be temperature independent. However, the $T = 0.07$°K data alone are fit quite well by $-\Delta\rho_S/\rho_0 = 0.28B_{\frac{3}{2}}^2(H/(T+\theta))$, with $g = 2$ and $\theta = 1.05 \pm 0.1$°K. Another possible form for $M(H)$ at $T \ll T_K$ has been given by Nam and Woo.[4] To fit the higher-temperature data, it would be necessary to let θ increase with temperature, as happens in Cu(Fe). A more detailed understanding of whether the behavior of the magnetoresistance is simply related to M^2 awaits suitable low-temperature measurements of the magnetization of very dilute Cu(Cr) alloys, and/or the results of theoretical calculations currently in progress. The present data do, however, indicate that T_K is between 0.4 and 0.9°K and that Cu(Cr) is a nearly ideal system for study of the quasibound state phenomenon. These results show that the d-wave scattering must be taken into account in any comprehensive theory of the Kondo effect.

The authors wish to acknowledge the expert assistance of Dr. W. P. Pratt in taking these measurements.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

[1]D. R. Hamann, Phys. Rev. 158, 570 (1967).
[2]P. E. Bloomfield and D. R. Hamann, to be published.
[3]H. Suhl and D. Wong, Physics (N.Y.) 3, 17 (1967).
[4]S. B. Nam and J. W. F. Woo, Phys. Rev. Letters 19, 649 (1967).
[5]M.-T. Béal-Monod and R. A. Weiner, to be published.
[6]J. R. Schrieffer, J. Appl. Phys. 38, 1143 (1967).
[7]M. D. Daybell, Rev. Sci. Instr. 38, 1412 (1967).
[8]M. D. Daybell and W. A. Steyert, Phys. Rev. Letters 18, 398 (1967).
[9]U. Herbst and D. Wagner, to be published.
[10]A. Kjekshus and W. B. Pearson, Can. J. Phys. 40, 98 (1962).
[11]G. Borelius, W. H. Keesom, C. H. Johansson, and J. O. Linde, Commun. Kamerlingh Onnes Lab. Univ. Leiden 217e, 34 (1932).
[12]P. Monod and S. Schultz, private communication.
[13]L. Creveling, private communication.
[14]K. Yosida, Phys. Rev. 107, 396 (1957).
[15]P. Monod, Phys. Rev. Letters 19, 1113 (1967).
[16]F. Hedgcock, W. B. Muir, T. Raudorf, and R. Szmidt, to be published.
[17]L. Dworin, private communication.
[18]M. D. Daybell and W. A. Steyert, to be published.
[19]C. M. Hurd, Phys. Rev. Letters 18, 1127 (1967).

SUPERCONDUCTIVITY OF RHENIUM AND SOME RHENIUM-OSMIUM ALLOYS AT HIGH PRESSURE*

C. W. Chu, T. F. Smith,† and W. E. Gardner‡
Institute for the Study of Matter, Department of Physics,
University of California, San Diego, La Jolla, California
(Received 20 July 1967)

We have measured the pressure dependence of the superconducting transition temperature (T_c) of single crystal and polycrystal samples of rhenium and a number of Re-Os solid solutions. In contrast to the nearly linear dependence of T_c on pressure observed at low pressures for the majority of superconductors, the T_c of rhenium exhibits an anomalous behavior under pressure. This behavior was rapidly destroyed by the addition of small amounts of Os (>0.2 at.%). We attribute this unusual behavior of T_c under pressure to a change of the Fermi-surface topology of the type proposed by Lifshitz.[1] We find $T_c = 1.694 \pm 0.002$°K at atmospheric pressure which is in excellent agreement with the values reported by Hulm and Goodman[2] and Blanpain,[3] and we find that at low pressures $\partial T_c/\partial P = (-2.3 \pm 0.1) \times 10^{-6}$ °K bar^{-1}, a value which is a little larger than that reported by Olsen et al.[4]

