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ON THE EVIDENCE FOR ELECTRON–ELECTRON SCATTERING IN THE ELECTRICAL RESISTIVITY OF In

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Experimental measurements of the electrical magnetoresistivity of high purity Indium at low temperatures have been performed and clearly indicate that:

(a) A generalized Kohler's rule can be used to describe all experiments.
(b) A reliable method is therefore obtained for extrapolating the zero magnetic field resistivity to temperatures below the superconducting transition temperature.
(c) Clear-cut and reliable data show that no T^2 dependence of the resistance is found; therefore no evidence of electron–electron interaction appears, contrary to information previously reported in the literature.

THE PURPOSE of this paper is to report that a generalized Kohler's rule, similar to that proposed by Jones and Sondheimer,[1] holds for the magnetoresistance of very pure Indium.

This provides a reliable method for extrapolating the resistivity at zero field, which shows clearly a T^5 dependence with temperature and no detectable T^2 term.

Previously reported measurements by Garland and Bowers[2] suggested that electron–electron interactions can be detected in the transport properties of In, as seen by a T^2 dependence at the zero field resistivity. They obtained this result by assuming the validity of Kohler's rule in their extrapolation of the magnetoresistance to zero field. Our high precision measurements, which agree with later work by Garland and Bowers,[3] show strong deviations from Kohler's rule. If, nevertheless, the zero field resistivity is extrapolated from fields larger that H_c to $H = 0$ (by means of Kohler's rule and with coefficients obtained from measurements at one temperature higher than T_c), then a strong spurious deviation from the T^5 law appears. This might be wrongly interpreted as due to electron–electron interactions (see Fig. 4).

SAMPLE PREPARATION

The experimental details are similar to those described in reference 4 and the ingot from which our sample was cut was also the same. The sample was rolled between Teflon sheets to $2.5 \times 5 \times 160$ mm. From this, two samples (A and B) of $1.5 \times 2.5 \times 150$ mm. were obtained. Sample A was irradiated during 50 min in a flux of 1.8×10^{12} ther-neut/cm^{2}sec.

After two months the sample was annealed during 24 hs. at 120°C. Sample B was also annealed at 50°C during 24 hr. This is an extremely clean method of doping In with Sn in the range of a few ppm. since the defects created in the process are eliminated after annealing.

Activation methods measurements were used to determine the amount of Sn introduced which was found to be close to 0.3 ppm, which is the same order of that obtained from residual resistance ratios.[5] The resistivity ratio from room temperature to 0°K was then 0.72×10^5 for sample A and 1.0×10^5 for sample B.

METHOD OF MEASUREMENT

The electrical measurements were made by sending a constant current through the sample and measureing the voltage drop. The current was measured with an Ernest Turner A – meter. The voltage was measured with a Keithlay 148 nanovoltmeter and the output was amplified and recorded. The temperature was measured with the Bourdon tube method in a Texas precision pressure gauge. The linearity of the magnetic field was checked with two Hall effect Ball Hall-Pak B H–203 probes.

The electrical resistivity measurements were made, at constant magnetic field, with an absolute error at each point of 0.6%.

EXPERIMENTAL RESULTS

The magnetoresistance of sample A was measured for eight different temperatures above T_c, with fields up to 10 kOe. Fig. 1 shows

$$\frac{\rho(H,T) - \rho(O,T)}{\rho(O,T)} \text{ vs. } H/\rho(O,T).$$

It is worth emphasizing that $\rho(O,T)$ for these temperatures is obtained experimentally. It can be seen from Fig. 1 that large deviations from Kohler's rule occur, since if the rule were obeyed all the points should be on a single curve.

A feature worth noticing is that there is no saturation of the magnetoresistance at high fields. Similar results have been obtained by Garland and Bowers[3] in magnetic fields of the order of 100 kOe, which are higher than those used by us. However, since our samples have a smaller residual resistivity and $H/\rho(O,T)$ is the relevant variable of the problem we infer that we are observing the same phenomenon.

