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DISCLAIMER

Precession of μ^+ in Single Crystal Nickel*

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We have observed long-lived μ^+ precession in single crystal nickel at 300 and 77K. Inhomogeneous local fields which cause rapid depolarization in polycrystalline samples are avoided. Muon precession in a magnetically saturated sample is reported.

In a recent letter [1], Kossler et al. reported the first observation of the precession of positive muons in polycrystalline nickel. We have extended this investigation to single crystal nickel and have greatly enlarged the range of external field and sample temperature over which measurements can be made. Our observations have led to a modified interpretation of the experimental data.

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A beam of polarized positive muons is stopped in a nickel target situated in a magnetic field B_{ext}, which is transverse to the initial muon polarization direction. The muons are presumably trapped at the octahedral or tetrahedral interstitial sites in the nickel lattice, where they precess in the local magnetic field. The muons decay with a mean life of 2.2 μsec. Since the decay positrons are emitted preferentially along the muon spin, there is an asymmetric positron angular distribution which precesses with the muon at the Larmor frequency. A measurement of this Larmor frequency gives B_μ, the local field at the muon, the muon gyromagnetic ratio being well known [2]. At the same time, the asymmetry A and the depolarization time T_2 can be measured. These three quantities provide new data about the interstitial site.

The measured value of B_μ is +1.48 kG at 77K. This seems at first surprisingly small. Since the dipole fields from Ni cores cancel by symmetry at both octahedral and tetrahedral interstitial sites, B_μ must arise from a contact interaction with 4s and 3d conduction electrons. B_μ may be estimated by taking the electron density at the μ^+ to be the same as that in free 1s muonium, where the hyperfine field is 160 kG. We first assume that only 4s-electrons screen the μ^+, and we estimate the 4s polarization as follows: each Ni atom contributes 0.54 electron to the 4s band; assuming that these electrons are uniformly distributed throughout the lattice, we deduce an unperturbed 4s-electron density of $4.9 \times 10^{22} cm^{-3}$. Neutron diffraction studies yield an interstitial magnetization of $-0.85 \times 10^{22} \mu_B/cm^3$, [3] which implies a 4s polarization of -17%. This gives $B_\mu = -0.17 \times 160$ kG = -27 kG, in contradiction with the observed B_μ. The high 3d density of states at the Fermi level assures that 3d-electrons will participate significantly in the screening, reducing the 4s density at the muon and perhaps changing the sign of B_μ through either a direct 3d-μ^+ interaction or an indirect 3d-4s-μ^+ exchange interaction. Only a detailed calculation can predict the strengths and inter-relationship of these effects.

Kossler's group [1] used a polycrystalline nickel sample and made measurements of B_μ, A, and T_2 over a range of temperature and external fields, but because of magnetic field limitations, they could not saturate their sample. We have been able to observe precession both below and above saturation in a small, ellipsoidal, polycrystalline sample. We have also studied a single crystal sample and have found long-lived precession even at 77K. Kossler was unable to detect any precession below room temperature in his polycrystalline sample.

We interpret the disappearance of precession in a polycrystalline sample at low temperature to arise from an extremely short depolarization time caused by a large inhomogeneous linewidth ΔB. T_2 and ΔB are related by:

$$\Delta B = 2/\gamma_\mu T_2,$$

where γ_μ is the muon gyromagnetic ratio. A depolarization time of 0.1 μsec implies a ΔB of about 200 Gauss. Figure 1 shows values of ΔB calculated from Kossler's T_2 measurements compared with ^{61}Ni NMR linewidths in polycrystalline nickel from work by Streever and Bennett [4]. Also included are our rather uncertain measurements of very rapid ($T_2 \sim 10$-100 nsec) depolarization in a polycrystal at 300 and 77K. The approximate equality of ΔB as measured with muons and NMR is significant considering that the field at the nickel nuclei is larger than that at the μ^+ by a factor of 50. If the broadening were due to strains in the sample, one would expect the linewidth to scale approximately with the field measured. This is not the case, and we conclude that the broadening observed in polycrystalline nickel is due to macroscopic field inhomogeneities.

