(continuous line) using

$$I_2(t) = \tfrac{1}{2}(t/\lambda_1)^2 \exp(-t/\lambda_e) + (t/\lambda_2)\exp(-t/\lambda_e),$$

with $\lambda_2 = 7.41\lambda_1$, the value from the Ashley and Ritchie result using $k_c = 1.5$ Å^{-1}. This k_c value is approximately the mean of several experimental results.[4] The value for λ_0 is then 1020 Å.

The fit between theory and the experimental data is not so good at low thicknesses. This is probably because of the presence of oxide and contamination layers, which are more important in the low-thickness region. An analysis of this problem and also details of the errors inherent in the thickness rescaling, the one-beam approximation, and the large-angle scattering will be reported in a later paper. While these errors affect slightly the numerical values for the individual parameters, the present results apparently confirm the existence of the double plasmon and show good agreement with the theoretical value of the ratio λ_2/λ_1. It should be noted, however, that the theoretical λ_2/λ_1 is extremely sensitive to the value assumed for k_c (being proportional to $k_c^{\ 5}$) and a sufficiently accurate value of this parameter is not available. The value of λ_1 obtained here is much larger than previously reported by several authors. This is because of the previous use of a single-parameter Poisson distribution which neglects the double plasmon and other processes.

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New Mechanism for Internal Friction*

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Simultaneous measurements of damping and elastic modulus of copper as affected by electron irradiation have been made. These data do not follow the standard analysis, using the Granato-Lücke theory for damping, in which point defects, created by irradiation, are presumed to act as firm pinning points on dislocation lines. It is proposed instead that these defects are *dragged* along by the dislocation line moving under oscillating stress. This dragging can lead to an observed "anomalous" peak (initial increase and subsequent decrease) in the decrement as a function of electron dose.

The analyses of a large number of experiments on internal friction in metals have been based, with remarkable success, on a formulation of Koehler,[1] amplified in detail by Granato and Lücke,[2] the G-L theory. This theory, a string model for dislocation bowing under applied stress, is best known for its predictions, at reasonably low frequencies, for the strain amplitude-independent decrement δ and modulus change $\Delta E/E$:

$$\delta = aB\omega\Lambda L^4, \tag{1}$$

$$\Delta E/E = b\Lambda L^2, \tag{2}$$

B is a viscous damping constant, ω is the angular drive frequency, Λ is the total length of dislocation line per unit volume, L is the average length of dislocation between pinning points, and a and b are constants. The L^4 and L^2 dependences in Eqs. (1) and (2) are watermarks of the G-L theory. Irradiation experiments are particularly well suited for testing this L^4-L^2 prediction since the accretion of defects on dislocation lines during bombardment or subsequent annealing provides a controlled method for apparently systematically shortening the loop length L while not affecting any other parameters. If we let

$$Y \equiv \frac{\Delta E/E}{(\Delta E/E)_0} \simeq \frac{\Delta E}{\Delta E_0} \tag{3}$$

and

$$Z \equiv \delta/\delta_0, \tag{4}$$

the G-L theory predicts a proportionality at low strain amplitudes between Y^2 and Z during irradiation. (The subscript 0 designates initial values. Background contributions to the decrement or modulus are presumed to be subtracted.) On occasion, such fits have been reported[3]; more commonly, the proportionality has not been obeyed.

A second concern with the G-L theory centers on its prediction of linear frequency dependence of δ. The reported values over a relatively wide range of frequencies have shown little, if any, dependence on frequency, at relatively low frequency (e.g., near or below 1 kHz).

The observations reported here show that the G-L theory must be amended and a new damping mechanism is considered here.

