Spin depolarization of muons in condensed nitrogen

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The temperature dependence of the depolarization rate, initial amplitude, and the initial phase of the muon precession in liquid nitrogen and crystalline nitrogen have been measured. An anomalous behavior of the initial amplitude and phase of the muon precession has been observed near the α–β transition in solid nitrogen.

Barsov *et al.*,[1] have detected a depolarization of muons in parahydrogen which led them to conclude that a formation of an $H_2\mu^+$ ion had taken place. The positive muons apparently form analogous ions in all the cryocrystals. Evidence of this process is supported by the large binding energy that binds the proton with the molecules of cryocrystals.[2] In gaseous nitrogen 84% of the muons form a muonium atom (Mu)

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and 16% of the muons are contained in the diamagnetic fraction.[3] The most probable diamagnetic muon compound in nitrogen is the $N_2\mu^+$ ion. A similar N_2p^+ ion has a linear structure with the spacings $r_{NN} = 1.1$Å, $r_{Np} = 1.0$ Å, and a binding energy of 5.1 eV (Ref. 4). The rates at which muons depolarize in condensed nitrogen, which were determined in Ref. 5, can be explained on the basis of the dipole-dipole mechanism for the relaxation in a $n_2\mu^+$ ion, without turning to the mechanism for the interaction of muons with the particles of the tracks formed by them. Unfortunately, the values for the polarization of muons in nitrogen, from which we could draw some conclusions concerning the nature of the compound formed by the muon, were not given in Ref. 5. We report here the results of an experimental study of condensed nitrogen by the μSR method. Our goal was to determine the mechanism for the relaxation of muons in N_2.

The experiment was carried out on the JINR phasotron with use of a standard μSR method. We measured the parameters of muon spin precession in condensed nitrogen in a transverse magnetic field at temperatures in the range 8–75 K. The nitrogen was condensed into a cylindrical chamber, which contained the sample and which had a radius of 40 mm and a height of 24 mm, by blowing with cold helium. The cylinder axis coincided with the axis of the muon beam. The windows of the chamber were made from 40-mm-thick mylar. The helium chamber, inside which the chamber containing the sample was placed, had windows made from 100-μ-thick brass foil. The ratio of the effective thickness of all cryostat windows to the effective thickness of the crystalline nitrogen sample was 0.07 at $T = 20$ K. The temperature was controlled and stabilized within 0.1 K by blowing gaseous helium. The nitrogen temperature was measured with a semiconductor thermometer which was inserted directly into the chamber containing the sample.

The experimental spectra were analyzed using the expression $N(t) \sim Ae^{-\Lambda t} \times \cos(\omega t + \varphi$, where Λ is the depolarization rate of muons, A and φ are the initial amplitude and initial phase of the muon precession, and ω is the muon precession frequency. The channel width was 5.5ns. A Fourier analysis of the muon precession spectra has identified only one line at the muon frequency. There were no auxiliary lines, within 1% error, from the spectrum amplitude at the muon frequency. this circumstance shows unambiguously that at long time scales ($t \gtrsim 10^{-7}$s) a muon in a condensed nitrogen is situated in the diamagnetic compound or in the free state. The temperature dependence of the muon depolarization rate in a condensed nitrogen is shown in the upper part of Fig. 1. The value of Λ, which does not depend on the temperature over the entire temperature interval, is $0.12 \pm 0.02\ \mu s^{-1}$. The value of Λ, which was calculated on the basis of the mechanism for the dipole-dipole interaction localized in the interstitial lattice site or in the vacancy of a free-muon surrounded by nitrogen molecules, is much lower than the experimental value. The rate of muon depolarization in a $N_2\mu^+$ ion at rest with the parameters of $N_2\mu^+$ ion[3] is estimated to be $\Lambda \approx 0.1\ \mu s^{-1}$, in good agreement with the experimental value.

