Diffusion of μ^+ mesons in vanadium

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The relaxation rate Λ of the μ^+-meson spin is measured in two vanadium samples of different purity in the temperature interval $T = 10$–300 K. The obtained $\Lambda(T)$ dependence is interpreted as the result of capture of a diffusing μ^+ meson by an impurity in the metal.

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Diffusion of a μ^+ meson in metal is revealed by the change of the rate of the μ^+-meson spin relaxation due to the dipole interactions with the magnetic moments of the nuclei and of the substance.[1] The relaxation rate should be largest when the time τ that the μ^+ meson stays in one crystal cell is much longer than the observation time, i.e., when there is practically no diffusion. For a diffusing μ^+ meson, the value of Λ decreases because the dipole magnetic fields at the muon begin to vary with time. Of course, this method of observing μ^+ meson diffusion can be used only if the nuclei of the substance in which the μ^+ meson diffuses have a magnetic moment.

The rate of magnetic dipole relaxation of the μ^+-meson spin is usually revealed by the damping of the μ^+-meson precession amplitude in a transverse magnetic field H. The time dependence of the number of $\mu^+ \to e^+$ decay positrons emitted in a direction opposite to that of the primary μ^+-meson polarization is then expressed in the form

$$N(t) = N_0 e^{-t/\tau_0}[1 - aP(t)\cos\omega t]. \qquad (1)$$

Here $\tau_0 = 2.2\times10^{-8}$ sec is the μ^+ meson lifetime; a is the experimental coefficient of asymmetry of the angular distribution of the $\mu^+ \to e^+$ decay positron; $P(t)$ is a

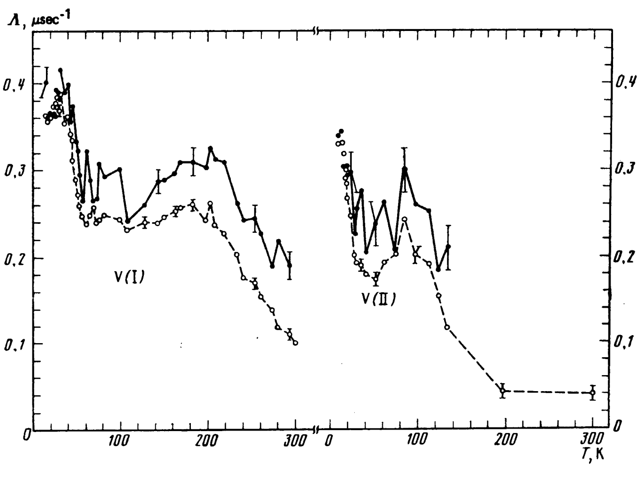

FIG. 1. Temperature dependence of the relaxation rate Λ of the μ^+ meson spin in two vanadium samples V(I) and V(II). The values of Λ were determined from the experimental $N(t)$ dependences (1) in the intervals $\Delta t_1 = 0$–2 μsec (●) and $\Delta t_2 = 0$–7 μsec (○).

function that describes the relaxation of the μ^+-meson spin; $\omega = eH/m_\mu c$ is the Larmor frequency of the μ^+-meson spin precession. A detailed description of the experimental procedure is given in Ref. 2.

The diffusion-induced temperature dependence $\Lambda(T)$ of the relaxation rate of the μ^+-meson spin in vanadium was investigated in a number of studies.[3-8] It follows from the obtained data that $\Lambda(T)$ in vanadium is nonmonotonic and depends essentially on the purity of the metal. These peculiarities of $\Lambda(T)$ in vanadium can be naturally explained as being due to the capture of the diffusing μ^+ mesons in traps; the latter can be various impurity atoms.[4]

In the present paper we consider in detail μ^+-meson spin relaxation in two polycrystalline vanadium samples of different purity. The other elements contained in the vanadium as impurities are indicated in Table I.

It is seen from the table that sample V(II) is purer, although the resistance ratio $\gamma = R(293)/R(4) = 25$ measured for this sample still remains very low. Figure 1 shows the experimentally measured relaxation rates $\Lambda(T)$ of the μ^+-meson spin in a transverse magnetic field $H \approx 70$ G for V(I) and V(II) in the temperature interval $T = 10$–300 K.[1)] The values of Λ shown in Fig. 1 were obtained by comparing, by the maximum likelihood method, the theoretical dependence (1) and the experimental $N(t)$ dependences under the assumption that the function describing the μ^+-meson spin relaxation is Gaussian:

$$P(t) = e^{-\Lambda^2 t^2}. \qquad (2)$$

The comparison of $N_{theor}(t)$ and $N_{exp}(t)$ was made for two intervals of the time t, namely $\Delta t_1 = 0$–2 μsec and $\Delta t_2 = 0$–6 μsec. The difference between the values of $\Lambda(\Delta t_1)$ and $\Lambda(\Delta t_2)$ obtained for the same vanadium sample point to a deviation of the experimental relaxation function $P_{exp}(t)$ from the Gaussian (2).

