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MUONIUM SPIN RELAXATION IN ICE OF ORDINARY AND HEAVY WATER

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We measured the relaxation rate λ of the muonium spin in frozen H_2O and D_2O at 77°K. The values obtained for λ of ordinary and heavy water are 5.7 ± 0.9 and 2.0 ± 0.2 μsec, respectively.

In [1] we proposed a method for the investigation of magnetic dipole interaction and the diffusion of μ^+ mesons in a solid. The method is based on determining the damping rate λ of the precession amplitude a of the μ^+ meson in the given substance, which is placed in a magnetic field that is transverse relative to the μ^+-meson spin. The precession damping or the spin relaxation of the μ^+ meson is the result of the action exerted on the μ^+ meson by local magnetic fields produced by the magnetic moments of the lattice nuclei. Owing to the action of these magnetic fields, the muons in different crystal cells precess with different frequencies, and this causes damping of the observed muon spin precession. As the muon diffuses over the lattice, the local magnetic fields at the muon become alternating in time, and their influence on the muon precession decreases, and it is this which decreases the damping rate λ. The damping of the precession amplitude of the diffusing muon can be described by the formula [2]:

$$a = a_0 \exp\left\{-2\sigma^2\tau^2\left[\exp\left(-\frac{t}{\tau}\right) - 1 + \frac{t}{\tau}\right]\right\}. \quad (1)$$

Here a_0 is the precession amplitude at the initial instant t = 0, τ is the average time spent by the diffusing muon in one crystal cell, and σ characterizes the damping rate of the amplitude a in the absence of diffusion (τ = ∞). It can be shown that for the given crystal lattice

$$\sigma \sim \mu\sqrt{\frac{I+1}{I}}, \quad (2)$$

where I and μ are the spin and magnetic moment of the lattice nuclei. It follows from (1) that in the absence of diffusion we have

$$a = a_0 \exp(-\sigma^2 t^2), \quad (3)$$

and in the case of fast diffusion, when the observation time is t >> τ,

$$a = a_0 \exp(-2\sigma^2 \tau t). \quad (4)$$

Everything said above concerning the magnetic interactions and the μ^+-meson diffusion in a solid is valid also for the muonium atom (μ^+e^-), the only difference being that the magnetic moment of muonium is m_μ/m_e = 207 times larger than the μ^+-meson magnetic moment, and the Larmor-precession frequency $\omega = eB/2m_ec$ of muonium is 103 times larger than that of the muon in the same field B. Here m_e and m are the masses of the electron and μ^+ meson.

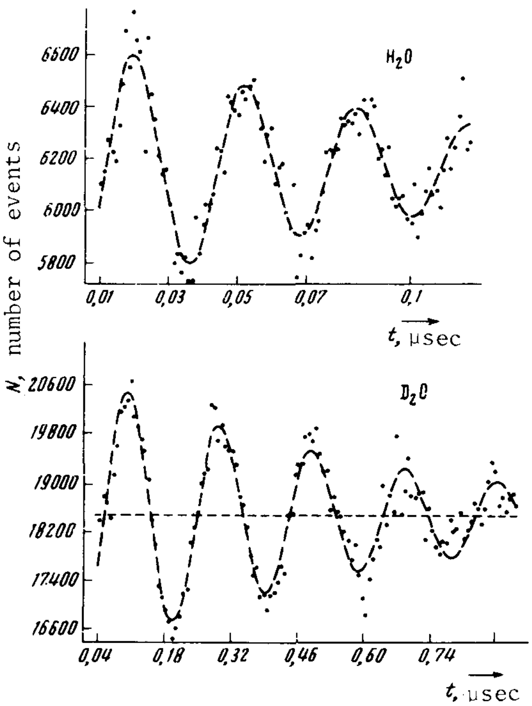
We have investigated the following isotopic difference between the damping rates of the muonium precession amplitude in ice of ordinary and heavy water. The experiment was performed with the beam of polarized μ^+ mesons at the Joint Institute of Nuclear Research in Dubna. The experimental setup was described earlier [1, 3]. The observed damped muonium precession in H_2O ice and D_2O ice at 77°K is shown in the figure. It is seen from the figure that the muonium precession damping rate λ is larger in H_2O than in D_2O, with respective values 5.7 ± 0.9 and 2.0 ± 0.2 μsec. The cited values of λ were taken to be the reciprocals of the time t_e needed for the precession amplitude to decrease by a factor e. The difference between the two rates means that the local magnetic fields at the muonium in H_2O and D_2O are different. These fields can be only the dipole magnetic fields of the magnetic moments of the hydrogen and deuterium nuclei. The experimentally obtained ratio

$$\frac{\lambda_{H_2O}}{\lambda_{D_2O}} = 2.9 \pm 0.5 \quad (5)$$

can be compared with the theoretical value 4 - 16 calculated on the basis of formulas (1) and (2). The minimal value

$$\frac{\lambda_{H_2O}}{\lambda_{D_2O}} = \frac{\sigma_H}{\lambda_D} = \frac{\mu_H\sqrt{(I_H+1)I_D}}{\mu_D\sqrt{(I_D+1)I_H}} = 4$$

