high-energy states above threshold, the electron-magnon cross section is negligible (varying as $1/E^2$). Therefore, the conduction-band polarization could be measured directly by polarization measurements of high-energy photoelectrons. Experimental techniques are available for the very accurate measurement of photoelectron energies[11] thus making it possible to probe directly the polarization of electrons at various levels in the conduction band. In principle, by measuring the polarization as a function of the energy of the photoelectrons at low temperatures, it should be possible to deduce the value of $\mu_{e\text{-}m}^-$ as a function of energy. We would like to thank R. C. Eden for helpful discussions.

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DIRECT DETECTION OF NUCLEAR ACOUSTIC RESONANCE OF A MAGNETIC NUCLEUS IN AN ANTIFERROMAGNET: Mn^{55} in $RbMnF_3$†

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An intense, frequency-dependent absorption of ultrasound in antiferromagnetic $RbMnF_3$ has been observed and attributed to resonant phonon coupling to the Mn^{55} magnetic nuclei. The angular dependence at 4.3 K and the temperature dependence between 4.3 and 38 K of the absorption are reported.

In this paper we report an extraordinarily intense frequency-dependent absorption of ultrasonic energy in antiferromagnetic $RbMnF_3$, which we have identified as due to resonant acoustic coupling to the Mn^{55} nucleus. The resonant absorption (>40 dB/cm for certain magnetic field configurations) was accompanied by a dispersion (shift in the acoustic phase velocity) of greater than 0.1%. The techniques of nuclear acoustic resonance (NAR) were extended to the 600-MHz region and used to observe directly the dependence of the Mn^{55} absorption on frequency and on the direction of an external magnetic field in the temperature range 4.3 to 38 K. The present NAR technique provides a method of studying directly the nuclear spin-lattice interaction mechanisms in antiferromagnets.

Anomalies in the attenuation of 50- to 190-MHz ultrasound in antiferromagnetic MnTe as a function of temperature near the Néel temperature had previously been studied by Walther.[1] The results of the present work support Walther's tentative proposal that the attenuation anomalies observed by him were due to coupling of ultrasound to the Mn^{55} nucleus. There have been no other reports to our knowledge of coupling of ultrasound to magnetic nuclei in antiferromagnets or ferromagnets.

In the present work, the coupling of energy to the Mn^{55} nuclear spin system from longitudinal waves propagating along the [100] crystal axis was measured as a function of direction of applied field, frequency, and temperature. The specimen of $RbMnF_3$ was that used by Melcher et al.[2-4] in their studies of F^{19} NAR at lower frequencies. Measurements were made with a uhf transmission cw spectrometer, with broad-band thin-film CdS piezoelectric transducers evaporated onto the plane-parallel (100) faces of the specimen. The intensity of the absorption rendered unnecessary the use of the usual sophisticated NAR-detection techniques. The magnitude of the Mn^{55} absorption, as well as its dependence on angle φ between the direction of $\vec{H}_0$ and $\vec{k}$, the acoustic propagation vector, is demonstrated in the swept-frequency patterns of Fig. 1, all for $T=4.3$ K. For H_0 along a cube axis [Fig. 1(a)], the NAR absorption vanishes. For $\varphi=1°$ the absorption increases markedly, as shown in Fig. 1(b). For $\varphi=45°$, the absorption is a maximum, with an attenuation greater than 40 dB/cm. [Because such an absorption completely wipes out the swept-frequency pattern, Fig. 1(c) shows the pattern for the smaller angle, $\varphi=10°$.] The NAR linewidth at 4.3 K was 560 kHz, which agrees with the NMR linewidth reported by Freiser et al.[5]

