The Muonium Atom as a Probe of Physics beyond the Standard Model

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Abstract. The observed interactions between particles are not fully explained in the successful theoretical description of the standard model to date. Due to the close confinement of the bound state muonium (\(M = \mu^+e^-\)) can be used as an ideal probe of quantum electrodynamics and weak interaction and also for a search for additional interactions between leptons. Of special interest is the lepton number violating process of spontaneous conversion of muonium to antimuonium.

1 Introduction

Precision measurements on atomic systems have played an important role in the course of the development of modern physics. In many cases they have lead to discoveries which had significant impact on the understanding of the physical laws of nature. The explanation of the carefully measured electromagnetic spectrum of atomic hydrogen by the Schrödinger equation was a great success for quantum mechanics. The observed fine structure was included in the solutions to the Dirac equation which demonstrated the necessity of a relativistic description of the atomic structure. The observed hyperfine splitting in hydrogen [2] from the value predicted in Fermi’s theory on the 0.1% level could be explained by the anomalous magnetic moment of the electron. This discovery together with the observation of the Lamb-shift \(\left(2^2S_{\frac{1}{2}} - 2^2P_{\frac{1}{2}}\right)\) in hydrogen [3] has initiated and boosted the development of the modern field theory of quantum electrodynamics (QED).

The unification of the weak and electromagnetic interactions in the electroweak standard model was strongly supported by the observation of parity violation in precise spectroscopic measurements in heavy atoms. Today electroweak processes examined both at high energies [4] at the LEP electron-positron storage ring collider at CERN, Geneva, Switzerland, and in atomic parity violation experiments in heavy atoms, e.g. in cesium and thallium [5, 6], have ascertained the power of the unified electroweak theory which is valid over a range of 10 orders of magnitude in momentum transfer.

Today the standard model appears to be a very successful effective description of all known interactions between particles and no significant deviation from it could be established so far. Its predictions are subject to high precision experiments which allow to extract a set of intrinsic parameters including the masses in the leptonic and the quark sectors and mixing angles between different quarks. However, there still remain unresolved questions within this sophisticated theoretical framework like the number of interactions, the number of lepton and quark generations or the nature of parity.
violation. Particularly the question of lepton number conservation is investigated by various experiments, since no underlying symmetry could be discovered to be associated with it yet.

The muonium atom ($M = \mu^+ e^-$), the bound state of a positive muon $\mu^+$ and an electron $e^-$, can be considered a light hydrogen isotope. This fundamental system is ideally suited for investigating bound state quantum electromagnetic theory and it renders the possibility to test fundamental concepts of the standard model. The spectroscopic measurements of electromagnetic transitions like the hyperfine interval in the ground state or the 1s-2s energy splitting are generally considered precise tests of QED and are used to infer accurate values of fundamental constants [7]. In addition, they may be used to extract information on fundamental symmetries. For example, the latest measurement of the 1s-2s energy interval [7, 8] can be regarded as the best test of the charge equality of leptons from different particle generations at a level of $10^{-8}$ relative accuracy [9]. The system offers further unique possibilities to search for yet unknown interactions between leptons, in particular, since the close confinement of the bound state allows its constituents a rather long interaction time which is ultimately limited by the lifetime $\tau_\mu = 2.2 \mu$s of the muon.

2 Test of Lepton Number Conservation

A spontaneous conversion of muonium into antimuonium ($\overline{M} = \mu^+ e^-$) would violate additive lepton family (generation) number conservation by two units. This process is not provided in the standard model like others which are intensively searched for, e.g. $\mu \to e\gamma$ [10], $\mu \to eee$ [11], $\mu - e$ conversion [12] or the muon decay mode $\mu^+ \to e^+ + \nu_\mu + \overline{\nu}_e$ [13]. However, in the framework of many speculative theories, which try to extend the standard model in order to explain some of its not well understood features, lepton number violation is a natural process and muonium to antimuonium conversion is an essential part in several of these models (Fig. 1) [14-19].

Traditionally, muonium-antimuonium conversion is described as an effective four fermion interaction with a coupling constant $G_{\overline{M}M}$ which can be measured in units of the Fermi coupling constant of the weak interaction $G_F$ [20]. Many of the speculative models would allow a strength of the interaction as large as the experimental bound at the time they were created.

In minimal left-right symmetric theory muonium and antimuonium could be coupled through a doubly charged Higgs boson $\Delta^{++}$. In this case even a lower bound has been predicted for $G_{\overline{M}M}$: provided the muon neutrino mass $m_{\nu_\mu}$ were larger than 35 keV/$c^2$ [14]. With the present experimental limit of $m_{\nu_\mu} \leq 170$ keV/$c^2$ [21] the coupling constant $G_{\overline{M}M}$ should be larger than $2 \cdot 10^{-4} \ G_F$. This figure would even increase for an improved bound on $m_{\nu_\mu}$.