Measurements were made on samples cut from Materials Research Corporation (MRC) Grade 1 (zone-refined, 99.9 wt% purity, with major impurities given in ppm by weight as Fe 3.0, Ni 0.3, Nb 1.2, Mo 4.0, Ta 3.0, and W 15.0) polycrystalline and single-crystal Re. Now the sharpness of the superconducting transition in Re is extremely sensitive to plastic deformation and internal strain.[5] Thus samples cut directly from the "as received" material had extremely broad transitions, starting as high as 3°K, with a sharp step at ~1.7°K. An accurate determination of the pressure dependence of T_c would be impossible with such broad transitions and, therefore, it was necessary to reduce considerably the width of these initial transitions. This was achieved by annealing the rhenium sample in an induction

furnace at a temperature in the region of 1500°C for a period of one hour, or by casting the sample on the water-cooled copper hearth of an arc furnace under an atmosphere of very pure Ar or He. A summary of the treatments given and the observed transition temperatures is given in Table I.

Solid solutions of Os in Re were prepared by arc-melting together rhenium (MRC Grade 1) and 99.8%-purity osmium (Varlacoid Chemical Company). The weight losses which occurred during melting were small, and the compositions quoted are those calculated from the relative starting proportions of the constituents. The sharpness of the superconducting transitions were taken as evidence of the homogeneity of the samples. It is observed that the T_c for the Re-Os system increases initially with the addition of Os, passes through a maximum at ~5.5-at.% Os, and then decreases as the Os content is increased further (see Fig. 1). This variation of T_c with osmium content does not scale with the density of states which is observed[6] to decrease continuously over this range of compositions. An extensive study of the superconducting transition temperatures of Re solid solutions will be presented elsewhere.

The extreme sensitivity to strain of the superconducting transition in Re placed stringent requirements on the homogeneity of the pressure applied in the study of the pressure dependence of T_c. The previously employed technique[7] of transmitting a pressure, applied at room temperature, to the sample through a quasihydrostatic solid medium was found to be unsuitable as this broadened the transition and produced irreversible behavior. This difficulty was overcome with the development of a Teflon-cell technique for containing a fluid medium in a conventional piston-and-cylinder arrangement similar to that described by Jayaraman et al.[8] A 1:1 mixture of n-pentane and isoamyl alcohol was used to transmit the pressure, which was retained to low temperatures by means of the "clamp" technique.[9] With this arrangement we did not detect any broadening of the transition up to a maximum pressure of 18 kbar, and the atmospheric-pressure transition was reproducible within 1 mdeg on cycling the pressure. The pressure at low temperature was determined with a tin manometer,[10] which was placed next to the sample in the Teflon cell.

Table I: Summary of metallurgical treatments and atmospheric pressure T_c for a number of Re samples.

Sample	T_c (°K)	Annealing Conditions: Temperature (°C)	Time (hr)	Vacuum (mm Hg)	Remarks
Re 1					MRC, grade 1, 99.9 wt% purity polycrystalline
I	~3.1-1.7				As received
II	1.698-1.694				Arc melted, He atmosphere
III	1.695-1.692	1400	1	$2\text{-}3 \times 10^{-5}$	
IV	1.696-1.694				Arc melted, Ar atmosphere
V	1.695-1.693	1350	1	$\sim 7.5 \times 10^{-5}$	
VI	1.695-1.693				Arc melted, He atmosphere
Re 2					MRC, grade 1, 99.9 wt% purity single crystal
I	~2.8-2.0				As received
II	1.696-1.693	1600-1700	1	$3\text{-}5 \times 10^{-5}$	Spark cut
III	1.696-1.690	1500-1680	$1\frac{1}{2}$	$\sim 10^{-2}$	Cut on carborandum wheel
IV	1.695-1.694	1600-1750	1	$2\text{-}3 \times 10^{-5}$	Cut on carborandum wheel
V	1.695-1.694	1500	1	$6.7\text{-}7.5 \times 10^{-5}$	Cut on carborandum wheel
VI	1.695-1.693	1500	$1\frac{1}{2}$	$4.5\text{-}5 \times 10^{-5}$	Spark cut

