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[2]A. Baldareschi and F. Bassani, Phys. Rev. Letters 19, 66 (1967).

[3]The behavior of Landau levels in the neighborhood of a singular point was also treated by M. Ya. Azbel' {Zh. Eksperim. i Teor. Fiz. 39, 1276 (1960) [translation: Soviet Phys.-JETP 12, 891 (1961)]}. His work is closely connected with a similar problem. However, his considerations do not apply to those effects in which the energy must be considered fixed; e.g., the only interacting electrons belong to the Fermi surface, as in the case for the magnetoacoustic absorption.

[4]Cf., e.g., V. L. Gurewich, V. G. Skobov, and Y. A. Firsov, Zh. Eksperim. i Teor. Fiz. 40, 786 (1961) [translation: Soviet Phys.-JETP 13, 552 (1961)]; M. Giura, T. Papa, R. Marcon, and F. Wanderlingh, Nuovo Cimento 51B, 150 (1967).

[5]For $\epsilon > \epsilon_0$ the role of k_x and k_y are interchanged. The result is the same.

[6]Fifty-second Congress of the Italian Society of Physics, Bologna, Italy, October, 1967 (unpublished), Paper 3b.B7.

POSITRON ANNIHILATION IN COPPER SINGLE CRYSTALS AND ITS RELEVANCE TO THE FERMI SURFACE*

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Positron annihilation studies with a collinear point detector geometry have been carried out on a copper single crystal and reveal an angular dependence consistent with the shape of the Fermi surface superimposed upon an anisotropic contribution from the filled Brillouin zones.

The first attempt to relate the results of positron annihilation in copper single crystals to the shape of the copper Fermi surface was made by Berko and Plaskett.[1] Their results revealed little anisotropy since their detector geometry was arranged in the standard manner known as the "wide-slit" geometry. In this geometry the specimen is placed with respect to two parallel detector slits so that coincidences are detected only between annihilation γ rays corresponding to a well-defined z component of the center-of-mass momentum of the electron-positron pair. No restriction is placed upon the size of the other momentum components. The results obtained revealed that a considerable fraction of the annihilation occurred at momenta larger than the Fermi momentum, and it was suggested that the results could be treated as a superposition of the momentum distribution of the $3d$ and $4s$ electrons.

Fujiwara and collaborators[2] have since improved the resolution by restricting the length of the two slits so as to limit a second component of the momentum to a value less than the Fermi momentum. This substantially reduces the fraction of the coincidences due to high-momentum states while retaining those due to states within the Fermi surface. The results reveal considerable structure which may be correlated with the known Fermi surface of copper[3]; in particular, the necks forming contact with the Brillouin-zone boundary may be detected. In a preliminary experiment[4] using a rather different detection geometry which we shall call a collinear point geometry, our group independently observed the necks in the copper Fermi surface. The present Letter reports an experiment carried out with improved resolution.

The specimens used were copper single crystals which were neutron irradiated at Chalk River to produce positron-active Cu^{64} (half-life 12.7 h) and then flown to Vancouver. The initial positron activity of the samples of approximately 200 mCi allowed useful measurements to be taken for two days. Each detector presented a small circular aperature of 6 mm diam to the γ rays, and the detectors and sample were arranged collinearly so that coincidences were detected only between γ-ray pairs having an angular correlation of 180° to within the resolution of the apparatus. The detectors were 25 ft distant from the specimen and the experimental resolution function was calculated to be closely a Gaussian of half-width 1 mrad with cylindrical symmetry about the axis of the apparatus.

Neglecting the small effect of the positron momentum, the coincidences observed correspond, in the limit of infinitely narrow resolution, to those electrons whose momenta are in the direction of the γ-ray detectors. Were

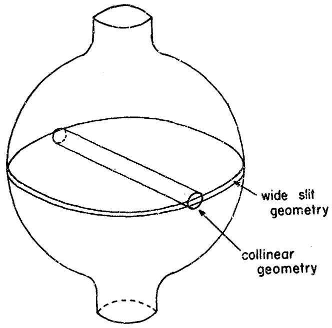

FIG. 1. Diagram illustrating the regions in k space sampled by the wide slit and collinear point geometries, respectively, for a model Fermi surface.

the annihilation to occur solely with those electrons occupying states in the unfilled Brillouin zone which contains the Fermi surface, and if the annihilation probability were independent of the k state of the electron, the coincidence rate would be proportional to the diameter of the Fermi surface in the direction of the detectors. Rotation of the crystal would then reveal the shape of the surface. Figure 1 illustrates the states selected by the two types of detector geometry.