In the experiments reported here, copper foils, oscillated near 500 Hz, were irradiated in a configuration similar to that reported previously by Sosin and co-workers.[4] (However, the method of sample oscillation was electrostatic in the present experiments.) Data points were taken every 3 sec; only a few of the points are displayed in Fig. 1. The samples were annealed to 725°C prior to the initial irradiation and to 460°C between irradiations, in place. Little or no amplitude dependence was found in the strain amplitude range employed here, as determined on

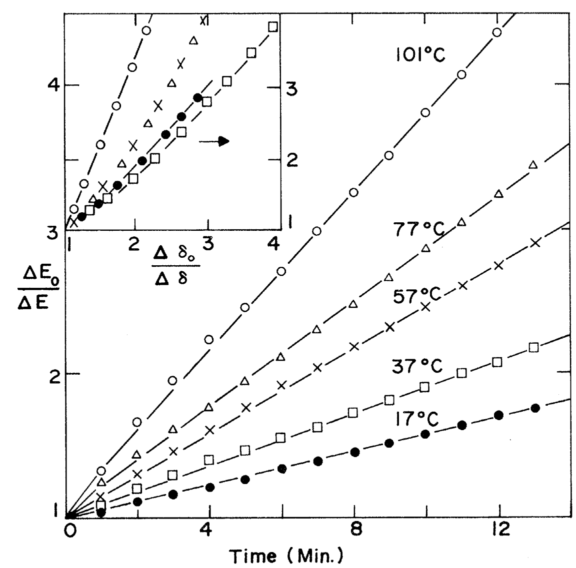

FIG. 1. The normalized inverse modulus defect plotted as a function of time for the indicated temperatures. The sample material was copper (99.9 %) and the production rate was 2.5×10^{10} defects/sec cm^3. The inset shows a plot of the normalized inverse modulus defect Y^{-1} versus the normalized inverse decrement Z^{-1}.

varying the drive by a factor of 6.

The main experimental results, which lead to the conclusion that the usual G-L theory does not extend to these data, are presented in Fig. 1, plots of Y^{-1} versus both time and Z^{-1} for several irradiations. The curves for the lower temperature irradiations are well described by a Y^{-1} (not Y^{-2}) proportionality to Z^{-1}, while a power Y^{-n} proportionality to Z^{-1}, with $n>1$, is better at higher temperatures.[5] Note also the excellent proportionality between Y^{-1} and time, except at initial times, over the range of times shown.

The data of Fig. 1 were obtained using a tough pitch, electrolytic, 99.9% grade copper sample; similar results were obtained using a sample of 99.999% (American Smelting and Refining Co.) purity. Apparently impurities play a minor role in these experiments.

Any hypothesis that the proportionality of Y^{-1} or Z^{-1} on t may be due in some manner to a constant rate of defects accumulated on dislocations by atomic displacements directly in the region of dislocation is ruled out by Fig. 2. Here the sample was irradiated for 22 sec. The beam was then shut off, but the change in Y^{-1} continued with no change in character initially. Clearly diffusion over long distances is involved. This is further implied by a plot of $\ln(dY^{-1}/dt)$ versus inverse temperature which yields a straight line with slope of about 0.17 eV; the implication of this low energy is discussed below.

It is highly reasonable to conclude that dY^{-1}/dt and dZ^{-1}/dt are measures of the rate at which

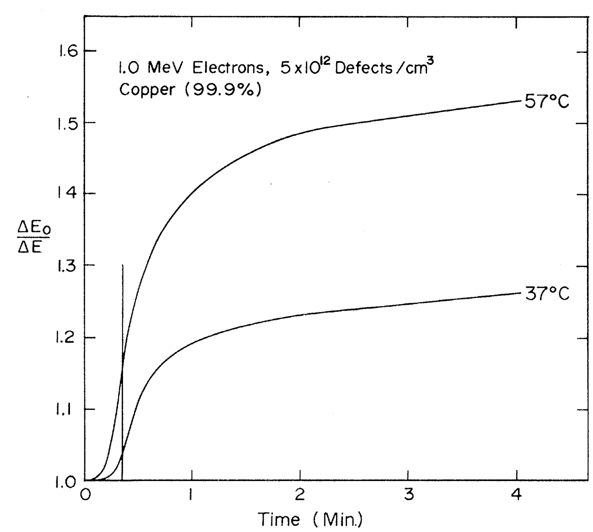

FIG. 2. The normalized inverse modulus defect plotted as a function of time for the indicated temperatures. The vertical line at 22 sec indicates the end of the pulse irradiation.