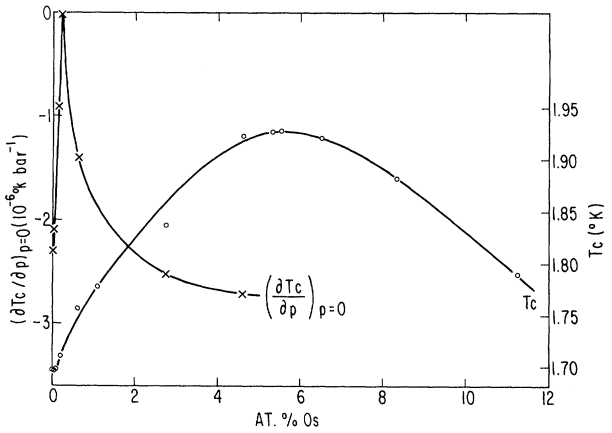

FIG. 1. T_c and $(\partial T_c/\partial P)_{P=0}$ plotted as a function of Os composition for Re-Os solid solutions.

In Fig. 2 we plot the change of transition temperature, ΔT_c, as a function of pressure for a single-crystal and polycrystal sample of pure Re and the Re-Os alloys. T_c for both the polycrystalline and single-crystal material initially decreases with the application of pressure, passes through a minimum at ~7 kbar, increases and finally levels off between 13 and 18 kbar. Addition of Os rapidly displaces the minimum to lower pressures and removes the anomalous behavior for alloys containing more than 0.2 at.% Os, for which T_c decreases almost linearly with pressure.

The only other superconductor to exhibit an

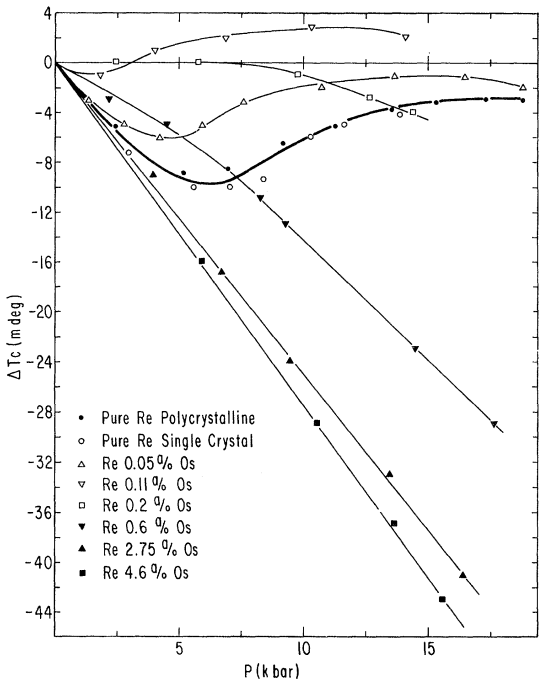

FIG. 2. ΔT_c plotted as a function of pressure for Re and Re-Os solid solutions.

anomalous pressure dependence of T_c similar to the present observations on rhenium is thallium, for which T_c increases with pressures up to ~2 kbar and then decreases.[11] An extensive study of the pressure dependence of T_c for Tl and Tl-rich solid solutions has led Lazarev[12] and co-workers to suggest that the anomalous behavior of this element is associated with a change in the Fermi-surface topology. A characteristic change, first considered by Lifshitz,[1] would be a closed surface transforming to an open surface by the formation of a "neck." This would lead to a change in the density of states at the Fermi surface and consequently to a change of the associated thermodynamic properties such as electronic specific heat, thermal expansion, etc. Specifically, it was later shown by Markarov and Bar'yakhtar[13] that the effect of such a change in the density of states on the superconducting energy gap would result in a nonlinear contribution to the pressure dependence of T_c. A further consequence of such a transition could well be reflected by a change in the energy-gap anisotropy. In fact, it is this very approach which Gey[14] has adopted, without considering the source of such a pressure-dependent anisotropy, to explain the pressure dependence of the T_c of Tl. While such an approach may be applicable for pure Tl, it fails to explain the behavior[12] of the Tl-rich solid solutions for which gap anistropy is expected to have been destroyed. However, this difficulty is not present with the model proposed by Lazarev and co-workers.

