lished); N. F. Berk, thesis, University of Pennsylvania, Philadelphia, Pennsylvania, 1966 (unpublished).

[8]S. Doniach and S. Engelsberg, Phys. Rev. Letters 17, 750 (1966); S. Doniach, S. Engelsberg, and M. I. Rice, in Proceedings of the Tenth International Conference on Low Temperature Physics, Moscow, USSR, 31 August-6 September 1966 (to be published).

[9]S. Doniach, Phys. Rev. Letters 18, 554 (1967).

[10]J. R. Schrieffer, Phys. Rev. Letters 19, 644 (1967).

[11]L. R. Windmiller and J. B. Ketterson, Bull. Am. Phys. Soc. 12, 286 (1967), and following Letter [Phys. Rev. Letters 20, 324 (1968)].

[12]J. B. Ketterson, M. G. Priestley, and J. J. Vuillemin, Phys. Letters 20, 452 (1966).

[13]M. D. Stafleu and A. R. DeVroomen, Phys. Letters 19, 81 (1965).

[14]We are indebted to Dr. F. M. Mueller for allowing us the use of his results prior to their publication.

de HAAS–van ALPHEN EFFECT AND FERMI SURFACE IN Pt †

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The Fermi surface for both the s- and d-like carriers in Pt has been determined by observation of the de Haas–van Alphen effect. The Fermi surface is in good agreement with recent augmented-plane-wave band-structure calculations.

A detailed knowledge of the Fermi surface in transition metals is of considerable experimental and theoretical interest at the present time. Of particular interest is a metal such as platinum, where it is known from the heat capacity[1,2] and the magnetic susceptibility[2,3] that the density of states at the Fermi surface is anomalously high.

One area of theoretical interest centers around the calculation of the energy bands themselves. Augmented-plane-wave calculations are known to be capable of yielding reasonably good energy bands, and a comparison with the recent Pt calculations of Andersen and Mackintosh[4] will be presented. Another approach to band-structure calculations (which is the view held by the authors) is to find an appropriate "fitting procedure" so as to generate the energy bands directly from the experimental data. The "interpolation scheme"[5] or Korringa-Kohn-Rostoker method[6,7] seem particularly suited to such a program. As a first step, we have collected an exhaustive set of de Haas–van Alphen (dHvA) areas in Pt, only a small part of which can be presented here. The detailed cyclotron effective-mass measurements have been presented in the preceding Letter.[8]

Another area of current theoretical research centers around the "many-body" contributions to the density of states. In addition to the well-known electron-electron and electron-phonon contributions, the recently suggested exchange enhancement[9-12] due to short-lived magnons may play a quantitative role. The starting point for any quantitative estimate of these effects would involve a complete set of "single-particle" energies which could best be derived from the present experiment.

We report here measurements of the extremal areas taken using the field-modulation technique, a 60-kG solenoid, and temperatures down to 0.3°K.

Figure 1 shows the extremal cross-sectional areas for field directions in the (110) plane associated with the s-like electron surface centered on the point Γ in the Brillouin zone.[13,14] The surface is only slightly distorted from a sphere by small bumps in the [100] and [111] directions. These distortions result in an additional area extremum for field directions near [111], the upper area branch in Fig. 1 corresponding to the noncentral area extremum while the lower branch corresponds to the central one.

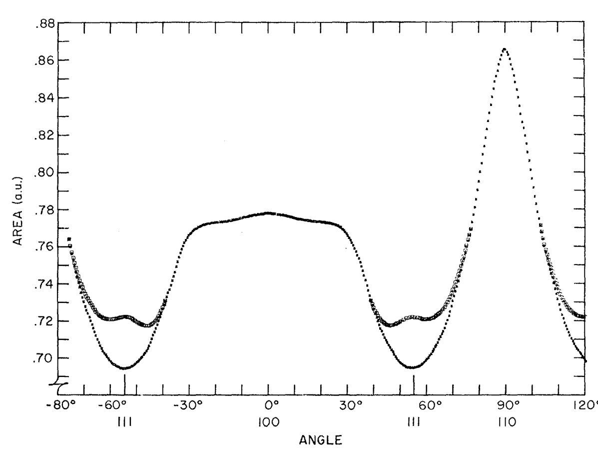

FIG. 1. The s-band extremal areas observed in Pt for H in the (110) plane.

