Variation of Radiation Damage Parameters in Metals*

P. G. LUCASSON† AND R. M. WALKER
General Electric Research Laboratory, Schenectady, New York

(Received March 23, 1962)

Electron damage measurements have previously been used to obtain values for the average threshold energies and for the electrical resistivities of Frenkel pairs in a number of metals. In this paper it is shown that there is an empirical correlation between the point defect resistivities so obtained and the normal, high-temperature electrical resistivities of different metals. The threshold energies are discussed and extrapolations are made to predict values for certain metals whose threshold energies have not yet been measured. The low-temperature (stage I) recovery of most of the metals studied is shown to be qualitatively similar to that in copper, and the correlation of recovery temperatures with certain bulk properties is discussed. The radiation damage parameters derived from the electron results are used to compare theory and experiment for irradiations performed with heavy particles. It is shown for neutron irradiations that there is a general tendency for the simple displacement theory to give better agreement with experiment as the atomic weight of the bombarded material increases.

I. INTRODUCTION

IN a previous paper[1] we presented experimental results on the production of electron-induced radiation damage in a number of metals, specifically: Al, Ag, Au, Cu, Fe, Mo, Ni, Ti, W, and Zn. The data on the production of damage as a function of bombarding electron energy were analyzed using simple displacement theory to obtain approximate values of threshold energies and point defect resistivities. The irradiations were performed at 20°K or less, and recovery data extending to 300°K were also presented.

Copper has been extensively studied in the past[2] and has served as a standard metal for radiation damage studies. The present work was undertaken in order to compare the behavior of other metals with that of copper, and to obtain an over-all picture of radiation damage in metals. In this paper we discuss some of the implications of the numbers obtained from the analysis of the electron damage results. The point-defect resistivities are discussed first and it is shown that there is an empirical correlation between their values and the bulk properties of the metals. The threshold energies are discussed next and the measured values are extrapolated to predict values for some metals which have not yet been measured experimentally. The general pattern of recovery behavior is considered next, following which we discuss the comparison of the electron bombardment results with those obtained using heavier bombarding particles. Finally, we discuss briefly the anomalous behavior of Zn.

The behavior of other metals appears to be qualitatively similar to that of copper. In addition to this qualitative similarity there appears to be a systematic and reasonable variation of the basic damage parameters.

II. EMPIRICAL CORRELATIONS BETWEEN THE BULK PROPERTIES OF METALS AND THE CHARACTERISTICS OF FRENKEL PAIRS

The comparison of experimentally measured resistivity changes with radiation damage theory is difficult because the resistivities of Frenkel pairs ($\Delta\rho_f$) are usually not known. Various estimates in copper have differed by an order of magnitude and it has long been a central problem to determine $\Delta\rho_f$. In a preceding paper we have described a technique for obtaining $\Delta\rho_f$ values from electron damage experiments. In this section we show that the values so obtained follow a simple empirical rule. If this rule has general validity, it gives a way of predicting $\Delta\rho_f$ values in metals not yet studied.

Within 0.2 to 2 times the Debye temperature, the resistivity of a normal, nonferromagnetic metal is given approximately by KT. K is constant for a given metal and reflects the electronic and elastic properties of the material. Comparing our previously obtained results we find that $\Delta\rho_f$ is approximately proportional to K. More specifically, the following rule is observed to hold: The value of $\Delta\rho_f$ determined in the electron damage experiments, expressed in Ω-cm per at.%, is equal within a factor of 2 to the 0°C thermal resistivity of a particular metal expressed in Ω-cm. The evidence is shown in Fig. 1 where we have plotted $\Delta\rho_f$ for different metals, determined from electron damage measurements, as a function of the normal resistivity at 0°C. Of course, thermal resistivity values taken anywhere in the linear thermal resistance region would give equally good correlation and the 0°C reference is chosen simply for convenience. It can be seen that Ag, Cu, Al, Mo, and Ti follow the rule closely, whereas the ferromagnetic metals Fe and Ni fit less well. The above rule says essentially that defects and phonons scatter electrons similarly. This is not surprising and we believe that the rule may be approximately valid for a

* This research reported in this paper was sponsored by the Electronics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command.

† Permanent address: Laboratoire de Chimie Physique, Faculté des Sciences de Paris, Centre D'Orsay, Orsay, France.

