Modulated Kubo-Toyabe functions to study fluctuated weak magnetism and muon diffusion at pseudogap state of underdoped $La_{2-x}Sr_xCuO_4$

M. D. Umar[*1,*2] and I. Watanabe[*1,*2]

One of the interesting puzzles for understanding the nature state of the pseudogap at the cuprate-based high-temperature superconductor is the discrepancy between neutron scattering and muon spin relaxation experiments in the detection of spontaneous magnetic order by, for instance, orbital (loop) current or intra-unit-cell (IUC) magnetic order. A neutron scattering experiment on YBCO[1)] has shown the presence of an ordered magnetic state preserving the translational symmetry of the underlying lattice, indicating the orbital current model. This result was also supported earlier by an angle-resolved photoemission spectroscopy (ARPES) experiment, which confirmed time-reversal-symmetry breaking (TRSB) at the pseudogap state of Bi-2212.[2)] Contrary to Neutron scattering and ARPES results, μSR has confirmed the absence of TRSB associated with the spontaneous ordered magnetic state in the single crystal of LSCO.[3)] However, using a pulse-μSR experiment, Watanabe *et al.*[4)] strongly indicated the presence of weak magnetism at the pseudogap state in a polycrystalline LSCO sample.

A theoretical study[5)] on the effect of screening charge density on a muon (point charge) has been proposed to explain the discrepancy. To confirm the presence of weak magnetism associated with the orbital current model or IUC magnetic order due to the screening process, by applying the Kubo-Golden Formula, we have extended known Kubo-Toyabe functions (muon spin relaxation functions) for four scenarios of the internal field distribution of nuclear moments on muon sites broadened by a comparable weak magnetism. The scenarios of two independent sources include a Gaussian distribution (nuclear moments) broadened by a delta-function distribution (ordered magnetic state in a polycrystalline sample), Lorentzian distribution, and Voigtian distribution. Another possibility for nuclear moments belonging to a Voigtian distribution broadened by weak sources with a Lorentzian distribution has been developed.

Since muon diffusion and the dynamic behavior of weak magnetism in the dependence of temperature and doping concentration can also possibly occur in a μSR experiment, we have extended muon spin relaxation functions for dynamic cases (modulated Kubo-Toyabe functions). The dynamic cases are constructed by applying a strong collision model with a modulated internal field on muon sites treated as a Markovian process. The equations of the modulated Kubo-Toyabe function for the developed scenarios exist in the Volterra integral equation, and they can be solved numerically. In our ongoing research, we have been implementing the numerical solution of Volterra integral equation in Mathematica software with the trapezoidal method, in which every area of the partitioned integration interval is approached as a trapezoid.

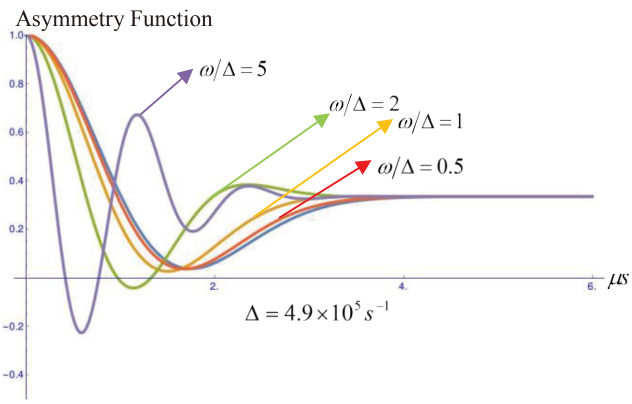

Fig. 1. Line shapes of the muon spin relaxation function for the summation of internal fields from the ordered magnetic state of a polycrystalline sample and nuclear moments in the zero-field condition plotted for different ratios of the field from the ordered magnetic state ($\omega = \gamma_\mu B$) to the width of the dipole nuclear field (Δ).

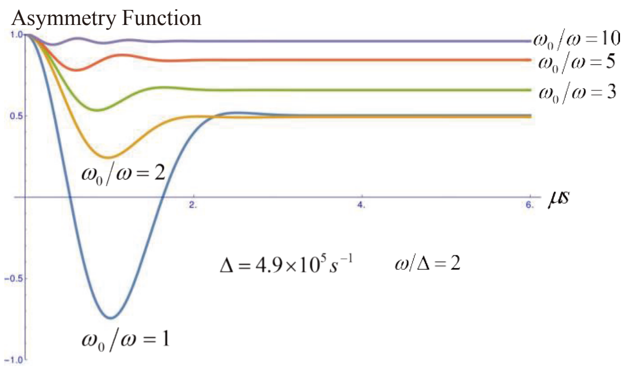

Fig. 2. Line shapes of muon spin relaxation function for the summation of internal fields from the ordered magnetic state of a polycrystalline sample and nuclear moments in the longitudinal-field (LF) condition plotted for different ratios of the applied longitudinal field ($\omega_0 = \gamma_\mu B_{LF}$) to the field from the ordered magnetic state ($\omega = \gamma_\mu B$).

References

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*1 RIKEN Nishina Center
*2 Department of Physics, Hokkaido University