atoms in a cold glass can remember their previous atomic coordinates for a time duration of hundreds of microseconds, whereupon on signal, they cooperatively return to their initial positions. It is somewhat paradoxical that these coherent effects should occur in a completely disordered solid system but, in fact, not in the perfectly ordered crystalline state.

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[9]The discrepancy between the measured and calculated T_1 may be significant in view of the substantially shorter relaxation times observed near 0.5 K, $T_1 \approx 0.5$ μsec from which was inferred $\gamma_t \approx 3$ eV[5]. These times would extrapolate to roughly ≈ 10 μsec at 20 mK. However, in previous unpublished experiments in this laboratory, we have observed an effective relaxation time at temperatures below 50 mK, which increased rapidly with acoustic power. The suggestion that the phonons emitted by the decaying states do not leave the acoustic beam region (B. I. Halperin, private communication) may be a possibility, or that other phonon "bottleneck" phenomena may be responsible for the anomaly.

Spin-Wave Damping in a Heisenberg Antiferromagnet

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Neutron scattering measurements are reported on the linewidth Γ of spin waves in the simple cubic antiferromagnet $RbMnF_3$ at relatively low temperatures T and spin-wave energies E_q. The results are well fitted by $\Gamma = AE_q^{\alpha}T^{\beta}$, where $\alpha = 2.13 \pm 0.18$, consistent with the scaling law prediction $\alpha = 2$ of Halperin and Hohenberg, and $\beta = 3.29 \pm 0.39$, in agreement with the prediction $\beta = 3$ of two regimes considered by Harris, Kumar, Halperin, and Hohenberg, although the magnitude A is not in agreement with theory.

Interactions between spin waves give rise to a linewidth or damping,[1-4] and the extensive theoretical work on the damping of spin waves in Heisenberg magnets reflects its importance as an illustrative case of the general problem of interacting bosons. Study of the Heisenberg anti-ferromagnet in this connection has the attraction that a realistic comparison with experiment is possible, since crystals exist whose Hamiltonians mirror closely that assumed in the theoretical studies. Thus $RbMnF_3$ is known to correspond closely to a simple cubic antiferromagnet with spin $S = \frac{5}{2}$, negligible anisotropy,[5] and exchange interactions essentially limited to the nearest-neighbor shell having $J = 0.068$ THz and $z = 6$ nearest neighbors.[6,7] A few experimental studies of spin-wave linewidths using neutron scattering techniques have already been made[7,8] but considerations of resolution have meant that these studies have been largely confined to the temperature range above half the Néel temperature T_N and the larger wave vectors where the widths are most easily observed. In contrast, theoretical work, with some exceptions,[4] has tended to concentrate on low temperatures and wave vectors where analytic methods may be used. The present experimental study examines $RbMnF_3$ in the temperature range from $0.2T_N$ to $0.6T_N$ and the wave-vector range up to 0.4 times the zone-boundary wave vector along the [111] direction (defined as a reduced wave vector $q^* = 0.4$). In terms of the reduced temperature $\tau = kT/zJS$ and reduced energy

$\epsilon = \hbar\omega_q/2zJS$ this range corresponds to τ from 0.3 to 1.0 and ϵ from 0.15 to 0.62 and so is not too far from the region $\tau \ll 1$ and $\epsilon \ll 1$ of most theoretical interest.

The experiments were performed using the "tanzboden" triple-axis spectrometer IN3 at the Institute Laue-Langevin at Grenoble.[9] The necessary high resolution was obtained by using the longest possible wavelengths, and so the largest possible scattering angles, consistent with the desired wave vector and frequency. Thus at a reduced wave vector $q^* = 0.1$, an incident wavelength of 3.4 Å was produced for the (220) reflection from a copper monochromator crystal at a scattering angle of 94°. The sample scattering angle was in the region of 79°, and the analyzer reflection angle near 64° from the (002) planes of pyrolytic graphite. The angular collimations were determined entirely by the divergence from the nickel guide tube transmitting the incident neutrons (~0.6°) and by the effective sizes of the monochromator, sample, and counter aperture (30, 15, and 40 mm, respectively) and their relative distances (1.8 m between monochromator and sample and 2.4 m between sample and counter). The analyzer crystal (at 1.4 m from the sample) always presented an aperture large compared with that accepted by the counter, assuming specular reflection. By this means the unfocused frequency resolution of the spectrum measured by a vanadium specimen was reduced to 0.085 THz while focused spin-wave peaks had measured widths as low as 0.047 THz.

Figure 1 shows the constant-Q scans obtained at a reduced wave vector of $q^* = 0.3$ in the [111] direction. The increase in the spin-wave width with increasing temperature is clearly seen, together with the renormalization or lowering of the spin-wave frequency. The dashed line shows the profile caused by resolution effects calculated using the formalism of Cooper and Nathans.[10] The parameters describing the instrumental resolution were adjusted to give a good fit to the measured Bragg reflection profiles, to the measured vanadium profile, and finally to the 5-K profiles, making the assumption that there is negligible intrinsic spin-wave width at this temperature. The solid lines show the profiles obtained by a least-squares fit with a Lorentzian scattering function, corrected by the $k^3 \cot\theta_A$ factor required to convert this to a scattering intensity[11] and finally convoluted with the instrumental resolution function. The measured background during this experiment was negligible (~1 count per 5 min) so that no background contribution was necessary in the fits. This situation made possible the accurate determination of linewidths less than the instrumental linewidth, since the intensity in the wing of the Lorentzian contributed to the accuracy in estimating the width of the Lorentzian.

