Generalization of muon spin relaxation function to study the pseudogap state of the underdoped $La_{2-x}Sr_xCuO_4$

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The origin of the partial gap in the charge and spin sectors at the normal state of cuprate-based superconductors called, pseudogap state, and its interplay with the superconducting state are still elusive. One study proposed that the pseudogap state is a precursor of the superconducting state, while another study argued that the state is a competing order such as spin or charge density waves, stripes, and other exotic orders, for instance, d-density wave and circular current models.[1)]

The μSR technique is a sensitive tool to investigate the static and dynamic behaviors of the internal magnetic fields. The previous μSR time spectra of the underdoped regime of $La_{2-x}Sr_xCuO_4$ showed that the initial line shapes change from the Gaussian-shape depending on the temperature and doping concentration.[2,3)] At a low temperature range, the characteristic temperatures due to the changes in the Gaussian-shape are related to the formation of a spin glass system[2)], and at a low temperature range and, at a higher temperature range, they are correlated with a minimum resistivity from the metal-insulator crossover experiments.[3)] A product of the Lorentzian and Gaussian functions can approach the changes from the Gaussian-shape in the two previous studies.[2,3)] In a fast fluctuation limit, the longitudinal field dependence of the relaxation rate is described by Redfield formula.[4)] However, the relaxation rate of the Lorentzian function may represent static or dynamic internal fields on the muon site.[5)] Replacing the Gaussian or Lorentzian exponentials of the Kubo-Toyabe functions with a stretched exponential[6)] and convoluting the Gaussian and Lorentzian probability density functions (PDFs)[7)] are two static scenarios that have been proposed earlier to fit the intermediate state of the line shape between the Gaussian- and Lorentzian-shapes.

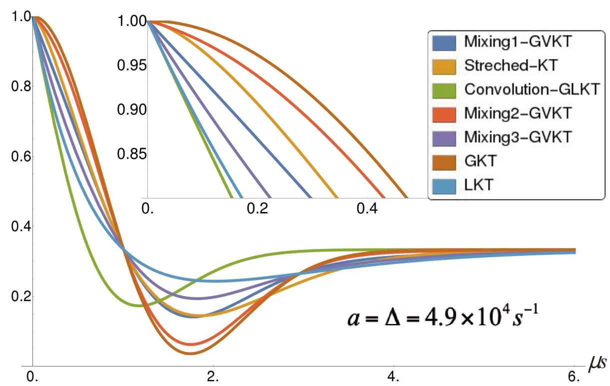

Fig. 1. The line shapes of the mixture of the Gaussian and Lorentzian PDFs in the ZF conditions with three different ratios of weight factors (n) compared to the convolution of the Gaussian and Lorentzian PDFs and the stretched exponential scenarios plotted with the same width of the Gaussian (Δ) and Lorentzian (a) distributions.

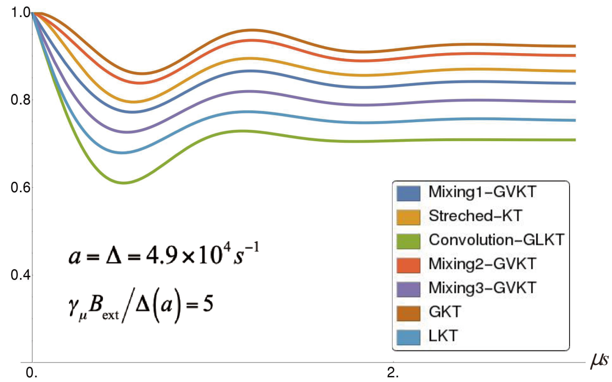

Fig. 2. Calculated time spectra in the LF experiment for all cases in Fig. 1, plotted for the same ratio of the applied longitudinal field ($\gamma_\mu B_{\rm exp}$) to the width distributions (Δ, a).

As an alternative for the static scenario due to the tiny changes in the Gaussian-shape, we propose a mixture of Gaussian and Lorentzian PDFs. In general, mixing two or more PDFs is interpreted in terms of either the non-normal behavior of the PDF or the presence of two or more subpopulations.[8)] Moreover, the mixing of the Gaussian and Lorentzian PDFs can approach a convolution of the Gaussian and Lorentzian PDFs.[9)] We apply the Kubo Golden Rule (KGR) formula to derive the muon spin relaxation functions resulting from the mixing of the Gaussian and Lorentzian PDFs for both zero- (ZF) and longitudinal-field (LF) experiments. Our result shows that the mixture of the Gaussian and Lorentzian PDFs can approach the convolution and stretched exponential scenarios. Our derivation also confirmed that the KGR formula for the LF condition can analytically produce the Lorentzian part, which is contrary to a previous claim.[10)] The analysis function of the mixture of the two PDFs exhibits initial slopes between the Gaussian and Lorentzian shapes in both the ZF and LF conditions, whereas the depth and position of a dip in the ZF lineshape change with the ratio of the Gaussian and Lorentzian weighting factors.

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