PAST, PRESENT AND FUTURE OF MUONIUM

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Muonium, the atom which consists of a positive muon and an electron, has been discovered by a team led by Vernon W. Hughes in 1960. It is in many respects the most ideal atom available from nature. Due to the close confinement in the bound state muonium can be used as an ideal probe of electro-weak interaction, including particularly Quantum Electrodynamics, and to search for additional yet unknown interactions acting on leptons. Recently completed experiments cover the ground state hyperfine structure, the 1s-2s interval and a search for spontaneous conversion of muonium to antimuonium. The experiments yield precise values for the fine structure constant, the muon mass and its magnetic moment. The results from these precision measurements have provided restrictions for a number of theories beyond the Standard Model of particle physics. Future precision experiments will require new and intense sources of muons.

1. Muonium - The Atom discovered by Vernon Hughes

Atomic hydrogen is generally considered the simplest and most fundamental atom in nature. Its role in development of modern physics is outstanding. Our physical picture of atoms, the success of quantum mechanics and the start of quantum field theories such as Quantum Electrodynamics (QED) are just a few examples for insights which go back to careful analysis of what had been observed in this atom. Hydrogen has been exploited in numerous precision measurements to determine fundamental constants and to reconfirm fundamental concepts such as, e.g. the equality of the electron and proton charge units.

Unfortunately, the presence of the proton as the nucleus in this one electron atom reduces the possibilities for a complete theoretical description. Precise measurements are at present orders of magnitude more accurate than calculations can be performed. Proton properties such as its mean square charge radius or its magnetic radius or even the dynamics of the

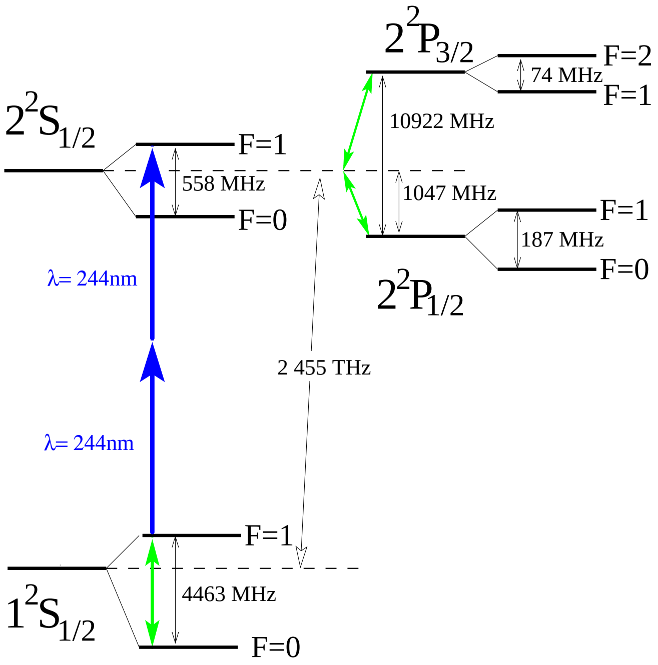


Figure 1. Energy levels of the hydrogen-like muonium atom for states with principal quantum numbers n=1 and n=2. The indicated transitions could be induced to date by microwave or laser spectroscopy. High accuracy has been achieved for the transitions which involve the ground state. The atoms can be produced most efficiently for n=1.

charge and spin carrying constituents inside the proton are not known to sufficient accuracy.

High energy scattering experiments have shown for leptons no structure down to dimensions of 10^{-18} m. They may therefore be considered "point-like". As a consequence, complications as those arising from the structure of the nucleus in natural atoms and such artificial systems that contain hadrons are absent in the muonium atom ($\mathrm{M} = \mu^+ e^-$), which is the bound state of two leptons, a positive muon (μ^+) and an electron (e) [1,2]. It may be considered a light hydrogen isotope.

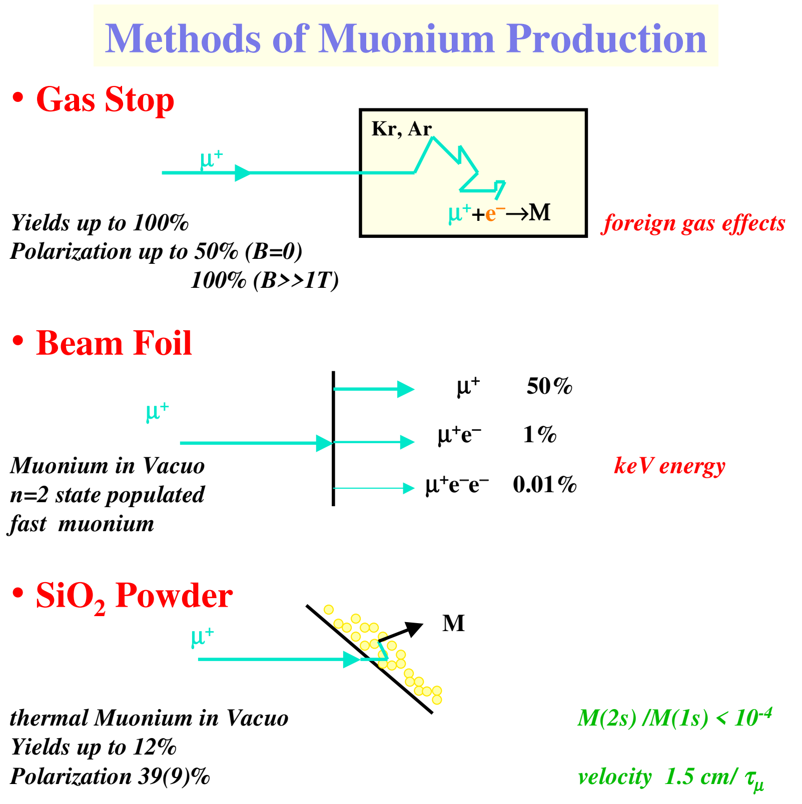
The dominant interaction within the muonium atom (see Fig. 1) is electromagnetic. In the framework of bound state Quantum Electrodynamics (QED) the electromagnetic part of the binding can be calculated to sufficiently high accuracy for modern high precision spectroscopy experiments. There are also contributions from weak interactions arising through Z^0-boson exchange and from strong interactions owing to vacuum polarization loops containing hadrons. The corresponding energy level shifts can be obtained to the required level of precision using standard theory. Precision experiments in muonium can therefore provide sensitive tests of the Standard Model of particle physics and sensitive searches for new and yet unknown forces in nature become possible. Parameters in speculative theories can be restricted. In particular, such speculations which try to expand the Standard Model in order to gain deeper insights into some of its not well understood features, i.e. where the standard theory gives well a full description, but lacks a fully satisfactory explanation of the observed facts. In addition, fundamental constants like the muon mass m_μ, its magnetic moment μ_μ and magnetic anomaly a_μ and the fine structure constant α can be measured precisely by muonium spectroscopy.