For neutrinos being Majorana particles a coupling between muonium and antimuonium is possible by an intermediate pair of neutrinos. A limit on the effective coupling can be estimated based on the Majorana mass limit of the electron neutrino which has been deduced from experimental searches for neutrinoless double $\beta$-decay [22] to $G_{\overline{M}M} \leq 10^{-5} G_F$ [15].

Supersymmetric theories allow an interaction to be mediated by a $\tau$-sneutrino $\tilde{\nu}_\tau$, the supersymmetric partner of the $\tau$-neutrino. The predictions are $G_{\overline{M}M} \leq 10^{-2} G_F$ for a mass value $m_{\tilde{\nu}_\tau}$ of 100 GeV/$c^2$ [18].
Some of these speculative theories need to introduce neutral scalar bosons to explain the mass spectrum in the leptonic sector. These models predict a coupling strength of $10^{-2}G_F$ which is in the range of the sensitivity of present experimental search [16].

In the framework of grand unification theories (GUT) muonium-antimuonium conversion could be explained by the exchange of a gauge boson $X^{++}$ which carries both an electronic and a muonic lepton number. Bhabha scattering experiments at PETRA storage ring at DESY in Hamburg, Germany, bounded the mass of this dileptonic particle to $m_{X^{++}}/g_3 \geq 340 \text{ GeV}/c^2$, where $g_3$ depends on the particular symmetry and is of order unity [23]. This can be translated into $G_{\text{MM}} \leq 10^{-2}G_F$.

### 3 The Conversion Process

Muonium and antimuonium are neutral atoms which are degenerate in their energy levels in the absence of external fields. In 1957 Pontecorvo suggested the possibility of a muonium to antimuonium conversion process even before the atom had been formed for the first time by V.W. Hughes and his coworkers in 1960 at the NEVIS cyclotron of Columbia University, New York, USA [24]. He proposed a coupling by an intermediate neutrino pair state in analogy to the $K^0 - \bar{K}^0$ oscillations, which were discovered at that time [25].

Any possible coupling between muonium and its antiatom will give rise to oscillations between the two species. For atomic s-states with principal quantum number $n$ a splitting of their energy levels

$$\delta = \frac{8G_F}{\sqrt{2n^2\pi a_0^3}} \frac{G_{\text{MM}}}{G_F}$$

is caused, where $a_0$ is the Bohr radius of the atom. For the ground state $\delta$ equals $1.5 \cdot 10^{-12} \text{ eV} \cdot (G_{\text{MM}}/G_F)$ which corresponds to 519 Hz for $G_{\text{MM}} = G_F$. We note that this value is three times larger than the uncertainty reported for the best measurement of the muonium ground state hyperfine structure interval [26]. Therefore, the interpretation
Fig. 2. Time dependence of the probability to observe an antimuonium decay for a system which was initially in a pure muonium state. The solid line represents the exponential decay of muonium in the absence of a finite coupling. The decay probability as antimuonium is given for a coupling strength of $G_{MM} = 1000$ by the dotted line and for a coupling strength small compared to the muons decay rate (dashed line). In the latter case the maximum of the probability is at 2 muon lifetimes. Only for strong coupling several oscillation periods could be observed.

of precise measurements of the hyperfine structure must include considerations on how such a process would affect the accuracy under the particular experimental conditions [27].

A system starting at time $t = 0$ as a pure state of muonium could be observed in the antimuonium state at a later time $t$ with a probability of (Fig. 3)

$$p_{\text{MM}}(t) = \sin^2 \left( \frac{\delta t}{2\pi} \right) e^{-\lambda_\mu t} \approx \left( \frac{\delta t}{2\pi} \right)^2 \cdot e^{-\lambda_\mu t},$$ (2)

where $\lambda_\mu = 1/\tau_\mu$ is the muon decay rate. The approximation is valid for a weak coupling as suggested by the known experimental limits on $G_{MM}$. In this case the process should be considered a conversion rather than an oscillation. The maximum of the probability for a decay as antimuonium is found at $t_{\text{max}} = 2/\lambda_\mu$, while the ratio of antimuonium to muonium continuously increases with time. The total conversion probability integrated over all decay times is

$$P_{\text{MM}} = 2.56 \cdot 10^{-5} \left( \frac{G_{\text{MM}}}{G_F} \right)^2.$$ (3)

This demonstrates the advantage of experiments in which the system is allowed an extended time interval (a duration of order $\tau_\mu$ or longer) for developing a conversion.

