

Observation of "slow" negative-muon spin relaxation in oxides

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Observation is reported of a decrease, with time, of the asymmetry of the angular distribution of the muon-decay electrons in the mesic atoms of oxygen in oxides.

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The study of matter with the aid of muons has recently been the subject of many experiments in which the asymmetry of the angular distribution of the muon-decay electrons has been determined by measuring the Larmor precession of the muon spin in a transverse (relative to the spin direction) magnetic field. Experimental investigations of solids by positive muons are quite plentiful.^[1] Analogous experiments with negative muons have until recently been the subject of only a few studies (e.g.,^[2,3]), in which, however, no muon-spin relaxation was observed.

We have measured the time dependence of the asymmetry of the decay electrons from the mesic atom of oxygen in a number of oxides, for the purpose of observing the muon spin relaxation (recently observed in single-crystal manganese oxide^[4] in experiments with negative muons,^[4,5] and the effect exerted on it by the velocity of the medium surrounding the mesic atom, particularly elements with paramagnetic electron shells. The experiments were performed with a separated muon beam from the synchrocyclotron of the Nuclear Problems Laboratory of our Institute. The apparatus for the measurement and the reduction of the results were described earlier.^[3] The polarized muons were stopped in targets of polycrystalline oxides ~ 5 g/cm² thick, placed in a transverse magnetic field $H \sim 50$ – 120 Oe at room temperature and at liquid-nitrogen temperature.

The decay electrons from the oxygen mesic atom had a lifetime τ_0 different from the lifetime τ_e of the decay electrons from the mesic atoms of the elements. In a transverse magnetic field, the time distribution of the decay electrons from the oxygen was modulated at the Larmor precession frequency $\omega = gH$ (g is the gyromagnetic ratio of the μ^- meson on the K shell of the oxygen mesic atom, and is close in value to that of the free muon). This distribution $N(t)$ (after a computer calculation of the background and of the decays in the mesic atoms with times τ_0 and τ_e) is given by

$$N(t) \sim [1 + a_0 \exp(-t/T_r^{-1}) \cos(\omega t + \delta)] = 1 + a(t),$$

where a_0 is the asymmetry coefficient of the decay electrons from the oxygen mesic atom at the instant $t=0$ (the time that the muon is stopped in the target), T_r is the relaxation time of the muon spin in the oxygen mesic atom, and δ is the phase shift.

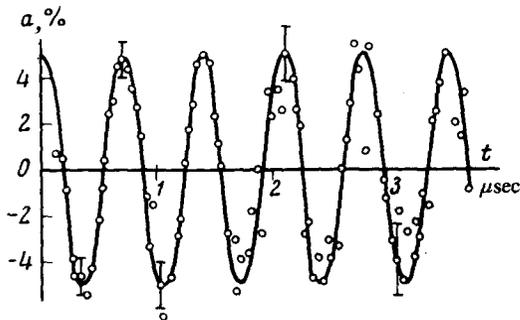
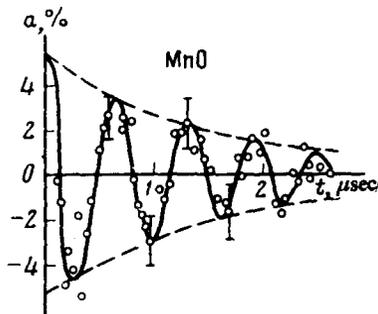
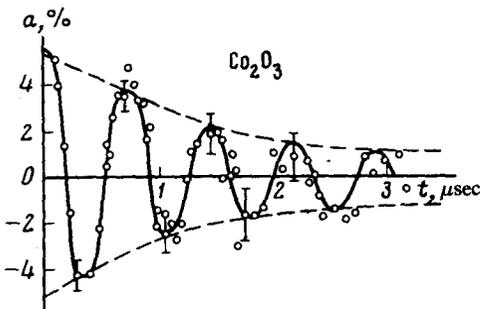


FIG. 1. Experimental dependence of $a(t)$ in the oxides Co_2O_3 , MnO and in graphite in a transverse field of 120 Oe and at room temperature.