In 1960 a team led by Vernon W. Hughes has observed the muonium atom for the first time [3]. The details of the exciting circumstances around this discovery and the research in the early years are described in this volume by an eye witness, Richard Prepost [4]. They are also available from the viewpoint of the leader, Valentin Telegdi, of the very group, which was competing in muonium research with the Yale team of Vernon Hughes for more than a decade [5].

2. Muonium Formation

In the early years muonium research concentrated on measurements that were possible with atoms created by stopping muons in a material and studying them in this environment (see Fig. 2). Besides important work on condensed matter in the framework of muon spin rotation (μSR) there were in particular precision experiments which concerned the ground state hyperfine structure and a search for muonium-antimuonium conversion. In the 1980ies the spectrum of possible experiments could be significantly expanded when methods where developed which allowed to have the atoms in vacuum [1,2].

All high precision experiments in muonium up to date atom have involved the 1s ground state (see Fig.1), in which the atoms can be produced in sufficient quantities. The most efficient mechanism is e^- capture after stopping μ^+ in a suitable noble gas, where yields of 80(10) % were achieved for krypton gas. This technique was used in the most recent precision measurements of the atom's ground state hyperfine structure splitting $\Delta\nu_{HFS}$ and μ_μ at the Los Alamos Meson Physics Facility (LAMPF) in Los Alamos, USA [6].



Methods of Muonium Production

- **Gas Stop**

Kr, Ar

μ^+

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

Yields up to 100%
Polarization up to 50% (B=0)
100% (B>>1T)

foreign gas effects

- **Beam Foil**

μ^+

μ^+	50%
μ^+e^-	1%
$\mu^+e^-e^-$	0.01%

Muonium in Vacuo
n=2 state populated
fast muonium

keV energy

- **SiO_2 Powder**

μ^+

M

thermal Muonium in Vacuo
Yields up to 12%
Polarization 39(9)%

$M(2s)/M(1s) < 10^{-4}$

velocity 1.5 cm/ τ_μ

Figure 2. Muonium atoms for precision experiments have been produced by three different methods. Stopping muons in a noble gas gives atoms at thermal energies which are subject to collisional effects. Due to velocity a beam foil technique yields muonium atoms in vacuum at keV energies. Muonium atoms diffuse at thermal velocities in vacuum after being produced by muon stopping in a fluffy SiO_2 powder.

Muonium at thermal velocities in vacuum can be obtained by stopping μ^+ close to the surface of a SiO_2 powder target, where the atoms are formed through e^- capture and some of them diffuse through the target surface into the surrounding vacuum. This process has an efficiency of a few percent and was an essential prerequisite for Doppler-free two-photon laser spectroscopy of the $1^2S_{1/2}$-$2^2S_{1/2}$ interval $\Delta\nu_{1s2s}$ at the Rutherford Appleton Laboratory (RAL) in Chilton, United Kingdom [7], which yields an accurate value for m_μ.

Electromagnetic transitions in excited states, particularly the $2^2S_{1/2}$-$2^2P_{1/2}$ classical Lamb shift and $2^2S_{1/2}$-$2^2P_{3/2}$ fine structure splitting could be induced by microwave spectroscopy, too. Only moderate numbers of atoms in the metastable 2s state can be produced with a beam foil technique. Because furthermore these atoms have keV energies due to a velocity resonance in their formation, the experimental accuracy is now the 1.5 % level [8,9], which represents not yet a severe test of theory.

