Effect of a magnetic field on the longitudinal spin relaxation of μ^+ in isotropic ferromagnets in the critical paramagnetic vicinity of T_C

A. V. Lazuta and V. Yu. Yushankhaĭ

B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR; Joint Institute for Nuclear Research

(Submitted 11 July 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **44**, No. 10, 466–468 (25 November 1986)

A theory is derived for the behavior of the longitudinal spin relaxation $\Lambda_{\parallel}(\tau,H)$ of muons as a function of the magnetic field H in ferromagnets in the critical region above T_C. The results show that a study of $\Lambda_{\parallel}(\tau,H)$ would make it possible to determine the spin diffusion coefficient of the magnetic material.

The μSR method has been used to study the critical behavior of the ferromagnetic metals Ni and Pd (2.0 at.% Mn).[1,2] In the paramagnetic phase, the spin relaxation rate of μ^+ has been observed to increase toward T_C because of a critical retardation of spin fluctuations of the magnetic metal atoms. It also turns out that applying a relatively weak magnetic field H causes a qualitative change in the temperature dependence of $\Lambda_{\parallel}(\tau,H)$ $[\tau=(T-T_C)/T_C]$ (Ref. 2). No systematic study has been made of the H dependence of $\Lambda_{\parallel}(\tau,H)$, and the effect observed in Ref. 2 has not been theoretically explained.

Let us examine the effect of H on $\Lambda_{\parallel}$ in cubic ferromagnets near T_C. We will show that a study of $\Lambda_{\parallel}(\tau,H)$ would offer a unique opportunity for studying the hydrodynamic region of critical fluctuations in ferromagnetic metals. In particular, such a study would make it possible to work from the μSR data to determine the spin diffusion coefficient D. The question of a determination of D by an ESR method was studied in Ref. 3. On the basis of that analysis, values were found for D for the ferromagnetic semiconductors $CdCr_2Se_4$ and $CdCr_2S_4$ (Ref. 4). However, the ESR techniques are severely limited in metals, and we know of no experimental study on ESR in metals in the critical region above T_C.

We write the interaction of the magnetic moment $\frac{1}{2}\gamma_\mu \vec{\sigma}$ of a muon localized at the position $\mathbf{r}_\mu$, with magnetic moments $g\mu S$ of the magnetic material at sites $\mathbf{l}$, as follows:

$$V(\mathbf{r}_\mu) = \frac{1}{2}\gamma_\mu g\mu \sum_{\mathbf{l}} \sum_{\alpha,\beta} \sigma_\alpha(\mathbf{r}_\mu) \widetilde{\mathscr{F}}_{\alpha\beta}(\mathbf{r}_\mu - \mathbf{l}) S_\beta(\mathbf{l}) . \quad (1)$$

Here $\hat{\mathscr{F}}$ is a tensor which in metals is determined by dipole forces and by an isotropic hyperfine interaction with a constant A_{hf}. For $\hat{\mathscr{F}}$ in the $\mathbf{q}$ representation, which we will need below, we have the expression

$$\widetilde{\mathscr{F}}_{\alpha\beta}(\mathbf{q}) = \frac{4\pi}{v_0}\left(\frac{1}{3}\delta_{\alpha\beta} - \frac{q_\alpha q_\beta}{q^2}\right) + \frac{1}{v_0} A_{hf}\delta_{\alpha\beta} , \quad (2)$$

where v_0 is the volume of the unit magnetic cell. Introducing a retarded binary spin Green's function $\hat{G}(\mathbf{q},\omega)$ of the magnetic material, and using (1) and (2), we find the following expression for $\Lambda_\parallel$ in a coordinate system with z axis running along $\mathbf{H}$:

$$\Lambda_\parallel(\tau, H) = (\gamma_\mu g\mu)^2 \sum_{\alpha = x, y} \sum_{\beta, \rho} \frac{v_0}{(2\pi)^3}$$

$$\times \int d\mathbf{q}\, \mathscr{F}_{\alpha\beta}(\mathbf{q})\, \mathscr{F}_{\alpha\rho}(\mathbf{q}) \frac{T_C \operatorname{Im} G_{\beta\rho}(\mathbf{q}, \omega, \mathbf{H})}{\omega}\Big|_{\omega = \omega_\mu} , \quad (3)$$

where ω_μ is the precession frequency of the μ^+. In deriving (3) we allowed for the fact that in cubic ferromagnetic metals μ^+ localizes in either octahedral or tetrahedral voids. Expression (3) is essentially the well-known purturbation-theory result used in NMR.[5,6]

