evacuated cryostat near the crystal. Thus it was proved definitely that the peaks are due to condensed films and should not be related in any way to the color centers in the crystal.

The effect of this trap is illustrated in Fig. 1, which is a photocopy of two independent records of the absorption of an uncolored KCl crystal *vs* temperature, on warming the crystal from 90°K to about 500°K. Curve *a* was obtained with the aforementioned trap made ineffective by keeping it at room temperature. It shows the peaks due to condensed vapor films. The main peak at about 225°K corresponds to about 20 percent absorption in this case. (The small regular marks to the lower side of the curve are temperature indictions from 100 to 450°K, every 50°K.)

Curve *b* shows the results of the same measurement repeated but this time with the trap kept at 90°K during warming. No traces are now left of the peaks which appeared in curve *a*. The small slope in the curve seems to be due to a slight increase in the transparency of the crystal with increase in temperature.

The undisturbed curve of the thermal bleaching of *F*-centers in a KCl crystal colored by x-rays at 90°K was now measured with the new arrangement. The trap was kept at 90°K during the time of x-irradiation and during warming after the irradiation, when the absorption of the crystal at 5500 A was continuously recorded as function of time of warming. The rate of heating was kept nearly constant (about 25 deg/min for the range 120–600°K) by suitable adjustment of the power of the heater. A plot of the optical density *vs* temperature, as obtained from this record is given in Fig. 2. No restoration of *F*-centers takes place. The shape of the curve, however, shows that the trapped electrons leave the *F*-centers mainly at several fixed temperature regions, which indicates the existence of several activation energies. These measurements were repeated several times and found to be reproducible. Hesketh and Schneider claim that in their measurements the "peaks" appeared only after *F*-irradiation at 90°K before warming. To check this, a crystal colored at 90°K was partially bleached optically by *F*-light before warming. However, the thermal bleaching curve obtained in this case was essentially the same as in Fig. 2.

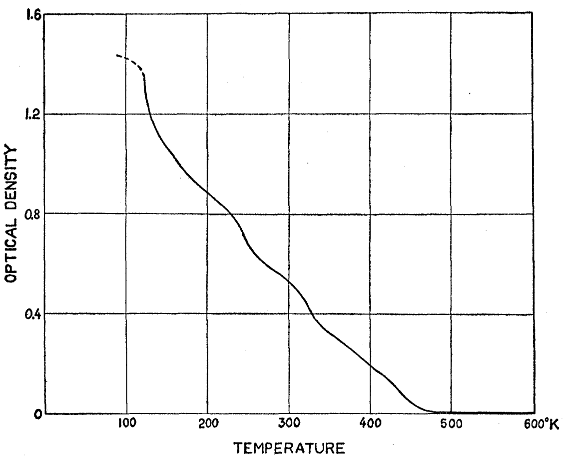

FIG. 2. Thermal bleaching curve of *F*-centers in a colored KCl crystal.

The thermoluminescence of the same crystal colored similarly by x-rays at 90°K was also measured; once with a phototube sensitive in the ultraviolet-blue region as detector, and then with one of maximum sensitivity at about 9000 A. Several luminescence peaks were recorded in these measurements and were found to fit well the temperatures at which *F*-centers are released, as obtained from Fig. 2. Thus, with the "blue" detector the main thermoluminescence peaks were at 220°K and 315°K (in addition to a few minor peaks). With the "red" detector a strong peak was obtained at 450°K and minor peaks at 220 and 350°K.

The existence of several activation energies for *F*-centers in KCl crystals was already reported from thermoluminescence experiments[3,4] and from "current glow curves."[5] The temperatures of the peaks correspond fairly well to those obtained in the present work.

Investigation is being carried on and a fuller account will be published later.

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Dislocation Relaxations at Low Temperatures and the Determination of the Limiting Shearing Stress of a Metal

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RECENTLY, Bordoni[1] has measured attenuation peaks at low temperatures in lead, aluminum, copper, and silver which indicate relaxation effects. Measurements of Bömmel[2] on lead single crystals whose Q^{-1} values are shown by Fig. 1 verify that this is a relaxation effect. Plotting the log of the frequency against the inverse of the absolute temperature, Fig. 2, one determines an activation energy U of 790 calories per mole with a constant $C=2.9\times10^9$ in the equation $\omega_0=Ce^{-U/RT}$.

It is shown that the values obtained agree with a displacement of a dislocation from a minimum energy position in a close-packed glide plane by one atomic spacing against the limiting shearing stress of the crystal. The model considered is one used by Koehler.[3] Dislocations are tied down at irregular intervals by impurity atoms, giving loops of average length l.

