less than at room temperature.) To investigate how singular is the dependence of the transition temperature on the stress, ΔT_c was measured at very low stresses. It is found that, as ΔT_c becomes of the order of the width of the transition curve, or smaller, the change in the transition temperature at different parts of the crystal is different, and therefore, ΔT_c is not very well defined. The singularity observed in this work is probably closely associated with the spontaneous distortion discussed in reference 5 and observed by Batterman and Barrett.[9]

The effect of the stress in the [100] direction can be tentatively described as a broadening of the narrow Clogston-Jaccarino peak. This broadening reduces the density of states at the Fermi level and therefore results in a lowering of the transition temperature, and less impurity scattering from s to d states, resulting in a lower electrical resistance. We have no theory to account for the singular behavior of V_3Si under stress; however, the extremely anisotropic behavior seems to confirm the suggestion that the electronic band structure of V_3Si is extremely anisotropic.

The present experiment was suggested by Dr. G. Feher. The work was initiated and carried out with the support of Dr. V. Jaccarino and Dr. A. M. Clogston. Several suggestions and discussions with Dr. W. Kohn were of considerable help. One of us (M.W.) wishes to acknowledge with thanks many stimulating discussions with Dr. B. T. Matthias and Dr. H. Suhl, and considerable assistance in the experimental work by Dr. M. Merriam. Discussions with Dr. Olsen, Dr. Reed, Dr. Hauser, and Dr. Bommel were also very helpful. We are also thankful to Dr. Mattheiss and Dr. Batterman for showing us their unpublished results. The experimental setup was constructed with the assistance of Mr. J. Froman.

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EVIDENCE OF SPIN-ORBIT COUPLING IN METALLIC TUNGSTEN

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Among the transition metals, i. e., those whose conduction electrons have appreciable d character, tungsten ($5d^46s^2$) has proved most easily obtainable in high-purity, single-crystal form. As a result, most of the available techniques for studying electronic properties of metals have been applied to tungsten. The experimental data, many of which remain to be published in detail, are generally compatible with the Fermi surface model for chromium-group metals without spin originally proposed and recently modified by Lomer.[1] Augmented-plane-wave calculations by Mattheiss[2] for the specific case of tungsten confirm Lomer's qualitative predictions. In this Letter we present measurements of extremal linear dimensions of the tungsten Fermi surface which show that, while the shapes of the principal sheets are correctly given by the model, they fail to contact each other as predicted. This discrepancy provides clear evidence of appreciable spin-orbit coupling, an interaction thus far not included in the calculations. A quantitative evaluation of the spin-orbit coupling parameter from our data is given in the following Letter by Mattheiss and Watson.[3]

The experiment is similar in principle to those

performed by Khaikin[4] and by Gantmakher[5] but makes use of a technique developed for studying helicon wave propagation in metals[6]: A magnetic field $\vec{H}$ is applied parallel to the plane of a thin metal slab of thickness t. A radio-frequency oscillator drives a transmitter coil placed near one face of the sample. A similar coil on the opposite face receives transmitted energy when cyclotron orbits of carriers in the metal just span the sample thickness. The success of the method depends on the carriers traversing at least one half of a cyclotron orbit without scattering; i.e., one must have $\omega_c\tau \geq \pi$ where ω_c is the cyclotron angular frequency and τ is the carrier scattering time. By using audiofrequency modulation of the magnetic field and synchronous detection of the rectified, received signal, the field derivative of that signal is plotted versus the field strength. This display exhibits narrow peaks at values of H which cause extremal orbits to "fit" in the sample. Extremal-dimension orbits are those whose crystal-momentum-space (k-space) dimension perpendicular to $\vec{H}$ and to the sample normal is a maximum or a minimum on a sheet of the Fermi surface. The relationship between the k-space dimension Δk of an orbit and the field H at which its real-space dimension equals the sample thickness is $\Delta k = (e/\hbar c)Ht$. The data reported here were taken at 4.2°K with a (110)-plane sample 0.235 mm thick prepared from a tungsten crystal of resistance ratio $\rho_{300°K}/\rho_{4.2°K} \simeq 37000$ obtained from Dr. H. Sell of the Westinghouse Lamp Research Division. Several frequencies were used to check that peak positions were independent of frequency, 4 Mc/sec being the most commonly used value.

Having an even number of electrons per atom, tungsten is a compensated metal, that is, it has equal numbers of holes and electrons. The topology of the Fermi surface has been shown by magnetoresistance studies to be extremely simple: All sheets are closed[7] and no open orbits occur due to magnetic breakdown phenomena.[8] The principal electron and hole surfaces of the Lomer model are illustrated in Fig. 1. The major electron surface, centered at the Brillouin zone center Γ, consists of an octahedral "body" with ball-like protruberances on the six vertices. Sparlin and Marcus[9] have named this entity the "jack." The principal hole surface is a simple "octahedron" with rounded edges, centered on the point H, the ⟨100⟩ vertex of the dodecahedral zone. A characteristic property of present significance is that the electron "jack" and the hole "octahedron" must touch along the line ΓH in the absence of spin-orbit coupling.

