from the Ornstein-Zernike theory in the neighborhood of the Curie temperature were of limited success. While we did observe anomalies in the data in this temperature region, we were not able to establish that they were the expected effects. This question certainly warrants further investigation if apparatus of improved resolution becomes feasible in the future.

ACKNOWLEDGMENTS

We wish to express our appreciation for the continued support and encouragement of Professor Ctto Kofoed-Hansen and Professor H. Højgaard-Jensen. It is also a pleasure to acknowledge our obligation to Dr. Walter Marshall who originally directed our attention to this interesting field. Dr. M. E. Fisher and Dr. E. W. Hart gave very generously of their time to discuss details of their work with one of us (L.P.) and Dr. J. Kocinski was kind enough to communicate some of his calculations to us in advance of publication. We also wish to take this opportunity to thank our colleagues, W. K. Kofoed who was responsible for the design and construction of the apparatus, F. Hansen who designed the oven control system, and D. Heidebo who rendered valuable assistance. The numerical calculations were performed on the GIER-computer of Afdeling for Numerisk Analyse, University of Copenhagen.

PHYSICAL REVIEW VOLUME 139, NUMBER 6A 13 SEPTEMBER 1965

Magnetoacoustic Effect in Rhenium near 1 Gc/sec*

C. K. JONES
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

AND

J. A. RAYNE
Carnegie Institute of Technology, Pittsburgh, Pennsylvania

(Received 19 April 1965)

Magnetoacoustic measurements near 1 Gc/sec have been made in very pure rhenium. The resulting extremal dimensions are compared with the Fermi surface model deduced from low-field de Haas–van Alphen data. Reasonable agreement is found for the dumbbells of the model, but there appears to be some difficulty with respect to the ellipsoids. Possible reasons for this discrepancy are considered. Dimensions corresponding to large pieces of the Fermi surface are also observed and are tentatively correlated with the results of pulsed-field de Haas–van Alphen data.

I. INTRODUCTION

THERE is a considerable body of theoretical and experimental work concerning many of the cubic transition metals. Relatively little information, however, is available about the transition elements of hexagonal symmetry. Band calculations exist only for titanium[1] and zirconium,[2] and experimental data relating directly to the nature of the Fermi surfaces of hexagonal transition metals is quite sparse. In this respect rhenium is somewhat exceptional in that both high- and low-field de Haas–van Alphen[3,4] as well as magnetoresistance[5] data are available, and that crystals of high purity are readily obtainable. In this paper, we report magnetoacoustic measurements up to 930 Mc/sec on single-crystal rhenium having a resistance ratio in excess of 20 000 to 1. In the absence of any theoretical band structure, a comparison of the extremal dimensions is made with the model deduced from de Haas–van Alphen (dHvA) data.

II. EXPERIMENTAL TECHNIQUE

The rhenium crystal used in this work was grown in an electron-beam furnace by H. Sell of the Westinghouse Lamp Division, Bloomfield, N. J. An accurate figure for the resistance ratio of the resulting monocrystal is not available, but it is believed to be in excess of 20 000 to 1. Samples suitable for ultrasonic measurements, oriented with faces perpendicular to [0001], [10$\bar{1}$0], and [1$\bar{2}$10], were spark cut from the crystal. The opposite ends of each sample were subsequently lapped for parallelism to within 0.0001 cm and flatness to within a fringe over their entire surfaces. The samples were then indium bonded to z-cut quartz delay lines, approximately one inch in length.

Magnetoacoustic measurements up to 930 Mc/sec were made on these composite specimens, using the

* Supported in part by the National Science Foundation.
[1] S. L. Altmann and N. V. Cohen, Proc. Phys. Soc. (London) 71, 383 (1958).
[2] S. L. Altmann and C. J. Bradley, Phys. Letters 1, 336 (1962).
[3] A. C. Thorsen and T. G. Berlincourt, Phys. Rev. Letters 7, 244 (1961).
[4] A. S. Joseph and A. C. Thorsen, Phys. Rev. 133, A1547 (1964).
[5] W. A. Reed, E. Fawcett, and R. R. Soden, Phys. Rev. 139, A1557 (1965).