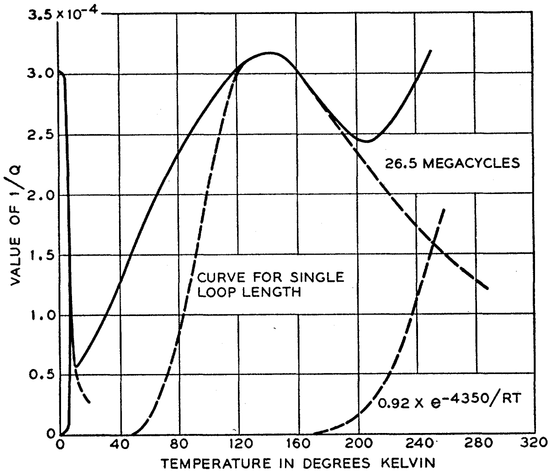

FIG. 1. Internal friction for single-crystal lead at 26.5 Mc/sec. Dot-dash line, theoretical curve for one loop length. Dashed curve —high-temperature attenuation due to breakaways.

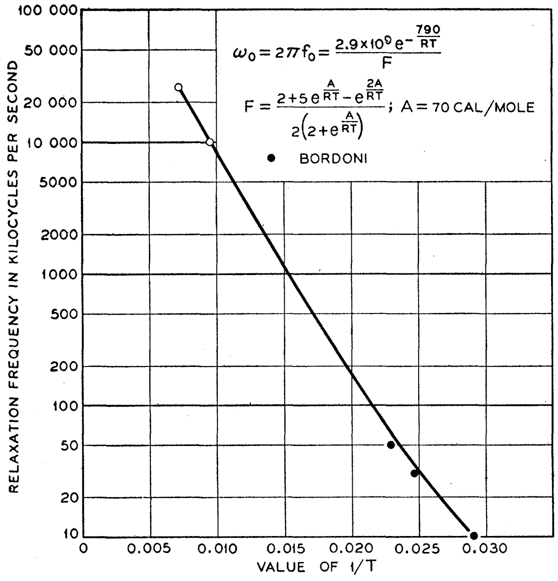

FIG. 2. Semilogarithmic plot of f_0 *versus* $1/T$.

TABLE I. Ratio of limiting shearing stress to elastic shear moduli for four face-centered metals.

Metal	Temp. of max. atten.	Act. energy $H-A$ in cal/mole	b in cm $\times10^8$	μ dynes/cm²	$(T_{13})_0$ dynes/cm²	$(T_{13})_0/\mu$
Pb	35°K	790	3.5	7.0×10^{10}	3.9×10^5	5.5×10^{-6}
Cu	85°K	1910	2.55	4.6×10^{11}	1.75×10^6	3.8×10^{-6}
Al	100°K	2260	2.86	2.5×10^{11}	1.6×10^6	6.4×10^{-6}
Ag	70°K	1580	2.88	2.7×10^{11}	1.1×10^6	4.1×10^{-6}

Thermal agitation causes loops to be displaced to adjacent minimum energy positions against the limiting shearing stress and the force to stretch dislocations. The model, Fig. 3(b), is a straight section connected to the pinning points by "kinks." Direct calculations show that the model results in the potential well arrangement of Fig. 3(c), with the energies

$$H=(T_{13})_0 b^2 l/\pi;\quad A=2b^3[(T_{13})_0\mu/2\pi]^{\frac{1}{2}} \text{ in ergs,} \tag{1}$$

where b is the atomic spacing along the glide plane, l the average loop length, μ the shear elastic constant along the glide plane, and $(T_{13})_0$ the limiting shearing stress. From reaction rate theory, one can show that there is a relaxation having a Q^{-1} given by

$$\frac{1}{Q}=\frac{2e^{-A/RT}}{1+2e^{-A/RT}}\left[\frac{N_0(1-p)b^4l^2\mu}{kT}\right]\left[\frac{\omega/\omega_0}{1+(\omega/\omega_0)^2}\right], \tag{2}$$

where $\omega_0=Ce^{-(H-A)/RT}$, N_0 is the number of loops per cc, and p the percentage of the total loop covered by one "kink." C is 2π times the frequency that the dislocation attacks the barrier H. This should be comparable to the resonant frequency of a dislocation in the potential well given by

$$C=2\pi f=(1/b)[(T_{13})_0/\rho]^{\frac{1}{2}}, \tag{3}$$

which is within a factor of 2.5 of C determined experimentally.

A single-sized loop results in an attenuation curve shown by the dot-dash line of Fig. 1. A distribution of lengths centered around the mean value gives the form of the measured curve. Numerically, using the high temperature attenuation of Fig. 1,

$$l \doteq 4\times10^{-4};$$
$$N_0 l=\text{number of dislocations per sq cm} \doteq 4\times10^6. \tag{4}$$

Table I shows the limiting shearing stress determined from the four measurements of Bordoni using the activation energy determined here for lead, and Eq. (1) for $(H-A)$.