Further support of this conclusion is given by our observation of long-lived ($T_2 > 2\mu$sec)[‡] μ^+ precession signals in a single crystal sample at 300 and 77K. The linewidths inferred ($\Delta B_{77} < 18$G, $\Delta B_{300} < 10$G) are an order of magnitude smaller than Barclay's linewidth from NMR of oriented ^{60}Co nuclei in single crystal nickel [5], and to our knowledge they are the narrowest absolute linewidths yet observed in nickel.

It is well known that considerable line-broadening occurs in polycrystalline ferromagnets because of the inhomogeneous fields of randomly oriented crystallites. The general trend of ΔB in fig. 1 toward larger values at lower temperatures may be qualitatively understood in terms of an increase in the anisotropy energy with decreasing temperature [6] causing an increase in magnetization inhomogeneity.

[‡]Only an upper limit for T_2 can be given due to the short muon lifetime (2.2 μsec) and the interference of the low temperature muon precession signal with a 19 MHz background signal arising from the time structure of the cyclotron beam.

Kossler's ΔB data [1] shows a sharp rise above 550K. The experimental dependence of B_μ on temperature is shown in fig. 1 [7]. Since $B_\mu(T)$ becomes very steep near the Curie temperature T_c = 631K, imperfect temperature homogeneity would produce an internal field inhomogeneity which gets worse closer to T_c. One finds Kossler's ΔB data near T_c can be explained if one assumes an experimental temperature spread ~10K.

By using a small ellipsoidal target, we have been able to observe precession in a magnetically saturated sample. It was found, in agreement with Kossler, that B_μ is independent of B_{ext} below saturation. Above saturation, B_μ rises linearly with B_{ext} with unit slope (see fig. 2). The knee in the experimental curve occurs at the calculated saturation field of our ellipsoidal sample. The B_μ vs. B_{ext} dependence can be explained through the mechanism of magnetic shielding in a highly permeable material.

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FIGURE CAPTIONS

Fig. 1. The local field B_μ at the muon site and linewidths ΔB observed in polycrystalline and single crystal nickel by various techniques. The solid curve is from normalized magnetization data in Ni of reference [7].

Fig. 2. The local field at the muon site in nickel vs. B_{ext}, the external field measured with target out. N is the sample demagnetizing factor. The points denoted by triangles are from data on an approximately spherical single crystal with the [111] axis parallel to B_{ext} at 300 and 77K. Other points are from data on a polycrystalline ellipsoid (4.5"×2"×.5"). Solid and open circles refer to the 4.5" axis parallel to B_{ext} (N = 0.69) at 523 and 573K respectively. Solid and open squares refer to the 2" axis parallel to B_{ext} (N = 2.24) at 523 and 573K. The fields B_μ and B_{ext} have been normalized to bring measurements at various temperatures to the same vertical level and to exhibit saturation for all samples at zero on the horizontal scale.