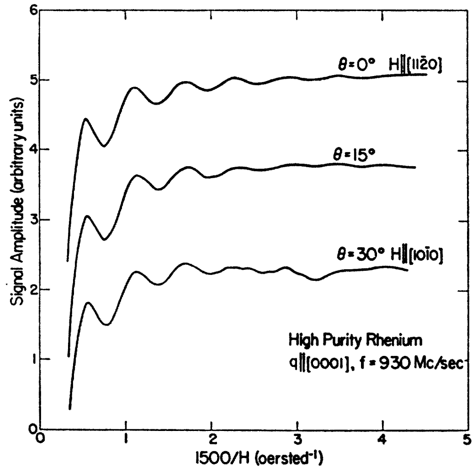

FIG. 1. Tracing of representative data obtained in rhenium with $\mathbf{q}\|[0001]$ for various directions of magnetic field. The frequency is 930 Mc/sec.

techniques reported previously.[6] The methods of generation and detection of the hypersound were those employed by Bömmel and Dransfeld.[7] Experiments were made with longitudinal waves in transmission, using 30-Mc/sec X-cut quartz overtone transducers to generate and detect the sound. The transmitting crystal was excited by $\frac{1}{2}$ μsec rf pulses produced by a plate-modulated MCL triode oscillator tunable from 500 to 1000 Mc/sec. Data were recorded automatically, using a gated pulse integrator to permit the plotting of the transmitted signal as a function of the inverse of the transverse magnetic field H. All data were obtained at 4.2°K, since the effects of scattering due to thermal phonons are negligible owing to the high Debye temperature of rhenium.

III. RESULTS AND DISCUSSION

Representative tracings of the data, for the three propagation directions, are shown in Figs. 1 through 3. From the measured periods of oscillation in $1/H$, the corresponding extremal dimensions may be readily calculated from the usual formula[8]

$$k_{\text{ext}}=\frac{e}{2\hbar c}\frac{\lambda}{\Delta(1/H)}. \qquad (1)$$

The sound wavelength λ used in this equation was obtained from direct measurement of the wave velocities for 10-Mc/sec longitudinal waves, propagating along the hexad axis and in the basal plane, respectively. These measurements give at 4.2°K[8a]

$$v_{[0001]}=5.9\times10^5 \text{ cm sec}^{-1},$$

$$v_{[10\bar{1}0]}=v_{[11\bar{2}0]}=5.4\times10^5 \text{ cm sec}^{-1}.$$

[6] J. A. Rayne, Phys. Rev. **129**, 652 (1963).
[7] H. E. Bömmel and K. Dransfeld, Phys. Rev. **117**, 1254 (1960).
[8] A. B. Pippard, Proc. Roy. Soc. (London) **A257**, 165 (1960).
[8a] *Note added in proof.* These velocities agree with those determined independently by M. L. Shepard and J. F. Smith, J. Appl. Phys. **36**, 1447 (1965).

TABLE I. Extremal dimensions of Fermi surface in rhenium (E—Ellipsoids of Joseph and Thorsen model; D—Dumbbells of Joseph and Thorsen model.)

Propagation direction	Field direction	k_{ext}[a] (10^7 cm^{-1}) Magnetoacoustic	de Haas–van Alphen
[0001]	[11$\bar{2}$0]	1.20±0.05	0.8, 2.2 (E,D)
	[10$\bar{1}$0]	1.20±0.05	1.2, 0.6 (E,D)
		3.5 ±0.5	2.2 (D)
[1$\bar{2}$10]	[0001]	1.0 ±0.1	2.2 (D,E)
		4 ±1	0.8 (E)
	[10$\bar{1}$0]	1.8 ±0.1	1.9 (D)
		0.8 ±0.1	0.4 (E)
[10$\bar{1}$0]	[0001]	3.5 ±0.5	1.2, 0.6 (E,D)
		0.6 ±0.1	2.2 (D)
	[1$\bar{2}$10]	1.9 ±0.1	1.9 (D)
		0.35±0.1	0.4 (E)

[a] Note that k_{ext} is in the direction $\mathbf{q}\times\mathbf{H}$.

The relevant extremal dimensions, computed using these data, are given in Table I. The principal dimensions, plotted as a function of crystallographic direction, using the fact that k_{ext} for a sound propagation direction $\mathbf{q}$ and field direction $\mathbf{H}$ is measured along $\mathbf{q}\times\mathbf{H}$, are shown in Fig. 4. The shaded regions correspond to dimensions obtained from poorly defined oscillations; the width of the shading is *not* to be interpreted as a measure of the uncertainty in the value of k_{ext}.