TABLE I. Impurities of certain elements in the investigated vanadium samples V(I) and V(II). The impurity density is given in percent by weight.

	C	N	O	Fe	Al	Si	Mn	Ta	W
V(I)	$2\cdot10^{-2}$	$2\cdot10^{-2}$	$2\cdot10^{-2}$	10^{-2}	$3\cdot10^{-2}$	10^{-1}	—	—	—
V(II)	10^{-4}	$3\cdot10^{-3}$	$2\cdot10^{-2}$	$4\cdot10^{-3}$	—	—	10^{-3}	10^{-4}	$2\cdot10^{-3}$

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It follows from Fig. 1 that agreement between $\Lambda(\Delta t_1)$ and $\Lambda(\Delta t_2)$, and consequently a Gaussian form (2) of $P_{exp}(t)$, is observed for the low-temperature plateau of the $\Lambda(T)$ dependence, i.e., at $T<30$ K for sample V(I) and $T<15$ K for sample V(II). At higher temperatures the values of $\Lambda(\Delta t_1)$ and $\Lambda(\Delta t_2)$ show a systematic difference. This difference is natural for a diffusing μ^+ meson, when the value of Λ varies with temperature.[2] In our preceding paper[2] it was shown that for a sufficiently rapidly diffusing μ^+ meson the relaxation function $P(t)$ becomes exponential. The plateau of $\Lambda(T)$ is usually interpreted as localization of the μ^+ meson in the metal lattice, i.e., as absence of diffusion. The systematic diffusion between $\Lambda(\Delta t_1)$ and $\Lambda(\Delta t_2)$ on the high-temperature plateau $\Lambda(T)$ at $T=60-200$ K means that at these temperatures the μ^+ mesons are not fully localized. It should be noted that comparison of $\Lambda(\Delta t_1)$ and $\Lambda(\Delta t_2)$ is a very sensitive measure of the extent to which the experimental $P_{exp}(t)$ is described by expression (2) which, as shown by the χ^2 criterion, favors the exponential form of $P(t)$ for both $\Lambda(T)$ plateaus.

For a clearer idea of the $P_{exp}(t)$ dependence, Figs. 2 and 3 show the precession of the μ^+ meson in V(I) on the low-temperature plateau and on the high-temperature plateau of $\Lambda(T)$, respectively. To increase the statistical reliability, the precession curves shown in these figures were obtained by summing the individual $N(t)$ dependences (1) at $T=15-30$ K and $T=80-180$ K. The experimental plots of $N(t)$ on Figs. 2 and 3 were compared with corresponding calculated precession curves with the Gaussian attenuation (2). It is seen from Fig. 2 that at $T=15-30$ K the experimentally observed attenuation of the precession amplitude is well described by the Gaussian law (2). The aforementioned deviation of $P_{exp}(t)$ from a Gaussian form at $T=80-180$ K for V(I) manifests itself, as seen from Fig. 3, in a slower relaxation of the μ^+ meson spin. A possible explanation of this effect is that the high-temperature plateau for V(I) is a superposition of individual $\Lambda(T)$ peaks connected with the unstable capture of the μ^+ meson by various impurities. One such peak, as seen from Fig. 1, is distinctly observed for sample V(II) at $T\approx 85$ K.

It is seen from Fig. 1 that the $\Lambda(T)$ plots for samples V(I) and V(II) are significantly different in the entire

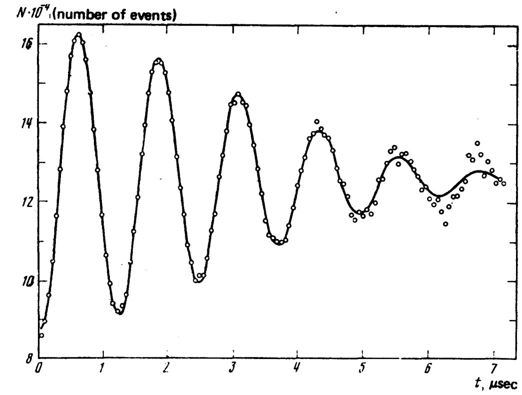

FIG. 3. Precession of μ^+-meson spin in V(I) at T= 80–180 K. The attenuation of the calculated precession curve drawn through the experimental data is described by the Gaussian function (2).