3. Muonium Ground State Hyperfine Structure

3.1. *The Last LAMPF Experiment*

The most recent experiment at LAMPF had a krypton gas target inside of a microwave cavity at typically atmospheric density and in a homogeneous magnetic field of 1.7 T. Microwave transitions between the two energetically highest respectively two lowest Zeeman sublevels of the n=1 state at the frequencies ν_{12} and ν_{34} (Fig. 3) involve a muon spin flip. Due to parity violation in the weak interaction muon decay process the e^+ from μ^+ decays are preferentially emitted in the μ^+ spin direction. This allows a detection of the spin flips through a change in the spatial distribution of the decay e^+. As a consequence of the Breit-Rabi equation, which describes the behaviour of the muonium ground-state Zeeman levels in a magnetic field B, the sum of ν_{12} and ν_{34} equals at any value of B the zero field splitting $\Delta\nu_{HFS}$. For sufficiently well known B the difference of these two frequencies yields the magnetic moment μ_μ. The latest LAMPF experiment [6] has utilized the

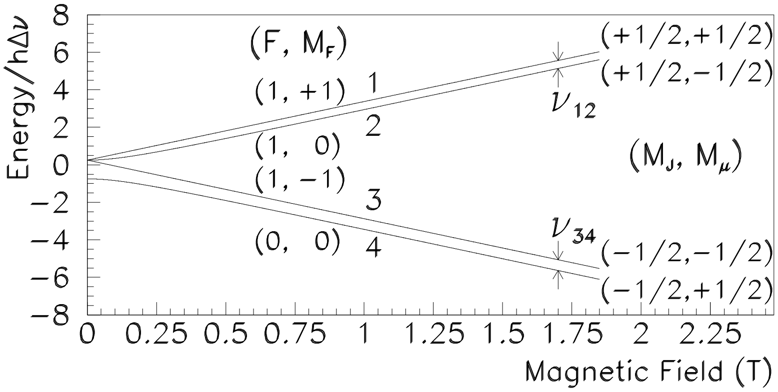


Figure 3. The muonium ground state Zeeman splitting.

technique of "Old Muonium", which allowed to reduce the line width of the signals below half of the "natural" line width $\Delta\nu_{nat} = 1/(2\pi\tau_\mu)$ (Fig. 4)[12], where $\tau_\mu = 2.2\mu$s is the muon lifetime. For this purpose an essentially continuous muon beam was chopped by an electrostatic kicking device into 4 μs long pulses with 14 μs separation. Only decays of atoms which had been interacting coherently with the microwave field for periods longer than several muon lifetimes were detected. Here, the first quoted uncertainty is due to the accuracy to

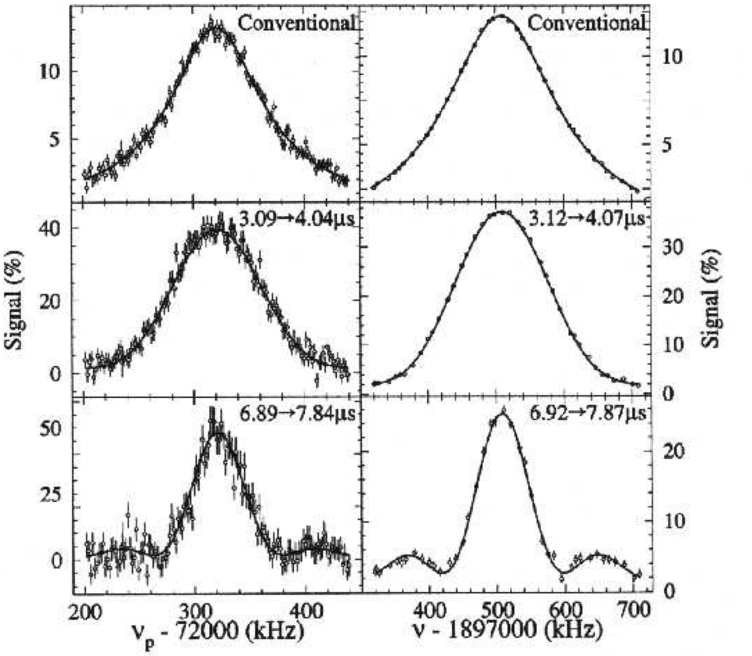


Figure 4. Samples of conventional and "Old Muonium" resonances at frequency ν_{12}. The narrow "old" lines exhibit a larger signal amplitude. The signals were obtained with magnetic field sweep (left column, magnetic field in units of proton NMR frequencies) and by microwave frequency scans (right column).

The magnetic moment was measured to be μ_μ= 3.183 345 24(37) (120 ppb) which translates into a muon-electron mass ratio μ_μ/m_e = 206.768 277(24) (120 ppb). The zero-field hyperfine splitting is determined to $\Delta\nu_{HFS}(exp) = 4\,463\,302\,765(53)$ Hz (12 ppb) which agrees well with the theoretical prediction of $\Delta\nu_{HFS}(theo) = 4\,463\,302\,563(520)(34)(<100)$ Hz (120 ppb).

which m_μ/m_e is known, the second error is from the knowledge of a as extracted from Penning trap measurements of the electron magnetic anomaly, and the third uncertainty corresponds to estimates of uncalculated higher order terms. Among the non-QED contributions is the strong interaction through vacuum polarization loops with hadrons (250 Hz) and a parity conserving axial vector-axial vector weak interaction (-65 Hz).

For the muonium hyperfine structure the comparison between theory and experiment is possible with almost two orders of magnitude higher precision than for natural hydrogen because of the not sufficiently known proton charge and magnetism distributions. The achieved – some six orders of magnitude higher – experimental precision in hydrogen maser experiments can unfortunately not be exploited for a better understanding of fundamental interactions. Among the possible exotic interactions, which could contribute to $\Delta\nu_{HFS}$, is muonium-antimuonium conversion [10]. Here, an upper limit of 9 Hz could be set from an independent experiment described in section 6.

