Muon diffusion in dysprosium

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(Submitted 7 July 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **40**, No. 4, 137–140 (25 August 1984)

A method is proposed for measuring the scale time for a diffusive hop of a positive muon in a crystal of a helicoidally ordered antiferromagnet. The diffusion of a muon in dysprosium is a tunneling process.

The usual procedure for determining the scale time (τ) for a diffusive hop of a muon between adjacent interstitial sites in a crystal lattice of a metal is to measure the rate of the relaxation of the muon's spin caused by dipole interactions with the magnetic moments of surrounding nuclei or atoms. The diffusion of a muon through a crystal causes the dipole fields at the muon to become time-varying, so that the rate of the dipole relaxation of the muon's spin decreases.[1] This process is equivalent to a diffusive narrowing of an NMR line.

In the present study the scale time (τ) for a diffusive hop of a positive muon in a dysprosium crystal was determined by making use of the particular features of the helicoidal magnetic structure of the antiferromagnetic state of this metal, which make it possible to measure the dependence $\tau(T)$ over the temperature interval $T = 90-180$ K. The results show that the diffusion of a muon is a tunneling process in this temperature interval. The experiments were carried out on the synchrocyclotron of the Leningrad Institute of Nuclear Physics at Gatchina.

The dysprosium sample consists of six disks 35 mm in diameter and 5 mm thick, arranged in such a manner that the planes of their bases are parallel. The disks are made from a polycrystalline material with an impurity concentration below 0.01%. A subsequent deformation annealing with two-sided compression increases the dimensions of the individual grains to 4–10 mm, and their hexagonal c axes become oriented predominantly perpendicular to the plane of the base of the disk. This orientation of the sample corresponds to the maximum magnitude of the observable polarization of the muon in the antiferromagnetic state of the dysprosium. The sample temperature is measured within $\delta T = 0.3$ K by using germanium thermometers.

In the experiments we measured the time dependence

$$N(t) = N_0 e^{-t/\tau_0}(1 + ae^{-\Lambda t}) + B \tag{1}$$

of the number of positrons from the decay $\mu^+ \rightarrow e^+$ which are emitted along the polarization direction of the muons in a zero external magnetic field. Here

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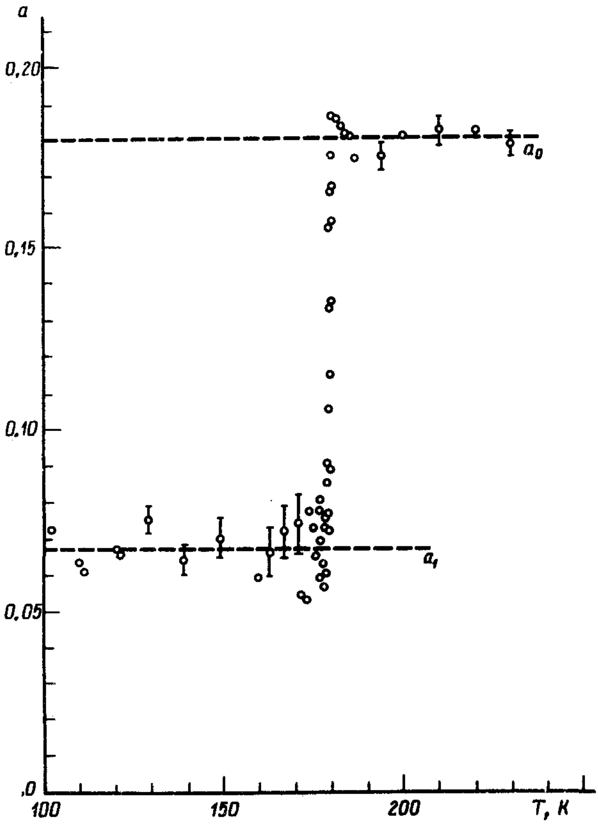

FIG. 1. The temperature dependence, $a(T)$, of the measured asymmetry coefficient of the positrons from the decay $\mu^+ \to e^+$ in dysprosium.

