Expansion of the crystal lattice of tantalum and indium by a μ^+ meson

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A method is proposed for taking into account the influence of the quadrupole interactions on the dipole relaxation of the μ^+-meson spin in a metal. The method can be used in those cases when the quadrupole interaction of the μ^+ meson and the nuclei of the metal is much larger than their dipole interaction. The volume expansion of the tantalum and indium lattices by impurity μ^+ mesons is determined.

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The μ^+-meson spin relaxation due to dipole–dipole interaction of its magnetic moment with magnetic moments of metal nuclei was first observed in copper.[1] Subsequently dipole relaxation of the μ^+ meson was observed[2] in a large number of metals. Measurements of the rate Λ of the dipole relaxation of the μ^+-meson spin and a comparison with the calculated value makes it possible to determine the type of interstitial pore in which the μ^+ meson is localized, and the degree of deformation of this pore. Comparison of the experimental value of Λ with the calculated one is possible in any external magnetic field B perpendicular to the initial polarization of the μ^+ mesons. This comparison, however, is complicated by two circumstances. First, calculation of Λ for an arbitrary field B entails very great difficulties. By now, the values of Λ were calculated at $B = 0$, at $B \gtrsim B_{\rm dip}$, where $B_{\rm dip} \approx 10$ Oe is the dipole magnetic field produced at the μ^+ meson by the metal nuclei, and at $B \gg B_{\rm dip}$.[3,4] Second, account must be taken of the influence of the electric quadrupole interactions of the μ^+ meson with the metal nuclei on the measured value of Λ. To suppress this influence it is necessary to supply a sufficiently strong magnetic field. Experiment has shown[5] that in copper, whose nuclear quadrupole moment is $Q_{\rm Cu} = 0.21$ b, which calls for a field $B \approx 10$ kOe. The production of such appreciable magnetic fields with the experimentally required inhomogeneity $\Delta B/B \lesssim 10^{-4}$ is a rather complicated task. If the nuclei of the investigated metals have a quadrupole moment much larger than $Q_{\rm Cu}$, the method of suppressing the quadrupole interactions by a strong magnetic field can apparently not be used at all because of the encountered experimental difficulties.

We propose in this paper another method of taking into account the influence of the quadrupole interactions on the rate of dipole relaxation of the spin of the μ^+ meson. This method can be used when the energy of the quadrupole interaction of the μ^+ meson and the nuclei of the metal is much larger than the energy of their magnetic dipole interactions.

The calculated value of Λ is determined from the time dependence of the μ^+-

meson polarization $P(t)$. To calculate $P(t)$ we represent it as a series in even powers of t (Ref. 3):

$$P(t) = 1 - M_2 \frac{t^2}{2!} + M_4 \frac{t^4}{4!} - \ldots . \quad (1)$$

We confine ourselves henceforth to the calculation of the coefficient $M_2 = 2\Lambda^2$. This approximation is justified in practice because the experimental $P(t)$ dependences are well described[1,2] by the expression $P(t) = \exp(-\Lambda^2 t^2)$. The standard calculation procedure with the Van Vleck Hamiltonian[3] leads to the following expression for M_2 in a polycrystalline sample at $B \gtrsim B_{\rm dip}$ (Ref. 4):

$$M_2(B \gtrsim B_{\rm dip}) = \frac{2}{3} (\gamma_\mu \gamma_I \hbar)^2 I(I+1) \sum_i r_i^{-6} \quad (2)$$

and to the following relation between the values of M_2 in different magnetic fields B:

$$M_2(B \ll B_{\rm dip}) : M_2(B \gtrsim B_{\rm dip}) : M_2(B \gg B_{\rm dip}) = 5 : \frac{5}{2} : 1 . \quad (3)$$

Here γ_μ and γ_I are the gyromagnetic ratios of the μ^+ meson and of the metal nuclei; I is the nuclear spin; r_i is the distance from the μ^+ meson to the ith nucleus.