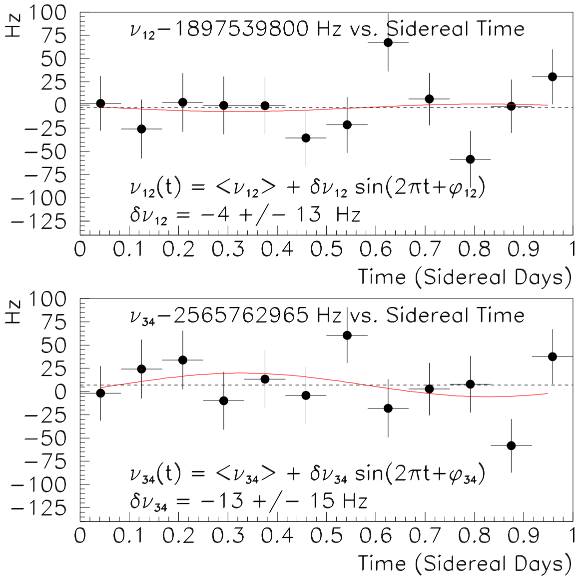


Figure 5. The absence of a significant siderial oscillation confirms CPT invariance at the best level tested for muons.

3.2. *Search for CPT violation*

Recently, generic extensions of the Standard Model, in which both Lorentz invariance and CPT invariance are not assumed, have attracted widespread attention in physics.

Diurnal variations of the ratio $(\nu_{12} - \nu_{34})/(\nu_{12} + \nu_{34})$ are predicted (see Fig. 5). An upper limit could be set from a reanalysis of the LAMPF data at $2 \cdot 10^{-23}$ GeV for the Lorentz and CPT violating parameter. In a specific model by Kostelecky and co-workers a dimensionless figure of merit for CPT tests is sought by normalizing this parameter to the particle mass. In this framework $\Delta\nu_{HFS}$ provides a significantly better test of CPT invariance than electron g-2 and the neutral Kaon oscillations[11].

3.3. *The Fine Structure Constant*

The hyperfine splitting is proportional to $\alpha^2 \cdot R_\infty$ with the very precisely known Rydberg constant R_∞. Comparing experiment and theory yields α^{-1}= 137.035 996 3(80) (58ppb). If R_∞ is decomposed into even more fundamental constants, one finds $\Delta\nu_{HFS} = \alpha^4 m_e/h$. With h/m_e as de-

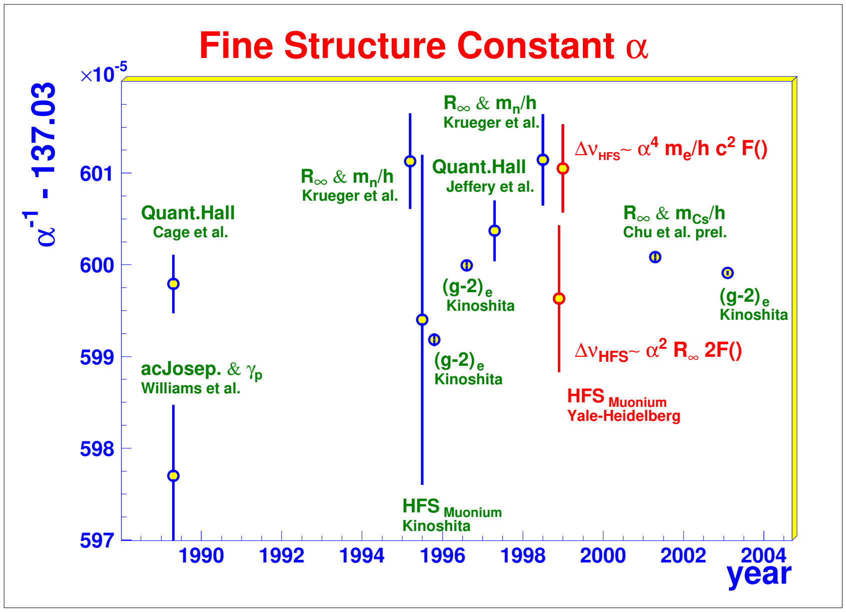


Figure 6. Various determinations of the fine structure constant α.

termined in measurements of the neutron de Broglie wavelength we have α^{-1}= 137.036 004 7(48) (35 ppb). In the near future a small improvement in this figure can be expected from ongoing determinations of h/m_e in measurements of the photon recoil in Cs. A better determination of the muon mass, e.g. will result in a further improvement and may contribute to resolving the situation of various poorly agreeing determinations of the fine structure constant, which is important in many different fields of physics.

It should be mentioned that the present agreement between α as determined from muonium hyperfine structure and from the electron magnetic anomaly is generally considered the best test of internal consistency of QED, as one case involves bound state QED and the other one QED of free particles.

3.4. *Future Possibilities for $\Delta\nu_{HFS}$*

The results from the LAMPF experiment are mainly statistics limited and improve the knowledge of both $\Delta\nu_{HFS}$ and μ_μ by a factor of three over previous measurements. This gain could be significantly surpassed with an experiment based on the "Old Muonium" technique at a future high flux muon source (see section 7). As a useful starting point one would like to have $5 \cdot 10^8$ μ^+/s at below 28 MeV/c momentum with typically 1 % momentum width. The beam should be pulsed with 1μs wide pulses of up to several 10 kHz repetition frequency. One can expect that theory will be continuously improved to allow the extraction of fundamental physics information from a precision experiment[13].

4. Muonium 1s-2s Two-photon Spectroscopy

In muonium the 1s-2s energy difference is essentially given by the relevant quantum numbers, R_∞ and a reduced mass correction. Therefore, this transition may be regarded ideal for a determination of the muon-electron mass ratio. QED corrections are well known for the needs of presently possible precision experiments and do not play an important role here.

