μSR study of the magnetism and superconductivity in the multi-layered Bi-2223 high-T_c superconductor

T. Adachi,[*1,*2] M. A. Baqiya,[*3] K. M. Suzuki,[*1,*4] K. Tsutsumi,[*4] M. Fujita,[*1,*4] S. Adachi,[*5] T. Watanabe,[*5] I. Watanabe,[*1] and Y. Koike[*1,*3]

In the research of high-T_c cuprate superconductors, the relationship between the magnetism and superconductivity has been a central issue. Nuclear-magnetic-resonance (NMR) experiments in the so-called multi-layered Hg-based cuprate Hg-1245 with 5 CuO_2 planes in the unit cell have revealed that the hole concentration per Cu, p, in the CuO_2 plane is larger in the outer planes (OP's) than in the inner planes (IP's) due to the difference in the coordination number of Cu between OP's and IP's.[1)] Moreover, it has been suggested that both antiferromagnetic (AF) order and superconductivity coexist homogeneously in a CuO_2 plane with a small p value. In the optimally doped Hg-1245 cuprate, it has been reported from zero-field (ZF) μSR measurements that a muon-spin precession is observed at low temperatures, suggesting the coexistence of AF order and superconductivity.[2)]

Fujii et al. have succeeded in growing sizable single-crystals of a tri-layered Bi-based cuprate $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ (Bi-2223) with $T_c = 110$ K.[3)] Recently, we have performed ZF-μSR measurements of the underdoped Bi-2223 single-crystals with $T_c = 87$ K, obtained through the reduction annealing. It has been found that the depolarization rate of muon spins, λ, increases with decreasing temperature and exhibits a local maximum at 10 K, followed by an increase below 5 K. This suggests the existence of two distinct Cu-spin correlations in a crystal probably originating from IP and OP's. However, the development of the Cu-spin correlation is weak even at 0.3 K, preventing us from investigating the detailed magnetic state in Bi-2223 cuprates. Based on the results, we have performed μSR measurements of Bi-2223 in the heavily underdoped (HUD) regime with $T_c = 40 - 60$ K, obtained through the further reduction-annealing. The ZF and longitudinal-field μSR measurements were carried out using a fly-past HELIOX cryostat at temperatures down to 0.3 K at RIKEN-RAL.

Figure 1 shows ZF spectra of the HUD Bi-2223. At 250 K, the spectrum shows a slow depolarization of muon spins, indicating that Cu spins fluctuate fast beyond the μSR frequency range. With decreasing temperature, it is found that the depolarization becomes fast gradually and an exponential-like depolarization is observed at 0.3 K, indicating the development of the Cu-spin correlation. The λ at 0.3 K is more significant than that observed in the underdoped crystals at 0.3 K. Moreover, the temperature dependence of λ exhibits local maxima at 40 K and 1 K probably corresponding to the development of the Cu-spin correlation in IP and OP's, respectively. The temperatures are higher than those observed in the underdoped crystals, respectively. These results suggest that the Cu-spin correlation is more developed in the HUD crystals than in the underdoped crystals, although no muon-spin precession due to the formation of a magnetic order is observed even at 0.3 K. Accordingly, the p value of IP in the HUD Bi-2223 cuprate may reside in the vicinity of the boundary between the AF and superconducting (SC) phases in the phase diagram.

In summary, we have found two distinct developments of the Cu-spin correlations probably originating from IP and OP's in the HUD Bi-2223 crystals. The p value of IP probably resides in the vicinity of the boundary between the AF and SC phases in the phase diagram, suggesting that the Bi-2223 crystals with T_c lower than ~ 40 K exhibit an AF ground state.

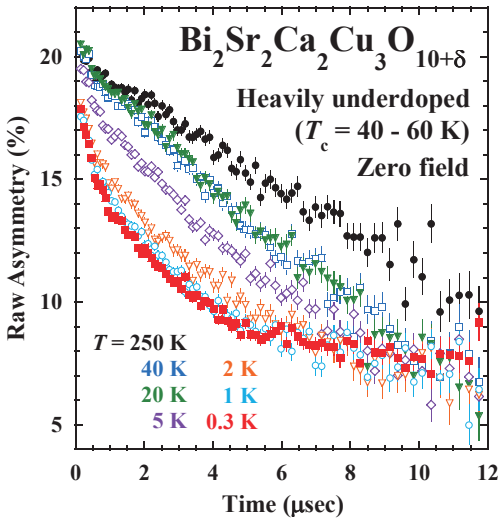

Fig. 1. Zero-field μSR time spectra of the heavily underdoped $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ single crystals with $T_c = 40 - 60$ K.

*1 RIKEN Nishina Center
*2 Department of Engineering and Applied Sciences, Sophia University
*3 Department of Applied Physics, Tohoku University
*4 Institute for Materials Research, Tohoku University
*5 Graduate School of Science and Technology, Hirosaki University

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