of suffering a collision. As shown in Fig. 2 the amplitude of the echo decreases as l increases. The quantitative description of collisional effects will be reported in a future publication.

Our experimental observations together with preliminary interpretations can be summed up as follows:

(1) The position of the echo varies linearly with grid separation and has the proper dependence on the excitation frequencies. The displacement of the echo seems to be due to the fact that the drifting plasma alters the position where the waves are excited in the plasma.

(2) The echo does not appear unless $\omega_2 > \omega_1$.

(3) The amplitude of the echo depends linearly on the product of the amplitude of the two excited waves.

(4) Both ion-ion and ion-neutral collisions tend to decrease the amplitude of the echo.

(5) As shown in Fig. 2, the echo is asymmetrical. It rises to its maximum value faster than it dies out showing that the assumption of noninteracting particles and a simplified excitation scheme which predicts a symmetrical echo is not sufficient. Collective effects and the biased grid excitation must be considered.

In summary, our preliminary investigation of ion-wave echoes promises a useful means of studying collisional phenomena. The echo depends on the particles retaining the phase information imparted by the excited waves and is sensitive to relatively weak interactions. It may be possible to use the echo to study the effects of particle-wave or wave-wave interactions in a collisionless turbulent plasma.

We wish to acknowledge useful discussions with Dr. G. Johnston and Professor B. D. Fried.

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†Alfred P. Sloan Research Fellow.

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ANISOTROPY AND MASS ENCHANCEMENT OF THE CYCLOTRON EFFECTIVE MASS IN Pt †

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Detailed and accurate measurements of the cyclotron effective masses for both s- and d-like carriers have been made in Pt. Comparison with recent augmented-plane-wave band-structure calculations indicate that the many-body mass enhancement factor is roughly isotropic with a value of about 1.5.

Recent band-structure calculations in Pt[1,2] have attempted to expain its anomalously large heat capacity[3,4] and magnetic susceptibility.[4-6] These calculations have shown, however, that in order to achieve quantitative agreement with experiments many-body interactions must be considered. Two well-known contributions to the density of states in addition to that due to band structure are electron-electron and electron-phonon interaction. Recently a third mechanism has been suggested[7-10] that in special cases could greatly enhance the density of states. This is the so-called exchange enhancement due to short-lived spin fluctuations. Estimates of the magnitude of this exchange enhancement in Pt have varied from 2 to 8, but these estimates were based on simple models and appear, from the results of the present experiment, to be quantitatively in error.

Detailed and accurate de Haas–van Alphen (dHvA) measurements of both the extremal areas and cyclotron effective masses on all the sheets of the Fermi surface of Pt have been made. The extremal area measurements and a detailed description of the shape of the Pt Fermi surface deduced from them will be the subject of a separate Letter.[11] The Pt Fermi surface consists of three distinct sheets not related by symmetry: (1) an approximately spherical s-like electron surface centered at the point Γ of the Brillouin zone[12]; (2) a set of d-like hole surfaces having the form of ellipsoids of revolution, centered on the points X and prolate along the line ΓX with major-to-minor axis ratio[13] of 1.56; (3) an open d-like hole surface having the topology of cylinders extending in the [100] directions and intersecting in pairs at the points X. A section of this latter surface, drawn in the extended zone representation, is shown in Fig. 1.[14]

Cyclotron effective masses were determined (to an accuracy usually better than 0.5%) by measuring the amplitude of the dHvA oscillations as a function of temperature. After the masses are determined by this technique, the Dingle scattering temperature (and thus the relaxation time) can be estimated from the field dependence of the amplitude. Estimates at several orientations in the (110) plane for each of the carriers yielded Dingle temperatures in the range 0.3-0.5°K.