temperature interval. This phenomenon is attributed to a decrease of the probability of the capture of a diffusing μ^+ meson by impurity atoms in a purer sample. Since the impurity density, as seen from the table, is low, they can produce a noticeable effect only if the μ^+ meson diffuses rapidly enough through the vanadium crystal lattice, so that the diffusing μ^+ meson manages to "find" a corresponding trap during the observation time. An even more significant decrease of Λ was observed in Ref. 8 for very pure ($\gamma\sim 1000$) vanadium sample.

It follows furthermore from Fig. 1 and from other results that the $\Lambda(t)$ for different vanadium samples have a number of features in common. At low temperatures Λ increases with decreasing temperature. The maximum of $\Lambda(T)$ of sample V(II) at $T\approx 85$ K was observed also in Ref. 5 and was particularly distinct in Ref. 8. The plateau of $\Lambda(t)$ for sample V(I) at $T=600-200$ K (see Fig. 1) was observed in Ref. 7 similar singularities of $\Lambda(T)$ for different vanadium samples are connected apparently with traps that are typical of this metal and are produced by definite impurities.

We consider, finally, the temperature dependence of the precession frequency $\omega(T)$ of the μ^+-meson spin

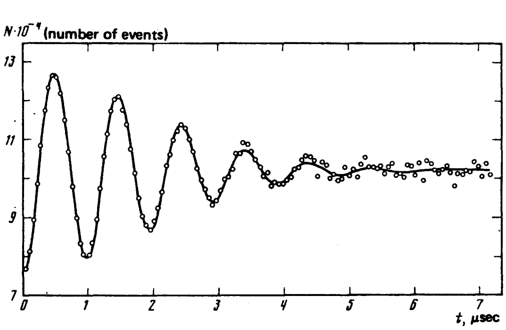

FIG. 2. Precession of μ^+-meson spin in V(I) sample at T= 15–30 K. The smooth line is the calculated precession curve, which attenuates in accord with the Gaussian law (2). The calculated and experimental $N(t)$ plots shown in the figure were "corrected" for the exponential decay $\exp(-t/\tau_0)$ of the μ^+ meson.

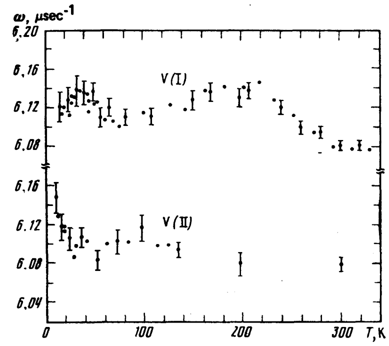

FIG. 4. Temperature dependence of the μ^+ meson spin precession frequency in two vandium samples V(I) and V(II).

precession in vanadium. Plots of $\omega(T)$ for samples V(I) and V(II) are shown in Fig. 4. It is seen from Fig. 4 that the frequency ω and hence the magnetic field at the μ^+ meson in vanadium do not remain constant in the investigated temperature interval $T = 10-300$ K. The lowest value of ω is observed at the high temperature $T \approx 300$ K, when the μ^+ meson diffuses rapidly. The μ^+-meson precession frequency increases with increasing Λ, i.e., when the μ^+ meson is localized. The μ^+-meson precession frequency increases with increasing Λ, i.e., upon localization of the μ^+ meson. The maximum increase of ω in both vanadium samples reaches 1%. It must be noted that the values of the frequency ω, determined by comparing by the maximum-likelihood method the theoretical (1) and experimental $N(t)$ dependences, differ somewhat for different forms of $P_{\text{theor}}(t)$. This effect, however, hardly affects the $\omega(T)$ plots shown in Fig. 4. An increase in the frequency ω with increasing relaxation rate Λ of the μ^+ meson spin was observed also in antimony.[9] A possible explanation of the observed $\omega(T)$ dependences in vanadium and antimony may be the formation of an orbitally coupled paramagnetic μ^+, e^- state on the impurity atoms. This explanation is confirmed by the qualitative correlation of the $\omega(T)$ and $\Lambda(T)$ dependences in these metals.

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[1)] Preliminary results on the $\Lambda(T)$ dependence for sample V(I) were published earlier.

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