experimental data because a reasonable choice of activation volume (10^{-20} cm^3) yields the observed result that a factor of 50 change in strain rate does not produce a detectable (1-g/mm^2) change in flow stress. This equation also implies that changes in ρ, d, or ν_0 between the normal and superconducting states are unlikely candidates for an explanation of the flow-stress observations not only because these parameters appear with the logarithmic term, but also because the kT term multiplying the logarithm would introduce a linear temperature dependence that is not consistent with the observations displayed in Fig. 3. This leaves changes in V, U_0, and σ_0 as possible candidates, and it is speculation to attempt to relate these parameters to electron drag at this time.

We are thus led to the following conclusions:

(1) Since the strain rate has little or no effect upon the difference in flow stress between the normal and superconducting states, an explanation based on a simple viscous drag on dislocations as controlling the rate of plastic flow appears to be oversimplified.

(2) The temperature dependence of the additional flow stress in the normal state does not correspond to the temperature dependences of either the BCS energy-gap function or the density of superconducting electrons in the two-fluid model. Instead it follows more nearly the $1-(T/T_c)^2$ dependence of the critical magnetic field.

(3) The electron-dislocation interaction which gives rise to this effect must be rather insensitive to the lattice type because the same qualitative features have now been observed in fcc, face-centered tetragonal, and bcc lattices even though the rate-controlling mechanisms for the plastic flow of these lattice structures are entirely different.

(4) Although high-frequency internal-friction effects[3,6] may still be dominated by electron-drag effects, the present experiments imply that changes in the strength of dislocation pinning may also accompany the transition between the normal and superconducting states.

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ZERO RESISTANCE IN A LONGITUDINAL MAGNETIC FIELD FOR GALLIUM SINGLE CRYSTALS AT LIQUID-HELIUM TEMPERATURES

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A zero resistance has been observed in three single crystals of gallium at liquid-helium temperatures for the case of magnetic field parallel to current parallel to a axis, for fields greater than 2 kG. The onset of zero resistance is insensitive to impurity content as measured by the value of the residual resistance ratio, and to temperature in the range 2 to 4.2°K. The most probable explanation of our results is in terms of magnetic breakdown. Calculation of energy gaps from our data range from 1.4×10^{-2} eV to 4.7×10^{-3} eV, dependent on the effective mass used.

The electronic transport properties of gallium single crystals at liquid-helium temperatures have been extensively investigated in the past several years, both experimentally and theoretically.[1] The present paper describes the results of magnetoresistance measurements in several single crystals of gallium at liquid-helium temperatures and mostly deals with the longitudinal case where a zero resistance has been observed in three crystals, a result not reported before

Table I. Characteristics of crystals. Configuration of current, potential probes and magnetic field: crystal a_1, $B \| J \| a$ axis, potential probe position not known; crystal a_2, $B \| J \| a$ axis, potential probes in b plane; crystal a_3, $B \| J \| a$ axis, potential probes in b plane.

	Length	Width (mm)	Thickness	Distance between potential probes	Resistivity (Ω cm) at temperatures absolute listed 300° (×10⁵)	77° (×10⁶)	20.3° (×10⁸)	4.2° (×10¹⁰)	2.0° (×10¹⁰)	Residual-resistance ratio (10⁻⁵)
Crystal a_1	6.4	1.6	0.8	1.8	1.68	2.87		20	20	12
Crystal a_2	15	2.0	2.0	6.7	1.68	3.00	10.8	9.6	7.2	5.7
Crystal a_3	15	2.0	2.0	5.9	1.70	3.06	11.1	5.5	4.1	3.2

this.