$\tau_0 = 2.2 \times 10^{-6}$ s is the muon lifetime, a is the measured asymmetry coefficient of the angular distribution of positrons from the decay $\mu^+ \to e^+$, Λ is the relaxation rate of the muon spin, and B is the background. It is assumed in (1) that the relaxation of the muon spin in dysprosium occurs exponentially, $P(t) = e^{-\Lambda t}$; the experimental results confirm this functional dependence $P(t)$.

Figure 1 shows the temperature dependence $a(T)$ of the measured asymmetry coefficient over the temperature interval $T = 100$–250 K. The values of a_0 and a_1 shown here are average values of the coefficient a for the paramagnetic state $(T > T_N)$ and the antiferromagnetic state $(T < T_N)$ of dysprosium ($T_N = 180$ K is the Néel temperature). The coefficient a decreases at the transition to the antiferromagnetic state because of an unobservably rapid precession of the muon spin in strong magnetic fields at $T < T_N$. The local magnetic fields H_μ at a muon at octahedral and tetrahedral interstitial sites in dysprosium at $T < T_N$ are $H_\mu \gtrsim 10^4$ Oe and are directed perpendicular to the hexagonal c axis of the crystal.[2] The coefficient a_1 thus refers to the relaxation of those components of the muon's spin which are longitudinal with respect to the field H_μ. The corresponding decrease in the observable polarization of the muons is

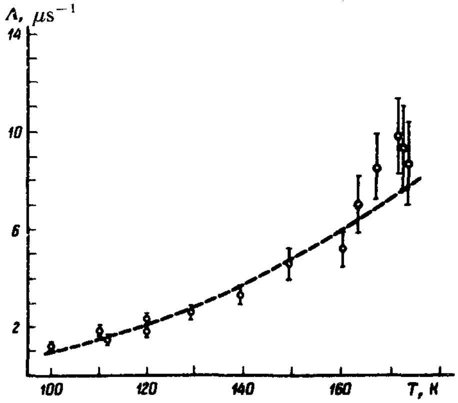

FIG. 2. The temperature dependence, $\Lambda(T)$, of the relaxation rate of the muon's spin. The curve is theoretical function (7), $\Lambda_{\text{teor}}(T)$.

$$P_{\text{obs}} = \frac{a_1}{a_0} = \langle \cos^2\theta \rangle = 0{,}375. \tag{2}$$

Here $\langle \cos^2\theta \rangle$ is the mean square cosine of the angle between the polarization direction of the muons and the directions of the local fields H_μ. It follows from the experimental behavior $a(T)$ and $\Lambda(T)$ near T_N that the transition of dysprosium to the antiferromagnetic state occurs over a rather broad temperature interval, in contrast with that in erbium.^{3} Accordingly, the temperature dependence of the scale time for a diffusive hop of a muon in the dysprosium crystal, $\tau(T)$, was measured at $T < 174$ K, where all the transient processes were definitely completed, and where the magnetic structure of the sample was ordered in an antiferromagnetic helicoid.

Figure 2 shows the temperature dependence of the relaxation rate of the muon spin, $\Lambda(T)$, in the antiferromagnetic state at $T = 100$–174 K.

From Fig. 2 we see that at $T < T_N$ the rate Λ increases with increasing temperature. This $\Lambda(T)$ behavior is attributed to a diffusion of the muon among interstitial sites in the helicoidally ordered structure of dysprosium. Upon a diffusive hop of a muon between two adjacent interstitial sites, the longitudinal component of its spin, σ_{long} (the component along the direction of the field H_μ), decreases, becoming equal to $\sigma_{\text{long}} \cos\varphi$, where φ is the angle between the directions of H_μ at these interstitial sites. We show below that this process leads to an exponential dependence $P(t) = e^{-\Lambda t}$ with

$$\Lambda = \frac{k}{\tau} \sin^2\varphi , \tag{3}$$

where $k \lesssim 1$ is the relative probability for a diffusive hop of a muon to an interstitial site in a neighboring atomic layer caused by atomic spins which are rotated through an angle φ.

