Relaxation of μ^+-meson spin in chromium

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

I. V. Kurchatov Institute of Atomic Energy
(Submitted 22 July 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 7, 456–460 (5 October 1978)

The relaxation of the μ^+-meson spin in the antiferromagnetic state of chromium is investigated in longitudinal and transverse magnetic fields. The probability $1/\tau \sim 10^{11}$ sec^{-1} of the diffusion hopping of the μ^+ meson between two pores of the crystal lattice of chromium is investigated at $T = 100$–300 K.

PACS numbers: 75.50.Ee, 76.90. + d

Earlier investigations[1,2] were devoted to the relaxation of the spin of a μ^+ meson in rare-earth elements in the paramagnetic and antiferromagnetic states. We report here an investigation, with the JINR synchrocyclotron in Dubna, of magnetic interactions of a μ^+ meson in chromium. It is known that at a temperature $T < T_N = 311$ K chromium is in a magnetically ordered antiferromagnetic state characterized by a rather large atomic magnetic moment, $M = 0.6$ Bohr magnetons. At $T > T_N$, the chromium atoms have no magnetic moment.

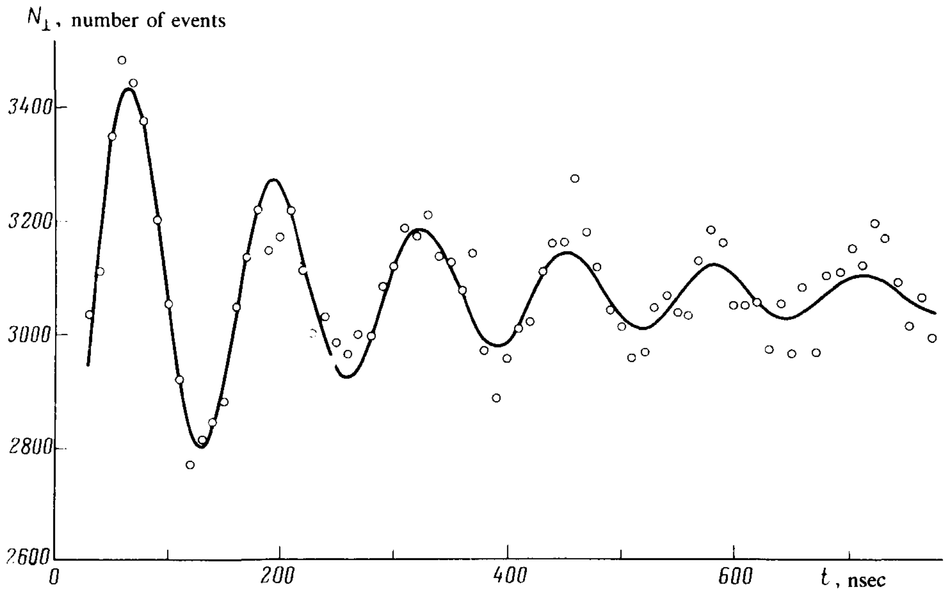

FIG. 1. Precession of μ^+-meson spin in chromium in a transverse magnetic field $B_\perp = 300$ Oe at $T = 213$ K. The solid line is a plot of $N_\perp(t)$ [Eq. (1)].

Figure 1 shows the precession of the μ^+-meson spin in a transverse magnetic field $B_\perp$ in chromium in the antiferromagnetic state ($T = 213$ K). We used a polycrystalline chromium sample with less than 1% impurities. The plot of $N_\perp(t)$ shown in Fig. 1 represents the counting rate of the positrons of the $\mu^+ \to e^+$ decay, emitted in the direction opposite to the initial spin direction of μ^+ at the instant of time $t = 0$:

$$N_\perp(t) = N_0 e^{-t/\tau_0} [1 - a e^{-\Lambda t} \cos \omega t]. \quad (1)$$