A plot of the dependence of $(\partial T_c/\partial P)_{P=0}$ of a metal solution permits a more extensive investigation of changes in the Fermi-surface topology with changes in Fermi energy than that provided by application of pressure alone.[15] In Fig. 1 we plot $(\partial T_c/\partial P)_{P=0}$ for Re and Re-Os alloys as a function of Os concentration. The sensitivity of $(\partial T_c/\partial P)_{P=0}$ to Os concentration is striking and in this respect is also very similar to the dependence observed in Tl solid solutions.[12] From Figs. 1 and 2 we deduce that the energy change required for the Fermi energy to pass through the critical energy for a change in the Fermi-surface topology of rhenium corresponds to the application of ~7 kbar or to the addition of approximately 0.2 at.% Os.

Thallium and rhenium are the only two elements which have been found to show anomalous pressure dependence of T_c which may be associated with a Fermi energy close to a critical energy for a change in the Fermi-surface topology. As yet, studies of the Fermi surface at high pressure by conventional techniques have not revealed changes of this nature.[16] However, measurements have not been made on Tl or Re and in view of the above discussion these elements merit early investigation.

Further work is at present in progress on other Re-solid solutions.

---

*Research sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, U. S. Air Force, under AFOSR Grant No. AF-AFOSR-631-67.

†Present address: Solid State Physics Division, Atomic Energy Research Establishment, Harwell, Didcot, Berkshire, England.

[1]I. M. Lifshitz, Zh. Eksperim. i Teor. Fiz. 38, 1569 (1960) [translation: Soviet Phys.—JETP 11, 1130 (1960)].

[2]J. K. Hulm and B. B. Goodman, Phys. Rev. 106, 659 (1957).

[3]R. Blanpain, Bull. Classe Sci., Acad. Roy. Belg. 47, 750 (1961).

[4]J. L. Olsen, K. Andres, H. Meier, and H. de Salaberry, Z. Naturforsch. 18a, 125 (1963).

[5]J. J. Hauser and E. Buchler, Phys. Rev. 125, 142 (1962); N. E. Alekseyevsky, M. N. Mikheyeva, and N. A. Tulina, Zh. Eksperim. i Teor. Fiz. 52, 875 (1967).

[6]E. Bucher, F. Heiniger, and J. Muller, in Proceedings of the Ninth International Low Temperature Conference (Plenum Press, New York, 1965) p. 1059; J. P. Maita, private communication.

[7]W. E. Gardner and T. F. Smith, Phys. Rev. 154, 309 (1967).

[8]A. Jayaraman, A. R. Hutson, J. H. McFee, A. S. Coriell, and R. G. Maines, Rev. Sci. Instr. 38, 44 (1967).

[9]P. F. Chester and G. O. Jones, Phil. Mag. 44, 1281 (1953).

[10]T. F. Smith and C. W. Chu, to be published.

[11]J. Hatton, Phys. Rev. 103, 1167 (1956); L. D. Jennings and C. A. Swenson, Phys. Rev. 112, 31 (1958).