[1] P. G. Lucasson and R. M. Walker, Phys. Rev. **127**, 485 (1962).

[2] For a recent review see Proceedings of the Summer School sponsored by Italian Physical Society, Ispra 1960, Nuovo cimento (to be published).

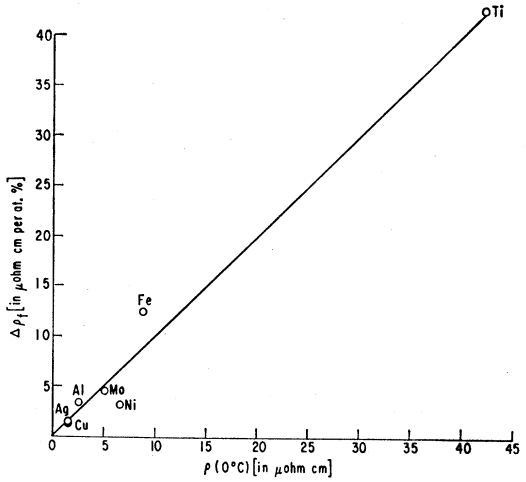

FIG. 1. The electrical resistivity of Frenkel pairs as determined from electron damage experiments (see reference 1) plotted against the normal bulk resistivity of different metals at 0°C.

number of metals, providing a useful rule of thumb for predicting and interpreting experimental results.

We have also compared the $\Delta\rho_f$ values with other quantities such as the resistivity per unit vibration amplitude $\rho(0°C)/M\theta_d^2$. The correlation appears less good although still within the limits with which $\Delta\rho_f$ is determined from the electron experiments.

It is interesting to note a further correlation between point defect and bulk properties in the case of copper. In this metal the ratio of resistivity change to fractional volume change produced by adding point defects is about the same as the ratio of resistivity change to fractional volume change produced by heating a bulk sample. If α is the thermal coefficient of resistivity change and β is the linear expansion coefficient, then the ratio of resistivity change to fractional length change is given by

$$R_T=\rho(T)\alpha/\beta\sim 4\times 10^{-4}\ \Omega\ \text{cm} \quad \text{at} \quad 273°\text{K}. \qquad (1)$$

Using $\Delta\rho_f=1.3\ \mu\Omega$ cm per at. % and taking a change of 1.0 atomic volume for each Frenkel pair in Cu, the corresponding ratio for point defects turns out to be numerically equal to R_T.

A more direct comparison is obtained by comparing R_T with the lattice parameter measurements of Simmons and Balluffi[3] and the length change measurements of Vook and Wert.[4] These experiments give a ratio of $\Delta\rho/(\Delta L/L)\sim 7.2\times 10^{-4}\ \Omega$ cm for the defects produced by deuteron bombardment. This is within about a factor of 2 the value of R_T.

If we assume that the above relationship between thermally-induced and defect-induced changes holds for metals other than Cu, then we can estimate the ratio of resistivity to length changes which would be measured in other radiation damage experiments. For example, R_T ranges from $3.5\times 10^{-4}\ \Omega$ cm for Ag to $38\times 10^{-4}\ \Omega$ cm for Mo. Ti gives a factor of 8 higher still. Further, if the aforementioned rule relating $\Delta\rho_f$ to $\rho(T)$ were strictly valid, then the atomic volume change for defects would be simply proportional to the linear expansion coefficients of the metals. This follows because the temperature coefficient of resistivity is nearly constant for normal metals.

III. VARIATION OF THRESHOLD ENERGIES

The calculation of threshold energies from first principles is a difficult task. The difficulty arises partly from the many-body nature of the problem (which makes detailed numerical computations necessary) and partly from the fact that the interatomic potentials are not known with sufficient accuracy. Gibson *et al.*[5] have performed extensive computer calculations on copper but such calculations are not available for other metals. Even in the case of copper, as we have previously discussed,[1] the agreement between the computer calculations and the experimental threshold results is quite uncertain.