The degeneracy of corresponding states in the atom and its antiatom is removed by external magnetic and electric fields which can cause a suppression of the conversion and a reduction of the probability $p_{\text{MM}}$. The influence of an external magnetic field depends on the interaction type of the process. The reduction of the conversion probability has been calculated for all possible interaction types as a function of field strength (Fig. 3) [28, 29]. In the case of an observation of the conversion process the
coupling type could be revealed by measurements of the conversion probability at two different magnetic field values.

The conversion process is strongly suppressed for muonium in contact with matter, since a transfer of the negative muon in antimuonium to any other atom is energetically favored and breaks up the symmetry between muonium and antimuonium by opening up an additional decay channel for the antiatom only. In gases at atmospheric pressures the conversion probability is about five orders of magnitude smaller than in vacuum [30] mainly due to scattering of the atoms from gas molecules. In solids the reduction amounts to even 10 orders of magnitude. Therefore a sensitive experiment will benefit largely from employing muonium atoms in vacuum.

4 History of Experimental Search

There is a strong connection between experimental searches for muonium to antimuonium conversion and the development of efficient sources of muonium atoms. In the earliest experiment in 1967 at the NEVIS cyclotron [31] muons were stopped in a Ar noble gas target of pressure 1 atm with a technique similar to the one which was used in the discovery of muonium. A large fraction of the muons forms muonium by electron capture. A conversion process would be indicated by Kα X-rays originating from an argon atom after the transfer of the negative muon from antimuonium. A sensitivity of \( G_{MM} < 5800 G_F \) (95% C.L.) could be reached which was mainly limited by the strong suppression of the conversion in gases.

One year later Møller scattering was investigated at the Princeton-Stanford electron storage rings at Stanford, USA. An analysis of the channel \( e^- + e^- \rightarrow \mu^- + \mu^- \), which is essentially the same physical process as muonium-antimuonium conversion, yielded nearly two orders of magnitude higher sensitivity on the coupling strength [32].

\[^1\] Today \( e^- + e^- \) scattering experiments would have to run for approximately 1 year
Significant increases in sensitivity could be achieved after 1980 by taking advantage of newly developed sources of muonium in vacuum. At the Los Alamos Meson Physics Facility (LAMPF) in Los Alamos, USA, muonium in vacuum could be produced by a beam foil technique from thin aluminum foils. The velocity-resonant nature of the electron capture process causes typical kinetic energies of the atoms of a few keV. The corresponding high velocities and finite dimensions of the apparatus restricted the time interval available for the conversion. Antimuonium could have been discovered by secondary electrons and muonic X-rays from a bismuth catcher foil. The coupling constant $G_{\text{MM}}$ could be limited to below $7.5 \, G_F$ (90% C.L.) [33].

The discovery of muonium formation in fine grain SiO$_2$ powders [34, 35] with about 60% efficiency [36], after stopping muons from a surface beam stimulated experimental work at the Tri University Meson Facility (TRIUMF) in Vancouver, Canada, in the early 80’s. The signature for antimuonium was the detection of X-rays after capturing the negative muon in a calcium host atom. The data were analyzed under the assumption that the muonium atoms escape from the grains into the intergranular voids and yielded $G_{\text{MM}} \leq 42 \, G_F$ (95% C.L.) [37]. With a more complete understanding of the behaviour of muonium atoms inside of a powder target a reanalysis of the data limited the coupling constant $G_{\text{MM}}$ to less than $20 \, G_F$ (95% C.L) [38].

The observation of a few percent of the muonium atoms leaving SiO$_2$ powder target surfaces with thermal energies at TRIUMF [38] and at the Paul Scherrer Institut (PSI) in Villigen, Switzerland [39], was a major breakthrough in the mid 80’s. It has boosted experimental efforts searching for muonium to antimuonium conversion and has been employed in all new approaches since.

At TRIUMF an experiment using thermal muonium in vacuum requested a signature consisting of X-rays generated by the transfer of the negative muon to a host atom and followed by the delayed decay of a radioactive tantalum nucleus created by nuclear muon capture. A sensitivity of $G_{\text{MM}} \leq 0.29 \, G_F$ (90% C.L.) could be reached [40].

The thermal kinetic energy of the muonium atoms corresponds to a velocity of $7.4(1) \, \text{mm/µs}$ [39]. This assures that the atoms will stay in a small volume of about $100 \, \text{cm}^3$ for several natural lifetimes $\tau_\mu$ and allows for long times for the conversion to antimuonium.