The crystals investigated were grown from either 99.99 or 99.9999% gallium in Plexiglas molds, using the original method developed by Yahia[2] as well as improved methods due to Yaqub and Cochran.[3] The seeding was by oriented crystals, the grown crystal being checked for accuracy of alignment of crystallographic and specimen axes by the use of either a Bragg diffractometer or back Laue reflection photographs; the alignment is, on this basis, of the order of a degree for the crystals used in the measurements. A conventional sample support system and Dewar system was used, the crystals being immersed in liquid helium. The magnetic field was generated by a rotating-base electromagnet with current supplied by a bank of batteries or a regulated power supply (to 1 part in 10^5). Current through the crystals was maintained by a lead cell and regulated by a variable resistor and monitored by a $\frac{1}{4}$% ammeter. The voltages were measured using either a Rubicon Type-D microvolt potentiometer in conjunction with a Rubicon photocell galvanometer amplifier or a Guildline Type-9174 microvolt potentiometer together with a Tinsley photocell galvanometer amplifier Type 5214. The sensitivity of this measuring apparatus was somewhat better than 10^{-8} V, the finest division on the potentiometer. Table I identifies the crystals used as well as giving information with respect to their geometry and the placing of potential and current leads. These were placed on the crystals using the method developed by Yahia.[2] Figure 1 is a plot of the magnetoresistance versus field angle for crystals a_1, a_2, and a_3 and Fig. 2 their field dependence for the case of the magnetic field parallel to the current. It was found, from transverse data, that the magnetoresistance is highly anisotropic for these crystals, reaching enormous values for $B \perp I$: For one crystal, a_3, the fractional change reached the value of 99 000 for a field of 9.7 kG. From the transverse measurements, the magnetoresistance was found to be a quadratic function of magnetic field. For the crystals a_1, a_2, and a_3 these measurements were for the following specific cases: $J \| a$ axis, $B \| c$ axis (crystals a_2 and a_3) and $J \| a$ axis, $B \| b$ axis (crystal a_1). The result that quadratic magnetoresistance is observed for the case $J \| a$ axis, $B \| b$ axis is unexpected. However, measurements on several crystals for this configuration of field and current were made and quadratic behavior observed in each case. For the current parallel to the magnetic field, $\Delta\rho/\rho = -1$. Here $\Delta\rho = \rho(B) - \rho(0)$, $\rho = \rho(0)$, with ρ the resistivity. This can be seen clearly both in the rotation curves, Fig. 1, and the field-dependence curves for the parallel case, Fig. 2. The

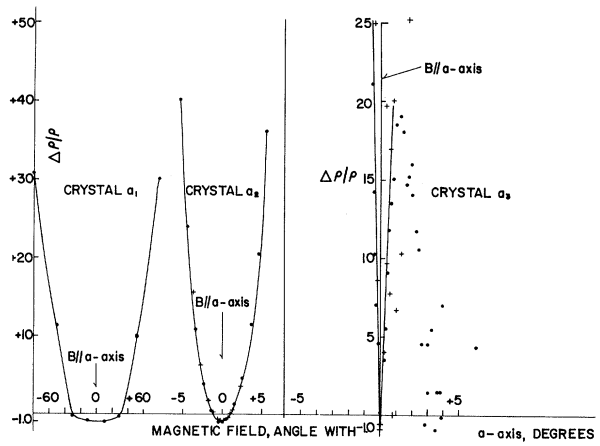

FIG. 1. Variation of magnetoresistance with magnetic-field angle for the three single crystals. For the three crystals, $I \| a$ axis and has the value 5 A. B is 15 kG for crystal a_1 and 6.2 kG for crystals a_2 and a_3. For crystal a_1, rotation of the magnetic field is in the ab plane, and for a_2 and a_3 it is in the ac plane. Points shown by closed circles are data at 4.2°K and those shown by crosses, data at 2°K. Note the change of angular scale between the plots for crystals a_1, a_2, a_3, and the change in magnetoresistance scale between a_3 on the one hand and a_1 and a_2 on the other. The sharp variation of $\Delta\rho/\rho$ with angle is notable for crystals a_2 and a_3. Crystal a_3 exhibits a structure with several minima which was absent in the other two crystals.

