Search for muonium atom in copper

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A method is proposed for determining the frequency ω_0 of the hyperfine splitting of the muonium atom in a metal. The method is based on measuring the temperature dependence of the μ^+-meson precession-frequency shift due to polarization of the muonium electron. It was found that in copper the frequency is $\omega_0 \lesssim 0.01(\omega_0)_{\text{vac}}$ where $(\omega_0)_{\text{vac}}$ is the frequency of the hyperfine splitting of the muonium atom in vacuum.

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One of the important problems of metal physics is the study of the wave function of an impurity hydrogen atom in a metal. In this paper we use for this purpose the light hydrogen isotope, namely the muonium atom, and investigate the possible existence, in a metal, of muonium in the paramagnetic state, i.e., with an unpaired electron spin. It must be emphasized that the use of μ^+ mesons instead of protons makes it possible to eliminate completely the mutual influence of the impurity atoms, since the μ^+-meson concentration in the investigated sample is practically equal to zero.

An impurity paramagnetic muonium atom in matter is usually revealed[1,2] by the characteristic frequency $\omega_{\text{Mu}} = eH/2m_ec$ of the Larmor precession, where H is the external magnetic field and m_e is the electron mass. In a metal, however, this method of observing muonium is impossible, since the spin of the muonium electron relaxes rapidly, owing to the interaction with the conduction electrons. A qualitative estimate shows that the interaction with the conduction electrons flips the spin of the muonium electron with frequency $\nu \sim 10^{12}T$ sec^{-1}, where T is the absolute temperature. This quantity ν greatly exceeds the frequency ω_0 of the hyperfine splitting in the muonium atom, the vacuum value of which is[3]

$$(\omega_0)_{\text{vac}} = \frac{32\pi\beta_e\beta_\mu}{3\hbar}\rho_{\text{vac}}(0) = 2{,}8\cdot 10^{10}\ \text{sec}^{-1}. \tag{1}$$

Here β_e and β_μ are the magnetic moments of the electron and muon respectively; $\rho_{\text{vac}}(0)$ is the density of the electron wave function at the μ^+ meson in vacuum. Since one should expect $\omega_0 < (\omega_0)_{\text{vac}}$ in a metal, the relation $\nu \gg \omega_0$ is satisfied at all practically obtainable temperatures T. The relation $\nu \gg \omega_0$ causes the precession frequency of the μ^+ meson in metals to be practically the same as the frequency

$$\omega = eH/m_\mu c, \tag{2}$$

of the precession of the free μ^+ meson (m_μ is the μ^+-meson mass) regardless of the orbital state of the (μ^+e^-) system.

The rapid relaxation of the muonium electron spin in a metal can lead only to a weak damping of the μ^+-meson precession amplitude in accordance with the law[4]

$$P(t) = e^{-\Lambda t}, \quad \Lambda = \omega_0^2/4\nu\ . \tag{3}$$

Relations (3) can be used in principle to prove the existence, in the metal, of a muonium atom in a paramagnetic state and to determine the hyperfine-splitting frequency ω_0 characterizing this state. For a practical utilization of this method, however, it is necessary to be able to calculate sufficiently reliably the value of ν and to be assured that the observed relaxation rate Λ of the μ^+-meson spin is determined only by the process described above.

In the present experiment we sought to observe the impurity paramagnetic muonium atom in copper by determining the change $\Delta\omega$, due to the interaction with the polarized conduction electrons, of the precession frequency (2) of the μ^+-meson spin. The change $\Delta\omega$ of the μ^+-meson precession frequency is in essence the Knight shift at the nucleus of the paramagnetic atom in the metal. Unlike the usual Knight shift, when the atoms are in the diamagnetic state, i.e., the spins of the atomic electrons are cancelled out, the frequency shift $\Delta\omega$ in paramagnetic muonium is determined by the polarization of the bound electron and consequently increases with decreasing temperature.

