discussions, and to B.V. Seleznev and E.L. Kondrat'ev for help with the experiments.

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TWO-PARTICLE PRECESSION OF MUONIUM IN STRONG MAGNETIC FIELDS

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We consider here the change of the polarization P(t) of the μ^+ meson of muonium in a transverse magnetic field B (perpendicular to the μ^+-meson spin). Under these conditions the state of the muonium is not stationary, but is a superposition of states with different energies. The general form of the time dependence of P(t) was obtained for such a case in [1]. In the present article we point out several peculiarities of P(t) in strong transverse magnetic fields. These peculiarities can be used to determine the frequency ω_0 of the hyperfine splitting of the muonium atom in matter.

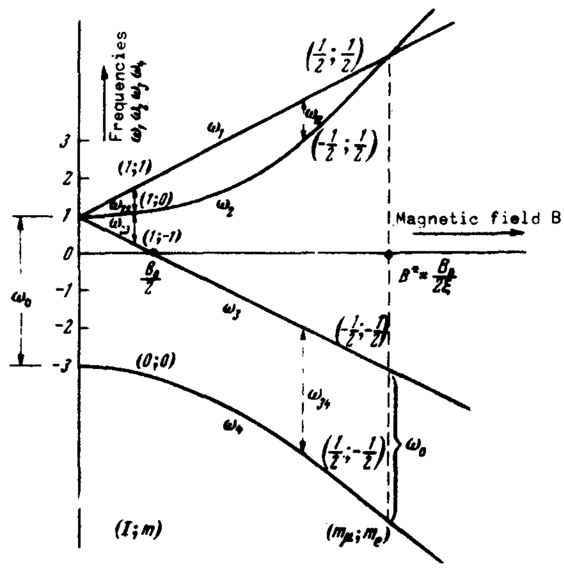

Fig. 1. Breit-Rabi diagram for the muonium terms in a magnetic field. The arrows designate the frequencies ω_{12}, ω_{23} and ω_{12}, ω_{34}, which determine the two-frequency precession for weak ($B \ll B_0$) and strong ($B \gg B_0$) fields, respectively. The figure shows the quantum numbers that determine the state of the muonium atom in weak and strong fields. The good quantum numbers are the total angular momentum I of the muonium and its projection m on the direction of the field B in a field $B \ll B_0$. The good numbers and the projections of the separate spins μ^+ meson and the electron in the region $B \gg B_0$.

Figure 1 shows schematically plots of the frequencies $\omega = E/\hbar$ of the eigenstates of the muonium atom against the external magnetic field B. The expression obtained for P(t) in [1] is

$$P(t) = \frac{1}{4}\Big\{[\cos\omega_{12}t + \cos\omega_{23}t + \cos\omega_{14}t + \cos\omega_{34}t] + $$

$$+ \frac{B(1+\xi)}{\sqrt{B_0^2 + B^2(1+\xi)^2}}[\cos\omega_{12}t - \cos\omega_{23}t - \cos\omega_{14}t + \cos\omega_{34}t]\Big\}. \qquad (1)$$

The transition frequencies ω_{ik} cited here are equal to

$$\omega_{12} = \frac{\omega_0}{2} + \omega_- - \sqrt{\frac{\omega_0^2}{4} + \omega_+^2}\,.$$

$$\omega_{23} = -\frac{\omega_0}{2} + \omega_- + \sqrt{\frac{\omega_0^2}{4} + \omega_+^2}\,.$$

$$\omega_{14} = \frac{\omega_0}{2} + \omega_- + \sqrt{\frac{\omega_0^2}{4} + \omega_+^2}\,.$$

$$\omega_{34} = \frac{\omega_0}{2} - \omega_- + \sqrt{\frac{\omega_0^2}{4} + \omega_+^2}\,. \qquad (2)$$

where $\omega_\pm = \omega(1 \pm \xi)$, $\xi = M_e/M_\mu = 1/203$ is the ratio of the electron and μ^+-meson masses, $\omega = eB/2M_ec$ is the frequency of the Larmor precession of the muonium atom in the field B, $B_0 = \omega_0(M_ec/e$ is the magnetic field produced by the μ^+ meson at the electron of the muonium.

Expression (1) for P(t) becomes much simpler for the cases $B \ll B_0$ (the region of the Zeeman effect) and $B \gg B_0$ (the region of the Paschen-Back effect).

The case $B \ll B_0$ was investigated in detail in [1] and leads to the expression

$$P_1(t) \cong \frac{1}{4}[\cos\omega_{12}t + \cos\omega_{23}t] = \frac{1}{2}\cos\omega t\cos\Omega_1 t\,. \qquad (3)$$

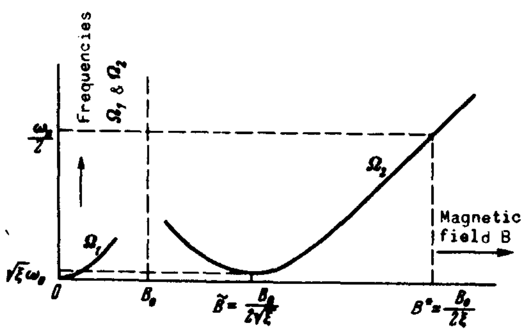

Fig. 2. Dependence of the modulating frequencies Ω_1 and Ω_2 in expressions (3) and (5) on the transverse magnetic field B for two-frequency precession in weak ($B \ll B_0$) and strong ($B \gg B_0$) fields, respectively. The scale is arbitrary.