defects are added to dislocation lines. The relative rates at which defects are added at 1 and 2 MeV (determined in other experiments in this study) are then well predicted by standard radiation-damage displacement cross sections. A theoretical model which we have developed to explain these observations is rather complex. The major feature of our model is that damping of dislocations, on which point defects have accumulated, is determined mainly by the damping characteristics of the point defects being *dragged* with the oscillating dislocation line, rather than with the line friction itself. An extreme limiting case of our model is treated by a force equation

$$(B_0 + nB_d)dy/dt = \sigma b L, \tag{5}$$

where B_d is the damping constant for each of the n dragging points, B_0 is the damping constant appropriate in the absence of point defects, and L is the length of dislocation between firm anchor points (e.g., dislocation nodes). In addition, σ is the applied stress of angular frequency ω:

$$\sigma = \sigma_0 \sin\omega t; \tag{6}$$

$\vec{b}$ is the Burgers vector of the dislocation, y is the displacement of the dislocation from its position in the absence of applied stress, and t is time.

The strain associated with the dislocation motion is

$$\epsilon_{\rm dis} = \Lambda b \bar{y}, \tag{7}$$

and the damping is

$$\delta = \frac{E}{\sigma_0^2}\oint \epsilon_{\rm dis}\, d\sigma = \frac{\pi E \Lambda b^2 L}{\omega(B_0 + nB_d)}. \tag{8}$$

The important features of this model are these: (1) The frequency dependence, ω^{-1}, is inverse to the normal G-L theory, implying that the dragging point effects as formulated here become less important at higher frequency (the full treatment shows that the effect also becomes less important at still lower frequencies); and (2) Z^{-1} increases linearly with the number of dragging points n. The last point explains the general linearity of Z^{-1} with time when cognizance is taken that a steady state is quickly established in these experiments in which the rates of creation of point defects, their arrival at dislocations, and their loss from dislocations are in constant ratio (this can also be demonstrated analytically). The activation energy of 0.17 eV is, we propose, the energy for diffusion of point defects to dislocations minus the energy of migration down dislocations.

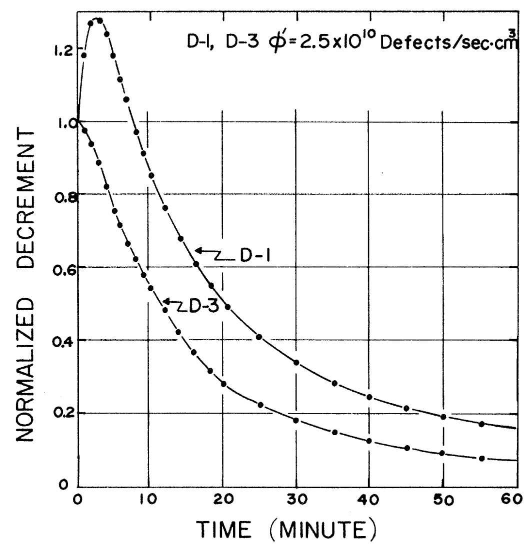

FIG. 3. The decrement normalized to its value at time $t=0$ and plotted as a function of time of irradiation at 290°K. The sample temperature during irradiation, the high-temperature annealing temperature, and the initial decrement are, for *D*-1, $T_{\rm irr}$ =290°K, $T_{\rm anneal}$ =1003°K, $\delta_0 = 2.44\times10^{-3}$; for *D*-3, $T_{\rm irr}$ =290°K, $T_{\rm anneal}$ =1053°K, $\delta_0 = 10.7\times10^{-3}$.

Note that this limiting-case model is inadequate to treat the behavior of the modulus defect since the line tension of the dislocation was ignored in Eq. (6). More complete analysis indicates that Y^{-1} is proportional to time at relatively early times, then becomes even more strongly dependent on time subsequently, with a limiting time dependence of $Y^{-1} \propto t^{3/2}$.