Doppler-free excitation of the 1s-2s transition has been achieved in pioneering experiments at KEK [14] and at RAL [15]. In all these experiments two counter-propagating pulsed laser beams at 244 nm wavelength were employed to excite the n=2 state. The successful transitions were then detected by photo-ionization with a third photon from the same laser field. The released μ^+ was then registered on a micro-channel plate detector.

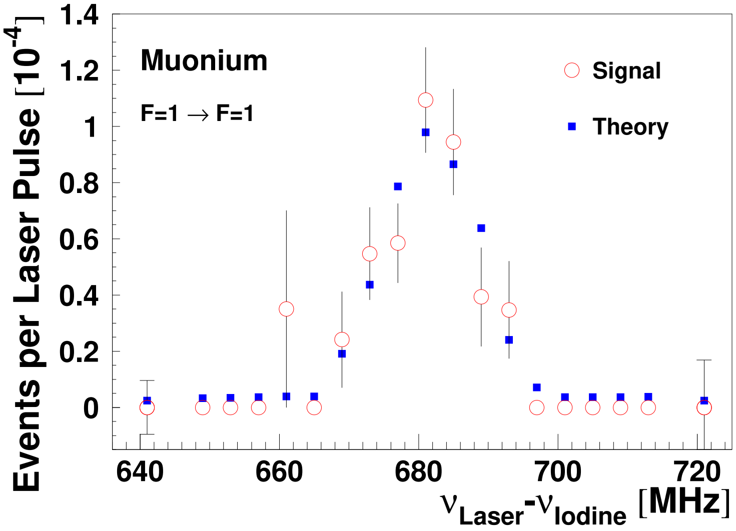


Figure 7. Muonium 1s-2s signal. The frequency corresponds to the offset of the Ti:sapphire laser from the iodine reference line. The open circles are the observed signal, the solid squares represent the theoretical expectation based on measured laser beam parameters and a line shape model.

4.1. *The recent RAL Experiment*

The accuracy of the early measurements was limited by the ac-Stark effect and rapid phase fluctuations (frequency chirps), which were inherent properties of the necessary pulsed high power laser systems (see Fig. 8). The key feature for the latest high accuracy measurement at RAL was a shot by shot recording of the spatial laser intensity profile as well as the time dependences of the laser light intensity and phase. This together with a newly developed theory of resonant photo-ionization [16] allowed a shot-by-shot prediction of the transition probability as a basis for the theoretical line shape (Fig. 7). The latest RAL experiment [7] yields $\Delta\nu_{1s2s}(exp)$= 2 455 528 941.0(9.8) MHz in good agreement with a theoretical value $\Delta\nu_{1s2s}(theo)$=2 455 528 935.4(1.4) MHz [17]. The muon-electron mass ratio is found to be $m_{\mu^+}/m_{e^-} = 206.768\,38(17)$.

Alternatively, with m_{m^+}/m_{e^-} as extracted from $\Delta\nu_{HFS}$, a comparison of experimental and theoretical values for the 1s-2s transition can be interpreted in terms of a $\mu^+ - e^-$ charge ratio, which results as $q_{m^+}/q_{e^-} + 1 = -1.1(2.1) \cdot 10^{-9}$. This is the best verification of charge

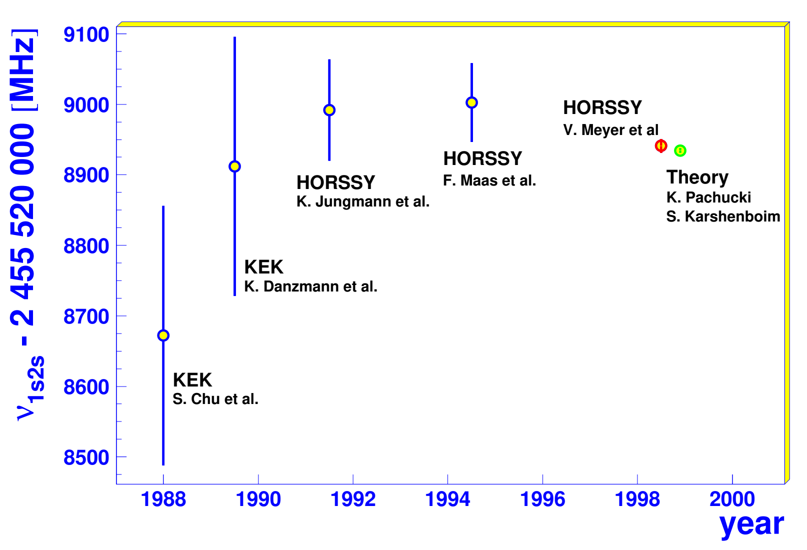


Figure 8. Evolution of muonium 1s-2s measurements. The two results labeled KEK accelerator facility refer to one single measurement by a Japanese - American collaboration and its reanalysis. The newer measurements were made by the **H**eidelberg - **O**xford - **R**utherford - **S**ussex - **S**iberia - **Y**ale collaboration and have reached a level of accuracy comparable to theory, where the limitation arises primarily to the muon mass.

equality in the first two generations of particles. The existence of one single universal quantized unit of charge is solely an experimental fact and no underlying symmetry could yet be revealed. The interest in such a viewpoint arises because gauge invariance assures charge quantization only within one generation of particles.