Let us examine the exchange temperature region, in which the magnetic susceptibility satisfies[7] $4\pi\chi(\tau) \ll 1$; we begin with the case of a weak field,[8] $g\mu H \ll T_C \tau^{5/3}$. In a zero field, using the hypothesis of dynamic similarity for G, we easily find[6] $\Lambda_\parallel(\tau,0) \equiv \Lambda(\tau) \propto \tau^{-1}$. As was shown in Ref. 3, in a weak field there is a substantial change in only the dynamics of transverse spin hydrodynamic fluctuations. The corresponding expression for the cyclic components $C_{\pm\mp}$ under the condition $q \ll R_C^{-1}$ ($R_C \propto \tau^{-2/3}$ is the correlation radius) is

$$G_{+-}(q, \omega, H) = G_{-+}(q, \omega, -H) = G_0(\tau) \frac{-g\mu H + iD(\tau)q^2}{\omega - g\mu H + iD(\tau)q^2} ; \quad (4)$$

where G_0 is the static Green's function. As a result, the transverse components of $\hat{G}$ determine the field dependence of $\Lambda_\parallel$, for which we find from (1)–(4), ignoring ω_μ in comparison with $g\mu H$,

$$\Delta\Lambda_{\parallel}(\tau, H) = \Lambda_{\parallel}(\tau, H) - \Lambda(\tau) = -c_i \frac{(\gamma_\mu g\mu)^2}{v_0} T_C G_0(\tau) \frac{(g\mu H)^{1/2}}{D(\tau)^{3/2}}, \tag{5}$$

$$c_i = \frac{\pi}{\sqrt{2}} \frac{56}{45} + \frac{2}{(2\pi)^2} A_{hf}^2 .$$

We see that applying a field H reduces Λ. The proportionality $\Delta\Lambda_{\parallel} \propto H^{1/2} D^{-3/2}$ is a direct consequence of the circumstance that a fluctuating field acting on the μ^+ spin contains a nonlocal hydrodynamic diffusion mode. A study of $\Delta\Lambda_{\parallel}(\tau,H)$ will make it possible to determine D if the A_{hf} are known and if we know $\chi(\tau)$ from static measurements. The latter quantity is related to $G_0(\tau)$ by $4\pi\chi = \omega_0 G_0$ $[\omega_0 = 4\pi(g\mu)^2 v_0^{-1}]$. For this purpose, at a fixed value of τ, we need to find the interval of H in which the relation $\Delta\Lambda_{\parallel} \propto H^{1/2}$ holds. As is clear from (5), the proportionality coefficient in this dependence determines $D(\tau)$.

We ignored the uniform dipole damping of Γ_d above.[9] When we take it into account, Dq^2 in (4) acquires an increment[3] Γ_d, which in turn leads to a replacement of $(g\mu H)^{1/2}$ in (5) by $\{[(g\mu H)^2 + \Gamma_d^2]^{1/2} + \Gamma_d\}^{1/2} - (2\Gamma_d)^{1/2}$. Expression (5) thus holds at $T_C \tau^{5/3} \gg g\mu H \gg \Gamma_d$.

Let us examine $\Lambda_{\parallel}(\tau,H)$ in the case of a field which is not too weak $(g\mu H \gg \Gamma_d)$ but which is otherwise arbitrary. Working from the hypothesis of dynamic similarity in a field,[6] we find

$$\Lambda_{\parallel}(\tau, H) = \frac{\Lambda_0}{\tau} \varphi\left(\frac{h}{\tau^{5/3}}\right), \qquad h = \frac{g\mu H}{T_C}, \tag{6}$$

where $\varphi(0) = 1$, and $\Lambda_0 \sim (\gamma_\mu g\mu/v_0)^2 T_C^{-1}$. In (5) we have actually determined the first term in an expansion of $\varphi(x)$ under the condition $x \ll 1$. Since $D \propto \tau^{1/3}$ and $G_0(\tau) \propto \tau^{-4/3}$ (Ref. 6), we find from (5) $\varphi(x) = 1 - c\sqrt{x}$, where $c \sim 1$. We must emphasize that a weak field has a greater effect on $\Lambda_{\parallel}$ than on the static quantities, to which the corrections are on the order of $(h/\tau^{5/3})^2$. In a strong field $(h \gg \tau^{5/3})$, $\Lambda_{\parallel}$ depends primarily on H. As follows from (6), we have $\Lambda_{\parallel}(0,H) \propto H^{-3/5}$. It is not possible to theoretically determine whether $\Lambda_{\parallel}$ remains a monotonic function of τ or goes through a maximum when a field H is applied. A maximum was observed in Ref. 2. By virtue of (6), its position would then be $\tau_m \propto H^{3/5}$, and we would have $\Lambda_{\parallel}(\tau_m, H) \propto H^{-3/5}$.

Let us take a closer look at Ref. 2, where a study was made of $\Lambda_{\parallel}$ in PdMn above T_C. At $H = 0$, the rate Λ increased with decreasing T, all the way to $T_C = 5.8$ K. In a field $H = 5$ kOe, a maximum appeared in the dependence $\Lambda_{\parallel}(\tau)$ at $T_m = 10$ K $(\tau_m \approx 0.7)$. Using $g_{\text{eff}} = 2.7$ for Mn in Pd (Ref. 2), we find that at $\tau = \tau_m$ the corrections to the static quantities are $(h/\tau_m^{5/3})^2 \approx 7 \times 10^{-2}$, whereas Λ decreases more than twofold: $\Lambda_{\parallel}(\tau_m, H) \approx 0.4\Lambda(\tau_m)$. Such a sharp change in Λ in a statically weak field is evidence that a field dependence of $\Lambda_{\parallel}$ of a "diffusion" nature was probably observed in Ref. 2.

Finally, since we have $\Lambda_{\parallel}(0,h) = c_1 \Lambda_0 h^{-3/5}$ by virtue of (6), we find from the experimental results that the constant c_1 satisfies $c_1 \ll 1$.

We wish to thank A. G. Aronov for useful comments.

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Translated by Dave Parsons