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Yale University
Physics Department

260 Whitney Avenue
New Haven, CT 06511

TECHNICAL PROGRESS REPORT

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Basic Energy Research
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TECHNICAL PROGRESS REPORT
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A. POLARIZED LEPTON–NUCLEON and LEPTON-NUCLEUS SCATTRING.

A.1 Review Of Research

A brief review of our research in the field of polarized lepton- nucleon and lepton-nucleus scattering follows with references to our principal publications in this field from an early article in the IInd International Conference on Polarized Targets through 1991. A short but complete summary of this work is given in Ref. 25 which is appended (appendix A).

Polarized Electron Source for SLAC

The basic atomic physics for the production of polarized electrons by photoionization of a polarized atomic beam was done at Yale.[2] The atomic beam polarized electron source (PEGGY), was developed initially at Yale and used at SLAC for all the measurements of spin dependent structure functions and for the first search for parity violation due to the electroweak interference. A detailed description of PEGGY is given in Ref. 9.

We participated some in the development and operation of the high intensity GaAs polarized electron source used in the successful parity violation experiment.[7]

Measurement of Electron Polarization at High Energy

The method of Moller scattering of polarized electrons in a high energy beam by polarized electrons in a magnetized iron foil to measure electron polarization at high energy was developed.[3] This method of polarization measurement was used in all our experiments at SLAC in the energy range from about 1 GeV to 22 GeV and achieved an accuracy of 3%.

Measurement of Spin-Dependent Structure Function of Proton at SLAC

Our measurements of spin-dependent asymmetries in the high energy scattering of polarized electrons by polarized protons, which are the only such measurements yet made, focussed principally on deep inelastic scattering but included also elastic scattering and resonance-region scattering. The deep inelastic scattering was inclusive scattering in the scaling regime and determined the proton spin dependent structure function.[5,6,18] The results agreed with the Ellis-Jaffe sum rule within the rather large 30% error dominated by the need to extrapolate to the low x region below x=0.1 not covered by the measured points. The predicted scaling behaviour of the virtual photon-proton asymmetry $A_1(x)$ increased with x and was consistent with the prediction of nonperturbative QCD that $A_1(1) = 1$. $A_1(x)$ was compared with various phenomenological models of proton structure.

The asymmetry in elastic scattering[4] is predicted theoretically using values for the electric and magnetic form factors obtained from unpolarized elastic e-p scattering. Our measured asymmetry agreed with this prediction and hence confirmed our experimental method of measuring asymmetries.

Our measurement of asymmetries in the resonance region was exploratory.[14] The results were consistent with the predictions of phase shift analyses based on extensive unpolarized scattering studies. The data unexpectedly obeyed the scaling relation applicable to deep inelastic scattering even at low Q^2 and in this resonance region except for the region of the Δ resonance where the predicted negative asymmetry was observed.

SLAC decided to terminate our program in polarized electron-nucleon scattering in the early 1980's, primarily due to their plans for the SLAC Linac Collider.

A review of the theoretical and experimental situation on spin-dependent structure functions is given in Ref. 17.

Polarized Target Development SLAC

The polarized target used in our experiments at SLAC was developed jointly by Yale and SLAC. It used a hydrocarbon (butanol) material with a paramagnetic dopant (prophyrexide) and the standard method of dynamic nuclear polarization. However, our target did use a high magnetic field of 5 T and a correspondingly high microwave frequency of 140 GHz. Radiation damage of the polarizable material was a troublesome problem requiring annealing or change of the target every 2 to 3 hours.[4,5]

Parity Nonconservation in Inelastic Electron-Nucleon Scattering

For inelastic inclusive scattering of longitudinally polarized electrons by unpolarized nucleons the differential scattering cross section will not depend on the helicity of the incident electrons unless there is parity nonconservation in the scattering. The first measurements at SLAC done with the atomic beam polarized electron source PEGGY observed no asymmetry or dependence of the cross section on the helicity with a sensitivity of 10^3.[5,8]

A more sensitive experiment was then done using the higher intensity GaAs polarized electron source and a liquid D_2 target.[7] This measurement found an unambiguous parity violation and was indeed the first definitive observation of electroweak interference which is a central feature of the Glashow-Salam-Weinberg unified electroweak theory. Subsequently more extensive measurements were made covering a broader kinematic range in $y=\nu/E_e$ and using a liquid H_2 target as well.[10] These data provided a determination of the weak mixing angle $\sin^2\theta_w$ to an accuracy of about 10% in agreement with other determinations of $\sin^2\theta_w$.

Experimental Test of Special Relativity

As an inevitable by-product of bending the high energy polarized electron beam from the accelerator into the experimental area we measure the g-2 frequency $\omega_a = \omega_s - \omega_c = \frac{e}{mc} B a_e$ associated with the anomalous magnetic moment of the electron at the very high γ value of 2 x 10^4. This can be interpreted as a test of Thomas spin precession or of special relativity.[11]

Parity Nonconservation in Polarized Electron-Carbon Elastic Scattering at Bates

In the elastic scattering of longitudinally polarized electrons by carbon nuclei parity violation is predicted due to the electroweak interference between photon and Z exchange and the C form factor cancels in the expression for the asymmetry A. This asymmetry was measured using the Bates electron linear accelerator with a 250 MeV beam.[26] The polarized electron source built at Yale was a GaAs source with a high instantaneous current of 3–6 mA and a duty factor of 1%.[23] The helicity-dependent asymmetry predicted by the electroweak theory was small, $A \simeq 0.70 \times 10^{-6}$. It was observed and measured with a relative accuracy of about 25%, which was dominantly due to the high statistical error associated with the short running time made available. The systematic error achieved was $\delta A = 0.02 \times 10^{-6}$.

Measurement of Spin-Dependent Structure Function of Proton at CERN (with EMC)

After the SLAC measurements of the proton spin-dependent structure function the European Muon Collaboration (EMC) whom we were invited to join, undertook similar measurements using the 100–200 GeV (polarized) muon beam at CERN together with a large volume polarized proton target.[20,24] Spin dependent asymmetries were measured with about the same accuracies as our SLAC results in the kinematic range $0.1 < x < 0.7$ and agreed with the SLAC data. However, the EMC results extended to lower x of 0.01. The extended range allowed a more accurate test of the Ellis-Jaffe sum rule, and it was indeed found that the first moment of the structure function as measured disagreed with the predicted value. Within the naive quark-parton model the implications of this disagreement are that strange quarks in the sea have a rather large polarization and that the contribution of all quarks to the proton spin is small. These surprizing results have stimulated great interest and led to many new ideas and theoretical papers. The contribution to the proton spin of gluons (via the Adler-Bell-Jackiw triangle anomaly) and of orbital angular momenta are now regarded as possibly relevant.

The EMC results have also stimulated new experiments. One of these is the CERN SMC experiment in which our Yale group is deeply involved and is described in the following section. There are also experiments on spin dependent structure functions planned at SLAC and HERA, and possibly at LEP.

Several review type papers have been published or are in preparation.[27,28]

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A. 2 High Energy Polarized Muon-Nucleon Scattering at CERN to Measure the Spin-Dependent Structure Functions of the Proton and Neutron (NA47) (SMC)

Objective and Time Scale

A major new experiment at CERN (NA47) to measure the spin dependent structure functions of the proton and neutron through polarized deep inelastic muon-nucleon scattering has been fully approved. Indeed experimental checkout and initial data-taking took place in 1991. The initial and primary objective of this approved experiment is given in the abstract of our proposal of December, 1988 which follows.

ABSTRACT

We propose a new measurement of spin-dependent asymmetries in the deep inelastic scattering of polarized muons by polarized protons and deuterons in an experiment similar to the EMC polarization experiment, using a modified CERN/EMC polarized target, the EMC/NMC spectrometer and including a muon polarimeter. The measurement will determine the spin-dependent structure functions of the proton and neutron, $g_1^p(x)$ and $g_1^n(x)$, in the scaling regime from $x = 0.01$ to $x = 0.7$ and hence their first moments $\Gamma = \int_0^1 g_1(x)dx$. A test of the fundamental Bjorken polarization sum rule at about the 10% accuracy level should be achieved. Also tests of individual sum rules for the proton and neutron will be made. Measurements of these quantities will make it possible to test further nucleon models and to explore the contribution of quark spins to the nucleon spin.

The full proposal, including an updated list of the Spin Muon Collaboration (SMC), is given in Appendix B and the Memorandum of Understanding between CERN and our SMC Collaboration is given in Appendix C. The basic reference on the EMC polarization experiment is the full report of the EMC experiment.[1]

In addition, in NA47 an initial, exploratory measurement of the second spin dependent structure function g_2, or of the spin dependent asymmetry A_2, will be made. As yet there is no experimental information on A_2 or g_2. Measurements of asymmetries with a longitudinally polarized muon beam and transversely polarized nucleons are required. Our apparatus is capable of doing this measurement.

NA47 has been approved for 220 days of beam time and the CERN SPSC program committee has estimated that three years of running (probably 1991, 1992 and 1993) will be required to obtain the data. As mentioned above experimental checkout and initial data-taking with a polarized deuteron target took place in a 120 day run in Spring and Summer 1991.

If NA47 progresses well, we anticipate that SMC will make a proposal, probably late in 1992, to do a dedicated measurement of A_2 (or g_2). This data-taking will require at least 1 year of running time, which we anticipate would occur in 1994. One or two years for concluding analysis and write-up of publications will be required subsequently in 1995 and 1996. Hence we expect rather firmly a very active and productive program for SMC for about the next five years.

Yale Responsibilities in NA47

Hughes is Spokesman for experiment NA47 and has major coordination duties for this large experiment and large group (~141 physicists and 25 institutions). The Yale responsibility and effort in the development of the apparatus for the experiment is in the NMR measurement of the proton and deuteron polarization of the polarized target. The NMR system to be used in the major experimental run this summer (1991) is completed and installed on the polarized target. A more sensitive and accurate measurement system using pulsed NMR is under development for future runs. A fuller account of the status and future plans for the NMR system is given later.

About six physicists from Yale will participate actively in the experiment at CERN. We are planning, as for the EMC experiment, a major effort in the off-line analysis and physics interpretation of the experiment.

Review of Status

A brief summary of our achievements in 1991 included in the CERN 1991 Annual Report on Experiments follows.

> The NA47 experiment of the Spin Muon Collaboration (Bielefeld, UCLA, CERN, Freiburg, GKSS Geesthacht, Helsinki, Houston, JINR Dubna, Mainz, Mons, Munich, Nagoya, NIKHEF, Northeastern, Northwestern, Rice, Saclay DAPNIA, Santiago, Tel Aviv, Trieste, Uppsala, Virginia, Warsaw, Yale) will determine the spin-dependent structure function $g_1(x)$ for the proton and the neutron. For a momentum transfer $Q^2 > 1$ GeV^2 the measurements will cover the range $0.005 < x < 0.7$ of the Bjorken scaling variable and thus extend to very low values of x. This is essential for a reliable evaluation of the sum rules. In particular a test of the fundamental Bjorken sum rule for the integral $\int_0^1 [g_1^p(x) - g_1^n(x)]$ to about 10% should be achieved. Also the individual sum rules for the proton and the neutron will be tested. These are related to the internal spin structure of the nucleon.
>
> The experiment measures the asymmetries in deep inelastic scattering of longitudinally polarized muons by longitudinally polarized protons and deuterons.

