SR-86 REPORT ON THE 4th INTERNATIONAL CONFERENCE AT UPPSALA

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μSR - 86 Report on the 4th International Conference at Uppsala

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"His Majesty the Spin and μSR, the Youngest Princess,"--this was the title of the scientific address of Professor A. Abragam which opened the 4th International Conference, μSR 86, held in Uppsala in June. With more than 100 participants and almost 150 papers, the topics discussed covered a wide range of subjects from the most recent level-crossing resonance technique, quantum diffusion of muons, muons in spin glass semiconductors, halides and oxides, muonium radical chemistry and reaction pion dynamics, channeling and other new techniques. Although μSR first began in 1957, the real advances in the technique were not made until the mid 70's. The last ten year period has also seen an influx of material scientists and chemists joining with the nuclear and particle physicists at the meson factories: LAMPF at Los Alamos, TRIUMF in Canada, CERN at Geneva, SIN at Zurich and KEK at Tokyo.

The U.S., which dominated the field ten years ago, has been eclipsed by the TRIUMF/SIN competition. The federal support of "user" visiting groups at the pion facilities to investigate topics in the material sciences has been minimal and uncertain, and the national priority of μSR remains controversial. The status was recently discussed in a National Academy of Science panel study.[1]

In this summary the author has chosen to examine a few central problems of the science of μSR, to let the readers outside the field catch a glimpse of the excitement of the subject, and to defer matters of science policy to others.

What are the level-crossing resonances in μSR? Two years ago at TRIUMF, Kreitzman and Brewer were preparing to look in a single crystal of copper for the effect on the asymmetry of adjusting the muon Larmor freqeuncy. This was to be done by varying the longitudinal magnetic field, until this frequency was equal to the nuclear quadrupole transition frequency. The quadrupole energy shift is produced by the inhomogeneous electric field resulting from octahedral sites in the copper lattice.

To their surprise and pleasure, a preprint copy of Abragams[2] paper discussing the situation theoretically appeared in the mail. The TRIUMF experimental result[3] in Figure 1 shows how the observed change in the asymmetry revealed the large depolarization at the approximate resonance condition.

At the Uppsala Conference, Kreitzman[4] presented resonance studies for copper at various crystal orientations relative to the spin axis, taken at several temperatures. In his talk he surveyed the main considerations in the theory, including the effect of the two copper isotopes. The careful analysis of these resonance spectra at various temperatures is expected to shed light on the quantum diffusion of the muon in pure copper at low temperatures.

Professor J. Kondo[5] presented a review of the theory of diffusion of muons in metals. In copper below 5 K there is an anomalous decrease in depolarization caused by the copper nuclear moments--suggesting an increase in the muon diffusion, or hopping rate, as shown in Figure 2. Kondo has shown that the electron screening cloud produces a large reduction of the tunneling matrix element which varies with temperature proportional to 1/T. Thus the temperature dependence of the hopping rate is a power law, T^{2K-1}. This screening, then, accounts for the apparent increase in the muon hopping rate as the temperature is lowered. The screening modification comes entirely from high-order corrections to the muon-electron interaction and arises from Anderson Orthogonalization. As for experimental results, on the other hand, the latest LCR results[3] show two bumps at 160 K. These may be interpreted as indicating that, at temperatures > 150 K, there may be a change from t to o site as originally proposed by Professor Seeger[6] in his attempt to explain the low temperature plateau in the damping rate. In this regard Professor Brewer presented data[7] shown in Fig. 3 at 4.2 K and 0.7 K, which are clearly fitted by Kondo's enhanced hopping model.

After years of study the muons in copper may still have other new twists. Future experiments using LCR[4] or electron drift enhanced diffussion[8] may contribute to the interpretation of the quantum diffusion observed in this system.

