Searches for muonium atoms in aluminum, copper, zinc, and carbon

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No temperature dependence of the μ^+-meson precession was observed, with accuracy $\sim 0.03\%$, in Al, Cu, Zn, and C at $T = 4$ to 90°K. It follows from these data that the frequencies ω_0 of the hyperfine splitting of the muonium atom $(\mu^+ e^-)$ in these substances are $\omega_0 < 10^{-4}\,(\omega_0)_{vac}$, where $(\omega_0)_{vac}$ is the frequency of the hyperfine splitting of muonium in vacuum. So small a value of ω_0 in the investigated substances can be interpreted as the absence of an orbitally bound paramagnetic state of $(\mu^+ e^-)$.

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We proposed in[1] a method of measuring the frequency ω_0 of the hyperfine splitting of a paramagnetic-impurity muonium atom in a metal. It should be recalled that in a metal it is practically impossible to measure ω_0 in coherent interactions of the spins of the μ^+ meson and the electron of the muonium, owing to the large frequency $\nu \gg \omega_0$ of the flipping of the electron spin in exchange scattering of the conduction electrons by the muonium atom. The method proposed in[1] is based on observation of the temperature-dependent shift $\Delta\omega$ of the μ^+-meson Larmor precession frequency in a transverse magnetic field B:

$$\Delta\omega = \frac{e}{m_\mu c} B_k = \frac{e}{m_\mu c} \frac{8\pi}{3} \beta_e P \rho(0) = \omega a \frac{11}{T}, \tag{1}$$

where

$$B_k = \frac{8\pi}{3} \beta_e P \rho(0) \sim \frac{a}{T} \tag{2}$$

is the contact magnetic field of the polarized muonium electron at the μ^+ meson. Here $P = \beta_e B/kT$ is the polarization of the muonium electron in the metal in an external field B; β_e is the magnetic moment of the electron; T is the absolute temperature; $\rho(0)$ is the density of the electronic wave function of the muonium at the μ^+ meson; $a = \rho(0)/[\rho(0)]_{vac}$, where $[\rho(0)]_{vac}$ is the density of the electronic wave function at the μ^+ meson of the muonium in vacuum; $\omega = eB/m_\mu c$ is the precession frequency of a free μ^+ meson in a field B, and m_μ is the mass of the μ^+ meson.

The quantity $P = \beta_e B/kT$ is the equilibrium polarization of the electron of the paramagnetic muonium atom in the metal. The time required to establish this polarization is $t_e \sim 1/\nu$, where $\nu \sim 10^{11} T\ \text{sec}^{-1}$, i.e., much less than the observation time usually determined by the μ^+-meson lifetime $\tau_0 = 2.2 \times 10^{-6}$ sec. The indicated value of ν follows from expression (3):

TABLE 1. Values of ω_{exp} in aluminum, copper, zinc, carbon, and teflon at $T_1 = 4.2$ °K and $T_2 = 60$ to 90 °K [1)]

Material	$\omega_{exp}(T_1)$, μsec^{-1}	$\omega_{exp}(T_2)$, μsec^{-1}
Aluminum	59.26 ± 0.01	59.26 ± 0.01
Copper	59.28 ± 0.01	59.30 ± 0.01
Zinc	59.29 ± 0.01	59.29 ± 0.01
Carbon	59.33 ± 0.02	59.36 ± 0.01
Teflon	59.29 ± 0.03	59.29 ± 0.02

[1)]The values of T_2 were measured accurate to $\delta_{T_2} = 1$ °K, but were different for the indicated substances in the range of $T_2 = 60$ to 90 °K.

$$\nu = \sigma v n \frac{kT}{E_f} \sim 10^{-11} T \text{ sec}^{-1}, \tag{3}$$

where $\sigma \approx 10^{-15}$ cm^2 is the exchange-scattering cross section, $v \approx 10^8$ cm/sec is the velocity of the conduction electrons, $n \approx 10^{23}$ cm^{-3} is the density of the collectivized electrons, kT/E_f is the fraction of the electrons that can experience scattering with spin flip, and E_f is the Fermi energy.