At the Phasotron accelerator in Dubna, Russia, another experiment has been carried out using muonium in vacuum from a SiO$_2$ target. The only signal required was the observation of a single energetic electron from the negative muon’s decay in a narrow momentum band of 6.3 MeV/c right below the maximum possible momentum 53 MeV/c of the decay electron in muon decay. A limit of $G_{\text{MM}} \leq 0.14 \, G_F$ (90% C.L.) was deduced after one single event has been observed to fulfill the weak required criterion [41].

## 5 Coincidence Signatures of the Atom’s Decay

Major progress was achieved using a new powerful and clean signature requesting the coincident detection of both constituents of the antimuonium atom in its decay. This method was developed and applied for the first time in an approach at LAMPF, where a magnetic spectrometer was used to search for an energetic electron from the $\mu^-$ decay. The positron, which is expected to be left behind from the atomic shell with a
mean kinetic energy corresponding to the system’s Rydberg energy [42], could be electrostatically extracted from the interaction region and registered on a microchannel plate (MCP) detector. A limit of $G_{\text{Min}} \leq 0.16 G_F$ (90% C.L.) could be established [43]. The latest experiment at PSI (Fig. 5) [44, 45], implemented major improvements over the LAMPF setup. The solid angle for the detection of the energetic electron was increased by three orders of magnitude to 70% of $4\pi$ by using a cylindrical magnetic spectrometer equipped with five concentric proportional chambers and a 64-fold segmented hodoscope which was constructed from the former SINDRUM I detector. The atomic positron is electrostatically accelerated and guided in a momentum selective transport system parallel to the magnetic field lines to a position sensitive MCP with resistive anode readout [46]. The tracks of these particles can be traced back to the interaction region for reconstructing a decay vertex providing an additional suppression of background. Further the annihilation radiation of the positrons can be observed in a 12-fold segmented undoped, highly pure CsI crystal calorimeter (Fig. 5).

One of the design goals for the setup was to achieve as high as possible symmetry for the detection of both, antimuonium and muonium, in order to reduce the systematic uncertainties arising from corrections for efficiencies and acceptances of the detector.
subsystems. The production of the atoms has been monitored by reversing all electric and magnetic fields regularly every few hours for half an hour.

The setup at PSI has a significantly higher sensitivity for observing the decay of muonium atoms in vacuum than to those decaying inside of the production target, as it allows the coincident detection of a fast and a slow particle after the decay. Therefore a new determination method for the muonium production yield could be uniquely exploited. It is based on a model established in independent dedicated experiments [39], which assumes that the atoms are produced inside of the SiO$_2$ powder at positions given by the stopping distribution of the muons. A one dimensional diffusion process describes the escape of the muonium atoms into vacuum where their velocities follow a Maxwell-Boltzmann distribution. The distribution of time intervals between a stop of a muon and the detected decay of a muonium atom in vacuum includes full information on the atom’s production rate (Fig. 5). Using an effective diffusion equation for the movement of atoms inside the target parallel to an axis ($y$) orthogonal to the target surface the time distribution is derived for a diffusion length $l = \sqrt{D_M/\lambda_M}$ which is small compared to the target thickness $a$.

$$n_{M\text{vac}}(t) = f_M \cdot \exp(-\lambda_M t) \cdot \frac{1}{\sqrt{\pi \cdot D_M}} \cdot \int_0^t dt' \int_0^a dy S(y) \cdot \sqrt{\frac{a - y}{4 \cdot D_M \cdot t'}} \cdot \exp \left( \frac{(a - y)^2}{4 \cdot D_M \cdot t'} \right),$$  (4)

with $D_M$ the diffusion constant, $f_M$ the fraction of muons stopped with a density $S(y)$ inside of the target and forming muonium. There is no muonium in vacuum at $t = 0$. The maximum of $n_{M\text{vac}}(t)$ is approximately at 1.5 $\mu$s which is about the average time of diffusion for the muonium atoms in the target. The spectra contain a small exponentially decaying background arising from muon decays within the target which can be associated with the release of a secondary electron from the target material. Numerical fits (Fig. 5) typically yield a few percent of muonium atoms in vacuum with respect to the incoming muons. For a flat stopping distribution $S(y)$ and target thickness $a$ large compared to the diffusion length $l$ an analytical integration results in

$$n_{M\text{vac}}(t) = f_M \cdot \exp(-\lambda_M t) \cdot \frac{D_M}{\pi t}.\quad (5)$$

The expression contains the diffusion constant $D_M$ only as a part of the normalization factor.