In spite of the complicated nature of the problem we feel that the present threshold results on different metals fall into a sensible pattern and that these results can be extrapolated to make predictions for certain metals not yet studied. Gibson *et al.* calculate a threshold energy of 24 eV in copper for atoms projected in the [100] direction. Taking the same potential and placing an atom in the symmetry position half-way to its nearest neighbor in the [100] direction, we find an energy of 12 eV when all the atoms are held rigidly in position. This is within a factor of 2 of the value found by the exact calculation and suggests that the relative values of the threshold energies of all elements of the same crystal structure might be approximated by a similar calculation using the proper value of the interatomic potential. That is, the threshold energy may be given approximately by the interaction energy of an atom placed in a particular symmetry position, leaving all other atoms fixed in position. If this is so, then the threshold energy for a given crystal structure will depend only on the lattice parameter r_0 and the interatomic potential. At the same lattice parameter the threshold energy will reflect the Z dependence of the potential. We know that at very small separations $V(r)\sim Z^2e^2/r$ and we therefore might expect that the threshold energies will increase with increasing Z. Similarly, the threshold energy of elements with nearly the same Z might decrease with increasing lattice parameter.

The experimental results are in accord with this point of view. Consider first the elements Ni and Cu. They have nearly the same Z and lattice parameter

[3] R. O. Simmons and R. W. Balluffi, Phys. Rev. **109**, 1142 (1958).

[4] R. Vook and C. Wert, Phys. Rev. **109**, 1529 (1958).

[5] J. B. Gibson, A. M. Goland, M. Milgram, and G. H. Vineyard, Phys. Rev. **120**, 1229 (1960).

and are observed to have nearly the same threshold energy. In going from Ag to Au the atomic number increases but the lattice parameter remains virtually the same. As would be expected from the above arguments, the threshold energy increases. There are a number of metals whose threshold behavior has not yet been studied which are grouped closely in atomic number and lattice parameter around each of the metals which have been studied. If we assume that the threshold energies for a given crystal structure increase with the ratio of Z^2/r_0 for closely related metals, then approximate threshold energies of the unmeasured metals can be predicted. For example, Cr has a Z^2/r_0 ratio only slightly less than Fe and hence should have a threshold energy close to but less than the 24 eV measured for Fe. Vanadium should have a still lower threshold. Near Ag we find the metals Rh and Pd both of which should have nearly identical thresholds; Rh somewhat less, and Pd somewhat greater than Ag. The threshold for Ir should be close to that of Au while Pt should be slightly higher yet. Tantalum should have a value somewhat lower than that for W. Based on the comparison of the measured values for Mo and Ag we would also expect the threshold energy in W to be somewhat higher than for Au. The final sequence is {V, Cr, *Fe*}{Rh, *Ag*, Pd}{*Au*, Ir, Pt}{Ta, *W*}. Elements with similar thresholds are enclosed in curly brackets only, these major groupings are probably significant, elements for which experimental information is available are in italic type.

It should also be noted that there is a class of metals, primarily the alkali and alkaline earth metals, but including other metals as well, which have very large lattice parameters and hence may be expected to have anomalously low threshold energies. None of these metals has been examined experimentally.

IV. RECOVERY BEHAVIOR

When copper is irradiated at ~4°K and subsequently annealed, the damage is observed to recover in a series of temperature regions (or stages). This recovery behavior has been extensively studied in the past and a detailed model has been proposed to account