Expression (3) is derived in the following way. We write

$$P(t) = \sum_i P_i(t) \cos\theta_i , \tag{4}$$

where $P_i(t)$ is the contribution to the measurable polarization $P(t)$ from muons which at the time t are in interstitial positions at which the field H_μ makes an angle θ_i with the direction of the original field; i.e., this is the measurable polarization of the muons. The summation is over all interstitial sites. The rate of change of $P_i(t)$ during the diffusion of a muon can be written

$$\frac{dP_i}{dt} = \frac{W}{2}\cos\varphi\,[P_{i-1}(t) + P_{i+1}(t)] - WP_i(t), \tag{5}$$

where $W = k/\tau$. The first term in (5) describes the increase in $P_i(t)$ due to the diffusion of muons to the i-th interstitial site from the neighboring $(i-1)$st and $(i+1)$st interstitial sites, while the second describes the decrease in $P_i(t)$ due to the diffusion of muons away from the i-th interstitial site. From (4) and (5) we find

$$\frac{dP}{dt} = -\,WP(t) + \frac{W}{2}\cos\varphi\,\sum_i[\cos\theta_i P_{i-1}(t) + \cos\theta_i P_{i+1}(t)\;.$$

Expressing the angles θ_{i+1} and θ_{i-1} in terms of θ_i, we find

$$\frac{dP}{dt} = -\,P(t)\,[W(1-\cos\varphi) + W\cos\varphi\,(1-\cos\varphi)] = -\,P(t)\,W\sin^2\varphi\;,$$

from which it follows that the function $P(t)$ in expression (3) for the relaxation rate Λ is exponential.

For the incoherent diffusion of a muon through a crystal, the temperature dependence $P(t)$ can be written[1]

$$\frac{1}{\tau} = \nu e^{-Q/T}. \tag{6}$$

It then follows from expressions (3) and (6) that

$$\Lambda_{\text{theo}} = k\nu e^{-Q/T}\sin^2\varphi\quad . \tag{7}$$

The parameters $k\nu$ and Q are determined from the experimental dependence $\Lambda(T)$ shown in Fig. 2. It should be kept in mind here that the angle φ is dysprosium depends strongly on the temperature. Neutron-diffraction measurements reveal that the angle φ increases nearly linearly from $\varphi = 26°$ at $T = 90$ K to $\varphi = 43°$ at $T = 180$ K. Figure 2 shows the theoretical function (7) found with this $\varphi(T)$ behavior. The values found for the parameters $k\nu$ and Q by the maximum-likelihood method are

$$k\nu = 10^{8{,}0\,\pm\,0{,}1}\ \text{s}^{-1},\quad Q = 316 \pm 27\,\text{K}. \tag{8}$$

The values of the parameters $k\nu \simeq \nu$ and Q in (8) correspond to a tunneling diffusion[1] of a muon in dysprosium.

In principle, the method described above for measuring the dependence $\tau(T)$ in dysprosium can reveal whether the diffusion of a muon in this metal is a sequence of hops to neighboring interstitial sites or an unobservably rapid (band) motion through the crystal between relatively remote local impurity trapping centers. In the latter case the relaxation rate of the muon's spin should be independent of the function $\varphi(T)$.

Unfortunately, the statistical error of the present experiments permits only the qualitative assertion that an interstitial diffusion of a muon in dysprosium is the more probable process. As measures of the agreement of the experimental and theoretical functions $\Lambda(T)$ for these two diffusion processes we have $\chi^2 = 17$ for the function $\varphi(T)$ given above (Fig. 2) and $\chi^2 = 20$ for the case $\varphi = \text{const}$, with an average statistical value $\chi^2 = 12$.

We thank O. I. Sumbaev and A. A. Vorob'ev for their cooperation and support; we also thank M. T. Berezov, A. F. Burtsev, and A. N. Zaikaev for assistance.

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Translated by Dave Parsons
Edited by S. J. Amoretty