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Muon polarization in the presence of exotic spin correlations

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Abstract

We investigate the signatures of the correlation functions $q(t) = 2ct^{-x}\exp[-(\nu t)^y]$ on the muon polarization $P(H,t)$, in a longitudinal field $[H]$ experiment. We find three major features: (I) $\dot{P}(H,0) = 0$ as for a Gaussian, (II) the smaller the x the easier the decoupling, and (III) there is always time t long enough, and H high enough that scaling relations of the form $P(H,t) = P(t/H^{\gamma})$ hold; if $\gamma < 1$ then $\gamma = 1 - x$; however if $\gamma > 1$ then $\gamma = 1 + y$. The required range for t and H where scaling should exist is discussed. © 2000 Elsevier Science B.V. All rights reserved.

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Recently [1], a longitudinal field μSR (LF-μSR) experiment in the Heisenberg spin glass AgMn (0.5 at%) demonstrated a magnetic field-time scaling relation, for high fields, of the form

$$P(H,t) = P(t/H^{\gamma}). \tag{1}$$

Here P is the muon-spin polarization, H is a magnetic field applied in the initial muon-spin direction, t is the time from the moment the muon enters the sample, and γ is an exponent to be determined by the experiment. At $T \to T_g^+$, an unusual value of $\gamma < 1$ was found and interpreted as a sign of a non-exponential [exotic] field–field dynamical auto correlation function $q(t) \equiv \gamma_{\mu}^2 \langle \boldsymbol{B}(t)_{\perp} \cdot \boldsymbol{B}_{\perp}(0) \rangle$ ($\perp$ is perpendicular to H). This conclusion was based on the assumption that in the most simplified approach (SA), the muon-spin relaxation rate is determined by the Fourier transform (FT) of $q(t)$, evaluated at $\omega = \gamma_{\mu} H$, where γ_{μ} is the muon gyromagnetic ratio. The FT of an exponent is a Lorenzian which asymptoticaly falls off as ω^{-2}, therefore, the exponential case should give $\gamma = 2$. However, this is in contrast with experimental finding in AgMn (0.5 at%) and hence the conclusion of exotic correlations.

However, the SA is sometimes over simplified. Moreover, the scaling relation in Eq. (1) could not hold at $H \to 0$. The purpose of this paper is therefore to put the scaling relation on firm grounds as well as to extend the analysis of "exotic" correlation functions to fields which approach zero.

The starting point for our more complete approach (CA) is the following expression [2,3],

$$P(H,t) = P_0 \exp[-\Gamma(t)t]$$

$$\text{where } \Gamma(t)t = \int_0^t (t-\tau) q(\tau) \cos(\omega\tau)\, d\tau. \tag{2}$$

It is instructive to examine this expression in the exponential case where $q(t) = 2\Delta^2 \exp(-\nu t)$, ν is the fluctuation rate, and Δ/γ_{μ} is the RMS of the instantaneous field distribution experienced by the

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muon. This leads to

$$\Gamma(t)t = 2\Delta^2([\omega^2 + v^2]vt + [\omega^2 - v^2] \times e^{-vt}\cos(\omega t)]2v\omega e^{-vt}\sin(\omega t))/(\omega^2 + v^2)^2 \quad (3)$$

an expression which was shown to agree very well with Monte Carlo simulation, as well as the dynamical Kubo–Toyabe formalism [3].

Several important conclusions could be immediately derived from Eq. (3): (1) from the experimental point of view, v could be estimated as inverse of the time that wiggles are observed in the data $[t_w]$, (2) at later times $(t > t_w)$ $\Gamma(t)t \simeq \Gamma t = 2\Delta^2 vt/(\omega^2 + v^2)$ and the relaxation rate Γ (also know as $1/T_1$) is indeed a Fourier transform of $q(t)$, (3) at late time and high field determined by $H \gg (\gamma_\mu t_w)^{-1}$ one expects a magnetic field time scaling relation $P(H,t) = P(t/H^2)$ as previously discussed. Thus the CA leads to the same conclusions as the SA at least for the exponential case.