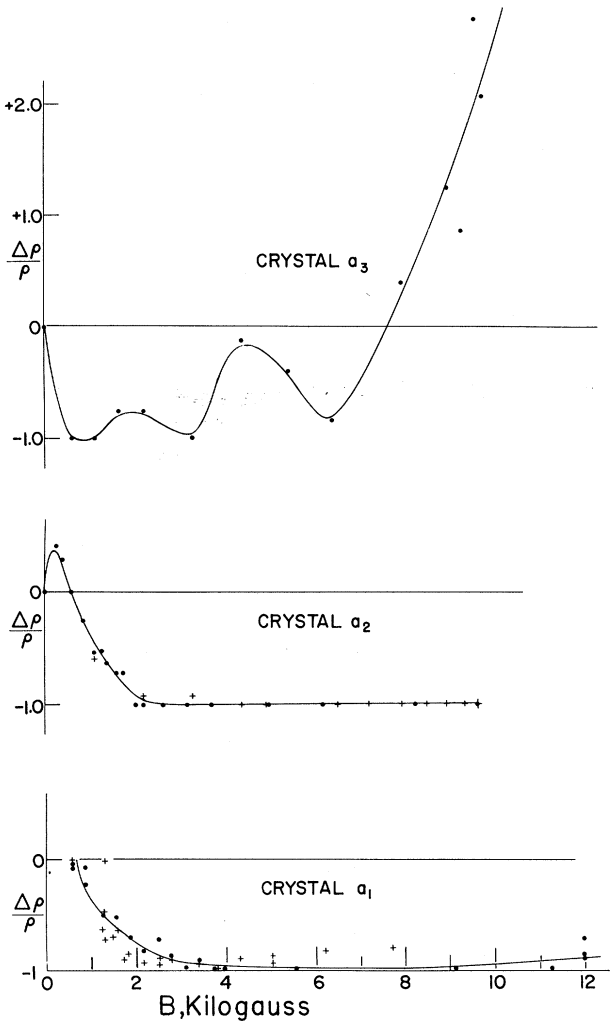

FIG. 2. Field dependence of the magnetoresistance for the longitudinal case, $I \parallel B \parallel a$ axis, for the three single crystals reported on. Current I is 5 A for each case. Data points marked by closed circles are for the temperature of 4.2°K, those marked by crosses are at 2°K. The field dependence for a_3 was measured for the position of magnetic field corresponding to the principal minimum shown in Fig. 1.

parallelism between the current and the magnetic field is critical for a_2 and a_3 but not for a_1. Rotation of the magnetic field is in the ab plane for a_1 and the ac plane for a_2 and a_3, and this fact probably explains both the differences in anisotropy that were observed and sensitivity to angle between these crystals. The longitudinal magnetoresistance in these crystals has all the appearance of superconductivity: A reversal of current of several amperes (typically 5) through the crystal does not change the potential read on the potential probes, as to either sign or magnitude. It is clear that, under these circumstances, what is being measured are the extraneous (but even in current) emf's in the circuit and that the resistive voltage is zero. This phenomenon cannot be one of superconductivity, however, as it takes the presence of a magnetic field to produce it: In the absence of the field the resistance is finite. The application of the field alters the situation in that the resistance is zero, to the highest fields used in the measurements. Crystals a_1 and a_2 show this the most clearly.

To determine the temperature dependence of the phenomenon, measurements were made at pumped-helium temperatures for a_1, a_2, and a_3 and at liquid-hydrogen temperatures for a_2 and a_3. It was found that at 20.3°K, all unusual behavior was absent and the data obtained suggested strongly that large numbers of phonons were present and giving the main contribution to the scattering. These data are not included here for the sake of brevity. Figure 2 shows that there is no appreciable difference in behavior of the crystals as one changes the temperature in the range 4.2 to 2.0°K. Table I shows that the zero-field resistance of the samples does not change greatly on going to lower temperatures in the liquid-helium range, inplying a saturation impurity resistance at these temperatures.