In the usual application of the G-L theory to irradiation experiments, it is assumed that point defects located on dislocation lines serve as firm pinning points, shortening the vibrating lengths of dislocations. Thus both δ and $\Delta E/E$ should decrease with irradiation. The latter is inevitably observed; Fig. 3 shows that δ may *increase* with irradiation.

A 99.999% Cu sample was annealed at 1003°K prior to irradiation, for $\frac{1}{2}$ h (D-1)—a peak in decrement is fully evident—then further annealing at 1053°K for one hour (D-3)—no peak.

We have investigated this "peaking" effect as a function of irradiation temperature, annealing temperature, etc. These results will be presented in a subsequent report. Our full theoretical studies account for this peak quantitatively, but the main features can be understood by the following equalitative argument. Place one point defect on the dislocation. Any significant drag of this point defect by the oscillating dislocation will enhance the amount of energy being dissipated, i.e., increase the decrement. However, as the number of point defects on the line increases, the amount of dislocation motion in oscillation is sufficiently reduced that the dragging of point defects tends to become negligible, i.e., the dragging points become pinning points. The decrement is decreased toward zero. Notice that the modulus defect is continually decreased since the dislocation motion is steadily reduced.

A detailed analysis of the peaking effect shows that it depends on the magnitude of the universal parameter

$$\mu = \omega B_t L^2/2C, \tag{9}$$

where C is the dislocation line tension. For large values of μ, the peaking effect will not be observed. This explains why annealing in the critical temperature range around 1050°K can eliminate the peaking effect. An increase in μ results from an increase in L on annealing. Similarly, the failure of other investigators to observe the peak can be due to their working in a high frequency range (kilohertz and above).

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Experimental Evidence for Proton-Pair Correlation in Ti and Cr Low-Lying Excited States

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The two-proton–transfer reactions ^{44,48}Ca(^{16}O, ^{14}C)^{46,50}Ti and ^{48,50}Ti(^{16}O, ^{14}C)^{50,52}Cr studied at 48-MeV ^{16}O incident energy show that the first excited states must include strong proton-pair components. It appears that the (^{16}O, ^{14}C) two-proton–transfer reaction is a new and useful spectroscopic tool.

A systematic study of the (^{16}O, ^{12}C) reaction in the Ca and Ti region[1] has been performed to investigate the four-nucleon correlations. It has been found that the (^{16}O, ^{14}C) two-proton–transfer reaction competes strongly with α transfer when the Q value is no more negative than a few MeV. The importance in nuclear spectroscopy of transfer reactions involving two identical nucleons, such as (t, p) or (^{3}He, n), does not need to be emphasized. The (^{3}He, n) reactions are experimentally difficult to carry out because of neutron detection. It appears that the (^{16}O, ^{14}C) two-proton transfer using a Van de Graaff tandem accelerator and solid-state detectors can offer an easier approach.

The (^{16}O, ^{14}C) transfer reaction has been studied on ^{44,48}Ca and ^{48,50}Ti targets, using the 48-MeV ^{16}O beam of the Saclay model FN Van de Graaff tandem accelerator. The targets (100 μg/cm^2) are made of separated isotopes on a thin carbon backing. The heavy ions are detected with a two-counter telescope using ORTEC solid-state detectors. The thickness of the ΔE and E counters are, respectively, 20 and 150 μm. The identification and energy measurement of the heavy ions are carried out on-line with the electronic setup described previously.[2] The overall resolution is about 200 keV.

On the particle identification spectra, four groups of emitted particles are selected, corresponding, respectively, to carbon 12, carbon 13 + carbon 14, nitrogen (all masses), and oxygen (all masses). The signature of each isotope in the different groups is clearly established by its reaction kinematics and the relevant energy calibration. Figure 1 shows a typical result obtained with a ^{50}Ti target. The comparison of the three spectra indicates a strong difference in selectivi-