Muonium to Anti-muonium Conversion and $\mu^- - \mu^+$ Conversion

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A facility PRISM (**P**hase **R**otated **I**ntense **S**low **M**uon) is currently under an intense design work as one of physics projects for the forthcoming high intensity proton synchrotron in Tokai, Japan The Joint Project team of JAERI and KEK [1999]. With this very high intensity muon beam (10^{12} muons per second), we could be able to push forward physics in lepton flavor violation in near future. Muonium-antimuonium conversion could be studied below a level of $G_{\mathrm{Mu}\overline{\mathrm{Mu}}} < 10^{-4} G_F$, and $\mu^- - \mu^+$ conversion could be also studied.

1. Introduction

Muon has been being a very attractive particle for the study of the Lepton Flavor Violation (LFV) in the charged lepton sector since it can be produced copiously and the life time is reasonably large so that the design of the experimental setup becomes relatively easy. Muon is getting more interests in connection to the neutrino factory project since the number of muons available is expected to be bumped up more than several orders of magnitudes at the factory.

A facility called PRISM (**P**hase **R**otated **I**ntense **S**low **M**uon) utilizes the technology developed for the neutrino factory and dedicated for low energy muon experiments such as $\mu^- - e^\pm$ conversion PRISM [1998]. However, the application of PRISM beam is not limited to that, but covers wide varieties of particle physics experiment. In this report, the author will discuss Muonium–Antimuonium conversion experiment and $\mu^- - \mu^+$ conversion experiment at PRISM.

2. Muonium-Antimuonium Conversion Experiment

The spontaneous conversion of a muonium atom (a hydrogen-like bound state of μ^+ and e^-, $\mu^+ e^-$ or Mu) to its anti-atom (anti-muonium, $\mu^- e^+$ or $\overline{\mathrm{Mu}}$) is very interesting class of muon LFV process.

The present world record obtained at PSI Willmann et al. [1999] is $G_{\mathrm{Mu}\overline{\mathrm{Mu}}} \leq 3.0 \times 10^{-3} G_F$. In this experiment, high energy e^- from $\overline{\mathrm{Mu}}$ decay is measured by cylindrical wire chamber, and low energy e^+ (typically 13.5 eV) was detected by micro-channel plate detectors after electrostatic acceleration to 8 keV. The estimated number of background was more than one, $N_{BG} = 1.7$, and a single event was observed in the signal box.

There are two known major sources of background in this measurement. One is accidental coincidence between an energetic e^- produced by Bhabha scattering of e^+ from μ^+ decay in a muonium and a scattered e^+. The second is the physics background from the $\mu^+ \to e^+ \nu_e \overline{\nu_\mu} e^+ e^-$ decay (branching ratio being 3.4×10^{-5}). It would not impossible to reduce those background furthermore, and improve the $G_{\mathrm{Mu}\overline{\mathrm{Mu}}}$ another order of magnitude by modification of this detector. However, the author believes that it would be very difficult to improve more than that.

2.1. Activation Method

There is totally different experimental technique developed almost 10 years ago in TRIUMF Huber et al. [1990]. In this method, anti-muonium is detected by making it absorbed in tungsten nucleus, $\mu^- \mathrm{W} \to \nu_\mu\, {}^{184}\mathrm{Ta}$, at very thin surface of the target material. Tantalum is identified by observing triple coincidence of β decay with 8.7 hours of life time, and successive prompt 414

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keV γ decay and delayed γ cascade decays (mostly 921 keV). This method is totally insensitive to the background sources which limited PSI experiment. Furthermore, it could be able to handle practically almost infinite intensity of muon beam with this method because there is no active devices.

The only one disadvantage of this method is its small sensitivity. In the TRIUMF measurement, the sensitivity was only $(4.6 \pm 1.1) \times 10^{-7}$ per muon and this is almost four orders of magnitude smaller than that of PSI experiment (3×10^{-3} per muon). Because of this, the counter experiment was the right choice in the past, and the quite impressive improvements has been achieved in the last decade.

However, once we hit the physics background limit in the counter experiment, it would be worth to re-consider the activation method. Especially with PRISM, the smallness of the sensitivity would be no longer serious limitation since there will be an abundant muons.

2.2. Sensitivity and Background

By closely examining a detailed breakdown of the sensitivity of the activation method Huber et al. [1990], The author believes that it would be possible to improve the sensitivity by more than one order of magnitude. Firstly, the probability of ^{184}Ta production could be improved by factor 3 by using enriched pure ^{184}W material as target instead of natural abundant W in which the ^{184}W abundance is only 30.7%. Secondly, 414 keV γ detection efficiency could be improved by using large scale (relative efficiency being more than 120%) state-of-the-art Ge detector, more than factor 5. Delayed γ detection efficiency could be also improved by factor 1.5. As a result, the sensitivity would become a level of 10^{-5} per muon.

Exposing the apparatus to the $10^{12}\mu^+$/s from PRISM for 2000 hours with the above sensitivity would give us more than 3 orders of magnitudes of the improvement over the recent PSI result in the $\mathrm{Mu} - \overline{\mathrm{Mu}}$ conversion probability. Thus, $G_{\mathrm{Mu}\overline{\mathrm{Mu}}}$ would be studied below a level of $10^{-4}G_F$.