4.2. *Slow Muons from Muonium Ionization*

A new development aims at providing low energy (<1 eV energy spread) muons for condensed matter research. At RIKEN-RAL facility a new muon source is being set-up which bases on the laser photo-ionization of muonium. The atoms are produced from hot metal foils which they leave at thermal velocities. The ionization process involves one-photon excitation of the 1s-2p transition and subsequent ionization with a second laser. At present the yield is a few μ^+/s. [18]

4.3. *Future Muonium Laser Spectroscopy*

Major progress in the laser spectroscopy of muonium can be expected from a continuous wave laser experiment, where frequency measurement accuracy does not present any problem because light phase fluctuations are absent. For this an intense source of muons will be indispensable (see section 7). which provides at least a factor of 1000 higher flux of (pulsed) surface muons. As a promising starting point one would like to have a pulsed beam $5 \cdot 10^8$ μ^+/s below 20 MeV/c with typically 3 % momentum width and about 100 Hz repetition rate.

5. Muonium and the Muon Magnetic Anomaly

The muon magnetic anomaly a_μ (see contributions by Francis Farley and Ernst Sichtermann to this volume [19]) is given, like in case of the electron, mostly by virtual photon and electron-positron fields. However, the effects of heavier particles can be enhanced by the square of the muon - electron mass ratio $m_\mu/m_e \approx 4 \cdot 10^4$.

At the level of present experimental accuracy there are contributions to the muon magnetic anomaly which are absent in the electron case. For the muon the contributions of the strong interaction, which come in through vacuum polarization loops with hadronic content, can be determined using a dispersion relation and the input from experimental data on e^+-e^- annihilation into hadrons and hadronic τ-decays. They amount to 58 ppm. The weak interactions contributing through W or Z boson exchange give a 1.3 ppm correction. At present standard theory yields a_μ to about 0.7 ppm. Contributions from physics beyond the Standard Model could arise from, e.g., supersymmetry, compositeness of fundamental fermions and bosons, CPT violation and many other sources. They could be at the ppm level.

The experimental values for the magnetic anomaly of μ^+ and μ have been determined very recently by a collaboration headed by Vernon Hughes at the Brookhaven national Laboratory (BNL). It is a "g-2" experiment in which the difference of the spin precession and the cyclotron frequencies is measured. The experimental results for muons of both sign of electric charge are accurate to 0.7 ppm and agree well. Assuming CPT invariance they yield a combined value of a_μ to 0.5 ppm [20]. At this time it is unclear, whether there is a small difference between theory and experiment at the level of 2 to 3 standard deviations due to unresolved issues in the theory of hadronic corrections.

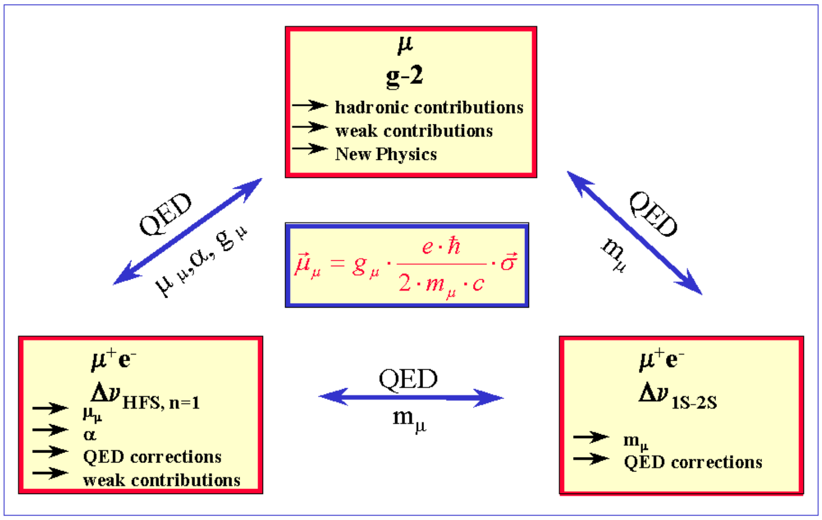


Figure 9. The spectroscopic experiments on the hyperfine structure of muonium and the 1s-2s energy interval are closely related to a precise measurement of the muon muon magnetic anomaly. The measurements put a stringent test on the internal consistency of the theory of electroweak interaction and on the set of fundamental constants involved.

The microwave and laser spectroscopy of muonium are closely related to the measurement of the muon magnetic anomaly. The fundamental constants such as m_μ, μ_μ, α and q_{μ^+}/q_{e^-} are indispensable input for the theory and the experiment on a_μ. It should be noted that prior to a future significant experimental improvement of a_μ, such as planned at the Japanese J-PARC accelerator complex [21], an improvement in the knowledge of muon related fundamental constants would be required. Muonium spectroscopy offers a clean way to obtain them.

6. Muonium-Antimuonium Conversion

In addition to the indirect searches for signatures of new physics in the muon magnetic anomaly and in electromagnetic interactions within the muonium atom the bound state offers also the possibility to search more directly for predictions of speculative models.

