Spin depolarization of muons in ^{4}He

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An attenuation of the precession of spins of positive muons in liquid helium has been observed. In the normal state the depolarization rate is $\lambda = 0.08\,\mu s^{-1}$, while in the superfluid state this rate increases with decreasing temperature, reaching $\lambda = 0.15\,\mu s^{-1}$ at $T = 1.5$ K. In He-II, this process is accompanied by a rapid depolarization with a scale time $\tau \simeq 0.5\,\mu s$.

After the fruitless attempts to observe muonium in liquid helium, skepticism arose regarding the use of muon spin relaxation to study ^{4}He, in which the electron and nuclear spins are zero. However, because of their positive charge, muons may form a bound state with the atoms of the medium under study, and in such a state a spin relaxation would be entirely possible. This is apparently the nature of the attenuation of muon precession observed[2] by us in solid para-hydrogen containing ortho-molecules in a concentration less than 2%.

In this paper we report a study of the precession of the spins of muons in normal helium (He-I) and superfluid helium (He-II). The experiments are carried in the μ-meson channel of the synchrocyclotron of the Leningrad Institute of Nuclear Physics with the apparatus described in Ref. 2. The helium is poured into the low-temperature chamber of a cryostat made of stainless steel foil 45 μm thick. The ratio of the "effective" thickness of all the walls of the cryostat to the thickness of the helium target is no greater than 0.15. The thickness of the scintillator of the trigger counter is $d = 1.7$ mm. The helium temperature is regulated with the help of a membrane vacuostat, and it is monitored through measurements of the saturation vapor pressure and measurements with two carbon thermometers in the upper and lower parts of the target. The temperature drift during the experiments is no greater than 10 mK. The magnetic field $H = 286$ Oe, directed transverse with respect to the axis of the muon beam and of the strength required for observing the spin precession, is produced by a pair of Helmholtz coils. The relative nonuniformity of the field over the sample and also its stability are on the order of 10^{-3}.

The spin precession is described by the standard expression for a moving muon:

$$n(t) = A e^{-\lambda t} \cos(\omega t + \varphi), \tag{1}$$

where A is the asymmetry coefficient of the decay $\mu \to e$, which depends on the experimental geometry; λ is the rate at which the precession is attenuated (the depolarization rate); and ω and φ are the frequency and phase of the precession.

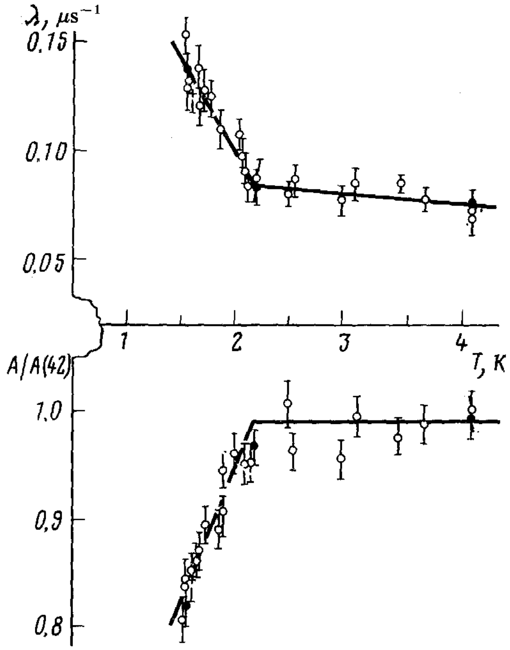

FIG. 1. Temperature dependence of the depolarization rate λ and of the asymmetry A. ○—Natural helium; ●—helium with an oxygen concentration of 2×10^{-7}; +—after the admission of air into the cryostat.

The temperature dependence of the depolarization rate is shown in the upper part of Fig. 1. For helium in its normal state, we may assume that the depolarization rate is essentially constant. The observed value $\lambda \simeq 0.08\ \mu\text{s}^{-1}$ cannot be explained by instrumental effects, since the depolarization rate in liquid hydrogen under the same experimental conditions is lower by a factor of two.[2] Roughly the same value of λ was found in Ref. 1 at $T = 2$ and 4.2 K.

