Effect of impurities on μ^+-meson diffusion in aluminum

V. G. Grebinnik, I. I. Gurevich, A. Yu. Didyk, V. A. Zhukov, A. P. Manych, E. V. Mel'nikov, B. A. Nikol'skiĭ, V. S. Roganov, V. I. Selivanov, and V. A. Suetin

I. V. Kurchatov Institute of Atomic Energy
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The rate of spin relaxation of μ^+ mesons in aluminum doped with copper was measured at temperatures 7–300 K. It is shown that even a small (0.04%) copper impurity slows down greatly the μ^+-meson diffusion in aluminum.

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It was shown in[1] that the relaxation rate Λ of the μ^+-meson spin in copper increases with decreasing temperature. The observed $\Lambda(T)$ dependence can be naturally explained as being due to magnetic dipole interactions and to μ^+-meson diffusion. With decreasing temperature, the μ^+-meson diffusion slows down and the dipole interactions of the μ^+ meson with the magnetic moments of the surrounding nuclei leads to a rather rapid rate of μ^+-meson spin relaxation. At high temperatures, when the μ^+-meson diffusion rate is large, the nuclear magnetic fields at the μ^+-meson become alternating in time and the relaxation rate Λ decreases. An increase of Λ with decreasing temperature was observed also in other metals (Be,V,Nb).[2] An exception is aluminum, in which the calculated value $\Lambda \approx 0.3\ \mu\text{sec}^{-1}$ is not reached even at very low

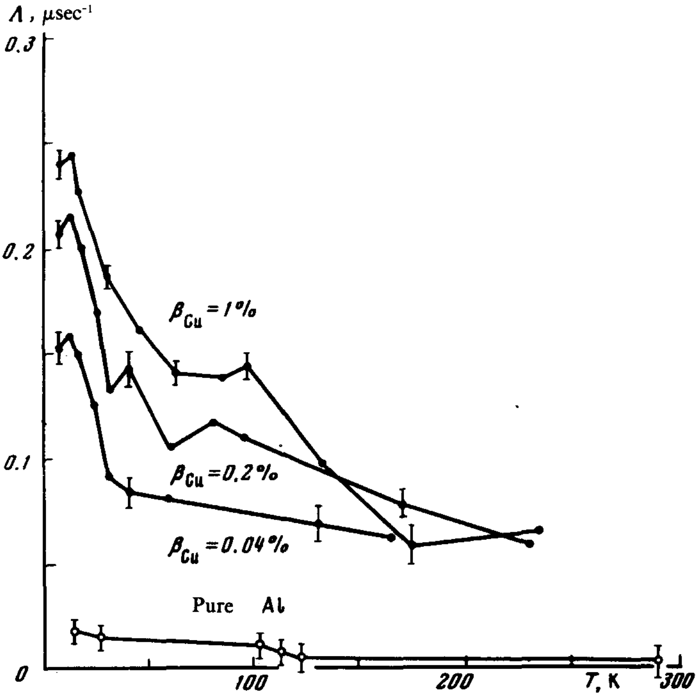

FIG. 1. Temperature dependences of the μ^+-meson spin relaxation rate in AlCu alloys with different copper contents (β_{Cu}). The straight lines joining the experimental points were drawn for the sake of clarity.

temperatures. It is shown in[2] that in aluminum $\Lambda < 0.02$ μsec^{-1} in the entire investigated temperature interval $T = 15$–300 K. This result means that, in contrast to other metals, the diffusion of the μ^+ meson in aluminum remains rapid enough down to $T = 15$ K. One of the possible explanations of the rapid diffusion of the μ^+ meson in aluminum is the assumption that the μ^+ meson diffuses coherently in this metal. In the case of coherent diffusion, the μ^+ meson moves over the crystal as in a stationary periodic field, i.e., without exciting a phonon spectrum. Therefore lowering the temperature favors coherent diffusion.

Coherent diffusion can occur only in a sufficiently perfect crystal with undisturbed periodicity of its structure. It is therefore of interest to ascertain the variation of the μ^+-meson diffusion in aluminum with a crystal lattice that is deformed, say by introducing impurities. In the present study, using the JINR sychrocyclotron, we investigated the spin relaxation of the μ^+ meson in aluminum doped with small amounts of copper. The results are shown in Figs. 1 and 2.