In the absence of any theoretical band-structure calculations, it will be expedient to compare the extremal Fermi surface dimensions with the model proposed by Joseph and Thorsen[4] to explain their low-field dHvA data. Their model is shown schematically in Fig. 5. Along the lines of degeneracy AL, which are parallel to $\langle10\bar{1}0\rangle$, there are ellipsoids whose major axes are coincident with AL. From an analysis of their

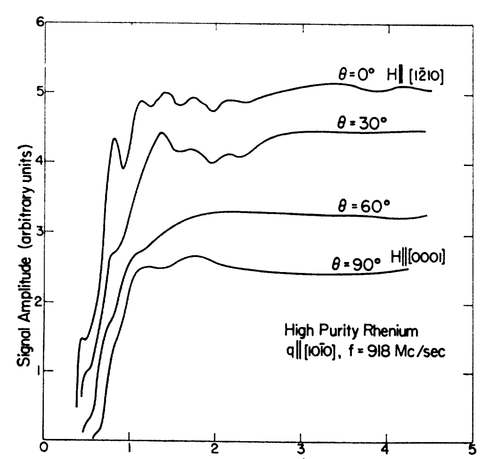

FIG. 2. Tracing of representative data obtained in rhenium with $\mathbf{q}\|[10\bar{1}0]$ for various directions of magnetic field. The frequency is 918 Mc/sec.

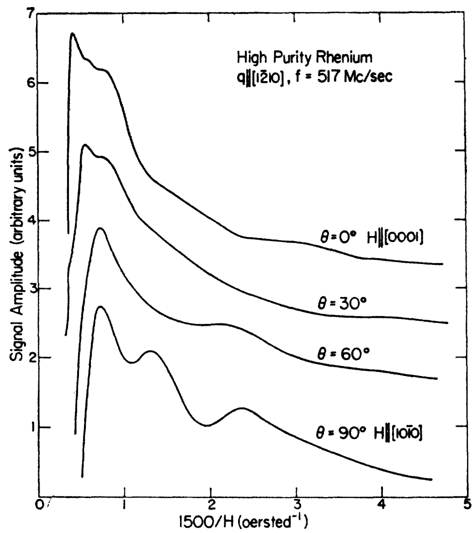

FIG. 3. Tracing of representative data obtained in rhenium with q‖[1$\bar{2}$10] for various directions of magnetic field. The frequency is 517 Mc/sec.

data Joseph and Thorsen find that these ellipsoids have semiaxes of length $a=2.19\times10^7$ cm^{-1}, $b=0.63\times10^7$ cm^{-1}, and $c=0.37\times10^7$ cm^{-1}, the smallest dimension being along [0001]. The ellipsoids lie within dumbbell-shaped regions, depicted in the lower half of the figure; these dumbbells can be represented as spheres deformed along ⟨11$\bar{2}$0⟩ as shown in Fig. 6. The minimum dHvA period associated with the cross section shown in Fig. 6(a) is $7.4\times10^{-8}\,G^{-1}$, which corresponds to an assumed *circular* cross section of radius 2.0×10^7 cm^{-1}. If, on the other hand, we assume that the dimension along [10$\bar{1}$0] is identical with the major axis of the ellipsoid, we obtain for the dimension along [0001] a value of 1.9×10^7 cm^{-1}. Thorsen and Berlincourt[3] have also observed much shorter periods, corresponding to larger

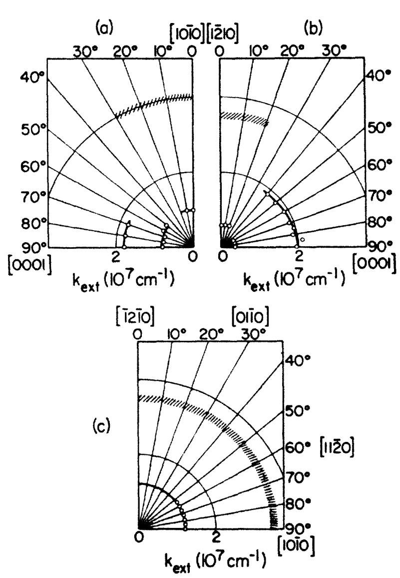

FIG. 4. Extremal dimensions for rhenium obtained from present experiment using Eq. (1). The shaded regions represent extrema deduced from poorly defined oscillations; the width of these shaded areas does not represent the estimated errors.

extremal areas, in rhenium using pulsed field dHvA techniques. Their data are not sufficiently detailed to give any picture of the larger pieces of the Fermi surface in rhenium.