Expressions (2) and (3) were obtained without allowance for the electric quadrupole interactions which, as shown in Ref. 5, greatly affect the value of Λ. Calculation of $\Lambda(B,Q)$ at arbitrary values of B and Q encounters very serious difficulties. However, if the quadrupole interaction energy of μ^+ meson with the metal nuclei is much larger than the energy of the dipole interaction, i.e., at sufficiently high values of Q, the influence of the quadrupole interactions manifests itself qualitatively in the fact that only the radial components of the dipole magnetic fields at the μ^+ meson remain effective. A standard calculation leads in this case to the following correction factors χ for the quantities M_2:

$$\chi_{I=n} = \frac{2}{3}, \qquad \chi_{I=n-1/2} = \frac{2}{3} + \frac{1}{4I(I+1)} \quad (4)$$

where $n = 1,2,\cdots$. The correction factors (4) are exact in magnetic fields $B \ll B_{qu}$, where B_{qu} are the magnetic fields necessary for a complete suppression of the quadrupole interactions of the μ^+ meson and the nuclei of the metal.

A unique experimental $\Lambda(B)$ dependence should be observed in strong quadrupole interactions, viz., the quantity $\Lambda(B \ll B_{\rm dip})$ decreases in accordance with (3) by a factor $(2)^{1/2}$ at $B \gtrsim B_{\rm dip}$, and then remains constant when B increases, even at $B \gg B_{\rm dip}$. Only at $B \approx B_{\rm qu}$, when the quadrupole interactions are suppressed by the external magnetic field B, is the value of Λ obtained by Van Vleck[3] reached. We therefore obtain for the ratio of the value of M_2 in strong quadrupole interactions, in accordance with (3) and (4),

$$M_2(B \ll B_{\rm dip}) : M_2(B \gtrsim B_{\rm dip}) : M_2(B \gtrsim B_{\rm qu}) = 5 : \frac{5}{2} : \frac{3}{2} \quad (5)$$

for integer I and

$$M_2(B \ll B_{\rm dip}) : M_2(B \gtrsim B_{\rm dip}) : M_2(B \gtrsim B_{\rm qu}) = 5 : \frac{5}{2} : \frac{1}{\dfrac{2}{3} + \dfrac{1}{4I(I+1)}} \quad (6)$$

for half-integer values of I.

For an experimental check on this picture, we measured $\Lambda(B)$ in indium, whose nucleus has a large quadrupole moment $Q_{\text{In}} = 1.16$ b. The procedure of obtaining Λ from the experimental relations is described in detail in Refs. 1 and 2. The values of Λ were measured at sufficiently low temperatures, when the μ^+ meson does not diffuse over the indium crystal during the entire time of observation (10 msec).[2]

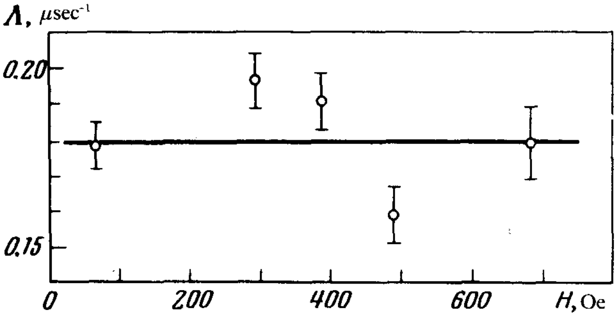

FIG. 1. $\Lambda(B)$ in indium at magnetic fields $B \gtrsim B_{\text{dip}}$. The straight line is the average value of Λ in the temperature interval 5–27 K.

