Muonium - Physics of a most Fundamental Atom
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The hydrogen-like muonium atom (M=μ⁺e⁻) offers possibilities to measure fundamental constants most precisely and to search sensitively for new physics. All experiments on muonium at the presently most intense muon sources are statistics limited. New and intense muon sources are indispensable for improved measurements.

1. Introduction

The dominant interaction within the M atom [1,2] 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 Z⁰-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 M can provide sensitive tests of the Standard Model of particle physics. Sensitive searches for new, 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 satisfactory explanation of the observed facts. In addition, fundamental constants like the muon mass mµ, its magnetic moment µµ and magnetic anomaly aµ and the fine structure constant α can be measured precisely by M spectroscopy.

Recent precision experiments in M include spectroscopy of electromagnetic transitions in the atom and a search for muonium-antimuonium (M-%M) conversion. All these experiments involve M atoms in the ground state where they can be produced with highest efficiency. The spectroscopy experiments are a microwave measurement of the Zeeman splitting in the ground state hyperfine structure ∆ν_{HFS} and a two-photon laser excitation of the 1S_{1/2}-2S_{1/2} transition. Both energy intervals can be calculated to very high precision, which allows to extract fundamental constants.

2. Hyperfine structure

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 [3]. 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} 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⁺. The experiment has utilized the technique of "Old Muonium", which allowed to reduce the line width of the signals below half of the "natural" line width Δν_{nat} = 1/(2πτµ) [4], where τµ = 2.2μs is the muon lifetime.

The magnetic moment was measured to 120 ppb, which translates into a muon-electron mass ratio µµ/m_e of the same accuracy. The zero-field hyperfine splitting is determined to 12 ppb and agrees well with the theoretical prediction which is known to 120 ppb [5]. For the M 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. Most of the corrections to the Fermi HFS splitting in M arise from QED. This allows for the most precise determination of the fine structure constant \( \alpha \) from a bound state. Among the non-QED contributions is the strong interaction through vacuum polarization loops with hadrons (56 ppb) and a parity conserving axial vector-axial vector weak interaction (-14 ppb).

It should be noted that \( \mu \mu \) is an essential input into the muon g-2 measurement. Future g-2 experiments might be limited by this quantity unless some improved number will be determined in a future high precision experiment.

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. An upper limit could be set from a reanalysis of the LAMPF data at \( 2 \cdot 10^{-23} \text{GeV} \) 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 \( \Delta \nu_{\text{HFS}} \) provides a significantly better test of CPT invariance than electron g-2 and the neutral Kaon oscillations[6].

3. 1s-2s interval

Doppler-free excitation of the 1s-2s transition has been achieved in pioneering experiments at KEK [7] and at RAL [8]. 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 through the released \( \mu^+ \).

The RAL experiment [9] yields \( \Delta \nu_{1s2s}(\text{exp}) \) to 4 ppb in good agreement with a theoretical value which is known to 0.6 ppb[10]. The muon-electron mass ratio can be extracted from this to 0.8 ppm. Alternatively the measurement can be interpreted as a test of the charge quantization in the first two lepton generations which results as \( q_{m^+}/q_{e^-} + 1 = -1.1(2.1) \cdot 10^{-9} \). This is the best verification of charge equality in the first two generations. The existence of one single universal unit of charge is solely an experimental fact. No underlying symmetry could yet be identified.

4. 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 M atom the bound state offers also the possibility to search more directly for predictions of speculative models. The process of (M-M) conversion violates additive lepton family number conservation. It would be an analogy to the well known \( K^0 - \bar{K}^0 \) and \( B^0 - \bar{B}^0 \) oscillations. M-M conversion appears naturally in many theories beyond the Standard Model. The interaction could be mediated, e.g., by a doubly charged Higgs boson \( \Delta^{++} \), Majorana neutrinos, a neutral scalar, a supersymmetric \( \tau \)-sneutrino, or a doubly charged bileptonic gauge boson.

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 [11]. Thermal M atoms in vacuum from a SiO\(_2\) powder target, are observed for decays. (Vacuum is indispensable, as in a gas or in condensed matter the conversion would be significantly suppressed.) Energetic electrons from the decay of the \( \mu^- \) in the atom can be identified in a magnetic spectrometer. The positron in the atomic shell of \( \bar{M} \) 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 \( 5.7 \cdot 10^{10} \) M 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. 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. The upper limit on the conversion probability is $8.2 \cdot 10^{-11}$ (90% C.L.). The coupling constant is bound to below $3 \cdot 10^{-3}$ $G_F$, where $G_F$ is the 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 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 $2.6 \text{ TeV}/c^2 \times g_3$ (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, $g_3$ is of order unity and depends on the details of the underlying symmetry. For 331 models the experimental result can be translated into $850 \text{ GeV}/c^2 \times g_3$ which excludes some of their minimal Higgs versions, where an upper bound of $600 \text{ GeV}/c^2$ 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. For R-parity violating supersymmetry the bound on the relevant coupling parameters could be lowered by a factor of 15 to $\lambda_{12} \cdot \lambda_{231} \leq 3 \cdot 10^{-4}$ for assumed super-partner masses of 100 GeV/$c^2$. At present there is strong interest in the process in connection with 331 models, heavy neutrinos, doubly charged bileptons and many more models [12].

5. Conclusions

As all precision $M$ experiments are statistics limited, a number of precision experiments is waiting to be carried out at a new and intense muon facility [13]. In particular the search for $M$-$\bar{M}$ conversion would benefit from a pulsed muon source. There the 'Old Muonium' technique could be beneficially employed, because the conversion progresses with time squared and beam related background falls off exponentially with time.

REFERENCES