If we assume a generalized Kohler's rule similar to that proposed by Jones and Sondheimer[1]

$$\frac{\rho(H,T) - \rho(O,T)}{g.\rho(O,T)} = F\left[\frac{H}{g.\rho(O,T)}\right] \quad (1)$$

where g is an arbitrary parameter, it is possible to superimpose log–log plots of

$$\frac{\rho(H,T) - \rho(O,T)}{\rho(O,T)} \text{ vs. } H/\rho(O,T)$$

for different emperatures, by displacing them along a 45° axis. This procedure is a graphical way of determining the parameter of g of Equation (1). The results are shown in Fig. 2 as circles.

The magnetoresistance at twenty six different values of temperature between 1.34°K and T_c was also measured. Log–log graphs of

$$\frac{\rho(H,T) - \rho(O,T)}{\rho(O,T)} \text{ vs. } H/\rho(O,T)$$

were made for each temperature and for various assumed values of $\rho(O,T)$. It was found that for each T, there was one curve, corresponding to a particular value of $\rho(O,T)$, which could be superimposed by 45° displacement to that obtained for $T > T_c$.

The success of this procedure confirms the validity of formula (1) and provides a method of extrapolation to find $\rho(O,T)$ with an accuracy of 2%. Several points taken at random from the $T < T_c$ curves are shown as triangles in Fig. 2 to illustrate the validity of the rule.

The value of the 45 degree displacements give the values of the ratio $g(T)/g(To)$ where To is an arbitrary reference temperature. They are shown in Fig. 3.

Similar measurements were made for sample B. They are indicated by squares in Fig. 2. The fact that the same curves fit the measurements in the two samples, suggests that the validity of the rule[1] can be extended to samples of different purities. Values of $g(T)/G(\text{To})$ for both samples are also shown in Fig. 3, where the full line corresponds to $g = a.T^b$.

A least squares fitting gives $b = 1.58$.

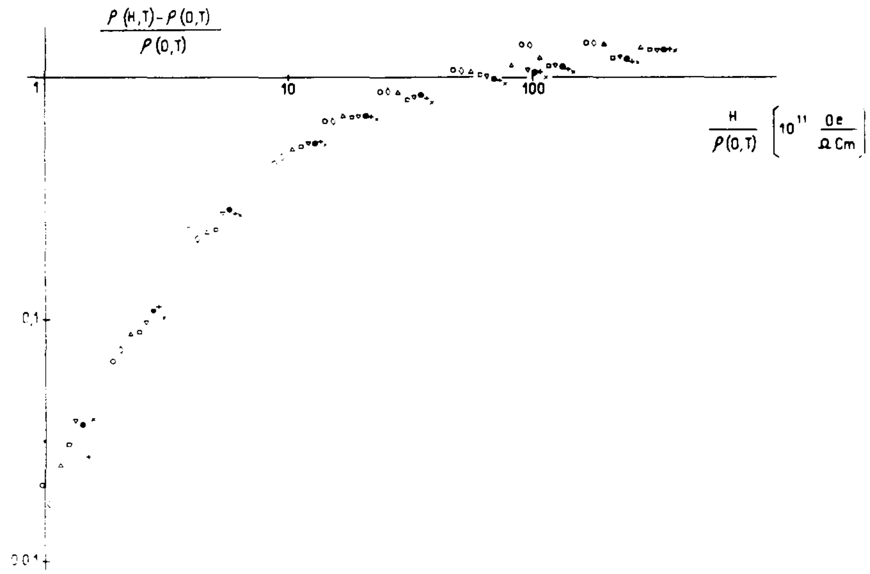

FIG. 1. Log–log plot of $\frac{\rho(H,T)-\rho(O,T)}{\rho(O,T)}$ vs. $\frac{H}{\rho(O,T)}$ for eight temperatures. Sample A. T in degrees Kelvin

o → $T = 4.07$, ◇ → $T = 3.98$, Δ → $T = 3.76$, □ → $T = 3.75$,
∇ → $T = 3.67$, O → $T = 3.59$, + → $T = 3.51$, X → $T = 3.43$.