The function $\Lambda(B)$ in indium is shown in Fig. 1. It is seen from Fig. 1 that Λ is independent of B in indium up to fields $B \approx 700$ Oe$\gg B_{\text{dip}} \approx 10$ Oe. This confirms the assumption that a strong quadrupole interaction exists between the μ^+ meson and the indium nuclei. A strong quadrupole interaction was observed also in copper,[5] where there is no $\Lambda(B)$ dependence up to $B \approx 500$ Oe. The experimentally proved presence of strong quadrupole interactions in indium makes it possible to use formula (2) with the correction factor (4) to obtain the calculated values Λ_{calc} in this metal (as well as in tantalum, whose quadrupole moment $Q_{\text{Ta}} = 3.9$ b and is larger by one order of magnitude than the quadrupole moment of the copper nucleus).

Table I lists the calculated and experimental values of Λ for indium and tantalum

TABLE I.

Metal	T, K	Type of pore	Λ_{calc} ($B \gtrsim B_{\text{dip}}$) μsec⁻¹	Λ μsec⁻¹	$a = \Lambda_{\text{calc}}/\Lambda$
Indium	5 - 27	octa tetra	0.250 0.308	0.179± 0.003	1.39 ± 0.03
Tantalum	5 - 36	octa tetra	0.198 0.184	0.133 ± 0.003	1.38 ± 0.03

in a field $B \gtrsim B_{\text{dip}}$. The calculated values Λ_{calc} were obtained with formula (2) and the correction factor (4) for undeformed metal lattices.

The structure of indium is a face-centered tetrahedral (slightly distorted fcc) lattice with an axes ratio $c/a = 1.075$. The localization of the μ^+ meson in the octapore of the fcc lattice of indium is assumed to be similar to the localization of the μ^+ meson in the fcc lattice of copper.[5] The localization of the μ^+ meson in the tetrapore of the dcc lattice of tantalum was assumed to be similar to the localization of the hydrogen atom.[6] The experimental values of Λ are averages obtained in the temperature intervals listed in Table I, where the values of T are the same within the limits of errors (see Fig. 2).

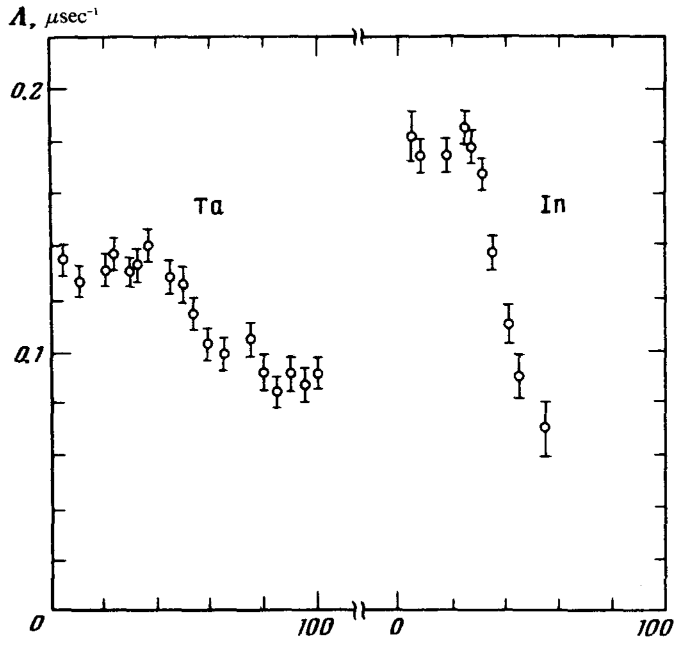

FIG. 2. $\Lambda(T)$ dependences at $B \simeq 70$ Oe in indium and tantalum at low temperatures. The experimental $P(t)$ were described by the expression $P(t) = \exp(-\Lambda^2 t^2)$.

Table I lists also the values of $\alpha = \Lambda_{calc}/\Lambda$. The quantity constitutes the relative volume expansion of the pore, primarily of its first coordination sphere, since the metal nuclei closest to the μ^+ meson, as follows from (2), account for more than 90% of the calculated value Λ_{calc}.

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