Development of magnetic shield for the MuSEUM experiment

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Muonium is a hydrogen-like atom consisting of a positive muon and an electron. Precision spectroscopy of its ground state hyperfine splitting (HFS) is the most stringent test of bound-state QED theory and the most precise determination of the muon mass. At J-PARC, the MuSEUM (Muonium Spectroscopy Experiment Using Microwave) collaboration is planning a new measurement of muonium HFS proceed in two stages; indirect measurement under a 1.7 T high magnetic field and direct measurement under a precise controlled zero magnetic field. The zero-field experiment is a preliminary measurement with existing facility toward the definitive high-field experiment, which requires a new muon beam line under construction. Our goal is to improve the precision of muonium HFS by about one order of magnitude in both experiments.

Spectroscopy of muonium HFS is performed by the measurement of positron angular asymmetry from muonium decay, which depends on the muonium energy state. The hyperfine transition is induced by microwave and muon spin flips when the transition occurs. Result of the most recent zero-field experiment[1] is 4.463022 (1.4) GHz (300 ppb) where the error is the statistical uncertainty. In the zero-field measurement of muonium HFS, one of the major sources of systematic uncertainty is the non-uniformity of a magnetic field in the muonium formation volume. According to the numerical simulation, requirement for the field non-uniformity is less than 100 nT peak-to-peak.

To perform the zero-field experiment, we developed muon and positron detectors[2], three-dimensional muon stopping distribution imager[3], RF cavity[4], magnetic field monitor, and magnetic shield of permalloy (high-permeable alloy of nickel and iron). Figure 1 shows the developed magnetic shield and field probe with a moving system. The shield was designed based on the results of a stray field analysis by the finite-element method. It consists of a three-layered box made of permalloy where the layer thickness is 1.5 mm and interlayer distance is 50 mm. The magnetic field strength is measured by a high-precision fluxgate probe (MTI FM3500) with a resolution of 0.5 nT. Without shielding, the typical magnetic field strength in the target volume was 100 μT and field non-uniformity was about 20 μT peak-to-peak.

Figure 2 shows the measurement result of the stray field inside the magnetic shield. The magnetic probe was moved on the beam-axis. The target volume corresponds to the probe position ranging from -150 mm to 80 mm. Typical field strength was suppressed to about 150 nT. A shielding factor, i.e., the ratio of the field strength with magnetic shield B_{w} and without shield B_{wo} was estimated at $B_{\mathrm{wo}}/B_{\mathrm{w}} = 700$. The field non-uniformity was about 30 nT peak-to-peak and the performance specification of the magnetic shield satisfied the requirement.

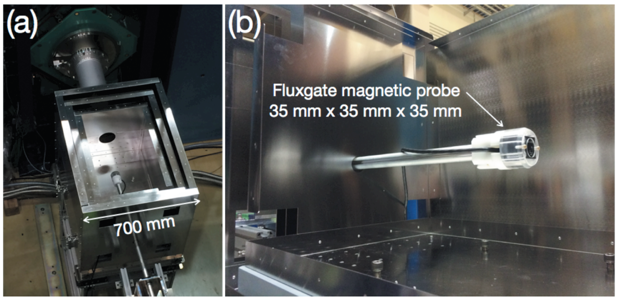

Fig. 1. Magnetic shield and fluxgate probe

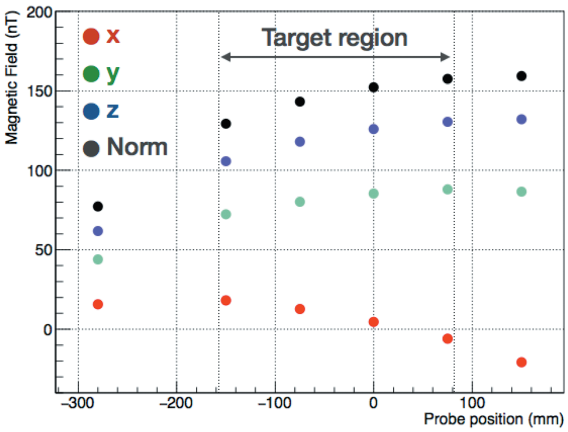

Fig. 2. Magnetic field distribution

The measured field non-uniformity was acceptable for the experiment. However, a factor of two higher shielding factor is expected from the simulation and laboratory measurement results. The field investigation implied that the shield is magnetized by the environmental magnetic field during assembly. Magnetization of inner layers of the shield should be suppressed by the attenuation current supplied by the degaussing coils. The degaussing device and method are under study. The development of every other experimental component has been completed and the first trial of zero-field measurement is scheduled in Feb. 2016 at J-PARC MLF MUSE.

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References

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