Strange diffusion of μ^+ mesons in bismuth

V. G. Grebinnik, I. I. Gurevich, V. A. Zhukov, A. I. Klimov, V. N. Maĭorov, A. P. Manych, E. V. Mel'nikov, B. A. Nikol'skiĭ, A. V. Pirogov, A. N. Ponomarev, V. I. Selivanov, and V. A. Suetin

I. V. Kurchatov Institute of Atomic Energy
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The temperature dependence of the μ^+-meson spin relaxation rate $\Lambda(T)$ in bismuth was measured at $T < 250$ K. One way to interpret the experimental $\Lambda(T)$ dependence is to assume coherent quantum diffusion of the μ^+ meson at $T < 80$ K.

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The temperature dependence of the μ^+-meson spin relaxation rate $\Lambda_{Cu}(T)$ in copper was measured in[1,2]. This dependence is flat-topped, i.e., $\Lambda_{Cu}(T) = \text{const}$ at $T \lesssim 80$K and is a monotonically decreasing function ($\Lambda_{Cu}(T) \to 0$) at higher temperatures. The rate of relaxation of the μ^+-meson spin on the flat top of $\Lambda_{Cu}(T)$ is determined by the dipole relaxation of the μ^+-meson spin on account of the interaction of the magnetic moment of the μ^+ meson and the copper nuclei. The drooping part of $\Lambda_{Cu}(T)$ at increased temperature can be naturally attributed to diffusion of the μ^+ meson over the copper lattice.

We have measured the temperature dependence of the μ^+-meson spin relaxa-

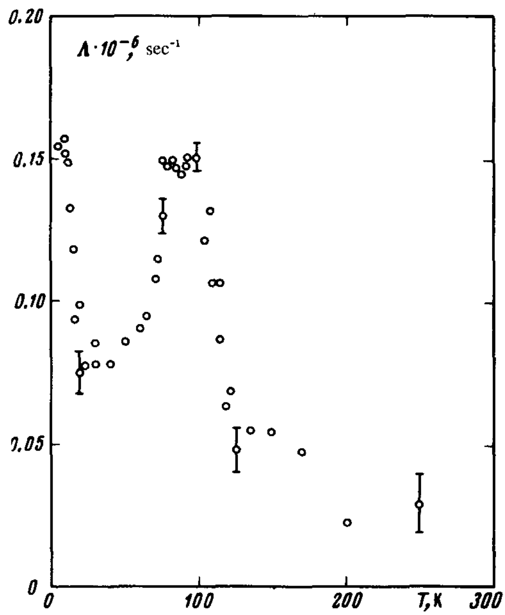

FIG. 1. Temperature dependence of the μ^+-meson spin relaxation rate in bismuth.

tion rate $\Lambda(T)$ in bismuth; this dependence differs substantially from the above-described $\Lambda(T)$ in copper. The employed bismuth sample was prepared from polycrystalline material with less than 0.01% impurities. The work was performed with the cyclotron of the JINR Laboratory of Nuclear Problems in Dubna. The obtained experimental $\Lambda(T)$ dependence is shown in Fig. 1. The values of Λ shown in Fig. 1 were determined by the maximum-likelihood. method from the damping of the precession amplitude of the μ^+-meson spin in a transverse magnetic field $H=70$ Oe, by comparing the experimental precession curves with the theoretical expression

$$N(t) = N_0 e^{-t/\tau_0}[1 - a e^{-\Lambda^2 t^2} \cos \omega t]. \tag{1}$$

Here $N(t)$ is the number of positrons of the $\mu^+ \to e^+$ decay, emitted in the direction of the primary μ^+-meson polarization corresponding to the time $t=0$; $\tau_0 = 2.2\times 10^{-6}$ sec is the lifetime of the μ^+ meson; a is the experimental asymmetry coefficient of the angular distribution of the $\mu^+ \to e^+$ decay electrons; $\omega = eH/m_\mu c$ is the Larmor precession frequency of the μ^+-meson spin in a field $H=70$ Oe. It follows from (1) that the μ^+-meson spin relaxation rate Λ is determined under the assumption that the μ^+-meson polarization has a Gaussian time dependence $P(t)=\exp(-\Lambda^2 t^2)$. A Gaussian $P(t)$ should indeed be observed in the absence of μ^+-meson diffusion.[2] For a diffusing μ^+ meson, the $P(t)$ dependence is more complicated, and with increasing diffusion rate (i.e., at high temperatures) it approaches asymptotically an exponential function of the time.[3] Figure 1 shows $\Lambda(T)$ plotted, for the sake of uniformity, under the assumption that $P(t) = \exp(-\Lambda^2 t^2)$, i.e., that it agrees with (1) in the entire investigated temperature interval.

It is seen from Fig. 1 that $\Lambda(T)$ in bismuth is nonmonotonic and its description is not as simple as that of the corresponding relation for copper.[2] The appreciable decrease of the relaxation rate at temperatures $T \gtrsim 150$ K can be naturally explained as being due to the rapid diffusion of the μ^+ meson at high temperatures. To explain the minimum of the $\Lambda(T)$ curve at $T\approx 25$ K, however, it is necessary to take into account some other processes. One of the possible explanations of this effect may be the relatively slow (at low temperatures) diffusion of the μ^+ meson in the more stable equilibrium positions. At higher temperatures, this diffusion becomes too fast to be observed in the experiment.

Another possible explanation of the minimum of $\Lambda(T)$ at $T\sim 25$ K is the coherent quantum diffusion[4,5] of the μ^+ meson in bismuth at $T<80$ K. In contrast to ordinary diffusion, the average particle velocity in quantum diffusion increases with decreasing temperature. In quantum diffusion the relaxation rate of the μ^+-meson spin should therefore decrease with decreasing temperature, as in indeed observed at $T<80$ K. To explain the experimentally observed increase of $\Lambda(T)$ at $T<20$ K it must be assumed that the μ^+ meson can be captured by a dislocation or by some other bismuth crystal-lattice defect, which becomes possible precisely at low temperatures, when the coherent diffusion velocity increases sharply.

We note in conclusion that the limiting temperature T_0, below which coherent diffusion in the crystal is possible, depends essentially on the mass m of the diffusing particle. This dependence is determined by the expression[4] $T_0 \sim \Theta(\Delta/\Theta)^{1/7}$. Here Θ is the Debye temperature of the given crystal; $\Delta - \exp(-\text{const}\sqrt{m})$ is the width of the coherent band for the diffusing particle of mass m. Quantitative estimates show that for a μ^+ meson in metal we have $\Delta \sim 1$ K and T_0 does not differ substantially from the Debye temperature Θ. Thus, for bismuth, where $\Theta = 120$ K we have $T_0 \sim 50$ K, in full agreement with the possibility of observing coherent μ^+-meson diffusion in this metal at $T < 80$ K. Notice should also be taken of the monoisotopic composition of bismuth, which also favors the coherent processes.

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