The beautiful LCR spectra in C_6 F_6 - Mu radical have demonstrated the success of the integral μSR technique in which the time sequence is averaged out by taking the ratio of forward/backward decay in the longitudinal field geometry with the muon spin parallel to the magnetic field. The gain in rate, together with the modulation of the longitudinal field to minimize systematic effects, was combined by Dr. R. Kiefl to obtain the results[9] shown in Figure 4. The resonances occur at magnetic fields where a muon spin-flip transition frequency matches the corresponding ^{19}F transition frequency. The positions of these resonances for the four inequivalent flourine locations is in excellent agreement with predictions, and the accuracy of these results is certainly remarkable. Dr. Keifl's results were the high point in the conference for this observer.

Spectra[9] in the semiconductors GaA and GaP also show interesting complex structure. One would not be surprised that, at the next international conference, this meeting would be remembered as another turning point demonstrating the power of the μLCR technique.

Dr. J. L. Smith, from Los Alamos, presented a survey[10] of the heavy fermion research. He reported on μ^+ zero field relaxation and Knight shift studies in $U_{1-x}Th_xBe_{13}$ for x=0 and x=0.033. UBe_{13} exhibits a strong decrease in Knight shift as it becomes superconducting,whereas, for Th complex, it remains constant. They conclude that if the superconducting state in UBe_{13} has odd-parity, the decrease of K_μ at temperatures below T_c suggests that the order parameter is pinned to the lattice. Either spin-orbit scattering or the existence of two distinct superconducting states with different spin susceptibilities in the $(U,Th)Be_{13}$ system would explain the differences observed in the Th-doped and pure UBe_{13} materials. The latter hypothesis would exclude conventional BCS superconductivity. No evidence for magnetic order was seen in the zero-field relaxation rate for either material down to 0.3 K.

From the SIN Laboratory, W. Odermatt reported on the absolute sign of the anisotropic muonium centers (Mu^*) hyperfine parameter in diamond. The results[11] indicate that the isotropic part of the Mu^* hyperfine interaction is negative. Since the ratio $A_{||}/A_{\perp}$ was known to be negative, one can now compare directly with the predictions of various models. The negative sign for the isotropic part of the Mu^* hyperfine interaction implies that Mu^* is not simply a bloated, pancake-shaped version of isotropic Mu; this would require a positive hyperfine interaction. Instead, it is a paramagnetic complex similar to a molecular radical where, for example, the muon is chemically bound to one or more neighboring carbon atoms and the unpaired electron is removed from the muon. The weak, negative spin density at the muon is then the result of a 'core polarization' mechanism.

Dr. Uemura from Brookhaven reported[12] on anti-ferro magnets, pure MnF_2 and site-diluted $Mn_{0.5}Zn_{0.5}\ F_2$. At TRIUMF, two different muon signals have been found in pure MnF_2; the precession frequency is $\nu_A = 1.3$ GHz for site A and $\nu_B = 152$ MHz for site B measured in zero external magnetic field at T = 5 K. It was proposed that the signal from the A site represents the "muonium" state, and the characteristic features of muonium in magnetic materials were discussed. The spin relaxation rate, $1/T_1$, measured in zero external field, decreases rapidly with decreasing temperature below T_N as shown in Figure 5. The mechanism of the spin relaxation above T_N is explained by the exchange fluctuations of the Mn moments, and below T_N by the Raman scattering of spin waves. At the same normalized temperature, T/T_N, $1/T_1$ observed in the diluted $(Mn_{0.5}Zn_{0.5})F_2$ is significantly larger than that in the pure MnF_2 below T_N. The difference between the pure and diluted systems is related to the large spectral weight of low-energy magnons in $(Mn_{0.5}Zn_{0.5})F_2$, as found by neutron scattering.

The TRIUMF group reported[13] that in LiF, NaF and CaF_2 the muon pulls two F-ions together in a strong "hydrogen bond" until the ^{19}F nuclei are separated by roughly twice the nominal F-ionic radius, with the μ^+ is midway between. The resultant "FμF" center is easily observed via the distinctive behavior of the collinear $^{19}F{:}\mu^+{:}^{19}F$ spin system (coupled by dipole-dipole interactions between the muon and the fluorine nuclei) in both transverse-field muon-spin rotation and zero-field muon-spin relaxation experiments. Figure 6 shows the power spectrum for NaF at 100 K. The group speculates that implanted H^+ ions may initially form similar hydrogen bonds between adjacent F^- ions in many metal fluoride crystals.