[12]B. G. Lazarev, L. S. Lazareva, and V. I. Makarov, Zh. Eksperim. i Teor. Fiz. 44, 481 (1963) [translation: Soviet Phys.-JETP 17, 328 (1963)]; B. G. Lazarev, L. S. Lazareva, V. I. Makarov, and T. A. Ignat'eva, Zh. Eksperim. i Teor. Fiz. 46, 829 (1964) and 48, 1065 (1965) [translations: Soviet Phys.-JETP 19, 566 (1964), and 21, 711 (1965)]; N. B. Brandt, N. I. Ginzburg, T. A. Ignat'eva, B. G. Lazarev, L. S. Lazareva, and V. I. Makarov, Zh. Eksperim. i Teor. Fiz. 49, 85 (1965) [translation: Soviet Phys.-JETP 22, 61 (1966)].

[13]V. I. Makarov and V. G. Bar'yakhtar, Zh. Eksperim. i Teor. Fiz. 48, 1717 (1965) [translation: Soviet Phys. -JETP 21, 1151 (1965)].

[14]W. Gey, Phys. Rev. 153, 422 (1967).

[15]This compositon dependence of $(\partial T_c/\partial P)_{P=0}$ has led to support {V. I. Makarov and I. Ya. Volynskii, Zh. Eksperim. i Teor. Fiz.-Pis'ma Redakt. 4, 369 (1966) [translation: JETP Letters 4, 249 (1966)]} for the earlier suggestion [M. F. Merriam, Phys. Rev. 144, 300 (1966)] that there is a change in Fermi-surface topology for In-Cd alloys at 3-4 at.% Cd.

[16]J. E. Schirber, in Physics of Solids at High Pressures, edited by C. T. Tomizuka and R. M. Emrick (Academic Press, Inc., New York, 1965), p. 46.

SPIN POLARIZATION AROUND A LOCALIZED MAGNETIC IMPURITY IN A MAGNETIZED METAL

D. J. Kim and Brian B. Schwartz
Francis Bitter National Magnet Laboratory,* Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 14 December 1967)

Recently, neutron diffraction experiments[1] have been used to obtain the spatial distribution of the magnetic disturbance about solute atoms in Pd, Ni, and Fe. These measurements show that the disturbance produced around a magnetic impurity is quite different for different host metals. For low-concentration Pd:Fe alloys, the range of the conduction-electron polarization about the Fe impurity is long—on the order of 10 Å. In contrast to this long-range behavior, the disturbance due to a magnetic impurity in ferromagnetic Ni is almost confined to the impurity site. A magnetic impurity in ferromagnetic Fe produces a disturbance intermediate in range between Pd:Fe and Ni. In this Letter we present calculations which correlate the behavior of the disturbance associated with a localized moment with the band splitting of the host-metal electrons including exchange effects fully. We find that the range and amplitude of the polarization produced by a magnetic impurity are very sensitive to the spin splitting of the host-metal band. The range is large for small magnetization (dilute Pd:Fe) and on the order of an atomic distance for nearly complete magnetization (a magnetic solute atom in ferromagnetic Ni where one spin band appears to be full).[2] Furthermore, in dilute Pd:Fe alloys we can account for the sharp concentration-dependent decrease of the magnetic moment per Fe atom[3] by considering the increase in the splitting of the host Pd bands caused by adding Fe impurities.[4]

Although Low and his collaborators' experiments cover more complicated situations, we consider those situations in which an impurity forms a localized moment and calculate the spin polarization about the impurity.

This problem has two aspects. The first is the formation of the localized magnetic state on the impurity site, and the second is the spin polarization around the impurity.[5,6] In this paper we concentrate our discussion on the second aspect of this problem.

Our problem may be simplified without losing any essential features by replacing the effect of an impurity spin with an effective δ-function magnetic field $H\delta(r)$,[7] where we assume that the site of the impurity is at the coordinate origin. The conduction-electron spin polarization $\sigma(\vec{r})$ around the impurity is given as

$$\sigma(\vec{r}) = H\frac{1}{(2\pi)^3}\int \chi(\vec{q})e^{i\vec{q}\cdot\vec{r}}d\vec{q}, \qquad (1)$$