Low emittance, slow muon source for new g-2 experiment

K. Ishida for the J-PARC muon g-2 source group

RIKEN Nishina Center, RIKEN, Wako, Saitama 351-0198, Japan

Abstract. We are developing of an ultra slow muon source for the new muon g-2 experiment at J-PARC. The purpose of the study and developments at TRIUMF and RIKEN-RAL are described.

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INTRODUCTION

The anomalous magnetic moment of the muon, ($a_\mu = (g-2)/2$), has served as a valuable testing ground for the Standard Model of particle physics. The most recent measurement, E821 at Brookhaven National Laboratory (BNL), has measured a_μ to a precision of 0.54 ppm [1]. The value obtained has been compared with the most updated Standard Model predictions, showing that a_μ exhibits significant deviation of $\sim$3.5 σ. Obviously further clarification is required to conclude that there is an indication of new physics beyond the standard model.

We submitted a proposal to J-PARC for the measurement of the muon g-2 [2] using a compact muon storage ring without any focusing field, by employing an ultra-cold muon beam where the transverse momentum dispersion is significantly smaller than its longitudinal momentum. If a muon is produced with room temperature energy ($\sim$25 meV, 2.3 keV/c in momentum) and then accelerated to $\sim$300 MeV/c, it would stay in the storage ring for more than ten times of its lifetime. The basic idea was presented in the previous nufact workshop[3].

It is estimated that an ultra-cold muon intensity of 10^6 /sec ($\sim 10^{13}$ /year) is required to complete the measurement in a few years. To achieve this intensity, we need efficient production of the ultra cold muon beam. The cold muon beam is produced by the following steps. The surface muon beam of around 4 MeV energy produced from the pion decay is stopped in a thin material; muons are emitted mostly as muoniums from the surface; muonium atoms are ionized with a high intensity pulsed Lyman-α laser; low energy muons are accelerated to make a cold muon beam.

Presently, the most critical factor for its application to the new muon g-2 experiment is the rate of low energy muons, which is 15 μ^+ per second at RIKEN-RAL[4]. We would need to increase the intensity nearly 5 orders of magnitudes. For the muon g-2 experiment at J-PARC, it is planned to increase the primary muon source intensity by 300 times with an all-solenoid muon channel[5] coupled to a J-PARC proton beam of 1 Megawatt. So we are left with the task of improving by a factor $\sim$200 the efficiency of the ultra-cold muon beam generation by developing an intense Lyman-α laser system. The muonium emission is also a key process for the generation of intense ultra-cold muon beam.

PRODUCTION OF THERMAL MUONIUM

The thermal energy of muonium emitted from hot tungsten, as used at the RIKEN-RAL facility, is around 2300 K, so its energy spread is 10 times larger than admissible and the beam is more difficult to confine in the storage ring. An alternative is to use silica powder. It is well known that silica powder emits muonium in vacuum even at room temperature. The emission of muonium in vacuum from silica powder was actively studied in the 1980s [6, 7, 8]. Muonium is formed with about 60% probability inside silica powder particles [9] and is emitted from the particles with 97% probability [10]. The nominal particle radius is as small as 3.5 nm (Cab-O-Sil EH-5 fumed silica). Emission from silica particles is followed by diffusion through the voids between particles at thermal speeds. This allows migration of the polarized muonium atoms over distances of the order of 0.3 mm within the powder, prior to decay. If the powder forms a layer in which the muonium is formed, it may escape the surface of the layer with significant probability, of order 20% for a layer of thickness 0.3 mm [6, 7, 8].

There are other advantages in using a room temperature target rather than high temperature targets. Due to the reduced thermal velocity of muonium, the resonant line for muonium excitation has a smaller Doppler broadening and also the spatial spread of muonium in vacuum is smaller, so we need less laser power to ionize the muonium.

On the other hand, the use of powder as the production target has several handling inconveniences. A stable

shaping of the target is required for the reliable operation of the cold muon source. So we started a study to find a self-supporting (solid) sample which has a similar or even better yield of muonium.

As the first step we carried out a μSR measurement at TRIUMF for various candidate materials in June 2010. We placed the sample in a vacuum chamber and stopped the muon in the sample. For the sample to be a good producer of muonium in vacuum, 1) muonium must be formed and muon polarization maintained (polarization is also important for muon g-2 measurements), and 2) muonium has to be emitted from the powder surface. These were tested by firstly observing the muonium spin precession signal under the applied magnetic field, and then observing if the muonium precession signal was quenched (namely, the relaxation rate becomes faster) by introducing oxygen gas in the vacuum chamber [10]. The muonium spin will react via spin exchange with paramagnetic oxygen molecules only if the muonium is in void between particles or in vacuum. Although this measurement cannot say whether the muonium could be emitted from the surface of a layer or not, it is a quick and simple screening test to reject poor muonium-in-vacuum production materials.