With these results in mind we now examine $P(H,t)$ for a cut off power law type correlation function $q(t) = 2\Delta^2[\tau_c^x/(t+\tau_c)^x]\exp[-(vt)^y]$. We introduced the time τ_c so that $q(t)$ is properly normalized at $t = 0$. However, for μSR this expression could be replaced with

$$q(t) = 2ct^{-x}\exp[-(vt)^y], \quad (4)$$

where $c = \Delta^2\tau_c^x$ since τ_c is expected to be on the scale of 10^{-13}–10^{-11} s, while the first point in time where the muon polarization is measured is at $t \simeq 10^{-7}$ s. To demonstrate the validity of this replacement let us consider the case where $y = 0$ and zero field. In this case we can write $\Gamma(t)t = \int_0^{10\tau_c}(t-\tau)q(\tau)\,d\tau + \int_{10\tau_c}^{t}(t-\tau)q(\tau)\,d\tau$. The first term is smaller than $20\Delta^2 t\tau_c$. The second term is $2\Delta^2\tau_c^x t^{2-x}/(2-x)(1-x)$ [using $q(\tau) = 2\Delta^2\tau_c^x/t^x$]. The ratio between the first and second terms is smaller than $10(2-x)(1-x)(\tau_c/t)^{1-x}$, which for $x > 0.5$ is less than 0.1. Thus, we can safely replace the properly normalized $q(t)$ with Eq. (4) knowing that the contribution to $\Gamma(t)t$ from the singularity at $t = 0$ is negligible. We note, however, that x and τ_c could be temperature dependent and therefore c is a function of T.

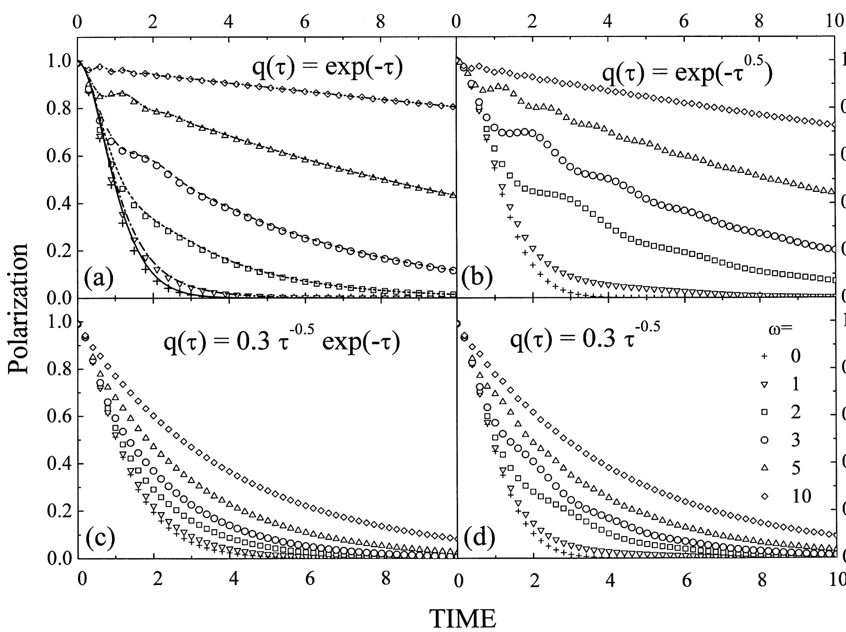

Fig. 1 . Muon-spin polarization obtained numerically (lines) for different correlation functions and various longitudinal fields. In (a) the polarization obtained analytically (symbols) using Eq. (3) is shown.

