# Measurement of muon polarization in condensed carbon monoxide

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(Submitted 19 October 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**(11), 1173–1176 (10 December 1990)

The characteristics of the spin relaxation of muons in liquid and crystalline carbon monoxide have been measured in a transverse magnetic field over the temperature range 10–80 K. Carbon monoxide is an analog of nitrogen, with zero nuclear magnetic moments. The polarization of the muons in CO changes from 0.5 in the crystal to 0.2 in the liquid.

Polarized positive muons entering dielectrics may form both diamagnetic compounds and the hydrogen-like muonium atom[1] ($\mu^+ e^-$). Since the mass of a muon is 1/9 of the mass of a proton, muonium may be thought of as a light hydrogen isotope, and for this reason there is particular interest in muonium. The polarization of muons inserted into a medium consists of the diamagnetic component $P_d$, the muonium polarization $P_{\mathrm{Mu}}$, and the "lost" polarization $P_l$: $P_d + P_{\mathrm{Mu}} + P_l = 1$ (Ref. 1).

The depolarization of muons in condensed nitrogen in a transverse magnetic field was studied in Ref. 2. It was found that the diamagnetic fraction is 0.3 to 0.5 of the muon polarization. The remainder of the polarization is classified as a "lost" fraction, since muonium has not been observed in either liquid or crystalline nitrogen. Two factors may be responsible for the failure to observe a long-lived muonium atom in condensed nitrogen: (1) a rapid decay of the muonium precession because of dipole fields of the nuclear magnetic moments of nitrogen and (2) a chemical reaction of the muonium, which results in a transition from a paramagnetic state to a diamagnetic state over a short time (a time unobservable experimentally).

The first of these factors is analogous to a phenomenon which has been observed in crystalline ortho hydrogen,[3] in which a rapid decay of the muonium precession resulted from an interaction with the nuclear magnetic moments of the ortho $H_2$ molecules. In para hydrogen, in which the nuclear magnetic moments are zero, a precession has been observed at the muonium frequency.

The second factor was proposed in Ref. 2 in an effort to explain the lost polarization in condensed nitrogen. The reaction which was proposed,

$$\mathrm{Mu} + \mathrm{N_2} \rightarrow \mathrm{N_2}\mu^+, \qquad (1)$$

can proceed only if muonium forms in an excited state in the condensed nitrogen.[2]

The actual reason for the absence of a long-lived muonium atom in condensed nitrogen might be found by measuring the polarization of muons in condensed carbon monoxide (CO). Crystalline CO is completely analogous to nitrogen in terms of its

  

properties,[4] with the important distinction—one of decisive importance for $\mu SR$ studies—that it has no nuclear magnetic moments. For this reason CO can be used to determine why muonium is not found in condensed nitrogen. If a muonium precession is observed in CO, the first of the factors proposed above may be operating. If, on the other hand, muonium is not observed in CO, the first factor can be ruled out absolutely, since there would be no reason for a decay of the muonium precession in CO.

Measurements in carbon monoxide are useful beyond the effort to identify the reason for the absence of muonium in condensed nitrogen. Such measurements also make it possible to test the suggestion in Ref. 5 that the nuclear hyperfine interaction, which depends on the rotation velocity of the nitrogen molecules, determines the temperature dependence of the residual polarization of the muons in nitrogen. If this is so, the temperature dependence of the residual polarization of muons in condensed CO should be represented by a constant $P = 1/2$, without any structural features near the $\alpha$–$\beta$ transition, at least at low temperatures.

We have carried out a $\mu SR$ study of liquid and crystalline carbon monoxide in a transverse magnetic field. To the best of our knowledge, this was the first study of condensed phases of carbon monoxide by the $\mu SR$ method. The carbon monoxide used in these experiments had an oxygen content no greater than $10^{-4}$. Standard $\mu SR$ apparatus was used. The properties of the CO sample (its dimensions, "effective thickness," etc.) were approximately the same as those of the nitrogen sample of Ref. 2.

Attempts to observe a long-lived muonium atom in carbon monoxide were undertaken both in the liquid at $T = 80$ K and in the $\alpha$ phase of crystalline CO at $T = 37.8$ K. The precession was studied in a magnetic field $H = 5.2$ Oe. A Fourier analysis of the precession spectra revealed only a single line. The muonium component did not exceed the background level, which was in turn less than 4% of the amplitude of the spectrum at the muon frequency.

There is thus no long-lived muonium atom in either the liquid or crystalline phase of carbon monoxide. This result permits an unambiguous decision in favor of the chemical reaction as the reason for the observation of a "lost" polarization in both nitrogen and carbon monoxide.