From the measured spectra we obtained with a computer, by least squares, the parameters noted above and the sought values of a_0 and T_r . At a field intensity ~ 120 Oe and an observation time $\sim 6 \mu\text{sec}$, we traced approximately 8 precession periods and registered reliably attenuation times from 0.4 to $8 \mu\text{sec}$.

The measured $a(t)$ dependence in the mesic oxygen atoms Co_2O_3 and MnO is shown in Fig. 1, and it is seen that the amplitude of the precession in these oxides decreases with time. For comparison, we show the $a(t)$ dependence for graphite, in which no such relaxation is observed. Table I lists the value of $a_0 a_C^{-1}$ ($a_C = (4.8 \pm 0.1)\%$ in graphite) measured in the oxides, and also the value $\bar{a} a_C^{-1}$ obtained after time averaging [$\exp(-t/T_r) = 1$]. The value of T_r for MnO agrees well with the value^[4] $1.5 \pm_{-0.4}^{+0.8}$, but the values indicated in^[4] are only approximate, within 3%.

The asymmetry ($a \neq 0$) observed for the oxides listed in Table I at the frequency of the quasi-free muon signifies that the paramagnetism of the electron shell in the oxygen mesic atom is cancelled out (by the chemical reaction of the mesic atom, by its occupation of an impurity level in the lattice, or by some other means). The measured values of the asymmetry in other oxides, MgO , FeO , Fe_2O_3 , and ZnO , are close to zero. This means either "fast" relaxation ($T_r < 0.1 \mu\text{sec}$) or the absence of the cancellation indicated above, or else the presence of mechanisms other than the cascade mechanism in the depolarization.

It follows from Table I that we have observed "slow" relaxation of the muon spin with the time on the order of microseconds. In paramagnetic oxides of transition metals with unfilled $3d$ electron shell this relaxation is apparently due to local magnet-

TABLE I.

Oxide	T_r , μsec	$a_0 a \bar{c}^{-1}$	$\bar{a} a \bar{c}^{-1}$
Room temperature			
V_2O_3	3.8 ± 1.1	0.63 ± 0.08	0.39 ± 0.03
MnO	1.5 ± 0.4	1.10 ± 0.19	0.42 ± 0.06
Mn_2O_3	3.6 ± 1.6	0.42 ± 0.05	0.28 ± 0.04
CoO	1.9 ± 0.5	0.73 ± 0.14	0.31 ± 0.04
Co_2O_3	1.6 ± 0.3	1.08 ± 0.14	0.35 ± 0.03
SeO_2	6.1 ± 2.1	0.71 ± 0.08	0.51 ± 0.04
Sb_2O_3	4.2 ± 2.5	0.59 ± 0.14	0.39 ± 0.05
Sb_2O_5	1.2 ± 0.4	0.77 ± 0.16	0.25 ± 0.06
Liquid-nitrogen temperature			
V_2O_5	4.6 ± 1.8	0.52 ± 0.07	0.37 ± 0.03
Co_2O_3	2.3 ± 0.9	0.55 ± 0.11	0.22 ± 0.03

ic fields in the region of the mesic-atom localization. Observation of relaxation in diamagnetic oxides (of S and Sb) can also be evidence of the presence of local magnetic fields due to disarray of the crystal structure, to the magnetic moments of the nuclei, and to other factors. It is also possible that the observed relaxation in the oxides is due to the instability of the diamagnetic compounds produced by the mesic oxygen atom after completion of the cascade depolarization. Better understanding of the mechanism of the relaxation phenomena will be aided by further investigation of the dependence of the residual polarization of the negative muons in solids on the intensities of the longitudinal and transverse magnetic fields at various temperatures.

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