The topics touched on here were just a few of the many outstanding papers at this conference.

Having this new young Princess in town to celebrate Uppsala's 700-year Birthday (the celebration was for the new name as the city, in fact, has a much longer history) gave the participants many chances to speculate, worry, enjoy and marvel at the show she created.

If you are still wondering whether this spectacle has had any impact on the material sciences, the author highly recommends the two volumes of the printed proceedings in the Journal of Hyperfine Physics when it appears next year.[14]

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FIGURE CAPTIONS

Figure 1: LCR in a Cu single crystal at 20 K with B parallel to the [100] axis. The relaxation parameter Λ was fit using a phenomenological function of the form $G(t)=\exp(-(\Lambda t)^{1.29})$, which accurately fit the slowly decaying part of the muon depolarization.

Figure 2: The hopping rate of the positive muon in Cu. K: electron-muon coupling; S: linear muon-lattice coupling; d: quadratic muon-lattice coupling parameters. The best fit to the experiment is obtained for d=200.

Figure 3: Positive muon relaxation functions in Cu crystal for zero applied field (ZF) at 4.2 K (squares) and 0.7 K (circles) and for 9 G longitudinal field (LF) at 4.2 K (triangles) and 0.7 K (diamonds). The data fits with global parameters obtained from data as shown, for example, in Figure 2 assuming undisturbed O-site.

Figure 4: Muon level-crossing spectrum for the C_6F_6-Mu radical. The magnetic field was applied along the muon-spin direction.

Figure 5: Relaxation rate $1/T_1$ of muon spins in pure MnF_2 and diluted $(Mn_{0.5}Zn_{0.5})F_2$ derived from measurements of zero-field relaxation functions. Two different signals from the high-field ("A") site and the low-field ("B") site were observed in both systems. When plotted versus normalized temperature T/T_N, the relaxation rate for the two systems shows significantly different temperature dependence.

Figure 6: Fourier-transform frequency spectra of the TF-μSR signals in NaF at 100 K with the indicated crystal axes aligned parallel to an applied magnetic field H_0=220 Oe. The bar diagrams are predicted line

spectra for the collinear FμF configuration along the <110> direction, through use of a dipolar interaction frequency ν_d=0.220 MHz.

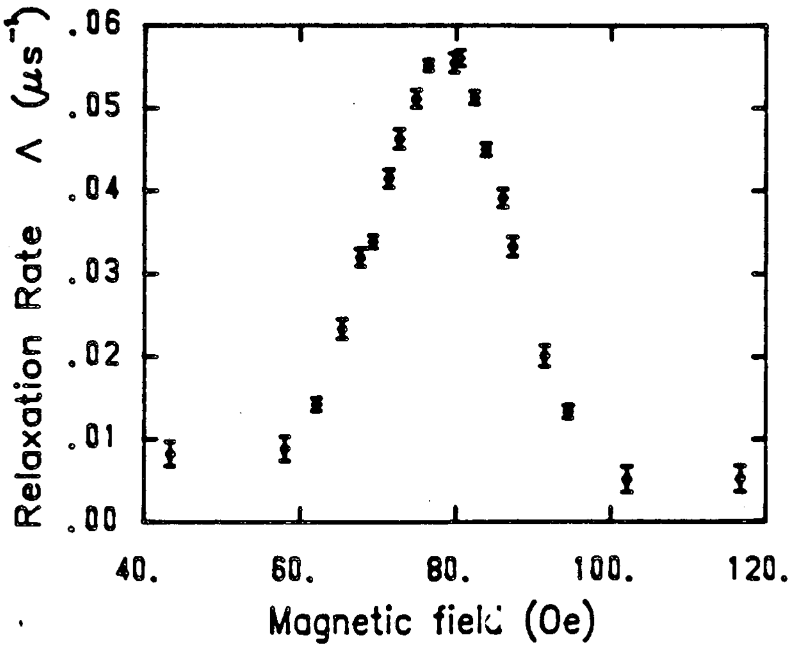

Relaxation Rate Λ (μs^{-1})
.06
.05
.04
.03
.02
.01
.00
40.
60.
80.
100.
120.
Magnetic field (Oe)