Here $\omega = eB/2M_ec$ is the carrier frequency, and

$$\Omega_1 \approx \frac{\omega^2}{\omega_0} \sim B^2 \qquad (4)$$

is the modulation and beat frequency. Expression (3) and $P_1(t)$, called two-frequency precession, is an approximation, from which there were omitted the terms with the frequencies ω_{14} and ω_{34}, which are much higher than ω_{12} and ω_{23} in fields $B \ll B_0$, and are usually not registered. Two-frequency precession of muonium in fields $B \ll B_0$ was observed experimentally in a number of substances [1].

It is curious, and this is the gist of our article, that the case $B >> B_0$, as follows from (1), also leads to two-frequency precession:

$$P_2(t) \cong \frac{1}{2}[\cos\omega_{12}t + \cos\omega_{34}t] = \cos\frac{\omega_0}{2}t\cos\Omega_2 t\ . \quad (5)$$

Here

$$\Omega_2 = \frac{\omega_{34} - \omega_{12}}{2} \cong 2\xi\omega + \frac{\omega_0^2}{8\omega}\ , \quad (6)$$

where $2\xi\omega = \omega_\mu = eB/M_\mu c$ is the frequency of the Larmor precession of the μ^+ meson in the field B. Thus, in the two-frequency precession (5), the carrier frequency does not depend on the external magnetic field and is equal to $\omega_0/2$. Relation (6) determines the modulating frequency Ω_2 and its dependence on the external magnetic field B. The $\Omega_2(B)$ dependence (6) is not monotonic and is shown in Fig. 2. $\Omega_2(B)$ first decreases with increasing B, reaches at $\tilde{B} = (1 - \xi)B_0/(1 + \xi)2\sqrt{\xi}$ its minimum value $\tilde{\Omega}_{min} = \sqrt{\xi}\omega_0$, and then begins to increase. Here $\Omega_2 \cong (\omega_0^2/8\omega) \sim 1/B$ in fields $B << \tilde{B}$ and $\Omega_2 \cong 2\xi\omega \sim B$ in fields $B >> \tilde{B}$, reaching at $B^* = (1 - \xi)B_0/2\xi$ a value $\Omega_2(B^*) = \omega_0/2$, which corresponds to the intersection of the terms ω_1 and ω_2 (see Fig. 1), i.e., to the case of "cessation of the precession" of the muonium μ^+ meson [1]. When $B \to B^*$ and $\Omega_2 \to \omega_0/2$ we have $P(t) \to (1 + \cos\omega_0 t)/2$. If the resolution of the detecting instrument is poor, the term $\cos\omega_0 t$ averages out to zero, and $P(t) = 1/2 = \text{const}$, meaning cessation of the precession. In the case of good resolution, a precession with frequency ω_0 is observed.

For the vacuum value of ω_0 we have $B_0 = 1594$ G, $\tilde{B} = 11.3$ kG, and $B^* = 164$ kG. The field B at which the frequency ω_{12} reaches a maximum, and the frequency ω_{34} reaches a minimum was used in [2] for a precise determination of the frequency ω_0 of muonium in vacuum. Expression (5) for two-frequency precession in the Paschen-Back region is characterized by two frequencies ω_{12} and ω_{34} corresponding to precession of the μ^+ meson of muonium: $\Delta m_\mu = \pm 1$, $\Delta m_e = 0$ (m_μ and m_e are the projections of the μ^+-meson and electron spins). The frequencies ω_{23} and ω_{14} drop out from expression (5) for P(t) ($\Delta m_\mu = 0$, $\Delta m_e = \pm 1$), since the magnetic feeld of the muonium electron is averaged out because of the rapid precession of its spin in the external field B.

Observation of the precession (5) makes it possible to determine with high accuracy the frequency ω_0 in matter, particularly when the muonium lifetime is short. It may seem that an experimental study of two-frequency precession at $B >> B_0$ calls for a temporal resolution which is as yet unattainable. This is not the case, however. For muonium in vacuum the carrier frequency $\omega_0/2 = 1.403 \times 10^{10}\ \text{sec}^{-1}$ is indeed quite high. But for muonium in a medium the frequency ω_0 is lower. Thus, for example, for germanium $\omega_0/2$ - $(0.811 \pm 0.031) \times 10^{10}\ \text{sec}^{-1}$ [1], corresponding to a precession period T = 0.78 nsec. One should therefore expect an experimental determination of ω_0 by observation of the two-frequency precession (5) in the Paschen-Back region to be quite feasible for a number of substances.

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