In the superfluid state of the helium ($T < 2.17$ K), the depolarization rate increases with decreasing temperature and has the value $\lambda = 1.55\ \mu\text{s}^{-1}$ at $T = 1.4$ K.

The lower part of Fig. 1 shows the temperature dependence of the asymmetry parameter, normalized to the value of A at $T = 4.2$ K. Although the parameter $A(T = 4.2\text{ K})$ ranged from 0.229 to 0.236 in different experiments, its relative temperature dependence is the same in all cases, as shown in this figure. In He-I, the parameter A remains essentially constant; during the cooling of He-II, the asymmetry decreases monotonically. This result apparently cannot be attributed to the formation of muonium: An attempt to detect muonium was unsuccessful. The corresponding amplitude is no greater than 1.5% of the amplitude of the muon frequency and comparable to the background level.

On the other hand, we found that the attenuation of the muon precession in He-II is not described by a common exponential function (1) in the initial region ($\simeq 1\ \mu$s), as it is in He-I. A numerical analysis reveals a "fast" depolarization with a typical rate $\lambda = 2\ \mu\text{s}^{-1}$. The asymmetry of this fast depolarization is zero in He-I and increases monotonically during the cooling of He-II, reaching a value $a_f = 0.03$ at $T = 1.5$ K.

The mobility of charges in helium is known[3] to have a temperature dependence similar to the $\lambda(T)$ dependence shown in Fig. 1. One might suggest that the depolarization of muons in helium results from a trapping of muons by paramagnetic impurities such as oxygen[1)] ($\mu \simeq 0.5\mu_B$) and that the structural features in the temperature dependence stem from changes in the diffusion coefficient. In an effort to determine the role played by impurities, we prepared some liquid helium with oxygen and nitrogen concentrations below 2×10^{-7}. As can be seen from Fig. 1, the depolarization rates are the same in the natural helium and this purified helium. In a next experiment, we admitted some air (15 liters) into the superfluid helium. Again in this case, the depolarization rate remained the same, within the experimental errors. If we assume that the muons move without a loss of polarization through the helium, and they are depolarized instantaneously upon meeting a paramagnetic center (O_2), then by taking the diffusion coefficient in He-I to be the same as for positive charges[3] ($D = 1.5\times10^{-5}$ cm^2/s), we can use the relation $\lambda l^2 = D$ to quickly find the distance between depolarization centers: $l = 1.2\times10^{-5}$ cm. This estimate shows that a finely dispersed suspension of air could hardly be the cause of the depolarization. For particles with a size $\simeq 0.01$ μm, the oxygen content would have to be $> 10^{-3}$, which is not likely. Furthermore, a natural purification of liquid helium occurs in the superfluid state, and it would seem that the depolarization rate would have to decrease. However, it might be suggested that oxygen molecules (not a suspension) are always present in a concentration of 10^{-7}–10^{-8} in liquid helium. If this is the case, and the depolarization is caused by the trapping of a muon by an oxygen molecule, i.e., if the dynamic line contraction during the motion of the spins is not important, then we could explain the observed $\lambda(T)$ dependence and its good reproducibility.

An alternative mechanism for the depolarization is the formation of $He\mu^+$ or $He_2\mu^+$ ions, some in excited electronic states. Because of the difference between the magnetic interactions of excited electrons with a muon, the spin of the muon is in a weak local magnetic field, which weakens as the electrons move closer to the ground state. According to this mechanism, the increase in λ in He-II and the appearance of the fast depolarization would result from an increase in the lifetime of the excited states in superfluid helium.[4]

Studies of helium purified with a superfluid filter will make it possible to determine the actual reason for the observed effect.

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[1)] Other possible impurities—^{3}He, N_2, and H_2—are not important, since they have only a nuclear magnetism.

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