Muon-spin relaxation in para-hydrogen

S. G. Barsov,(1) A. L. Getalov,(1) V. A. Gordeev,(1) L. A. Kuz'min,(1)
S. P. Kruglov,(1) S. M. Mikirtych'yants,(1) G. V. Shcherbakov,(1)
E. P. Krasnoperov, V. P. Smilga, and V. G. Storchak
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 4 February 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 6, 275–276 (25 March 1985)

The decay of the spin precession of positive muons has been studied in liquid and solid para-hydrogen containing fewer than 2% ortho-molecules. The precession decay rate in solid hydrogen has a maximum as a function of the temperature at $T = 4$ K.

A study of the spin precession of positive muons in solid hydrogen with various ortho-para compositions[1] has shown that as the concentration of ortho-molecules ($J = 1$) is lowered, the muon depolarization rate decreases more slowly than would follow from the theory of a dipole-dipole interaction of the muon with surrounding ortho-molecules. This circumstance has motivated an experimental study of para-hydrogen in an effort to determine the kinetics of the charged particles.

The experiment was carried out in the muon channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics by the standard μSR technique.[2] We measured the decay rate of the precession amplitude of μ^+ mesons (the depolarization rate) in hydrogen containing fewer than 2% ortho-molecules over the temperature range 1.5–20 K in a transverse magnetic field $H_\perp = 286$ Oe.

The hydrogen is placed in a special low-background cryostat. The inner jacket of the cryostat (its lower part) is made of annealed 1-Kh-18N-10T stainless-steel foil, 45 μm thick, in order to reduce the amount of structural material in the path of the muons. A window 60 mm in diameter in the outer shell is covered by a foil of the same

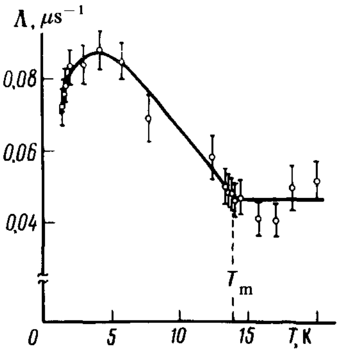

FIG. 1. Temperature dependence of the damping rate (Λ) of the precession amplitude (the depolarization rate) of the spin of a muon in para-hydrogen. $\Lambda = 1/\tau$, where τ is the time over which the precession amplitude decreases by a factor of e.

material. The stainless steel was selected because below 40 K it is antiferromagnetic, and the depolarization rate in it is very high: $\Lambda > 100\ \mu s^{-1}$. The cold cryostat walls thus do not generate a precession signal, so that the background level is significantly reduced. The ratio of the number of muons stopped in the walls of the cryostat to the number stopped in the sample is $\lesssim 0.2$.

The hydrogen is crystallized by putting it in contact with a copper plate cooled by helium. Temperatures below 4 K are reached by pumping off the helium poured over the hydrogen crystal. The sample temperature is measured by two carbon thermometers outside the muon beam in the upper and lower parts of the sample. The accuracy of the temperature measurements is better than 0.5%.

The Fourier spectrum of the precession of the muon spin consists of a single line (at the muon frequency) broadened by depolarization. There are no side lines within 1%. The precession amplitude is described by the simple exponential law $A \sim \exp(-\Lambda t)$, where Λ is the depolarization rate.

Figure 1 shows the temperature dependence of the muon depolarization rate. The experimental data have been corrected for muons stopped in the cryostat walls.

The systematic errors in the determination of small values of Λ rule out a determination of its temperature dependence. Below the melting point, the depolarization rate increases, goes through a maximum at $T \cong 4$ K, and then decreases. At low temperatures ($T \cong 1.5$–2 K) the derivative $\partial\Lambda/\partial T$ is very high.

The effective depolarization of the muons in the solid para-hydrogen indicates that the muons are not free but instead form some bound state. Since the binding energy of a proton in the H_3^+ ion is 4.6 eV, it is extremely likely that a muon will be captured by a hydrogen molecule, forming an $H_2\mu^+$ ion. In an ion of this type, depolarization results from the magnetic fields of the protons. The magnetic field distribution corresponds to a Gaussian decay with a parameter $\sigma^2 = 0.25\ \mu s^{-2}$. Since the observed decay is slight, we are completely justified in describing the precession amplitude by the expression $A \sim \exp(-\Lambda t)$.

The depolarization rate depends strongly on whether an ion is rotating. During a fast, random rotation of an $H_2\mu^+$ ion, the depolarization is slight because of the averaging of the nuclear magnetic fields. The depolarization rate increases when the rotation is frozen. This effect, known as dynamic line contraction in NMR, furnishes a qualitative explanation for the small value of Λ in liquid hydrogen. In the solid phase, when the temperature is lowered below T_m, the rotations of the ion are apparently frozen, with the result that Λ is increased. The decrease in Λ below 4–5 K apparently might be due to quantum phenomena.

According to the theory of Ref. 3, at low temperatures the exponents in the temperature dependence of the depolarization may be high (e.g., $\sim T^9$). This circumstance may be responsible for the large derivative $\partial\Lambda/\partial T$ below 2 K.

We are deeply indebted to N. A. Chernoplekov for support and to I. I. Gurevich and V. I. Selivanov for a discussion of the results.

1)B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR.

---

[1] E. P. Krasnoperov *et al.*, Tezisy dokladov NT XXIII (Proceedings of Low-Temperature XXIII), Tallin, Vol. 28, 1984, p. 58; S. G. Barsov *et al.*, Preprint No. 1021, Leningrad Institute of Nuclear Physics.

[2] A. Seeger, Positive Muons as Light Isotopes of Hydrogen. Hydrogen in Metals, I, Topics in Applies Physics, Vol. 28, Springer, New York, 1978, p. 349.

[3] A. F. Andreev and I. M. Lifshitz, Zh. Eksp. Teor. Fiz. **56**, 2057 (1969) [Sov. Phys. JETP **29**, 1107 (1969)]; Yu. M. Kagan and L. A. Maksimov, Zh. Eksp. Teor. Fiz. **84**, 792 (1983) [Sov. Phys. JETP **57**, 459 (1983)].

Translated by Dave Parsons