The muon precession frequency corresponds within $10^{-3}$ to the transverse external magnetic field. This result means that the muon is in a diamagnetic state in condensed CO at times $t > 10^{-8}$–$10^{-7}$ s. Analysis of possible diamagnetic states of a muon in CO reveals that the most likely state is the ion $CO_\mu^+$. We know that a proton incident on carbon monoxide causes the formation of a $CO_p^+$ ion with a binding energy of 6.26 eV (Ref. 6). The muon depolarization rate in crystalline CO, which is 0.03 $\mu$/s, is independent of the temperature. This rate is determined by the variations in the magnetic field along the sample.

Figure 1 shows the temperature dependence of the muon polarization ($P_d$) in carbon monoxide according to an analysis of the precession spectra in a 100-Oe magnetic field. The polarization values were found by normalizing the initial amplitude of the muon precession in CO to the total muon amplitude measured in a copper sample. Over the entire temperature range from 10 K to 80 K the residual muon polarization in CO is less than unity. This result means that a rapid depolarization of muons occurs

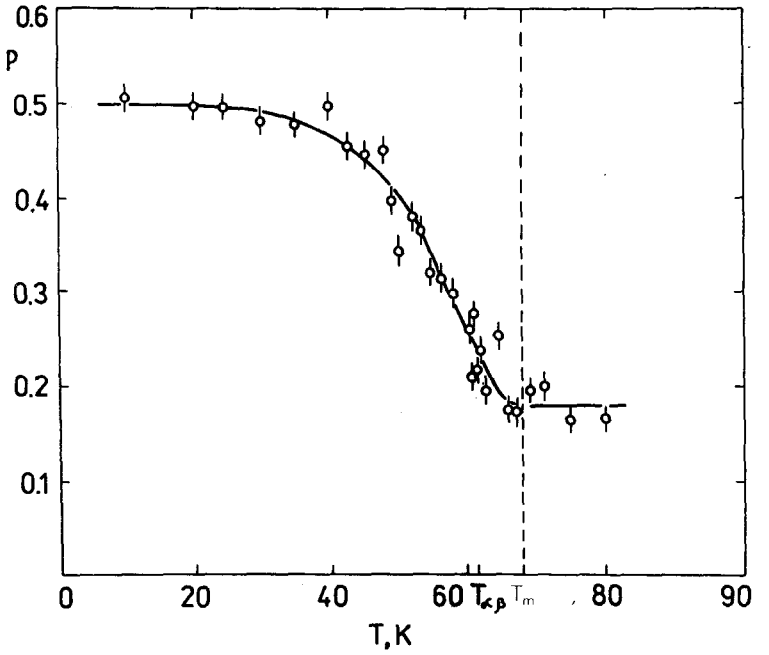


FIG. 1. Temperature dependence of the muon polarization in condensed carbon monoxide.

in condensed carbon monoxide. The reason for this rapid depolarization of muons in CO is, as in nitrogen,[2] the formation of a muonium atom, which quickly undergoes a chemical reaction in which the $CO_\mu^+$ ion is formed. The suggested reaction,

$$Mu + Co \rightarrow Co_\mu^+, \qquad (2)$$

is analogous to reaction (1). It apparently occurs at least in the crystalline CO at $T < 40$ K. Like reaction (1), reaction (2) can occur only if an excited Mu atom is involved.

The fact that the residual polarization of the muons in the $\alpha$ phase of CO is 1/2 at $T < 40$ K is evidence in favor of the suggestion in Ref. 5 regarding the nature of the temperature dependence of the muon polarization in condensed nitrogen, i.e., the suggestion that a hyperfine nuclear interaction is involved. In nitrogen, the hyperfine nuclear interaction leads to a flip of the electron spin of the muonium, so the polarization will fall below 1/2. In carbon monoxide there is no hyperfine nuclear interaction, and at low temperatures the value $P = 1/2$ prevails.

As can be seen from Fig. 1, the muon polarization decreases from 0.5 in the $\alpha$ phase of CO to 0.2 in the liquid. It is difficult at this point to draw an unambiguous conclusion regarding the nature of this phenomenon. One possibility is an interaction of muonium with a paramagnetic oxygen impurity. One cannot rule out the possibility that the muonium is interacting with the rotational magnetic moments of the CO molecules, which are the same in order of magnitude as the nuclear magnetic mo-

ments. A final possibility is an explanation based on various chemical reactions of muonium in the liquid and solid states.

We are indebted to I. I. Gurevich for support of this work, N. V. Prokof'ev and V. G. Firsov for a discussion of the results, and V. G. Ol'shevskiĭ and V. Yu. Pomyakushin for assistance in the experiments.

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Translated by D. Parsons