Figure 2(a) shows the experimental results obtained from a rotation about the [111] axis with the detectors placed at an angle of $70\frac{1}{2}°$ to this axis so that the other three [111] axes appear at 120° intervals. This rotation was chosen because the necks were of major interest and its three-fold symmetry improved the statistics. Figure 2(b) shows the results of

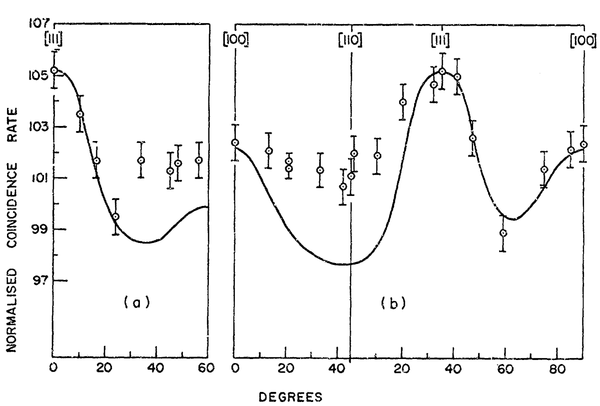

FIG. 2. Experimental results. The solid line is obtained from a 50% contribution calculated using Roaf's Fermi surface added to a 50% isotropic contribution. The experimental resolution function width of 1 mrad corresponds to a width at the Fermi surface of 13 deg.

more conventional rotations. Also shown for comparison is a curve showing a 50% isotropic contribution added to a 50% contribution of the form expected from the unfilled Brillouin zone by folding the experimental resolution function into Roaf's[5] four-parameter expression for the copper Fermi surface. The following points are worthy of comment:

(a) The experimental results are clearly not interpretable in terms of an isotropic contribution from the filled Brillouin zones. Furthermore, since the angular dependence of this contribution is unknown, there is some doubt as to its magnitude. The deduced 50% contribution is in reasonable agreement with an extrapolation of the results of Fujiwara, and with this assumption the results reveal an anisotropy of this contribution of about 8% (i.e., 4% of the total) in directions close to the [110] direction, which is the nearest-neighbor direction and the direction of maximum overlap of the 3d functions. The early data[1] show a similar increase in the high-momentum annihilation in this orientation, and we intend to study the orientation dependence of the annihilation at momenta greater than the Fermi momentum to obtain more information about the filled Brillouin zones. However, the value of 50% is unlikely to be in error by more than 10% in view of the good fit in orientations away from the [110] direction.

(b) The dependence of the annihilation probability upon the k state of the electron has been shown to agree with the theoretical predictions of a 10% increase as k tends to k_F in sodium.[6] Any such effect in copper should enhance the Fermi-surface structure.

(c) Copper was chosen for this study since the crystal itself could be made positron radioactive and because its Fermi surface is confined to one Brillouin zone. The large contribution from the filled zones complicates the analysis and reduces the accuracy of the Fermi-surface determination, but it is clear that features exhibiting rapid angular variations such as the necks can be studied with some confidence. This technique has since been applied to the study of $Cu_{70}Zn_{30}$ alloy.[7] This technique should be especially valuable in determining Fermi surfaces of materials with small contributions to the annihilation from the filled zones, and we believe it to be limited mainly by the resolution required in the time available for the experiment.

(d) It should be noted that the present method is not appreciably affected by any smearing of the momentum distribution by such factors as the thermalization of the positron. This is in contrast to the method relying upon the discontinuity of the slope in the momentum distribution.[8]

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SPIN-WAVE RESONANCE IN "FLASH-EVAPORATED" PERMALLOY FILMS

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It is shown that the recent Letter by Lykken which claims to confirm Kittel's model of standing-spin-wave resonance in Permalloy films does not in fact confirm that model.

In a recent Letter[1] it is claimed that the Kittel model of standing-spin-wave resonances[2] in ferromagnetic films is confirmed. We wish to point out that the data presented in Figs. 1 and 2 of that Letter do not confirm this model. Kittel's model is a perfectly uniform film with the surface spins partially or completely pinned. For complete pinning a uniform rf field will excite the sinusoidal modes with an odd number of half-wavelengths, $n=1,3,5,\cdots$, equal to the film thickness, where the fields for the resonances H_n are displaced from the field for the uniform precession H_0 by $H_0-H_n \propto n^2$ and the intensities of the modes vary as n^{-2}.

The intensities taken from Fig. 1 of Ref. 1 together with the theoretical values for the completely pinned Kittel model are shown in Table I. The agreement is poor. If the pinning is assumed to be less than complete, the theoretical values for $n \cong 3, 5, \cdots$ will become smaller and the discrepancy will increase. One may be able to ascribe the disagreement to a nonuniform rf field, but then Kittel's model is not demonstrated since a uniform rf field is a requirement for its demonstration. Furthermore, in order to get an rf field nonuniform enough to produce higher order modes of the intensity shown, one must allow the microwave energy to impinge on only one side of the film as done by Holzer, Perry, and Portis.[3]

The second point of disagreement between the data presented in Ref. 1 and the Kittel model is the departure from quadratic mode spacing for the first mode [Fig. 2, curve (a)]. It is characteristic of inhomogeneous films that the lower order modes are not spaced as n^2.[4,5] Yet, higher order modes always tend toward quadratic spacing for almost all films.[6-8] This is true for weakly inhomogeneous films with any strength of surface-spin pinning since the wave functions always tend to become sinusoi-

Table I. Comparison of the experimental mode intensities from Ref. 1, Fig. 1, with the theoretical values from the Kittel model with complete pinning. The intensities of the mode $n=1$ are normalized to unity.

n	Experimental intensities	Theoretical intensities
1	1	1
2	0.250	0
3	0.500	0.111
4	0.116	0
5	0.047	0.040
6	0.014	0
7	0.024	0.020
8	0.006	0
9	0.007	0.012