Updated Name List 31.3.92

CERN/SPSC 88-47
SPSC/P242
22 December 1988

MEASUREMENT OF THE SPIN-DEPENDENT STRUCTURE FUNCTIONS OF THE NEUTRON AND PROTON

The Spin Muon Collaboration (SMC)

University of Bielefeld
G. Baum, S. Bültmann, W. Thiel
University of California, Los Angeles
C. Dulya, M. Grosse-Perdekamp, G. Igo, S. Trentalange, C. Whitten
CERN
P. Hautle[1], T.O. Niinikoski, J.M. Rieubland, R. Voss
Delft University of Technology
H. Postma
University of Freiburg
A. Brüll, H. Engelien, R. Kaiser, H.J. Kessler, U. Landgraf, A. Witzmann
GKSS
W. Knop, H. Stuhrmann, R. Wagner
Helsinki University of Technology
P. Berglund, J. Kyynäräinen
University of Houston
K. Lau, B. Mayes, L. Pinsky, L. Pyrlik, D. Sanders, Y. Tzamouranis, R. Weinstein
JINR, Dubna
I.A. Golutvin, M. Kadykov, A. Karev, I. Kiryushin, Yu. Kisselev, V. Krivokhizhin,
V. Kukhtin, B. Neganov, D. Peshekhonov, D. Pose, I. Savin, S. Sergeev, G. Smirnov, Y. Yatsunenko
University of Mainz
D. von Harrach, E.M. Kabuss, G. Mallot, R. Seitz
University of Mons
R. Windmolders
University of Munich
L. Betev, C. Heusch, U. Mayer-Berkhout, A. Staude
Nagoya University
T. Hasegawa[2], N. Hayashi, N. Horikawa, S. Ishimoto[3], T. Iwata, A. Kishi, S. Okumi
NIKHEF, FOM and Free University, Amsterdam
M. Ballintijn, R.van Dantzig, M. de Jong, T. Ketel, L. Klostermann, G.van Middelkoop, J.E.J. Oberski, F. Sever
Northeastern University
E.von Goeler, J. Moromisato
Northwestern University
D. Fasching, D. Miller, R. Segel, P. Shanahan, M. Velasco
Rice University
D.L. Adams, S. Ahmad, B.E. Bonner, J. Buchanan, J. Clement, M.D. Corcoran, J. Cranshaw,
S. Eichblatt, T. Gaussiran, M. Lowe, H.E. Miettinen, G.S. Mutchler, J.B. Roberts
Saclay DAPNIA
G. Bardin, I.G. Bird, N. de Botton, J. Bystricky, C. Cavata, J.C. Faivre, F. Feinstein, B. Frois, F. Lehar,
A. de Lesquen, A. Magnon, F. Marie, J. Martino, F. Perrot-Kunne, S. Platchkov, T. Pussieux
University of Santiago de Compostela
B. Adeva, C. Fernandez, A. Gomez, C. Garabatos, J.A. Garzon, S. Lopez-Ponte, M. Plo,
M. Rodriguez, J. Saborido, A. Yanez
Tel Aviv University
J. Lichtenstadt, I. Sabo
University of Trieste
R. Birsa, F. Bradamante, S. Dalla Torre, M. Giorgi, M. Lamanna, A. Martin, A. Penzo,
G. Salvato, P. Schiavon, F. Tessarotto, A. Villari, A.M. Zanetti
Uppsala University
A. Arvidson, P. Björkholm, A. Dyring, S. Kullander, T. Lindqvist
University of Virginia
D. Day, J.-P. Chen, D. Crabb, J. McCarthy, J. Mitchell, O. Rondon
Warsaw University and Institute for Nuclear Studies
B. Badelek, J. Nassalski, E. Rondio, L. Ropelewski, A. Sandacz, W. Wislicki
Yale University
M. Bouteneur, Y. Butt, S. Dhawan, V.W. Hughes, R. Piegaia[4], P. Schüler

1 ETH
2 Miyazaki University
3 KEK
4 University of Buenos Aires

Spokesman: V.W. Hughes
Contactman: G. Mallot

The apparatus is the upgraded forward spectrometer which was designed by the European Muon Collaboration and later improved by the New Muon Collaboration. In 1990-1991 an upgraded version of the polarized target originally built by the EMC for the NA2'–experiment was installed and successfully operated with deuterated butanol in 1991. In this configuration a considerable amount of data on the deuteron was obtained for the first time. A major polarimeter to measure the polarization of the muon beam is operating as part of the experiment.

For 1992 measurements are planned with the same polarized target configuration as used in 1991 using both a deuteron and a proton polarized target. For 1993 a new polarized target with higher field homogeneity, larger cooling power and longer target sections is under construction. Additional data will be taken on $g_1(x)$. An additional dipole coil will provide the possibility of transverse polarization. This will allow an exploratory measurement of the second spin-dependent structure function $g_2(x)$ which involves quark-gluon-correlations.

A particularly notable achievement in the 1991 run was the observation of an excellent thermal equilibrium NMR signal for the deuteron. This was due largely to the reduction of the noise in the RF Q-meters provided by Yale, which had the special feature of using temperature controlled NMR at a temperature where the cable dielectric constant is stable.[2] One of these NMR thermal equilibrium signals obtained is shown in Fig. 1a; it is of a quality that does not appear to have been reported yet in the literature. With this calibration signal measurement of the deuteron polarization to 3 to 5% has been achieved as was projected in our CERN proposal. Fig. 1b shows an enhanced deuteron signal corresponding to a polarization of about 26%.

During about 4 weeks of successful data-taking in 1991 some 10^6 scattered events were obtained with our polarized deuteron target, which is comparable to the number of events obtained in the entire EMC experiment with a polarized proton target.

Reports on the status of NA47 are given in conference papers appended (Igo and Hughes,[3] (Appendix D) Mallot[4] (Appendix E).

Activities Planned in Coming Years

Active analysis of our 1991 data is in progress. A major data-taking run of some 140 days will start May 21, 1992 and continue until approximately the end of November, 1992. In our 1992 run the so-called EMC configuration of our polarized target will be used. Data on both the deuteron and the proton are planned. The combination of the 1991 and 1992 data should provide a result on the first moment of the proton spin dependent structure function $\Gamma_1(p)$ with considerably improved statistical and systematic errors as compared to the EMC result. With the deuteron and proton data we should test the fundamental Bjorken sum rule for the first time to about 15%.

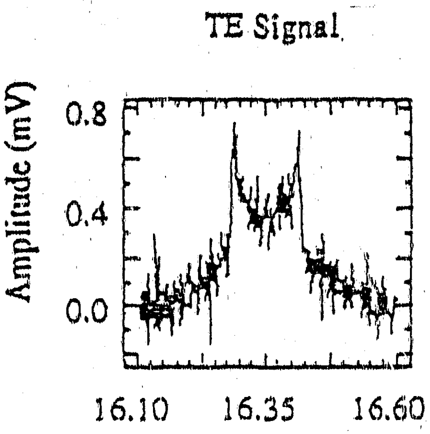

Fig. 1a: Thermal equilibrium deuteron signal averaged with 2000 sweeps with baseline subtraction.

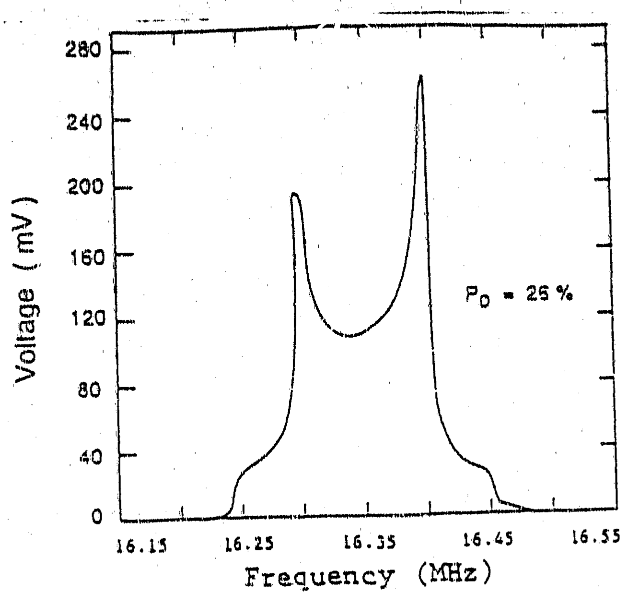

Fig. 1b: Signal for enhanced positive deuteron polarization.

The so-called SMC target configuration is now being actively developed and it is planned to use it in 1993 and subsequently. It will involve a new magnet system consisting of a solenoid/dipole and a major new dilution refrigerator. Its advantages are indicated in the accompanying Table 1.

SMC plans for data-taking are given in Table 2.

Table 1: The New SMC Polarized Target

Principal New Components

(1) Solenoid-Dipole Magnet System
Solenoid: B = 2.5 T
$\frac{\Delta B}{B} < 2 \times 10^{-5}$
Active Region : 1.5 m length, 5 cm diam.
Dipole : B = 0.5 T

(2) Dilution Refrigerator
Operating Temperature Without Heat Load; 50 mK
Cooling Power, 2 W at 0.5 K

Operating Features as a Polarized Target

	SMC	EMC
(1)	$P_p \geq 0.8$ $P_d \cong 0.4$	$P_p = 0.75$ $P_d = 0.25$
(2) Polarization Reversal		
	By field rotation	By change in microwave frequency
	Time required, 1/2 hr	Time required, 1 to 2 hrs
(3)	Length = 120 cm	Length = 80 cm
(4) Transverse Polarization in Frozen Spin Mode		
	Possible with Dipole Field	Not Possible

TABLE 2: SMC Plans for Data-Taking

1992

EMC polarized target
Deuteron target (from late May to mid-September)
Proton target (from late September through until approximately end of November)

Projected data on A_1
(1) For deuteron about 1/4 of data projected in original SMC proposal.
(2) For proton number of events about 2 x that of EMC experiment. Lower systematic errors.
(3) Test of Bjorken sum rule to about 15 to 20%.

1993

SMC polarized target

Both deuteron and proton data on A_1. Complete proton A_1 measurement.
Start as soon after mid-April as SMC target is operating and continue as long as CERN operates, perhaps until late Fall.

1994

Continue deuteron A_1 measurement with SMC polarized target.

Exploratory measurement of A_2 (proton).

1995

Perhaps measurement of A_2 (proton) and A_2 (neutron) with SMC polarized target.

Some initial results of the off-line analysis are now beginning to become available from our 1991 data with the polarized deuteron target. Figure 2 shows the momentum distribution of the incident μ^+ beam centered about 100 GeV. Figures 3a, 3b, 3c and 3d display the distribution of some reconstructed events in x, Q^2, θ and x_{vertex} respectively. Figure 4 gives a joint distribution of reconstructed events in x and Q^2. Figure 5 gives the distribution in events along the beam direction and shows that events from the upstream and downstream halves of the target are well resolved. Finally Figure 6 shows preliminary values of the virtual photon-proton asymmetry A_1 for the 90K reconstructed events obtained with the polarized deuteron target in 30 hrs of data-taking. The statistical error is dominant.

By now off-line analysis has been organized so that within two weeks after the end of a two week data run the reconstructed events including their kinematics are available for the so-called physics analysis. This major and important reduction in off-line analysis time has been achieved with the addition of major computer power in SMC equipment and also of computer power available to us from CERN.

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3. *Experiments on Nucleon Spin-Dependent Structure Functions* G. Igo and V.W. Hughes, **Particles & Fields '91** ed. by D. Axen (World Scientific, 1992) p. 593.