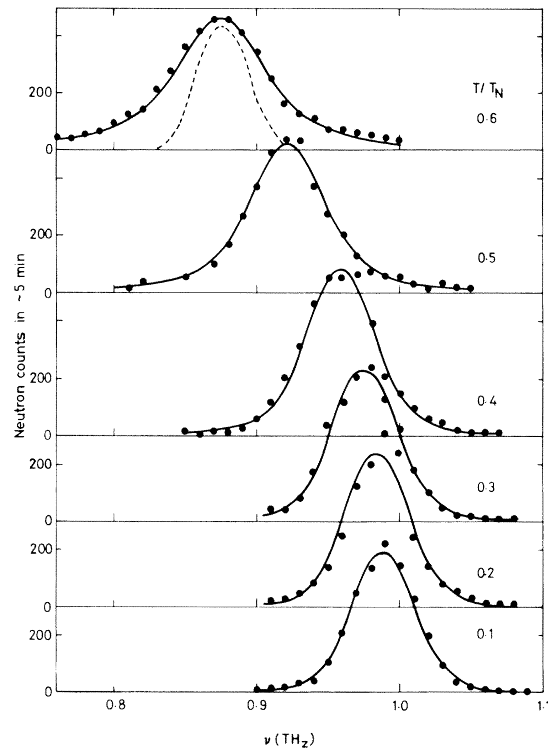

FIG. 1. Constant-Q frequency scans for $RbMnF_3$ at $\vec{q}^* = 0.3$ times the zone boundary wave vector in the [111] direction [$Q = (1.15, 1.15, 0.85)\pi/a_0$], where the lattice parameter $a_0 = 4.207$ Å at 5 K. The six temperatures covered correspond roughly from $0.1T_N$ to $0.6T_N$. The solid lines show the scattering calculated from a Lorentzian frequency distribution convoluted with the experimental resolution function (shown dashed).

Table I shows, for each of the four reduced wave vectors $q^* = 0.1$, 0.2, 0.3, and 0.4 in the [111] direction, the values of the measured spin-wave frequency and damping. In Fig. 2 the reduced widths $\Gamma/\omega_E = \Gamma/2zJS$ are plotted as functions of the reduced temperature $\tau = kT/zJS$ and energy $\epsilon = \hbar\omega_q/2zJS$, assuming the value $2zJS = 2.03$ THz. Fitting these data by the power law $\Gamma/\omega_E = A\epsilon^{\alpha}\tau^{\beta}$ gives the values $\alpha = 2.13 \pm 0.18$, $\beta = 3.29 \pm 0.39$, and $A = 0.154 \pm 0.007$, but the curves in the figure show that the data are fitted satisfactorily by the function $0.135\epsilon^2\tau^3$.

The energy dependence of the damping is thus consistent with the ϵ^2 dependence predicted generally by Halperin and Hohenberg[2] for the long-

TABLE I. The measured spin-wave energies and linewidths (parentheses denote errors in the last quoted figure).

T (K) \ q^*	E_q (THz)				Γ_q (THz)			
	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
8.0	0.333(4)	0.669(1)	0.9835(1)	1.2701(7)	0.001(1)	0.002(2)	0.000(1)	0.006(1)
16.5	0.321(4)	0.668(1)	0.9829(9)	1.2670(8)	0.002(1)	0.004(5)	0.001(1)	0.011(3)
24.9	0.325(7)	0.661(1)	0.9702(1)	1.2546(6)	0.003(4)	0.006(5)	0.009(1)	0.015(3)
33.2	0.319(5)	0.6475(4)	0.9504(2)	1.2272(1)	0.004(2)	0.010(3)	0.013(2)	0.027(1)
41.5	0.305(5)	0.6209(4)	0.9162(1)	1.1854(1)	0.006(3)	0.016(2)	0.029(2)	0.062(2)
49.8	0.291(2)	0.5892(5)	0.8694(4)	1.1334(1)	0.008(2)	0.024(2)	0.054(2)	0.099(4)

wavelength hydrodynamic regime. Their result is strictly valid only where the spin-wave frequency is less than the thermal curvature $\epsilon \ll (\tau/2)^3$; but since this restriction largely excludes our results, it is clear that the ϵ^2 dependence is in practice a good approximation to appreciably higher energies.