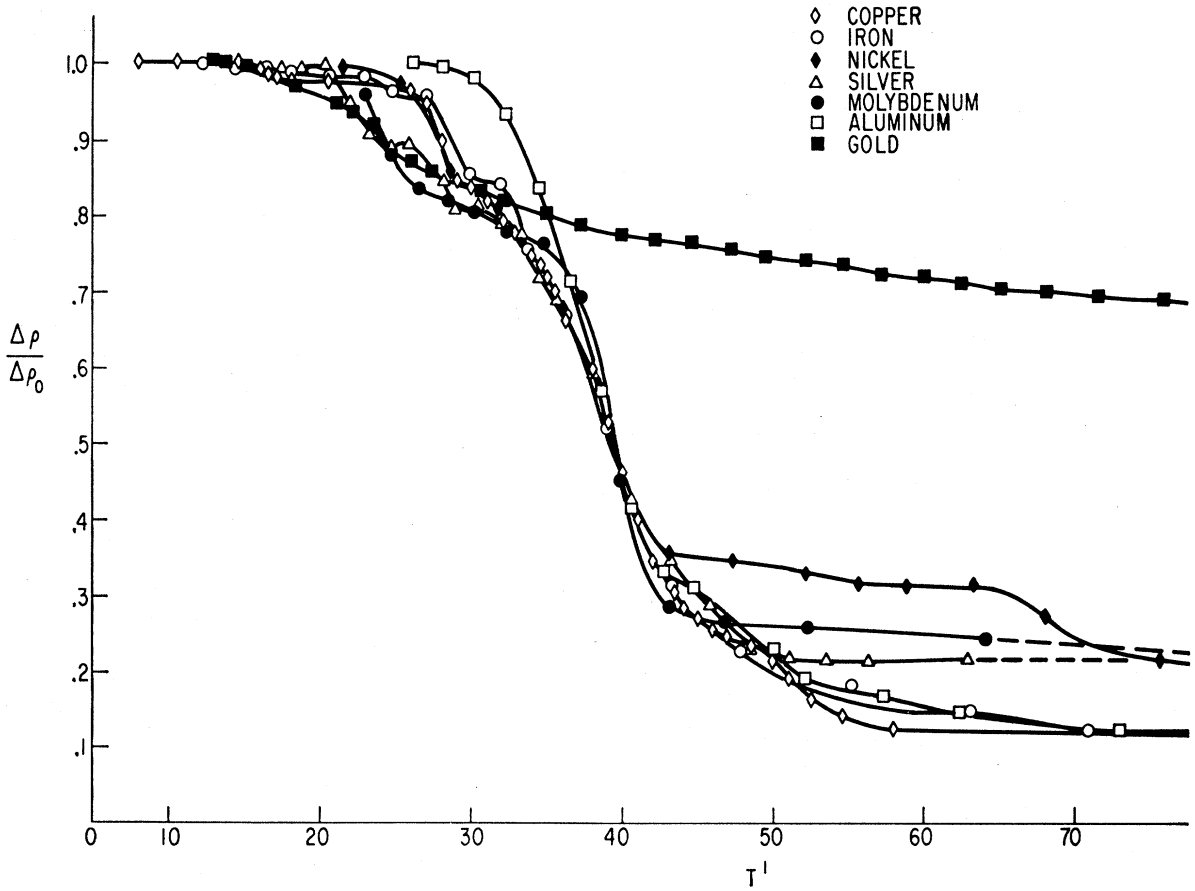

FIG. 2. Normalized plot of stage-I recovery in different metals. The experimental temperatures for a given metal are all multiplied by a constant to give the values plotted here. The value of the constant for each metal is determined by requiring that the 50% recovery level occur at the same temperature as in Cu. In the case of Au, which shows less than 50% recovery, the constant was chosen arbitrarily. The data for this plot came from reference 1 except in the case of Au where the data were taken from reference 8.

for the observed low-temperature behavior.[6] In very pure copper ~90% of the induced resistivity recovers below 80°K [stage I]. This stage-I recovery is further divided into a number of substages I_A–I_E in which the lowest temperature substages (I_A–I_C) are attributed to close pairs of interstitials and vacancies which self-annihilate on warming. Substages I_D and I_E are attributed to the free migration of interstitials. Above 80°K there are several other stages (II, III, and IV) which differ markedly in their importance depending on trace impurities in the copper.[6,7] Only stage III is important in very pure copper.

The low-temperature recoveries of the electron irradiated metals reported in reference 1 appear quite analogous to that in copper. This is most easily seen by referring to Fig. 2 which shows the recovery data for different metals plotted on a reduced temperature scale. Because of the strong similarity of the low-temperature recovery behavior, the model previously developed for copper probably is equally valid for the other metals studied. The single exception appears to be gold where an anomalously low amount of stage-I recovery was observed by Ward and Kauffman.[8] It is possible that recovery had already taken place at the irradiation temperature employed. This will have to be checked by further experiment.

The reduced temperatures used to obtain Fig. 2 are arbitrary, being chosen simply by requiring that the 50% recovery levels occur at the same temperature as in Cu. They bear no simple relation to either the melting points or Debye temperatures of the metals. In fact, the recovery temperatures appear not to be correlated at all with the melting points and there is no support for the oft-stated view that higher melting point metals should have higher stage-I recovery temperatures. The correlation with Debye temperature is considerably better although still imperfect. Still another correlation with the bulk properties is obtained by comparing the recovery temperatures with the product $\gamma\Omega$, where γ is the Grüneisen constant and Ω the atomic volume. This product is an approximate measure of the local frequency change around a defect and it might be expected that metals with low values of $\gamma\Omega$ would have higher recovery temperatures and vice versa. There is a tendency in this direction, although nothing like a simple linear relationship exists. The various parameters discussed above are shown explicitly in Table I.