$RbMnF_3$, a cubic antiferromagnet with a Néel temperature $T_N=83$ K, has a particularly low anisotropy field. A magnetic field H_0 a few times greater than the spin-flop field $[\cong(\frac{3}{2}H_EH_A)^{1/2}$, where H_E and H_A are the exchange and anisotropy fields, respectively] pins the sublattice magnetization virtually perpendicular to H_0 regardless of the orientation of H_0. In $RbMnF_3$, also, the relatively low-frequency antiferromagnetic resonance (AFMR) modes are coupled to the nuclear modes; this gives rise to "pulling" of the nuclear resonance frequency, producing (in the spin-flopped state) two resonant modes with frequencies[6]

$$\nu_{1,2}=\nu_0[1-2\gamma_e^2H_EH_N/\omega_{1,2}^2]^{1/2}, \quad (1)$$

where γ_e is the electronic gyromagnetic ratio, ν_0 is the unpulled resonant frequency due solely to the hyperfine field ($\simeq$686 MHz), $H_N=9.43/T$ is the effective field due to nuclear polarization, and $\omega_{1,2}$ are the longitudinal (1) or transverse (2) AFMR modes. An analytic expression for ω_1 when $\vec{H}_0$ is in the (100) plane has been given by Teaney, Freiser, and Stevenson[7]:

$$\left(\frac{\omega_1}{\gamma_e}\right)^2=H_0^2+2H_EH_N-\frac{12\cos4\varphi}{7+\cos4\varphi}H_EH_A, \quad (2)$$

where $\varphi=\angle(\vec{H}_0,[100])$. All the measurements reported in this paper were taken with $H_0=6$ kOe, well above the spin-flop field (~2.5 kOe) for $RbMnF_3$.

In Fig. 2 is shown the observed NAR frequency as a function of temperature from 4.3 to 38 K. For $T<10$ K, the temperature dependence of the NAR frequency agrees well with that calculated using the pulled-mode theory, Eqs. (1) and (2). The solid line in Fig. 2 is a plot of the calculated ν_1 mode versus temperature. The parameters used in the calculation were taken from published antiferromagnetic[7] and nuclear[5] resonance data taken at 4.2 K. A good fit to the low-temperature data was obtained with a value of H_E of 8.0×10^5 Oe, in substantial agreement with the value of 8.16×10^5 Oe recently reported.[8] Above ≈10 K, the temperature dependence of ν_0, which is proportional to the sublattice magnetization, is ex-

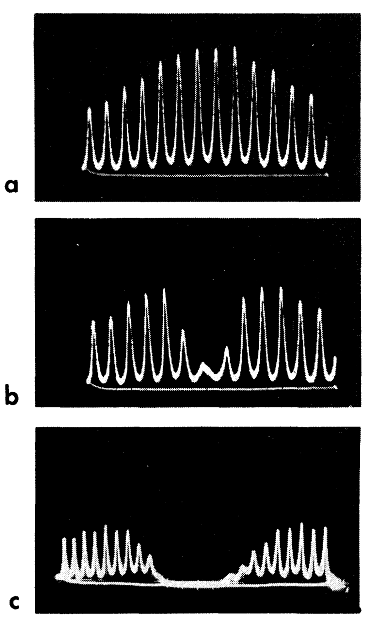

FIG. 1. Swept-frequency oscilloscope traces of ultrasonic mechanical resonance patterns in $RbMnF_3$ for 650-MHz longitudinal waves propagated along [100] axis. Spacing between mechanical resonance peaks is ≈330 kHz. $\vec{k}\parallel[100]$. $\varphi\equiv\angle(\vec{H}_0,\vec{k})$ was (a) 0°, (b) 1°, and (c) 10°. $H_0=6.0$ kOe. $T=4.3$ K.

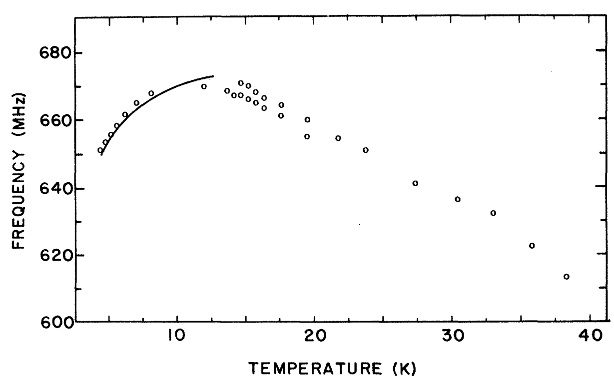

FIG. 2. Mn^{55} NAR frequency versus temperature for longitudinal acoustic waves propagated along [100] axis. $H_0=6.0$ kOe. $\varphi\cong1°$.