Figure 1 shows plots of $\Lambda(T)$ for AlCu alloys with copper contents $\beta_{Cu} = 1\%, 0.2\%$ and 0.04% (atomic percent). The presented values of Λ were determined by the maximum-likelihood method from the experimental time dependences of the polarization $P(t)$ of the μ^+-meson spin in a transverse magnetic field of 70 Oe. In the calculation of Λ it was assumed that $P(t) \propto \exp(-\Lambda^2 t^2)$, i.e., a Gaussian dependence. Theoretically, a Gaussian $P(t)$ dependence should be observed in the absence of

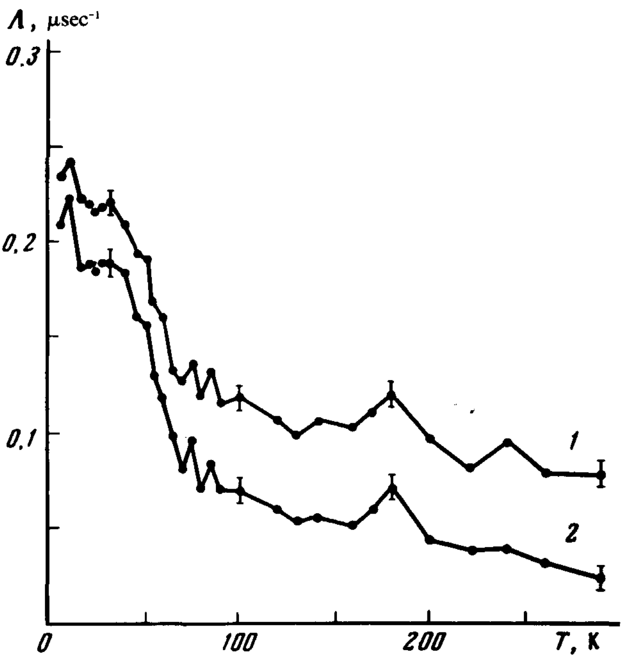

FIG. 2. Temperature dependence of the μ^+-meson spin relaxation rate in duraluminum. The values of $\Lambda(T)$ were obtained assuming a Gaussian (1) and an exponential (2) $P(t)$ dependence. The lines joining the experimental points were drawn for the sake of clarity.

μ^+-meson diffusion; in the case of a diffusing μ^+ meson, $P(t)$ becomes exponential. For the investigated AlCu alloys at $T \lesssim 40$ K, a better agreement with experiment was observed for a Gaussian $P(t)$ dependence at all values of β_{Cu}. Figure 1 shows also the values of $\Lambda(T)$ for pure aluminum,[2] calculated for an exponential $P(t)$.

Figure 2 shows a plot of $\Lambda(t)$ for commercial duraluminum containing approximately 1% impurities, mostly copper, assuming Gaussian and exponential $P(t)$ dependences. Figure 2 illustrates the degree of difference between the values of Λ calculated by interpolating the experimental plots of $P(t)$ with the aid of the theoretical expressions $P(t) \propto \exp(-\Lambda^2 t^2)$ and $P(t) \propto \exp(-\Lambda t)$.

It follows from Figs. 1 and 2 that addition of a small amount of impurities ($\beta_{Cu} \geqslant 0.04\%$) slows down substantially the diffusion of the μ^+ meson in aluminum, and at $\beta_{Cu} = 1\%$ and $T \lesssim 20$ K the relaxation rate Λ of the μ^+-meson spin corresponds approximately to the rate for non-diffusing μ^+ mesons. As stated above, this result can mean that the small copper impurity disturbs the coherent diffusion of the μ^+ meson in copper, a diffusion possible only in the pure metal. Of course, this interpretation of the results is not unambiguous. The copper impurity atoms can serve as traps for the rapidly diffusing μ^+ mesons, and thus slow down their diffusion regardless of the mechanism of the diffusion itself. This still leaves open, of course, the question of why the μ^+ mesons diffuse so rapidly in pure aluminum at low temperature.

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