The materials measured were as follows. 1) silica powder (Cabot Cab-O-sil) and particulate silica aerogel (Cabot Nanogel) 2) silica aerogels of different densities (0.03, 0.05, 0.10 g/cm^3), 3) porous silica made by patterned etching and oxidation, 4) porous alumina of various pitch and pore diameters.

The relaxation rate increased linearly with oxygen concentration for the silica powder (Cab-O-sil, which is known to produce muonium), Nanogel, and three silica aerogel samples. The relaxation rate was very similar for all the samples at low oxygen concentrations, supporting the assumption that this is determined by the muonium spin interaction with the oxygen in the vacuum. We also tested porous silica samples and porous alumina samples. However, porous alumina didn't show a muonium polarization signal while porous silica didn't show any increased muonium polarization relaxation with the addition of oxygen.

After the muonium emission to voids, muonium diffuses through the void spaces between particles. Some of them may reach the target boundary and emerge to the material-free vacuum. Such muoniums can be detected by positrons from muon decay with position sensitive detectors such as MWPC. We will observe that the number of muon decays in the vacuum region adjacent to the target surface to increase with time after the muon stopping as the muons emerge as muoniums from the surface.

Since the ratio of the number of emitted muonium atoms to the number of muons staying in the sample is rather small, we need a positional resolution better than the typical separation of the muonium from the sample. Since the thermal velocity is of the order of 5 mm/μs and the time duration is of the order of the muon lifetime (2.2 μs), we need a positional resolution of a few mm or less.

An apparatus has been designed to use some of the MWDC planes remaining from the TWIST experiment at TRIUMF[11]. The intrinsic positional resolution of the drift chamber is of the order of 0.2 mm or better . It is the multiple scattering of positrons and parallax effect of the extrapolation that limits the tracking resolution. The tracking resolution at the sample was about 6 mm (FWHM) in previous measurements at TRIUMF [6].

We plan to use an MCP (micro channel plate) in addition to MWDCs to improve the measurement as shown in Fig. 1. While the MWDCs provide the decay positron track that can be extrapolated back to the approximate decay position at the muon stopping target, the MCP measures the source position of the remaining low energy electron following muon decay in muonium. The MCP measures a two-dimensional projection of the muonium decay position in a direction perpendicular to the positron track. Here, the electric and magnetic fields are designed to transport the electron to the MCP so a good imaging of the source position can be obtained at the MCP.

The spatial and time distribution is important by the following reasons. 1) Intense pulsed laser light is needed to ionize the muonium for later muon acceleration. Precise information on the muonium distribution is needed to design the costly laser system as well as the initial acceleration components optimally. 2) The spatial distribution reflects the velocity distribution of the emitted muonium and gives hints on the mechanism of the muonium emission. It also reflects the timing of muonium emission after muon stopping giving us the distance of the muonium to diffuse with time from the bulk to the surface. Such an information can be used to test models of the muonium emission and is useful in designing a optimized target.

The detection system was successfully committed for measurement at TRIUMF in Nov 2010, A preliminary analysis shows that the MCP works mostly as expected and greatly helps to identify the signal from muonium in vacuum. Unfortunately, because of the accelerator problem, we could study only one aerogel sample, which showed somewhat less efficiency than silica powders. We expect further measurement in 2011 to select the best materials for muonium emission.

MUONIUM IONIZATION WITH LASER

Another important factor for improving the slow muon yield is the ionization efficiency of the muonium. A high power ionizing laser is being developed in RIKEN to increase the Lyman-α laser power by two orders of mag-

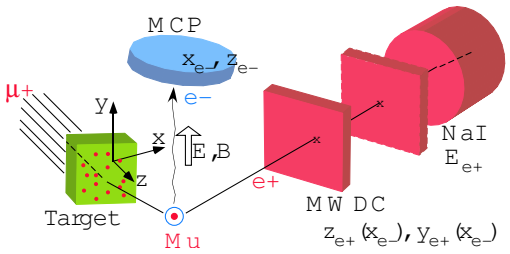

FIGURE 1. Conceptual layout of the muonium decay position measurement with MWDC and MCP.

nitudes. We expect at least 10 times more 212.5 nm laser power can be achieved than used for previous RIKEN-RAL experiments. It is simply expected that the Lyman-α (122 nm) intensity from the 4-wave mixing increases bi-linearly with the 212.5 nm laser power though too much ionization in the Kr/Ar mixing cell could destroy the phase matching condition. We will test the best mixing condition with the help of a simulation code in early 2011.

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