(see (3)) is obtained for non-diffusing muonium, and the maximum value $\lambda_{H_2O}/\lambda_{D_2O} = (\sigma_H/\sigma_D)^2 = 16$ corresponds to the case (4) of fast diffusion. It is assumed here that $\tau_{H_2O} = \tau_{D_2O}$. The experimental relation (5) shows thus that the iumpurity muonium ion does not diffuse in ice at 77°K. More accurately speaking, the time τ spent in one crystal cell exceeds the damping time $t_e = 1/\lambda_{H_2O}$ = 0.5 μsec in D_2O ice. The absence of muonium diffusion in ice could be determined also from the time dependence of a(t), which in this case has a Gaussian form (3). However, to distinguish experimentally between the Gaussian a(t) relation (3) and the exponential one (4) one must have a much higher statistical accuracy.



Muonium spin precession damping in H_2O ice and D_2O ice. The smooth curves are calculated values of N(t) that fit best the experimental results.

In addition to the dipole relaxation considered above, there can also be other causes of the muonium precession damping in ice. Thus, for example, the muonium may enter in a chemical reaction, replacing the hydrogen to form a diamagnetic compound. The ratio $\lambda_{H_2O}/\lambda_{D_2O}$ of the muonium precession damping is equal to unity in all such processes. The possible dipole relaxation of the muonium spin, naturally, makes the interpretation of the experimental results more complicated. Additional information can be obtained by investigating the temperature dependence of λ(T).

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THE GELL-MANN — LOW FUNCTION IN SINGLE-CHARGE SCALAR QUANTUM FIELD THEORY

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The first three terms of the Gell-Mann — Low function are obtained in the $\lambda\phi^4$ theory. It is shown that the "zero-charge" situation remains in force when terms up to $\lambda^2[\lambda \ln(\lambda/k)]^4$ are taken into account.

An examination of the usual renormalized quantum field theories has shown that a general property of these theories is the "zero charge" situation, characterized by the appearance of a logarithmic pole in the scattering amplitude a(k) at momenta k >> m (m is the particle mass, e.g., in scalar field theory with interaction $H_{int} = \lambda\phi^4$

$$a(k^2) = \frac{a(m^2)}{1 - \frac{3}{2} a(m^2) \ln \frac{k^2}{m^2}} \quad . \tag{1}$$

The last formula was obtained in the principal logarithmic approximation and is valid when a(k) << 1. The renormalizability of the theory [1] allows us to introduce the Gell-Mann — Low function $\Psi(a)$, which describes the asymptotic behavior of the invariant charge at short distances.

$$\frac{da}{dx} = \Psi(a), \tag{2}$$

where $x = \ln(\lambda^2/k^2)$, and λ is the cutoff momentum. This function can be obtained with the aid of perturbation theory in the form of a power-series in a. The first term of this series

$$\Psi(a) = -\frac{3}{2}\frac{a^2}{16\pi^2} + \dots \tag{3}$$

leads to (1). The problem is to determine the change introduced into this solution by allowance for the last two terms of the expansion in $\Psi(a)$. In particular, if the Gell-Mann — Low function has a zero at the point a, then it can be readily seen from (2) that

$$a(k) \to a \quad . \tag{4}$$

This possibility was discussed in [2, 3]. The coefficient of the term a^3 in the function $\Psi(a)$ was determined, viz.,

$$\Psi(a) = -\frac{3}{2(16\pi^2)} a^2 + \frac{17}{6(16\pi^2)^2} a^3 - \dots \tag{5}$$

The question of the behavior of the Gell-Mann — Low function is of interest also in connection with the recent studies of Yang-Mills fields [4, 5]. It turns out that the ultraviolet behavior of the Green's functions in this theory is such that the ineraction of the vector mesons at short distances becomes asymptotically small, corresponding to the Bjorken scaling. In this theory, however, the vector mesons have no mass. One of the ways of overcoming this difficulty is to include an interaction between the vectors and scalar mesons; this interaction leads, via the Higgs mechanism, to a nonzero mass of the vector mesons.

As follows from (5), inclusion of a^3 leads to a zero of the function $\Psi(a)$. The next higher approximation, however, makes this zero disappear. We present here the result of a calculation of the Gell-Mann — Low function for the theory of n-component scalar field, accurate to terms of order a^4:

$$\Psi(a) = -\frac{(n+8)}{6(16\pi^2)} a^2 + \frac{3n+14}{6(16\pi^2)^2} a^3 - \frac{Da^4}{(16\pi^2)^3} + \dots \tag{6}$$