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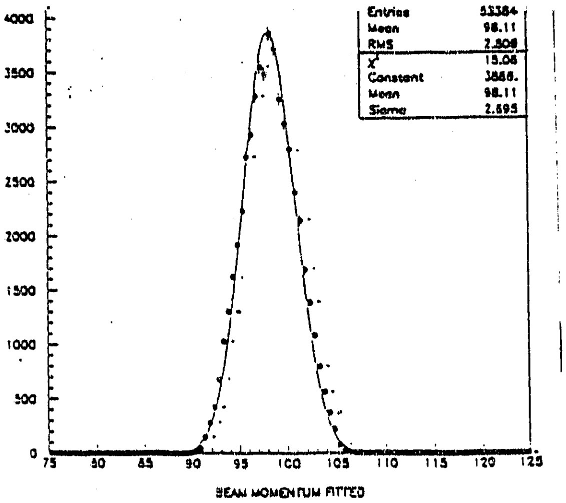

Figure 2:

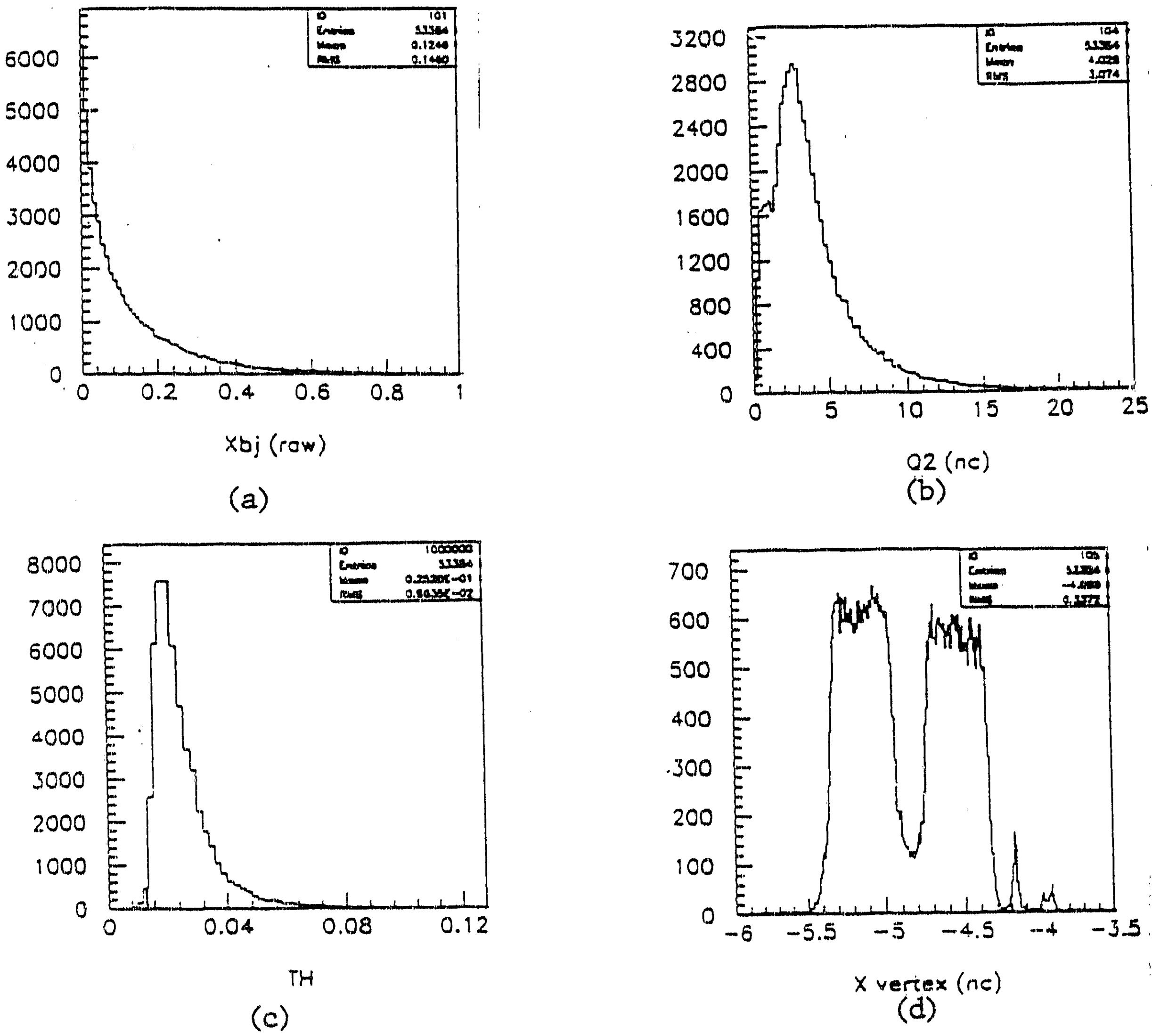

Figure 3:

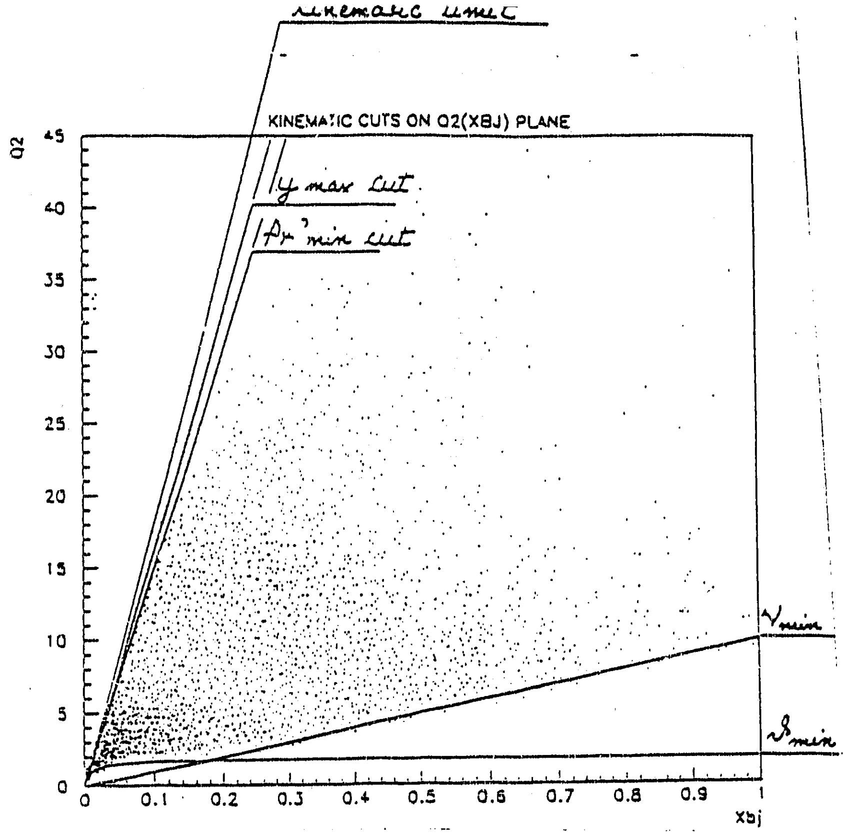

Figure 4:

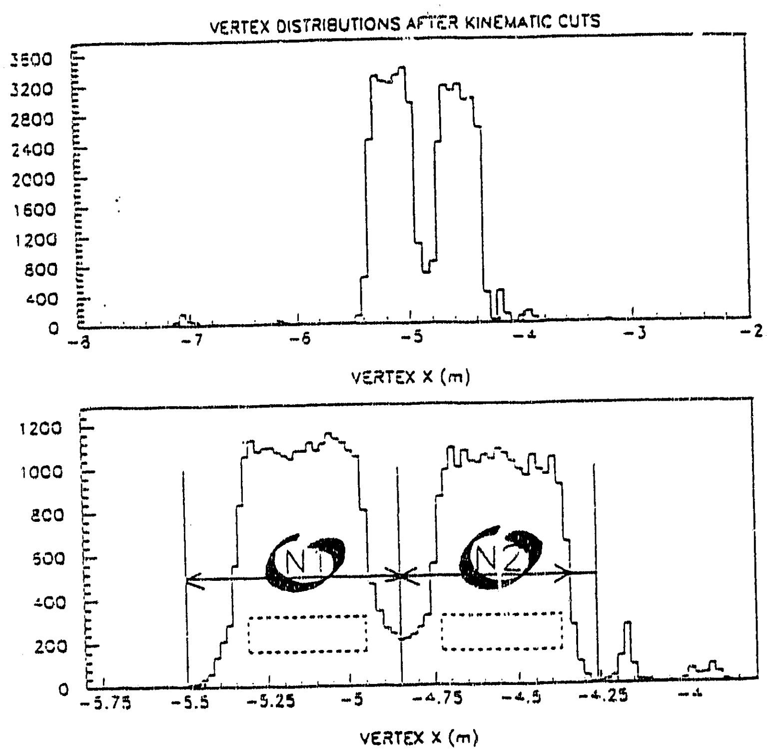

Figure 5:

Runs	72 — 91 13 h data t.		112 — 131 17 h data t.	
Events	~ 45 k		~ 45 k	
P_{target}	+0.19	−0.17	−0.17	+0.18
$\sigma(P_t)$	3%			
P_{beam}	0.80			
$\sigma(P_b)$	5 %			
dil. fac.	0.19			
$\sigma(f)$	2 %			

4 BINS OF X_{Bj}:

$x < 0.03$
$0.03 < x < 0.08$
$0.08 < x < 0.18$
$x > 0.18$

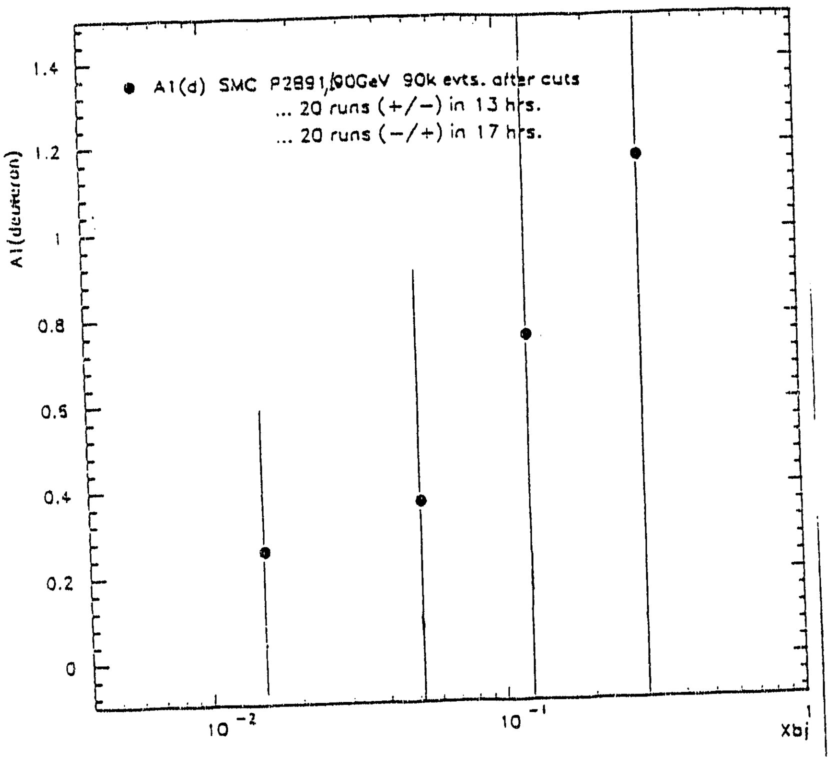

Fig. 6:

B. MUONIUM

B.1 Review of Research

The Yale group has been involved for many years in research in muon physics, particularly in studies of muonium, the μ^+e^- atom. Indeed the discovery of muonium was made by our group in an early experiment at the Columbia Nevis Labortory in 1960 following the discovery of parity non-conservation in the weak interactions which mediate the $\pi \rightarrow \mu \rightarrow e$ decay chain. Since then extensive experimental studies of the fundamental properties of muonium have been made by our group, first at Nevis until about 1970 and then principally at LAMPF with the Heidelberg group up to the present time.