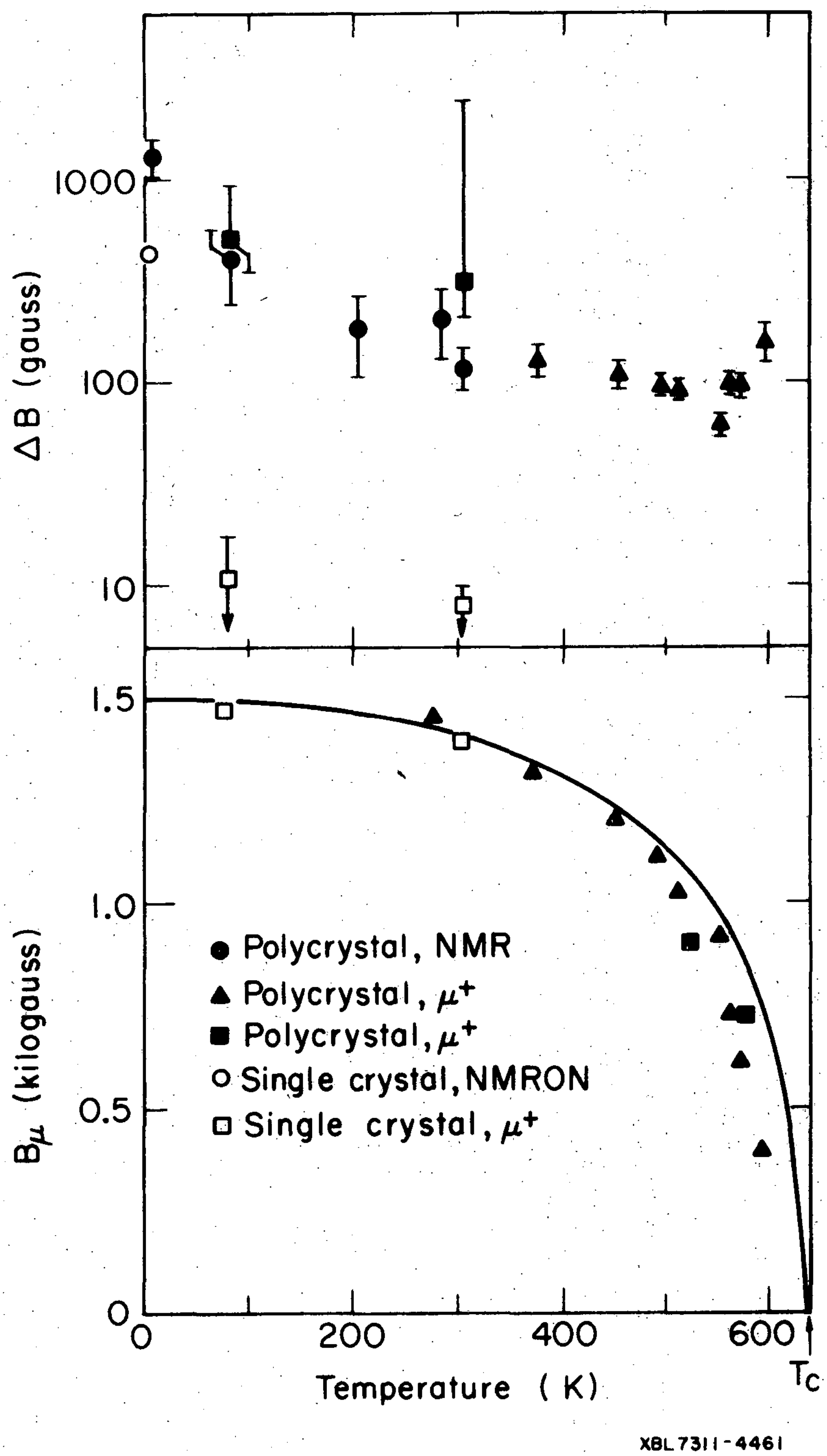
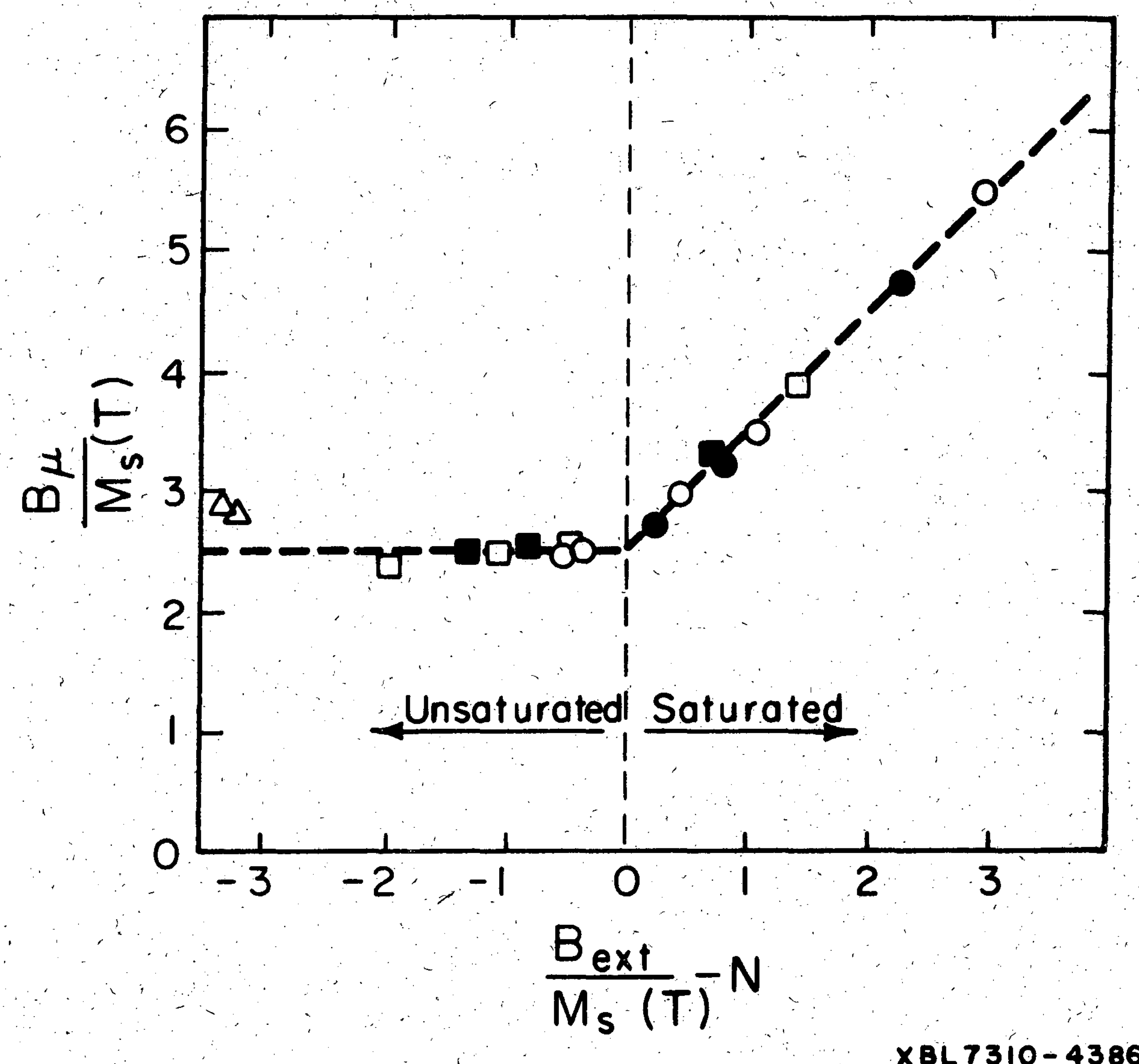

1000
100
10
ΔB (gauss)
1.5
1.0
0.5
0
B_μ (kilogauss)
Polycrystal, NMR
Polycrystal, μ^+
Polycrystal, μ^+
Single crystal, NMRON
Single crystal, μ^+
0
200
400
600
T_c
Temperature (K)
XBL 7311-4461

Fig. 1.



$\frac{B_\mu}{M_s(T)}$
0
1
2
3
4
5
6
Unsaturated
Saturated
-3
-2
-1
0
1
2
3
$\frac{B_{ext}}{M_s\ (T)} - N$
XBL 7310-4386

Fig. 2.

0 0 0 0 4 1 0 1 5 4 9

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