pected to predominate over the pulling. Van Loef[9] has shown that the sublattice magnetization of various anti-, ferro-, and ferrimagnets fits a simple power law $\approx(T_c-T)^\beta$ with $\beta=0.28$-0.35 over the temperature range $0.5T_c < T < 0.99T_c$, where T_c is the critical temperature. The data of Fig. 2 appear indeed to be asymptotically approaching a $(T_N-T)^{1/3}$ dependence at the highest temperatures reached. The measurements are presently being extended to higher temperatures. Between 14 and 20 K two distinct resonant absorptions, as indicated in Fig. 2, were observed. The two absorptions differed in the dependence on φ of their intensities. The temperature dependence of the new absorption signal does not fit that predicted for the ν_2 mode. We have no adequate explanation at this time of the appearance and subsequent disappearance of the additional resonant absorption.

The observed angular dependence of the NAR frequency at 4.3 K agrees well with that calculated from Eqs. (1) and (2): The observed shift in frequency between $\varphi=0°$ and $\varphi=45°$ was (8 ± 2) MHz; the calculated value, 10 MHz. The angular behavior of the NAR line intensity at 4.3 K indicates a $\sin^2 2\varphi$ dependence. This is the same as the dependence calculated by Silverstein[10] in his theory of NAR in an antiferromagnet. The apparent agreement may be more fortuitous than real, however, since, as contrasted to cubic $RbMnF_3$, Silverstein considered a uniaxial system.

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THERMAL FLUCTUATIONS AND THE JOSEPHSON SUPERCURRENT*

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The effects of thermal fluctuations on the dc Josephson effect are examined experimentally through measurements of the current-voltage characteristic. The results are compared with a calculation due to Ambegaokar and Halperin which uses an analogy with the Brownian motion of a particle in a field of force.

The effects of thermal fluctuations on superconducting systems have recently been the subject of intensive study. Fluctuations play an important role in the dc and ac Josephson effects[1,2] where they may be understood using relatively simple models. In this Letter we report measurements on a Josephson junction in a regime in which the current-voltage characteristic is rounded by thermal fluctuations.[3,4] The results are found to be in qualitative agreement with a theory due to Ambegaokar and Halperin.[5,6]

There are two methods which can be used to reduce the coupling energy across a Josephson junction to the order of thermal energies. One can apply sufficient magnetic field so as to bias the junction in the neighborhood of one of the minima[3] of the $I_1(H)$ curve, or one can set the temperature to a value just below the transition temperature T_c. For a uniform junction of transverse dimensions $L < \lambda_J$ these procedures produce essentially identical results. In this Letter, however, we present only data obtained near T_c. Results obtained at minima of the $I_1(H)$ curve will be discussed in a later publication.

The present experiments were conducted on an almost ideal junction in a carefully controlled environment. The apparatus was completely housed in an all-metal rf-shielded room.[7] The cryostat

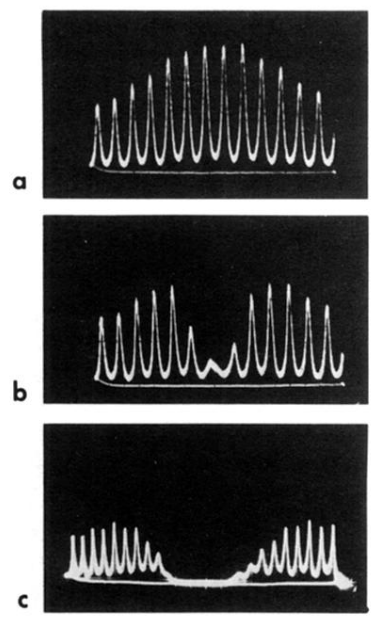

FIG. 1. Swept-frequency oscilloscope traces of ultrasonic mechanical resonance patterns in $RbMnF_3$ for 650-MHz longitudinal waves propagated along [100] axis. Spacing between mechanical resonance peaks is ≈330 kHz. $\vec{k} \parallel [100]$. $\varphi \equiv \angle(\vec{H}_0, \vec{k})$ was (a) 0°, (b) 1°, and (c) 10°. $H_0 = 6.0$ kOe. $T = 4.3$ K.