force from the inverse effect (i.e., from the temperature gradient produced by moving vortices, described above). This calculation yields numbers in the range 3 to 10 A/cm^2 for several specimens of the same alloy under the same conditions. These numbers are consistent with the measured value.

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OBSERVATION OF MAGNON-PHONON INTERACTION AT SHORT WAVELENGTHS

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Measurements have been made of the magnon and phonon dispersion relations in uranium dioxide at 9°K. These measurements provide evidence of a strong interaction between the magnon and phonon excitations and enable a value to be deduced for the coupling constant. The interaction of long-wavelength magnons in ferromagnetic materials has been studied previously with ultrasonic techniques; however, inelastic scattering of slow neutrons enables both the magnon and phonon dispersion relations to be determined for short wavelengths. In those magnetic materials which have been studied by earlier workers,[1] the magnons and phonons either interacted with one another very weakly or else their frequencies were very different. The results could then be understood without introducing any magnon-phonon interaction. In this note we report measurements of both the magnon and the phonon spectra of antiferromagnetic uranium dioxide, which lead to a magnon-phonon coupling constant of 9.6 ± 1.6°K. Since the Néel temperature[2] is 30.8°K, this coupling constant is of a similar magnitude to the direct magnetic interactions.

The specimen, a single crystal of close to stoichiometric composition, was aligned with a $(1\bar{1}0)$ plane horizontal, and cooled to 9°K. The experiments were conducted on the triple-axis crystal spectrometer[3] at the C5 facility of the NRU reactor at Chalk River. The constant-"$\vec{Q}$" technique[3] was used throughout the experiments with the analyzer energy held fixed at either 13.70 or 11.37 meV. The centers of the neutron groups then give the frequencies of the excitations in the crystal.

The magnetic structure of uranium dioxide consists of ferromagnetic sheets perpendicular to an [001] axis, with the magnetic moments aligned in the sheets.[2,4] Since in the paramagnetic phase there are three equivalent [001] axes, the antiferromagnetic specimen had a domain structure corresponding to the different possible orientations of the ferromagnetic sheets.

A careful study was made of the interaction between the magnons and the transverse acoustic (TA) phonons propagating in the $[00\zeta]$ direction ($\zeta = aq/2\pi$). Figure 1 shows a reciprocal lattice diagram of uranium dioxide illustrating two of the regions in which the measurements were made at 9°K. Also shown are the nuclear and magnetic reciprocal lattice points in the $(1\bar{1}0)$ plane.

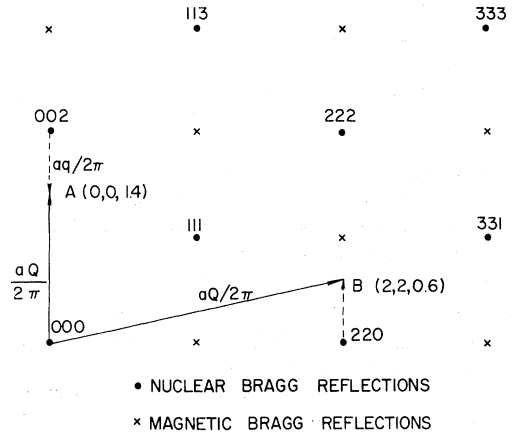

FIG. 1. The $(1\bar{1}0)$ plane of the reciprocal lattice of antiferromagnetic uranium dioxide. Points A and B show two different positions in which the $[00\zeta]$ direction ($\zeta = 0.6$) excitations were studied.

Near the nuclear Bragg reflection (002), along the line defined by $(0, 0, 2-\zeta)$, the polarization vector of the TA $[00\zeta]$ phonon is perpendicular to the momentum-transfer vector $\vec{Q}$, so that the phonon cross section is zero. (It is believed that double-scattering processes involving the TA mode which relax this zero cross-section rule[5] do not contribute significantly in these experiments.) Since, in addition, the longitudinal modes have much higher frequencies,[6] any scattered intensity will therefore arise from a magnetic contribution to the cross section. On the other hand, near the nuclear Bragg reflection (220), the cross section for the TA phonon is expected to be large, as found in practice in our earlier experiments.[6] Furthermore, in this latter case $|\vec{Q}|^2$ is larger than for the other measurements so that the magnetic part of the scattering is expected to be less intense.

Figure 2 shows the neutron groups obtained in these two regions of reciprocal space at 9°K. The results at (0, 0, 1.4) and (2, 2, 0.6) show that the lower frequency mode is of phonon character when $\zeta = 0.6$. As ζ increases the intensity of this mode along the line $(0, 0, 2-\zeta)$ increases showing an increasing magnetic contribution. On the other hand, the intensity of this branch at $(2, 2, \zeta)$ tends to decrease as ζ increases. These results show that the character of this branch is changing from phonon to magnon as ζ increases.