Consider next the higher temperature recovery data. Of the metals studied only Ni, Al, and Ag showed additional recovery up to room temperature. It has been shown for copper that trapping reactions with trace impurities can dominate the observed behavior in this temperature region[6,7] and thus the interpretation of data in the high-temperature region is difficult. For example, in

TABLE I. Comparison of stage-I recovery temperatures with various parameters.

Crystal type	Element	T for 50% recovery (°K)	θ_D[a] (°K)	$T_{melting}$ (°C)	$\gamma\Omega$[b]
fcc	Au	<30 ?	165	1063	31
	Ag	30	225	961	25
	Al	37.8	418	660	22
	Cu	38.3	340	1083	14
	Ni	57.1	456	1455	13
bcc	Mo	42.9	425	2625	15
	Fe	99.8	467	1540	11

[a] Taken from *Introduction to Solid State Physics* by C. Kittel (John Wiley & Sons, Inc., New York), 2nd ed.
[b] γ is the Grüneisen constant and Ω the atomic volume.

Ni two recovery peaks were observed at 100 and 270°K. The total amount of recovery in these peaks is considerably larger than the recovery observed by Sosin and Brinkman[9] when they warmed an irradiated Ni sample from 90°K to room temperature. We attribute the difference to the effects of impurity trapping. The nickel employed in the present experiments contained enough impurities to trap all the radiation defects. The same is also true of the nickel employed by Sosin and Brinkman. In copper it is found that high-temperature production curves are linear only in impure samples, and the linear production curves observed at 90°K by Sosin and Brinkman constitutes additional evidence for the importance of impurity trapping.

The situation is somewhat different in the case of Al. This was a very pure zone-refined sample from the same batch that was used by DeSorbo and Turnbull[10] for their quenching work. In principle, the present results afford a direct comparison of the recovery behavior of irradiated and quenched samples. However, as discussed in detail by Walker,[6] the fact that multiple defects are formed in the case of the irradiated Al coupled with the lack of information on activation energies, precludes any definitive conclusions concerning the similarity of the defects produced in the two experiments.

We consider the comparison of the recovery following electron damage with that produced by heavy particles. In deuteron bombardments,[11] the characteristic fine structure is observed in the stage-I recovery. More damage is retained after stage-I recovery is complete, and a fairly large and broad recovery region is observed between stage I and stage III. Blewitt *et al.*[12] have observed a prominent stage-I recovery following neutron bombardments. Thompson[13] has also

[6] R. M. Walker, Nuovo cimento (to be published).
[7] D. G. Martin, Phil. Mag. **6**, 839 (1961).
[8] J. B. Ward and J. W. Kauffman, Phys. Rev. **123**, 90 (1961).
[9] A. Sosin and J. A. Brinkman, Acta Met. **7**, 478 (1959).
[10] W. DeSorbo and D. Turnbull, Phys. Rev. **111**, 810 (1958); **115**, 560 (1959).
[11] G. D. Magnuson, W. Palmer, and J. S. Koehler, Phys. Rev. **109**, 1990 (1958).
[12] T. H. Blewitt, R. R. Coltman, D. K. Holmes, and T. S. Noggle, *Dislocations and the Mechanical Properties of Solids*, edited by J. C. Fisher (John Wiley & Sons, Inc., New York, 1957).
[13] M. W. Thompson, Phil. Mag. **5**, 278 (1960).

shown similar behavior for tungsten. However, the fine structure in stage I is missing in these neutron experiments. The initial recovery is depressed to somewhat lower temperatures and accounts for still less of the total recovery than in the deuteron bombardments. A large stage II is present and stage III is variable depending on the element studied. In some elements it is necessary to go to temperatures near melting before final recovery is observed.