Figure 1

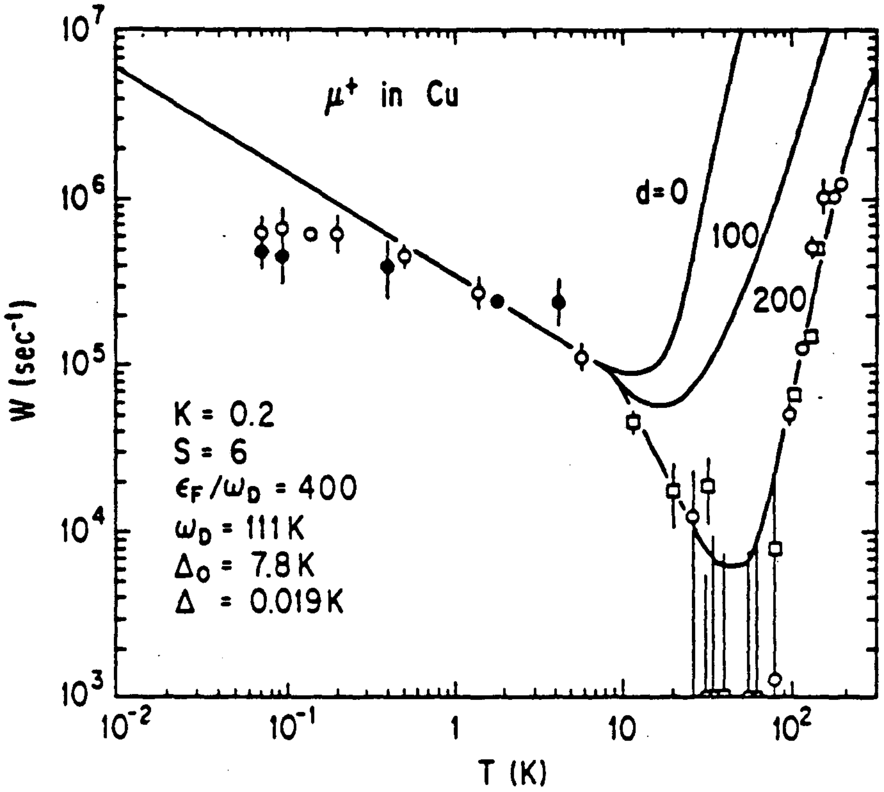

μ^+ in Cu
d=0
100
200
K = 0.2
S = 6
ϵ_F/ω_D = 400
ω_D = 111 K
Δ_0 = 7.8 K
Δ = 0.019 K
W (sec^{-1})
T (K)
10^7
10^6
10^5
10^4
10^3
10^{-2}
10^{-1}
1
10
10^2