The primary focus of our research has been the quantum electrodynamics of muonium, including the hyperfine structure $\Delta\nu$ and Zeeman effect in the ground n=1 state, the fine structure and Lamb shift in the n=2 state, and the 1S $\rightarrow$ 2S energy interval. Another major topic has been the search for the spontaneous conversion of muonium to antimuonium, a process which would violate the additive law for muon number conservation. The 1S-2S transition experiment is being done at Rutherford-Appleton Laboratory led by our Heidelberg colleagues and the new $M \rightarrow \bar{M}$ search at PSI again led by our Heidelberg colleagues.

A brief review of Yale research in the field of muonium follows with references to our principal publications in this field, from an early article in Physical Review Letters in 1960 to 1992. A quite complete review of fundamental muonium research apart from the topic of muonium to antimuonium conversion is given in Ref. 31 which is appended.

Discovery of Muonium and Its Formation in Gases

The discovery of parity nonconservation in the $\pi \rightarrow \mu \rightarrow$e decay chain in 1957 made it possible to search for muonium formation. Muonium was discovered in 1960 through the observation of the precession of polarized muonium formed in argon gas.[1,7] It took three years to find muonium because it was not realized initially that an oxygen-free gas is required to avoid depolarization of muonium in electron spin exchange collisions with paramagnetic molecules.[4,5]

Careful studies of the fraction of muons stopping in a gas that form muonium were made later.[11]

Hyperfine Structure and Zeeman Effect of Muonium in Its Ground State

Microwave magnetic resonance spectroscopy experiments were done to measure the energy intervals in ground state muonium.[3] The first spectroscopic experiment was done shortly after the discovery of muonium[2] and has been followed by a long sequence of measurements by the Yale group (later the Yale-Heidelberg group) and subsequently also by the Chicago group. The latest and most precise measurement was made at Los Alamos by the Yale-Heidelberg group[20] and determined $\Delta\nu$ to 36 ppb and μ_μ/μ_p to 0.36 ppm.

Our future program includes as its main feature a more precise measurement of $\Delta\nu$ and of μ_μ/μ_p by a factor of 5 to 10. The importance of this measurement will be discussed in the next section.

Lamb Shift in the n=2 State

After the discovery of the formation of fast muonium ($\sim$ 10 keV) in vacuum by an electron capture reaction as a fast muon emerges from a foil,[18] it was possible to measure the Lamb shift[22,24,30] and fine structure[32] of the n=2 state by a microwave spectroscopy technique. The Lamb shift has been measured to about 1% and the fine structure to 0.1% in agreement with theory.

The 1S $\rightarrow$ 2S Transition

Using a pulsed muon beam from the RAL laboratory a laser spectroscopy measurement has been made of the 1S $\rightarrow$ 2S transition to about 3 parts in 10^8.[34] (Led by our Heidelberg colleagues) This determines the Lamb shift in the n=1 state to about 1%. A more precise measurement is being planned both to determine the Lamb shift more accurately and to measure the muon mass.

Muonium to Antimuonium Conversion

The spontaneous conversion of muonium (μ^+e^-) to antimuonium (μ^-e^+) would violate the additive law of muon number conservation. Such a violation has not yet been seen and would be in contradiction to the standard theory of particle physics.

The first search was made at Nevis by the Yale group[6] and the most accurate one to date was done at LAMPF by the Yale-Heidelberg group.[33]

This subject is reviewed in Ref. 29.

A new experiment is getting underway at PSI, led by the Heidelberg group and including the Yale group as well.

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B.2 Future Yale Experiments on Muonium

Brief Summary

There are the following three on-going and developing experiments in which we are involved:

1. Ultraprecise measurement of the hyperfine structure interval $\Delta\nu$ and of the Zeeman effect in ground state muonium at LAMPF. This experiment is led by the Yale group and will be the principal focus of our muonium research in the next three years.

   The goal of this approved experiment (LAMPF 1054) is to measure $\Delta\nu$ to 5 to 10 ppb and μ_μ/μ_p to 30 to 50 ppb, which would represent an improvement in precision by a factor of 5 to 10 as compared to the last most accurate measurement done at LAMPF by our group. The motivations for this improvement are strong and include the following:

   - Sensitive test of the QED theory of the bound state and of the behaviour of the muon as a heavy electron. T Kinoshita tells us that a new important term has been evaluated so that the QED calculation of $\Delta\nu$ is now known to 0.16 kHz rather than to 1 kHz (see Table 2 page 31).
   - Determination of the fine structure constant α to about 25 ppb which will make possible a test of the theory of g-2 for the electron without the need of using the condensed matter value for α.
   - Precise determination of the magnetic moment ratio μ_μ/μ_p which is a fundamental property of the muon. The quantity μ_μ/μ_p is also the basis of the determination of the muon mass. Furthermore, it is needed as a constant for the determination of $g_\mu - 2$ from the BNL muon g-2 experiment.

   The new experiment is based on the same general approach as our previous experiment. An improved measurement is now possible for several reasons as follows.

   (a) Use of a chopped muon beam, which has been developed at LAMPF, to achieve resonance line narrowing by observing only "old" muonium ($\sim$ a factor of 3 reduction in line width).

   (b) The μ^+ beam is more intense (~ 3) and with the use of an $\vec{E} \times \vec{B}$ separator the μ^+ beam is largely free of positrons, which will lead to an important increase in signal to background.

   (c) A major new MRI magnet with 1 ppm homogeneity, high stability when operating in the persistent mode, and a higher magnetic field is available and will be used.

Taken together these improvements will make possible the greater precision being sought.

2. More precise measurement of the 1S→2S transition in muonium by laser spectroscopy at RAL.[1] The goal of this experiment is to measure the transition to about 3 parts in 10^9 and hence determine the n=1 Lamb shift to 0.1% or m_μ/m_e to about $1/10^7$. In the longer term with a more intense pulsed muon source at LAMPF from the Proton Storage Ring a still more precise measurement could be made.

3. More sensitive search for muonium to antimuonium spontaneous conversion at PSI.[2]

The latter two experiments are being led by our Heidelberg colleagues and we are collaborating.

The next section is a short article to be published soon in a Workshop on the Future of Muon Physics ed. by K. Jungmann, G. zu Putlitz and V.W. Hughes. It includes a quite detailed discussion of the motivations, goals and techniques for future muonium experiments, including the ground state measurements. The article also discusses the muonium to antimuonium conversion. The 1S → 2S laser spectroscopy measurement is discussed in Ref. 1.

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Motivations, Goals and Techniques of Muonium Research

MUONIUM (To be published in **Workshop on the Future of Muon Physics** ed. by K. Jungmann, G. zu Putlitz and V.W. Hughes.)

Vernon W. Hughes
Yale University, New Haven, Connecticut 06520

1 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 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, as has also the study of muonium collisions in gases, muonium chemistry and muonium in solids.

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 weights" 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 interactions.

For quantum electrodynamics high energy experiments test the high energy or short distance limits of the theory, whereas low energy high precision experiments test higher order radiative processes characteristic of the renormalized QED field theory. At present the most important low energy tests of QED are the following:

(1) Electron anomalous magnetic moment[1,2]
or g_e-2 value ($a_e = \frac{g_e-2}{2}$)

(2) Lamb shift in hydrogen (n=2 state)[3,4]
$[S_L = E(2^2S_{1/2} - 2^2P_{1/2})]$

(3) Muonium hyperfine structure interval[5]
$\Delta\nu$ (n=1 state)

(4) Muon anomalous magnetic moment[6,7]
or g_μ-2 value ($a_\mu = \frac{g_\mu-2}{2}$)

In addition to the muonium hfs interval $\Delta\nu$ - (3) in the above list - muonium studies can make important contributions to the other tests as well. The experimental value for a_e is

$a_e(\text{exp}) = 1\ 159\ 652\ 188.4(4.3)$ x 10^{-12}(4 ppb),

and the theoretical value can be written

$a_e(\text{th}) = \frac{\alpha}{2\pi} + A_2(\frac{\alpha}{\pi})^2 + A_3(\frac{\alpha}{\pi})^3 + A_4(\frac{\alpha}{\pi})^4 + \cdots$

for which the A coefficients have been calculated. At present the most precise value for α to use to evaluate a_e(th) is obtained from condensed matter physics (quantum Hall effect and ac Josephson effect) with an accuracy of 24 ppb, and hence it relies on condensed matter theory. As will be discussed in Section 2, the more precise measurement of $\Delta\nu$ and of the Zeeman effect in the ground n=1 state of muonium being undertaken at LAMPF should determine α to about 25 ppb or better where only QED and atomic theory are involved.

The Lamb shift in the n=2 state (D. Yennie, in this volume) of hydrogen is one of the classic tests of QED. The experimental value is $S_L(\text{exp}) = 1057.845\ (9)$ MHz (9 ppm) and the theoretical value can be written:

$S_L(\text{th})$ = QED terms + proton structure term.

The proton structure term is proportional to the mean square radius of the proton $< r_p^2 >$ and contributes 140 ppm to $S_L(\text{th})$ with an uncertainty of 9 ppm arising from the error involved in the measurement of $< r_p^2 >$ by high energy elastic electron proton scattering. The error in $S_L(\text{th})$ is due principally to this uncertainty in the proton structure term. The experimental and theoretical values for S_L are in reasonable agreement, and hence until the proton structure term is better known a more sensitive test of QED can not be provided by the Lamb shift.

The muon anomalous magnetic moment or g_μ-2 value provides a precise test of QED and of the behaviour of the muon as a heavy lepton, and indeed because of the higher mass scale involved as compared to the electron can provide an important, sensitive test of electroweak theory and of speculative theories beyond the standard model (F. Farley, T. Kinoshita, B.L. Roberts, in this volume). Determination of g_μ-2 from the muon g_μ-2 experiment requires a value for the muon mass m_μ or equivalently of the muon to proton magnetic moment ratio μ_μ/μ_p. At present μ_μ/μ_p is determined from the measurement of the Zeeman effect and hfs in the muonium ground state with a precision between 0.15 and 0.35 ppm; the new LAMPF experiment should reduce this error to about 50 ppb.

An important general point can be emphasized in comparing tests of QED and of the electroweak interaction with hydrogen and muonium. The effects of strong interactions or hadronic structure, which can not yet be calculated from the basic theory of quantum chromodynamics, are at present limiting importantly the QED tests of the simplest ordinary one-and two-electron atoms including hydrogen and helium. On the other hand high precision spectroscopic measurements can also be made on muonium where no hadronic structure effects are present and very precise theoretical values can be evaluated. In principle the proton structure effects in hydrogen could be evaluated from measurements by laser spectroscopy on muonic hydrogen, μ^-p, but such experiments have not yet been successful.

The energy level diagrams for hydrogen and muonium are shown in Figure 1. Several of the very precise measurements of H energy intervals are listed below in Table 1.[8,9] The corresponding muonium measurements of considerably less precision are listed as well. For hydrogen the theoretical accuracy for $\Delta\nu$ is limited at the several ppm level by uncertainty in the contributions of proton structure and polarizability[4] and for the 1S-2S interval at 1 part in 2 x 10^{10} due to uncertainty about proton structure.