An intermediate result from the PSI experiment, which is carried out in a two step approach, is available [45] on the basis of an effective measurement time of 210 hours during which $1.4(1) \cdot 10^9$ muonium atoms decayed inside of the fiducial volume of diameter 9 cm and length 10 cm. No decay of an antimuonium atom was observed. There are no entries in a 20 ns wide window around the expected time of flight of 70 ns for the positrons from the atomic shell (Fig. 6). The apparent structure around $t_{\text{TOF}} - t_{\text{expected}} = -50$ ns arises from the allowed rare decay mode $\mu^+ \rightarrow e^+ e^- e^- \nu_e \bar{\nu}_\mu$ in which one of the positrons is released with low kinetic energy, while the electron is detected in the magnetic spectrometer. Due to their significantly higher initial momenta positrons from these processes arrive at earlier times at the MCP and can be significantly distinguished from possible antimuonium decays. A small part of this observed background signal is due to positrons from normal muon decay which experience
Bhabha scattering in any structural component in the target region. The probability for a conversion in a 0.1 T magnetic field is \( P_{\text{MM}}(0.1 \text{ T}) \leq 2.8 \cdot 10^{-9} \) (90% C.L.), where corrections have been applied to account for differences in detection efficiencies while measuring the muonium production yield and while searching for antimuonium.

For \((V \pm A) \times (V \pm A)\) type interactions, the conversion probability is suppressed in a magnetic field of 0.1 T to 35% of the zero field value. This leads through Eq. (3) to an upper limit of \( G_{\text{MM}} \leq 1.8 \cdot 10^{-2} G_F \) (90% C.L.).

For dileptonic gauge bosons \(X^{++}\) in GUT models a tight new mass limit of \(M_{X^{++}}/g_3 > 1.1 \text{ TeV}/c^2\) (90% C.L.) can be extracted. This bound exceeds significantly the one deducted from high energy Bhabha scattering [23].

With these results from the first step of the PSI experiment models with dilepton exchange [19] as well as models with heavy leptons and radiative generation of lepton masses appear to be less attractive [16]. This is a nice examples for contributions of research using atomic objects for solving problems in the domain of particle physics.

6 Outlook for Future Experiments

The measurements in the second stage of the experiment at PSI promise further advances. Among the major improvements are a detector for positrons with four times enhanced efficiency [46] and a beam line (πE5) with 5 times higher muon flux. Data have been collected for some 1300 hours and a preliminary result [47] is available which sets in \((V \pm A) \times (V \pm A)\) coupling an upper limit of \( G_{\text{MM}} \leq 3.2 \cdot 10^{-3} \) \( G_F \) (90% C.L.). This provides an even more stringent test for speculative extensions to the standard model, in particular to the left-right symmetric models predicting a lower bound on \(G_{\text{MZ}}\) [14].
Fig. 6. The number of events with identified energetic electron and slow positron as a function of (a) the distance of closest approach $R_{dca}$ between the electron track in the magnetic spectrometer and the back projection of the position measured at the MCP and (b) the difference of the positron’s time of flight $t_{TOF}$ to the expected arrival time $t_{expected}$. The signal at earlier times is due to the allowed decay channel $\mu \to 3e2\nu$ and Bhabha scattering. It is smeared out because of the different acceleration voltages used. No event satisfied the required coincidence signature. The dotted and dashed curves correspond to a simulated signal for $G_{M\overline{M}} = 0.05G_F$.

In order to increase the sensitivity of detecting a possible conversion process of muonium into antimuonium considerably in the future a new experimental approach will be required. The present setup has come close to the limits imposed by the available muon fluxes at present meson factories, realistic durations of running times and the rate capabilities of available proportional wire chambers. The number of accidental coincidences is expected to become a serious problem for higher beam rates. At present, possible improvements to the existing setup at PSI appear to promise only marginal progress. However, at future highly intense pulsed muon sources one could take advantage of the time evolution of the conversion signal which increases quadratically in time (Eq. 2). Therefore a detection scheme could be envisaged which again uses the powerful coincidence detection of both constituents of antimuonium and which starts to look for antimuonium decays a few muon lifetimes after the formation of the system.

It should be noted that final state interaction in muonium decay could mimic an antimuonium decay, when energy is transfered from the positron of the $\mu^+ \to e^+ \nu$ decay to the electron in the atomic shell (internal Bhabha scattering). An energy transfer of more than 10 MeV while the positron remains with less than 0.1 MeV kinetic energy has a probability of well below $10^{-11}$ [44]. However, this process can be distinguished from an antimuonium decay by the characteristic energy spectra of the detectable particles as in the case of potential background from the allowed $\mu \to 3e2\nu$ decay. Therefore, there is no principle limitation which could prevent much more sensitive searches beyond the present bounds.

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