The qualitative features of the differences in recovery behavior can be understood on the basis of the energy transfers involved. In the electron experiments the damage is produced primarily as isolated point defects. Thus the close pair peaks are well defined and the observed kinetics are fairly simple. In neutron bombardments, the primary atom recoil energies are large and clusters of displaced atoms are formed. The varying strain fields in these clusters lead to a broadening of the substages and a lowering of the initial recovery temperature. The presence of multiple defects and large strain fields also produces the large stage-II recovery. The deuterons represent an intermediate situation. Because of the long-range nature of the Coulomb interaction, many individual defects are formed. However, as pointed out by Corbett and Walker,[14] Walker,[6] and Koehler and Seitz,[15] most displaced atoms in a deuteron bombardment are in relatively large clusters of other displaced atoms.

The reduced importance of stage I can be understood on the basis of interstitial clustering. In the interpretation of the recovery of electron damage stage I_D was attributed to the accidental recombination of a wandering interstitial with its own vacancy. I_E was attributed to the uncorrelated recovery of a wandering interstitial with other, more distant vacancies. In order to explain the damage which was retained after stage I was complete, it was necessary to postulate that interstitials could interact to form stable complexes. If many defects are produced in close proximity to one another, the chance for a wandering interstitial to find its own vacancy should be greatly reduced. The probability of finding other interstitials and combining to form stable complexes is correspondingly increased. Thus more interstitial complexes, which recover at higher temperatures, should be produced in deuteron and neutron experiments where the initial damage consists of clumps of displacements.

V. COMPARISON OF DAMAGE PRODUCTION RATES IN LIGHT- AND HEAVY-PARTICLE EXPERIMENTS

In this section, we compare the electron results with those obtained with more massive bombarding particles. Consider first the comparison with neutron experiments. The "simple" theory of neutron radiation damage outlined in Seitz and Koehler[16] assumes that the primary knock-ons are produced in elastic neutron encounters characterized by a single, energy-independent, isotropic cross section σ_s. The damage produced by the knock-ons is calculated on the basis of independent, two-particle collisions and the damage is assumed to consist of Frenkel pairs. With these assumptions it is easy to show that the expected resistivity change observed in a pile neutron experiment is given by:

$$\Delta\rho/n=(\Delta\rho_f\sigma_s/MT_d)F(E), \tag{2}$$

where M is the atomic weight of the bombarded metal and $F(E)$ is a complicated function of the neutron energy spectrum. It follows from this that the resistivity change per bombarding neutron, for different metals placed in the same pile, should be proportional to $\sigma_s\Delta\rho_f/MT_d$. The absolute value of the resistivity change depends on the evaluation of $F(E)$. In a recent discussion, Koehler and Seitz[15] give a ratio of about 4 between the values calculated from Eq. (2) and the experimentally measured resistivity changes of Blewitt *et al.*[12] Discussing the same data, Holmes[17] concludes that the ratio is about 8. Both authors use a value for $\Delta\rho_f\sim 2.0\,\mu\Omega$ cm/at.% and the difference apparently arises in the choice of the neutron energy spectrum $\phi(E)$. Holmes' calculation is to be preferred since it is based on a more recent determination of $\phi(E)$. If the value of $\Delta\rho_f$ found in the present work were taken at face value the discrepancy would be reduced by about 0.7.

Blewitt and co-workers[12] have measured the resistivity changes in a number of pile-irradiated metals. Combining their data with the present determinations of $\Delta\rho_f$ and T_d permits one to check the simple displacement theory. The relevant numbers are given in Table II. From Eq. (2) we have that

$$(\Delta\rho/n)_x/(\Delta\rho/n)_{\mathrm{Cu}} = (\sigma_s\Delta\rho_f/MT_d)_x/(\sigma_s\Delta\rho_f/MT_d)_{\mathrm{Cu}}. \tag{3}$$

If this relation holds, then columns 5 and 6 of Table II should be equal. It can be seen from the table that the equation holds quite well for Fe and Ni, less well for Al, Ag, and Au, and not at all for Mo and W. The fact that the damage rates in Cu, Ni, and Fe obey Eq. (3) suggests strongly that the high-energy damage processes are similar in these materials. The low-energy production curves are also very similar. Except for a considerable shift in absolute temperature, the recovery curves also are alike. All in all, the data suggest that the damage and recovery processes in these three materials are nearly identical.

For the metals heavier than copper, the disagree-

[14] See *Proceedings of the Defects in Noble Metals Conference, Canoga Park, 1958* (Atomics International, Inc., Canoga Park, California), Document NAA-SR-3250.