The density $\rho(0)$ is connected with the muonium-atom hyperfine-splitting frequency by[2]

$$\omega_0 = \frac{32\pi}{3\hbar} \beta_\mu \beta_e \rho(0), \tag{4}$$

where β_μ is the magnetic moment of the μ^+ meson. The value of $[\omega_0]_{vac}$ for the muonium atom in vacuum is $[\omega_0]_{vac} = 2.8 \times 10^{10}$ sec^{-1}.

Expression (1) for $\Delta\omega$ leads to the following dependence of the frequency $\omega_{obs}(T)$ of the μ^+-meson precession in an external field B:

$$\omega_{obs}(T) = \frac{e}{m_\mu c}(B + B_k) = \omega + \Delta\omega = \omega\left(1 + \alpha \frac{11}{T}\right). \tag{5}$$

Comparison of the theoretical relation (5) for $\omega_{obs}(T)$ with experiment makes it possible to determine the parameter α. Deviation of α from zero means that a bound paramagnetic state (μ^+e^-) exists in the metal, i.e., a muonium atom. The quantity $\alpha = \rho(0)/[\rho(0)]_{vac} = \omega_0/[\omega_0]_{vac}$ determines the density $\rho(0)$ of the electronic wave function or the frequency ω_0 of the hyperfine splitting of this bound state. No account was taken in (5) of the change in the observed frequency ω_{obs} due to the Knight shift. Allowance for this effect leads only to a small ($\sim 0.01\%$) increase of ω and hardly affects the measurement of the value of α of interest to us, since the Knight shift does not depend on temperature.

The experimentally measured frequencies ω_{exp} of the μ^+ meson precession in aluminum, copper, zinc, and oxygen at two values of the temperature T are given in Table 1. For comparison, analogous measurements were made in a substance where there are no free electrons (in teflon); the results are also indicated in Table 1. The work was performed with the JINR synchrocyclotron in Dubna.

TABLE 2. Experimental values of the parameters ω and α in Eq. (5).

Material	ω, μsec^{-1}	$\alpha \cdot 10^4$
Aluminum	59.26 ± 0.01	0 ± 1
Copper	59.30 ± 0.01	-1.5 ± 1
Zinc	59.29 ± 0.01	0 ± 1
Carbon	59.36 ± 0.01	-2 ± 2
Teflon	59.29 ± 0.02	0 ± 3

The $\omega_{exp}(T)$ dependence was measured in a magnetic field $B \approx 700$ Oe transverse to the μ^+-meson spin by registering the positrons of the $\mu^+ \to e^+$ decay. The stability of the external field B was determined by measuring the frequency of proton resonance in water and was better than 0.01%. A more detailed description of the experiment can be found, e.g., in[3].

The parameters ω and α obtained by comparing the theoretical relation (5) and the experimental data of Table 1 are given in Table 2.

Of course, calculation of the parameter α in Teflon with the aid of formula (5) is only a formal procedure, since there are no free electrons in this material, and we cannot state that the equilibrium polarization $P = \beta_e B/kT$ of the muonium electron sets in at a sufficiently fast rate.

It is seen from Table 2 that the parameter $\alpha = \rho(0)/[\rho(0)]_{vac}$ in the investigated metals is equal to zero accurate to 0.01%, i.e., the density of the electronic wave function of muonium in metal is $\rho(0) < 10^{-4}[\rho(0)]_{vac}$. With a hydrogenlike wave function in the S state, the radius $r \sim [\rho(0)]^{-1/3}$ of such a muonium atom exceeds substantially the dimensions of the crystal cell of the metal or, moreover, the dimensions of the tetrapores or octapores in which it could be situated: $r = \alpha^{-1/3}$, $r_0 \sim 10$ Å, where $r_0 = 0.5$ Å is the Bohr radius of muonium in vacuum. So "friable" a muonium atom seems little likely and therefore the results can be interpreted as the absence of a bound paramagnetic state ($\mu^+ e^-$) in the investigated metals.

It must be emphasized in conclusion that the electron wave function of the impurity atom of muonium in matter should be similar to the electronic wave function of hydrogen (pe^-). Therefore the conclusion drawn here that there is no paramagnetic muonium atom in the investigated metals means also the absence of an orbitally-bound paramagnetic state (pe^-).

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