The quantity $\Delta\omega$ represents the increase of the μ^+-meson precession frequency as a result of the contact field B_c at the μ^+ meson of the polarized muonium electron

$$B_K = \frac{8\pi}{3}\beta_e P\rho(0)\ . \tag{4}$$

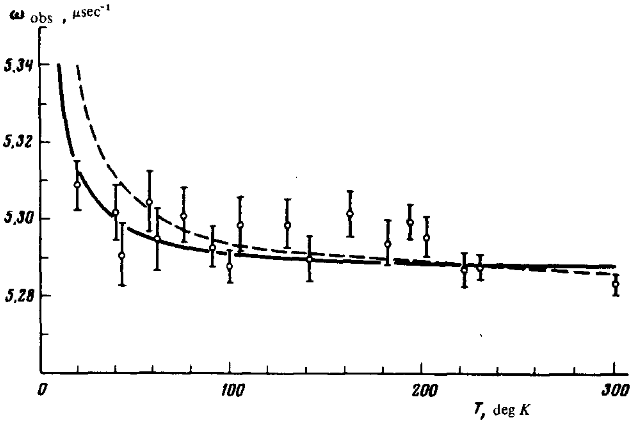
Here $P = \beta_eH/kT$ is the polarization of the muonium electron at the temperature T; $\rho(0)$ is the density of the electron wave function at the μ^+ meson in the muonium impurity atom; k is Boltzmann's constant. It follows from (4) that

$$\Delta\omega = \frac{\omega}{T}\,\frac{(\omega_0)_{\text{vac}}\hbar\alpha}{4k}\,\frac{\beta_e}{\beta_\mu} = \omega\alpha\frac{11}{T}\ , \tag{5}$$

where $\alpha = \omega_0/(\omega_0)_{\text{vac}}$ and T is the absolute temperature. Thus, the observed spin-precession frequency of the μ^+ meson in the metal takes the form

$$\omega_{\text{obs}} = \omega\left(1 + \alpha\frac{11}{T}\right). \tag{6}$$

A comparison of the theoretical function $\omega_{\text{obs}}(T)$ (6) with experiment makes it possible to find the parameter α. A deviation of α from zero denotes that a bound paramagnetic state (μ^+e^-) exists in the given metal. The quantity α determines the frequency ω_0 of the hyperfine splitting of this bound state.



Dependence of the spin precession frequency ω_{obs} of the μ^+ meson in copper on the temperature T. The solid curve is a plot of (6) with the parameters ω and α chosen by the maximum-likelihood method: $\omega = 5.286 \pm 0.001$ μsec^{-1} and $\alpha = (9 \pm 3) \times 10^{-3}$ (the error is statistical). The dashed curve corresponds to $\alpha = 2 \times 10^{-2}$.

The experimental temperature dependence of the μ^+-meson spin-precession frequency $\omega_{\text{exp}}(T)$ in copper is shown in the figure. The $\omega_{\text{exp}}(T)$ dependence was measured in a transverse magnetic field $H = 62$ Oe by a method in which the positrons of the $\mu^+ \to e^+$ decay were registered. The stability of the external field H during the time of the experiment was verified against the frequency of the proton resonance in water. The experimental procedure is described in[5].

It follows from the figure that the frequency ω_{exp} in copper does not exhibit a sufficiently definite (if the errors are taken into account) variation with temperature at $T = 20$–300 °K. The $\omega_{\text{exp}}(T)$ plot shown in the figure corresponds to a parameter $\alpha = (9 \pm 3) \times 10^{-3}$ (the error is statistical) in the theoretical relation (6). This value of α shows that the bound paramagnetic $(\mu^+ e^-)$ state in copper, if it does exist, is quite loose, $\alpha = \omega_0/(\omega_0)_{\text{vac}} = \rho(0)/\rho_{\text{vac}}(0) \approx 10^{-2}$. The figure shows also the theoretical plot (6) of $\omega_{\text{obs}}(T)$ at $\alpha = 2 \times 10^{-2}$. This dependence patently disagrees with experiment at $T = 20$ °K and thus demonstrates the sensitivity of the experimental data to the possible values of the parameter α.

An important task is to increase further the accuracy with which α is determined. This can be done most effectively by measuring the dependence $\omega_{\text{exp}}(T)$ in the region of lower temperatures. It is seen from the figure that if the parameter α actually differs from zero at the level $\alpha \approx 0.01$, then one should expect an appreciable change, exceeding the limits of errors, of the frequency ω_{exp} at $T < 10$ °K.

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