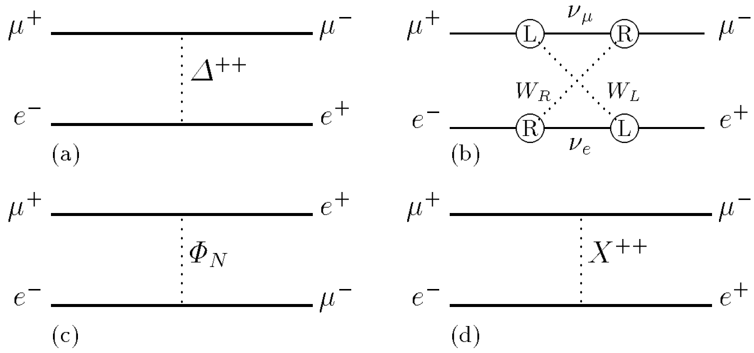


Figure 10. Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated by (a) a doubly charged Higgs boson Δ^{++}, (b) heavy Majorana neutrinos, (c) a neutral scalar Φ_N, e.g. a supersymmetric τ-sneutrino $\tilde{\nu}_\tau$, or (d) a bileptonic gauge boson X^{++}.

The process of muonium to antimuonium-conversion (M-$\overline{\mathrm{M}}$)violates additive lepton family number conservation. It would be an analogy in the lepton sector to the well known K^0-$\overline{K^0}$ and B^0-$\overline{B^0}$ oscillations in the quark sector. Muonium-antimuonium conversion appears naturally in many theories beyond the Standard Model. The interaction could be mediated, e.g., by a doubly charged Higgs boson Δ^{++}, Majorana neutrinos, a neutral scalar, a supersymmetric τ-sneutrino , or a doubly charged bileptonic gauge boson.

There have been a number of attempts to observe M-$\overline{\mathrm{M}}$ conversion. The pioneering work was again performed by a group guided by Vernon Hughes already in the 1960ies [22]. The early experiments [22,23] relied on the X-rays which would follow a μ^--transfer to a heavy element upon contact of $\overline{\mathrm{M}}$ with matter as part of their signature. A breakthrough was the availability of thermal muonium in vacuum [24] which led to a significant increase in sensitivity [25].

6.1. *The latest* M-$\overline{\mathrm{M}}$ *Experiment at PSI*

At PSI an experiment was designed to exploit a powerful new signature, which requires the coincident identification of both particles forming the anti-atom in its decay [10]. The technique had been pioneered by an international collaboration led by Vernon Hughes at LAMPF [25].

Thermal muonium atoms in vacuum from a SiO_2 powder target, are observed for decays. Energetic electrons from the decay of the μ^- in the atom

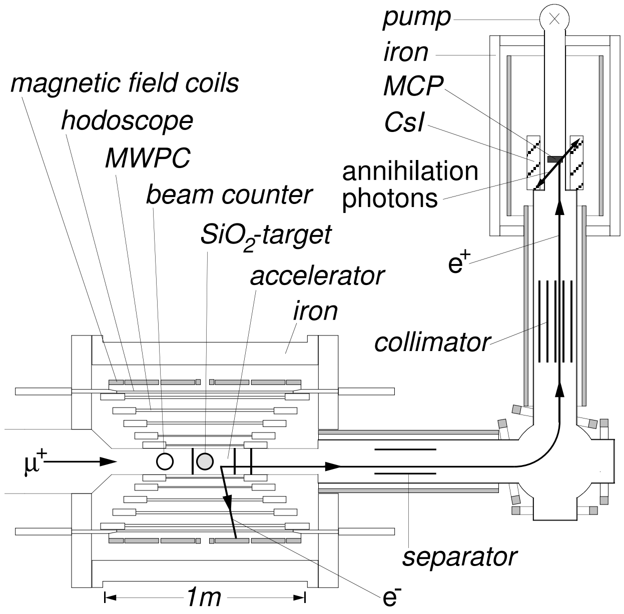


Figure 11. The Muonium-Antimuonium Conversion Spectrometer at PSI.

can be identified in a magnetic spectrometer (Fig. 11). The positron in the atomic shell of $\overline{\mathrm{M}}$ is left behind after the decay with 13.5 eV average kinetic energy. It has been post-accelerated and guided in a magnetic transport system onto a position sensitive micro-channel plate detector (MCP). Annihilation radiation can be observed in a segmented pure CsI calorimeter around it. The decay vertex can be reconstructed. The measurements were performed during a period of 6 months in total over 4 years during which $5.7 \cdot 10^{10}$ muonium atoms were in the interaction region. One event fell within a 99% confidence interval of all relevant distributions. The expected background due to accidental coincidences is 1.7(2) events (Fig. 12). Depending on the interaction details one has to account for a suppression of the conversion in the 0.1 T magnetic field in the spectrometer. This amounts maximally to a factor of about 3 for V±A type interactions. Thus, the upper limit on the conversion probability is $8.2 \cdot 10^{-11}$ (90% C.L.). The coupling constant is bound to below $3.0 \cdot 10^{-3}\ G_F$, where G_F is the weak interaction Fermi coupling constant.

This new result, which exceeds limits from previous experiments by a factor of 2500 and one from an early stage of the experiment by 35, has

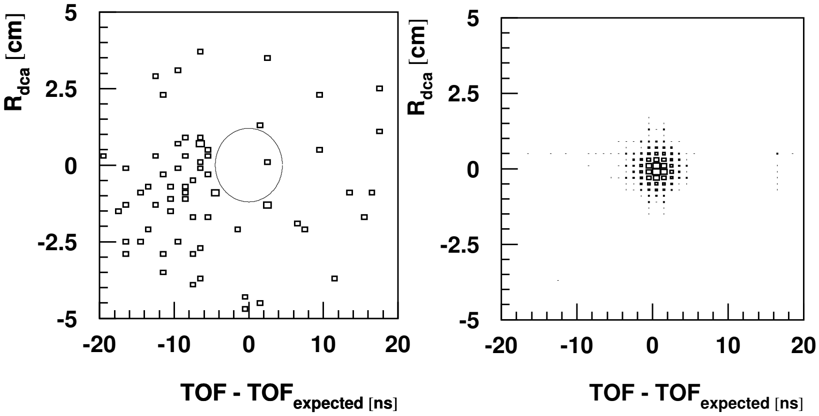


Figure 12. Time of Flight (TOF) and vertex quality for the final 4 month of integrated search data for antimuonium (left) and for a single 20 minutes measurement of muonium (right). In the antimuonium case one event falls into the indicated area, which corresponds to 3 standard deviations for the parameters of an expected antimuonium signature, which were calibrated with muonium decays when all electro-magnetic fields in the apparatus were reversed.