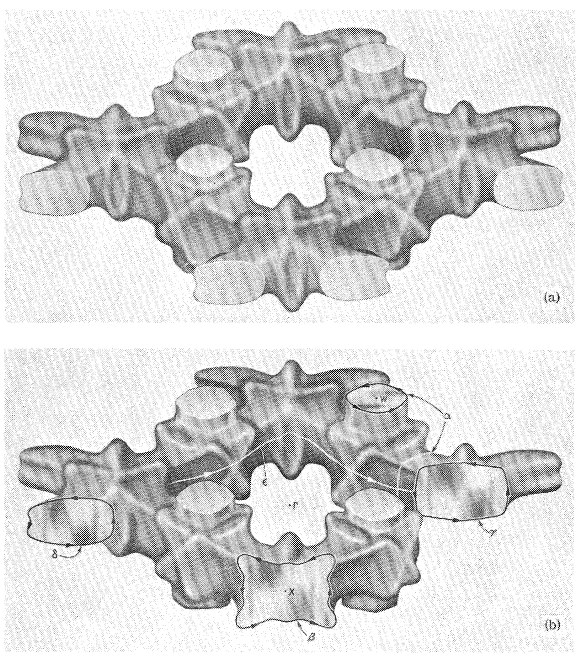

FIG. 1. (a) The open d-like hole surface as constructed by Dr. F. M. Mueller from the results of his combined interpolation scheme calculations shown in the extended-zone representation. The cylinderlike sections extend in the [100] directions and intersect in pairs at the point X of the Brillouin zone. (b) Orbits enclosing extremal cross-sectional areas normal to the magnetic field in the [100] and [110] directions. The β orbit, around a junction of two cylinders, is centered on point X and corresponds to a maximum extremal area. The γ orbits are noncentral minimums of the extremal areas in planes parallel to the β-orbit plane.

The angular variations of the cyclotron effective masses for field directions in the (110) plane are shown in Fig. 2. The upper branch, corresponding to the Γ-centered electron surface, shows an anisotropy for the cyclotron mass which is similar but larger in magnitude than that found for the extremal areas. Near [111] this surface has two extremal cross sections, a result of small bumps on the surface in the [100] and [111] directions, and the smaller mass section of this branch corresponds to the central extremal section. The lower branch in Fig. 2, existing within 30° of [100], corresponds to the effective cyclotron mass of the α orbit on the hole surface shown in Fig. 1. The amplitude of this branch decreases abruptly about 30° from [100] in this plane and disappears. Since the cyclotron effective mass is relatively small, it is probable that the α orbit ceases to exist due to the geometrical features of this surface.

The orientations where the amplitude of the dHvA oscillations vanished because of spin splitting are indicated in Fig. 2 by vertical lines. At such orientations the value of the cyclotron effective mass can be used to calculate the effective orbital g factor. From this it is possible to infer that the effective orbital g factor for the electron surface is anisotropic and probably varies by the same order of magnitude as the cyclotron effective mass.

The anisotropy of the cyclotron effective mass

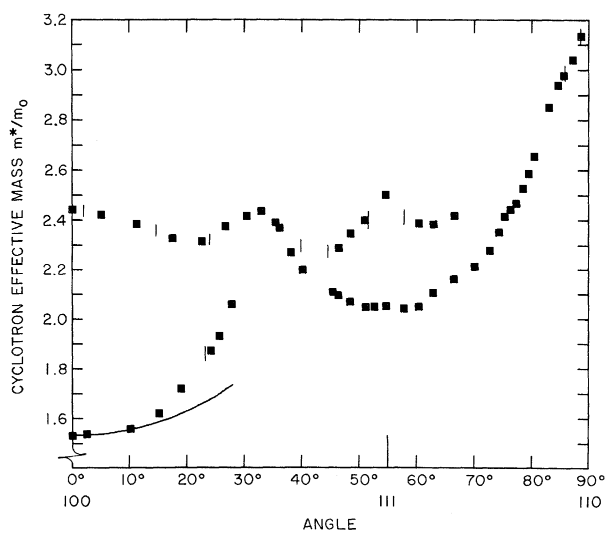

FIG. 2. Cyclotron effective masses observed in platinum for magnetic-field directions in the (110) plane.

Table I. Experimental and theoretical values of the cyclotron effective mass in platinum.

		Theory	Experimental	Enhancement
Electron surface	[100]	1.68	2.44	1.45
	[110]	2.07	3.16[a]	1.52
	[111]	1.43	2.06	1.44
Open-hole surface				
α orbit	[100]	0.88	1.53	1.74
β orbit	[110]	6.7		
γ orbit	[110]		3.32	
δ orbit	[110]		3.62	
Ellipsoids	[100]		0.426	
	[111]		0.363[b]	
	[110]		0.327	

[a]Extrapolated.
[b]Dr. Stafleu has informed us of an error in his reported value for the cyclotron effective mass (Ref. 8). His corrected value is in agreement with the present measurement.

of the γ and δ orbits (Fig. 1) near [110] in the (110) plane was also studied, the γ orbit rising from a value of 3.22 at [110] to 3.66, 10° away from [110], and the δ orbit rising from a value of 3.62 at [110] to 4.54, 10° away from [110]. The central section orbit β (Fig. 1) was not observed. The augmented-plane-wave (APW) calculation[1] predicts, however, an unenhanced cyclotron effective mass of 6.7 for this orbit, far too large to be observed in this experiment. The arm orbit δ is expected to split into two distinct branches for field directions near [110] but not in the (110) plane, and this splitting was observed in a separate experiment.