[15] J. S. Koehler and F. Seitz, Discussions Faraday Soc. **31**, 45 (1961).

[16] F. Seitz and J. S. Koehler, *Solid State Physics* (Academic Press Inc., New York, 1956), Vol. 2.

[17] D. K. Holmes, Nuovo cimento (to be published).

TABLE II. Comparison of neutron damage results with simple displacement theory using parameters determined in electron experiments.

Element	σ_s[a] (in barns)	$\Delta\rho/n$[b] for neutrons (arb. units)	$\sigma_s\Delta\rho_f/MT_d$ (arb. units)	$\frac{(\sigma_s\Delta\rho_f/MT_d)_x}{(\sigma_s\Delta\rho_f/MT_d)_{Cu}}$	$\frac{(\Delta\rho/n)_x}{(\Delta\rho/n)_{Cu}}$	Ratio of theory to exp.
Al	3	7.9	11.8	3.9	2.6	12
Fe	3	21.6	28.0	9.3	7.0	10.5
Ni	3.3	8.4	7.6	2.5	2.7	7.5
Cu	3.2	3.1	3.0	1.0	1.0	8[c]
Mo	6	128	7.6	2.5	41.3	0.5
Ag	6	3.4	2.8	0.9	1.5	4.8
W	7	118	<5.7[d]	<1.9	38.2	<0.4
Au	6	3.8	<1.7[d]	<0.56	1.4	3

[a] Taken from, *Neutron Cross Sections*, compiled by D. J. Hughes, B. A. Magurno, and M. K. Brussel, Brookhaven National Laboratory Report BNL-135 (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C., 1960).
[b] Values obtained by Blewitt *et al.* taken from *Radiation Damage in Solids* by D. S. Billington and J. H. Crawford (Princeton University Press, Princeton, 1961).
[c] Taken from D. K. Holmes, Nuovo cimento (to be published).
[d] $\Delta\rho_f$ assumed equal to $\rho(0°C)$.

ment is in the direction of observing more damage experimentally than is predicted from Eq. (2). Remembering that the absolute value of the copper result is off by a factor of ~ 8, this means that the absolute value of the damage calculated by the simple theory is in better agreement with experiment for these other elements. The reverse is true of aluminum. The ratio of the absolute value calculated from Eq. (2) to that observed experimentally is tabulated in the last column of Table II. It can be seen that there is a general trend (though by no means monotonic) for the theory to give better agreement with experiment as the atomic weight of the bombarded material increases. For W and Mo the theory actually predicts less damage than is observed.

Although it may well be that the basic damage mechanisms are qualitatively different in W and Mo, the tendency for the theory to give better agreement with experiment as the atomic weight increases should be expected on rather general grounds. At least three classes of explanations have been advanced for the observed discrepancy in copper. All these have the common feature that they weight high-energy recoils less than the simple theory. One correction to the theory is the introduction of a limiting "ionization" recoil energy. Above this energy the recoil is assumed to lose all its energy in ionization collisions. The primary recoil spectrum is thus cut off at an arbitrary energy in calculating the number of displacements. Another explanation has been proposed by several authors who have introduced the concept of a critical size for a cluster of displaced atoms. Beyond a certain size the cluster is assumed to be unstable and to self-annihilate. Still another reason which has been advanced for the low resistivity changes which are observed, is that the resistivity of a cluster of defects is less than the sum of the individual defect resistivities. All these proposed modifications have the common feature that the high-energy end of the recoil spectrum is given less weight than in the simple theory. Since the neutron energy is fixed, heavier atoms will recoil with less energy and the above effects should be relatively less important. Thus the simple theory should be expected to get better as the atomic weight of the material increases.

In principle, a detailed study of the variation of the agreement between theory and experiment can be used to shed light on the actual mechanism responsible for the failure of the simple theory. We have not pursued this approach for several reasons. Firstly, the parameters determined in our electron experiments are only approximate and cannot be used for precise quantitative calculation. Secondly, the neutron calculation outlined above has many serious faults which preclude its quantitative use. For example, it is assumed that the neutron scattering is both isotropic and energy independent. Neither assumption is valid.[16,17] The assumption that only elastic scattering of high-energy neutrons is responsible for the damage may also be in error. Walker[18] has shown that in some cases the damage produced by thermal-neutron capture with subsequent de-exitation by γ-ray emission may well outweigh the fast-neutron effects. Large resonance cross sections in the intermediate energy range may also play a role in certain elements. A basic shortcoming in the whole approach is the treatment of the process as a series of independent two-body collisions. With all these limitations, we feel that the best we can do at this point is to note the general trend of the results. The analysis could be much more meaningful if mono-energetic neutrons were used instead of the present pile spectrum.