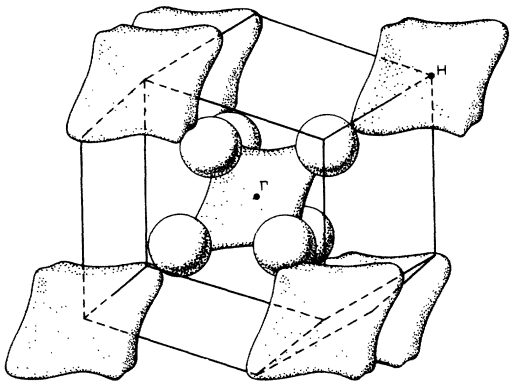

FIG. 1. The principal sheets of the tungsten Fermi surface in the absence of spin-orbit coupling. The major electron surface centered at Γ consists of an octahedral body whose vertices terminate in ball-like protrusions. The major hole sheet is nearly octahedral, is centered on the ⟨100⟩ zone vertex H, and touches the electron "jack" along the ⟨100⟩ axis ΓH. Minor pieces of the Fermi surface have been omitted for clarity.

The results of the size-effect experiments are summarized in Fig. 2. Most easily recognized is the cross section of the hole octahedron since its simple form permits observation over the entire (110) plane. A smaller piece having similar anisotropy is seen over a restricted angular range and is identified as the "body" of the electron "jack." Such a class of orbits has also

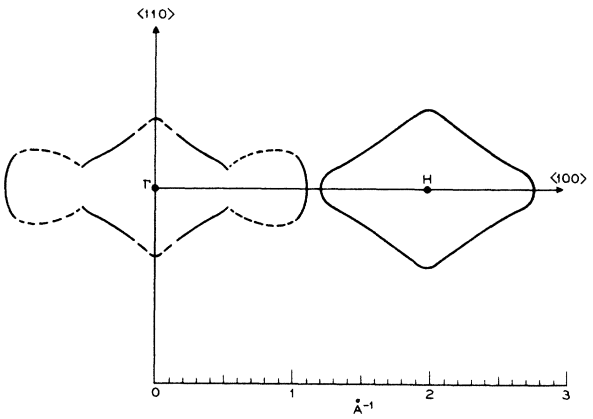

FIG. 2. Experimental k-vector determinations in the (110) plane of tungsten shown as solid curves. The dashed portions of the section centered on Γ are implied by the model but not directly observable because of the re-entrant nature of the surface. The gap between the two sections along ΓH is the result of spin-orbit interaction.

Table I. Radii of the principal electron and hole sheets of the tungsten Fermi surface ($Å^{-1}$).

Direction	Electron "jack" Expt 1[a]	Electron "jack" Expt 2[b]	Electron "jack" Theory[c]	Hole "octahedron" Expt 1[a]	Hole "octahedron" Expt 2[b]	Hole "octahedron" Theory[c]
⟨100⟩	1.11	1.10	1.09	0.78	0.78	0.79
⟨111⟩	0.415		0.47	0.50		0.50
⟨110⟩			0.51	0.60	0.62	0.60

[a]The size-effect experiment reported here.

[b]Magnetoacoustic data of Jones and Rayne.[12]

[c]Augmented-plane-wave calculation of Mattheiss.[2] The numbers for the ⟨100⟩ direction include spin-orbit interaction ($\xi_{5d}=0.03$ Ry, see following Letter[3]), whereas the others do not.

been observed in cyclotron resonance and has been shown to have electron character.[10] When the magnetic field direction comes within 15° of the ⟨110⟩ axis (k vector within 15° of the ⟨100⟩ direction), the "body" signal disappears but is replaced within a few degrees by another signal at much greater values of H. This is interpreted as due to orbits on the jack which pass over the "balls" as well as the "body." The body orbit signal also disappears when $\vec{H}$ is within 18° of the ⟨100⟩ axis, as is consistent with the re-entrant nature of the surface, but the expected larger orbit in this region has not been observed. A number of other signals corresponding to smaller dimensions have also been observed but will not be discussed here.

It is clear from Fig. 2 that the electron "jack" and the hole "octahedron" fail to make contact in the ⟨100⟩ direction. The observed gaps amount to 5% of the ΓH distance (1.987 $Å^{-1}$).[11] The radial dimensions shown in Table I are believed to be accurate to at least ±2%. Our results are in excellent agreement with the magnetoacoustic-effect data of Jones and Rayne[12] which are included for comparison. Theoretical k vectors computed by Mattheiss[2] and Mattheiss and Watson[3] are also given in the table, those for the ⟨100⟩ direction including a spin-orbit interaction of 0.03 Ry, which produces a gap of the observed magnitude between the electron and hole surfaces. The agreement between theory and experiment is generally good. The existence of the gap between the major electron and hole sheets also explains the observed absence of open orbits due to magnetic breakdown.[8]

The authors wish to acknowledge the expert assistance of G. Adams and L. W. Rupp, Jr. That the observed gap would be produced by spin-orbit interaction has been recognized by a number of colleagues. In particular, C. Herring brought the matter most clearly to our attention.

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