Relaxation of the spin of a positive muon in superconducting Nb_3Al

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The dipole relaxation rate σ has been measured for the spin of a positive muon in the superconducting state of the alloy Nb_3Al at 12 K. The experimental time dependence of the muon polarization can be described well by the Kubo-Toyabe function describing the static distribution of the dipole magnetic fields of the nuclei in the Nb_3Al crystal lattice in the absence of muon diffusion. The experimental value $\sigma = 0.402 \pm 0.002\,\mu s^{-1}$ corresponds to an rms value ~ 8.2 Oe of the nuclear magnetic field at the muon.

Measurements of the magnetic dipole interactions of the spin of a positive muon in a metal constitute an effective method for studying the diffusion of the muon,[1–3] which may be treated as a lighter isotope of the proton from the standpoint of solid-state physics. The diffusion properties are determined from the time evolution of the polarization of the muons, $P(t)$, caused by the dipole interactions of the muons with the magnetic moments of the nuclei of the crystal lattice of the metal.

In a study of slow diffusion of muons, the most sensitive method is to measure $P(t)$ in a zero external magnetic field, as proposed in Ref. 3. Interesting systems in this regard are metals in the superconducting state: The external field is exactly zero in the superconducting regions of such samples. Furthermore, working with superconductors has the important experimental advantage that it is possible to completely eliminate the background due to the stopping of some of the muons in the walls of the cryostat.

This background reaches levels as high a 20% and seriously distorts the time dependence $P(t)$ in the test sample. The cryostat background is eliminated in this case by using a relatively weak transverse external magnetic field H, which induces a Larmor precession of the "background" muons that have been stopped in the walls of the cryostat and thus do not penetrate into the superconducting sample. In order to eliminate the effect of the "freezing" of the external magnetic field in the superconductor, the field H is applied after the metal is cooled to the superconducting state, in this case after the Nb_3Al alloy is cooled to the measurement temperature $T = 12$ K. The relaxation of the spin of the muon in the superconductor results exclusively from the nuclear magnetic fields of the surrounding atoms, and the observed dependence $P(t)$ is the sum

$$P(t) = P_{\mathrm{Nb_3Al}}(t) + P_b(t) \tag{1}$$

of a precession signal (a background signal) and a relaxation signal (in the Nb_3Al). These signals can easily be distinguished from each other. The term "relaxation μ signal" emphasizes the fact that the relaxation of the spin of the muon in Nb_3Al, which is observed in this case, occurs in the absence of an external magnetic field.

The Nb_3Al sample used in the present experiments was prepared by arc melting in argon; it was a disk 30 mm in diameter and 10 mm thick. A chemical analysis of the alloy revealed a nearly stoichiometric composition: 75.4 at. % niobium and 24.6 at. % aluminum. The critical temperature of the alloy in a zero external magnetic field was found to be $T_{\mathrm{cr}} = 17.3$ K through measurements of the specific heat. The experiment was carried out in the muon channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics.

The $P(t)$ dependence for Nb_3Al was measured by a method involving detection of positrons from the decay $\mu^+ \to e^+$, as is described in detail in Ref. 4. To eliminate the background of precessing muons, the experimental dependence $P(t)$ was averaged over time intervals that were multiples of the Larmor precession period of a muon with a frequency $\omega = eH/m_\mu c$ in a transverse external magnetic field $H = 284$ Oe. The background precession signal $P_b(t)$ in expression (1) vanishes in this case. In this case the average experimental dependence $\overline{P(t)}$, is equal to $P_{\mathrm{Nb_3Al}}(t)$.

The experimental dependence $P(t)$ was compared with the Kubo-Toyabe formula,[5]

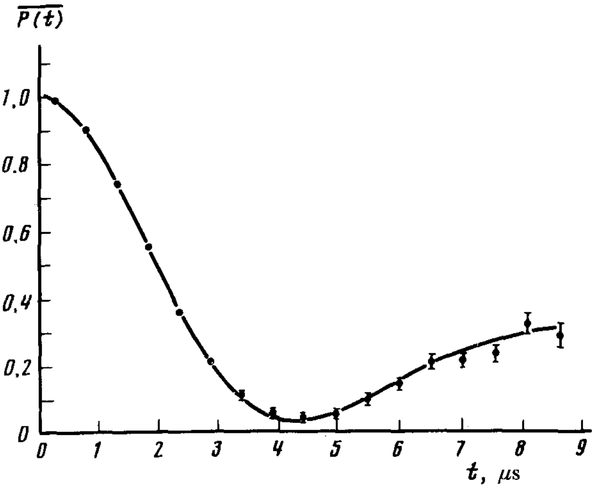

FIG. 1. The experimental dependence $\overline{P(t)}$ of the muon polarization in Nb_3Al at $T = 12$ K. The statistical errors in the experimental values of $\overline{P(t)}$ at $t < 3$ μs (not shown here) do not exceed 1%. The curve is theoretical function (2), $P_{\text{theo}}(t)$, with $\sigma = 0.402$ μs^{-1}.

$$P_{\text{theo}}(t) = \frac{1}{3} + \frac{2}{3}(1 - \sigma^2 t^2)\exp\left(-\frac{\sigma^2 t^2}{2}\right), \tag{2}$$

which describes the time dependence of the polarization of localized muons in a zero external field in the absence of oscillations of the magnetic dipole moments of the lattice nuclei. In the derivation of (2), it is assumed that the distribution of the internal nuclear magnetic fields at the positions of the muons is Gaussian with an rms deviation $\sqrt{\langle \Delta H^2 \rangle}$:

$$\sigma^2 = \frac{1}{3}\left(\frac{e}{mc}\right)^2 < \Delta H^2 >. \tag{3}$$

It follows from expression (2) that in the limit $t \to \infty$ the muon polarization is $P_{\text{theo}} \to 1/3$, as it should be in the relaxation of the spins of localized particles in isotropic magnetic fields that are constant over time. The value found for σ in the present experiment is $\sigma = 0.402 \pm 0.002$ μs^{-1}. Here we have $\chi^2 = 20$ with the average value $\langle \chi^2 \rangle = 15$. This value of σ corresponds to an rms field $\sqrt{\langle \Delta H^2 \rangle} = 8.2$ Oe at the muon.

Figure 1 shows the theoretical and experimental time evolution of the muon polarization. The good correspondence between the experimental data and the Kubo-Toyabe function (2) means that the scale time of the changes in the nuclear magnetic fields at the muon due to the diffusion of the muon through the crystal is, at the very least, greater than the average muon lifetime τ_μ. It can also be asserted on the basis of this result that the oscillation frequency of the nuclear spins of the niobium and the aluminum in the alloy Nb_3Al is substantially smaller than τ_μ^{-1} at 12 K.

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