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-

sistivity 3.0×10^{-9} Ω cm) rolled from 99.999% ASARCO bulk material. They were mounted on the tail of a liquid-helium cryostat, electrically isolated from it by means of metallized sapphires which could be soldered to the tail and to the samples. The temperature of the samples was measured with a radiation-protected (Au+0.03 at.% Fe)-vs-Cu thermocouple having the reference junction at 4.2°K. A detailed description of the mounting will be given elsewhere.[9] The electrical resistivity was measured at 4.2°K with a sensitivity of 2×10^{-12} Ω cm by standard potentiometric methods. The electron-beam flux density was homogeneous to 8% across the irradiated area of the sample. The time-integrated flux was measured over the whole sample area with a relative error of less than 1.5%, which essentially determines the accuracy of the measurements.

The temperature of the specimens during irradiation was kept constant and below 7.5°K. An increase of the irradiation temperature to 8.0°K did not affect the observed damage rate. A final integrated flux density of 3.0×10^{19} e^-/cm^2 produced a resistivity increase of 2.8×10^{-7} Ω cm. Figure 1 shows the resistivity increase per e^-/cm^2 versus the total resistivity increase. Assuming the resistivity increase

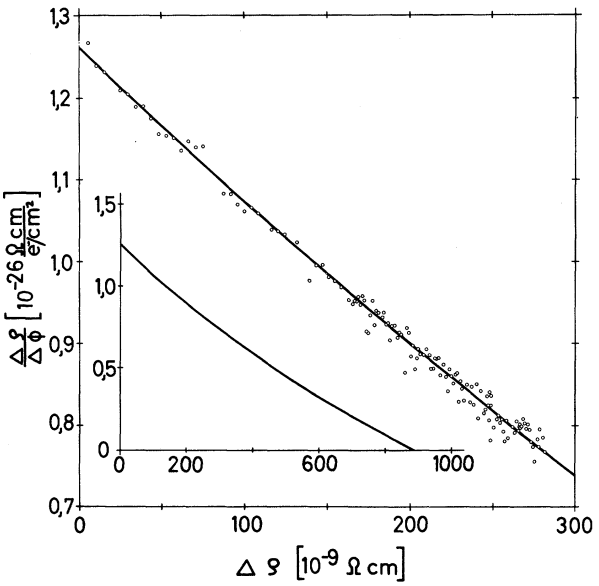

FIG. 1. Damage rate versus residual resistivity increase of 99.999+% copper irradiated with 3-MeV electrons below 7.5°K. The solid curve represents expression (3) fitted to the data. The small diagram included shows the behavior of (3) down to damage rate zero.

$\Delta\rho$ to be proportional to the atomic fraction of Frenkel pairs c, the measurements show approximately a linear decrease of the damage rate with increasing defect concentration as given by

$$dc/d\varphi = A(1-2\alpha c). \tag{1}$$

A is the effective defect production for vanishing concentration c, and α can be interpreted as the volume of spontaneous recombination[3] as given by the minimum distance between vacancy and interstitial. With $c=\Delta\rho/\Delta\rho_F$ and the resistivity increase per 100 at.% Frenkel pairs $\Delta\rho_F = 2.5\times10^{-4}$ Ω cm, one obtains from these data α as about 170 atomic volumina. Balarin and Hauser[10] corrected formula (1) by introducing a concentration-dependent α:

$$\frac{dc}{d\varphi} = A(1-c)[(1-\alpha_0 c)^2 - \alpha_0^2 c^2(1-2k) - 2\epsilon\alpha_0 c]. \tag{2}$$

This formula gives a better agreement with the experimental data than Eq. (1) and α_0, the spontaneous recombination volume for vanishing c, is now 200 atomic volumina.

Very recently Dettmann[11] treated in detail the influence of the spontaneous recombination of Frenkel pairs on the damage rate during electron irradiation and obtained

$$\frac{dc}{d\varphi} = P(1-\gamma)[2\exp(-V_S c)-1] - P\gamma\frac{1}{2V_S c}\{2V_S c - 1 + 4[\exp(-V_S c)](1-V_S c) - 3\exp(-2V_S c)\}. \tag{3}$$

Here P is the production rate of Frenkel pairs which also includes the fraction γ of unstable interstitials originally placed within the recombination volume V_S around their corresponding vacancies. The parameters $P = 1.34\times10^{-26}$ Ω cm/(e^-/cm^2), $\gamma = 0.1$, and $V_S = 200$ atomic volumina were obtained by fitting formula (3) to the experimental data (solid curve in Fig. 1). The damage rate according to formula (3) is rather insensitive to γ for small values of γ. Nevertheless, it can be deduced from the data that γ is certainly smaller than 0.2 which means that the fraction of subthreshold events as defined by Dettmann[11] is small compared with the total damage rate.

It is interesting to note that the value $V_S = 200$ atomic volumina is about half that found in neutron irradiation experiments.[3] Obviously, the larger value according to neutron irradiation cannot correspond to the true spontan-

eous recombination volume and is probably due to the high primary knock-on energies and the heavy agitation of the lattice.

In addition, this experiment allowed a recovery study of very high defect concentration induced by electron irradiation. It has been found that 64% of the resistivity increase annealed in stage I compared with about 85% observed at low-defect concentration.[6,7] The difference results primarily by a marked decrease of stage I_D and I_E and might be caused by clustering of defects[12] during irradiation.

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NECESSITY OF SECOND-NEIGHBOR INTERACTIONS IN ISING THEORIES OF ORDERED ANTIFERROMAGNETS AND ALLOYS ON FACE-CENTERED CUBIC LATTICES

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A number of recent advances have been made in discussing the ordering of face-centered cubic lattices within the framework of a nearest-neighbor Ising model.[1-5] The purpose of this Letter is to point out that second-neighbor interactions must be included in the theory, if the theory is to be used for predicting the properties of real systems.

Danielian[1] has shown that assuming a positive value for the nearest-neighbor interaction and neglecting higher-neighbor interactions, the ground state of a face-centered lattice is degenerate and may be described as having one of two possible configurations for each 100 plane normal to, say, the x direction. The two configurations, denoted by I and II, are shown in Fig. 1.

This leads to a "ground state" which is 2^R-fold degenerate, where R is the number of 100 planes ($\cong N^{1/3}$ in a lattice of N sites). This state is partially ordered in that it possesses perfect long-range order in directions within a plane but is completely disordered in directions out of a plane.

The question now arises as to whether physical systems (such as binary alloys) which are well described by an Ising Hamiltonian might show a transition at some temperature to this partially ordered state, and then perhaps show a second transition to a perfectly ordered state at a lower temperature due to very weak higher-neighbor interactions. Such double transitions are theoretically expected[6] and do occur in body-centered A_3B alloys (e.g., Fe_3Al[7]).

Since higher-neighbor interactions are probably always present to some degree in real systems, theoretical predictions based on nearest-neighbor calculations are tenable only if inclusion of very weak higher-neighbor inter-

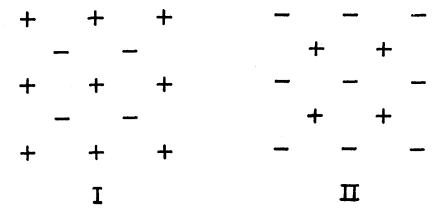

FIG. 1. The two possible configurations of a 100 phase in the ground state of an fcc antiferromagnet.