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EXCHANGE SCATTERING IN SUPERCONDUCTORS

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In a recent letter,[1] Anderson and Legvold have suggested that the depression of the superconducting transition temperature of lanthanum as a function of rare earth impurity content[2] may be traced to the exchange interaction between the conduction electron spins and the f-shell spins of the rare earth ions. They postulate that the conduction electrons interact via the ionic spins to modify the effective "V" in the theory of Bardeen, Cooper, and Schrieffer. We wish to comment on this view in the light of theories by Herring and by ourselves, previously presented orally[3,4] and by now submitted for publication in detail, and in the light of the further experiments reported by Matthias, Suhl, and Corenzwit.[5]

Electron interaction via virtual states of the scatterers (in the present case the ionic spins) can occur only if these are nondegenerate in energy. In the case of gadolinium, the various spin orientations are very nearly degenerate, since its closed-shell configuration admits of very little crystal field splitting, and the effective electronic interaction is therefore likely to be very small. This point is further borne out by the experiments of Lynton, Serin, and Zucker[6] with nonmagnetic impurities, which also depress the transition temperature, yet interactions via virtual states of the scatterer are here essentially ruled out.

To summarize our own view, we begin with the magnetic impurities. We believe that the effect is indeed due to exchange scattering. However, the depression of T_c seems to us to result from the fact that the scattering lowers the energy of the normal state more than that of the superconducting state. Adopting the Bardeen-Cooper-Schrieffer view of the superconducting state, we find that those scatterings in which one or both of the initial and final momentum states are within the gap contribute more to the depression of the energy of the normal state than to the depression of the energy of the superconducting state. The result is that as the impurity concentration is increased, the free energies of normal and superconducting states become equal, while the gap remains finite. A plot of transition temperature T_c versus impurity concentration ξ will not give a straight line but rather a convex curve with $dT_c/d\xi = 0$ at $\xi = 0$ and $dT_c/d\xi = \infty$ at $T_c = 0$. The value of the exchange integral required to account for the depression of T_c to absolute zero by the observed concentration of gadolinium in lanthanum is 0.15 volt, a reasonable value. As regards the shape of the curve, all cases, the newly measured ones (reference 5) as well as the (La, Gd) case seem to tend towards vertical tangency as $T \to 0$, in accord with the above predictions and at variance with a "shifted V" theory. A possible reason why at $\xi = 0$ the tangents to the $T_c - \xi$ curves are not zero will become clear in connection with our next topic, scattering by nonmagnetic impurities. In that case, we find that the free energies of the normal and superconducting states are depressed much more nearly equally; for the same magnitude of the scattering potential, the difference is an order of magnitude less than in the exchange case. The difference then has the same form that one would have obtained, had one assumed the Bardeen-Cooper-Schrieffer expression for the free-energy difference in the impure sample, and attributed the change in this difference to a reduction in the effective interaction potential. This change is effectively a consequence of the modification of the electron wave functions by the impurities. Thus it could happen in the nonmagnetic case, that the free-energy difference goes to zero by virtue of the gap going to zero with increasing concentration. Whether this is the case, or whether the difference goes to zero before the gap does, is now a question of detailed evaluation. In the exchange case there is also such a shift in effective V, but there its effects can be important only along a short initial stretch of the T-ξ curve, where $dT/d\xi$ tends to zero, while the shift in V produces a small but finite initial slope.

To summarize: If the Bardeen, Cooper, and Schrieffer theory of superconductivity is correct in its present form, the most important cause of the depression of T_c by exchange scattering is the disparity in the free-energy depressions of the normal and superconducting states. "Shifted V" effects, whether due to changes in wave function or due to electron interactions via virtual states (even when they can occur), are small by comparison. The exchange energy between conduction electrons and ionic spins necessary to account for the observed reductions in T_c on the basis of our viewpoint is 0.15 volt, a reasonable value.

The authors are indebted to C. Herring for frequent discussions of our work on this subject.