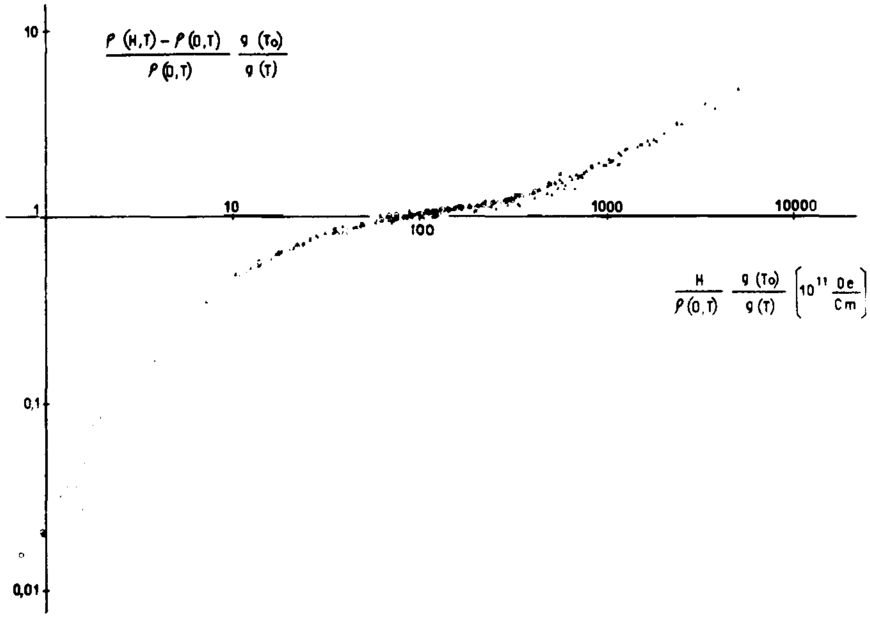

FIG. 2. Superposition of log–log plots $\frac{\rho(H,T)-\rho(O,T)}{\rho(O.T)}$ vs. $H/\rho(O,T)$ by 45° displacements.

O correspond to $T > Tc$, sample A.
Δ correspond to $T < Tc$, sample A.
□ correspond to sample B.

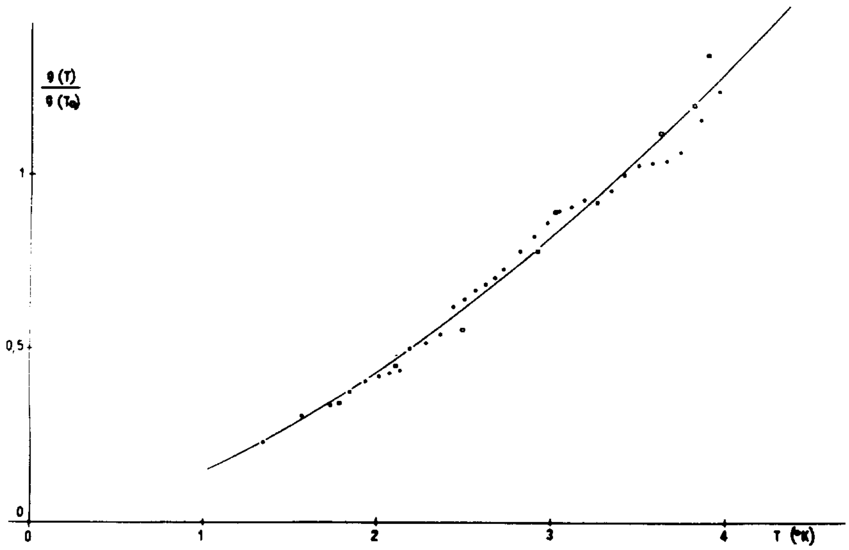

FIG. 3. $g(T)/g(To)$ vs. T, full line is aT^b, with $a = 0.1439$, $b = 1.579$.
□ = sample B
O = sample A