We now consider briefly the comparison of the present electron results with the experiments performed by the Illinois group using 10-MeV deuterons as the bombarding particles. As discussed recently by Koehler and Seitz,[15] the simple displacement theory overestimates the amount of damage which is produced by a factor of ~ 4.3. This is based on the stored-energy measure-

[18] R. M. Walker, J. Nuclear Materials 2, 147 (1960).

ments of Granato and Nilan[19] and an assumed stored energy per defect of ~3.9 eV. If the resistivity value found in the present electron experiments (1.3 $\mu\Omega$ cm/at.%) is taken, the discrepancy reduces to ~2.8. The simple theory predicts that the damage should be proportional to $\bar{\nu}Z^2\Delta\rho_f/MT_d$. $\bar{\nu}$ is the average number of secondaries per primary recoil and can be calculated as outlined by Seitz and Koehler.[16] Using the values of T_d and $\Delta\rho_f$ determined here, we find a predicted ratio of 1.21 for the damage rate in silver relative to that of copper. This is close to the experimental value of 1.19. Following the argument outlined by Corbett and Walker[20] if $\Delta\rho_f$ for Au is taken equal to that for Ag, the predicted ratio of Au to Cu damage rates is <1.27. Taking $\Delta\rho_f$ equal to $\rho(0°K)$ as discussed in the previous section gives a ratio <1.67. The experimental value of 1.71 is thus consistent with the theoretical ratio. Although there may be a tendency for the theory to give absolute values in somewhat better agreement with experiment as the atomic weight increases, the effect does not seem as pronounced as in the case of the neutron bombardments.

VI. DISCUSSION OF ZINC

Zinc was the only low-mass element which failed to give a linear increase of resistivity when electron bombarded at 20°K. After an initial increase, the resistivity change flattened out and no further change was observed. This result was surprising in view of the large linear increase which had previously been observed by Blewitt *et al.*[12] in neutron irradiations at the same temperature. The simplest explanation of the saturation behavior is to assume that interstitials are mobile at the irradiation temperature of 20°K. As has been outlined in detail by Walker,[6] electron irradiations at temperatures where defects are mobile can give rise to such a saturation behavior. The linearity of the neutron results can also be explained by the clustering of mobile interstitials in the large local concentrations of defects produced in each primary knock-on. However, the absolute magnitude of the neutron-induced changes seems rather large to explain this way. Still another possibility is that the highly worked condition of our polycrystalline specimens may have influenced the results. Further electron damage work using single-crystal samples would be desirable.

VII. CONCLUSION

In this paper we have noted certain correlations and trends which are apparent from electron damage studies of a number of metals. The intent of this work was to give an over-all picture of radiation-damage effects in metals, building on the detailed studies which have previously been made in copper. Even in copper, however, the picture is not yet complete and more work needs to be done. For example, the relationship between the detailed computer calculations of the Brookhaven group and our experimental results remains to be delineated. Experiments on single crystals such as those reported by Cusson, Lucasson, and Walker[21] need to be pursued in order to study the role of the crystal structure. The mobile defect in stage III still remains to be identified unambiguously. In spite of these remaining problems, we feel that the qualitative similarity between copper and the other metals studied, coupled with the systematic variation of the basic damage parameters noted here, indicates that it will be possible to construct a picture of radiation effects which will be generally valid for most metals.

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of E. Fontanella and Y. Cusson in carrying out this work. Thanks are due A. Lucasson for performing many of the calculations. We are also grateful for a NATO grant to one of us (P. L.) which made this work possible.

[19] A. V. Granato and T. G. Nilan, Phys. Rev. Letters **6**, 171 (1961).

[20] J. W. Corbett and R. M. Walker, Phys. Rev. **117**, 970 (1960).

[21] Y. R. Cusson, P. G. Lucasson, and R. M. Walker, *Proceedings of the Berkeley Conference on Radiation Effects, 1961* (Butterworths Scientific Publications, Ltd., London, to be published).