All the observed effective cyclotron masses for the field along the [100], [110], and [111] directions are listed in Table I. These values are compared in Table I with the APW masses calculated by Andersen and Mackintosh[1] and the apparent mass enhancement factor tabulated. The total mass enhancement factor is roughly isotropic with a value of about 1.5. The exchange enhancement factor need not be isotropic but must certainly be less than 1.5 for all orientations in the (110) plane, since electron-electron and electron-phonon interactions are also included in this figure.

Finally, it should be noted that, to the authors' knowledge, this is the first detailed study of the anisotropy of the cyclotron effective mass using the dHvA effect. The traditional technique for measuring these masses has been cyclotron-resonance experiments. Unfortunately, cyclotron-resonance experiments have been plagued with several difficulties which have limited their usefulness and accuracy. First, extremely pure, unstrained crystals with very carefully prepared surfaces are required. In addition, none of the discrimination techniques for distinguishing between competing resonances are at present being employed. Furthermore, the measurements are carried out at a relatively low phase so that the total number of observed resonances is limited. No such limitations exist if the effective cyclotron masses are determined from the dHvA effect when full advantage is taken of the frequency discrimination and excellent sensitivity inherent in the field-modulation measurement technique. With careful temperature measurement and a highly linear detection system, the present experiments illustrate that very accurate and complete results can be obtained.

We would like to thank Bill Rosevear and J. S. Tait for aid in data acquisition and equipment construction.

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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.

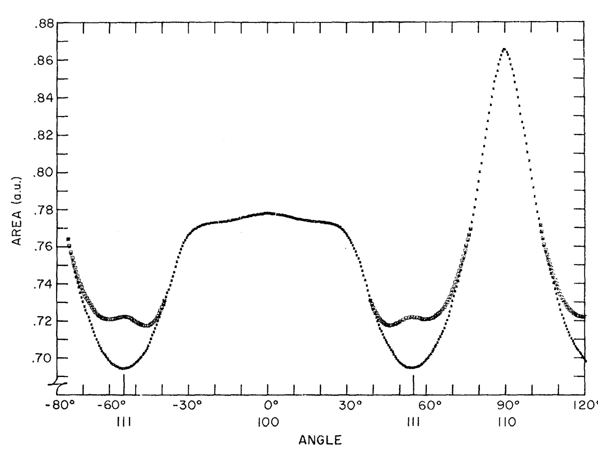

FIG. 1. The s-band extremal areas observed in Pt for H in the (110) plane.

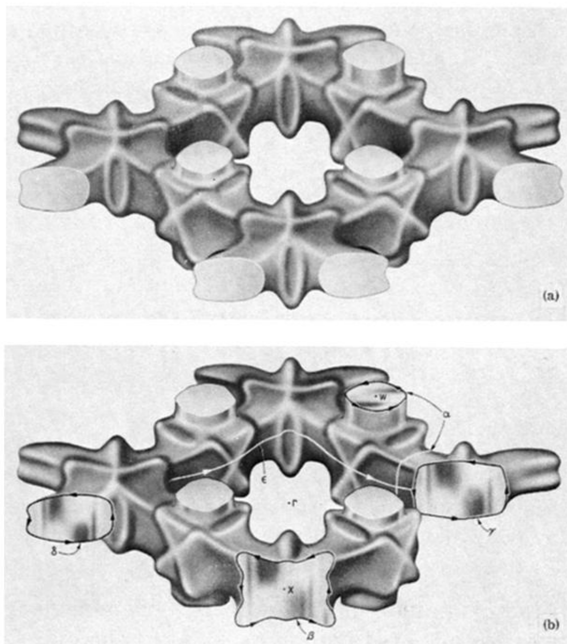

FIG. 1. (a) The open d-like hole surface as constructed by Dr. F. M. Mueller from the results of his combined interpolation scheme calculations shown in the extended-zone representation. The cylinderlike sections extend in the [100] directions and intersect in pairs at the point X of the Brillouin zone. (b) Orbits enclosing extremal cross-sectional areas normal to the magnetic field in the [100] and [110] directions. The β orbit, around a junction of two cylinders, is centered on point X and corresponds to a maximum extremal area. The γ orbits are noncentral minimums of the extremal areas in planes parallel to the β-orbit plane.