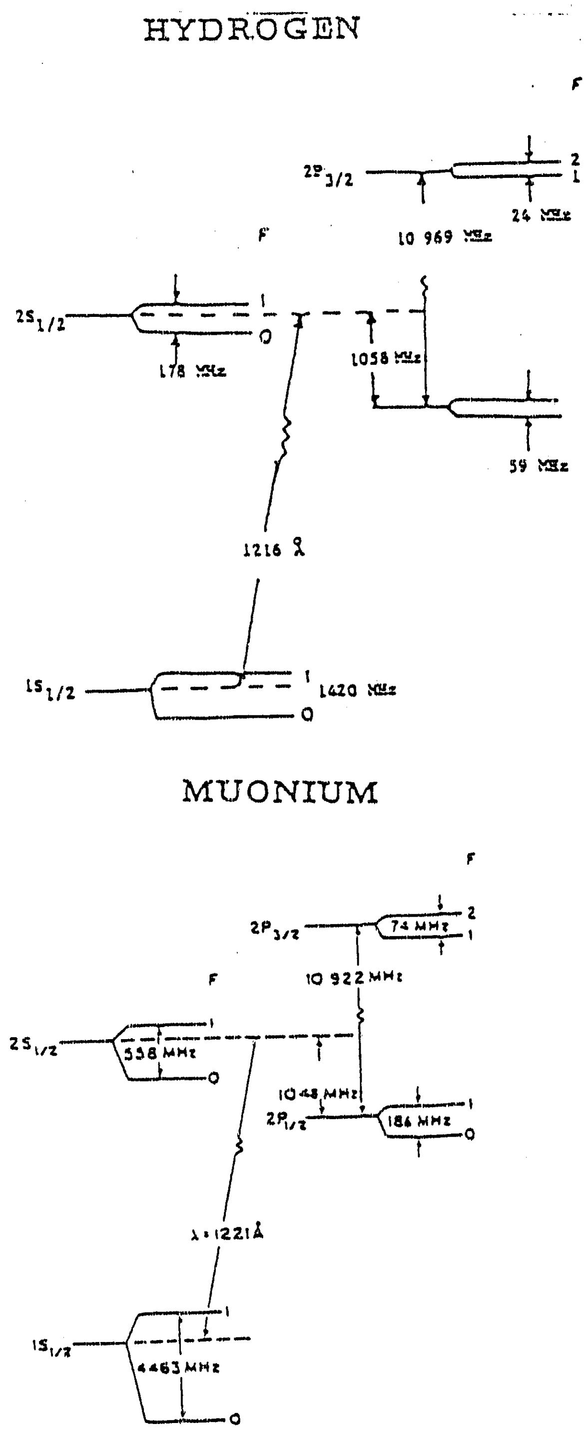

Figure 1: Hydrogen and Muonium energy level diagrams for n=1 and n=2 states.

TABLE 1
Precision Measurements

	Hydrogen	Muonium
$\Delta\nu$(n=1)	1 420.405 751 766 7 (9) MHz (7 parts in 10^{13})	4 463 302.88 (16) kHz (36 ppb)
ν(2S-1S)	2 466 061 414.1 (8) MHz (3 parts in 10^{10})	2 455 528 016 (72) MHz (3 parts in 10^{8})
$\nu(4P_{1/2} - 2S_{1/2})$	616 520 018.02(7) MHz (1 part in 10^{10}) (Determines R_∞)	not measure

The topics on muonium we shall discuss briefly below are the following:

1. Ground state hyperfine structure and Zeeman effect
2. Lamb shift and fine structure in the n=2 state
3. Muonium to antimuonium conversion

2 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. 2. 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 by both the Yale-Heidelberg and Chicago groups. The latest experiment at the Los Alamos Meson Physics Facility (LAMPF) was a strong field measurement.[10] A schematic diagram of the experimental arrangement is shown in Fig. 3. Typical resonance curves are shown in Fig. 4.

The experimental results for $\Delta\nu$ and μ_μ and the current theoretical value for $\Delta\nu$ are given in Table 2. The radiative and recoil corrections to the leading Fermi value for $\Delta\nu$ have been computed to high order.[4], [D. Yennie, in this volume.] The first error of 1.33 kHz or 0.30 ppm is due mostly to uncertainty in the value of the constant μ_μ/μ_p appearing in the Fermi term E_F. The second uncertainty comes from that of the α value used. The third uncertainty of 1.0 kHz is an estimate of uncalculated terms. Uncertainty in the small hadronic vacuum polarization contribution is less than 10 ppb. Weak neutral current

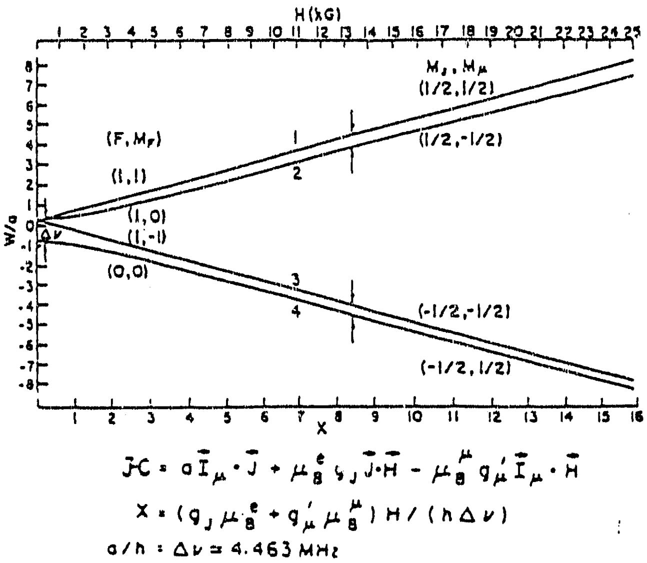

Figure 2: Breit-Rabi energy level diagram for muonium in its $1^2S_{1/2}$ ground state in a magnetic field. Several of the transitions measured are indicated by the arrows.

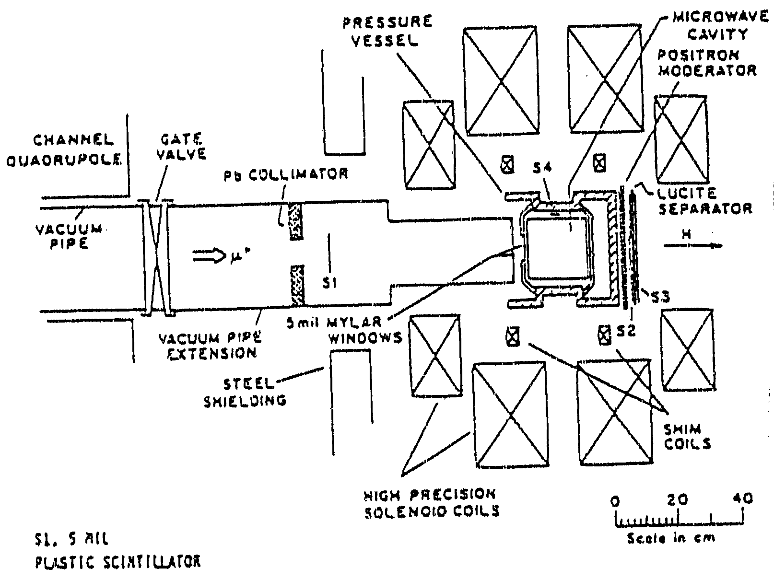

Figure 3: Experiment at LAMPF in which the latest precision measurement of the hyperfine structure interval $\Delta\nu$ in muonium was made.

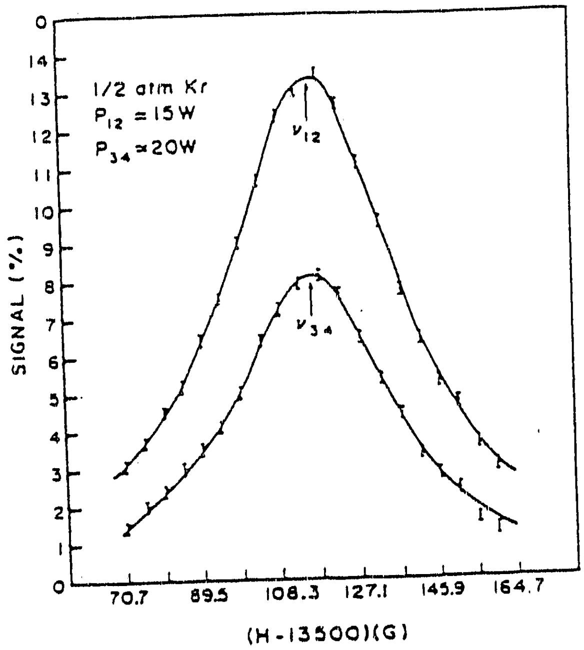

Figure 4: Resonance lines fitted to the data from the experiment shown in Fig. 3. P_{12} and P_{34} are input powers to the microwave cavity.

effects associated with Z exchange in the e-μ interaction are estimated to be 0.07 kHz or 16 ppb and are neglected. 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, in particular of the e-μ interaction in their bound state, and of the behaviour of the muon as a heavy electron. Figure 5 displays the history of the experimental precisions in the measurement of $\Delta\nu$ and of μ_μ/μ_p.

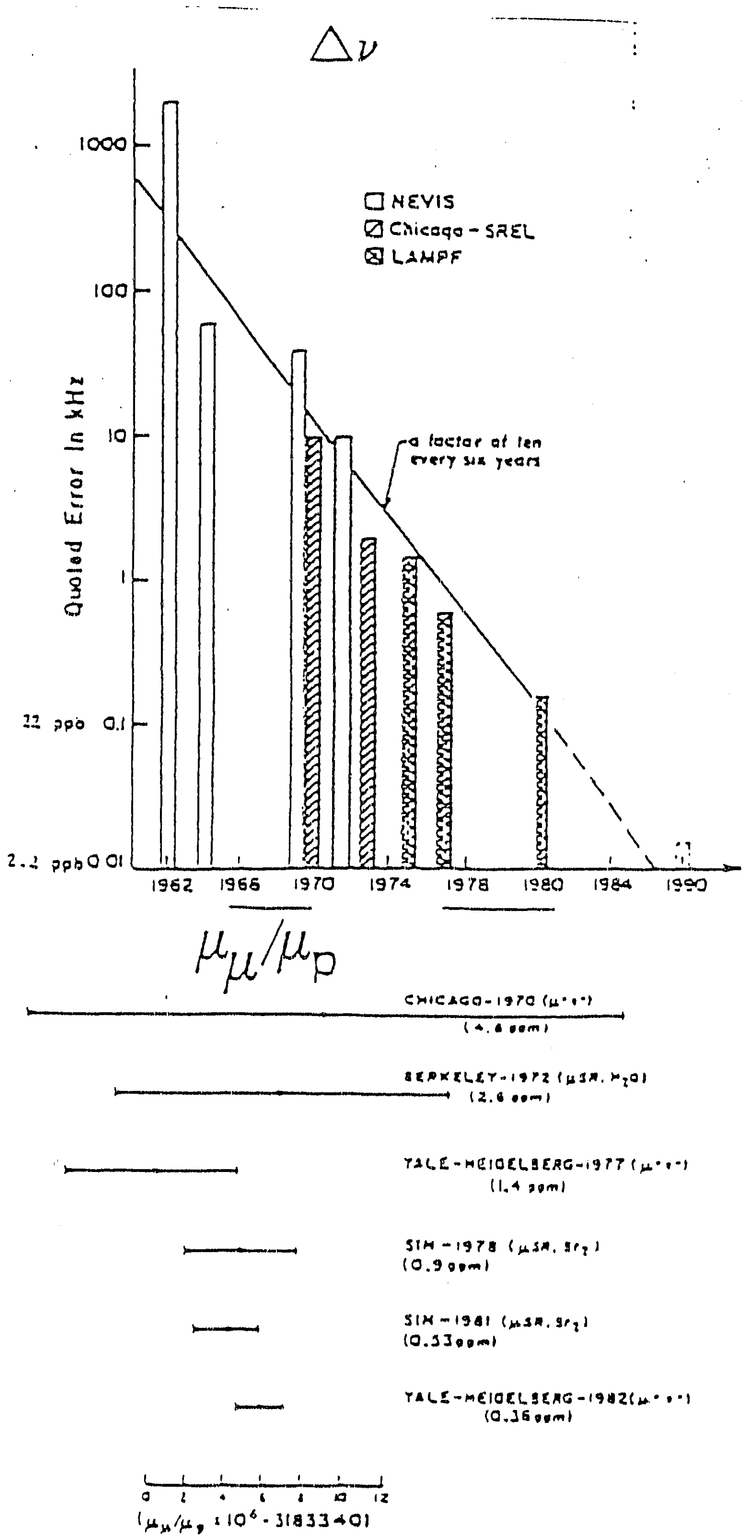

Figure 5: History of measurements of $\Delta\nu$ and of μ_μ/μ_p.