Figure 2(a) shows the angular dependence of the extremal areas for the set of d-like ellipsoidal hole surfaces centered on the points X of the Brillouin zone. If the field were rotated exactly in the (110) plane, the two nearly coincident area branches would be degenerate. The splitting of this degenerate pair is a measure of the deviation of the magnetic field out of the (110) plane and indicates that this deviation never exceeds 2°. The data fitted quite well a model for the surface [solid lines in Fig. 2(a)] consisting of ellipsoids of revolution, prolate along the ΓX line, with c/a ratio equal to 1.56.[15]

The third sheet of the Fermi surface, an open d-like hole surface, has the topology of cylinders extending along the [100] directions and intersecting in pairs at the points X of the Brillouin zone. Figure 1 of I shows a section of this surface, as calculated by Mueller,[16] in the extended zone representation.

Figure 2(b) shows the angular dependence of the extremal areas for the α orbit [Fig. 1(b) of I]. This area branch is only observed within 30° of [100] disappearing abruptly although the effective cyclotron mass has the relatively small value of 2.1. Such behavior indicates that, due to the geometrical features of the surface, the α orbit only exists within 30° of [100] in the (110) plane. Near [110] three extremal area branches (β, γ, and δ in Fig. 1 of I) are predicted from the band-structure calculation of Mueller,[16] but only the two area branches shown in Fig. 2(c) were observed. The unenhanced cyclotron effective mass for the central junction orbit β was calculated[4] to be 6.23, a mass far too heavy to be observed in the present experiment. For this reason the upper branch in Fig. 2(c) has been identified with the noncentral junction orbit γ and the lower branch with the cylinder orbit δ. The splitting of the two degenerate δ area branches expected for field directions close to [110] but not in the (110) plane was observed in an additional experiment in which the γ area branch remained single valued. This reinforced the identification of these area branches.

Andersen and Mackintosh have calculated the extremal areas of the Γ-centered electron surface and find the values 0.758, 0.842, and 0.676 for the magnetic field in the [100], [110], and [111] directions, respectively. The corresponding experimentally observed areas are 0.778, 0.865, and 0.695. The area of the α orbit on the open-hole surface for the field along [100] and the γ orbit for the field along [110] were also calculated by Andersen and Mackintosh. For the α orbit the theoretical and experimental areas are 0.0713 and 0.0743, respectively. For the γ orbit, the theoretical area is 0.217 compared with the experimental value of 0.218. Thus, while the agreement is

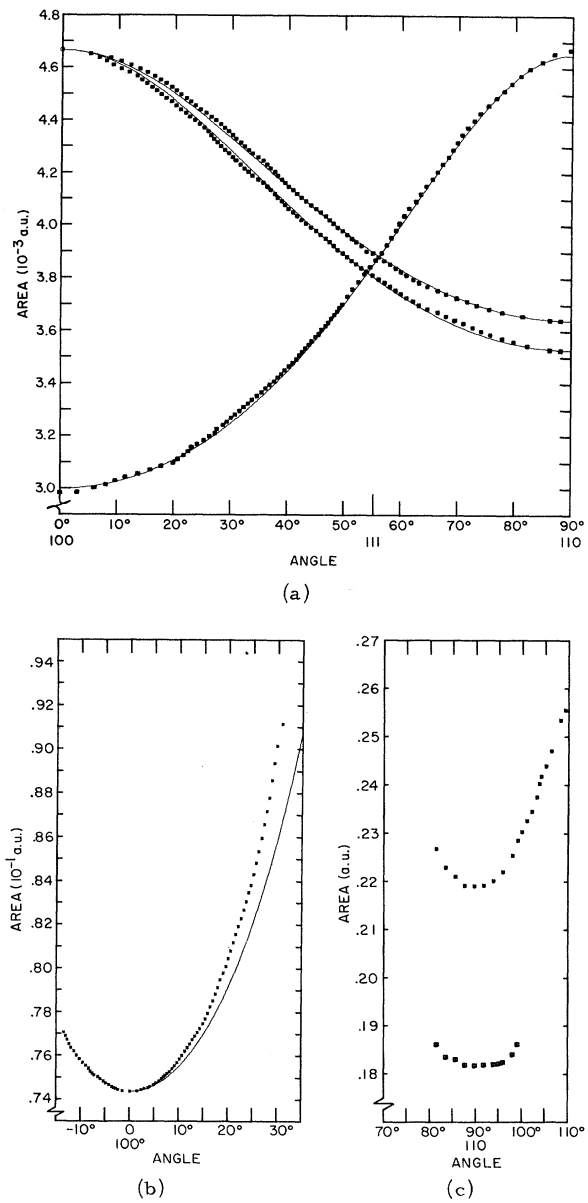

FIG. 2. (a) The d-band "pocket" extremal areas for H in the (110) plane. (b) The open d-band extremal areas, associated with the α orbit, observed for $\boldsymbol{H}$ near [100] in the (110) plane. The solid line shows the angular variation for a cylinder. (c) The open d-band extremal areas, associated with the γ and δ orbits, observed for H near [110] in the (110) plane.

satisfactory, the theoretical areas are systematically smaller than the corresponding experimental ones. Both holes and electrons are similarly affected; so a simple change of the Fermi level is not sufficient to correct all the areas.