The higher-temperature attenuation whose equation is shown by Fig. 1 results from the temporary unpinning of the pinned points. This allows mechanical energy to interchange between loops and makes the mechanical energy abstracted from the vibration by the loops incoherent. It is readily shown that this results in a loss independent of frequency equal to

$$1/Q=[2(T_{13})_0/\mu]^{\frac{1}{2}}N_0 l b V_s e^{-U/RT}/2\pi, \tag{5}$$

where $N_0e^{-U/RT}$ is the number of unpinned dislocation loops per cc and V_s the shear velocity. Using $N_0l=4$

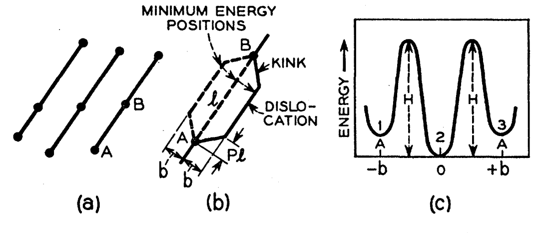

FIG. 3. Proposed model for dislocation relaxation.

$\times 10^6$, $U=4350$ cal/mole, $V_s=8\times 10^4$ cm/sec, a good agreement is obtained with the data. 4350 cal/mole is in good agreement with the binding energy of an impurity atom,[4]

$$U=\tfrac{2}{3}[(1+\sigma)/(1-\sigma)]\mu b^3\epsilon \text{ ergs,} \tag{6}$$

where σ is Poisson's ratio and $\epsilon=(r'-r)/r$ represents the increase in radius of the impurity atom over the normal atom.

It is a pleasure to acknowledge a number of helpful discussions with W. T. Read on dislocation theory.

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Effect of a Centrifugal Field upon the Rate of Transfer through a Helium II Film*

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THE rate of transfer of liquid in helium II films over surfaces is believed[1] to be slightly dependent upon the difference in height between the two levels of liquid helium II. This effect should be greatly magnified if the helium II film is acted upon by a centrifugal field which can be made many times larger than the gravitational field of the earth. An attempt has been made to investigate this effect by observing the transfer through a helium II film creeping from the periphery to the axis in a spinning rotor. The results, while complicated by rotor heating, are believed to be of sufficient interest to report at this time.

The rotor is spun on the lower end of a 60-cm long stainless steel 0.08-cm i.d. thin-walled hypodermic needle tube by an air turbine situated above the apparatus. The rotor contains two radial tubes tightly packed with radial one-mil nichrome wires and is so constructed that the only connection between the axis and periphery is through the channels between the wires. The rotor is surrounded by two concentric cylindrical Dewar flasks. The outer Dewar contains liquid nitrogen, while the inner contains liquid helium. The inner one is so arranged that it can be evacuated. A measured amount of helium slightly above atmospheric pressure is admitted through the hypodermic needle shaft and condenses in the rotor. The inner Dewar is next pumped down until the temperature of the liquid helium surrounding the rotor is below the lambda point. The rotor is always immersed at least 15 cm below the surface of the helium II. The temperature of the liquid helium II inside the rotor is determined approximately by the pressure at the upper end of the hypodermic needle shaft.

When the rotor is spun, a pressure difference is set up between the periphery and the axis. This produces a radial flow of vapor through the small channels between the wires from the axis to the periphery. At the same time, since there is a supply of liquid helium II at the periphery, it creeps toward the axis through the helium II films on the surfaces of the wires. The rotor is so constructed that the helium II cannot move continuously perpendicular to the radius. If the amount of radial flow of gas toward the periphery is greater than the creep of liquid to the axis, the pressure at the axis as measured through the spinning hollow hypodermic needle shaft should fall.

From measurements of the rate of flow of helium through the channels at room temperature the amount of flow of vapor produced by the pressure gradient in the spinning rotor at the low temperature could be calculated. Also the amount of transfer of helium II over the surfaces of the small wires to the axis could be reliably estimated when the rotor was not spinning. It was found that when the rotor (3.5 cm i.d. and 4.45 cm o.d.) was quickly accelerated to a speed between 100 and 140 rps, the pressure at the axis first dropped and then started rising. At these rotor speeds, the mass transfer through the helium II film to the axis should be over 10 times that of the gas flowing from the axis to periphery through the channels, provided that the amount transferred through the film was independent of the centrifugal field. Therefore, the drop in pressure at the axis indicated that the rate of transfer through the helium II film was reduced by the centrifugal field. The later rise in pressure was shown to be due to the heating of the rotor by surface friction produced by the surrounding helium II. At rotor speeds very much below 100 rps the calculated pressure drops produced by the centrifugal fields were too small to measure with precision, while above 140 rps the heating was too rapid for reliable observation. However, there seems to be good evidence that in a centrifugal field of the order of 10^3 times gravity or a centrifugal potential corresponding to a height of the order of 10 meters, the transfer through the film is definitely reduced. The effect, of course, may become appreciable at values below those listed above. It should be noted that radial temperature gradients inside the rotor produced say by evaporation at the axis or heating around the periphery also would produce radial flow of helium II toward the periphery and hence possibly produce a pressure drop. However, the effect of heating at the periphery was greatly reduced by using a double-walled (Dewar-flask-like) rotor with thermal connection near the axis only, while the effect of evaporation is estimated to be small. The writer is much indebted to Dr. J. W. Stewart and Dr. L. G. Hoxton for help with part of the experiment.

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