Figure 2

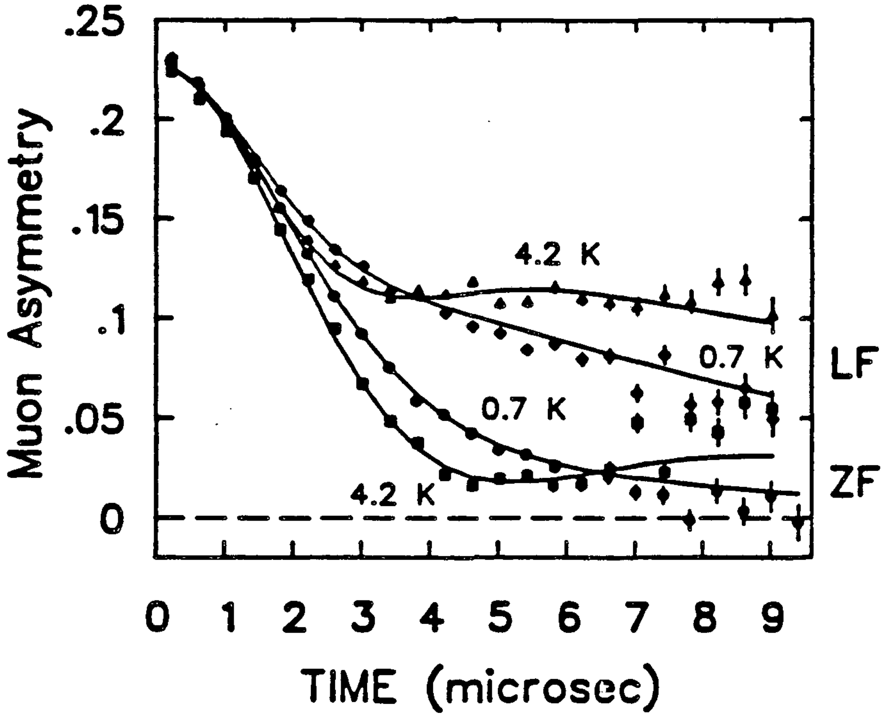
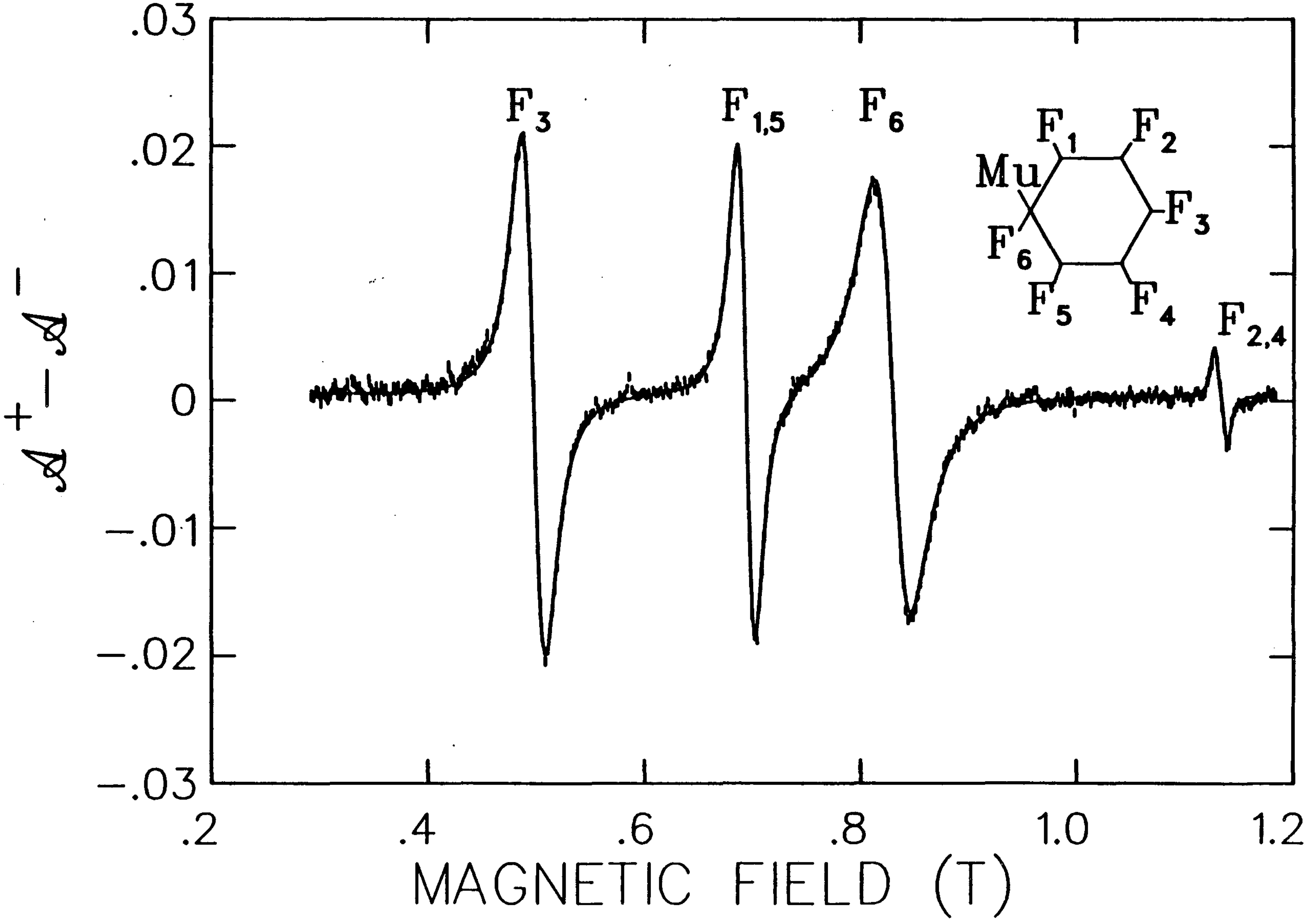