Reference to Figs. 1 through 3 shows that the best defined oscillations occur for **q**‖[0001], **H** being in the basal plane. If we attempt to associate the corresponding extremal dimensions with the ellipsoids of the Joseph and Thorsen model, a difficulty immediately arises. Owing to the symmetry of the crystal we require *six* ellipsoids located along ⟨10$\bar{1}$0⟩; these ellipsoids are inequivalently located with respect to a given field direction and should give rise to a rotation diagram of the form shown in Fig. 7. However, from Fig. 4(c) it is clear that an *isotropic* dimension is observed, the magnitude of which appears to be roughly the *mean* extremal dimensions of all six ellipsoids. Weak beats in the oscillations are present, but these do not correspond very accurately to those expected from the ellipsoids. As yet

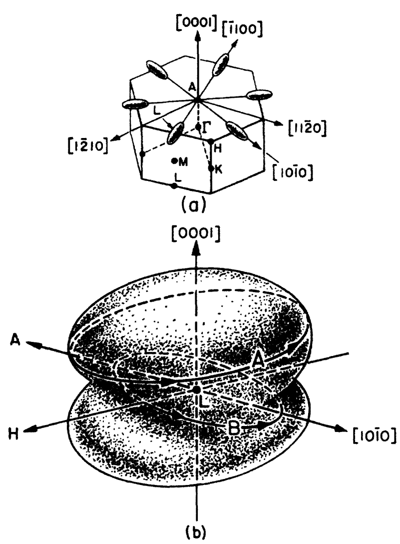

FIG. 5. Schematic representation of the model proposed by Joseph and Thorsen to explain their low-field de Haas–van Alphen data. The ellipsoids at the points L of the Brillouin zone are contained within the dumbbell-shaped regions shown in the lower part of the figure.

no satisfactory explanation of this discrepancy can be advanced.

For **q**‖[10$\bar{1}$0], **H**∼[1$\bar{2}$10] another well-defined group of oscillations occurs over a considerable angular range, as may be seen from Fig. 4(b). The observed dimension agrees very well with that expected from the nearly spherical dumbbells of the Joseph and Thorsen model. For the magnetic field along the symmetry direction in the basal plane, the extremal orbits of *one* set of dumbbells are approximately circular as in Fig. 6(a). As the field is tilted away from this direction, however, these orbits will ultimately encompass the dimpled regions of the dumbbells. Presumably the electrons will be more strongly scattered over these regions, owing to the large curvature of the Fermi surface. The oscillatory behavior is quite weak for these field directions, in apparent agreement with these conclusions. In further support of this hypothesis, it is noteworthy that oscillatory behavior, which can definitely be correlated with dumbbells, is quite weak for $\mathbf{q}\|[1\bar{2}10]$. In this propagation direction, the extremal orbits for the field in the basal plane are as shown in Fig. 6(b) and hence the scattering should again be very large.

For both propagation directions in the basal plane, extremal dimensions smaller than those expected from the *spherical* regions of the dumbbells are observed. For $\mathbf{q}\|[10\bar{1}0]$ these extrema agree quite well with the semiaxes b, c of the ellipsoids. The interpretation in the case $\mathbf{q}\|[1\bar{2}10]$ is less clear, since one would expect a dimension equal to the semiaxis c of the ellipsoids for the field in the basal plane. Reference to Fig. 4(a) shows that a value of k_{ext} roughly twice this figure is observed. For $\mathbf{H}\|[10\bar{1}0]$, k_{ext} again seems to correspond roughly with a mean dimension of the ellipsoids.

Both Fig. 4 and Table I show that other rather poorly defined extrema are observed, which are much larger than any dimension of the ellipsoids or the dumbbells in the Joseph and Thorsen model. Lacking any band-structure calculation, it seems rather fruitless to speculate as to the Fermi-surface topology giving rise to these extrema. From the high-field dHvA data of Thorsen and Berlincourt,[3] it is clear that the Fermi surface of rhenium contains other much larger sections than those given by the model considered here. Their data is not sufficiently detailed, however, to attempt a correlation with the results of our measurements.