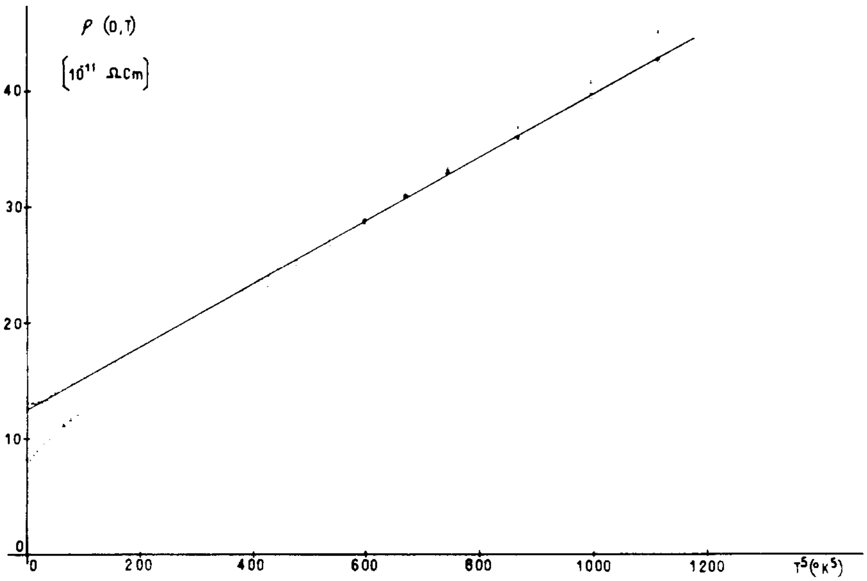

FIG. 4. $\rho(O,T)$ vs. T^5:
O = observed values for $T > Tc$
◇ = extrapolated values using the generalized rule
Δ = extrapolated values using Kohler's rule.

DISCUSSION

The theory of Jones and Sondheimer is based on the assumption that the scattering probability can be expressed in the following way

$$\rho(\vec{k}, \vec{k}) = \alpha\rho_0(\vec{k}, \vec{k}) + \beta\rho_1(\vec{k}, \vec{k}) \qquad (2)$$

where α and β may be functions of temperature and purity but are independent of $\vec{k}$ and $\vec{k}'$.

The general result is that each component of the resistivity tensor is of the form $\alpha.f(H/\alpha, \beta/\alpha)$.

In the particular case that $\rho_1(\vec{k}, \vec{k}') = \vec{v}.\vec{v}'$ it is possible to show that the magnetoresistivity is given by equation (1), were $g(T)$ is a function of the parameters α and β. If the magnetoresistivity saturates, i.e. $\rho(\infty, T)$ is finite, $g(T)$ becomes

$$\frac{\rho(\infty, t) - \rho(O, T)}{\rho(O, T)}$$

It is worth pointing out that in general $g(T)$ should be a function of purity. However, as previously mentioned, our results indicate that this is not the case.

Using equation (1) to extrapolate the magnetoresistivity to temperatures below Tc the usual temperature dependence of the form

$$\rho = \rho_0 + AT^5$$

was found. This as is usual, is interpreted as being due to scattering by impurities and phonons respectively. We may thus assert that the low temperature behavior of the resistivity in In shows no indication of a T^2 term, i.e. no evidence for electron–electron scattering effects are observed.

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REFERENCES

1. JONES M.C. and SONDHEIMER E.H., *Phys. Lett.* 11, 122 (1969).
2. GARLAND J.C. and BOWERS R., *Phys. Rev. Lett.* 21, 1007 (1968).
3. GARLAND J.C. and BOWERS R., *Phys. Rev.* 188, 1121 (1969).
4. DE LA CRUZ M.E., DE LA CRUZ F., COTIGNOLA J.M., BRESSAN O.J. and LUENGO C.A., *Phys. Rev.* 176, 871 (1969).
5. MERRIAM M.F., LIU S.H. and SERAPHIM D.P., *Phys. Rev.* 136, 17 (1964).

Des mesures de la magnétorésistivité électrique, aux basses témpératures, de l'indium très pure, ont été effectúees et indiquent clairement que:

(a) Une règle généralisée de Kohler peut être utilisée pour expliquer tous les résultats.

(b) Une méthode sûre d'extrapolation de la résistivité, sans champ magnétique, à des températures inférieures à la température de transition du superconducteur peut être obtenue.

(c) Un court raisonnement et des données sûres montrent qu'il n'existe pas de dépendence en T^2 de la résistance, c'est-a-dire que l'interaction électron–électron n'est pas évidente, contrairement a une précédente information parue dans la littérature.