There are four important effects which determine the energy bands in a transition metal.[16] These are the *d* bandwidth, hybridization, *s*-*d* shifts, and the spin-orbit coupling. Of these the spin-orbit coupling and *s*-*d* shifts are the most important, since the *d* bandwidth and hybridization seem to vary little between various calculations. Thus, to bring the calculations into agreement with the experimental data, it appears likely that corrections in the *s*-*d* shift and spin-orbit coupling in addition to an adjustment of the Fermi level will be required.

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[1]J. Rayne, Phys. Rev. 95, 1428 (1954).

[2]D. W. Budworth, F. E. Hoare, and J. Preston, Proc. Roy. Soc. (London), Ser. A 257, 250 (1960).

[3]S. Foner, R. Doclo, and E. J. McNiff, Jr., to be published.

[4]A. R. Mackintosh, Bull. Am. Phys. Soc. 11, 215 (1966); O. K. Andersen and A. R. Mackintosh, to be published.

[5]F. M. Mueller, Phys. Rev. 153, 659 (1967).

[6]J. Korringa, Physica 13, 392 (1947).

[7]W. Kohn and N. Rostoker, Phys. Rev. 94, 1111 (1954).

[8]J. B. Ketterson and L. R. Windmiller, preceding Letter [Phys. Rev. Letters 20, 000 (1967)], referred to as I.

[9]N. F. Berk and J. R. Schrieffer, Phys. Rev. Letters 17, 433 (1966), and Proceedings of the Tenth International Conference on Low Temperature Physics, Moscow, USSR, 31 August-6 September 1966 (to be published); N. F. Berk, thesis, University of Pennsylvania, Philadelphia, Pennsylvania, 1966 (unpublished).

[10]S. Doniach and S. Engelsberg, Phys. Rev. Letters 17, 750 (1966); S. Doniach, S. Engelsberg, and M. I. Rice, in Proceedings of the Tenth International Conference on Low Temperature Physics, Moscow, USSR, 31 August-6 September 1966 (to be published).

[11]S. Doniach, Phys. Rev. Letters 18, 554 (1967).

[12]J. R. Schrieffer, Phys. Rev. Letters 19, 644 (1967).

[13]J. B. Ketterson, M. G. Priestley, and J. J. Vuillemin, Phys. Letters 20, 452 (1966).

[14]L. R. Windmiller and J. B. Ketterson, Bull. Am. Phys. Soc. 12, 3, 286 (1967).

[15]M. D. Stafleau and A. R. DeVroomen, Phys. Letters 19, 81 (1965).

[16]F. M. Mueller, Bull. Am. Phys. Soc. 12, 3, 287 (1967), and to be published.

IDEAL FLUX-FLOW RESISTANCE IN A TYPE-II SUPERCONDUCTING ALLOY

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In an ideal type-II superconductor, between the fields H_{c1} and H_{c2}, a regular lattice of current vortices or "fluxoids" is formed. If a current I is applied at right angles to the applied field $\vec{H}$ in an ideal, defect-free superconductor, it is thought that the fluxoid lattice undergoes a translational motion at a uniform velocity in a direction mutually orthogonal to both I and $\vec{H}$.[1] The fluxoid motion gives rise to an electric field which is observed as a resistive voltage drop, V, in the direction parallel to I. This is the so-called "flux-flow" resistivity.[2,3] Theoretically, one expects the ideal behavior to be Ohmic, i.e., $V=IR$, where R depends only on H.[4,5] In real superconductors, one generally observes nonlinear I-vs-V curves and (equivalently) noncurrent-independent R-vs-H curves.

The deviation from the "ideal" linear behavior has been the subject of much discussion[2,6-8] and some controversy,[9,10] though the popular view appears to be that the departure from linearity is due to interactions with the surface and with volume defects (e.g., dislocations). These "pinning" forces are particularly effective at low values of I where the electromagnetic forces on the fluxoid are relatively small.

The purpose of this Letter is to report recent experiments in which we have been able to achieve linear V-vs-I and current-independent R-vs-H behavior and in which we find that this "ideal" resistivity is in excellent agreement with predictions of the recent microscopic theory[4,5] over a large variation of the dc current. The depinning of the fluxoids is achieved by superimposing on the transverse dc magnetic field