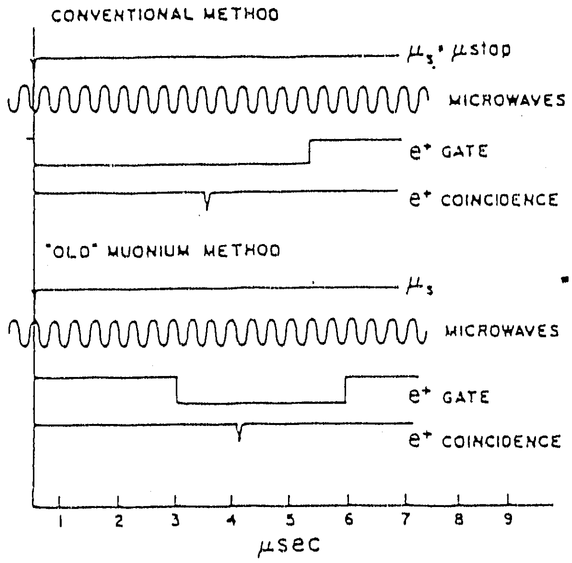

Figure 6: Line narrowing with a chopped muon beam.

TABLE 2

Theoretical Value for Hyperfine Structure Interval $\Delta\nu$ in Muonium Ground State

$$\Delta\nu = \frac{16}{3}\alpha^2 c R_\infty \left(\frac{\mu_\mu}{\mu_p}\right)\left(\frac{\mu_p}{\mu_B^e}\right)\left(1 + \frac{m_e}{m_\mu}\right)^{-3} \times$$

$$\left[1 + \text{QED terms } (\alpha, Z\alpha) + \text{Recoil terms } \left(\alpha \frac{m_e}{m_\mu}\right) + \text{Radiative-recoil terms } \left(\alpha^2 \frac{m_e}{m_\mu}\right)\right]$$

VALUES OF THE FUNDAMENTAL CONSTANTS

c = 2.997 924 58 × 10^{10} cm/sec (exact)
α^{-1} = 137.035 989 5 (61) (45 ppb)
R_∞ = 109 737.315 73 (2) cm^{-1} (0.2 ppb)
a_e = 1.159 652 193 (10) × 10^{-3} (9 ppb)
a_μ = 1.165 923 0 (84) × 10^{-3} (7.2 ppm)
μ_p/μ_B^e = 1.521 032 202 (15) × 10^{-3} (10 ppb)
μ_μ/μ_p = 3.183 345 5 (9) (0.3 ppm)
m_μ/m_e = 206.768 260 (60) (0.3 ppm)

$\Delta\nu$(th) = 4 463 303.11 (1.33) (0.40) (1.0) kHz (0.4 ppm)

(1.33) ↓ $\frac{\mu_\mu}{\mu_p}$; (0.40) ↓ α; (1.0) ↓ estimate uncalculated terms

$\Delta\nu$(exp) = 4 463 302.38 (0.16) kHz (0.036 ppm)
$\Delta\nu$(th) − $\Delta\nu$(exp) = 0.73 (1.7) kHz

$$\frac{\Delta\nu(\text{th}) - \Delta\nu(\text{exp})}{\Delta\nu(\text{exp})} = (0.05 \pm 0.4) \text{ ppm}$$

A new experiment is being undertaken at Los Alamos (LAMPF 1054) to measure $\Delta\nu$ and μ_μ/μ_p to precisions of 10 ppb and 50 ppb, respectively, thus reducing the present errors by a factor between 5 and 10. The general method of the experiment is the same as that discussed above. The measurement will be done at a strong magnetic field of about 17 kG and will use a high intensity clean muon beam. Resonance line narrowing using the old muonium technique is planned with the muon beam being chopped.

The old muonium method is indicated in Figure 6. A muonium atom will only be studied if it decays during the period of the e^+ gate and hence has lived at least until the time T when the gate is turned on after the arrival of the muon at time t=0. By contrast in the conventional method all muonium atoms are studied from time t=0 until the end of the period of the e^+ gate. In the conventional method the frequency half width of the resonance line is

$$\Delta f_{1/2} = [4\ |b|^2 + \gamma^2]^{1/2}/\pi$$

where $\gamma = 1/\tau_\mu$ (τ_μ = muon lifetime) and $|b|^2 \propto$ microwave power. In the limit of $|b|^2 = 0$, $\Delta f_{1/2} = \gamma/\pi = 145$ kHz; for $2\ |b|\ \tau_\mu = 1, \Delta f_{1/2} = 200$ kHz. In the old muonium method in the limit of $T >> \tau_\mu$ and $|b| << \gamma$, $\Delta f_{1/2} = 2|b|\ /\pi$; with $T = 3\tau_\mu$ and $2|b|T = 1$, $\Delta f_{1/2} =$ 60 kHz.

Figure 7 shows a photograph of the magnet which is a superconducting solenoid magnet (originally designed and constructed by Oxford Magnet Technologies as a MRI magnet). The magnet has an inner bore at room temperature 1 m in diameter and 2.2 m in length. It will be surrounded by an iron shield consisting of two side walls and two endcaps. It will be operated in persistent mode with a field of about 1.7 T. The magnet will be shimmed to a homogeneity of better than 1 ppm over a 20 cm diameter spherical volume, and in persistent mode operation should be stable to about 1 part in 10^8 per hour. Knowledge of the magnetic field to about 0.1 ppm in absolute value over the volume of the microwave cavity will be obtained by pulsed NMR with a H_2O probe which is calibrated against a standard spherical H_2O probe. Modulation of the magnetic field by about 200G to sweep through the resonance line will be provided by an additional pair of solenoidal coils located inside of the main solenoid and operated at room temperature.

Figure 8 shows the beam line from the output of the stopped muon channel at LAMPF into the solenoid where muonium is formed and studied. An $\vec{E} \times \vec{B}$ separator largely removes positrons from the beam, the ratio e^+/μ^+ being about 0.05 for a muon beam momentum p_μ = 25 MeV/c. An important element in the beam line is the electrostatic chopper which when pulsed on deflects the μ^+ beam out of its trajectory so that no μ^+ beam arrives at the gas target. The electrostatic kicker can provide voltages of +20kV and -20kV on two parallel plates spaced by 10 cm and 100 cm in length. The rise and fall times of the pulse are about 100 ns and the pulse repetition rate can be as high as 100 kHz with a variable width pulse. The muon extinction factor was measured to be about 0.03. The muon beam is deflected from its initial direction from the stopped muon channel by a dipole magnet to enter the gas target in the solenoid; this deflection should remove further background from the beam.

A more precise theoretical value for $\Delta\nu$ of muonium in its n=1 state should soon be available for comparison with the improved experimental value. (D. Yennie, in this vol-

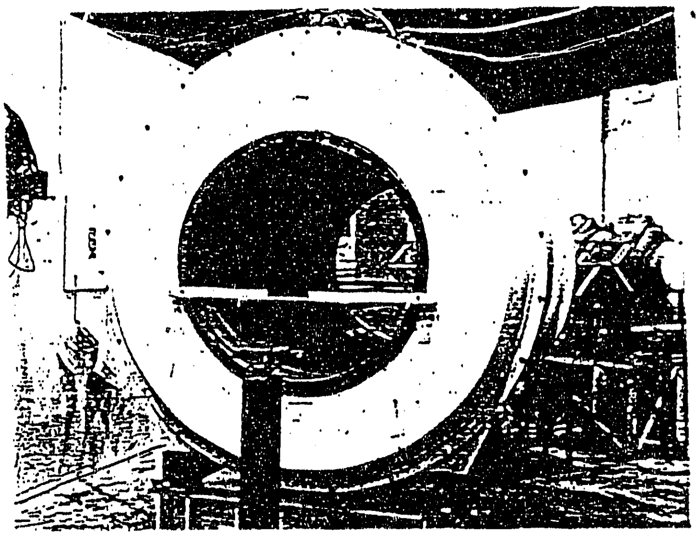

Figure 7: Photograph of the superconducting solenoid magnet.

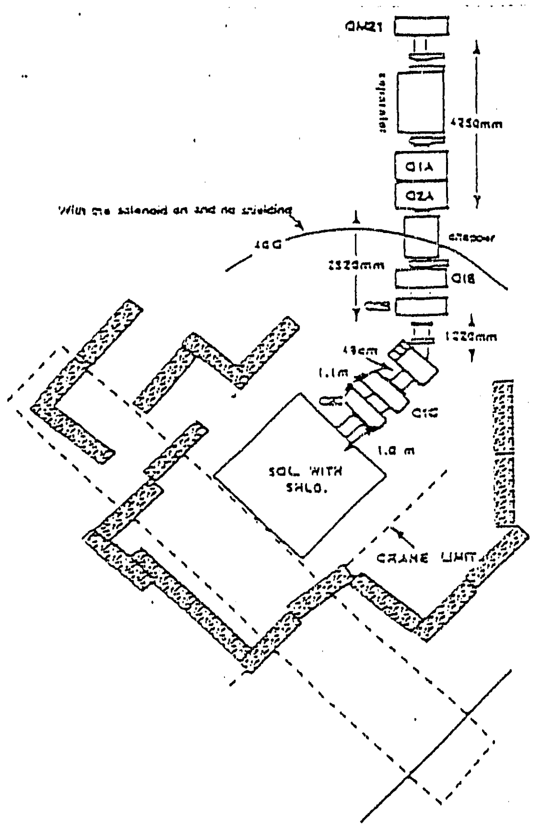

Figure 8: Muon beam line from stopped muon channel to LAMPF experiment on muonium ground state.

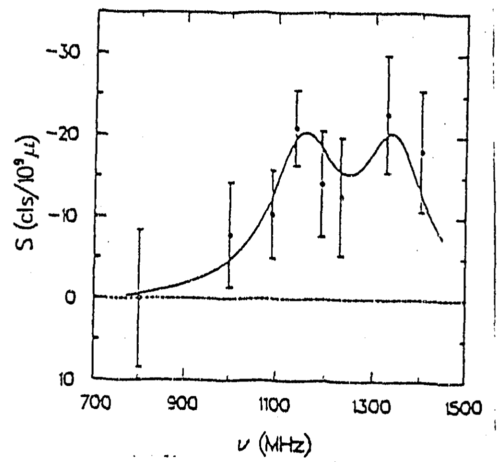

Figure 9: Microwave-resonance data and the best fit theoretical line shape.

ume). If instead of the α value from the 1986 Adjustment of the Fundamental Constants used in Table 2 a more recent value based on the electron g-2 value is used[11] then the uncertainty in $\Delta\nu$(th) associated with α is reduced to less than 20 ppb. Theoretical calculation of additional higher order terms are in progress (T. Kinoshita, private communication) which should reduce the error associated with uncalculated terms to about 20 ppb.

Clearly combination of the expected improved experimental values for $\Delta\nu$ and μ_μ/μ_p with an improved $\Delta\nu$(th) will provide a more sensitive test for muonium $\Delta\nu$ and could determine α to about 25 ppb.

In the future still more precise measurements of the muonium ground state would be possible if a more intense pulsed muon beam from the proton storage ring at LAMPF became available (H. White, in this volume).

3 Lamb Shift in Muonium

With the development of a fast muonium beam in vacuum,[5] measurement of the Lamb shift in muonium became possible. The energy level diagram of the n=1 and n=2 states of muonium is shown in Fig. 1. Two measurements[12,13] have determined the Lamb shift S_L in the n=2 state by observing the $2^2S_{1/2}$ to $2^2P_{1/2}$ transition in a radiofrequency spectroscopy experiment.