.25
.2
.15
.1
.05
0
Muon Asymmetry
4.2 K
0.7 K
LF
0.7 K
4.2 K
ZF
0
1
2
3
4
5
6
7
8
9
TIME (microsec)

Figure 3

Figure 4



.03
.02
.01
0
−.01
−.02
−.03
.2
.4
.6
.8
1.0
1.2
MAGNETIC FIELD (T)
$\mathcal{A}^+ - \mathcal{A}^-$
F_3
$F_{1,5}$
F_6
$F_{2,4}$
Mu
F_1
F_2
F_3
F_4
F_5
F_6

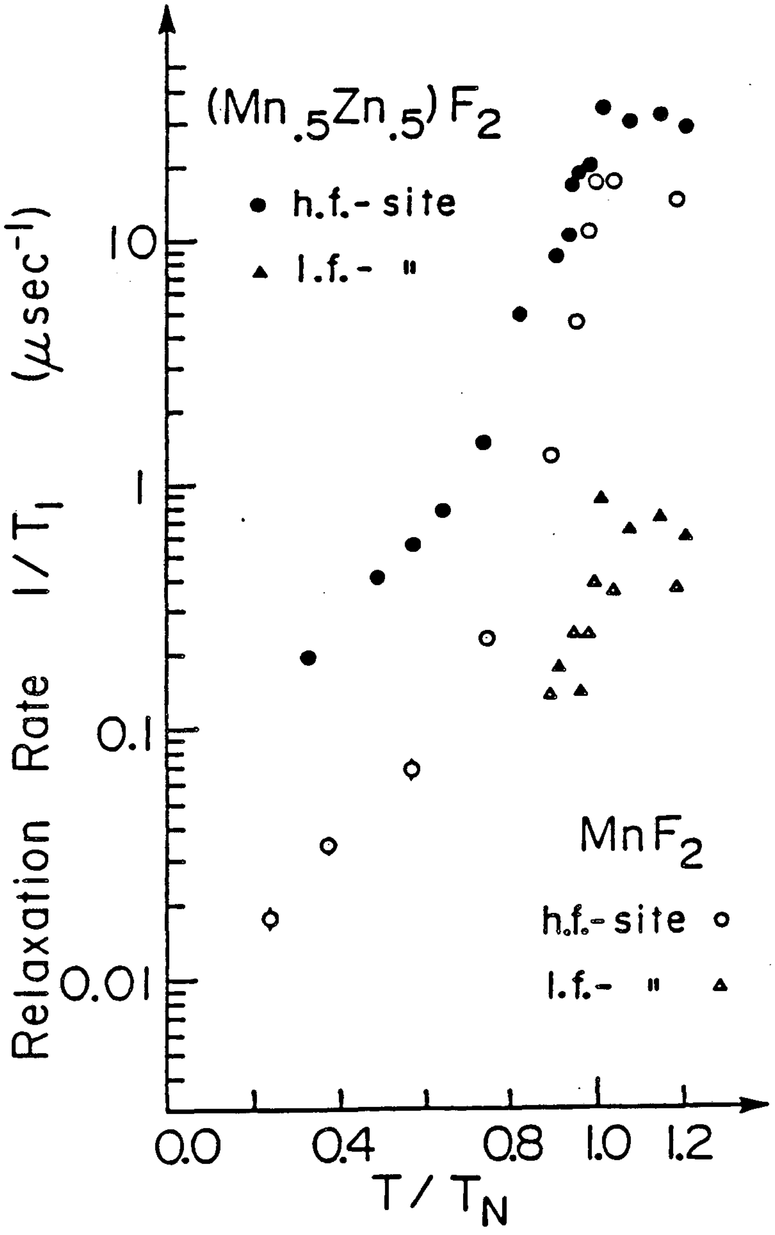

(Mn.5Zn.5)F2
● h.f.-site
▲ l.f.- "
MnF2
h.f.-site ○