The potential background sources are beam μ^- contamination and cosmic ray. As for the beam μ^- contamination, it is very essential to reduce it below 3×10^{-14} level. At PRISM with FFAG ring, it should not be so difficult because FFAG ring naturally select a single charge state. Double stage kicker at the injection sector of FFAG will also block the late muons with different charge.

As for the negative muons from cosmic ray, it would stop uniformly in a bulk of tungsten target while anti-muonium only stops in a very thin surface of the target. Even after taking into account of the recoil of ^{184}Ta, the first layer of only 28 nm depth is affected by anti-muonium exposure. Thus the effect of background from cosmic ray could be directly measured by observing ^{184}Ta contamination in the inner layer.

3. $\mu^- - \mu^+$ Conversion Experiment

When a negative muon is stopped in target material, it is trapped by an atom and forms a muonic atom. The trapped μ^- cascades down in energy levels in the muonic atom to its $1s$ ground state within a level of ten pico second time range Czarnecki [1999]. The fate of the muon is then either decay in an orbit ($\mu^- \to e^-\nu_\mu\overline{\nu_e}$) or capture by a nucleus of mass number A and atomic number Z, $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$, under the consequence of the Standard Model.

In addition to them, there would be another type of processes which could be taken place in the context of physics beyond the Standard Model, namely $\mu^- - e^-$ conversion in a muonic atom ($\mu^- + (A, Z) \to e^- + (A, Z)$), $\mu^- - e^+$ conversion in a muonic atom ($\mu^- + (A, Z) \to e^+ + (A, Z-2)$) and $\mu^- - \mu^+$ conversion in a muonic atom ($\mu^- + (A, Z) \to \mu^+ + (A, Z-2)$). The first and second processes are frequently discussed in other articles elsewhere thus are not discussed in here Kuno and Okada [2001]. The third process violates the lepton numbers by two units in the second generation. This is a muonic analogue process to nuclear double β decay, and has never been studied experimentally before. Since the energy release from this process is very small, there are only three nuclei (^{44}Ti, ^{72}Se and ^{82}Sr) which could be used as the target Missimer et al. [1994]. All the nuclei are radioactive, and ^{44}Ti is the only one realistic solution since the life time of the other nuclei are miserably small.

3.1. Event Signature and Background

The occurrence of the process could be identified by looking at the mono-energetic μ^+ release from the μ^- stopped target. The energy of μ^+ in the final state is very small (about 1.62 MeV for ^{44}Ti).

It could be possible to identify the μ^+ by looking at the e^+ from Michel decay of μ^+. The drawback of this method is the handling of higher detector rate caused by e^- coming from the μ^- Michel decay in orbit. Many e^+'s would be also produced by electromagnetic shower of e^-, and which could be indistinguishable from the e^+ of the real event.

The alternative method is the direct identification of μ^+. Electron backgrounds could be rejected by using standard mass spectroscopy technique, thus the detector rate could be drastically reduced. It is also important that the μ^+ production rate from lower energy μ^- is practically zero if the initial energy of μ^-, E_{μ^-}, is less than $2m_\mu$.

3.2. Conceptual Design of the Experiment

Because the target is not a stable nucleus, it has to be artificially produced. This limits the available amount of the target material. The radioactivity of the target material also limits the total mass of target from the point of the view of the human safely. In addition to that, target has to be thin enough so that the low energy μ^+'s could escape out of the target. After all, target should be in a form of a thin film.

In order to keep the reasonable reaction rate with a such thin target, initial energy spread of μ^- has to be minimized. PRISM will be the best facility for $\mu^- - \mu^+$ conversion experiment since it will provide muon beam with very narrow energy spread and high intensity. Almost complete elimination of μ^+ contaminations in μ^- beam with FFAG ring is also very important.

As for the mass spectroscopy of 1.62 MeV μ^+, A variant of ordinal surface muon beam lines would be sufficient.

3.3. Sensitivity

The intensity of μ^- beam from PRISM is about 10^{12}/sec and the momentum spread is $\Delta p/p = \pm 2.0\%$. Muon stopping efficiency on 50 μm thick Sc-^{44}Ti target would be 4%.

^{44}Ti could be produced by bombarding 50 MeV protons on Sc target. The linac of KEK/JAERI Joint Project could provide us 10 mA of 50 MeV proton beams, thus it would be possible to transmuted 0.3% of 2g of Sc to ^{44}Ti.

The μ^+ acceptance of surface muon beam line would be an order of 0.4% by assuing 50 msr geometrical acceptance and $\Delta p/p = 10\%$.

After the 1 nominal year run (10^7 sec), it would be possible to achieve the sensitivity to $\mu^- - \mu^+$ conversion on ^{44}Ti nucleus about $R < 2 \times 10^{-13}$. This would correspond to $R <$ several $\times 10^{-10}$ in the relevant process in Kaon decay, $K^+ \to \pi^+\mu^+\mu^-$ Littenberg and Shrock [2000], and would be one order of magnitude improvement over the current world limit.

4. Conclusion

PRISM will provide very clean muon beam for the experimental study of $|\Delta L_i| = 2$ processes. The muonium-antimuonium conversion coupling constant could be studied below a level of $10^{-4}G_F$. The $\mu^- - \mu^+$ conversion could be performed with an order of magnitude higher sensitivity compare to the current limit from the relevant Kaon process.

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