The method of the experiments is similar to that of the observation of the fine structure transition $2^2S_{1/2}$ to $2^2P_{3/2}$ discussed below. The resonance line observed in the LAMPF experiment[13] is shown in Fig. 9 in which the lower frequency component corresponds to the transition $2S_{1/2}(F=1)$ to $2P_{1/2}(F=1)$ and the upper to $2S_{1/2}(F=1)$ to $2P_{1/2}(F=0)$.

Table 3 gives the current theoretical value of S_L and the two experimental values. The theoretical value for the muonium Lamb shift differs from that in hydrogen by the

TABLE 3
Muonium Lamb Shift Theoretical Value

Contribution	Order (mc^2)		Value(MHz)
Self-energy	$\alpha(Z\alpha)^1[ln(Z\alpha)^{-2}, 1, Z\alpha, \cdots]$		1085.812
Vacuum polarization	$\alpha(Z\alpha)^4(1, Z\alpha, \cdots)$		-26.897
Fourth order	$\alpha^2(Z\alpha)^4$		0.102
Reduced mass	$\alpha(Z\alpha)^4(m_e/m_\mu)[ln(Z\alpha)^{-2}, 1]$		-14.493
Relativistic recoil	$(Z\alpha)^5(m_e/m_\mu[ln(Z\alpha)^{-2}, 1, Z\alpha]$		3.159
Higher-order recoil	$(Z\alpha)^4(m_e/m_\mu)^2$		-0.171
Radiative recoil	$\alpha(Z\alpha)^5 m_e/m_\mu$		-0.022
		Total	1047.490(300)

The uncertainty in the theoretical value is due to uncalculated terms of higher order in m_e/m_μ, i.e., terms (m_e/m_μ) (reduced mass term) and α(reduced mass term).

....

Experimental Value

$$S_L(exp) \;\; \begin{aligned} &= (1054 \pm 22) \text{ MHz, LAMPF} \\ &= (1070^{+12}_{-15}) \text{ MHz, TRIUMF} \end{aligned}$$

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.[14] Figure 10 indicates the experimental method. Muonium is formed in the metastable $2^2S_{1/2}$ state at an $A\ell$ 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 $2^2S_{1/2} \to 2^3P_{3/2}$. 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. 11 as a function of the microwave frequency, together with the fitted line shape. Three resonance transitions are involved,

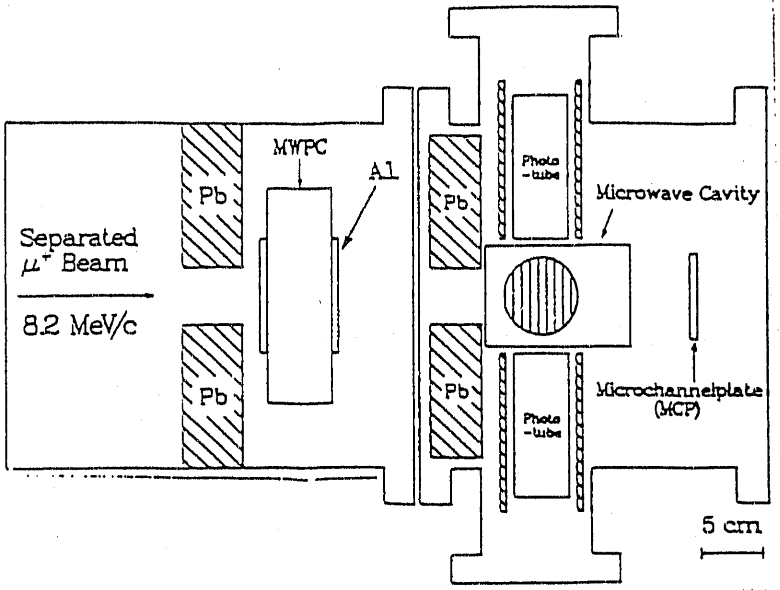

Figure 10: Diagram of the apparatus used in observation of the muonium fine structure transition $2^2S_{1/2} \to 2^2P_{3/2}$.

but they are not resolved. From the lowest to the highest frequencies these transitions are $2S_{1/2}$(F=1) to $2P_{3/2}$(F=1), $2S_{1/2}$(F=1) to $2P_{3/2}$(F=2) and $2S_{1/2}$(F=0) to $2P_{3/2}$(F=1) [Fig. 1]. Analysis gives the value 9783^{+35}_{-30} MHz for the transition frequency $2S_{1/2}$(F=1) to $2P_{3/2}$(F=2). Correcting for the hfs this gives the value 9895^{+35}_{-30} for the fine structure interval $2S_{1/2}$ to $2P_{3/2}$ in agreement with the theoretical value of 9874.3(3) MHz. This $2S_{1/2}$ to $2P_{3/2}$ resonance can also be used to determine the Lamb shift assuming the theoretical value for the fine structure interval and gives $S_L = 1027^{+30}_{-35}$ MHz.

Future improvement in the accuracy of determining the Lamb shift and fine struture interval in the n=2 state could be considered using the $2^2S_{1/2}$ to $2^2P_{3/2}$ transition. It should involve the suppression of the first-order 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 direction of the incident μ^+ to reduce the background associated with energetic μ^+[15], and use of UV photon detectors with higher acceptance and efficiency (perhaps using highly reflecting UV mirrors and a small photon gas counter). With these features the experiment might determine S_L to about 0.1%.

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. Fundamentally we need a major increase in the phase- space density of μ^+ beams (L. Simons, P. Taqqu, in this volume).

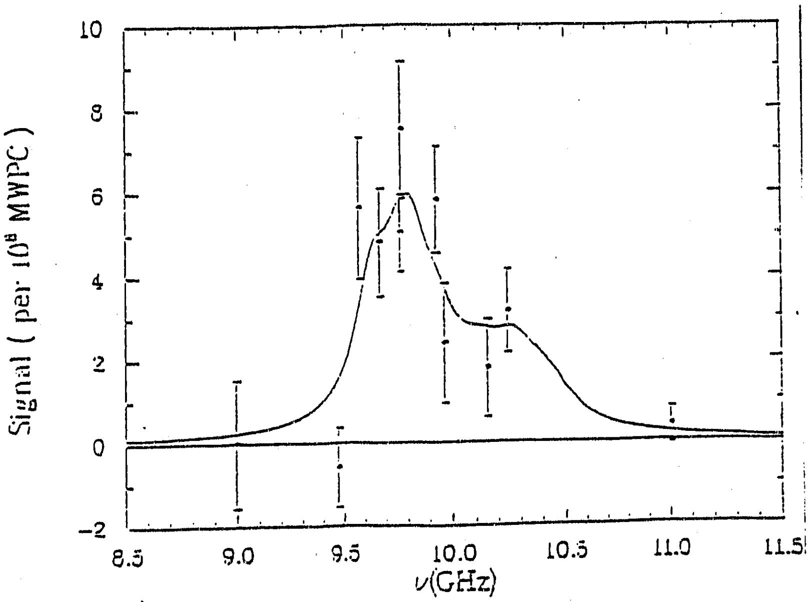

Figure 11: Muonium $2S^2_{1/2} - 2P^2_{2/3}$ transition showing data and a best fit theoretical line shape.

4 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 or obey independent conservation laws of muon number, (L_μ = +1(-1) for $\mu^-(\mu^+)$ and for $\nu_\mu(\bar{\nu}_\mu)$, 0 for other particles) and of electron number (L_e = +1(-1) for e-(e^+) and for $\nu_e/\bar{\nu}_e$, 0 for other particles) as required in the standard theory. 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 and to physics beyond the standard model. Speculative modern theories which seek a more unified theory of particles and their interactions, such as the left-right symmetric theory, predict muon number violating processes. Figure 12 shows possible processes allowed in the left-right symmetric theory (R. Mohapatra, P. Herczeg, in this volume). As yet no such rare decay process has been observed, (H.K. Walter, in this volume) 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, and like neutrinoless double beta decay would involve $\Delta L_e = 2$. The M-$\bar{M}$ system also bears some relation to the $K^\circ - \bar{K}^\circ$ system, since the neutral atoms M and $\bar{M}$ are degenerate in the absence of an interaction which couples them.

Usually the M to $\bar{M}$ conversion is discussed with the following postulated Hamiltonian which is of the four-Fermion, V-A type with the coupling constant $G_{M\bar{M}}$.

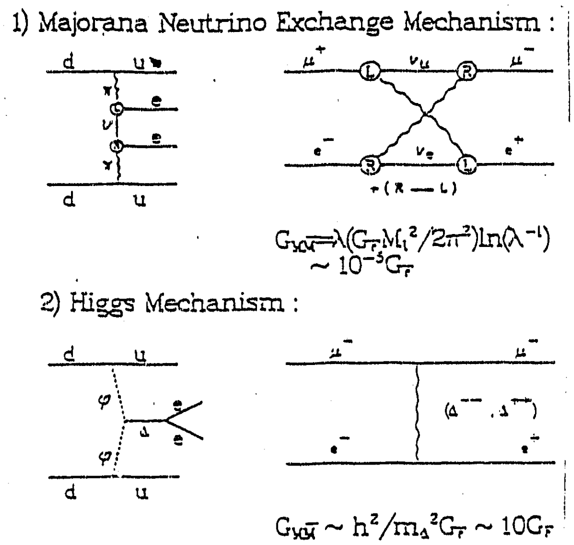

Figure 12: Majorana neutrino exchange mechanism: Higgs mechanism.

$H_{M\bar{M}} = \frac{G_{M\bar{M}}}{\sqrt{2}} \bar{\mu}\gamma^{\lambda}(1-\gamma_5)e\bar{\mu}\gamma_{\lambda}(1-\gamma_5)e$ + h.c.
where standard notation is used. The M→ $\bar{M}$ conversion violates the additive laws of muon and electron number conservation, but satisfies the multiplicative laws of muon and electron conservation for which $(-1)^{\sum L_\mu}$ = constant and $(-1)^{\sum L_e}$ = constant. The probability P($\bar{M}$) that a muonium atom formed at t=0 will decay from the $\bar{M}$ form due to the action of the Hamiltonian $H_{M\bar{M}}$ is given by:

$P(\bar{M}) = 2.5 \times 10^{-5} \left(\frac{G_{M\bar{M}}}{G_F}\right)^2$

where G_F is the Fermi coupling constant.

Thus far no spontaneous conversion of M→ $\bar{M}$ has been observed and the most sensitive search was done at LAMPF[16] with the apparatus shown in Fig. 13. Thermal muonium is formed by μ^+ stopped in a SiO_2 powder target and diffuses out into vacuum. The signal for an M→ $\bar{M}$ conversion would be a coincident high energy $e^-(\geq 30$ MeV) from a μ^- decay detected with the high energy spectrometer arm and a low energy atomic $e^+(\sim 10$ eV) detected with the low energy spectrometer arm. No candidate events were observed and the limit
$G_{M\bar{M}} < 0.16\ G_F$ (90% C.L.) was established. The history of the limits on $G_{M\bar{M}}$ in the various experimental searches since 1968 are shown in Fig. 14.

A new search for the M→ $\bar{M}$ conversion is being undertaken at PSI.[17] The method is the same as the latest LAMPF experiment just discussed and the experimental setup is shown in Fig. 15. The cw beam at PSI will be used and the spectrometer has a large solid angle and will also require the observation of the 2γ annihilation of e^+. The goal is a sensitivity $G_{M\bar{M}} \simeq 10^{-3} G_F$.