A negative magnetoresistance of reasonable size (i.e., $\Delta\rho/\rho > -1$, but still negative) has been observed in a number of metals, including gallium.[4] The usual explanation of this decrease in resistance has been by considering size effects to be important. If a large part of the scattering is assumed to come from surface reflections, and this would be the case when $\lambda/a \sim 1$ with λ the mean free path and a a cross section of the crystal, then a magnetic field parallel to the current would decrease the resistivity, the reason for this being that the field would tend to keep the electrons from hitting the surface and thereby eliminate a large part of the scattering. However, this would eliminate at most the part due to reflections and this model cannot give a resistance of zero as observed in the present measurements. This explanation also fails to account for the fact that the zero resistance has been observed for only the case $I \| B \| a$ axis. Discussions of negative longitudinal magnetoresistance along the lines of a size effect have been given by many authors.[4] Another explanation of a zero resistance assumes, as for the size-effect explanation, that the effect is not a fundamental property of the crystal.[5] The theory predicts that in some cases a redistribution of cur-

rent flow lines in a crystal will take place, such that these do not pass by the potential probes used to make the resistance measurement. Such an explanation for our observations appears inappropriate due to the following: A zero resistance would, on this hypothesis, be observed for the case $J \| b$ axis, potential probes in the c plane. For two of our crystals, we have just such a configuration and find a saturating positive magnetoresistance, in disagreement with the foregoing. Also, the potential probes on two crystals (a_2 and a_3) are in the b plane with the current in the a direction, which, on the anisotropy hypothesis would give $V \neq 0$. Here, also, the prediction runs contrary to the measurements. Finally, it would appear that the relative dimensions of crystal length and potential probe separation (Fig. 1) would preclude an unusual current distribution. Argyres and Adams,[6] in a theory of the longitudinal magnetoresistance, show that under certain circumstances, a negative magnetoresistance is to be expected. For this to occur, ionized impurity scattering is taken to be the dominant scattering mechanism and their calculations show that the magnetic field shortens the screening length of their screened potential leading to an increase in conductivity. There is also a modification, due to the field, of the density of charge carriers: This density is greater in the presence than in the absence of the field thus increasing the conductivity for the case where a field is applied. It does not appear, however, that this theory can account for our results, firstly because the conditions of its applicability are not met in the experiment: The Fermi energy is taken to be very small as in a semiconductor like InSb. In gallium, the Fermi energy is large, 5.4 eV.[7] Secondly, a zero resistance would imply a drastic shortening of the screening length and increase in number of carriers due to the application of the field. Thirdly, and most importantly, if this theory were to be the correct interpretation of our results, then one should see zero resistance in all the crystals measured (nine in all). As has been mentioned, only for the a-direction crystals has this been observed. One would not expect impurity scattering considerations to include anisotropies, that is, one would expect to see zero resistance in an a, b, or c crystal on this model.

The most probable explanation of our results, and the one proposed here, is that the zero resistance is due to magnetic breakdown. It is not unlikely that such effects will appear in gallium at 4.2°K: Indeed, observations in de Haas–van Alphen data and in resonance data have been interpreted on this basis.[8] The condition for the occurrence of magnetic breakdown (MB) is[9]

$$\hbar\omega_0 E_0 \gamma \cong \Delta^2,$$

where γ is a numerical factor, Δ an energy gap, E_0 the Fermi energy, and $\omega_0 = eH/mc$. Effective masses in gallium have a range of values, all fractions of the free electron mass and some rather small. These have been determined, for example, from de Haas–van Alphen measurements[10] or cyclotron-resonance measurements.[11] The mass factor alone cannot be responsible for observation of MB (note that the effect is enhanced by the presence of small masses) in our case, for then observation of zero resistance would not be limited to only one alignment of magnetic field with respect to current axis: $I \| B \| a$ axis. The separation between the two energy bands where transitions by MB are occurring comes into play, and it is the combination of these two factors in the proper way that gives the effect for the a axis only. We have noted that our observations of zero resistance are not affected either by temperature or by impurities in the crystals, a further indication that the principal scattering mechanism for electrons is one of MB at these temperatures. In such an essentially tunneling process, the intrinsic relaxation time may be considered to be infinite.[9]