l.f.- " △
Relaxation Rate 1/T1 (μsec-1)
10
1
0.1
0.01
0.0
0.4
0.8
1.0
1.2
T/TN

Figure 5

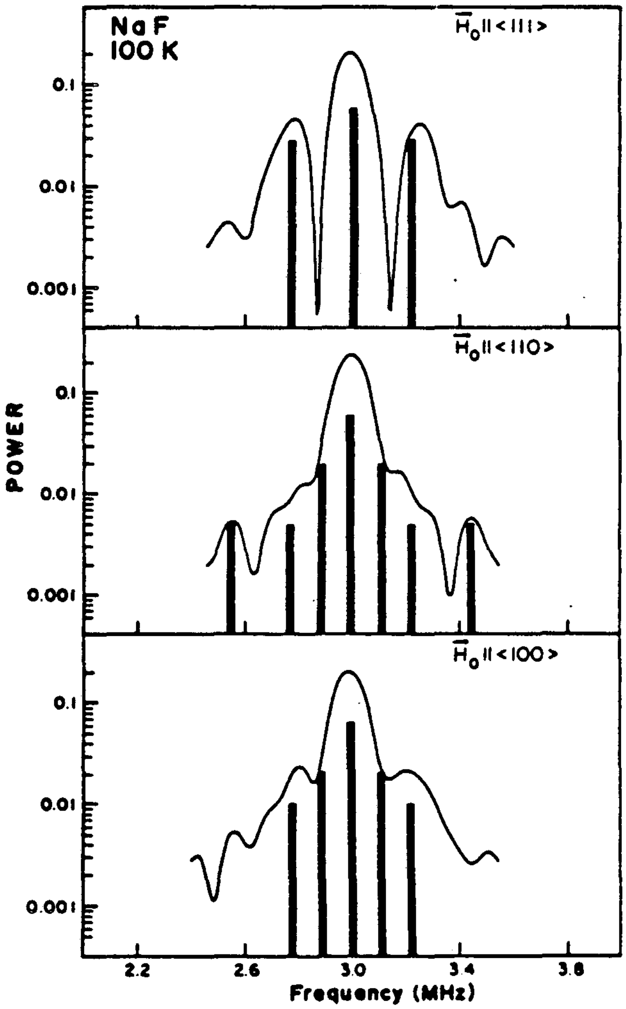

Na F
100 K
$\vec{H}_0 \parallel <111>$
$\vec{H}_0 \parallel <110>$
$\vec{H}_0 \parallel <100>$
POWER
0.1
0.01
0.001
0.1
0.01
0.001
0.1
0.01
0.001
2.2
2.6
3.0
3.4
3.8
Frequency (MHz)

Figure 6

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