In Fig. 3 are shown the results for the dispersion curves in this region as compared with

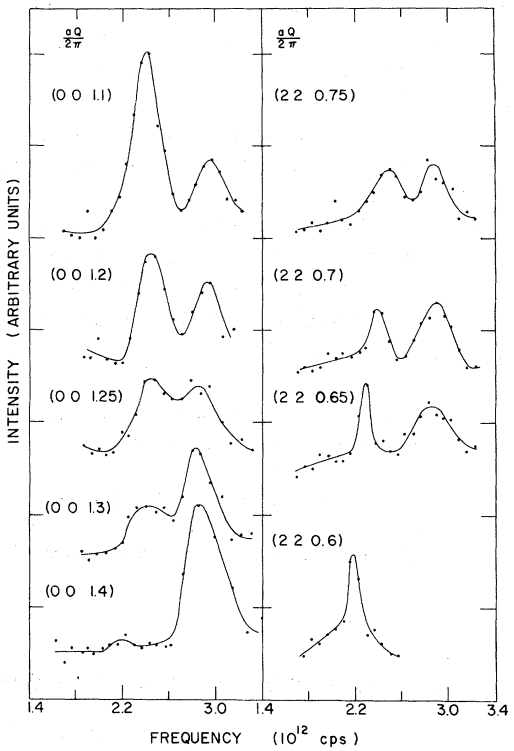

FIG. 2. Neutron groups corresponding to excitations propagating along the $[00\zeta]$ direction in uranium dioxide at 9°K.

similar measurements at 90°K, well above the Néel temperature. The drastic change in the shape and position of the phonon branch (seen at 90°K) as the magnetic excitation is introduced (at 9°K) is strong evidence of the magnon-phonon interaction.

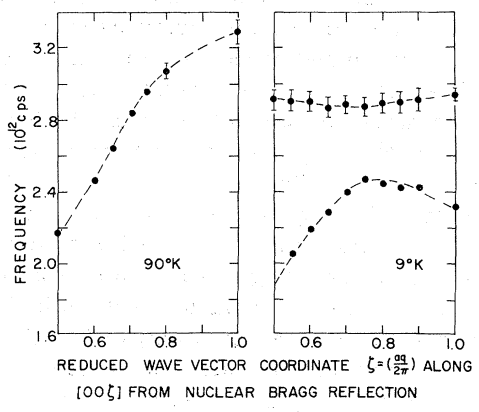

FIG. 3. The dispersion curves for the excitations of uranium dioxide in the $[00\zeta]$ direction at 9 and 90°K. At 90°K the curve corresponds to the TA phonon branch which is modified at 9°K by the magnon-phonon interaction.

The interpretation of these results is unfortunately complicated by the domain structure of the specimen, and it has not been possible to assign unambiguously the magnon mode to a particular magnetic domain. The domain structure allows the possibility of observing other magnetic modes in this direction, and it is thought likely that at least part of the scattering from the upper branch arises from such magnetic modes associated with other magnetic domains. However, an estimate of the magnon-phonon coupling constant can be deduced from the closest approach of the two branches, assuming a Hamiltonian for each wave vector q of the form[7]

$$h\nu_q^m a_q^\dagger a_q + h\nu_q^p b_q^\dagger b_q + C_q(a_q b_q^\dagger + a_q^\dagger b_q),$$

where ν_q^m and ν_q^p are the magnon and phonon frequencies and a_q and b_q the corresponding destruction operators. The minimum splitting of the two branches is then given by the coupling constant, $2C_q$, and leads to a value for C_q of 9.6 ± 1.6°K. However, the fact that the frequencies of both modes at 9°K, for ζ greater than 0.85 (Fig. 3), are substantially lower than the corresponding results at 90°K, would suggest a considerably larger coupling constant. They may arise because the upper branch is partly an additional magnon branch, as mentioned above.

A more comprehensive description of the magnetic excitations propagating in symmetry directions in uranium dioxide will be given in a future publication. These results contain further evidence of magnon-phonon interaction in other regions of reciprocal space. The results will be discussed in terms of simple spin-wave theory, and also on the basis of Blume's theory of uranium dioxide.[8]

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SATURATION BEHAVIOR OF THE DEFECT PRODUCTION IN ELECTRON-IRRADIATED COPPER BELOW 7.5°K

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Saturation effects of the defect production in very low-temperature irradiation experiments are of great interest. When thermal annealing can be excluded, they give information about the minimum separation which vacancies and interstitials must have in order to be mechanically stable. Such saturation behavior resulting in a reduction of the damage rate with increasing defect concentration has indeed been observed during heavy-particle irradiations.[1-5] However, in low-temperature electron irradiation experiments,[6-8] which are here especially interesting because of the very simple defect arrangement, no saturation behavior has yet been observed. Therefore, such an experiment was performed at this laboratory by irradiating Cu with 3-MeV electrons at low temperatures to sufficiently high defect concentration and measuring the change of the residual electrical resistivity with integrated electron flux.

Specimens were 50-μ Cu foils (residual re-