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EFFECT OF HYDROSTATIC PRESSURE ON THE ANOMALOUS HALL COEFFICIENT REVERSAL IN SINGLE CRYSTAL TELLURIUM

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Pure tellurium in the extrinsic range is a *p*-type semiconductor, and its Hall coefficient reverses sign in the vicinity of room temperature in the usual fashion. There is a second reversal[1] of the Hall coefficient back to *p*-type at approximately 230°C. This anomalous reversal has been most recently verified on crystals grown by the Bridgman method by Fukuroi et al.,[2] Bottom,[3] and Nussbaum.[4] It is further shown by Fukuroi et al. and Bottom that the upper reversal temperature is independent of sample purity for their particular samples. Explanations of this phenomenon have been advanced by Fritzsche,[5] Fukuroi et al.,[2] and Callen,[6] but exceptions have been taken to some of their arguments by Gáspár[7] and Dresselhaus.[8] An effort was made by Nussbaum[9] to gain an insight into the effect of a change in lattice size on the band structure of tellurium by measuring the shift in upper reversal temperature when hydrostatic pressure was applied. This experiment was performed on the alloy 87% Te - 13% Se, whose upper reversal temperature is 177°C. Due to apparatus limitations the results were inconclusive.

Recently, large single crystals of tellurium have been grown in this laboratory by the Czochralski method.[10] These crystals are an order of magnitude purer[11] than any previously available. Pressure apparatus with a range of 0 - 30 000 lb/in^2, as previously used by Long,[12] was kindly made available to us by J. Taylor, Morgan State College. Hall coefficient vs temperature was measured at atmospheric and at 30 000 lb/in^2 pressure on samples cut from two different crystals and oriented with the *c*-axis (3-fold axis) normal to the magnetic field. The results as shown in Fig. 1 indicate (1) that the upper reversal temperature is 246°C, which is about 15°C higher than has been previously reported, and (2) that the effect of pressure is to raise the re-

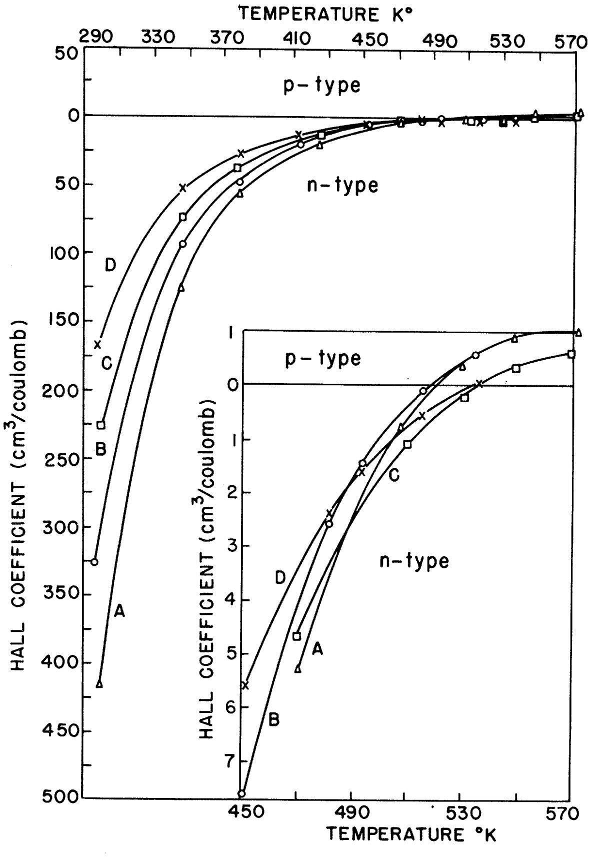

FIG. 1. Hall coefficient vs temperature for single-crystal tellurium. The inset shows the region near the anomalous reversal using an expanded scale. Curve A: Sample No. 1 at atmospheric pressure; Curve B: Sample No. 2 at atmospheric pressure; Curve C: Sample No. 1 at 2000 atmospheres pressure; Curve D: Sample No. 2 at 2000 atmospheres pressure.