From Figs. 1 through 3, it is seen that the field dependence of the attenuation for $\mathbf{q}\|[1\bar{2}10]$ differs markedly from that for $\mathbf{q}\|[10\bar{1}0]$ and $\mathbf{q}\|[0001]$. For

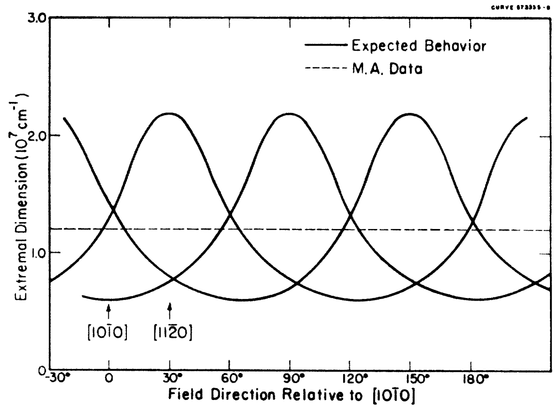

FIG. 7. Expected variation of k_{ext} for ellipsoids of Joseph and Thorsen model with $\mathbf{H}$ in the basal plane. The dashed line shows the dimension obtained from the present data with $\mathbf{q}\|[0001]$, $\mathbf{H}$ in the basal plane.

the former propagation direction there is a pronounced minimum in the attenuation as a function of field; the absolute value of the electronic attenuation in zero field also appears to be somewhat larger in this case. It is probable that those features can be associated with the deformation characteristics of the open sections of the Fermi surface in rhenium. Further experiments are being carried out to elucidate these observations.

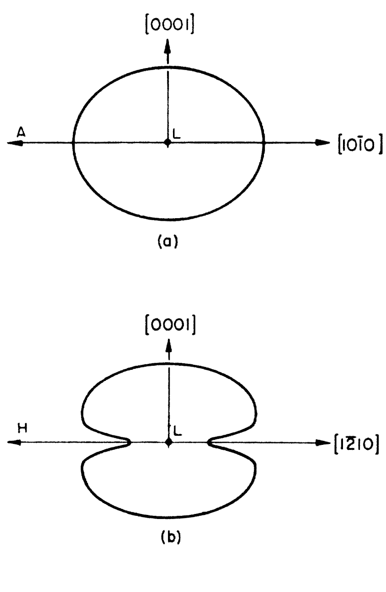

FIG. 6. Central cross sections of the dumbbells in $(1\bar{2}10)$ and $(10\bar{1}0)$ planes. The ellipsoidal cross section lying within the dumbbells is not shown.

IV. CONCLUSIONS

Many of the extremal dimensions obtained from magnetoacoustic measurements in rhenium agree quite well with the Fermi surface model deduced from low-field de Haas–van Alphen data. In this connection, better agreement obtains for the dumbbells of this model than for the ellipsoids. Other extremal dimensions are observed, which presumably correspond to the larger pieces of Fermi surface observed in pulsed field dHvA measurements. In the absence of any theoretical model, little information about the topology of these pieces can be duduced from the present work.

ACKNOWLEDGMENTS

The authors would like to thank F. Hauber for his care in cutting and polishing the rhenium crystals used in these experiments. Thanks are also due to R. Macfarlane for his measurements of the propagation velocities in these crystals. One of the authors (J. A. Rayne) wishes to acknowledge support by the National Science Foundation.

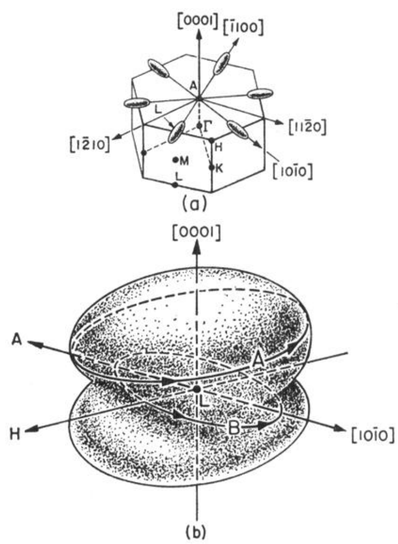

FIG. 5. Schematic representation of the model proposed by Joseph and Thorsen to explain their low-field de Haas–van Alphen data. The ellipsoids at the points L of the Brillouin zone are contained within the dumb-bell-shaped regions shown in the lower part of the figure.