If the dominant transport process is taken to be one involving MB, then our data can be used to calculate a value for the band gap Δ. The breakdown field is taken to be about 2000 G using our data and the Fermi energy 5.4 eV.[7] Furthermore, the values for the effective masses are taken from the cyclotron resonance measurements of Moore.[11] These range in value from $m^*/m_0 = 0.0973$ to $m^*/m_0 = 0.896$. The band gap is found to have values in the range 1.4×10^{-2} to 4.7×10^{-3} eV, using the expression giving the condition for the occurrence of MB. The calculations of Wood[7] show the possibility of the existence of such gaps between the different bands in gallium. Also, from his cyclotron-resonance data, Moore[8] has calculated an approximate figure for a band gap, which figure turns out to be 1.2×10^{-2} eV.

An interesting sidelight on the question of zero resistance is afforded by the work of Titeica.[12] This work shows that such a zero resistance is possible, under contions strikingly similar, formally, to those for MB. The theory of Titeica

assumes a large Fermi energy and scattering by acoustic modes only. For the high-field longitudinal magnetoresistance, $\hbar\omega_0 \gtrsim E_0$, the expression is

$$\frac{\Delta\rho}{\rho} = 4.24\frac{mw^2}{kT}\left\{\frac{I_{9/2}}{I_5}\frac{\hbar\omega_0}{kT} - \frac{1}{2}\frac{kT}{mw^2}\frac{I_{13/2}}{I_5}\right\} - 1.$$

I_μ is an integral of the form $\int_0^{\theta/T}[\xi^\mu e^\xi d\xi/(e^\xi-1)^2]$ and since $\theta = 125°K$ [13] for gallium, these integrals are readily evaluated giving numerical factors in the above expression. w is the velocity of sound. One finds, for the case where $\Delta\rho/\rho = -1$, that the following condition must be met:

$$\hbar\omega_0 mw^2(I_{9/2}/I_{13/2})2 = (kT)^2.$$

This expression is strikingly similar to the condition for MB, only the symbols differ. In MB, for tunneling processes to occur, a product of two characteristic energies must equal the square of a third: Magnetic energy times Fermi energy equals the band gap squared. In the Titeica theory, to obtain zero longitudinal resistance, the product of magnetic energy and phonon energy must equal the square of thermal energy. These are the characteristic energies in his theory and it is not surprising that a condition like the one given is obtained. In this case, zero resistance appears to be a resonance phenomenon, brought about by the phonons. Note that the Titeica theory will not explain our results, whereas MB does. It would be interesting to see if, for a critical temperature, it is possible to obtain conditions under which the Titeica predictions would be realized. It is a fact that at 20.3°K, we have not observed any such zero resistance.

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EFFECT OF DEEP TRAPS ON THE BARRIER HEIGHTS OF METAL-INSULATOR-METAL TUNNEL JUNCTIONS

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It is shown that the potential barrier φ_{max} in a thin-film metal-insulator-metal system increases rapidly with increasing insulator thickness when electrons are immobilized in deep traps in the insulator, and at low voltage biases $d\varphi_{max}/dV$ is independent of the insulator parameters. This effect may be an explanation of the observations of Lewicki and Mead.

Photoemissive measurements[1] of the barrier heights in thin-film Al-AlN-Mg tunnel junctions have shown that the barrier heights increase with increasing insulator thickness in the (measured) range 40-100 Å of insulator thickness. It is the object of this communication to offer a possible explanation for this phenomenon which when extended also accounts for the rate of decrease of