The nearly cubic temperature dependence of the damping is inconsistent with the predictions

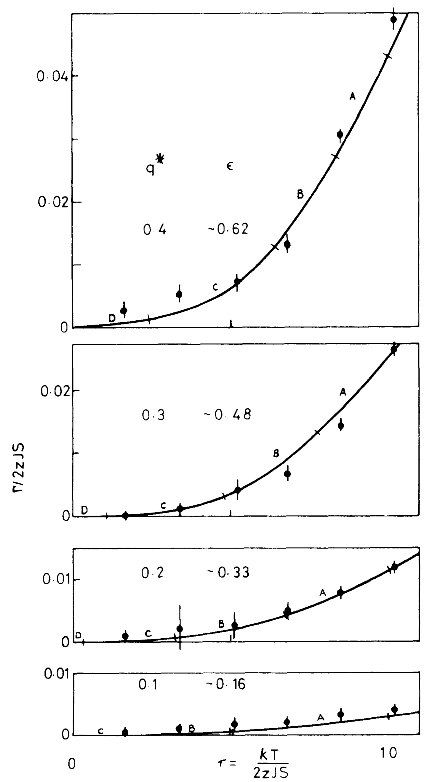

FIG. 2. The reduced spin-wave damping $\Gamma/\omega_0 = \Gamma/2zJS$, plotted against reduced temperature $\tau = kT/zJS$ for $q^* = 0.1$, 0.2, 0.3, and 0.4. The solid line shows the relationship $\Gamma/\omega_0 = 0.135\epsilon^2\tau^3$. The regimes A to D are defined as A, $\epsilon < \tau^3 < 1$; B, $\tau^3 < \epsilon < \tau$; C, $\tau < \epsilon < \tau^{1/3}$; and D, $\tau^{1/3} < \epsilon$.

of all the authors mentioned in Ref. 1. It is, however, in agreement with the exponents found by Harris, Kumar, Halperin, and Hohenberg[3] over some ranges of temperature and energy. These authors considered four such ranges whose limits are given in the caption to Fig. 2. This figure also shows the extent of each range in the present case if their limits are defined by simple inequalities. The greater part of the figure, where agreement with the cubic variation is good, corresponds to the regions A and B. Harris *et al.*[3] predict a basically cubic variation in both these regions although they also note further logarithmic terms which may modify the power laws. They predict τ^4 and τ^5 variations for regions C and D, respectively, but our measurements in these regions are not sufficiently accurate to enable these to be checked.

Harris *et al.*[3] have given expressions for the reduced damping magnitude which, for the case of a body-centered cubic lattice in regime A near $\tau = 1$, is of order $\Gamma/\omega_E = 0.021\epsilon^2\tau^3$. Our structure is simple cubic, but the difference by a factor of 6 from the measured coefficient of 0.135 is unlikely to be caused by changes in the structural parameters. The discrepancy with experiment for regime B is even larger.

We conclude that spin-wave damping in a Heisenberg antiferromagnet with reduced energies ϵ and temperature τ in the range up to unity are consistent with a power law $\epsilon^2\tau^3$.

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Correlation between Spin Polarization of Tunnel Currents from 3*d* Ferromagnets and Their Magnetic Moments

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We report measurements of spin-polarized tunnel currents from a wide compositional range of alloys of Ni with Fe, Mn, Cr, or Ti. The interpretation of the data indicates that all the alloys have an electron spin polarization P which is positive and whose magnitude follows closely the saturation magnetic moment of the alloy. This simple result greatly constrains possible explanations of spin-polarized tunneling from 3*d* ferromagnetic metals.

It was previously shown that the spin polarization P of the tunneling currents in elemental Ni, Co, and Fe is positive (predominantly in the majority spin direction).[1,2] Similar values of P for these metals had been obtained earlier from interpretations of the spin polarization of photoemitted electrons.[3] These results aroused great interest because they were apparently in direct contradiction to a simple interpretation of the band theory of ferromagnetism. This band-theory explanation would have the tunneling conductance for the two spin directions proportional to the magnitude of the two spin densities of states at the Fermi surface. For Ni the model predicts $P \approx -67\%$, which is wrong in sign as well as magnitude (measured P for Ni $\approx +10\%$). For Fe the magnitude of P in such a picture should be much less than for Ni, again contrary to experiment. Thus this simple band-theory explanation is incorrect. Because these unexplained results bear directly on the basic mechansim of ferromagnetism in the 3*d* metals, there has been much recent theoretical activity. Also experiments are in progress using tunneling, photoemission, field emission, and several other techniques. References to this current work are given in recent reviews.[4,5] Some preliminary results of Ni-Mn and Ni-Ti alloys were given in Ref. 5. The purpose of this Letter is to present measurements of the tunnel-current spin polarization over a wide range of 3*d* ferromagnetic metal alloys, which show that there is a striking correlation between the measured polarization and the saturation magnetic moment n_B of the alloys.

The technique and analysis of spin-polarized tunneling experiments have already been described in detail.[2] In essence the experiment consists of measuring the conductance dI/dV versus voltage V of a tunnel junction consisting of a 40-Å-thick superconducting Al film, an Al_2O_3 barrier, and the ferromagnetic metal film. With the junction in a parallel magnetic field of about 40 kOe and at a temperature of 0.4 K, the conductance shows an asymmetry of the spin-split tunneling conductance about $V = 0$ which can be used to determine the spin polarization of the tunneling electrons.[2]

The present experimental results are summa-