The central part of Fig. 1 shows the temperature dependence of the initial amplitude of the muon precession in nitrogen, which is normalized to the total muon amplitude measured experimentally using copper. This value is $A_0 = 0.160 \pm 0.002$. Over the entire temperature interval,the amplitude A/A_0 is much less than 1. this means

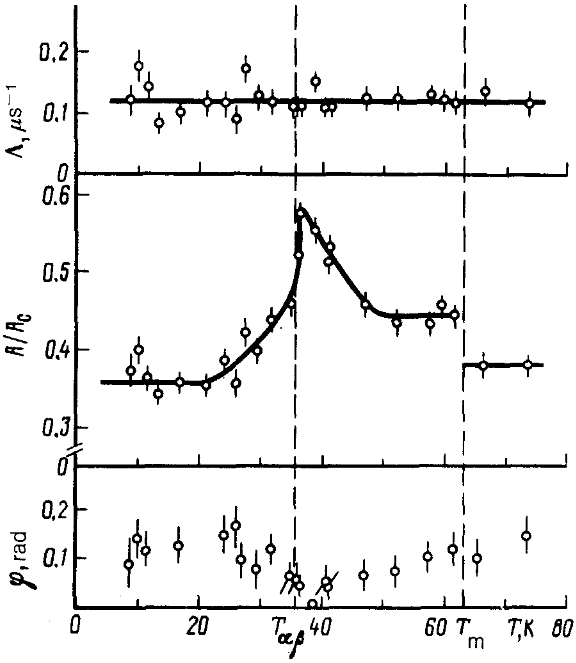

FIG. 1. Temperature dependences of the muon depolarization rate Λ, of the initial amplitude A/A_0, and of the initial phase φ_{Mu} of the muon precession in condensed nitrogen in a transverse magnetic field $H = 100$ Oe.

that muons depolarize rapidly in condensed nitrogen, in a time which cannot be measured experimentally. The fast ($t < 10^{-8}$ s) depolarization of muons in nitrogen can hardly be attributed to the interaction with the oxygen impurity molecules. The oxygen content measured in the original gas was 0.7×10^{-4}. Let us assume that oxygen is dissolved uniformly in nitrogen. The time it takes a thermalized muon and such an oxygen molecule to close on each other will then be on the order of 10^{-6}–10^{-5}s, a time which is much longer than t.

The muons depolarize rapidly in a condensed nitrogen apparently because of the formation of a muonium atom. On the basis of the muonium mechanism for rapid muon depolarization in nitrogen we can assume that at short time scales the following reaction occurs in nitrogen:

$$\mathrm{Mu} + \mathrm{N}_2 \rightarrow \mathrm{N}_2\mu^+ + Q. \qquad (1)$$

The muonium atom trapped in nitrogen reacts in a time τ with a nitrogen molecule, forming a diamagnetic $N_2\mu^+$ complex. The ensuing slow muon depolarization occurs in the $N_2\mu^+$ ion at a characteristic rate Λ which is measured experimentally. If the muonium in nitrogen is in the $1S$ ground state, then reaction (1) is highly improbable because of its extremely high endothermicity ($Q < 0$), since the binding energy of ground-state muonium (13.55 eV) is much higher than the binding energy of a muon in a $N_2\mu^+$ ion ($\sim$ eV). We know, however, that the lifetime of the $2P$ state of a hydrogen atom is 1.6×10^{-9}s, and that the $2S$ state is generally a metastable state whose lifetime is 0.14 s (Ref. 6). If the time τ is shorter than the lifetime of the excited state of a muonium atom, then reaction (1) may occur in a condensed nitrogen. The time τ of the chemical reaction can be estimated by measuring the initial phase of the muon precession φ. The lower part of Fig. 1 shows the temperature dependence $\varphi_{\rm Mu}=\varphi-\varphi_0$, where φ_0 is the instrumental phase which is associated with a certain angle between the direction of the muon beam and the positron telescope axis. The value of φ_0 measured experimentally with copper is 0.060 ± 0.015 rad. The advance of the muonium phase in a time τ is $\varphi_{\rm Mu}\sim\omega_{\rm Mu}\tau$, where $\omega_{\rm Mu}$ is the Larmor frequency of muonium. Near the α–β transition the phase shift $\varphi_{\rm Mu}$ does not exceed 0.04 rad, which corresponds to the time $\tau\sim0.5\times10^{-10}$s. Far from a α–β transition the upper limit of τ is estimated to be on the order of 2×10^{-10}s. Accordingly, even the upper limits of τ turn out to be lower than the lifetime of the excited state of muonium.

It is important to point out an alternative mechanism for the muon depolarization in nitrogen which may be related to the process $(N_2\mu^+)^*\rightarrow N_2\mu^+$, where $(N_2\mu^+)^*$ is the excited state of $N_2\mu^+$ ion with an unpaired electron spin.

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