Here $\tau_0 = 2.2 \times 10^{-6}$ sec is the lifetime of the μ^+ meson; a is the experimental asymmetry coefficient of the angular distribution of the positrons of the $\mu^+ \to e^+$ decay; Λ is the rate of relaxation of the μ^+-meson spin as a result of coherent interaction with the medium; ω is the Larmor frequency of the precession of the μ^+ meson. The precession frequency ω of the μ^+-meson spin in chromium was $\omega = eB_\perp/m_\mu c$ in the entire investigated temperature, where $B_\perp$ is the external magnetic field transverse to the direction of the μ^+-meson spin. In expression (1) it is assumed that the relaxation of the spin of the μ^+ meson is exponential, $p(t) = \exp(-\Lambda t)$. This is precisely the form of $p(t)$ to which the calculated $N_\perp(t)$ dependence shown in Fig. 1 corresponds. It is seen from Fig. 1 that the exponential $p(t)$ dependence describes the experimentally observed relaxation of the μ^+-meson spin only approximately. Actually the relaxation of the μ^+-meson spin in a transverse magnetic field is somewhat slower than exponential. We shall hereafter, however, characterize the rate of relaxation of the μ^+-meson spin in chromium by the quantity Λ, since the exact form of the $p(t)$ dependence is unknown.

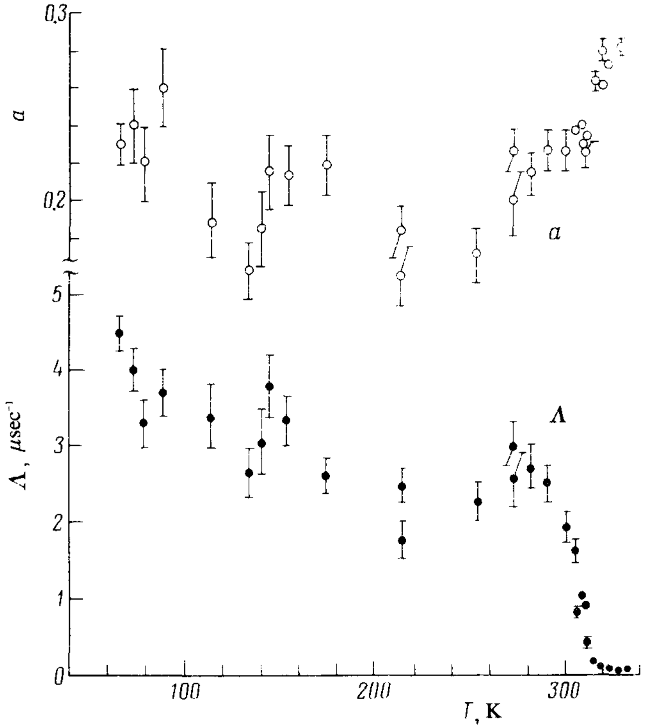

FIG. 2. Experimental $\Lambda(T)$ and $a(T)$ dependence in a transverse magnetic field $B_\perp = 300$ Oe.

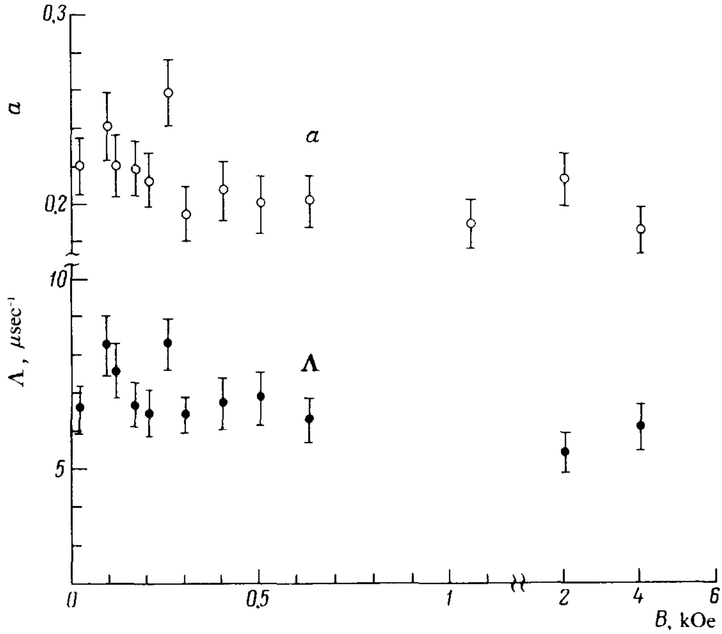

FIG. 3. Experimental plots of Λ (B) and $a(B)$ against the longitudinal magnetic field B at $T = 140$ K.

