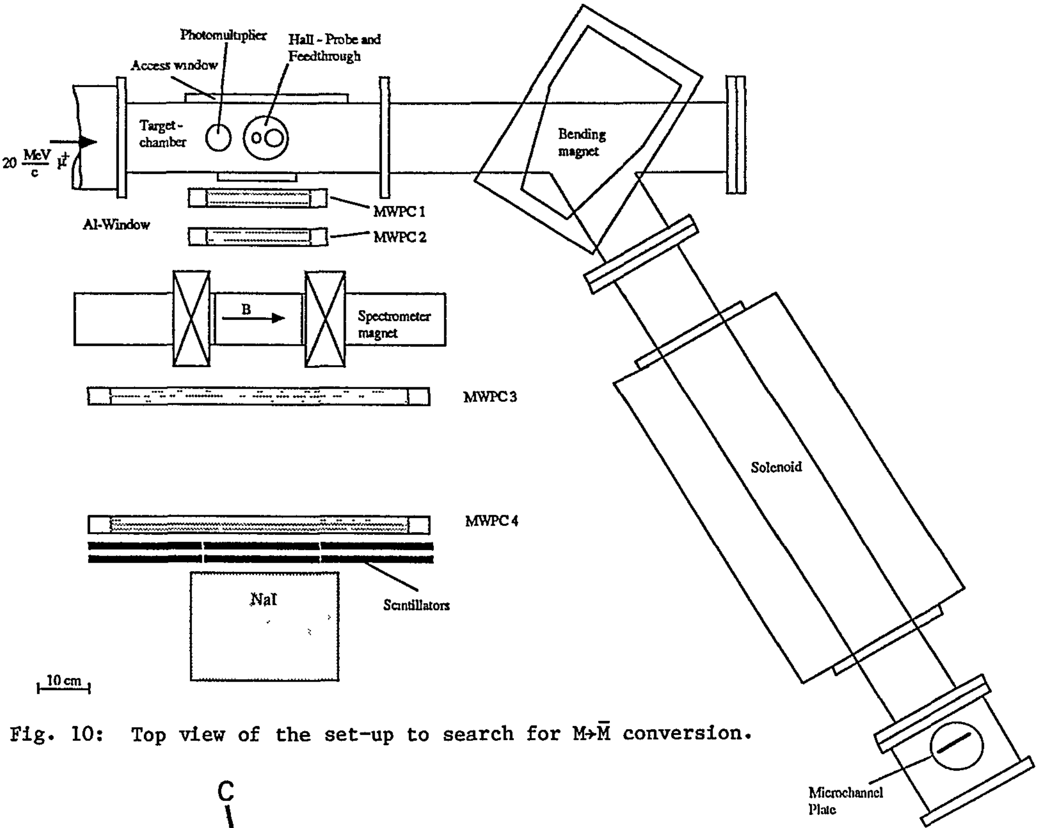


Fig. 10: Top view of the set-up to search for $M \rightarrow \bar{M}$ conversion.

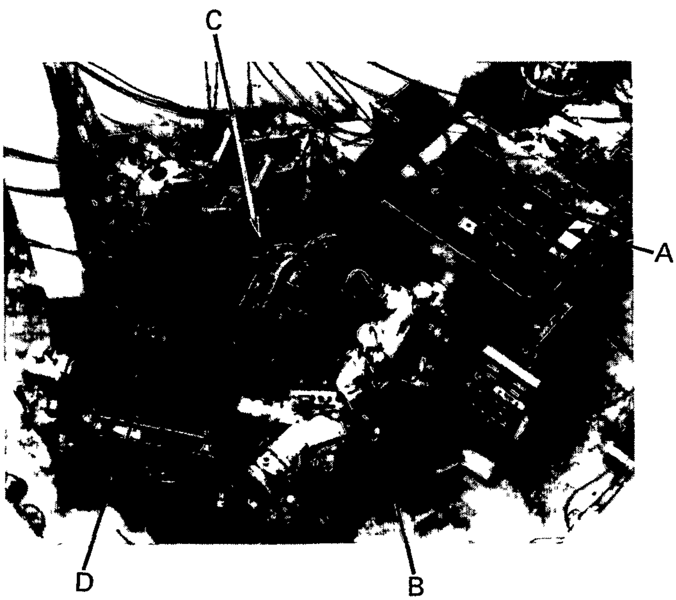


Fig. 11: Photograph of LAMPF apparatus to search for $M \rightarrow \bar{M}$ conversion. A is incoming μ^+ beam line; B is region where thermal muonium is formed and decays; C is high energy $e^\pm$ detector with magnet and MWPC; D is low energy $e^\pm$ detector with low energy keV spectrometer and microchannel plate.

VI. SUMMARY

As a concluding remark we emphasize that research on the fundamental properties of muonium is flourishing with many important recent advances and with bright prospects for the future. As this exciting Symposium has shown, fascinating and fundamental research on many aspects of the hydrogen atom, which we have known for some 200 yrs., is still most active, so it is not surprising that the same is true of muonium, a most fundamental isotope of hydrogen discovered less than 30 years ago.

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