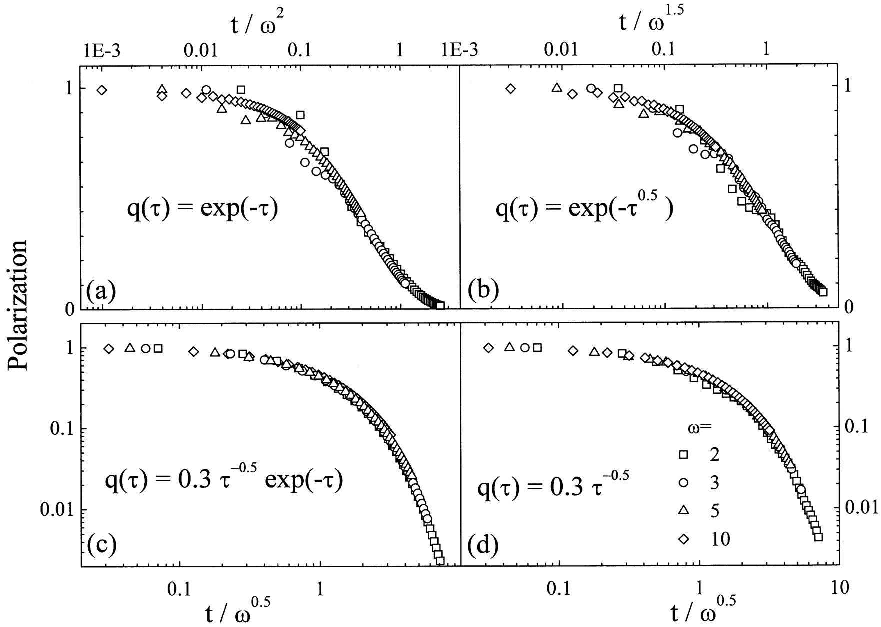

Fig. 2 . The muon polarization $P(H,t)$ as a function of t/ω^{γ} where $\omega = \gamma_{\mu}H$ and γ is indicated on the time scale.

Eq. (2) with Eq. (4) as an input is not integrable analytically, and so numerical methods must be applied. We use the "improper integration" method described in Ref. [4]. As a test of this approach we compare in Fig. 1a the numerical results (lines) for the case $x = 0$ and $y = 1$ (the pure exponential), with the analytical result given by Eq. (3) (symbols), at various fields. The agreement between the two methods demonstrates the accuracy of the computer program.

In Fig. 1b–d we show the expected muon polarization for $q(t) =: \exp(-t^{0.5})$, $0.3t^{-0.5}\exp(-t)$, and $0.3t^{-0.5}$, respectively, and various fields. The prefactor in the correlation function c was chosen so that all relaxation rates are nearly identical at zero field. This allows us to compare the effectiveness of the field in decoupling the muon polarization. Clearly, the decoupling is harder in cases which involve a power law. More important is the fact that wiggles are observed in the data. These wiggles are not obtainable with the SA.

The early time behavior of the numerical data indicates that in all cases $\dot{P}(H,0) = 0$. This, in fact, could be understood using term by term integration of Eq. (2) with (4) which leads to $\Gamma(t)t = 2ct^{2-x}/(2-x)(1-x) + O(t^{3-x})$. Thus, the derivative of P is zero at $t = 0$, and the smaller is x, the closer is the wave form to a Gaussian at early times. This conclusion is a special property of the CA.

In Fig. 2 we demonstrate that the scaling relation given by Eq. (1) holds for high enough fields and late enough time for the different correlation functions given in Fig. 1. In the cases involving a power law we find $\gamma = 1 - x$. Therefore, as $x \to 0$ the decoupling becomes easier. In the stretched exponents cases ($x = 0$) we obtain $\gamma = 1 + \beta$. The relations between γ and the parameters of the correlation function were derived previously, using the SA [1]. Thus, our numerical results demonstrate that the scaling relations holds even when the CA is used.

Finally, we discuss the critical value above which H and t are considered large. Our numerical results show that as in the pure exponential case this value is determined by the length of time wiggles are observed in the data t_{w}. Late times are $t > t_{\mathrm{w}}$, and high fields are $H > (\gamma_{\mu}t_{\mathrm{w}})^{-1}$. It is therefore very important to observe wiggles in the data before scaling could be applied in a meaningful way. Without the wiggles one is never sure if the applied fields are large enough. The application of these results to real data is demonstrated in Ref. [5].

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