Figure 2 shows the temperature dependences of Λ (T) and $a(T)$ at $T > 60$ K. At a temperature below 60 K, the relaxation rate Λ increases rapidly and at $T < 50$ K the experimental observation of the μ^+-meson spin precession becomes impossible. It is seen from Fig. 2 that on going to the magnetically ordered state $(T < T_N)$ a change takes place both in the relaxation rate Λ and in the asymmetry coefficient a: the relaxation rate increases sharply, and the asymmetry coefficient decreases, $a(T < T_N) \approx 0.7a(T > T_N)$. Some increase of the coefficient a at $T < 100$ K is not statistically reliable and is possibly due to deviation of the actual $p(t)$ dependence from exponential.

Figure 3 shows plots of Λ (B) and $a(B)$ against the longitudinal magnetic field along the direction of the μ^+-meson spin at a temperature $T < T_N$. The values of Λ and a in the longitudinal field B were determined from the experimental relation

$$N_{\parallel}(t) = N_0 e^{-t/\tau_0}[1 - ae^{-\Lambda t}], \tag{2}$$

which differs from relation (1) for $N_{\perp}(t)$ in the transverse magnetic field $B_{\perp}$ in the absence of the oscillating term $\cos\omega t$.

We examine now the conclusions that can be drawn from the experimental data shown in Fig. 2 and Fig. 3 on the relaxation of the μ^+-meson spin in chromium. It is seen from Fig. 3 that Λ and a remain practically constant when the longitudinal magnetic field is varied in the range $B = 0 - 4$ kOe. This means that the local magnetic fields B_{loc} at the μ^+ meson in chromium greatly exceed the value $B = 4$ kOe, and furthermore, vary with time. Strong magnetic field $B_{loc} \approx 10$ kOe are produced at the u^+ meson in chromium at $T < T_N$ by the electronic magnetic moments which appear following the antiferromagnetic ordering below the Néel temperature. The averages of these fields over all possible interstices of the crystal lattice of chromium is equal to zero. Therefore the μ^+ meson in chromium precesses at a Larmor frequency corresponding to the external magnetic field. The different values of B_{loc} in different pores leads to relaxation of the μ^+-meson spin. This relaxation would occur within a very short time $\delta t \sim 10^{-9}$ sec if the fields B_{loc} were to act on the μ^+ meson constantly. The relatively slow relaxation of the μ^+-meson spin in chromium ($\Lambda \sim 10^7$ sec) means that the local magnetic field at the μ^+ meson oscillates rapidly. A natural explanation of this fact is the rapid diffusion of the μ^+ meson over the chromium crystal. The observed relaxation rate makes it possible to estimate the time t that the diffusing μ^+ meson stays in a single crystal pore:

$$\tau = \Lambda(\delta t)^2 \sim 10^{-11} \text{ sec.} \qquad (3)$$

The weak Λ (T) dependence at $T = 100$–300 K shows that the diffusion rate changes insignificantly in this temperature interval.

The difference between the relaxation rates of the μ^+ meson spin in longitudinal and transverse magnetic fields (see Figs. 2 and 3) can be attributed to the relatively easy orientation of the atomic magnetic moments perpendicular to the external magnetic field and to the direction of the spin-density wave in the chromium crystal.[3] A possible explanation of the decrease of the coefficient a on going to the magnetically ordered state is the trapping of $\sim 30\%$ of the diffusing μ^+ mesons in the traps connected with irregularities of the crystal lattice of the chromium or with impurities. The μ^+ meson captured in the trap ceases to diffuse, and this leads to relaxation of its spin within a short time, $\delta t \sim 10^{-9}$ sec.

The authors thank V.P. Dzhelepov for the opportunity of performing this work with the synchrocyclotron in Dubna, and V.N. Maĭorov and V.S. Roganov for help with the work.

[1]I.I. Furevich, A.I. Klimov, V.N. Maĭorov, B.A. Nikol'skiĭ, V.S. Roganov, V.I. Selivanov, and V.A. Suetin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 345 (1976) [JETP Lett. **23**, 310 (1976)].

[2]V.G. Grebinnik, I.I. Gurevich, V.A. Zhukov, A.I. Klimov, A.P. Manych, B.A. Nikol'skiĭ, V.S. Roganov, V.I. Selivanov, and V.A. Suetin, Mezony v veshchestve (Mesons in Matter), JINR, D, 1, 2, 14-10908, Dubna, 1977.

[3]E.I. Kondorskiĭ, Zonnaya teoriya magnetizma (Band Theory of Magnetism), Moscow University Press, pt. 2, 1977, p. 50.