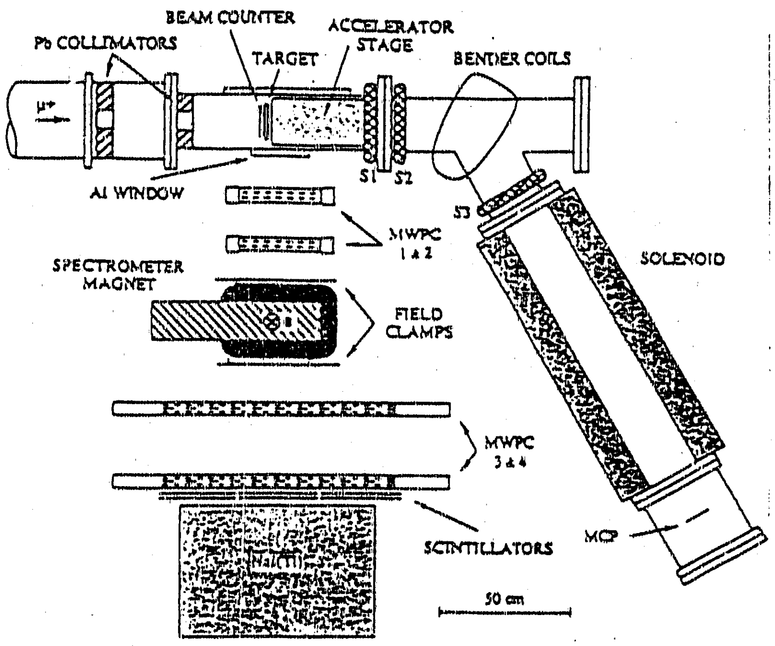

Figure 13: Top view of the experiment to search for $M \to \bar{M}$ conversion at LAMPF.

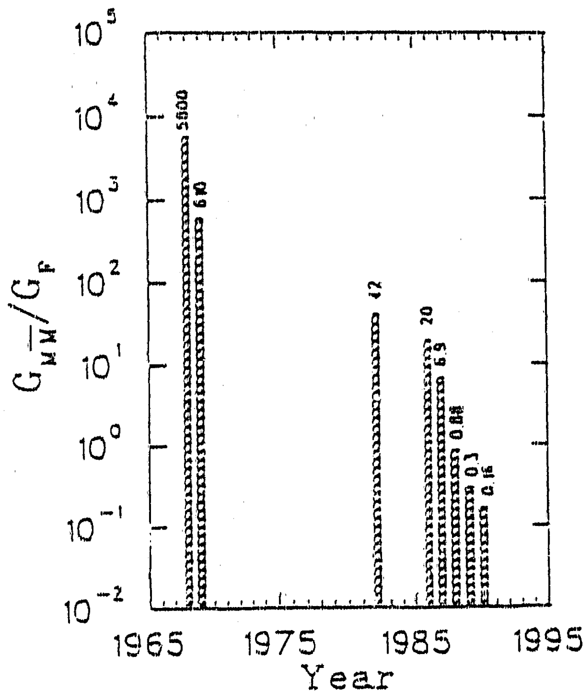

Figure 14: History of experimental upper limits on $G_{M\bar{M}}$.

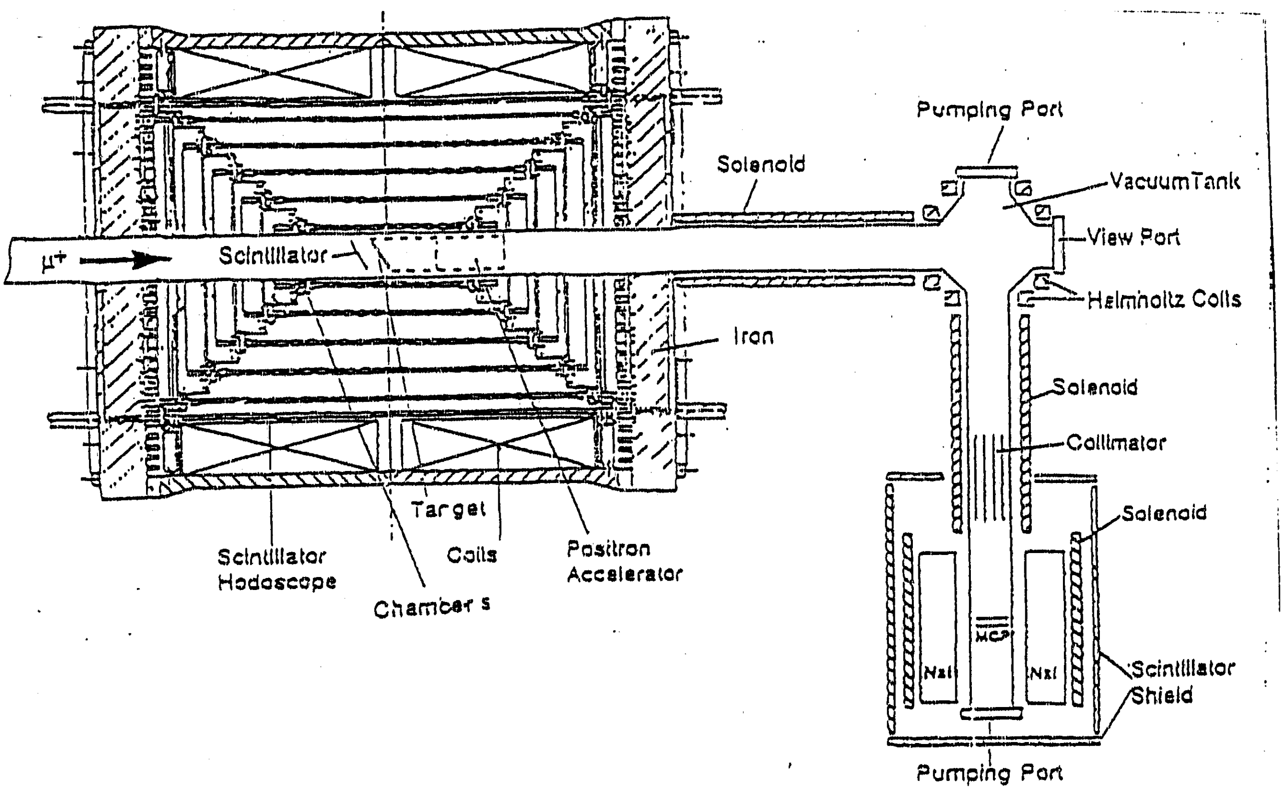

Figure 15: MAC's a new Muonium to Antimuonium Conversion Spectrometer.

5 Summary

Table 4 summarizes our present knowledge of muon properties.

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.

TABLE 4
Muon Properties

MASS

$$\frac{m_{\mu^+}}{m_e} = 206.768\,259(62)(0.3\text{ppm})$$

$$\frac{m_{\mu^-}}{m_e} = 206.765(10)(50\text{ppm})$$

SPIN

$$I_\mu = 1/2$$

MAGNETIC MOMENT

$$\frac{\mu_{\mu^+}}{\mu_p} = 3.183\,345\,47(95)(0.3\text{ppm})$$

$$\frac{\mu_{\mu^-}}{\mu_p} = 3.183\,4(9)(300\text{ppm})$$

G-VALUE

$$(g_{\mu^+}-2)/2 = 1\,165\,911(11) \times 10^{-9}(10\text{ppm})$$

$$(g_{\mu^-}-2)/2 = 1\,165\,937(12) \times 10^{-9}(10\text{ppm})$$

ELECTRIC DIPOLE MOMENT

$\mu_e \leq 7 \times 10^{-19}$ e-cm (95% confidence level)

STATISTICS

Fermi-Dirac

LIFETIME

$\tau_{\mu^+} = 2\,197.03(4)$ ns (18ppm)

MUON NEUTRINO MASS

$m_{\nu_\mu} < 0.25$ MeV

Rabi, *"Who Ordered That?"*
(the muon)

Research supported in part by DOE under contract DE-AC02-76ERO3075.

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Ultra High Precision Measurements on Muonium Ground State: Hyperfine Structure and Muon Magnetic Moment - LAMPF 1054

Participants in LAMPF 1054:

Spokesmen: V.W. Hughes (Yale), G. zu Putlitz (Heidelberg), P. Souder (Syracuse)

H. Ahn, M. Boshier, D. Ciskowski, S. Dhawan, X. Fei, V.W. Hughes, M. Janousch, W. Schwarz, W. Liu (Yale);
K. Jungmann, G. zu Putlitz, B. Matthias, postdocs and students (Heidelberg);
R. Homes, P. Souder, J. Xu (Syracuse);
C. Pillai, O. van Dyck (Los Alamos);
K. Woodle (Brookhaven).

Schedule for LAMPF 1054:

A run at LAMPF is scheduled for a ten day period in early September with some additional time to be available possibly in October. This run is an initial checkout of the majority of the experimental setup and will include checkout of our entire beam line with the chopper. We hope to reach the point of observing a resonance tranistion but will not be able to sweep through the resonance line until a field modulation coil has been obtained. In 1993 and 1994 (and possibly 1995) we plan to take our data.

B.3 Muon Beam Development at LAMPF

Review of Yale Contributions

Yale did the initial design of the stopped muon channel at LAMPF and then collaborated with LAMPF in its construction and testing.[1]

We also developed the surface[2] and subsurface[3] low momentum positive muon beams at LAMPF.

More recently for our present muonium experiment at LAMPF (LAMPF 1054) we developed and tested a chopped muon beam.[4] This development is discussed below.

Chopped Low Momentum μ^+ Beam

We have collaborated with LAMPF, particularly with C. Pillar of MP7, in the development of a chopped muon beam from the stopped muon channel (SMC). This has been achieved in recent tests with the muon beam at LAMPF in summer, 1990 using a 5 ft. $\vec{E} \times \vec{B}$ separator followed by a 3 ft. $\vec{E}$ chopper. The separator was used to produce a clean surface μ^+ beam of about 25 MeV/c with only small e^+ contamination ($< 1\%$ with separator voltages ± 70 kV) and subsequently the chopper either transmitted or rejected the μ^+ beam. The voltage across the chopper plates was 28 kV ($\pm$ 14 kV on the plates). The chopper operates up to a repetition rate of 100 kHz with variable on and off times and with 50 - 100 ns rise and fall times. Our studies were made with the μ^+ beam on (chopper voltage off) for 1 to 5 μs and with the μ^+ beam off (chopper voltage on) for 10 to 20 μs. With the chopper voltage on, the beam is reduced to 0.3% of its value with chopper voltage off. with 625 μA of H^+ on the A2 target and with the chopper off, 10^7 μ^+/sec at a momentum of 28 MeV/c with a spread of 8% were obtained at the end of our beam line. This was the expected value and is satisfactory for our muonium experiment (LAMPF 1054). Hence both the beam line configuration and chopping worked out satisfactorily.

A Pulsed Lepton Beam from the LAMPF Proton Storage Ring

We have been trying for many years to promote the idea of developing an intense pulsed muon beam for laser spectroscopy of muonic atoms as well as for many other applications. There is great interest in a pulsed neutrino beam from PSR as well. These two interests have been combined for a pulsed lepton facility.[5]

We helped organize and participate in a Workshop on a pulsed muon beam at PSR held at Los Alamos National Laboratory[6]. We are continuing to study and help LAMPF develop a proposal for such a pulsed lepton facility.

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2. *Summary.* V.W. Hughes, to be published in **Symposium on The Future of Muon Physics**, Heidelberg, May, 1991.

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1. *Search for Spontaneous Conversion of Muonium to Antimuonium Using Fast Muonium and the LAMPF Crystal Box Detector.* B. Ni et al., **Phys. Rev. D.**

2. *A Measurement of the $2^2S_{1/2}$-$2^2P_{3/2}$ Fine Structure Interval in Muonium.* S. Kettell et al., **Phys. Rev. A.**

3. *New Search for the Spontaneous conversion of Muonium to Antimuonium.* B.E. Matthias et al., **Phys. Rev. D.**

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