some impact on speculative models. For example: A certain Z_8 model is ruled out. It had more than 4 generations of particles and where masses could be generated radiatively with heavy lepton seeding. A new lower limit of 2.6 TeV/$c^2 \times g_{3l}$ (95% C.L.) on the masses of flavour diagonal bileptonic gauge bosons in GUT models is extracted, which lies well beyond the value derived from direct searches, measurements of the muon magnetic anomaly or high energy Bhabha scattering. Here, g_{3l} is of order unity and depends on the details of the underlying symmetry. For 331 models the experimental result can be translated into 850 GeV/$c^2 \times g_{3l}$ which excludes some of their minimal Higgs versions, where an upper bound of 600 GeV/c^2 has been extracted from an analysis of electro-weak parameters. The 331 models need now to refer to a less attractive and more complicated extensions. In the framework of R-parity violating supersymmetry the bound on the relevant coupling parameters could be lowered by a factor of 15 to $\lambda_{132} \cdot \lambda_{231} \leq 3 \cdot 10^{-4}$ for assumed super-partner masses of 100 GeV/c^2.

6.2. *Future Possibilities for* M-$\overline{\text{M}}$ *Experiments*

A future experiment to search for M-$\overline{\text{M}}$ conversion could particularly take advantage of high intensity pulsed beams. In contrast to other lepton (family) number violating muon decays, the conversion through its nature as particle-antiparticle oscillation has a time evolution in which the probability for finding a system formed as muonium decaying as $\overline{\mathrm{M}}$ increases quadratically in time. This gives the signal an advantage, which grows in time over exponentially decaying background. E.g., with a twofold coincidence as part of a signature: after a time $\Delta T = 2\tau_\mu$ beam related accidental background has dropped by almost two orders of magnitude, whereas a M-$\overline{\mathrm{M}}$-signal would not have suffered significantly at all. An almost ideal beam would have $1 \cdot 10^{10}$ μ^+/s at below 23 MeV/c with typically 1-2 % momentum width. The beam should be pulsed with up to 1μs wide pulses of up to several 10 kHz repetition frequency.

Such efforts appear well motivated among other reasons through the connection to numerous speculative models involving, e.g., lepton flavour violation in general or a possible Majorana nature of the neutrinos [27].

7. Future Possibilities for Fundamental Interaction Research with Muons

It appears that the availability of particles limits at present progress in research with muonium. This includes better fundamental constants as well as the possibility to find very rare processes and to impose significantly improved limits in continuation of the search program of dedicated experiments.

Therefore significant measures to boost the muon fluxes at existing accelerator centers and to create future facilities with orders of magnitude higher muon currents is indispensable prior to any significant progress. This requirement matches well with the demand of several communities within physics which request an intense particle accelerator. Such interest exists, e.g., worldwide for a Neutrino Factory and a Muon Collider [26], in Japan for the J-PARC facility and in Europe for EURISOL facility [28]. The perspectives for muonium research have beam worked out for such a scenario in some detail [26].

Examples of tailored intense muon sources at existing facilities are the $\pi - \mu$ converter at PSI, the planned muon production of the planned MECO experiment at BNL or the projected phase rotated intense source of muons (PRISM) [29] in connection with the upcoming J-PARC facility.

The design goal for such a new machine should be a minimum of 1 MW proton beam on a production target. This could become a reality at various places including BNL, CERN, GSI and J-PARC.

Figure 13. Vernon W. Hughes keeping contact with his colleagues during the Lepton Moments I conference in Heidelberg in 1999. Effective communication is a key to operate simultaneously several challenging large experiments at different research centers around the world.

8. Conclusions

More than 70 years after the muon was discovered [30], its properties still remain puzzling. The mysteries include not less than the reason for the muon's existence, the size of its mass, its charge and the fact of lepton number (and for charged species) lepton family number conservation. All precision experiments to date have confirmed that the muon is a heavy copy of the "point-like" electron. Standard theory appears to be an adequate description of all measurements, although it cannot answer some of the deeper questions.

Searches for a violation of the Standard Model were not blessed with a successful observation yet. However, both the theoretical and experimental work in this connection have led to a much deeper understanding of particle interactions. One special value of the precision experiments are their continuous contributions towards guiding theoretical developments by excluding various speculative models. The research of Vernon Hughes has most significantly added to shaping our knowledge about nature in this way. Research on muonium has contributed quite some essential facets to the picture of fundamental particles and fundamental interactions in physics.

9. Final Remarks

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The author owes his heartily gratitude to Vernon Willard Hughes for a long fruitful collaboration in the framework of a number of international collaborations. The measurements we could carry out together all involved muons. In particular, many of them involved centrally the fundamental atom we could find for our research:
Thank You Vernon for introducing muonium to the scientific community.

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